

THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION



Task Committee on Standardization of Reference Evapotranspiration

**Environmental and Water Resources Institute
of
the American Society of Civil Engineers**

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THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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ABSTRACT

This report describes the standardization of calculation of reference evapotranspiration (ET) as recommended by the Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of the American Society of Civil Engineers. The purpose of the standardized reference ET equation and calculation procedures is to bring commonality to the calculation of reference ET and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use. The basis of the standardized reference ET equation is the ASCE Penman-Monteith (ASCE-PM) method of ASCE Manual 70. For the standardization, the ASCE-PM method is applied for two types of reference surfaces representing clipped grass (a short, smooth crop) and alfalfa (a taller, rougher agricultural crop), and the equation is simplified to a reduced form of the ASCE-PM. Standardized calculations for vapor pressure, net radiation and wind speed adjustment are recommended for application to hourly and daily calculation time steps. Guidelines on assessing weather data integrity and estimating values for missing data are provided.

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Task Committee on Standardization of Reference Evapotranspiration

PREFACE

The concept of reference evapotranspiration (ET) was developed in the 1970's as a practical and definable replacement for the term potential ET. Reference ET is a function of local weather, represents the ET from a defined vegetated surface, and serves as an evaporative index by which engineers, hydrologists, water managers and other technical professionals can predict ET for a range of vegetation and surface conditions by applying "crop" coefficients for agricultural or landscaped areas. During the past decade, for convenience and reproducibility, the reference surface has been expressed as a hypothetical surface having specific characteristics. In the context of this standardization, reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation. The EWRI Task Committee concluded that two standardized surfaces were needed to serve the needs of the agricultural and landscape communities and to provide for continuity with past reference ET usage. The ASCE Penman-Monteith (ASCE-PM) equation of ASCE Manual 70 is used to represent the standardized surface and is applied for two types of surfaces (short and tall)-- clipped, cool-season grass and alfalfa.

This recommended standardization follows commonly used procedures for calculating vapor pressure terms, net radiation, and soil heat flux. The standardization represents reference ET for each of the reference surfaces using a single equation having fixed constants and standardized computational procedures. The computational procedures are relatively simple to apply, are understandable, are

supported by existing and historical data, are technically defensible, and are accepted by science and engineering communities. The Task Committee recognizes that the standardized reference equation, with fixed coefficients defining vegetation and surface conditions, may not correspond precisely with local measurements of ET from surfaces similar to the clipped, cool-season grass and full-cover alfalfa definitions. However, the Task Committee encourages the use of the standardized equation and procedure when possible to represent reference ET for the establishment of reproducible and universally transferable ET estimates, climatic description, and derived crop and landscape coefficients. The standardized equation has been investigated over a wide range of locations and climates across the United States and has the Task Committee's confidence for use as a standardized index of evapotranspirative demand.

Some of the computational procedures of the standardized reference method, for example, the computation of net radiation, may be updated by EWRI from time to time in the future, as developments and improvements in generalized computational techniques are made.

The development of this standardization report by EWRI was made at the request of, and has been endorsed by, the Irrigation Association.

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THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

**Task Committee on Standardization of Reference Evapotranspiration¹ of the
Environmental and Water Resources Institute of the American Society of Civil
Engineers**

INTRODUCTION

In May 1999, The Irrigation Association (IA) requested the Evapotranspiration in Irrigation and Hydrology Committee – Environmental and Water Resources Institute (American Society of Civil Engineers) (ASCE-ET) to establish and define a benchmark reference evapotranspiration equation. The purpose of the benchmark equation is to standardize the calculation of reference evapotranspiration and to improve transferability of crop coefficients.

IA envisioned an equation that would be accepted by the U.S. scientific community, engineers, courts, policy makers, and end users. The equation would be applicable to agricultural and landscape irrigation and would facilitate the use and transfer of crop and landscape coefficients. In addition, IA requested guidelines for using the equation in regions where climatic data are limited and recommendations for

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incorporating existing crop and landscape coefficients and existing reference ET calculations.

An ASCE-ET Task Committee (TC) comprised of the authors of this report responded to the request by IA. Their initial response is included in Appendix A. Members of the TC jointly authored several papers (Allen, et al., 2000; Itenfisu, et al., 2000; Walter, et al., 2000) at the IA 4th National Irrigation Symposium in November 2000 that described issues, challenges and analyses conducted by the TC. This report provides detail on development of the ASCE Standardized equation, recommendations on use of the equation, and example calculations. In addition, this report provides guidelines for assessing the integrity of weather data used for estimating ET and methodologies that can be used where data are limited or missing.

DEFINITION OF THE EQUATION

Evapotranspiration (ET) represents the loss of water from the earth's surface through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration (i.e., internal evaporation). Reference evapotranspiration (ET_{ref}) is the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). For convenience and reproducibility, the reference surface has recently been expressed as a hypothetical crop (vegetative) surface with specific characteristics (Smith et al., 1991, Allen et al., 1994a, Allen et al., 1998). In the context of this standardization report, reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation.

ASCE-ET recommends that the equation be referred to as the “Standardized Reference Evapotranspiration Equation” (ET_{sz}). ASCE-ET is of the opinion that use of the terms *standard* or *benchmark* may lead users to assume that the equation is

intended for comparative purposes (i.e., a level to be measured against). Rather, the use of the term “standardized” is intended to infer that the computation procedures have been fixed, and not that the equation is a standard or a benchmark or that the equation has undergone the degree of review in the approval process necessary for standards adopted by ASCE, ASAE, American National Standards Institute, or the International Organization for Standardization.

ASCE-ET and IA-WM members concluded that two ET_{ref} surfaces with *standardized* computational procedures were needed. The two adopted ET_{ref} surfaces are (1) a short crop (similar to clipped grass) and (2) a tall crop (similar to full-cover alfalfa). Additionally, the TC recognized that an equation capable of calculating both hourly and daily ET_{ref} was needed.

RECOMMENDATION

ET_{ref} from each of the two surfaces is modeled using a single Standardized Reference Evapotranspiration equation with appropriate constants and standardized computational procedures. The surfaces/equation are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_{os}): Reference ET for a *short* crop with an approximate height of 0.12 m (similar to clipped, cool-season grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_{rs}): Reference ET for a *tall* crop with an approximate height of 0.50 m (similar to full-cover alfalfa).

The two surfaces are similar to known full-cover crops of alfalfa and clipped, cool-season grass that have received widespread use as ET_{ref} across the United States. Each reference has unique advantages for specific applications and times of the year. As a part of the standardization, the ASCE Penman-Monteith (ASCE-PM) equation

(Appendix B and Jensen et al., 1990), and associated equations for calculating aerodynamic and bulk surface resistance have been combined and condensed into a single equation that is applicable to both surfaces.

The Standardized Reference Evapotranspiration Equation is intended to simplify and clarify the presentation and application of the method. As used in this report, the term ET_{sz} refers to both ET_{os} and ET_{rs} . Eq. 1 presents the form of the Standardized Reference Evapotranspiration Equation:

$$ET_{sz} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)} \quad (1)$$

where:

- ET_{sz} = standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps),
- R_n = calculated net radiation at the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),
- G = soil heat flux density at the soil surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),
- T = mean daily or hourly air temperature at 1.5 to 2.5-m height ($^{\circ}\text{C}$),
- u_2 = mean daily or hourly wind speed at 2-m height (m s^{-1}),
- e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,
- e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
- Δ = slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$),
- γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$),
- C_n = numerator constant that changes with reference type and calculation time step ($\text{K mm s}^3 \text{Mg}^{-1} \text{d}^{-1}$ or $\text{K mm s}^3 \text{Mg}^{-1} \text{h}^{-1}$) and
- C_d = denominator constant that changes with reference type and calculation time step (s m^{-1}).

Units for the 0.408 coefficient are $\text{m}^2 \text{mm MJ}^{-1}$.

Table 1 provides values for C_n and C_d . The values for C_n consider the time step and aerodynamic roughness of the surface (i.e., reference type). The constant in the denominator, C_d , considers the time step, bulk surface resistance, and aerodynamic roughness of the surface (the latter two terms vary with reference type, time step and daytime/nighttime). C_n and C_d were derived by simplifying several terms within the ASCE-PM equation and rounding the result. Equations associated with calculation of required parameters in Eq. 1, the detailed derivation of the parameters in Table 1 and simplification of the terms listed in Table 2 are explained in more detail in Appendix B. Daytime is defined as occurring when the average net radiation, R_n , during an hourly period is positive.

Table 1. Values for C_n and C_d in Eq. 1

Calculation Time Step	Short Reference, ET_{os}		Tall Reference, ET_{rs}		Units for ET_{os} , ET_{rs}	Units for R_n , G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d ⁻¹	MJ m ⁻² d ⁻¹
Hourly during daytime	37	0.24	66	0.25	mm h ⁻¹	MJ m ⁻² h ⁻¹
Hourly during nighttime	37	0.96	66	1.7	mm h ⁻¹	MJ m ⁻² h ⁻¹

Table 2. ASCE Penman-Monteith Terms Standardized for Application of the Standardized Reference Evapotranspiration Equation

Term	ET_{os}	ET_{rs}
Reference vegetation height, h	0.12 m	0.50 m
Height of air temperature and humidity measurements, z_h	1.5 – 2.5 m	1.5 – 2.5 m
Height corresponding to wind speed, z_w	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m ^a
Latent heat of vaporization	2.45 MJ kg ⁻¹	2.45 MJ kg ⁻¹
Surface resistance, r_s , daily	70 s m ⁻¹	45 s m ⁻¹
Surface resistance, r_s , daytime	50 s m ⁻¹	30 s m ⁻¹
Surface resistance, r_s , nighttime	200 s m ⁻¹	200 s m ⁻¹
Value of R_n for predicting daytime	> 0	> 0
Value of R_n for predicting nighttime	≤ 0	≤ 0

^a The zero plane displacement height for ET_{rs} assumes that the wind speed measurement is over clipped grass, even though the reference type is tall. This is done to accommodate a majority of weather stations that are located over

grass. See comments in Appendix B following Eq. B.14b. When wind speed is measured over a surface having vegetation taller than about 0.3 m, it is recommended that the “full” ASCE Penman-Monteith method (Eq. B.1) be employed, where the zero plane displacement can be varied. However, the standardized ET_{sz} equation can be used if wind speed are adjusted following guidelines in Appendix B.

USE OF THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Based on an intensive review of reference evapotranspiration calculated for 49 sites throughout the United States (as described in the following section), ASCE-ET found the standardized reference evapotranspiration equation to be reliable and recommends its use for:

- Calculating reference evapotranspiration and, in turn, crop evapotranspiration (ET_c)
- Developing new crop coefficients
- Facilitating transfer of existing crop coefficients

CALCULATING STANDARDIZED REFERENCE CROP EVAPOTRANSPIRATION

This section describes data requirements, equations, and procedures necessary for calculating ET_{sz} on a daily and hourly time step. A daily time step has historically been commonly used in the calculation of ET_{ref} . Selection of the appropriate time step is a function of data availability, climate, the intended application, and user preference.

REQUIRED DATA FOR THE STANDARDIZED REFERENCE EQUATION

The calculation of ET_{sz} requires measurements or estimates for air temperature, humidity, solar radiation, and wind speed. These parameters are considered to be the minimum requirements to estimate ET_{os} and ET_{rs} . Examples of the calculation of ET_{sz} are provided in Appendix C. When humidity, solar radiation or wind speed measurements are not available, substitute values for daily and longer time periods may be estimated using procedures described in Appendix E.

The accuracy of any evapotranspiration calculation depends on the quality of the weather data, which requires good quality control and quality assurance procedures. When possible, weather data should be measured at stations that are located in open, well-watered, vegetated settings (preferably grass). Preferred locations have low growing, well-watered vegetation in the immediate and near vicinity of the weather station (~50 m) and mostly the same or other well-watered vegetation for a few hundred meters beyond that². Suggestions for assessing and improving the integrity of collected weather data are described in Appendix D. Appendix D also provides

² This recommendation is similar to those found in ASAE Engineering Practice EP505 (ASAE 2004).

guidelines for evaluating the weather station site and the possible impact upon the measured meteorological parameters. Suggestions for replacing missing data or data that are of poor quality are presented in Appendix E.

Appendix B provides background on the development of the standardized form of the ASCE equation. The full form of the ASCE-PM equation, which includes explicit terms for aerodynamic and surface resistance, is not required, nor is it recommended, for calculation of ET_{sz} . The full form of the ASCE-PM equation is recommended when ET is measured over grass or alfalfa vegetation having substantially different height than the 0.12 m height defined for the short reference (grass) or 0.50 m height defined for the tall reference (alfalfa). Values for vegetation height are fixed in the standardized equation.

CALCULATIONS REQUIRED FOR DAILY TIME-STEPS

The calculation process for ET_{sz} for daily time steps is presented in this section. Several of the calculations are identical to those required for hourly time steps. Some equations are repeated in the hourly calculation section so as to detail that calculation process completely.

Psychrometric and Atmospheric Variables³

Latent Heat of Vaporization (λ)

The value of the latent heat of vaporization, λ , varies only slightly over the ranges of air temperature that occur in agricultural or hydrologic systems. For ET_{sz} , a constant value of $\lambda = 2.45 \text{ MJ kg}^{-1}$ is recommended. The inverse of $\lambda = 2.45 \text{ MJ kg}^{-1}$ is approximately 0.408 kg MJ^{-1} . The density of water (ρ_w) is taken as 1.0 Mg m^{-3} so that the inverse ratio of $\lambda \rho_w$ times energy flux in $\text{MJ m}^{-2} \text{ d}^{-1}$ equals 1.0 mm d^{-1} .

Mean Air Temperature (T)

For the standardized method, the mean air temperature, T , for a daily time step is preferred as the mean of the daily maximum and daily minimum air temperatures rather than as the average of hourly temperature measurements to provide for consistency across all data sets.

$$T = \frac{T_{\max} + T_{\min}}{2} \quad (2)$$

where:

- T = daily mean air temperature [$^{\circ}\text{C}$]
- $T_{\max}$ = daily maximum air temperature [$^{\circ}\text{C}$]
- $T_{\min}$ = daily minimum air temperature [$^{\circ}\text{C}$]

³ Many of the equations presented here are the same as those reported in ASCE Manual 70 (Jensen et al., 1990) and in FAO-56 (Allen et al., 1998).

Atmospheric Pressure (P)

The mean atmospheric pressure at the weather site is predicted from site elevation using a simplified formulation of the Universal Gas Law⁴:

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26} \quad (3)$$

where:

P = mean atmospheric pressure at station elevation z [kPa], and
 z = weather site elevation above mean sea level [m].

Psychrometric Constant (γ)

The standardized application using $\lambda = 2.45 \text{ MJ kg}^{-1}$ results in a value for the psychrometric constant, γ , that is proportional to the mean atmospheric pressure:

$$\gamma = 0.000665 P \quad (4)$$

where P has units of kPa and γ has units of kPa °C⁻¹.

Note: The variable γ is not the same variable as γ_{psy} used later in Eqs. 9 and 10 for converting psychrometric data (wet bulb and dry bulb temperature) to vapor pressure.

Slope of the Saturation Vapor Pressure-Temperature Curve (Δ)

The slope of the saturation vapor pressure-temperature curve⁵, Δ , is computed as:

$$\Delta = \frac{2503 \exp\left(\frac{17.27 T}{T + 237.3}\right)}{(T + 237.3)^2} \quad (5)$$

⁴ Reference: Burman et al. (1987)

⁵ References: Tetens (1930), Murray (1967)

where:

$$\begin{aligned}\Delta &= \text{slope of the saturation vapor pressure-temperature curve [kPa } ^\circ\text{C}^{-1}\text{]}, \\ &\text{and} \\ T &= \text{daily mean air temperature [} ^\circ\text{C}\text{]}.\end{aligned}$$

Saturation Vapor Pressure (e_s)

The saturation vapor pressure⁶ (e_s) represents the capacity of the air to hold water vapor.

For calculation of daily ET_{sz} , e_s is given by:

$$e_s = \frac{e^0(T_{\max}) + e^0(T_{\min})}{2} \quad (6)$$

where:

$$e^0(T) = \text{saturation vapor pressure function (Eq. 7) [kPa]}$$

The function to calculate saturation vapor pressure is:

$$e^0(T) = 0.6108 \exp\left(\frac{17.27 T}{T + 237.3}\right) \quad (7)$$

where vapor pressure is in units of kPa and temperature is in $^\circ\text{C}$.

Actual Vapor Pressure (e_a)

Actual vapor pressure (e_a) is used to represent the water content (humidity) of the air at the weather site. The actual vapor pressure can be measured or it can be calculated from various humidity data, such as measured dew point temperature, wet-bulb and dry-bulb temperature, or relative humidity and air temperature data.

Preferred procedures for calculating e_a

When multiple types of humidity or psychrometric data are available for estimating e_a , the preferences listed in Table 3 are recommended for the calculation method. These recommendations are based on the likelihood that the data will have integrity and that estimates for e_a will be representative. The availability and quality of local data, as well as site conditions, may justify a different order of preference.

Table 3. Preferred method for calculating e_a for daily ET_{sz}

Method No.	Method	Preference Ranking	Equation(s)
1	e_a averaged over the daily period (based on hourly or more frequent measurements of humidity) ^{a,b}	1	7, 41
2	Measured or computed dew point temperature averaged over the daily period	1	8
3	Wet-bulb and dry-bulb temperature averaged over the daily period	2	7, 9, 10
4	Measured or computed dew point or measured wet-bulb and dry-bulb temperature at 7 or 8 am	2	8 or 7, 9, 10
5	Daily maximum and minimum relative humidity	2	7, 11
6	Daily maximum relative humidity	3	7, 12
7	Daily minimum relative humidity	3	7, 13
8	Daily minimum air temperature (see Appendix E)	4	--
9	Daily mean relative humidity	4	7, 14

^a In many data sets, e_a may be expressed in terms of an equivalent dew point temperature.

^b Some data logging systems may measure relative humidity (RH) and T , but calculate e_a or T_{dew} internally for output as averaged values over some time interval. See ASAE (2004) for further detail.

⁶ Reference: Jensen et al. (1990) and Tetens (1930)

When humidity and psychrometric data are missing or are of questionable integrity, dew point temperature can be estimated from daily minimum air temperature as described in Appendix E. This estimation process should be verified locally. The assessment of weather data integrity is discussed in Appendix D.

e_a from measured dew point temperature

The dew point temperature (T_{dew}) is the temperature to which the air must cool to reach a state of saturation. For daily calculation time steps, average dew point temperature can be computed by averaging over hourly periods or, for purposes of estimating ET_{sz} , it can be determined by an early morning measurement (generally at 0700 or 0800 hours). The value for e_a is calculated by substituting T_{dew} into Eq. 7 resulting in:

$$e_a = e^o(T_{\text{dew}}) = 0.6108 \exp \left[\frac{17.27 T_{\text{dew}}}{T_{\text{dew}} + 237.3} \right] \quad (8)$$

e_a from psychrometric data

The actual vapor pressure can also be determined from the difference between the dry and wet bulb temperatures (i.e., the wet bulb depression) of the air:

$$e_a = e^o(T_{\text{wet}}) - \gamma_{\text{psy}} (T_{\text{dry}} - T_{\text{wet}}) \quad (9)$$

where:

- e_a = actual vapor pressure of the air [kPa],
- $e^o(T_{\text{wet}})$ = saturation vapor pressure at the wet bulb temperature [kPa] (Eq. 7),
- γ_{psy} = psychrometric constant for the psychrometer [kPa °C⁻¹], and
- $T_{\text{dry}} - T_{\text{wet}}$ = wet bulb depression,
- where
- T_{dry} = dry bulb temperature and
- T_{wet} = the wet bulb temperature [°C] (measured simultaneously).

The psychrometric constant for the psychrometer at the weather measurement site is given by:

$$\gamma_{\text{psy}} = a_{\text{psy}} P \quad (10)$$

where

a_{psy} = coefficient depending on the type of ventilation of the wet bulb [$^{\circ}\text{C}^{-1}$], and
 P = mean atmospheric pressure [kPa].

The coefficient a_{psy} depends primarily on the design of the psychrometer and on the rate of ventilation around the wet bulb. The following values are often used⁷:

a_{psy} = 0.000662 for ventilated (Asmann type) psychrometers having air movement between 2 and 10 m s^{-1} for $T_{\text{wet}} \geq 0$ and 0.000594 for $T_{\text{wet}} < 0$,
 = 0.000800 for naturally ventilated psychrometers having air movement of about 1 m s^{-1} , and
 = 0.001200 for non-ventilated psychrometers installed in glass or plastic greenhouses.

Generally, the wet-bulb and dry-bulb temperature data are measured once during the day.

e_a from relative humidity data

The actual vapor pressure of air can be calculated from relative humidity (RH) and the corresponding air temperature. When using RH data, it is essential that the RH and air temperature data are “paired,” i.e., that they represent the same time of day or time period and that they are taken at the weather measurement site. For daily data, daily maximum relative humidity (RH_{max}) can be paired with T_{min} , which will both

⁷ Allen et al., (1998).

occur, generally, during early morning. Daily minimum relative humidity ($RH_{\min}$) is paired with $T_{\max}$.

Depending on the availability of the RH data, the following equations apply, with preference of method listed in Table 3:

- Daily e_a from $RH_{\max}$ and $RH_{\min}$.

$$e_a = \frac{e^o(T_{\min}) \frac{RH_{\max}}{100} + e^o(T_{\max}) \frac{RH_{\min}}{100}}{2} \quad (11)$$

where:

- e_a = actual vapor pressure [kPa],
- $e^o(T_{\min})$ = saturation vapor pressure at daily minimum temperature [kPa],
- $e^o(T_{\max})$ = saturation vapor pressure at daily maximum temperature [kPa],
- $RH_{\max}$ = daily maximum relative humidity [%], and
- $RH_{\min}$ = daily minimum relative humidity [%].

When computing the average daily ET_{sz} during a week, a ten-day period or a month, $RH_{\max}$ and $RH_{\min}$ are obtained by averaging daily $RH_{\max}$ or $RH_{\min}$ values.

- Daily e_a from $RH_{\max}$

Older styles of electronic relative humidity sensors, for example those manufactured before about 1990, often experienced difficulty in accurately measuring RH when at low levels. When using equipment where errors in estimating $RH_{\min}$ may be large, or when integrity of the RH data is doubtful, the actual vapor pressure can be computed from $RH_{\max}$:

$$e_a = e^o(T_{\min}) \frac{RH_{\max}}{100} \quad (12)$$

When accuracy of RH data is in doubt, error in $RH_{\max}$ causes smaller error in e_a than error in $RH_{\min}$, due to the smaller value for the multiplier $e^o(T_{\min})$ as compared to $e^o(T_{\max})$. In addition, $RH_{\max}$ data are generally easier to assess for accuracy than is $RH_{\min}$. The value of $RH_{\max}$ generally exceeds 90% and approaches 100% in well-watered settings such as within irrigation projects and in sub-humid and humid climates. This proximity to 100% serves as a first check on reasonableness, representativeness, and integrity of the data. Exceptions to this trend are where substantial advection of dry or warm air from dry regions outside the area occurs during nighttime, including, but not limited to, some desert areas of New Mexico, Arizona and California.

- Daily e_a from $RH_{\min}$

Sometimes, only high quality estimates of daily $RH_{\min}$ are available and must be used to predict e_a :

$$e_a = e^o(T_{\max}) \frac{RH_{\min}}{100} \quad (13)$$

However, estimates using Eq. 13 may be less desirable than estimates using Eq. 11 or 12, due to greater impact of error in $RH_{\min}$ on e_a , as discussed previously. In addition, it is more difficult to assess the integrity of $RH_{\min}$ data (see Appendix D):

- Daily e_a from RH_{mean}

In the absence of $RH_{\max}$ and $RH_{\min}$ data, but where daily RH_{mean} data are available, the actual vapor pressure may be estimated as:

$$e_a = \frac{RH_{\text{mean}}}{100} e^o(T_{\text{mean}}) \quad (14)$$

where RH_{mean} is the mean daily relative humidity, generally defined as the average between $RH_{\max}$ and $RH_{\min}$ and T_{mean} is mean daily air temperature, defined in Eq. 2

Eq. 14 is less desirable than Eqs. 12 or 13 because the $e^o(T)$ relationship is nonlinear. Eq. 14 produces estimates of e_a that are closer to those by Eq. 11 and to daily average e_a computed from hourly values than is the use of alternative forms of Eq. 14, such as $e_a = RH_{\text{mean}}/100 [e^o(T_{\text{max}})+e^o(T_{\text{min}})]/2$ described in Allen et al., (1998) or as $e_a = RH_{\text{mean}}/100 [1/(50/e^o(T_{\text{max}}) + 50/e^o(T_{\text{min}}))]$ described in Smith et al., (1991). These latter two methods are not recommended in the standardized procedure.

Net Radiation (R_n)

Net radiation (R_n) is the net amount of radiant energy available at a vegetation or soil surface for evaporating water, heating the air, or heating the surface. R_n includes both short and long wave radiation components⁸:

$$R_n = R_{\text{ns}} - R_{\text{nl}} \quad (15)$$

where:

- R_{ns} = net short-wave radiation, [$\text{MJ m}^{-2} \text{ d}^{-1}$] (defined as being positive downwards and negative upwards),
- R_{nl} = net outgoing long-wave radiation, [$\text{MJ m}^{-2} \text{ d}^{-1}$] (defined as being positive upwards and negative downwards),

R_{ns} and R_{nl} are generally positive or zero in value.

Net radiation is difficult to measure because net radiometers are problematic to maintain and calibrate. There is good likelihood of systematic biases in R_n measurements. Therefore, R_n is often predicted from observed short wave (solar) radiation, vapor pressure, and air temperature. This prediction is routine and generally highly accurate. If R_n is measured, then care and attention must be given to the calibration of the radiometer, the surface over which it is located, maintenance of

⁸ Reference: Brutsaert (1982), Jensen et al., (1990), Wright (1982), Doorenbos and Pruitt (1975,1977), Allen et al., (1998).

the sensor domes, and level of the instrument. The condition of the vegetation surface is as important as the sensor. For purposes of calculating ET_{sz} , the measurement surface for R_n is generally assumed to be clipped grass or alfalfa at full cover.

Net Solar or Net Short-Wave Radiation (R_{ns})

Net short-wave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = R_s - \alpha R_s = (1 - \alpha) R_s \quad (16)$$

where:

- R_{ns} = net solar or short-wave radiation [$MJ\ m^{-2}\ d^{-1}$],
- α = albedo or canopy reflection coefficient, is fixed at 0.23 for the standardized short and tall reference surfaces [dimensionless], and
- R_s = incoming solar radiation [$MJ\ m^{-2}\ d^{-1}$].

The calculation of ET_{sz} uses the constant value of 0.23 for albedo for daily and hourly periods. It is recognized that albedo varies somewhat with time of day and with time of season and latitude due to change in sun angle. However, because the solar intensity is less during these periods, the error introduced in fixing albedo at 0.23 is relatively small (Allen et al., 1994b). Users may elect to use a different prediction for albedo, however, it is essential to ascertain the validity and accuracy of an alternative method using good measurements of incoming and reflected solar radiation. Some types of pyranometers are invalid for measuring reflected radiation due to the difference in spectral response between the instrument and reflecting surface. Predictions of R_n made using an alternate method for albedo (i.e., other than 0.23) may not agree with those made using the ASCE standardized procedure.

Net Long-Wave Radiation (R_{nl})

There are several variations and coefficients developed for predicting the net long wave component of total net radiation. The standardized ASCE procedure is the same as that adopted by FAO-56 and is based on the Brunt (1932, 1952) approach for predicting net emissivity. If users intend to utilize a different approach for calculating R_{nl} , it is essential to ascertain the validity and accuracy of their R_n method using net radiometers in excellent condition and that are calibrated to some dependable and recognized standard. In all situations, users should compare measured R_n or R_{nl} computed using an alternative method with R_n calculated using the standardized procedure. Substantial variation (more than 5 %) should give cause for concern and should indicate the need to reconcile or justify the differences.

R_{nl} , net long-wave radiation, is the difference between upward long-wave radiation from the standardized surface (R_{lu}) and downward long-wave radiation from the sky (R_{ld}), so that $R_{nl} = R_{lu} - R_{ld}$. The following calculation for daily R_{nl} follows the method of Brunt (1932, 1952) of using vapor pressure to predict net emissivity:

$$R_{nl} = \sigma f_{cd} \left(0.34 - 0.14 \sqrt{e_a} \right) \left[\frac{T_{K \max}^4 + T_{K \min}^4}{2} \right] \quad (17)$$

where:

- R_{nl} = net long-wave radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
- σ = Stefan-Boltzmann constant [$4.901 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{d}^{-1}$],
- f_{cd} = cloudiness function [dimensionless] (limited to $0.05 \leq f_{cd} \leq 1.0$),
- e_a = actual vapor pressure [kPa],
- $T_{K \max}$ = maximum absolute temperature during the 24-hour period [K] ($K = ^\circ\text{C} + 273.16$),
- $T_{K \min}$ = minimum absolute temperature during the 24-hour period [K] ($K = ^\circ\text{C} + 273.16$).

The superscripts “4” in Eq. 17 indicate the need to raise the air temperature, expressed in Kelvin units, to the power of 4. For daily and monthly calculation timesteps, f_{cd} is calculated as⁹:

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \quad (18)$$

where:

- R_s/R_{so} = relative solar radiation (limited to $0.3 \leq R_s/R_{so} \leq 1.0$),
- R_s = measured or calculated solar radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$], and
- R_{so} = calculated clear-sky radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$].

The ratio R_s/R_{so} in Eq. 18 represents relative cloudiness and is limited to $0.3 < R_s/R_{so} \leq 1.0$ so that f_{cd} has limits of $0.05 \leq f_{cd} \leq 1.0$.

Clear-Sky Solar Radiation (R_{so})

Clear-sky solar radiation (R_{so}) is used in the calculation of net radiation (R_n). Clear-sky solar radiation is defined as the amount of solar radiation (R_s) that would be received at the weather measurement site under conditions of clear-sky (i.e., cloud-free). The ratio of R_s to R_{so} in the equation for R_n is used to characterize the impact of cloud-cover on the downward emission of thermal radiation to the earth’s surface. Daily R_{so} is a function of the time of year and latitude. R_{so} is also impacted by station elevation (affecting atmospheric thickness and transmissivity), the amount of precipitable water in the atmosphere (affecting the absorption of some short-wave radiation), and the amount of dust or aerosols in the air.

Extraterrestrial radiation (R_a), as defined in Eq. 21, can be used as a means for determining a theoretical R_{so} envelope as illustrated in Figure 1. The envelope can be expressed in tabular form or as an equation. In this section, a simple procedure¹⁰ is

⁹ Jensen et al., (1990); Allen et al., (1998)

¹⁰ Reference: Allen (1996)

demonstrated for estimating R_{s0} for purposes of predicting net radiation. A more involved procedure, useful for evaluating R_s data integrity, is described in Appendix D. The clear sky envelope can alternatively be developed using measured R_s from a period of one year or longer. The measured data should be confirmed for accuracy, including sensor calibration and maintenance (levelness and cleanliness). When measured R_s data are used to define an R_{s0} envelope for a location, the resulting envelope should be compared with a theoretically derived envelope to confirm that there are no substantial differences in shape or magnitude. In general, the theoretically derived curve (Figure 1) is recommended.

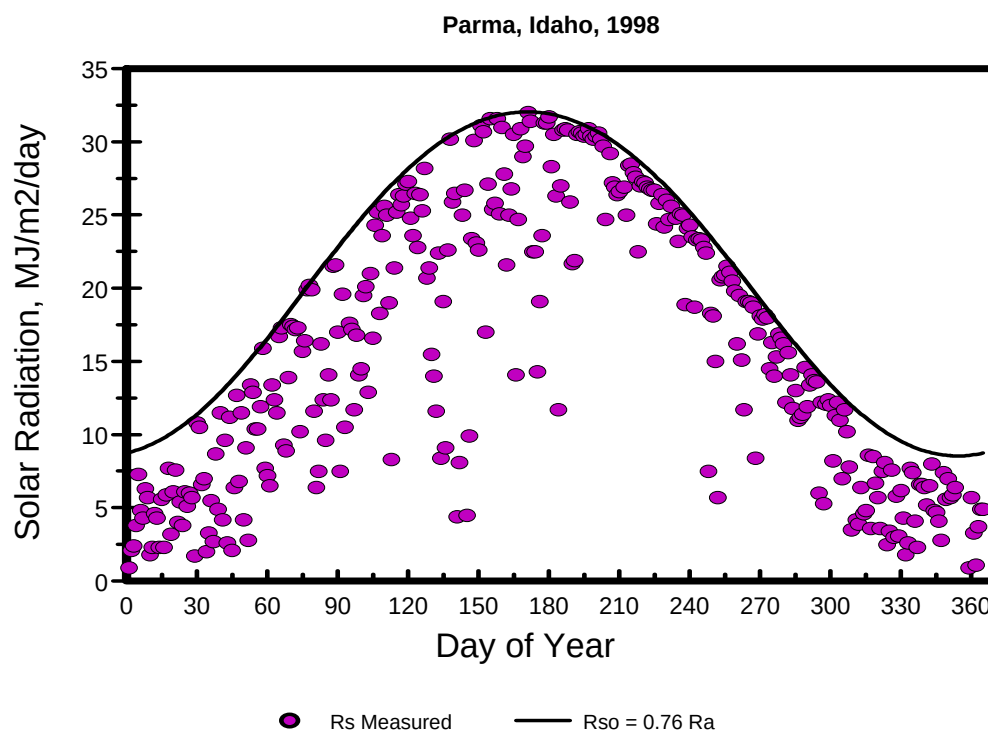


Figure 1. Daily R_s at Parma, Idaho during 1998 (elevation 703 m, Lat. 43.8°) and R_{s0} envelope from Eq. 19.

When a dependable, locally calibrated procedure for determining R_{SO} is not available, R_{SO} , for purposes of calculating R_n , can be computed as:

$$R_{SO} = \left(0.75 + 2 \times 10^{-5} z\right) R_a \quad (19)$$

where:

z = station elevation above sea level [m].

Eq. 19 predicts progressively higher levels of clear sky radiation with increasing elevation, and is the basis for the “0.76” factor for the R_{SO} curve drawn in Figure 1. Elevation serves as a surrogate for total air mass and atmospheric transmissivity above the measurement site.

When dependable, locally calibrated values are available for applying the “Angstrom” formula (see Eq. A.44), the clear sky radiation can be computed as:

$$R_{SO} = K_{ab} R_a \quad (20)$$

where:

R_{SO} = clear-sky solar radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
 R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
 K_{ab} = coefficient that can be derived from the a_s and b_s coefficients of the Angstrom formula, where $K_{ab} = a_s + b_s$, and where K_{ab} represents the fraction of extraterrestrial radiation reaching the earth on clear-sky days,
 a_s = constant expressing the fraction of extraterrestrial radiation reaching the earth’s surface on completely overcast days (see Eq. E.2 in Appendix E), and
 b_s = constant expressing the additional fraction of extraterrestrial radiation reaching the earth’s surface on a clear day (see Eq. E.2 in Appendix E).

Eqs. 19 or 20 are generally adequate for use in estimating R_{SO} in Eq. 18 when predicting net radiation, R_n . More complex estimates for R_{SO} , which include impacts of turbidity and water vapor on radiation absorption, can be used for assessing

integrity of solar radiation data and are discussed in Appendix D. The difference in ET_{RS} or ET_{OS} resulting from the use of Eq. 19 or 20, as opposed to the more complicated and accurate R_{SO} equations D.1 – D.5 of Appendix D, will be generally less than a few percent over an annual period.

Extraterrestrial Radiation for 24-Hour Periods (R_a)¹¹

Extraterrestrial radiation, R_a , defined as the short-wave solar radiation in the absence of an atmosphere, is a well-behaved function of the day of the year, time of day, and latitude. It is needed for calculating R_{SO} , which is in turn used in calculating R_n . For daily (24-hour) periods, R_a can be estimated from the solar constant, the solar declination, and the day of the year:

$$R_a = \frac{24}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (21)$$

where:

- R_a = extraterrestrial radiation [$MJ\ m^{-2}\ d^{-1}$],
- G_{sc} = solar constant [$4.92\ MJ\ m^{-2}\ h^{-1}$],
- d_r = inverse relative distance factor (squared) for the earth-sun [unitless],
- ω_s = sunset hour angle [radians],
- φ = latitude [radians], and
- δ = solar declination [radians].

The latitude, φ , is positive for the Northern Hemisphere and negative for the Southern Hemisphere. The conversion from decimal degrees to radians is given by:

$$\text{Radians} = \frac{\pi}{180} (\text{decimal degrees}) \quad (22)$$

and d_r and δ are calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (23)$$

¹¹ Reference: Duffie and Beckman (1980).

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (24)$$

where:

J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The constant 365 in Eqs. 23 and 24 is held at 365 even during a leap year. J can be calculated as¹²:

$$J = D_M - 32 + \text{Int}\left(275 \frac{M}{9}\right) + 2 \text{Int}\left(\frac{3}{M+1}\right) + \text{Int}\left(\frac{M}{100} - \frac{\text{Mod}(Y, 4)}{4} + 0.975\right) \quad (25)$$

where:

D_M = the day of the month (1-31),
 M = the number of the month (1-12), and
 Y = the number of the year (for example 1996 or 96).

The "Int" function in Eq. 25 finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient Y/4.

For monthly periods, the day of the year at the middle of the month (J_{month}) is approximately:

$$J_{\text{month}} = \text{Int}(30.4 M - 15) \quad (26)$$

The sunset hour angle, ω_s , is given by:

$$\omega_s = \arccos[-\tan(\phi)\tan(\delta)] \quad (27)$$

The "arccos" function is the arc-cosine function and represents the inverse of the cosine. This function is not available in all computer languages, so that ω_s can alternatively be computed using the arc-tangent (inverse tangent) function:

¹² Reference: Allen (2000).

$$\omega_s = \frac{\pi}{2} - \arctan \left[\frac{-\tan(\varphi) \tan(\delta)}{X^{0.5}} \right] \quad (28)$$

where:

$$X = 1 - [\tan(\varphi)]^2 [\tan(\delta)]^2 \quad (29)$$

and $X = 0.00001$ if $X \leq 0$

Soil Heat Flux Density (G)

Soil heat flux density is the thermal energy utilized to heat the soil. G is positive when the soil is warming and negative when the soil is cooling.

For Daily Periods

The magnitude of the daily, weekly or ten-day soil heat flux density, G , beneath a fully vegetated grass or alfalfa reference surface is relatively small in comparison with R_n . Therefore, it is ignored so that:

$$G_{\text{day}} = 0 \quad (30)$$

where:

G_{day} = daily soil heat flux density [$\text{MJ m}^{-2} \text{d}^{-1}$].

For Monthly Periods

Over a monthly period, G for the soil profile can be significant. Assuming a constant soil heat capacity of $2.0 \text{ MJ m}^{-3} \text{ }^\circ\text{C}^{-1}$ and an effectively warmed soil depth of 2 m, G for monthly periods in $\text{MJ m}^{-2} \text{d}^{-1}$ is estimated from the change in mean monthly air temperature as:

$$G_{\text{month},i} = 0.07 (T_{\text{month},i+1} - T_{\text{month},i-1}) \quad (31)$$

or, if $T_{\text{month},i+1}$ is unknown:

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$$G_{\text{month},i} = 0.14 (T_{\text{month},i} - T_{\text{month},i-1}) \quad (32)$$

where:

- $T_{\text{month},i}$ = mean air temperature of month i [$^{\circ}\text{C}$],
 $T_{\text{month},i-1}$ = mean air temperature of previous month [$^{\circ}\text{C}$], and
 $T_{\text{month},i+1}$ = mean air temperature of next month [$^{\circ}\text{C}$].

Wind Profile Relationship

Wind speed varies with height above the ground surface. For the calculation of ET_{sz} , wind speed at 2 meters above the surface is required, therefore, wind measured at other heights must be adjusted. To adjust wind speed data to the 2-m height, Eq. 33 should be used for measurements taken above a short grass (or similar) surface, based on the full logarithmic wind speed profile equation B.14 given in Appendix B:

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (33)$$

where:

- u_2 = wind speed at 2 m above ground surface [m s^{-1}],
 u_z = measured wind speed at z_w m above ground surface [m s^{-1}], and
 z_w = height of wind measurement above ground surface [m].

For wind measurements above surfaces other than clipped grass, the user should apply the full logarithmic equation B.14. A special application of Eq. B.14 is given in Appendix B for wind measured above alfalfa or similar vegetation having about 0.5 m height. It is noted that wind speed data collected at heights above 2 m are acceptable for use in the standardized equations following adjustment to 2 m, and may be preferred if vegetation adjacent to the station commonly exceeds 0.5 m. Measurement at a greater height, for example 3m, reduces the influence of the taller vegetation surrounding the weather measurement site.

CALCULATIONS REQUIRED FOR HOURLY TIME-STEPS

Many weather data networks collect and summarize hourly data that allow the user to calculate ET_{sz} for hourly periods. This capability is important where significant shifts in wind and humidity occur hourly. The calculation process for hourly time steps is analogous to that for daily calculations. The hourly equations can be used for shorter time periods, using fractional hours as the time parameter, but care must be taken to multiply the resultant ET rate in mm/h by the fractional hour. For example, if 30-minute data are used, one would input radiation in units of $MJ\ m^{-2}\ h^{-1}$. Then the output, in $mm\ h^{-1}$, would need to be multiplied by 0.5 h to arrive at the ET for the 30-minute period.

Psychrometric and Atmospheric Variables¹³

Latent Heat of Vaporization (λ)

The value of the latent heat of vaporization (λ), varies only slightly over the ranges of air temperature that occur in agricultural or hydrologic systems. For ET_{sz} , a constant value of $\lambda = 2.45\ MJ\ kg^{-1}$ is selected. The inverse of $\lambda = 2.45\ MJ\ kg^{-1}$ is approximately $0.408\ kg\ MJ^{-1}$. The density of water (ρ_w) is taken as $1.0\ Mg\ m^{-3}$ so that the inverse ratio of $\lambda\ \rho_w$ times energy flux in $MJ\ m^{-2}\ h^{-1}$ equals $1.0\ mm\ h^{-1}$.

Mean Air Temperature (T)

For hourly periods, the mean air temperature, T, represents an average over the period.

¹³ Many of the equations presented here are the same as those reported in ASCE Manual 70 (Jensen et al., 1990) and used in FAO-56 (Allen et al., 1998).

Atmospheric Pressure (P)

The mean atmospheric pressure at the weather site is predicted from site elevation using a simplified formulation of the Universal Gas Law¹⁴:

$$P = 101.3 \left(\frac{293 - 0.0065 z}{293} \right)^{5.26} \quad (34)$$

where:

P = mean atmospheric pressure at station elevation z [kPa], and
 z = weather site elevation above mean sea level [m].

Psychrometric Constant (γ)

The standardized application using $\lambda = 2.45 \text{ MJ kg}^{-1}$ results in a value for the psychrometric constant, γ , that is proportional to the mean atmospheric pressure:

$$\gamma = 0.000665 P \quad (35)$$

where P has units of kPa and γ has units of kPa °C⁻¹.

The variable γ is not the same variable as γ_{psy} used later in Eqs. 39 and 40 for converting psychrometric data (wet bulb and dry bulb temperature) to vapor pressure.

Slope of the Saturation Vapor Pressure-Temperature Curve (Δ)

The slope of the saturation vapor pressure-temperature curve¹⁵, Δ , is computed as:

$$\Delta = \frac{2503 \exp \left(\frac{17.27 T}{T + 237.3} \right)}{(T + 237.3)^2} \quad (36)$$

where:

¹⁴ Reference: Burman et al. (1987)

¹⁵ References: Tetens (1930), Murray (1967)

Δ = slope of the saturation vapor pressure-temperature curve [$\text{kPa } ^\circ\text{C}^{-1}$],
and
 T = mean air temperature [$^\circ\text{C}$].

Saturation Vapor Pressure (e_s)

The saturation vapor pressure¹⁶, e_s , represents the capacity of the air to hold water vapor.

For calculation of hourly ET_{sz} , e_s is given by:

$$e_s = e^0(T) = 0.6108 \exp\left(\frac{17.27 T}{T + 237.3}\right) \quad (37)$$

where vapor pressure is in units of kPa and T is mean air temperature during the hourly period in $^\circ\text{C}$. $e^0(T)$ is the saturation vapor pressure function.

Actual Vapor Pressure (e_a)

Actual vapor pressure (e_a) is used to represent the water content (humidity) of the air at the weather site. The actual vapor pressure can be measured or it can be calculated from various humidity data, such as measured dew point temperature, wet-bulb and dry-bulb temperature, or relative humidity and air temperature data.

Preferred procedures for calculating e_a

When multiple types of humidity or psychrometric data are available for estimating e_a , the preferences listed in Table 4 are recommended for calculation method. These recommendations are based on the likelihood that the data will have integrity and that estimates for e_a will be representative of the reference ET environment. The availability and quality of local data may justify a different order of preference.

¹⁶ Reference: Jensen et al. (1990) and Tetens (1930)

Table 4. Preferred method for calculating e_a for ET_{sz} for hourly periods

Method No.	Method	Preference Ranking	Equation(s)
1	e_a averaged over period ^{a,b}	1	--
2	Measured or calculated dew point temperature averaged over period	1	38
3	Average RH and T for the hour	1	37, 41
4	Wet-bulb and dry-bulb temperature	2	38, 39, 40
5	Daily minimum air temperature (see Appendix E)	3	--

^a In many data sets, e_a may be expressed in terms of an equivalent dew point temperature.

^b Some data logging systems may measure RH and T, but calculate e_a or T_{dew} internally for output as averaged values over some time interval.

When humidity and psychrometric data are missing or are of questionable integrity, dew point temperature can be estimated from daily minimum air temperature as described in Appendix E. This estimation procedure should be verified locally. The assessment of weather data integrity is discussed in Appendix D.

e_a from measured dew point temperature

The dew point temperature, T_{dew} , is the temperature to which the air must be cooled to reach a state of saturation. The value for e_a is calculated by substituting T_{dew} into Eq. 37 resulting in:

$$e_a = e^o(T_{dew}) = 0.6108 \exp \left[\frac{17.27 T_{dew}}{T_{dew} + 237.3} \right] \quad (38)$$

e_a from psychrometric data

The actual vapor pressure can also be determined from the difference between the dry and wet bulb temperatures (i.e., the wet bulb depression) of the air:

$$e_a = e^o(T_{wet}) - \gamma_{psy} (T_{dry} - T_{wet}) \quad (39)$$

where:

- e_a = actual vapor pressure of the air [kPa],
 $e^{\circ}(T_{\text{wet}})$ = saturation vapor pressure at the wet bulb temperature [kPa] (Eq. 37),
 γ_{psy} = psychrometric constant for the psychrometer [kPa °C⁻¹], and
 $T_{\text{dry}} - T_{\text{wet}}$ = wet bulb depression, where T_{dry} is the dry bulb temperature and T_{wet} is the wet bulb temperature [°C] (measured simultaneously).

The psychrometric constant for the psychrometer at the weather measurement site is given by:

$$\gamma_{\text{psy}} = a_{\text{psy}} P \quad (40)$$

where:

- a_{psy} = coefficient depending on the type of ventilation of the wet bulb [°C⁻¹], and
 P = mean atmospheric pressure [kPa].

The coefficient a_{psy} depends primarily on the design of the psychrometer and on the rate of ventilation around the wet bulb. The following values are often used¹⁷:

- a_{psy} = 0.000662 for ventilated (Asmann type) psychrometers having air movement between 2 and 10 m s⁻¹ for $T_{\text{wet}} \geq 0$ and 0.000594 for $T_{\text{wet}} < 0$,
 = 0.000800 for naturally ventilated psychrometers with air movement of about 1 m s⁻¹), and
 = 0.001200 for non-ventilated psychrometers installed in glass or plastic greenhouses (List, 1984).

e_a from relative humidity data

The actual vapor pressure of air for hourly periods can be calculated from relative humidity (RH) and saturation vapor pressure at the corresponding air temperature (from Eq. 37):

¹⁷ Allen et al., (1998).

$$e_a = \frac{RH}{100} e^o(T) \quad (41)$$

where:

RH = mean relative humidity for the hourly period, %, and
 T = mean air temperature for the hourly period, °C.

Net Radiation (R_n)

Net radiation (R_n) is the net amount of radiant energy available at the vegetation or soil surface for evaporating water, heating the air, or heating the surface. R_n includes both short and long wave radiation components ¹⁸:

$$R_n = R_{ns} - R_{nl} \quad (42)$$

where:

R_{ns} = net shortwave radiation, [$\text{MJ m}^{-2} \text{ h}^{-1}$] (defined as being positive downwards and negative upwards),
 R_{nl} = net outgoing long-wave radiation, [$\text{MJ m}^{-2} \text{ h}^{-1}$] (defined as being positive, upwards and negative downwards),

R_{ns} and R_{nl} are generally positive or zero in value.

Net radiation is difficult to measure because net radiometers are problematic to maintain and calibrate. There is good likelihood of systematic biases in R_n measurements. Therefore, R_n is often predicted from observed short wave (solar) radiation, vapor pressure, and air temperature. This prediction is routine and generally highly accurate. If R_n is measured, care and attention must be given to the calibration of the radiometer, the surface over which it is located, maintenance of the sensor domes, and level of the instrument. The condition of the vegetation surface is

¹⁸ Reference: Brutsaert (1982), Jensen et al., (1990), Wright (1982), Doorenbos and Pruitt, (1975, 1977), Allen et al., (1998).

as important as the sensor. For purposes of calculating ET_{sz} , the measurement surface for R_n is generally assumed to be clipped grass or alfalfa at full cover.

Net Solar or Net Short-Wave Radiation (R_{ns})

Net short-wave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = R_s - \alpha R_s = (1 - \alpha) R_s \quad (43)$$

where:

- R_{ns} = net solar or short-wave radiation [$\text{MJ m}^{-2} \text{h}^{-1}$],
- α = albedo or canopy reflection coefficient, is fixed at 0.23 for the standardized short and tall reference surfaces [dimensionless], and
- R_s = the incoming solar radiation [$\text{MJ m}^{-2} \text{h}^{-1}$].

The calculation of ET_{sz} uses the constant value of 0.23 for albedo for daily and hourly periods. It is recognized that albedo varies somewhat with time of day and with time of season and latitude due to change in sun angle. However, because the solar intensity is less during these periods, the error introduced in fixing albedo at 0.23 is relatively small (Allen et al., 1994b). Users may elect to use a different prediction for albedo, however, they are strongly encouraged to ascertain the validity and accuracy of an alternative method using good measurements of incoming and reflected solar radiation. Some types of pyranometers are invalid for measuring reflected radiation due to the difference in spectral response between the instrument and reflecting surface. Predictions of R_n made using an alternate method for albedo (i.e., other than 0.23) may not agree with those made using the ASCE standardized procedure.

Net Long-Wave Radiation (R_{nl})

There are several variations and coefficients developed for predicting the net long wave component of total net radiation. The standardized ASCE procedure is the

same as that adopted by FAO-56 and is based on the Brunt (1932, 1952) approach for predicting net surface emissivity. If users intend to utilize a different approach for calculating R_n , it is essential to ascertain the validity and accuracy of their method using net radiometers in excellent condition and that are calibrated to some dependable and recognized standard. In all situations, users should compare measured R_n or R_n computed using an alternative method with R_n calculated using the standardized procedure. Substantial variation (more than 5 %) should give cause for concern and should indicate the need to reconcile or justify the differences.

R_{nl} is the difference between long-wave radiation radiated upward from the standardized surface (R_{lu}) and long-wave radiation radiated downward from the atmosphere (R_{ld}), so that $R_{nl} = R_{lu} - R_{ld}$. The following calculation for R_{nl} is the method introduced by Brunt (1932, 1952) that uses near surface vapor pressure to predict net surface emissivity:

$$R_{nl} = \sigma f_{cd} \left(0.34 - 0.14 \sqrt{e_a} \right) T_{K\ hr}^4 \quad (44)$$

where

- R_{nl} = net outgoing long-wave radiation [$\text{MJ m}^{-2} \text{h}^{-1}$],
- σ = Stefan-Boltzmann constant [$2.042 \times 10^{-10} \text{ MJ K}^{-4} \text{ m}^{-2} \text{h}^{-1}$],
- f_{cd} = cloudiness function [dimensionless] (limited to $0.05 \leq f_{cd} \leq 1.0$),
- e_a = actual vapor pressure [kPa],
- $T_{K\ hr}$ = mean absolute temperature during the hourly period [K] ($K = ^\circ\text{C} + 273.16$).

The superscript “4” in Eq. 44 indicates the need to raise the air temperature, expressed in Kelvin units, to the power of 4. For periods during daytime when the sun is more than about 15° above the horizon (see procedures below), f_{cd} is calculated as:

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \quad (45)$$

where:

$$\begin{aligned}
 R_s/R_{s0} &= \text{relative solar radiation (limited to } 0.3 \leq R_s/R_{s0} \leq 1.0), \\
 R_s &= \text{measured or calculated solar radiation [MJ m}^{-2} \text{ h}^{-1}], \text{ and} \\
 R_{s0} &= \text{calculated clear-sky radiation [MJ m}^{-2} \text{ h}^{-1}].
 \end{aligned}$$

The ratio R_s/R_{s0} in Eq. 45 represents relative cloudiness and is limited to $0.3 < R_s/R_{s0} \leq 1.0$ so that f_{cd} has limits of $0.05 \leq f_{cd} \leq 1.0$.

During nighttime, R_{s0} , by definition, equals 0, and Eq. 45 is undefined. Furthermore, even small out of level of a pyranometer or imperfect correction for cosine error of the instrument (required for accurate measurement at low sun angle) can cause substantial deviation in the value for R_s/R_{s0} when the sun is near the horizon (i.e., when R_{s0} is small). Therefore, f_{cd} during periods of low sun angle and nighttime is defined using f_{cd} from a prior period having sufficient sun angle.

When sun angle above the horizon (β)¹⁹ at the midpoint of the hourly or shorter time period is less than 0.3 radians ($\sim 17^\circ$), then:

$$f_{cd} = f_{cd \beta > 0.3} \quad (46)$$

where:

$$f_{cd \beta > 0.3} = \text{cloudiness function for the time period prior to when sun angle } \beta \text{ (in the afternoon or evening) falls below 0.3 radians [dimensionless].}$$

Note that if the time period is shorter than one hour, f_{cd} from several periods can be averaged into $f_{cd \beta > 0.3}$ to obtain a representative average value. In mountain valleys where the sun may set near or above 0.3 radians ($\sim 17^\circ$), the user should increase the sun angle at which $f_{cd \beta > 0.3}$ is computed and imposed. For example, for a location where mountain peaks are 20° above the horizon, a period should be selected for computing $f_{cd \beta > 0.3}$ where the sun angle at the end of the time period is 25 to 30°

¹⁹ The sun angle β is defined as the angle of a line from the measurement site to the center of the sun's disk relative to a line from the measurement site to directly below the sun and tangent to the earth's surface. This definition assumes a flat surface.

above the horizon. The same adjustment is necessary when deciding when to resume computation of f_{cd} during morning hours when mountains lie to the east.

Only one value for $f_{cd \beta > 0.3}$ is calculated per day for use during dusk, nighttime and dawn periods. That value for $f_{cd \beta > 0.3}$ is then applied to the time period when β at the midpoint of the period first falls below 0.3 radians ($\sim 15^\circ$) and to all subsequent periods until after sunrise when β again exceeds 0.3 radians. Computation of β is given in Eq. 62 in the following section.

Equations 45 – 46 will not apply at latitudes and times of the year when there are no hourly (or shorter) periods having sun angle of 0.3 radians or greater. These situations occur for latitudes at 50° for about one month per year (in winter), for latitudes at 60° for about 5 months per year, and for latitudes at 70° for about 7 months per year. At extreme latitudes, some fall and winter months have little or no daylight. Under these conditions, the application can average $f_{cd \beta > 0.3}$ from fewer time periods or, in the absence of any daylight, can assume a ratio of R_s/R_{s0} ranging from 0.3 for complete cloud cover to 1.0 for no cloud cover. Under these extreme conditions, the prediction of R_n during nighttime and low sun angle is only approximate.

The application of Eq. 46 presumes that cloudiness during periods of low sun angle and nighttime is similar to that during late afternoon or early evening. This is generally a reasonable assumption and is commensurate with the relative simplicity and moderate accuracy of Eq. 45. Some applications may wish to split the nighttime period into two halves, with the first half using $f_{cd \beta > 0.3}$ computed from late afternoon or early evening and the second half using $f_{cd \beta > 0.3}$ computed from R_s measured during the following morning (for the period when β is first > 0.3 radians). However, this additional computation requires looking ahead within a data set and will generally not add accuracy to the computations, since the timing of any shift in cloudiness during nighttime is unknown and due to the general, approximate accuracy of the f_{cd} function (Eq. 45).

Clear-sky solar radiation

Clear-sky solar radiation, R_{s0} , is used in the calculation of net radiation, R_n . Clear-sky solar radiation is defined as the amount of solar radiation, R_s , that would be received at the weather measurement site under conditions of clear-sky (i.e., cloud-free). The ratio of R_s to R_{s0} in the equation for R_n is used to characterize the impact of cloud-cover on the downward emission of thermal radiation to the earth's surface. The value for R_{s0} is a function of the time of year and latitude, and, in addition, the time of day for hourly calculation periods. These parameters affect the potential incoming solar radiation from the sun. Clear-sky solar radiation is also impacted by the station elevation (affecting atmospheric thickness and transmissivity), the amount of precipitable water in the atmosphere (affecting the absorption of some short wave radiation), and the amount of dust or aerosols in the air.

A daily R_{s0} “envelope” was developed earlier in Figure 1 and compared to measured R_s . For purposes of calculating R_n , hourly R_{s0} can be calculated using the following simple approach:

$$R_{s0} = \left(0.75 + 2 \times 10^{-5} z\right) R_a \quad (47)$$

where:

- R_{s0} = clear-sky solar radiation [$\text{MJ m}^{-2} \text{h}^{-1}$],
- z = station elevation above sea level [m], and
- R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{h}^{-1}$].

Equation 47 predicts progressively higher levels of clear sky radiation with increasing elevation. Elevation serves as a surrogate for total air mass and atmospheric transmissivity above the measurement site. Equation 47 is generally adequate for use in predicting the ratio R_s/R_{s0} when calculating net radiation, R_n . Other more complex estimates for R_{s0} , which include turbidity and water vapor effects as well as impact of sun angle are discussed in Appendix D. Those equations are recommended

for assessing integrity of solar radiation data and may provide improved estimates for R_{s0} for calculating R_n . The impact on ET_{SZ} of using the equations in Appendix D for R_{s0} rather than Eq. 47 will generally be less than a few percent across a day and over an annual period.

Figure 2 illustrates a comparison of measured hourly solar radiation with R_{s0} computed using Eq. 47 and using the more complicated, but generally more accurate, method presented as Eq. D.1-D.5 of Appendix D. Data from two days in late June are plotted. June 19 had some morning and mid-day cloudiness. June 20 was a cloud-free day. The R_s data from June 20 compare relatively well with both R_{s0} methods throughout the day. The measured data plot slightly higher than either R_{s0} estimate at mid-day, with the more complicated R_{s0} method from Appendix D having better agreement than Eq. 48. Measured R_s exceeded the R_{s0} curves for the 1100 reading on June 19 because of reflection from clouds near the weather site. In general, the solar radiation data appear to be of excellent quality and calibration.

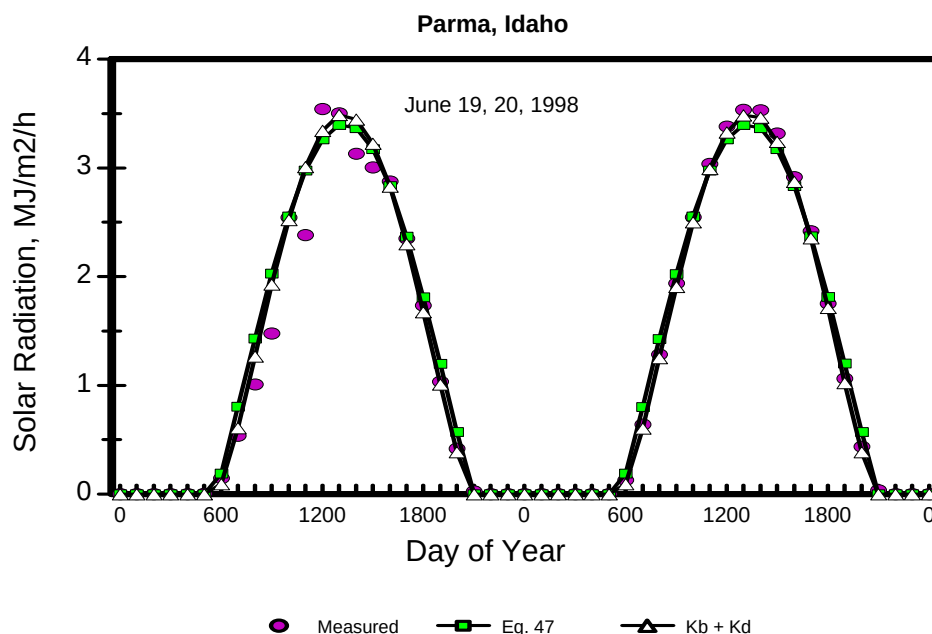


Figure 2. Measured and calculated hourly R_{s0} for two days at Parma, Idaho during 1998 using Eq. 47 and using the more accurate $K_B + K_D$ method of Appendix D.

Extraterrestrial radiation for hourly periods (R_a)²⁰

Extraterrestrial radiation, R_a , defined as the short-wave solar radiation in the absence of an atmosphere, is a well-behaved function of the day of the year, time of day, latitude, and longitude. For hourly time periods, the solar time angle at the beginning and end of the period serve as integration endpoints for calculating R_a :

$$R_a = \frac{12}{\pi} G_{sc} d_r [(\omega_2 - \omega_1) \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) (\sin(\omega_2) - \sin(\omega_1))] \quad (48)$$

where

- R_a = extraterrestrial radiation during the hour (or shorter) period [$\text{MJ m}^{-2} \text{ hour}^{-1}$],
- G_{sc} = solar constant = $4.92 \text{ MJ m}^{-2} \text{ h}^{-1}$,
- d_r = inverse relative distance factor (squared) for the earth-sun [unitless],
- δ = solar declination [radians],
- ϕ = latitude [radians],
- ω_1 = solar time angle at beginning of period [radians], and
- ω_2 = solar time angle at end of period [radians].

The latitude, ϕ , expressed in radians is positive for the Northern Hemisphere and negative for the Southern Hemisphere. The conversion from decimal degrees to radians is given by:

$$\text{Radians} = \frac{\pi}{180} (\text{decimal degrees}) \quad (49)$$

and d_r and δ are calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (50)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (51)$$

²⁰ Reference: Duffie and Beckman (1980).

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The constant 365 in Eqs. 50 and 51 is held at 365 even during a leap year. J can be calculated as²¹:

$$J = D_M - 32 + \text{Int}\left(275 \frac{M}{9}\right) + 2 \text{Int}\left(\frac{3}{M+1}\right) + \text{Int}\left(\frac{M}{100} - \frac{\text{Mod}(Y, 4)}{4} + 0.975\right) \quad (52)$$

where:

- D_M = the day of the month (1-31),
- M = the number of the month (1-12), and
- Y = the number of the year (for example 1996 or 96).

The "Int" function in Eq. 52 finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient Y/4.

The solar time angles at the beginning and end of each period are given by:

$$\omega_1 = \omega - \frac{\pi t_1}{24} \quad (53)$$

$$\omega_2 = \omega + \frac{\pi t_1}{24} \quad (54)$$

where:

- ω = solar time angle at the midpoint of the period [radians], and
- t_1 = length of the calculation period [hour]: i.e., 1 for hourly periods or 0.5 for 30-minute periods.

The solar time angle at the midpoint of the period is:

$$\omega = \frac{\pi}{12} \left[(t + 0.06667(L_z - L_m) + S_c) - 12 \right] \quad (55)$$

where:

²¹ Reference: Allen (2000)

- t = standard clock time at the midpoint of the period [hour] (after correcting time for any daylight savings shift). For example for a period between 1400 and 1500 hours, $t = 14.5$ hours,
- L_z = longitude of the center of the local time zone [expressed as positive degrees west of Greenwich, England]. In the United States, $L_z = 75, 90, 105$ and 120° for the Eastern, Central, Rocky Mountain and Pacific time zones, respectively, and $L_z = 0^\circ$ for Greenwich, 345° for Paris (France), and 255° for Bangkok (Thailand),
- L_m = longitude of the solar radiation measurement site [expressed as positive degrees west of Greenwich, England], and
- S_c = seasonal correction for solar time [hour].

Because ω_s is the sunset hour angle and $-\omega_s$ is the sunrise hour angle (noon has $\omega = 0$), values of $\omega < -\omega_s$ or $\omega > \omega_s$ from Eq. 55 indicate that the sun is below the horizon, so that, by definition, R_a and R_{so} are zero and their calculation has no meaning. When the values for ω_1 and ω_2 span the value for $-\omega_s$ or for ω_s , this indicates that sunrise or sunset occurs within the hourly (or shorter) period. In this case, the integration limits for applying Eq. 48 should be correctly set using the following conditionals:

$$\begin{aligned}
 &\text{If } \omega_1 < -\omega_s \text{ then } \omega_1 = -\omega_s \\
 &\text{If } \omega_2 < -\omega_s \text{ then } \omega_2 = -\omega_s \\
 &\text{If } \omega_1 > \omega_s \text{ then } \omega_1 = \omega_s \\
 &\text{If } \omega_2 > \omega_s \text{ then } \omega_2 = \omega_s \\
 &\text{If } \omega_1 > \omega_2 \text{ then } \omega_1 = \omega_2
 \end{aligned}
 \tag{56}$$

The above conditionals can be applied for all timesteps to insure numerical stability of the application of Eq. 48 as well as correctly computing the theoretical quantity of solar radiation early and late in the day. The user should recognize that Eqs. 48-56 and 62 presume an extensive, flat ground surface and are based on a vector to the center of the sun's disk. The calculations do not account for diffuse radiation occurring shortly before sunrise and shortly after sunset. Where there are hills or mountains, the hour angle when the sun first appears or disappears may increase for sunrise or decrease for sunset.

The seasonal correction for solar time is:

$$S_c = 0.1645 \sin(2b) - 0.1255 \cos(b) - 0.025 \sin(b) \quad (57)$$

$$b = \frac{2\pi(J-81)}{364} \quad (58)$$

where J is the number of the day in the year and b has units of radians.

The sunset hour angle, ω_s , is given by:

$$\omega_s = \arccos \left[-\tan(\phi) \tan(\delta) \right] \quad (59)$$

The “arccos” function is the arc-cosine function and represents the inverse of the cosine. This function is not available in all computer languages, so that ω_s can alternatively be computed using the arc tangent (inverse tangent) function:

$$\omega_s = \frac{\pi}{2} - \arctan \left[\frac{-\tan(\phi) \tan(\delta)}{X^{0.5}} \right] \quad (60)$$

where:

$$X = 1 - [\tan(\phi)]^2 [\tan(\delta)]^2 \quad (61)$$

and $X = 0.00001$ if $X \leq 0$

The user should confirm accurate setting of the datalogger clock. If clock times are in error by more than 5-10 minutes, estimates of extraterrestrial and clear sky radiation may be significantly impacted. This can lead to errors in estimating R_n on an hourly or shorter basis, especially early and late in the day. A shift in “phase” between measured R_s and R_{so} predicted from R_a according to the data logger clock can indicate error in the reported time. More discussion is given in Appendix D.

The angle of the sun above the horizon, β , at the midpoint of the hourly or shorter time period is computed as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega)] \quad (62)$$

where

- β = angle of the sun above the horizon at midpoint of the period [radians],
- φ = latitude [radians],
- δ = solar declination [radians],
- ω = solar time angle at the midpoint of the period [radians] (from Eq. 55).

The “arcsin” function is the arc-sine function and represents the inverse of the sine. This function is not available in all computer languages, so that β can alternatively be computed using the arc tangent (inverse tangent) function:

$$\beta = \arctan \left[\frac{Y}{(1 - Y^2)^{0.5}} \right] \quad (63)$$

where:

$$Y = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega) \quad (64)$$

and all other parameters are defined following Eq. 62.

Soil Heat Flux Density (G)

Soil heat flux density is the thermal energy that is utilized to heat the soil. G is positive when the soil is warming and negative when the soil is cooling. For hourly calculation periods, G beneath a dense cover of grass or alfalfa does not correlate well with air temperature, but can be significant. Hourly G generally correlates well with net radiation and amount of vegetative cover and can be approximated as a fraction of

R_n . The following equations are based on Eq. B.13 of Appendix B for fixed vegetation height and leaf area index²².

For the standardized short reference ET_{os} :

$$G_{hr\,daytime} = 0.1 R_n \quad (65a)$$

$$G_{hr\,nighttime} = 0.5 R_n \quad (65b)$$

where G and R_n have the same measurement units ($MJ\,m^{-2}\,h^{-1}$ for hourly or shorter time periods). For the standardized tall reference ET_{rs} :

$$G_{hr\,daytime} = 0.04 R_n \quad (66a)$$

$$G_{hr\,nighttime} = 0.2 R_n \quad (66b)$$

For standardization, nighttime is defined as when measured or calculated hourly net radiation R_n is < 0 (i.e., negative). When the soil is warming, the soil heat flux density, G , has a positive value. The amount of energy consumed by G is subtracted from R_n when estimating ET_{os} or ET_{rs} .

Wind Profile Relationship

Wind speed varies with height above the ground surface. For the calculation of ET_{sz} , wind speed at 2 meters above the surface is required, therefore, wind measured at other heights must be adjusted. To adjust wind speed data to the 2-m height, Eq. 68 should be used for measurements above a short grass (or similar) surface, based on the full logarithmic wind speed profile equation B.14 given in Appendix B.

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (67)$$

where

u_2 = wind speed at 2 m above ground surface [$m\,s^{-1}$],

u_z = measured wind speed at z_w m above ground surface [$m\,s^{-1}$], and

²² Leaf area index (LAI) is defined as the area (one-sided) of leaves per unit area of ground surface. Units are dimensionless (i.e., $m^2\,m^{-2}$)

z_w = height of wind measurement above ground surface [m].

For wind measurements above surfaces other than clipped grass, the user should apply the full logarithmic equation B.14. A special application of Eq. B.14 is given in Appendix B for wind measured above alfalfa or similar vegetation having about 0.5 m height. It is noted that wind speed data collected at heights above 2 m are acceptable for use in the standardized equations following adjustment to 2 m, and may be preferred if vegetation adjacent to the station commonly exceeds 0.5 m. Measurement at a greater height, for example 3 m, reduces the influence of the taller vegetation.

Negative Values Computed for ET_{sz}

Values calculated for reference ET for nighttime hours occasionally take on negative values. In practice, the user may wish to set negative values to zero before summing over the 24-hour period. However, in some situations, negative hourly computed ET_{os} or ET_{rs} may indicate some condensation of vapor during periods of early morning dew and should therefore be registered as negative during the summing of 24-hour ET. In other situations, negative hourly ET_{os} or ET_{rs} during nighttime reflect the uncertainties in some parameter estimates including R_n and assumptions implicit to the combination equation. The impact of negative hourly values on ET summed over daily periods is usually less than a few percent. In general, it may be appropriate to retain the negative values.

DEFINITION AND APPLICATION OF CROP COEFFICIENTS

Calculation of crop evapotranspiration (ET_c) requires the selection of the appropriate crop coefficient (K_c) for use with the standardized reference evapotranspiration (ET_{os} or ET_{rs}). It is recommended that the abbreviation for crop coefficients developed for use with ET_{os} be denoted as K_{co} and the abbreviation for crop coefficients developed for use with ET_{rs} be denoted as K_{cr} . ET_c is calculated as:

$$ET_c = K_{co} * ET_{os} \quad \text{or} \quad ET_c = K_{cr} * ET_{rs} \quad (68)$$

TRANSFER AND CONVERSION OF CROP COEFFICIENTS

Crop coefficients (K_c) and landscape coefficients available in the literature are referenced to either clipped, cool season grass or full-cover alfalfa. Without appropriate adjustment, crop coefficients for the two references are not interchangeable. For this standardization effort, a grass reference crop is defined as an extensive, uniform surface of dense, actively growing, cool-season grass with a height of 0.12 m, and not short of soil water. A full-cover alfalfa reference crop is defined here as an extensive, uniform surface of dense, actively growing alfalfa with a height of 0.50 m, and not short of soil water.

Grass-based crop coefficients should be used with ET_{os} , and alfalfa-based coefficients should be used with ET_{rs} . If a calculated or measured reference other than ET_{os} or ET_{rs} was used to develop the crop coefficients, it must be established that the reference equation or reference measurements provide values that are equivalent to ET_{os} or ET_{rs} (see Appendix A for comparisons between selected methods). It is important to establish the differences between ET equations since some equations developed to estimate grass or alfalfa reference ET may not agree exactly with ET_{os} or ET_{rs} during all time periods or under all climatic conditions.

K_c values that can be used with ET_{os} without adjustment include those reported in FAO-56 (Allen et al., 1998) and ASCE Manual 70 (Jensen et al., 1990, Table 6.8). Coefficients that can be used as is with ET_{os} for most practical applications are those reported by FAO-24 (Doorenbos and Pruitt, 1977) and SCS NEH Part 623 Chapter 2 (Martin and Gilley, 1993). Coefficients based on the CIMIS Penman equation (Snyder and Pruitt, 1992) should not require adjustment for use with ET_{os} . K_c values that can be used as is with ET_{rs} for most practical applications are those reported by Wright (1982) and ASCE Manual 70 (Jensen et al., 1990, Tables 6.6 and 6.9). There is a tendency for relatively minor overestimation of ET using K_c from Wright (1982) with ET_{rs} in spring and fall. Thus, the K_c values by Wright (1981, 1982) have been converted for direct use with ET_{rs} , with ET_{rs} calculated on a 24-h time step (Allen and Wright, 2002).

Some grass and alfalfa based crop coefficients are “mean” crop coefficients (e.g., Wright, 1979; 1981; Doorenbos and Pruitt, 1977). Mean crop coefficients incorporate the effects of irrigation, rainfall, and soil type at the development site. Users of these mean crop coefficients are cautioned that differences in irrigation frequency, rainfall patterns, and/or soil drying characteristics between the development site and the study site could cause error in the ET_c estimate.

The publications referenced in the above paragraphs contain descriptions on determination and application of crop coefficients during growing periods. This information will not be presented here. The following section discusses the application of ET_{sz} and K_c during non-growing periods.

CALCULATION OF REFERENCE EVAPOTRANSPIRATION DURING NON-GROWING PERIODS

During cold periods in many regions, freezing temperatures preclude vegetation from remaining green and actively growing. These periods are referred to as non-growing periods. Evapotranspiration from non-active vegetation during non-growing periods is generally less than reference ET because plants may be dormant and therefore may have substantially increased surface resistance. Besides surface resistance, albedo or reflectance of dormant or dead vegetation is generally greater than that of green vegetation. Both of these characteristics reduce the potential rate of ET from plant residue. This may make it difficult to assess the validity of reference ET equations under these conditions.

While it is recognized that the reference ET equations do not represent measurable quantities during non-growing periods, the ET_{sz} equation can still be useful as an evaporative index. However, the user must be aware that conditions for the reference surfaces for ET_{os} and ET_{rs} may not exist during non-growing periods. Under many non-growing conditions, it is possible to incorporate the differences between dormant or dead vegetation ET and ET_{sz} into the K_c value. However there are other factors to be considered. For example, the soil heat flux estimates may be uncertain, low sun angles and snow cover will influence albedo, and short day lengths will affect the calculation of net radiation and ET_{sz} for daily time steps.

In this document the Task Committee will not recommend a methodology for the application of reference evapotranspiration during non-growing seasons. Two other ASCE Task Committees are investigating evaporative losses during non-growing seasons and are developing estimation methodologies.

REFERENCES

- Allen, R.G. 1995. "Evaluation of procedures for estimating mean monthly solar radiation from air temperature." Rep. submitted to Water Resources Dev. and Mgmt Service, Land and Water Dev. Div., United Nations Food and Agriculture Service, Rome, Italy. 120 pp.
- Allen, R.G. 1996. "Assessing integrity of weather data for use in reference evapotranspiration estimation." *J. Irrig. and Drain. Engrg.*, ASCE. 122(2):97-106.
- Allen, R.G. 1997. "A self-calibrating method for estimating solar radiation from air temperature." *J. Hydrol. Engrg.*, ASCE 2(2):56-67.
- Allen, R. G. 1999. REF-ET, "Reference Evapotranspiration Calculator Version Windows 1.0." Univ. of Idaho Res. and Ext. Center, Kimberly, ID, 61 p.
- Allen, R. G. 2000. "REF-ET, Reference Evapotranspiration Calculator Version Windows 2.0." Univ. of Idaho Res. and Ext. Center, Kimberly, ID, 82 p.
- Allen, R.G. and F.N. Gichuki. 1989. "Effects of projected CO₂ - induced climatic changes on irrigation water requirements in the Great Plain States (Texas, Oklahoma, Kansas, and Nebraska)." *The potential effects of global climate change on the United States: Appendix C – Agriculture*, Vol. 1, EPA-230-05-89-053, J.B. Smith and D.A. Tirpak, (eds), U.S. EPA, Office of Policy, Planning and Evaluation, Washington, D.C., p 6/1-6/42.
- Allen, R.G. and W.O. Pruitt. 1986. "Rational use of the FAO Blaney-Criddle formula." *J. Irrig. and Drain. Engrg.*, ASCE, 112(2):139-155.
- Allen, R.G. and W.O. Pruitt. 1991. "FAO-24 reference evapotranspiration factors." *J. Irrig. and Drain. Engrg.*, ASCE 117(5):758-773.
- Allen, R.G. and J.L. Wright. 1996. "Estimating Soil Heat Flux for Reference Evapotranspiration." Unpublished paper, Univ. Idaho R&E Ctr., Kimberly, Idaho 83341., 15 p.
- Allen, R.G. and J.L. Wright. 1997. "Translating wind measurements from weather stations to agricultural crops." *J. Hydrologic Engrg.*, ASCE 2(1): 26-35.
- Allen, R.G. and J.L. Wright. 2002. "Conversion of Wright (1981) and Wright (1982) alfalfa-based crop coefficients for use with the ASCE Standardized Penman-Monteith Reference Evapotranspiration Equation." Research report by the

University of Idaho, Kimberly Research and Extension Center, Kimberly, ID 83341, 38 p. http://www.kimberly.uidaho.edu/water/asceewri/Conversion_of_Wright_Kcs_2c.pdf

Allen, R.G., Brockway, C.E., and Wright, J.L. 1983. "Weather station siting and consumptive use estimates." *J. Water Resour. Plng. and Mgmt. Div.*, ASCE 109(2): 134-146.

Allen, R.G., F.N. Gichuki and C. Rosenzweig. 1991. "CO₂-induced climatic changes and irrigation water requirements." *J. Water Resour. Plan. and Mgmt.* ASCE 117(2):157-178.

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. "Operational estimates of reference evapotranspiration." *Agron. J.*, 81:650-662.

Allen, R.G., W.O. Pruitt, J.A. Businger, L.J. Fritschen, M.E. Jensen, and F.H. Quinn. 1996. "Evaporation and Transpiration." Chap. 4, p. 125-252 *In: Wootton et al. (Ed.), ASCE Handbook of Hydrology*. New York, NY.

Allen, R.G., M. Smith, A. Perrier, and L.S. Pereira. 1994a. "An update for the definition of reference evapotranspiration." *ICID Bulletin*. 43(2):1-34.

Allen, R.G., M. Smith, L.S. Pereira and A. Perrier. 1994b. "An update for the calculation of reference evapotranspiration." *ICID Bulletin*. 43(2):35-92.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. "*Crop Evapotranspiration: Guidelines for computing crop water requirements*." Irrig. and Drain. Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Allen, R. G., I. A. Walter, R. Elliott, B. Mecham, M. E. Jensen, D. Itenfisu, T. A. Howell, R. Snyder, P. Brown, S. Eching, T. Spofford, M. Hattendorf, R. H. Cuenca, J. L. Wright and D. Martin. 2000. "Issues, requirements and challenges in selecting and specifying a standardized ET equation." *Proc., 4th National Irrig. Symp.*, ASAE, Phoenix, AZ.

ASAE, 2004. *Measurement and Reporting Practices for Automatic Agricultural Weather Stations*. Engineering Practice 505. St. Joseph, MI, 21 p.

Bosen, J.F. 1958. "An approximation formula to compute relative humidity from dry bulb and dew point temperatures." *Monthly Weather Rev* 86(12):486.

Brown, P.W., S.A. Musil, and B.T. Russell. 1987. "Stability of calibration of inexpensive polystyrene relative humidity sensors under field conditions." p. 11. *In: 1987 Agronomy Abstracts*. ASA, Madison, WI.

- Brown, P.W., 2001. "Personal communication to ASCE Task Committee for Standardization of Reference Evapotranspiration."
- Brunt, D. 1932. "Notes on radiation in the atmosphere: I.", *Quart. J. Roy. Meteor. Soc.*, 58:389-420.
- Brunt, D. 1952. "*Physical and Dynamical Meteorology*", 2nd ed., Uni. Press, Cambridge, 428p.
- Brutsaert, W. 1982. "*Evaporation into the Atmosphere.*" D. Reidel Pub. Co., Boston, 309 p.
- Burman, R.D., Wright, J.L., and Jensen, M.E. 1975. "Changes in climate and estimated evaporation across a large irrigated area in Idaho." *Trans. ASAE* 18(6):1089-1093.
- Burman, R.D., Jensen, M.E., and Allen, R.G. 1987. "Thermodynamic factors in evapotranspiration." p. 28-30. In: L.G. James, and M.J. English (eds) *Proc., Irrig. and Drain. Spec. Conf.*, ASCE, Portland, Oregon, July.
- Choudhury, B.J. 1989. "Estimating evaporation and carbon assimilation using infrared temperature data: vistas in modeling." p. 628-690, In A. Ghassem, (ed), *Theory and Applications of Optical Remote Sensing*, John Wiley & Sons. New York..
- Choudhury, B.J. S.B. Idso and R.J. Reginato. 1987. "Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infrared temperature based energy balance equation." *Agr. and For. Meteorol.*, 39:283-297.
- Dong, A., Grattan, S.R., Carroll, J.J., and Prashar, C.R.K. 1992. "Estimation of net radiation over well-watered grass". *J. of Irrig. and Drain. Engrg.*, ASCE 118 (3):466-479.
- Doorenbos, J. and W.O. Pruitt, 1975, 1977. "*Guidelines for predicting crop water requirements*," Irrig. and Drain. Paper 24, (1st and 2nd ed)." Food and Agriculture Organization of the United Nations, Rome, 179 and 156 pp.
- Duffie, J.A. and W.A. Beckman. 1980. "*Solar Engineering of Thermal Processes.*" John Wiley and Sons, New York, p 1-109.
- Evet, S.R., T.A. Howell, R.W. Todd, A.D. Schneider, J.A. Tolk. 2000. "Alfalfa Reference ET Measurement and Prediction." *Proc., 4th National Irrig. Symp.*, ASAE, Phoenix, AZ. p. 266-272.

- Gill, G.C. 1983. "Comparison testing of selected naturally ventilated solar radiation shields. *Final Rpt Contract # NA-82-0A-A-266.*" NOAA Data Buoy Off, Bay St. Louis, MS.
- Hargreaves, G.H. and Z.A. Samani. 1982. "Estimating potential evapotranspiration." Tech. Note, *J. Irrig. and Drain. Engrg.*, ASCE, 108(3):225-230.
- Hargreaves, G.H., and Z.A. Samani. 1985. "Reference crop evapotranspiration from temperature." *Appl. Eng. in Agr.*, 1(2):96-99.
- Hargreaves, G.L., G.H. Hargreaves, and J.P. Riley. 1985. "Agricultural benefits for Senegal River Basin." *J. Irrig. and Drain. Engrg.*, ASCE 111:113-124.
- Harrison, L.P. 1963. "Fundamental concepts and definitions relating to humidity." In A. Wexler, (ed) *Humidity and Moisture*. Vol. 3. Reinhold Publishing Company, New York, NY.
- Howell, T.A. 1998. "A Texas Sized Test of the ASCE ET Equation." Royce Tipton Lecture, Amer. Soc. of Civil Engr. USDA-ARS, Bushland, TX.
- Howell, T.A., D.W. Meek, C.J. Phene, K.R. Davis, and R.L. McCormick. 1984. "Automated weather data collection for research in irrigation scheduling." *Trans. ASAE* 27(2): 386-391, 396.
- Howell, T.A., S.R. Evett, A.D. Schneider, D.A. Dusek, and K.S. Copeland. 2000. "Irrigated fescue grass ET compared with calculated reference grass ET." *Proc.*, 4th National Irrig. Symp., ASAE, Phoenix, AZ. p. 228-242.
- Itenfisu, D., R.L. Elliott, R.G. Allen, and I.A. Walter. 2000. "Comparison of reference evapotranspiration calculations across a range of climates." p. 216-227, *Proc.*, 4th Decennial National Irrig. Symp., Phoenix, AZ, ASAE, St. Joseph, MI.
- Itenfisu, D. R.L. Elliott, R.G. Allen, I.A. Walter. 2003. Comparison of Reference Evapotranspiration Calculations as a Part of the ASCE Standardization Effort. *J. Irrig. and Drain. Engrg.*, ASCE. 129(6):440-448.
- Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. "Evapotranspiration and Irrigation Water Requirements." ASCE Man. and Rep. on Engineering Pract. No. 70, New York, 332 p.
- Ley, T.W., R.G. Allen, and R.W. Hill. 1996. "Weather station siting effects on reference evapotranspiration." p 727-734, *Proc.*, *Evapotranspiration and Irrigation Scheduling Conf.*, ASAE, San Antonio, TX.

- List, R. J., 1984. “*Smithsonian Meteorological Tables*”, 6th ed., Smithsonian Institution, Washington. 539 pp.
- Majumdar, N.C., B.L. Mathur, and S.B. Kaushik. 1972. “Prediction of direct solar radiation for low atmospheric turbidity.” *Solar Energy* 13, 383-394.
- Martin, D. L. and J. Gilley. 1993. “*Irrigation Water Requirements*,” Chapter 2, Part 623, National Engrg. Handbook, USDA, Soil Conservation Service, 284.
- Meek, D.W., and Hatfield, J.L. 1994. “Data Quality Checking for Single Station Meteorological Databases.” *Agric. and Forest Meteorol.* 69:85-109.
- Monteith, J.L. 1965. “Evaporation and the environment.” p. 205-234. In *The state and movement of water in living organisms*, XIXth Symposium. Soc. for Exp. Biol., Swansea, Cambridge Univ. Press.
- Monteith, J.L. 1981. “Evaporation and surface temperature.” *Q. J. Roy. Meteorol. Soc.*, 107:1-27.
- Murray, F. W. 1967. “On the computation of saturation vapor pressure.” *J. Appl. Meteorol.*, 6:203-204.
- Penman, H.L. 1948. “Natural evaporation from open water, bare soil and grass.” *Proc. Roy.Soc. London.* A193:120-146.
- Penman, H.L. 1956. “Estimating evaporation.” *Trans. Am. Geophys. Union*, 37: 43-50.
- Penman, H.L. 1963. “*Vegetation and hydrology*”. Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England. 125 pp.
- Pruitt, W.O.. amd Doorenbos. J. (1977). “Empirical Calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data?” *Int. Round Table Conf. On Evapotranspiration*, Int. Comm. on Irrig. and Drain., Budapest, Hungary. 20 pp.
- Shafer, M.A., C.A. Fiebrich, and D.S. Arndt. 2000. “Quality assurance procedures in the Oklahoma Mesonet.” *J. Atmospheric. and Oceanic. Tech.* 17: 474-494.
- Smith, M., R.G. Allen, J.L. Monteith, A. Perrier, L. Pereira, and A. Segeren. 1991. “Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements.” Food and Agriculture Organization of the United Nations, Rome, 54. pp.

Snyder, R.L. 2000. "PMDay.xls and PMhr.xls spreadsheet software for estimating daily or hourly reference evapotranspiration using the Penman-Monteith equation." Dept. Land, Air and Water Resources, Univ. Calif., Davis, CA. <http://biomet.ucdavis.edu/evapotranspiration/PMdayXLS/PMday.htm> and <http://biomet.ucdavis.edu/evapotranspiration/PMhrXLS/PMhr.htm>

Snyder, R.L and W. O. Pruitt. 1985. "Estimating Reference Evapotranspiration with Hourly Data. VII-1-VII-3." R. Snyder, D. W. Henderson, W. O., Pruitt, and A. Dong (eds), *Calif. Irrig. Mgmt. Systems*, Final Rep., Univ. Calif., Davis.

Snyder, R.L., and W.O. Pruitt. 1992. "Evapotranspiration Data Management in California. Presented at the Am. Soc. Civil Engr. *Proc. Water Forum '92'*, Aug. 2-6, 1992, Baltimore, MD.

Snyder, R.L., W.O. Pruitt, and A. Dong. 1985. "An automated weather station network for estimation of evapotranspiration." In: A. Perrier and C. Riou (ed.). *Crop Water Requirements*. Int. Commission Irrigation and Drainage. p. 133-142. Versailles, France.

Snyder, R.L., P.W. Brown, K.G. Hubbard, and S.J. Meyer. 1996. "A guide to automated agricultural weather station networks in North America." In: G. Stanhill (ed.). *Advances in Bioclimatology*. p. 1-61. Springer Verlag, New York, NY.

Stanhill, G. 1992. "Accuracy of Global Radiation Measurement at Unattended Automated Weather Stations." *Agric. and Forest Meteorol.* 61:151-156.

Tanner, B.D. 2001. "Evolution of Automated Weather Station Technology though the 1980s and 1990s," World Meteorological Organization 3-20.

Tetens, O. 1930. "Über einige meteorologische Begriffe." *Z. Geophys.*, 6:297-309. (in German)

Ventura, F., D. Spano, P. Duce and R.L. Snyder. 1999. "An evaluation of common evapotranspiration equations." *Irrig. Sci.* 18:163-170.

Walter, I. A. and R. L. Elliott. 2000. Irrigation Association Request for a Benchmark Evapotranspiration Equation. Letter to T. H. Kimmel, Irrigation Association.

Walter, I. A., Allen, R. G. , R. Elliott, M. E. Jensen, D. Itenfisu, B. Mecham, T. A. Howell, R. Snyder, P. Brown, S. Echling, T. Spofford, M. Hattendorf, R. H. Cuenca, J. L. Wright and D. Martin. 2000. "ASCE's Standardized Reference Evapotranspiration Equation." *Proc., 4th National Irrig. Symp.*, ASAE, Phoenix, AZ.

Wright, J.L., 1979. "Recent developments in determining crop coefficient values." *Proc. 1979 Irrig. and Drain. Div. Spec. Conf. ASCE*, pp. 161-162.

Wright, James L. 1981. "Crop Coefficient for Estimates of Daily Crop Evapotranspiration." *Proc. Am. Soc. Agric. Engrs., Irrig. Scheduling Conf.*, Dec. 1981, pp. 18-26.

Wright, J.L. 1982. "New Evapotranspiration Crop Coefficients." *J. Irrig. and Drain. Div.*, ASCE, 108:57-74.

Wright J. L. 1987. "Personal comm. to ASCE Committee of Irrigation Water Requirements."

Wright, J.L. 1988. "Daily and seasonal evapotranspiration and yield of irrigated alfalfa in southern Idaho." *Agron. J.*, 80:662-669.

Wright, J.L. 1996. "Derivation of alfalfa and grass reference evapotranspiration." p. 133-140, *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (eds). *Evapotranspiration and Irrigation Scheduling*, Proc. Int'l. Conf., ASAE, San Antonio, TX.

Wright, J.L. and M.E. Jensen. 1972. "Peak water requirements of crops in Southern Idaho." *J. Irrig. and Drain. Div.*, ASCE, 96(ir1):193-201.

Wright, J.L., R.G. Allen, and T.A. Howell. 2000. "Conversion between evapotranspiration references and methods." p. 251-259, *Proc.*, 4th Decennial National Irrigation Symposium, Phoenix, AZ ,ASAE, St. Joseph, MI.

GLOSSARY OF TERMS

FOR THE

ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION

EQUATION

C_d	denominator constant that changes with reference type and calculation time step ($s\ m^{-1}$)
C_n	numerator constant that changes with reference type and calculation time step ($K\ mm\ s^3\ Mg^{-1}\ d^{-1}$ or $K\ mm\ s^3\ Mg^{-1}\ h^{-1}$)
D_M	day of the month (1-31)
ET	Evapotranspiration ($mm\ d^{-1}$ or $mm\ h^{-1}$)
ET_c	Crop evapotranspiration
ET_{os}	Reference ET for a <i>short</i> crop with an approximate height of 0.12 m (similar to clipped grass) ($mm\ d^{-1}$ or $mm\ h^{-1}$)
ET_{ref}	Reference Evapotranspiration ($mm\ d^{-1}$ or $mm\ h^{-1}$)
ET_{rs}	Reference ET for a <i>tall</i> crop with an approximate height of 0.50 m (similar to full-cover alfalfa) ($mm\ d^{-1}$ or $mm\ h^{-1}$)
ET_{sz}	Standardized Reference Evapotranspiration Equation
G	soil heat flux density at the soil surface ($MJ\ m^{-2}\ d^{-1}$ for daily time steps or $MJ\ m^{-2}\ h^{-1}$ for hourly time steps)
G_{day}	daily soil heat flux density ($MJ\ m^{-2}\ d^{-1}$)
$G_{hr\ daytime}$	hourly soil heat flux density during daytime ($MJ\ m^{-2}\ h^{-1}$)
$G_{hr\ nighttime}$	hourly soil heat flux density during nighttime ($MJ\ m^{-2}\ h^{-1}$)
G_{month}	monthly soil heat flux density ($MJ\ m^{-2}\ d^{-1}$)
G_{sc}	solar constant ($4.92\ MJ\ m^{-2}\ h^{-1}$)
J	day of the year (1 – 365)
J_{month}	month of the year (1 –12)
K_{ab}	coefficient derived from the a_s and b_s coefficients of the Angstrom formula (unitless)
K_B	the clearness index for direct beam radiation (unitless)
K_c	crop coefficient
K_{co}	crop coefficient for use with ET_{os}
K_{cr}	crop coefficient for use with ET_{rs}
K_D	the transmissivity index for diffuse radiation (unitless)
K_G	coefficient used to calculate hourly soil heat flux (unitless)
K_t	atmospheric turbidity coefficient (unitless)
K_{time}	units conversion, equal to $86,400\ s\ d^{-1}$ for ET in $mm\ d^{-1}$ and equal to $3600\ s\ h^{-1}$ for ET in $mm\ h^{-1}$
K_o	average difference between T_{min} and mean daily T_{dew} ($^{\circ}C$)

LAI	leaf area index = area (one-sided) of leaves per unit area of ground surface ($\text{m}^2 \text{ m}^{-2}$)
LAI _{active}	active (sunlit) leaf area index, m^2 (leaf area) m^{-2} (soil surface)
L _m	longitude of the measurement site (expressed as positive degrees west of Greenwich, England)
L _z	longitude of the center of the local time zone (expressed as positive degrees west of Greenwich, England)
M	number of the month (1-12)
N	maximum duration of sunshine or daylight hours (h)
P	atmospheric pressure at station elevation z (kPa)
P _o	atmospheric pressure at sea level = 101.3 (kPa)
R	specific gas constant = $287 \text{ (J kg}^{-1} \text{ K}^{-1})$
R _a	extraterrestrial radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$) or ($\text{MJ m}^{-2} \text{ h}^{-1}$)
RH	relative humidity (%)
RH _{max}	daily maximum relative humidity (%)
RH _{mean}	mean daily relative humidity
RH _{min}	daily minimum relative humidity (%)
R _{lu}	long-wave radiation emitted from the surface
R _{ld}	long-wave radiation emitted from the atmosphere
R _n	net radiation at the crop surface ($\text{MJ m}^{-2} \text{ d}^{-1}$ or $\text{MJ m}^{-2} \text{ h}^{-1}$)
R _{nl}	net long-wave radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$ or $\text{MJ m}^{-2} \text{ h}^{-1}$), defined as being positive upwards and negative downwards
R _{ns}	net short-wave radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$ or $\text{MJ m}^{-2} \text{ h}^{-1}$), defined as being positive downwards and negative upwards
R _s	measured or calculated solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$) or ($\text{MJ m}^{-2} \text{ h}^{-1}$)
R _{so}	clear-sky radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$) or ($\text{MJ m}^{-2} \text{ h}^{-1}$)
S _c	seasonal correction for solar time (h)
T	mean daily or hourly air temperature at 1.5 to 2.5-m height ($^{\circ}\text{C}$)
T _{dew}	dew point temperature ($^{\circ}\text{C}$)
T _{dry}	dry bulb temperature ($^{\circ}\text{C}$)
T _{hr}	mean hourly air temperature ($^{\circ}\text{C}$)
T _K	mean absolute temperature (K)
T _{K hr}	mean absolute temperature during the hour (K)
T _{Ko}	reference temperature at elevation z_o (K)
T _{K max}	maximum absolute temperature during the 24-hour period (K)
T _{K min}	minimum absolute temperature during the 24-hour period (K)
T _{Kv}	mean virtual temperature for period (K)
T _{hr}	mean hourly air temperature ($^{\circ}\text{C}$)
T _{max}	daily maximum air temperature ($^{\circ}\text{C}$)
T _{mean}	mean air temperature for the time period of calculation ($^{\circ}\text{C}$)
T _{min}	daily minimum air temperature ($^{\circ}\text{C}$)
T _{month}	monthly mean air temperature ($^{\circ}\text{C}$)
T _{wet}	wet bulb temperature ($^{\circ}\text{C}$)
W	precipitable water in the atmosphere (mm)

Y	number of the year (for example 1996 or 96)
a_{psy}	coefficient depending on the type of ventilation of the wet bulb of a psychrometer ($^{\circ}\text{C}^{-1}$)
a_s	coefficient of the Angstrom formula (unitless)
b_s	coefficient of the Angstrom formula (unitless)
c_p	specific heat of the air, ($\text{MJ kg}^{-1} ^{\circ}\text{C}^{-1}$)
d	zero plane displacement height, (m)
daytime	hourly or shorter period when $R_n \geq 0$
d_r	inverse relative distance earth-sun (unitless)
e_a	mean actual vapor pressure at 1.5 to 2.5-m height (kPa)
$e_{\delta}(T)$	saturation vapor pressure function (kPa)
e_s	saturation vapor pressure at 1.5 to 2.5-m height (kPa)
f_{cd}	cloudiness function (unitless)
$f_{\text{cd } \beta > 0.3}$	cloudiness function for the time period prior to when sun angle β (in the afternoon or evening) falls below 0.3 radians (unitless)
g	gravitational acceleration = $9.807 \text{ (m s}^{-2}\text{)}$
h	reference vegetation height (m)
k	von Karman's constant, 0.41, (dimensionless)
k_{R_s}	adjustment coefficient for predicting R_s from air temperature ($^{\circ}\text{C}^{-0.5}$)
n	recorded duration of sunshine during a day (h)
nighttime	hourly or shorter period when $R_n < 0$
r_a	aerodynamic resistance (s m^{-1})
r_l	bulk stomatal resistance of a well-illuminated leaf (s m^{-1})
r_s	surface resistance (s m^{-1})
t	standard clock time at the midpoint of the period
t_l	length of the calculation period (h)
u_2	mean daily or hourly wind speed at 2-m height (m s^{-1})
u_z	wind speed at height z (m s^{-1})
z	weather site elevation above mean sea level (m)
z_h	height of air temperature and humidity measurements (m)
z_o	elevation at reference level (i.e., sea level) (m)
z_{om}	roughness length governing momentum transfer (m)
z_{oh}	roughness length for transfer of heat and vapor (m)
z_w	height corresponding to wind speed (m)
α	"alpha" = albedo or canopy reflection coefficient (unitless)
α_1	constant lapse rate moist air = $0.0065 \text{ (K m}^{-1}\text{)}$
β	"beta" = angle of the sun above the horizon (radians)
γ	"gamma" = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$)
γ_{psy}	psychrometric constant for the psychrometer ($\text{kPa } ^{\circ}\text{C}^{-1}$)
Δ	"delta" = slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$)
δ	"delta" = solar declination (radians)

ε	“epsilon” = ratio of the molecular weight of water vapor to dry air (unitless) ($\varepsilon = 0.622$)
λ	“lambda” = latent heat of vaporization (MJ/kg)
φ	“phi” = latitude (radians)
ρ_a	“rho” = air density (Kg m^{-3})
ρ_w	water density (Mg m^{-3}) (taken as 1.0 Mg m^{-3})
σ	“sigma” = Stefan-Boltzmann constant ($4.901 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}$)
ω	“omega” solar time angle (radians), solar noon = 0.
ω_s	sunset hour angle (radians)
ω_1	solar time angle at beginning of hourly or shorter period (radians)
ω_2	solar time angle at end of hourly or shorter period (radians)

APPENDIX A**DESCRIPTION OF TASK COMMITTEE'S
METHDOLOGY AND
PROCEDURES USED TO DERIVE THE
STANDARDIZED REFERENCE
EVAPOTRANSPIRATION EQUATION**

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ASCE-ET RESPONSE TO THE IRRIGATION ASSOCIATION

Cover Letter

January 26, 2000

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Fairfax, VA 22031-4513

Re: Irrigation Association Request for a Benchmark Evapotranspiration Equation

Dear Mr. Kimmell:

In May 1999, the Irrigation Association (IA) requested that the American Society of Civil Engineers Evapotranspiration in Irrigation and Hydrology Committee (ASCE-ET) help establish and define a benchmark reference evapotranspiration (ET) equation.

ASCE-ET is pleased to inform you that a task committee (ASCE Task Committee on Standardization of Reference Evapotranspiration) of ASCE-ET members has developed standardized reference evapotranspiration equations for calculating hourly and daily evapotranspiration (ET) for both a short reference crop and a tall reference crop. Members of the Task Committee (TC) include renowned scientists and engineers, and both researchers and practitioners. A list of the TC members is attached. Using IA's original request as a catalyst, these experts recognized several needs for a standardized method of calculating reference ET. These needs included a standardized calculated evaporative demand that can be used for transferring crop coefficients, reducing confusion among users as to which equation(s) to use, increasing use of the crop coefficient x reference ET procedure to calculate crop ET, and developing more accurate estimates of ET.

One of the first steps in the definition of the equations was the establishment of criteria to be used for the determination of the equation(s). The criteria included:

The equation(s) should be *understandable*, i.e., represent a defined crop or hypothetical surface.

The equation(s) should be *defensible* and should be *traceable* to quality field measurements.

The approach should use *accepted methods*.

The approach should maximize *simplification* without significant loss of accuracy.

The approach should use *existing, readily available data*.

In reviewing IA's request and in their initial evaluation, the TC was concerned that the terms *standard* and *benchmark* carry connotations that may be misconstrued. These terms could lead users to assume that the calculated values determined using "the equation" were for comparison purposes or were a level to be measured against. That is not the purpose of the TC recommendation. **The objective of the TC's recommendations is to establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of crop coefficients and the comparison of ET demands in various climates.**

The TC recommends that two Standardized Reference Evapotranspiration Equations along with *standardized* computational procedures be adopted. The equations are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_0): Reference ET for a *short* crop with an approximate height of 0.12 m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_T): Reference ET for a *tall* crop with an approximate height of 0.50 m (similar to alfalfa).

Two reference surfaces that are similar to known crops were recommended by the TC due to the widespread use of grass and alfalfa across the United States and due to

their individual advantages for specific applications and times of the year. Furthermore, the TC concluded that hourly and daily forms of the equations were needed.

The basis of the equations is the ASCE Penman-Monteith as described in ASCE Manual 70 (Jensen et al. 1990) and the net radiation procedure described in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998). Future publications and summaries from the task committee will contain calculation procedures for all parameters required for applying the standardized reference ET equations. These parameters are currently defined and calculation procedures are described in the following publications: Allen et al. 1994, ASCE Hydrology Handbook (Allen et al. 1996), and FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

In the attached document, which describes the form of the equations, the TC has reduced the equations down to a single equation with an accompanying table of constants. The constants are a function of time step (hourly or daily) and reference surface (ET_0 or ET_r).

Sincerely,

American Society of Civil Engineers
Evapotranspiration in Irrigation and Hydrology Committee
Standardization of Reference Evapotranspiration Equations Task Committee

Dr. Ronald Elliott, Chairman ASCE-ET

Ivan A. Walter, Chairman TC

Encl.

Cc: Bert Clemmens, ASCE Executive Committee

Equation As Sent to the Irrigation Association

Standardized Reference Crop Evapotranspiration Equations

ASCE Committee on Evapotranspiration
in Irrigation and Hydrology
January 2000

The Evapotranspiration in Irrigation and Hydrology Committee recommends that two Standardized Reference Evapotranspiration Equations be adopted for general practice along with *standardized* computational procedures. The standardized equations are derived from the ASCE Penman-Monteith (ASCE-PM) equation as described in ASCE Manual 70 (Jensen et al. 1990), in the ICID Bulletin (Allen et al. 1994), and in the ASCE Hydrology Handbook (Allen et al. 1996). The computation of parameters for the reference equations incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998). A constant latent heat of vaporization, λ , equal to 2.45 MJ kg^{-1} is used for simplicity. Albedo for the reference surfaces is fixed at a constant 0.23. The equations assume that measurement heights for air temperature and water vapor content are made at a height in the range of 1.5 to 2.5 m above the ground. The standardized equations require that wind speed, u_2 , is measured at or is adjusted to a 2 m measurement height. The coefficients in the ASCE standardized reference evapotranspiration equations presume that the weather data are measured over a grassed surface having a vegetation height of about 0.1 to 0.2 m.

The two standardized reference evapotranspiration (ET) equations are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_0): Reference ET for a *short* crop having an approximate height of 0.12 m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_r): Reference ET for a *tall* crop having an approximate height of 0.50 m (similar to alfalfa).

ASCE Standardized Reference Evapotranspiration Equation(s)

Both standardized reference equations were derived from the ASCE-PM by fixing $h = 0.12$ m for short crop (ET_o) and $h = 0.50$ m for tall crop (ET_r). The short crop and tall crop reference equations are traceable to the commonly used terms grass reference and alfalfa reference.

As a part of the standardization, the “full” form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and reduced to a single equation having two constants. The constants vary as a function of the reference surface (ET_o or ET_r) and time step (hourly or daily). This was done to simplify the presentation and application of the methods. The constant in the right-hand side of the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator (C_d) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime).

Equation 1 presents the form of the Standardized Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table 1 provides values for the constants C_n and C_d .

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where	ET_{ref}	Short (ET_o) or tall (ET_r) reference crop evapotranspiration [mm day ⁻¹ for daily time steps or mm hour ⁻¹ for hourly time steps],
	R_n	net radiation at the crop surface [MJ m ⁻² day ⁻¹ for daily time steps or MJ m ⁻² hour ⁻¹ for hourly time steps],
	G	soil heat flux density at the soil surface [MJ m ⁻² day ⁻¹ for daily time steps or MJ m ⁻² hour ⁻¹ for hourly time steps],
	T	mean daily or hourly air temperature at 1.5 to 2.5-m height [°C],

u_2	mean daily or hourly wind speed at 2-m height [m s^{-1}],
e_s	mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of e_s at maximum and minimum air temperature,
e_a	mean actual vapor pressure at 1.5 to 2.5-m height [kPa],
Δ	slope of the vapor pressure-temperature curve [$\text{kPa } ^\circ\text{C}^{-1}$],
γ	psychrometric constant [$\text{kPa } ^\circ\text{C}^{-1}$],
C_n	numerator constant for reference type and calculation time step, and
C_d	denominator constant for reference type and calculation time step.

Table 1. Values for C_n and C_d in Equation 1

Calculation Time Step	Short Reference, ET_o		Tall Reference, ET_r		Units for ET_o , ET_r	Units for R_n , G
	C_n	C_d	C_n	C_d		
Daily or monthly	900	0.34	1600	0.38	mm d^{-1}	$\text{MJ m}^{-2} \text{d}^{-1}$
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	$\text{MJ m}^{-2} \text{h}^{-1}$
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	$\text{MJ m}^{-2} \text{h}^{-1}$

Equations associated with calculation of required parameters in Equation 1 and Table 1 have been standardized and will be described in a detailed report by this committee.

Definition of Crop Coefficients

Calculation of crop evapotranspiration (ET_c) requires the selection of the correct crop coefficient (K_c) for use with the standardized reference evapotranspiration (ET_o or ET_r). It is recommended that the abbreviation for crop coefficients developed for use with ET_o be denoted as K_{co} and the abbreviation for crop coefficients developed for use with ET_r be denoted as K_{cr} . ET_c is to be calculated as shown in equation 2.

$$ET_c = K_{co} * ET_o \text{ or } ET_c = K_{cr} * ET_r \quad (2)$$

References

- Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman, 1989. Operational Estimates of Reference Evapotranspiration. *Agronomy Journal*, 81:650-662.
- Allen, R.G., M. Smith, L.S. Pereira, and A. Perrier, 1994. An Update for the Calculation of Reference Evapotranspiration. *ICID Bulletin*, 43(2):35-92.
- Allen, R.G., W.O. Pruitt, J.A. Businger, L.J. Fritschen, M.E. Jensen, and F.H. Quinn, 1996. Chapter 4 "Evaporation and Transpiration" in *ASCE Handbook of Hydrology*, New York, NY, p. 125-252.
- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. ***Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements***. United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56, Rome, Italy, 300 pages.
- Jensen, M.E., R.D. Burman, and R.G. Allen, 1990. ***Evapotranspiration and Irrigation Water Requirements***, ASCE Manuals and Reports on Engineering Practice No. 70:ISBN 0-872627632, 332 p.

The ASCE-ET Task Committee on Standardization of Reference Evapotranspiration developed the recommendations. This Task Committee is sanctioned by the Irrigation and Drainage Council of the Environmental and Water Resources Institute, ASCE. Members of this task committee included I. A. Walter, R. G. Allen, M. E. Jensen, R. L. Elliott, R. H. Cuenca, S. Eching, M. J. Hattendorf, T. A. Howell, D. Itenfisu, D. L. Martin, B. Mecham, R. L. Snyder, T. L. Spofford, P.W. Brown, and J. L. Wright.

TASK COMMITTEE METHODOLOGY AND PROCEDURES

ASCE-ET Meetings

In response to IA, ASCE-ET committee members met on five occasions¹ to discuss the issues and needs for standardizing the definition and calculation of reference evapotranspiration, to review results of analyses, and to organize the TC report. They first met with members of IA's Water Management Committee (IA-WM) in Denver, Colorado on May 25 and 26, 1999 to review the IA request in detail and to select the basis for a Standardized Reference Evapotranspiration Equation. In August 1999, ASCE-ET held its annual meeting in Seattle, Washington and established the ASCE Task Committee on Standardization of Reference Evapotranspiration (TC). Additionally, ASCE-ET selected equations to be evaluated as candidate standardized reference ET equations.

The third meeting, held November 18 and 19, 1999 in Phoenix, Arizona involved TC members (some TC members are joint members of the ASCE-ET committee and the IA-WM committee). The purpose of that meeting was two-fold: (1) to evaluate the results of evapotranspiration estimates calculated using thirteen previously selected equations or variants on equations, data from 12 states, 36 sites, and 61 site-years; and (2) to develop a recommended Standardized Reference Evapotranspiration Equation. Prior to the Denver meeting and continuing after the Phoenix meeting, an extensive amount of e-mail exchanges between ASCE-ET and TC members shared opinions and data on several of the technical issues that needed to be associated with the standardized reference equation. These included the calculation of net radiation, latent heat of vaporization, and measurement units for meteorological data.

¹ The fourth and fifth meetings were held in Phoenix, November 13, 2000 and Loveland, Colorado, April 5, 6, 2001 for review and editing of the TC report and standardization statement.

Additional meetings by the TC were Ft. Collins, CO, June 20-21, 2000; Phoenix, AZ, Nov. 13, 2000; Loveland, CO, April 4-5, 2001; Sacramento, CA, July 28-29, 2001; San Luis Obispo, CA, July 9-10, 2002.

Motivations For Implementation

The motivations for establishing and implementing a standardized equation were many. They included:

1. Standardized equation(s) provide a uniform calculation of evaporative demand, which improves transferability of crop coefficients from one region or state to another.
2. Practitioners have been confused by the numerous reference evapotranspiration equations that have been developed and published. The TC evaluated seven of these reference evapotranspiration equations for calculating reference evapotranspiration for grass, alfalfa, or both. A grass reference surface equation has been accepted internationally, but in the U.S.A., both grass and alfalfa reference equations are used.
3. Crop evapotranspiration (ET_c) rates are calculated as the product of reference evapotranspiration (ET_{ref}) and a crop coefficient (K_c). With standardization of a reference ET equation, the procedure will be more readily adopted by the private sector and government agencies.
4. Both the public and private sectors now operate automated weather stations that calculate ET_{ref} directly, and guidance, as to which equation to use, is needed.
5. A better hourly ET_{ref} equation is needed to improve ET_c estimation in coastal areas.
6. When summed over a 24-hour period, calculated hourly ET_{ref} should approximate calculated daily ET_{ref} .

Criteria

The TC established several criteria for the selection of the equation. The criteria used in the selection of the standardized reference evapotranspiration equation were:

1. The equation must be understandable.
2. Whether monthly, daily, or hourly data are used, the equation must be defensible, in that it will provide a precise, reliable measure of evaporative demand.
3. The equation should be a derivation of methods that have been accepted by the science and engineering communities such as those methods described in Jensen et al. (1990), Allen et al. (1989), Allen et al. (1994a, 1994b), and Allen et al. (1998).
4. Simplification of an accepted method to enhance its implementation and ease of calculations by users without significant loss of accuracy is desirable.
5. The equation should have the capability to use data from the numerous weather networks, which currently measure daily and hourly radiation, humidity, temperature, and wind speed.
6. The equation must be based on (or traceable to) measured or experimental data. Specifically, the user of the equation should be able to relate the equation to a known reference crop, evaporative index, or hypothetical surface.
7. Sums of hourly calculated ET should closely approximate daily computed ET values.

BACKGROUND FOR THE EQUATIONS EVALUATED BY THE TASK COMMITTEE

ASCE-ET members have a combined experience with numerous reference evapotranspiration equations totaling hundreds of years. The number of equations presently preferred by the members was relatively limited. They included:

1. ASCE Penman-Monteith (grass w/ $h=0.12$ m and alfalfa w/ $h=0.50$ m), Jensen et al. (1990)²
2. FAO-56 Penman-Monteith (grass), Allen et al.(1998)
3. Kimberly Penman (alfalfa), Wright (1982)
4. Penman (grass), Penman (1948, 1956, 1963)
5. CIMIS Penman (grass), Snyder and Pruitt (1985), Snyder and Pruitt (1992)
6. Hargreaves (grass), Hargreaves et al. (1985), Hargreaves and Samani (1985)

In their many years of research and practical experience, TC members have found that no method is perfect. The following is a list of observations and concerns expressed by TC members.

1. In northern Colorado, locating a climate station over alfalfa or grass did not result in significant difference in ET_{ref} values calculated using the 1982 Kimberly Penman (alfalfa reference) or the ASCE-PM (applied to grass reference only). This is a consideration in selecting an agricultural weather station site.
2. The 1982 Kimberly Penman net radiation procedure was developed for the growing season (April-October). Its use outside that period is questionable.
3. Comparison of the ASCE Penman-Monteith for alfalfa to a simplified FAO-24 (Doorenbos and Pruitt, 1977) grass reference on a monthly time step found

²The ASCE Penman-Monteith method for grass reference was adopted by the USDA-SCS (now NRCS) into Chapter 2 of the NRCS Irrigation Guide, Martin and Gilley (1993)

that the monthly ratios of ET_r/ET_o did not vary significantly during summer months.

4. Hourly computation of reference ET_o in coastal regions or windy areas where cold air advection occurs can result in significant differences among equations. Under these conditions, hourly estimates by the CIMIS Penman exceeded those by the FAO-56-PM.
5. Because of stomatal closure at night, the surface resistance (r_s) changes between day and night.
6. At Bushland, Texas and Kimberly, Idaho, comparison of daily-calculated ASCE-PM (0.50-m vegetation height) versus 1982 Kimberly Penman showed total ET estimated for the April-September period to be similar. The 1982 Kimberly Penman values were about 10% lower in the early spring and late fall months.
7. In Idaho, the 1982 Kimberly Penman more closely duplicated lysimeter ET than the ASCE-PM (height = 0.5 m), but differences were not significant. The 1982 Kimberly Penman equation had less scatter in the data, possibly because it reacts better to high wind. Additionally, the Kimberly equation places more weight on the R_n-G term than does the ASCE-PM equation.
8. At Bushland, Texas, comparisons of lysimeter-measured alfalfa and grass ET to the ASCE-PM equations, showed that on days of high wind and VPD the equations slightly under predicted ET. On other days, the ASCE-PM equations tracked the daily lysimeter well. Comparisons with hourly measured ET showed that the ASCE-PM with Manual 70 surface resistance values was slightly low during peak hourly periods.

Measure For Evaluating Equations

TC members have considerable experience comparing the ASCE Penman-Monteith (ASCE-PM) equation to ET measured using lysimeters for grass and alfalfa reference crops. TC members agreed that the ASCE-PM equation, when applied using aerodynamic and surface resistance algorithms presented in Jensen et al. (1990), provides accurate estimates of measured ET_{ref} . Wright et al. (2000) reported that the ratio of ET_r to lysimeter ET was 1.00 and the standard error of estimate was 0.65 mm d^{-1} at Kimberly, Idaho. Evett et al. (2000) reported ASCE-PM ET_r calculated using half-hour data compared well with measured reference lysimeter ET (regression r^2 of

0.91, SEE of 0.6 mm h⁻¹, slope of 0.94 and intercept of 0.2 mm). Use of daily data increased the SEE to 0.8 mm d⁻¹ ($r^2 = 0.91$, slope = 0.98) and introduced a positive offset of 0.7 mm. Howell (1998) reported that the ASCE-PM ET_r performed well when compared to measured lysimeter evapotranspiration at Bushland, Texas. Howell et al. (2000) compared FAO-56 PM to measured grass reference lysimeter ET and reported the equation tended to overestimate grass ET for low rates and underestimate ET for high ET rates. The results were a regression r^2 of 0.701, SEE of 1.16 mm d⁻¹, slope of 0.79 and intercept of 1.39 mm. Ventura et al. (1999) compared Penman-Monteith hourly ET_o with a surface resistance of 42 and 70 s m⁻¹ to lysimeter-measured ET for 0.12-m tall grass. It was reported that the root mean square errors were 0.26 and 0.44 W m⁻².

Since lysimeter-measured 0.12 m grass and 0.5 m alfalfa data are limited within the United States and worldwide, the TC selected the ASCE-PM reference ET values as the measure to evaluate proposed equations and variations on equations against. A detailed description of the ASCE-PM is presented in Appendix B.

Initially, TC members evaluated the performance of 12 ET_o equations and 8 ET_r equations. A listing of the equations and a brief description is provided in Table A-1. More detail is provided in Appendix B. See, for example, Table B-1 for definition of calculation of specific parameters in the equations and page B-4 for a more complete labeling and context for each equation.

Table A-1. Reference Evapotranspiration Equations and Procedures Evaluated¹

Abbreviation	Method or Procedure	Description
ASCE-PM	ET_o & ET_r	ASCE Penman-Monteith, Jensen et al. (1990) w/ R_n 56 ² , G 56 ³ , r_a & $r_s = f(h)$
FAO-56-PM	ET_o	ASCE-PM w/ $h = 0.12$ m, $r_s = 70$ s/m and albedo = 0.23, R_n 56, $G = 0$, $\lambda = 2.45$ MJ kg ⁻¹ , Allen et al. (1998)
ASCE-PMD	ET_o & ET_r	ASCE-PM, $r_a = f(h)$, albedo=0.23, daily ET_o , $r_s = 70$ s/m, hourly ET_o $r_s = 50$ & 200 s m ⁻¹ ; daily ET_r , $r_s = 45$ s m ⁻¹ , hourly ET_r , $r_s = 30$ s/m & 200 s m ⁻¹
ASCE-PMDL	ET_o & ET_r	ASCE-PMD, $\lambda = 2.45$ MJ kg ⁻¹
ASCE-PMv	ET_o & ET_r	ASCE-PMD & r_s specified by user
ASCE-PMDR	ET_o & ET_r	ASCE-PM with $R_n = R_{n \text{ Wright}} (1982)^4$
1982-Kpen	ET_r	1982 Kimberly Penman, Wright (1982 & 1987)
FAO24-Pen	ET_o	FAO-24 Penman, Doorenbos and Pruitt (1977)
1963-Pen	ET_o	1963 Penman, Penman (1963) (same wind function as Penman (1948))
1985-Harg	ET_o	1985 Hargreaves, Hargreaves et al. (1985)
ASCE-PMrf	ET_o & ET_r	ASCE-PM, reduced form: R_n 56, G 56, ET_o , $r_s = 70$ s m ⁻¹ ; ET_r , $r_s = 45$ s m ⁻¹ ; ET_o z_w & $z_h = 2$ m; ET_r z_w & $z_h = 1.5$ m, $d = 0.8$ m. The reduced form represented a test of the standardized equation
ASCE-PMrfh	ET_o & ET_r	ASCE-PM reduced form hourly only: ET_o , $r_s = 50$ s m ⁻¹ ; ET_r , $r_s = 30$ s m ⁻¹ .
CIMIS-Pen	ET_o	CIMIS Penman (hourly) with R_n 56 and $G = 0$, Snyder and Pruitt (1985)

¹ See table B-1 of Appendix B for definition of calculation of specific parameters in the equations and page B-4 for a more complete labeling and context for each of the Penman-Monteith equation forms.

² R_n 56 = net radiation calculated using FAO-56 procedures, Allen et al. (1998)

³ G 56 = Soil heat flux calculated using FAO-56 procedures, Allen et al. (1998)

⁴ $R_{n \text{ Wright}}$ = net radiation calculated using Wright (1982) procedure

Issues Addressed

Examination of Table A-1 and equations presented in the Appendices reveals that the TC evaluated several components of reference evapotranspiration. The methods for calculating net radiation and soil heat flux described in Jensen et al. (1990), Wright (1982), Doorenbos and Pruitt (1977), and Allen et al. (1998), were examined in detail. The latent heat of vaporization (λ) was evaluated over a wide range in air temperature and the impact on ET_{ref} of using a constant value ($\lambda = 2.45 \text{ MJ kg}^{-1}$) was evaluated. The adoption of standardized values for surface and aerodynamic resistance occurred after intense review and discussion by e-mail between TC members and following evaluation across the U.S.A. (described later). Other components discussed in detail included the calculation of vapor pressure deficit and measurement units for meteorological data. The TC worked diligently to ensure that its recommendation for each component was within the established criteria.

Description of Evaluation

The evaluation of various ET equations and variations on equation application was accomplished in part by using REF-ET, a software program capable of calculating reference ET using up to 15 of the more common methods (Allen, 1999, 2000). For the TC comparisons, Allen modified the software to incorporate the equations and application variations listed in Table 1 that were established by the TC selected for the initial evaluation. REF-ET was distributed to TC members who had volunteered to calculate ET_0 and ET_r using meteorological data within their region. A significant benefit resulting from using REF-ET was that outputs were standardized, which improved the efficiency of the TC analyses. At the 1999 meeting in Phoenix, the TC was able to evaluate results of reference evapotranspiration estimates at 36 sites within Arizona, California, Colorado, Idaho, Montana, Nebraska, Oklahoma, Oregon, South Carolina, Texas, Utah, and Washington. The elevations of sites varied from 2 to 2,895 meters. Mean annual precipitation amounts ranged from 152 to 2,032 mm.

Following the 1999 meeting in Phoenix, data from Florida, Georgia, Illinois, and New York were added to the analysis.

The results obtained using REF-ET at all sites were submitted to Drs. Itenfisu and Elliott of Oklahoma State University (Itenfisu et al. 2000), where the information was compiled and several equation-to-equation comparisons were conducted. The key comparisons were:

- ◆ ET_{ref} versus ASCE-PM using daily data.
- ◆ The sum of 24 hourly ET_{ref} values versus ASCE-PM using daily data
- ◆ The sum of 24 hourly ET_{ref} values versus ET_{ref} using the same equation but with daily data.

The comparisons were made for both ET_o and ET_r . Itenfisu et al. (2000) determined the mean ratios of each equation estimate to that from the ASCE-PM, the Root Mean Square Difference (RMSD), and the RMSD as a percentage of ASCE-PM. The RMSD is calculated as the square root of the sum of the squared differences between the two estimates divided by the number of estimates

$$RMSD = \left(\frac{\sum_{i=1}^n (x_i - y_i)^2}{n} \right)^{0.5} \quad (A.1)$$

where

- x_i = the i^{th} observation on estimate x
- y_i = the i^{th} observation on estimate y
- n = the number of observations.

For each of the site–year combinations, statistics were summarized for the growing season and, if available, for the full calendar year.

At the 1999 meeting in Phoenix, the TC spent two days reviewing and discussing the results for the 61 site-years. A detailed listing of the sites is presented in Appendix B. Conclusions from the analyses follow:

Review of the results of daily ET_0 versus ASCE-PM ET_0 for the growing season found:

1. The use of net radiation R_n computed using procedures from FAO-56 predicted ET_0 and ET_r that was about 2 to 3 percent higher than that predicted using R_n computed using procedures by Wright (1982). These differences were judged to be relatively minor. It was noted that the time-based equations for predicting albedo and emissivity coefficients in the Wright (1982) procedure were developed for use only during the growing season (April-October) and for latitude of approximately 40 degrees north. Some caution should be exercised in applying the Wright (1982) procedures for R_n during the non-growing season and at sites outside an approximately 35 to 45 degree latitude band. For consistency, it is recommended that FAO-56 procedures be used to calculate R_n .
2. The 1985 Hargreaves equation revealed considerable site-to-site scatter in ratios of the Hargreaves ET_{ref} estimates to ASCE-PM estimates than for the other methods evaluated. (See Fig. A-1 and A-3) The 1985 Hargreaves equation did not perform well, and therefore should be calibrated, in high wind and coastal areas. For example, at Bushland Texas (mean monthly wind = 4.25 m/s, range: 3.23 to 5.39 m/s (Howell, et al. 2000)) the ratio of 1985-Harg ET_0 to ASCE-PM ET_0 was 0.80. This equation may therefore need to be calibrated at other sites.
3. The 1963 Penman equation ET_0 estimates ranged from 0.5 % less to 13% higher than ASCE-PM estimate and averaged about 7% high.
4. FAO-24 Penman, which is an ET_0 equation, overestimated ET_0 by about 17 % on an annual basis and by about 20 % during the growing season. Ironically, the FAO-24 Penman equation appears to provide a reasonably good estimate of ET_r unless the FAO-24 correction factors for wind and relative humidity are applied.
5. The use of a reduced form of ASCE-PM using constants for lambda (heat of vaporization) and r_s (surface resistance) resulted in a limited loss of accuracy (ranging from -0.06% to 0.04% error).

6. The reduced form of ASCE-PM was always within 1% of estimates by the original (“full-form”) ASCE-PM.

The consensus of the TC was that the simplification of surface resistance, aerodynamic resistance, latent heat of vaporization and air density did not result in significant or unacceptable differences in ET_{ref} estimates. All differences were much less than the probable errors in actual ET_o measurements.

Review of the results of Daily ET_r versus ASCE-PM ET_r for the growing season found:

1. ASCE-PMDL (the ASCE-PM equation with heat of vaporization fixed at 2.45 MJ kg⁻¹) provides an excellent match to the ASCE-PM.
2. The use of the Wright (1982) Kimberly R_n procedure instead of the FAO-56 R_n procedure causes a reduction in the growing season ET_r estimate of approximately 2 to 3 percent. Largest decreases in ET_r occurred at Montana (4 to 5%), New York (4 to 5%), Georgia (3 to 4%) and Oregon (5 to 6%) stations.
3. Comparison of the 1982 Kimberly Penman to ASCE-PM for yearly data revealed that there was considerable variation, with ratios ranging from 0.86 to 1.04. (See Fig. A-2). The average ratio was about 0.94. Results indicated some correlation between the ratio and the latitude of the location. Additionally, the ratio of ET_r from the 1982 Kimberly Penman to the ASCE-PM ET_r tended to decrease with increase in ET during the peak month.
4. Comparison of the 1982 Kimberly Penman to ASCE-PM for growing seasons only, showed the ratio to range from 0.89 to 1.12 (see Fig. A-2). The average ratio was about 0.99. Ratios were within the range of 0.975 to 1.075 for more than 75% of the locations (Fig. A-2).
5. Comparison of ASCE-PMDR (i.e., the ASCE-PM using R_n from Wright (1982)) to ASCE-PM (using R_n from FAO-56) revealed that the ratio of the two methods was always 0 % to 3 % less than 1.0.

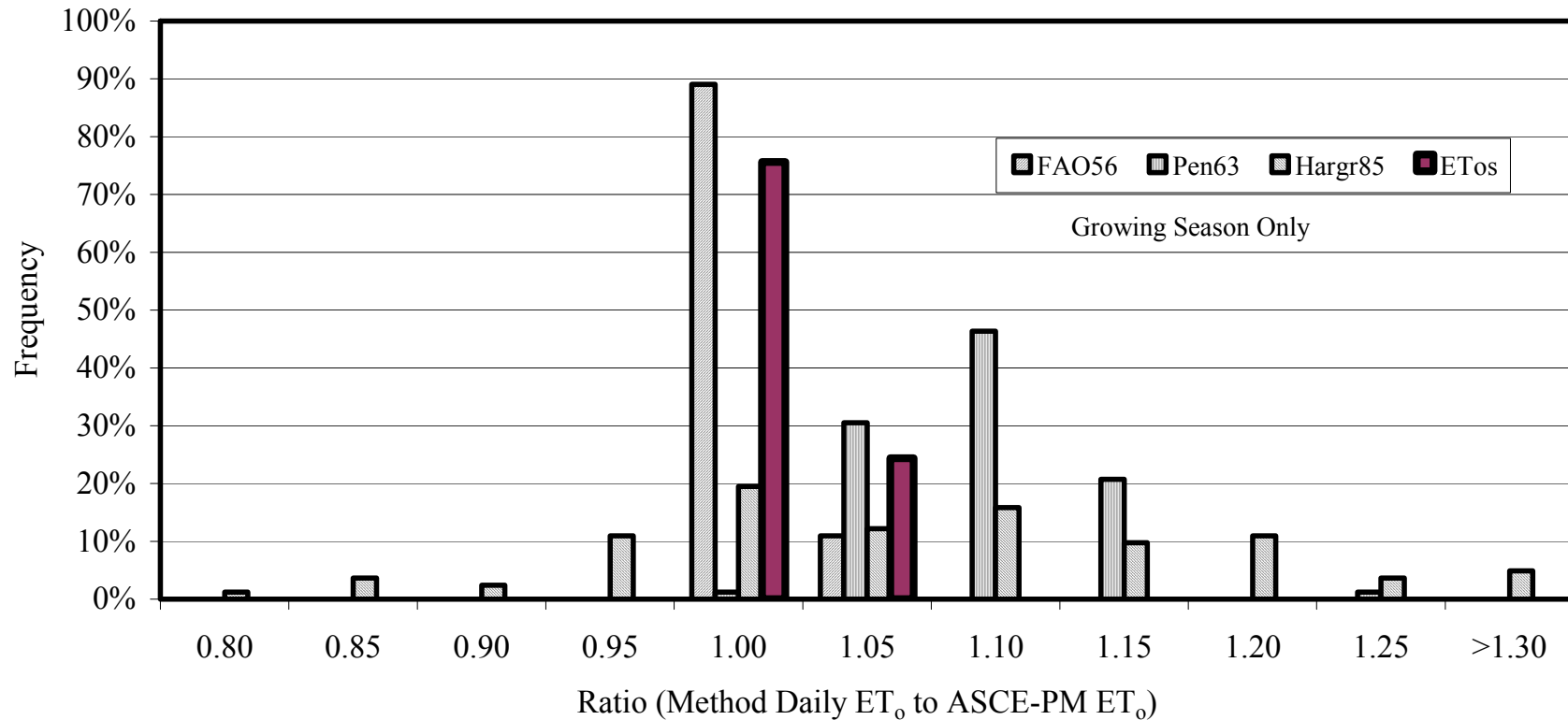


Figure A-1. Frequency of ratio of daily ET_0 or ET_{os} to daily ET_0 by ASCE-PM equation for 56 site-years covering 33 locations.

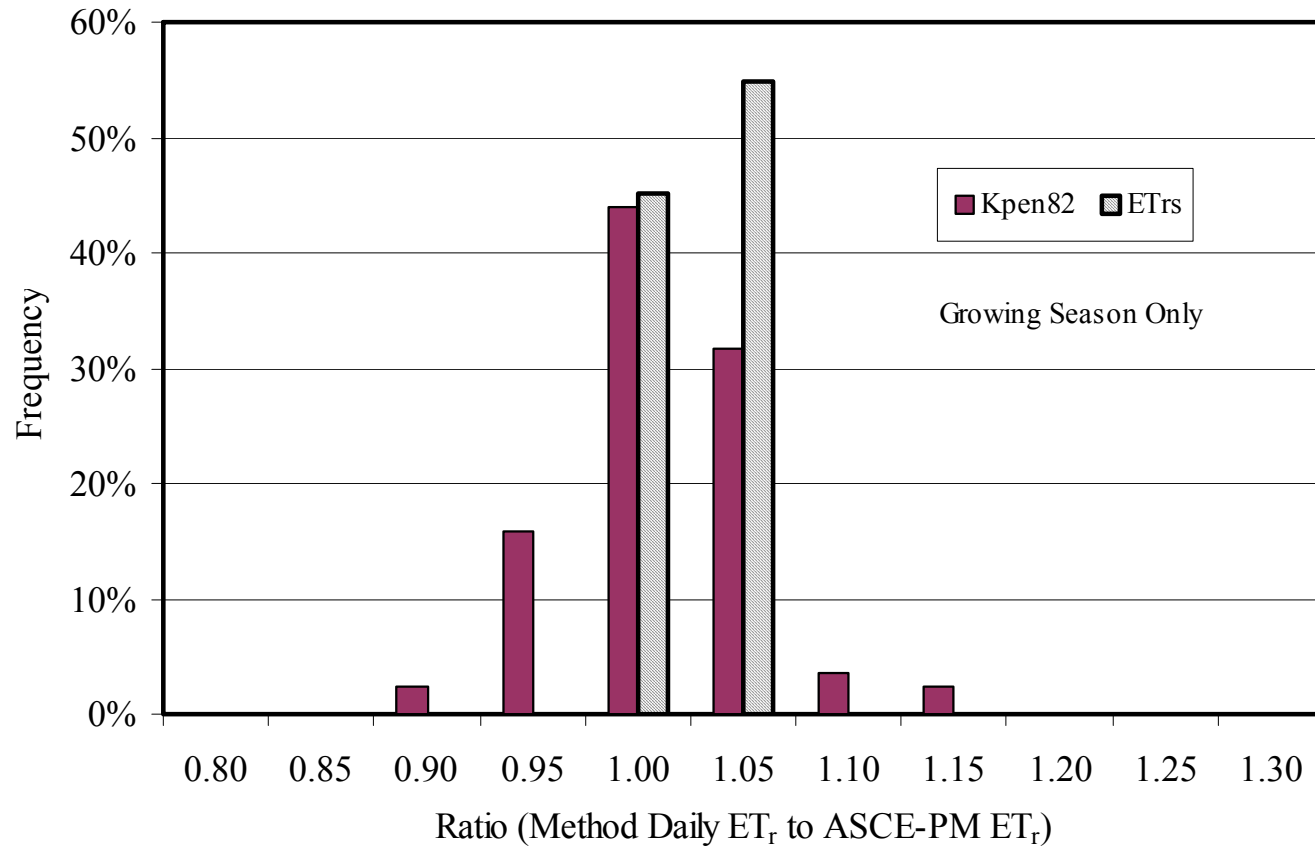


Figure A-2. Frequency of ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation for 56 site-years covering 33 locations.

When analyzing the results of summed hourly ET_0 to daily ASCE-PM ET_0 , the TC significant findings or discussions were as follows:

1. Soil Heat Flux (G). Concern was expressed that calculation of G in FAO-56 and ASCE Hydrology Handbook ($G=0.1 R_n$ [for daytime] and $G = 0.5 R_n$ [for nighttime]) might overpredict G. After viewing data provided by Cuenca from Oregon and Brown from Arizona, the TC concluded that the FAO-56 procedure provided good estimates.
2. Surface Resistance (r_s). The hourly r_s values of 50 and 200 $s\ m^{-1}$ (day and night) were concluded to be reasonably accurate in matching ET_0 calculated by the ASCE-PM using a daily time step. The yearly ratio averaged 0.996 and ranged from 0.938 to 1.052 and the growing season ratio averaged 1.003 and ranged from 0.940 to 1.078.
3. The ASCE-PMDL equation (same as the ASCE-PMD, but with fixed latent heat of vaporization) agreed well with and generally had a good fit relative to the ASCE-PM computed daily. The yearly ratio averaged 0.993 and ranged from 0.937 to 1.047 and the growing season ratio averaged 1.001 and ranged from 0.937 to 1.074. This indicates that the use of constant lambda does not introduce significant error.
4. The CIMIS equation (computed hourly and using R_n from FAO-56³ and $G=0$) showed the most variability from site to site relative to the ASCE-PM equation computed daily, with ratios for the growing seasons ranging from 0.969 to 1.220, averaging 1.08. Much of the higher estimation by the CIMIS equation stemmed from using $G = 0$ for hourly computations. The hourly applications of the ASCE-PM equation used $G = 0.1 R_n$ during daytime and $G = 0.5 R_n$ during nighttime.

When analyzing the results of summed hourly ET_T to daily ASCE-PM ET_T , the TC found the results were similar to and follow the discussion for ET_0 above.

1. The results showed that the ASCE-PM applied hourly and summed daily matched the daily ASCE-PM fairly well when applied with r_s values of 30 and 200 $s\ m^{-1}$ for day and night respectively (i.e., the ASCE-PMD method). The yearly ratio averaged 0.976 and ranged from 0.902 to 1.069 and the growing season ratio averaged 0.995 and ranged from 0.899 to 1.079.
2. The ASCE-PMDL (same as the ASCE-PMD, but with $\lambda = 2.45\ MJ\ kg^{-1}$) was within acceptable accuracy. The yearly ratio averaged 0.974 and ranged from 0.902 to 1.064 and the growing season ratio averaged 0.992 and ranged from 0.897 to 1.075.

³ The standard CIMIS Penman application by CIMIS utilizes a R_n calculation procedure that is different from that by FAO-56.

PERFORMANCE OF THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Following the 1999 meeting in Phoenix, sixteen additional sites were added to improve the overall coverage for the U.S.A. The final number of site-years was 82 at 49 locations in 16 states, ranging from 73° to 125° longitude, 27° to 48° latitude, 2 to 2900 m elevation, and with 150 to 1500 mm annual precipitation. Drs. Itenfisu and Elliott recompiled the results for preparation of the final report (Itenfisu et al. 2000). To avoid confusion, the standardized ET_{ref} symbols are referred to as ET_{os} for the 0.12 m tall vegetative surface and as ET_{rs} for the 0.5 m tall vegetative surface. A comprehensive summary of the final comparison of ET_{os} and ET_{rs} to the ASCE-PM at the 49 sites was presented in Itenfisu et al. (2000) and Itenfisu et al. (2003). A partial listing of the Itenfisu et al. (2000, 2003) results and statistical summary is provided in Table A-2 and Appendix F.

Table A-2 shows that the summed hourly ET_{os} and ET_{rs} compared as well or better versus daily ET_{os} and ET_{rs} as compared to the same analyses for the ASCE-PM equation. The comparisons of daily ET_{os} to daily ASCE-PM ET_o and daily ET_{rs} to daily ASCE-PM ET_r reveal only small differences; therefore, the simplifications are judged to have minimal impact on reference ET estimates. The third comparison of hourly sums of ET_{os} and ET_{rs} to daily ASCE-PM shows that ET_{os} and ET_{rs} agree closely with the ASCE-PM daily values.

The **daily-to-daily comparisons** are illustrated graphically in Figs. A-3 and A-4 for growing season periods. In these figures, the 82 site-year combinations are plotted along the horizontal axis in order of longitude (refer to Table A-3 to match a site to the corresponding site-year index). Figure A-3 shows mean ratios of daily calculations by the various ET_o equations to daily calculations by the ASCE-PM ET_o method. These ratios are the basis for the mean ratios presented in Table A-2. The

similarity of the ASCE Standardized ET_{os} , FAO56-PM ET_{os} , and ASCE-PM ET_{os} results is obvious and is due to the commonality in the equations.

Table A-2. Statistical summary of the comparisons between the Standardized Reference Evapotranspiration Equations and ASCE Penman-Monteith for the growing season for 82 site-years at 49 locations.

METHOD	RATIO				RMSD (mm d^{-1})				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	Mean
Hourly Sum ET_o vs. Daily ET_o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
Hourly Sum ET_r vs. Daily ET_r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
Daily ET_o vs. Daily ASCE-PM ET_o									
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
Daily ET_r vs. Daily ASCE-PM ET_r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
Hourly Sum ET_o vs. Daily ASCE-PM ET_o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
Hourly Sum ET_r vs. Daily ASCE-PM ET_r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41

Mean daily ET_0 and ET_r calculations for growing season periods for all locations are plotted against the full ASCE-PM equation estimates in Fig. A-5 and A-6. The data in Fig. A-5 show ET_0 estimates by the original Penman method (1963 Penman) to have an approximately 0.3 mm d^{-1} bias relative to the daily ASCE-PM ET_0 estimates across all locations and magnitudes of mean ET_0 . Fig. A-6 shows mean growing season daily estimates of ET_r by the 1982 Kimberly Penman method to have predicted progressively lower than the daily ASCE-PM ET_r as mean ET_r for the growing season increased. Calculations by the standardized PM equation (ET_{0s} and ET_{rs}) predicted closely to daily ET_0 and ET_r by the full ASCE-PM equation over all sites and ranges of climate.

Comparisons of the method hourly sums to ASCE-PM daily are shown in Figs. A-7 and A-8 for growing season periods. The hourly ET_0 by the 1963 Penman and CIMIS Penman equations have similar trends and both have ratios to ASCE-PM ET_0 that average about 1.1 at many sites. The higher ratio by the 1963 Penman can be attributed to its linear wind function which becomes relatively strong during day time hours when wind speed and vapor pressure deficit have larger values. The higher ratios for the CIMIS equation, which has a wind function that is calibrated for hourly time steps, is partially due to the absence of the soil heat flux term in the equation as applied by CIMIS (see Appendix B). The wind functions of the CIMIS equation were developed without the inclusion of a soil heat flux term. The ET_0 estimates by the FAO-PM and ASCE-PM methods applied hourly averaged about 5% below the ASCE-PM method applied daily due to the use of a constant 70 s m^{-1} surface resistance in those hourly applications (Fig. A-7). Hourly ET_r by the ASCE-PM method averaged about 5% below daily ET_r by the ASCE-PM due to the use of a constant $r_s = 45 \text{ s m}^{-1}$ for hourly periods.

Table A-3. Weather station sites in the study (listed from east to west longitude).

Site-Year Index	State	Site	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Mean Annual Precip. (mm)	Years (19--)	Peak-Month Mean ASCE-PM ET _o (mm d ⁻¹)	
								Year 1	Year 2
1	NY	Willsboro	73.38	44.38	43	760	98	3.79	
2, 3	NY	Valatie	73.68	42.43	76	910	97 98	3.90	3.89
4, 5	NY	Ithaca	76.45	42.45	123	910	97 98	3.82	3.88
6	SC	Florence	79.81	34.24	40	1120	86	5.91	
7	FL	Fort Pierce	80.44	27.57	7	1422	99	4.68	
8, 9	FL	Lake Alfred	81.89	28.03	46	1270	98 99	5.66	4.88
10, 11	GA	Blairsville	83.93	34.84	584	1307	97 98	4.48	4.63
12, 13	GA	Griffin	84.28	33.26	282	1447	97 98	5.05	5.99
14, 15	GA	Attapulgus	84.49	30.76	37	1460	97 98	4.54	6.29
16	IL	Bondville	88.37	40.00	213	1008	99	5.18	
17	IL	Belleville	89.88	38.52	133	974	99	5.53	
18	IL	Monmouth	90.73	40.92	229	942	99	5.23	
19, 20	OK	Wister	94.68	34.98	143	1188	97 98	5.13	6.03
21, 22	NE	Mead	96.30	41.08	366	743	97 98	5.15	4.57
23, 24	OK	Marena	97.21	36.06	331	889	97 98	5.63	6.84
25, 26	NE	Clay Center	98.08	40.31	552	685	97 98	5.46	5.15
27, 28	OK	Apache	98.29	34.91	440	757	97 98	6.59	8.60
29, 30	NE	Champion	101.43	40.22	1029	482	97 98	6.64	6.18
31, 32	OK	Goodwell	101.60	36.60	996	447	97 98	8.56	9.68
33, 34	TX	Bushland	102.05	35.11	1170	505	97 98	7.36	9.34
35, 36	TX	Dalhart	102.32	36.20	1228	467	97 98	6.44	7.30
37, 38	CO	Ovid	102.45	40.97	1089	448	98 99	5.50	6.08
39, 40	CO	Rocky Ford	104.00	38.00	1274	279	97 99	7.08	8.02
41, 42	CO	Wiggins	104.06	40.31	1367	353	97 98	5.88	5.93
43	CO	Fort Collins	105.00	40.60	1527	383	95	5.58	
44, 45	CO	Loveland	105.11	40.40	1540	406	97 98	5.59	5.30
46, 47	CO	Center	106.14	37.71	2348	178	97 99	5.62	5.96
48, 49	CO	Colton	106	39	2743	279	82 83	4.65	4.69
50, 51	CO	Portis	106	39	2895	279	82 83	4.38	4.30
52, 53	CO	Fruita	108.70	39.18	1377	228	97 99	7.87	6.75
54, 55	CO	Yellow Jacket	108.74	37.39	2085	406	97 99	5.92	5.96
56, 57	AZ	Tucson	110.94	32.28	713	300	97 98	8.54	8.21
58, 59	ID	Ashton	111.47	44.03	1615	430	97 98	4.96	5.70
60, 61	UT	Logan	111.80	41.60	1350	433	89 90	6.21	5.77
62, 63	AZ	Phoenix Encanto	112.10	33.48	335	175	97 98	7.49	7.60
64, 65	MT	St. Ignatius	114.10	47.31	896	360	97 98	4.52	5.27
66, 67	MT	Creston	114.13	48.19	899	390	97 98	4.16	4.73
68, 69	MT	Ronan	114.28	47.54	927	380	97 98	4.31	4.70
70, 71	ID	Twin Falls	114.35	42.61	1195	222	97 98	5.69	6.44
72, 73	ID	Parma	116.93	43.80	703	237	97 98	5.66	6.10
74	WA	Paterson	119.49	45.94	109	152	98	6.65	
75	CA	Fresno	119.70	36.80	103	269	98	7.11	
76	WA	Gramling	119.73	46.29	386	178	98	7.42	
77	WA	Roza	119.73	46.29	343	178	98	5.96	
78	CA	Santa Maria	120.40	35.00	82	314	98	4.42	
79	CA	Davis	121.80	38.50	18	461	98	6.71	
80	WA	Puyallup	122.30	47.10	61	1016	98	3.48	
81	WA	Grayland	124.00	46.78	2	2032	98	2.78	
82	OR	Haga	124.50	42.50	9	1778	99	3.32	

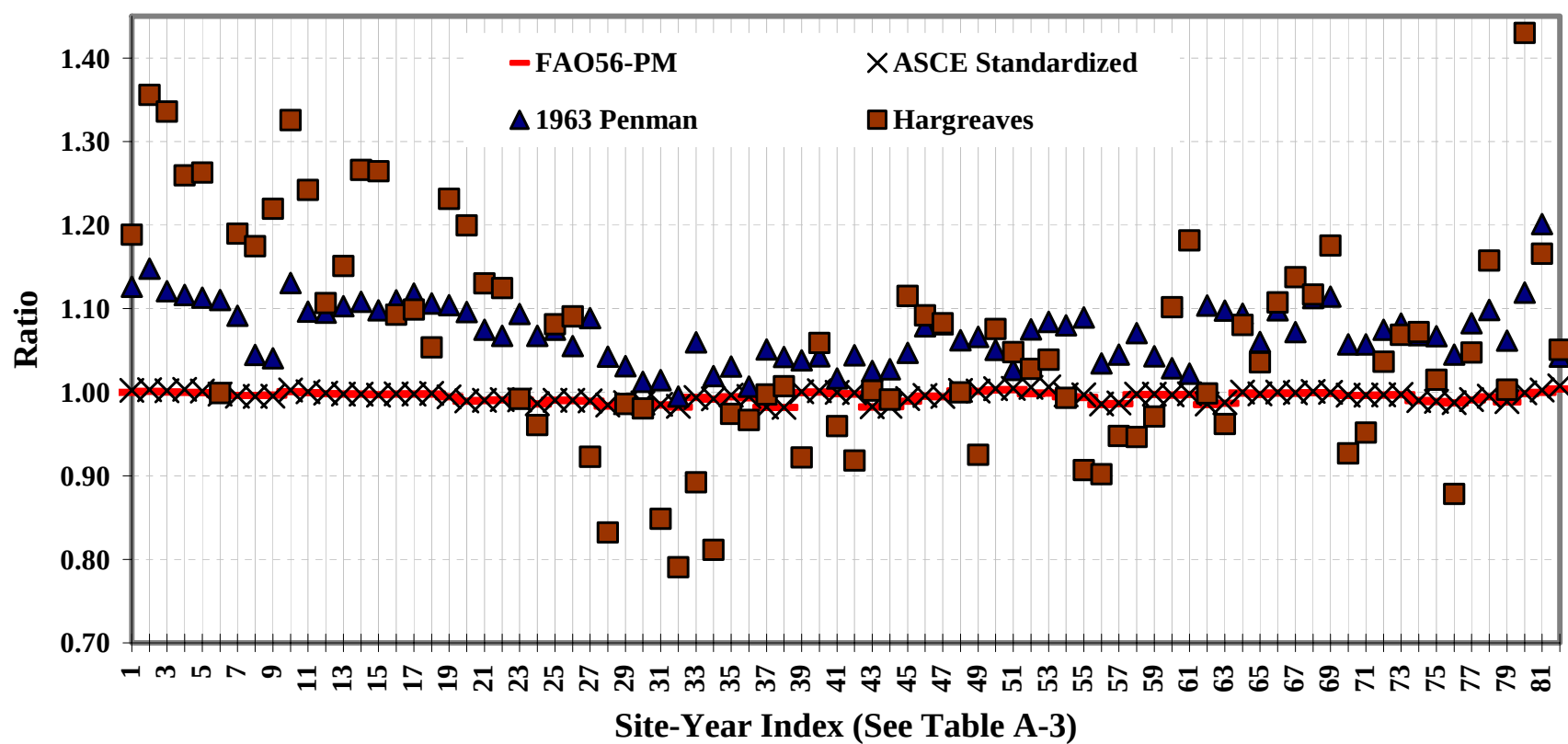


Figure A-3. Average ratio of daily ET_0 or ET_{os} to daily ET_0 by ASCE-PM ET_0 equation.

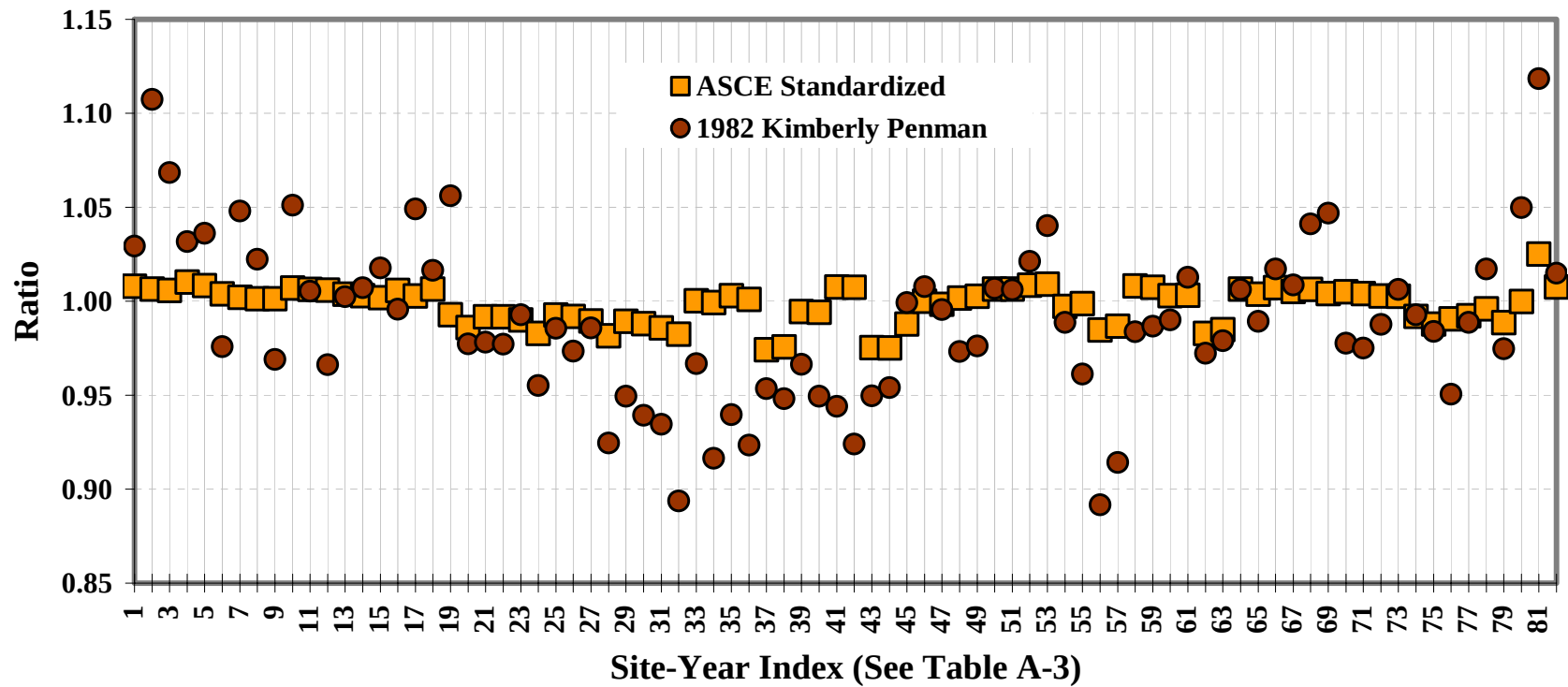


Figure A-4. Average ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation.

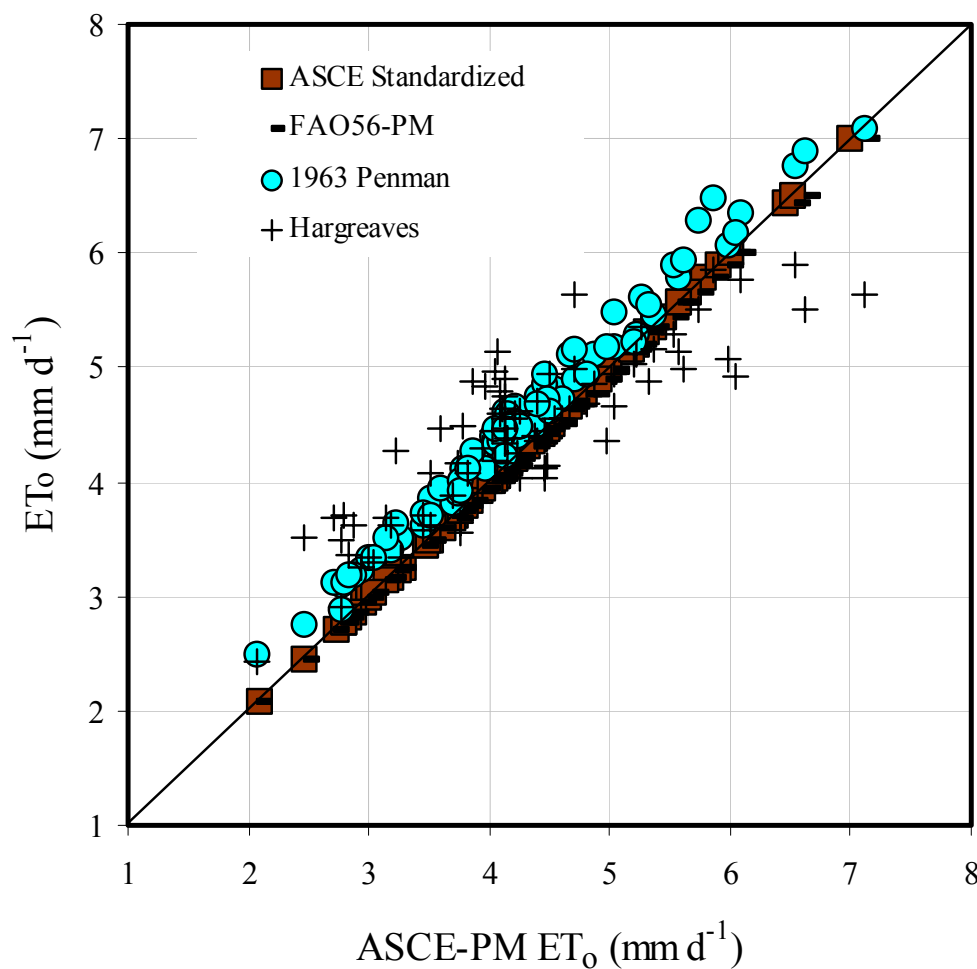


Figure A-5. Mean daily ET_0 for the growing season computed using various ET_0 methods and ET_{os} vs. mean daily ET_0 for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (82 total site-years (see Table A-3 and App. F)).

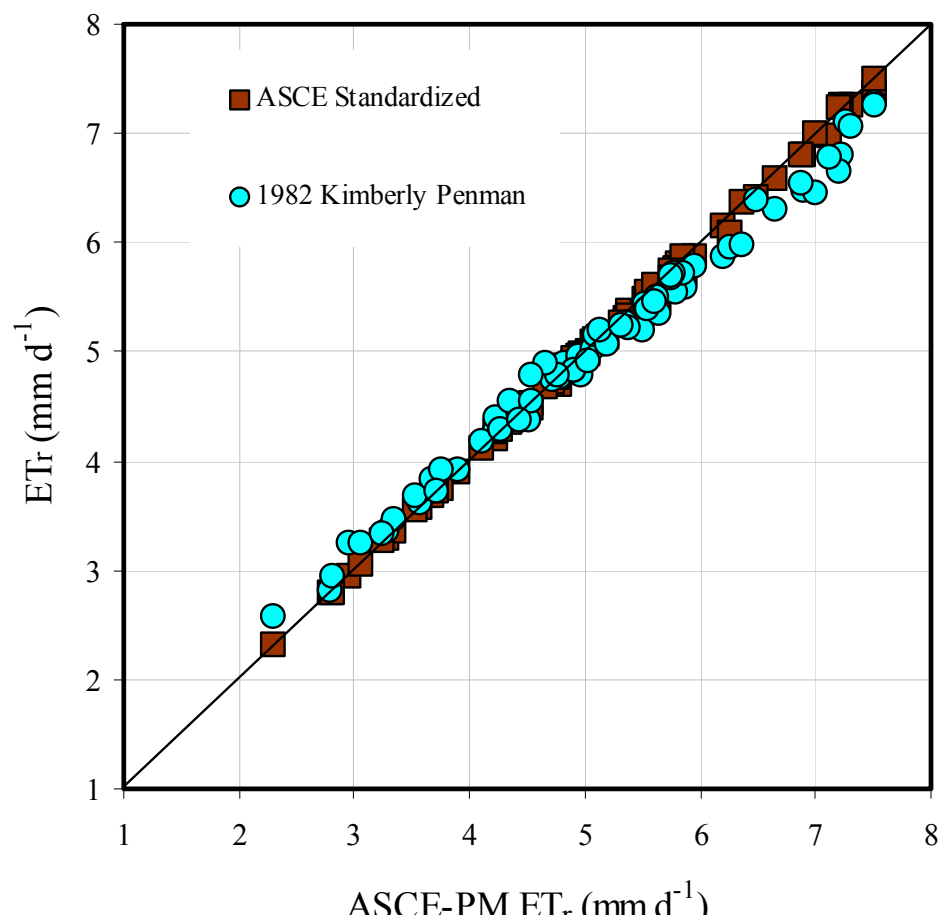


Figure A-6. Mean daily ET_r for the growing season computed using the 1982 Kimberly Penman method and ET_{rs} vs. mean daily ET_r for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (82 total site-years (see Table A-3 and App. F)).

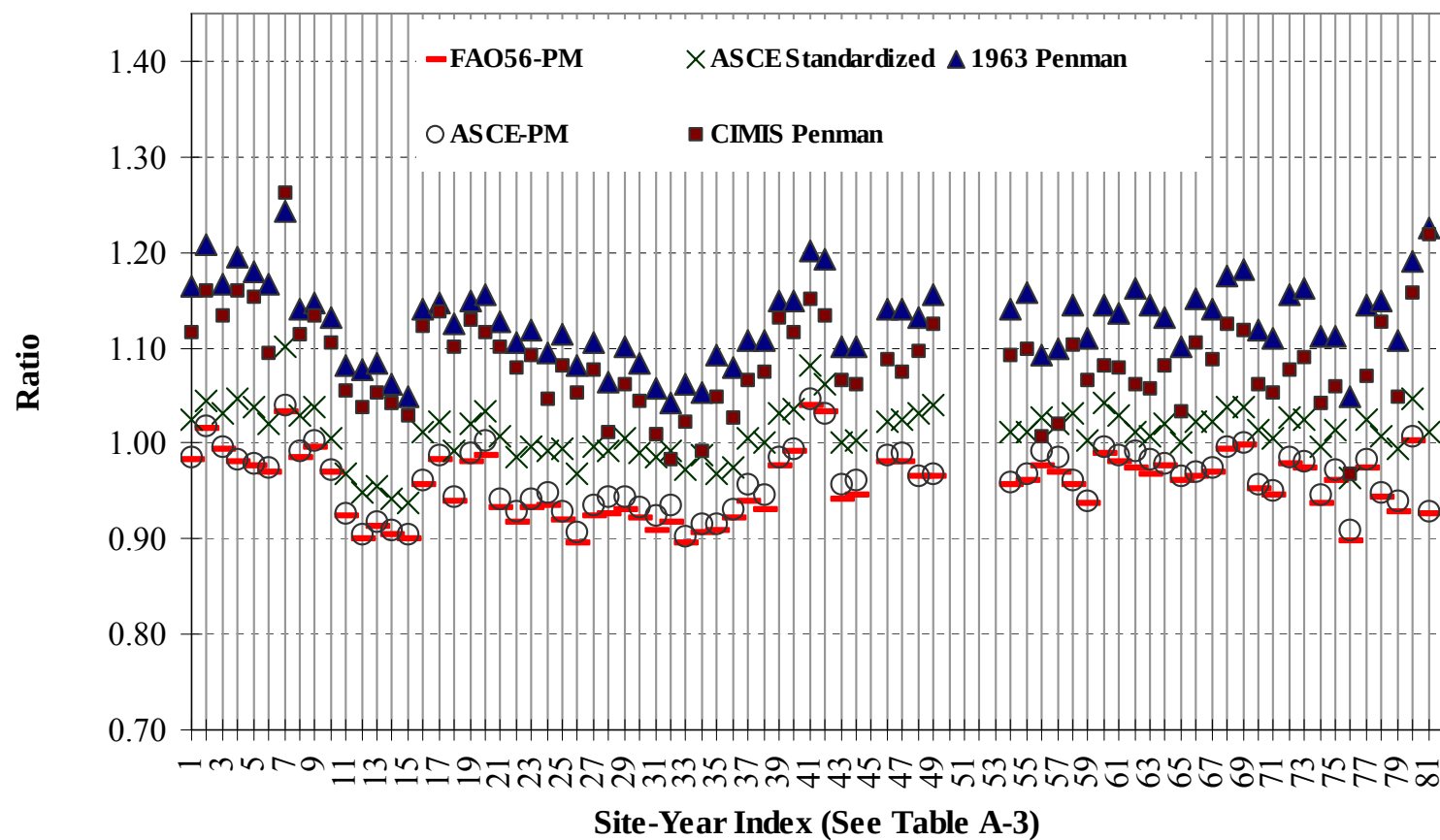


Figure A-7. Average ratio of summed hourly ET_0 or ET_{os} to daily ET_0 by ASCE-PM ET_0 equation.

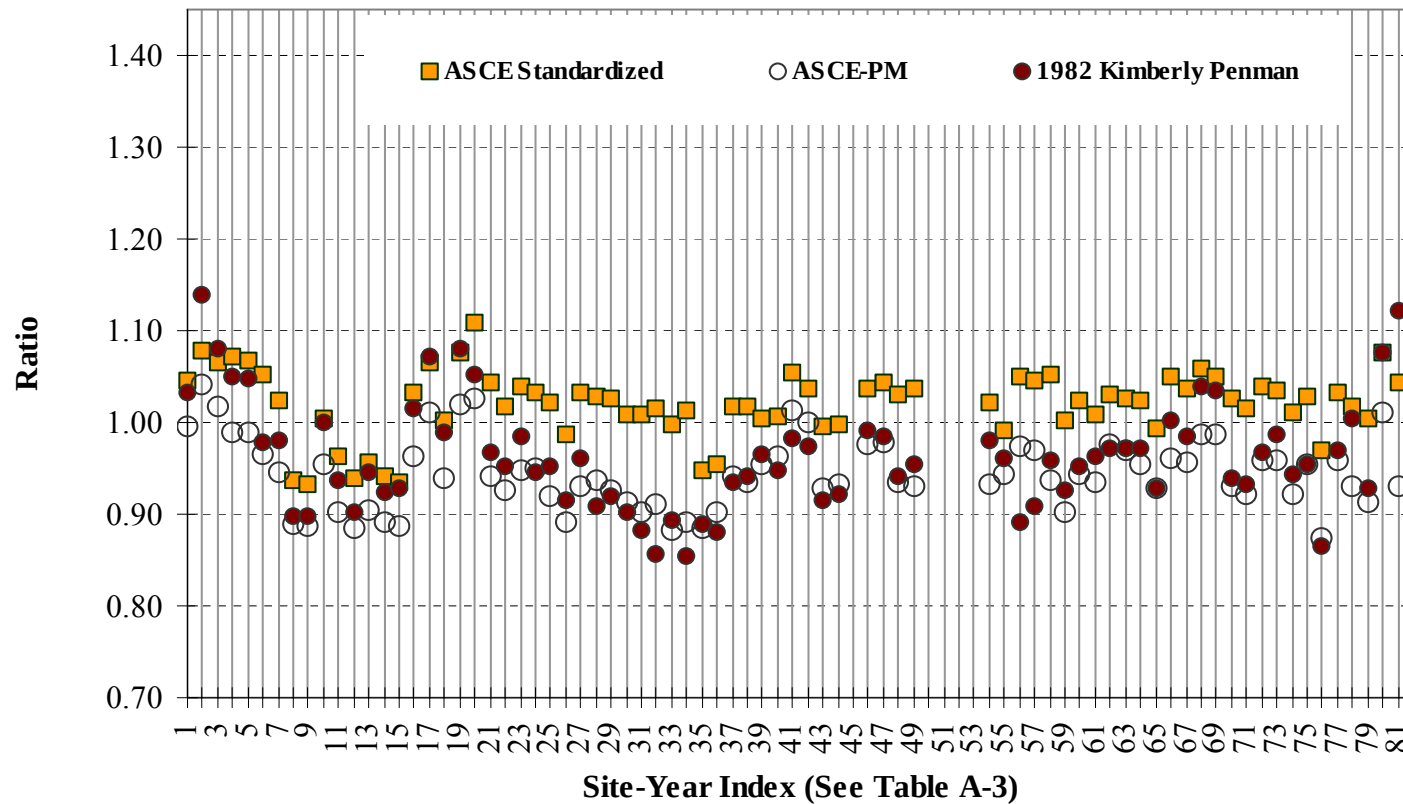


Figure A-8. Average ratio of summed hourly ET_r or ET_{rs} to daily ET_r by ASCE-PM ET_r equation.

TASK COMMITTEE CREDENTIALS

Credentials of members of the Task Committee are as follows:

Chairman Ivan A. Walter is a consulting engineer with Ivan's Engineering. He has 25 years of experience in water resources and agricultural and irrigation engineering. His engineering has involved projects related to surface and groundwater hydrology, water supply planning and development, irrigation engineering and water rights analysis. This involvement has included the investigation and analysis of evapotranspiration by agricultural crops and native vegetation, hydrologic studies and modeling of river basins, and computer modeling of surface water and groundwater hydrologic systems.

Vice-chairman Richard Allen is a professor of water resources engineering at the University of Idaho. He has 25 years of national and international experience in measuring weather and evapotranspiration and in developing methodologies for computing evapotranspiration parameters. Allen was a joint author of FAO-56 and coeditor of ASCE Manuals and Reports on Engineering Practice No. 70.

Ronald Elliot is head of the Department of Biological and Agricultural Engineering, Oklahoma State University and is a co-principal investigator for the Oklahoma Mesonet.

Marvin E. Jensen is retired from the Agricultural Research Service, USDA, in 1987 and from Colorado State University in 1993. Since 1993, he has been consulting on water consumption issues. He has 25 years experience in measuring evapotranspiration in field experiments and over 40 years experience in estimating evapotranspiration. Jensen was the editor of the 1974 ASCE Report Consumptive Use of Water and Irrigation Water Requirements and was senior editor of the 1990 ASCE Manuals and Reports on Engineering Practices No. 70.

Daniel Itenfisu is an irrigation engineer and was a postdoctoral fellow at Oklahoma State University during his task committee tenure. He is currently a Research Analyst with Alberta Agriculture Food and Rural Development. He has ten years of experience in irrigation water management, evapotranspiration and soil moisture modeling and measurements.

Brent Mecham is a Water Conservation Officer with the Northern Colorado Water Conservancy District. He has more than 20 years experience in developing landscape management techniques and practices and crop coefficients.

Terry Howell is an Agricultural Engineer and Research Leader with the USDA-ARS Water Management Laboratory in Bushland, Texas. He has over 30 years experience in crop water requirements and ET measurement including lysimeter systems.

Richard Snyder is a biometeorology specialist for the University of California-Cooperative Extension. He was the principle investigator on the California Irrigation Management Information System (CIMIS), which provides reference evapotranspiration to California growers, water purveyors and public agencies. He is also involved in research to measure evapotranspiration and to refine crop coefficients.

Paul Brown is a biometeorology specialist for Arizona Cooperative Extension. He developed and presently oversees the operation of the Arizona Meteorological Network (AZMET) which provides weather-based information, including reference ET information, to Arizona growers and municipalities. His research interests include improving crop coefficients for use in arid irrigation management, and impact of weather station siting on computed values of ET_{ref} .

Simon Eching is a water use and evapotranspiration specialist with the California Department of Water Resources with applications in the CIMIS network. He has over 15 years experience in irrigation water management, crop water use, and soil moisture measurement. He has been involved in several international projects to develop weather station networks that provide reference evapotranspiration to irrigators.

Tom Spofford was Irrigation Engineer with the USDA-NRCS Technical Center in Portland, Oregon and is now National Water Management Engineer in Washington D.C.

Mary Hattendorf is former director of the Washington Public Agriculture Weather Network (WSU-PAWS) and is an agricultural meteorologist with the Northern Colorado Water Conservancy District.

James Wright is a Soil Scientist (ret.) with the USDA-ARS Irrigation and Soils Research Laboratory at Kimberly, Idaho. He has 35 years experience in development of evapotranspiration equations and crop coefficients and measurement of evapotranspiration.

Derrel Martin is professor of Biological Systems Engineering at the University of Nebraska and has over 25 years experience in irrigation water management, irrigated systems, and irrigation water requirements.

DATA CONTRIBUTORS

The following individuals provided weather data sets and/or REF-ET results: Paul Brown* (Arizona); Richard Snyder* and Simon Eching* (California); Ivan Walter*, Marvin Jensen*, and Brent Mecham* (Colorado); Brian Boman (Florida); Wanda Cavender and Gerrit Hoogenboom (Georgia); Richard Allen* and Peter Palmer (Idaho and Montana); Bob Scott and Steve Hollinger (Illinois); Lineu Rodriquez and Derrel Martin* (Nebraska); Art DeGaetano (New York); Daniel Itenfisu* and Ronald Elliott* (Oklahoma); Indi Sriprisan and Richard Cuenca* (Oregon); Dean Evans and Carl Camp (South Carolina); Don Dusek and Terry Howell* (Texas); Richard Allen* and Robert Hill (Utah); and Mary Hattendorf* (Washington). (*member of the ASCE TC or standardization study team).

OTHER ACKNOWLEDGEMENTS

Drs. Thomas Ley, Colorado Division of Water Resources, Robert Hill, Utah State University, and Suat Irmak, University of Nebraska, members of the EWRI Technical Committee on Evapotranspiration in Irrigation and Hydrology, provided review and editorial suggestions to the report.

APPENDIX B

SUMMARY OF REFERENCE EVAPOTRANSPIRATION EQUATIONS USED IN EVALUATION

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INTRODUCTION

This appendix contains descriptions of the reference ET methods that were evaluated by the Task Committee at the 82 site-locations. The ET methods included well-known methods, (e.g. ASCE Penman-Monteith, 1982 Kimberly Penman) and hybrids of the ASCE-PM containing modifications to constants or parameterization of components. Definition of calculation procedures are summarized in Table B-1. Additional information for the hybrids of the ASCE-PM is provided in the discussion following Table B-1. Listed in Table B-1 for each parameter of each equation is the equation number, constant value, or procedure used to calculate that parameter. The labels for variations on the ASCE-PM equation are the same as those referred to in Table A-1, Appendix A.

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated												
Parameter	ASCE Penman-Monteith					ASCE Standardized Penman- Monteith	FAO-56 Penman- Monteith	1982 Kimberly Penman	1963 Penman	FAO- 24 Penman	CIMIS Penman	1985 Hargreaves
	“ASCE- PM”	“ASCE- PMD”	“ASCE- PMDL”	“ASCE- PMv”	“ASCE- PMDR”							
Reference Types	ET _O , ET _R	ET _O , ET _R	ET _O , ET _R	ET _O , ET _R	ET _O , ET _R	ET _{OS} , ET _{RS}	ET _O	ET _R	ET _O	ET _O	ET _O	ET _O
timestep	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, (h) ^a	m, d, h	m, d	h	m, d
Δ	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5	5	5	5	--
γ	B.12	B.12	B.12	B.12	B.12	4	4	B.12	B.12	B.12	B.12	--
λ	B.7	B.7	$\lambda = 2.45$ MJ/kg	B.7	B.7	$\lambda = 2.45$ MJ/kg	$\lambda = 2.45$ MJ/kg	B.7	B.7	B.7	B.7	--
P	B.8	B.8	B.8	B.8	B.8	3	3	B.8	B.8	B.8	B.8	--
α	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=B.25$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=B.25$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.23$	--
R _n	15-18, 42-46	15-18, 42-46	15-18, 42-46	15-18, 42-46	B.22- B.25	15-18, 42-46	15-18, 42-46	B.22-B.25	15-18, 42-46	15-18	42-46	--
G	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	B.26 (24- hr), 65-66 (hrly)	30,32, 65-66	30,32	G = 0.	--
R _{so}	19(24- hr), 47 (hrly)	19 (24- hr), 47 (hrly)	19 (24- hr), 47 (hrly)	19 (24- hr), 47- 47(hrly)	19 (24- hr), 47- (hrly)	19 (24-hr), 47 (hrly)	19 (24- hr), 47 (hrly)	19 (24- hr), 47 (hrly)	19 (24- hr), 47 (hrly)	19 (24- hr)	47 (hrly)	--
u ₂	Uses u _Z	Uses u _Z	Uses u _Z	Uses u _Z	Uses u _Z	33, 67	33, 67	33, 67	33, 67	33	67	--
r _s	B.3-B.6	70 and 45 s m ⁻¹ (24-hr), 50 and 30 s m ⁻¹ day, 200 s m ⁻¹ , night (hrly)	70 and 45 s m ⁻¹ (24-hr), 50 and 30 s m ⁻¹ day, 200 s m ⁻¹ , night (hrly)	User defined	70 and 45 s m ⁻¹ (24-hr), 50 and 30 s m ⁻¹ day, 200 s m ⁻¹ , night (hrly)	70 and 45 s m ⁻¹ (24-hr), 50 and 30 s m ⁻¹ day, 200 s m ⁻¹ , night (hrly)	70 s m ⁻¹ (all time steps)	--	--	--	--	--
r _a	B.2	B.2 for h=0.12m,	B.2 for h=0.12m,	B.2	B.2 for h=0.12m,	B.2 is embedded in	B.2 is embedded	B.18	1.0	1.0	0.29 day 1.14	--

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated												
Parameter	ASCE Penman-Monteith					ASCE Standardized Penman- Monteith	FAO-56 Penman- Monteith	1982 Kimberly Penman	1963 Penman	FAO- 24 Penman	CIMIS Penman	1985 Hargreaves
	“ASCE- PM”	“ASCE- PMD”	“ASCE- PMDL”	“ASCE- PMv”	“ASCE- PMDR”							
		h=0.5 m	h=0.5 m		h=0.5 m	Eq. 1 for h=0.12m, h=0.5 m	in Eq. B.15 for h=0.12m				night	
ρ	B.10	B.10	B.10	B.10	B.10	--	--	B.19	0.537	0.862	0.53 day 0.40 night	--
e_s	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6	37	--
e_a	order of preference is given in Tables 3 and 4 of the main text											

Numbers in cells refer to equations listed in the main text and appendices.

^a The Kimberly Penman equations are not intended to be applied hourly, but they were evaluated for hourly timesteps in this study.

“ASCE-PM” is the “full-form” ASCE Penman Monteith using resistance equations by Allen et al. (1989) and ASCE Manual 70 (Jensen et al. 1990) as a function of the height.

“ASCE-PMD” is the “full-form” ASCE Penman Monteith with values for r_s for hourly or shorter timesteps fixed at $r_s = 50 \text{ s m}^{-1}$ for 0.12 m tall grass and $r_s = 30 \text{ s m}^{-1}$ for 0.5 m tall alfalfa during daytime hours and $r_s = 200 \text{ s m}^{-1}$ for both grass and alfalfa during nighttime hours.

“ASCE-PMDL” is the “full-form” ASCE Penman Monteith, identical to ASCE-PMD except that λ is fixed at $\lambda = 2.45 \text{ MJ kg}^{-1}$.

“ASCE-PMv” is the “full-form” ASCE Penman Monteith with a user supplied resistance.

“ASCE-PMDR” is the “full-form” ASCE Penman Monteith, identical to ASCE-PMD except that net radiation follows Wright (1982).

“ASCE Standardized Penman Monteith” is the standardized form of the ASCE-PM equation (ET_{sz}) specified by equations in the main text.

“FAO 56 Penman Monteith” equation from FAO-56 (Allen et al., 1998).

“1982 Kimberly Penman” is an alfalfa reference from Wright (1982) with wind function expressed as in Jensen et al., (1990).

“1963 Penman” is the Penman equation form and wind function from Penman (1963) but using R_n and G for the standardized method.

“FAO-24 Penman” is the Penman equation from FAO-24 (Doorenbos and Pruitt, 1977) with correction factor = 1.0

“CIMIS Penman” is the hourly Penman equation traditionally used by the California Irrigation Management Information System (Snyder and Pruitt, 1985, Snyder and Pruitt, 1992) using R_n for the standardized method and $G=0$.

“1985 Hargreaves” is the air temperature based equation of Hargreaves et al., (1985).

The variations on the ASCE Penman-Monteith equation that were evaluated by the task committee are described as follows:

1. **“ASCE-PM” is the “full-form” ASCE Penman-Monteith** using resistance equations by Allen et al. (1989) and in ASCE Manual 70 (Jensen et al. 1990). In ASCE-PM, r_s is computed from the leaf area index (LAI), which is a function of the height specified for the reference type (grass or alfalfa). Algorithms for LAI depend on reference type. The value of r_s (and r_a) change with height specified for the reference. The values for r_s for 24-hour timesteps, based on the ASCE LAI algorithms, are $r_s = 70 \text{ s m}^{-1}$ for 0.12 m tall grass and $r_s = 45 \text{ s m}^{-1}$ for 0.5 m tall alfalfa. This equation, when computed using a daily calculation timestep, was the measure against which the other equations were compared. The ASCE-PM method, using resistance parameters as defined in Manual 70 to be functions of vegetation height and computed with a daily timestep, was the method found to perform best against lysimeter measurements in Manual 70.
2. **“ASCE-PMD” is the “full-form” ASCE Penman-Monteith** and is the same as (1) except that the values for r_s for hourly or shorter timesteps were fixed at $r_s = 50 \text{ s m}^{-1}$ for 0.12 m tall grass and $r_s = 30 \text{ s m}^{-1}$ for 0.5 m tall alfalfa during daytime hours and $r_s = 200 \text{ s m}^{-1}$ for both 0.12 m tall grass and 0.5 m tall alfalfa during nighttime hours. The purpose of the variation was to evaluate whether use of a lower value for r_s for daytime and higher value for nighttime could improve the prediction for hourly timestep calculations relative to the ASCE-PM computed daily.
3. **“ASCE-PMDL” is the “full-form” ASCE Penman-Monteith** and is identical to (2) except that the value for the heat of vaporization was fixed at $\lambda = 2.45 \text{ MJ kg}^{-1}$. The purpose of the variation was to evaluate whether use of a constant value for λ versus a calculated value impacted calculations significantly.
4. **“ASCE-PMv” is the “full-form” ASCE Penman-Monteith with a user supplied resistance.** This method is the same as number 1, except that members of the TC had the option of specifying unique values for 24-hour, daytime and nighttime surface resistance, r_s , for each site. The purpose of the variation was to allow the TC members to test data from their region to determine what value for r_s resulted in accurate estimates of ET_{ref} in their region.
5. **“ASCE-PMDR” is the “full-form” ASCE Penman-Monteith** and is identical to (2) except that net radiation was calculated following Wright (1982) rather than Eq. 15 – 18 and 42 – 47. The purpose of this variation was to evaluate the degree to which using the Wright (1982) net radiation procedure in place of the standardized procedure impacted the ET_{ref} calculation.
6. **ASCE Standardized Penman-Monteith equation** is the standardized form of the ASCE-PM equation (ET_{sz}) specified by equations provided in the main text.

7. FAO 56 Penman-Monteith equation. The FAO-56 PM method uses essentially identical calculation procedures as the standardized ET_{sz} equation, except for a constant surface resistance (70 s m^{-1}) that is applied to all timesteps and its application is to ET_o , only.

Basic equations and supporting parameter equations for equations other than the standardized equation are listed in the following sections.

ASCE PENMAN-MONTEITH METHOD

The Penman-Monteith form of the combination equation (Monteith 1965, 1981) is:

$$ET_{ref} = \left(\frac{\Delta(R_n - G) + K_{time} \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right)} \right) / (\lambda \rho_w) \quad (B.1)$$

where

ET_{ref}	= reference evapotranspiration [mm d^{-1} or mm h^{-1}],
R_n	= net radiation [$\text{MJ m}^{-2} \text{d}^{-1}$ or $\text{MJ m}^{-2} \text{h}^{-1}$],
G	= soil heat flux [$\text{MJ m}^{-2} \text{d}^{-1}$ or $\text{MJ m}^{-2} \text{h}^{-1}$],
$(e_s - e_a)$	= vapor pressure deficit of the air [kPa],
e_s	= saturation vapor pressure of the air [kPa],
e_a	= actual vapor pressure of the air [kPa],
ρ_a	= mean air density at constant pressure [kg m^{-3}],
c_p	= specific heat of the air [$\text{MJ kg}^{-1} \text{°C}^{-1}$],
Δ	= slope of the saturation vapor pressure temperature relationship [kPa °C^{-1}],
γ	= psychrometric constant [kPa °C^{-1}],
r_s	= (bulk) surface resistance [s m^{-1}],
r_a	= aerodynamic resistance [s m^{-1}],
λ	= latent heat of vaporization, [MJ kg^{-1}],
ρ_w	= density of water, [Mg m^{-3}] (taken as 1.0 Mg m^{-3}),
K_{time}	= units conversion, equal to $86,400 \text{ s d}^{-1}$ for ET in mm d^{-1} and equal to 3600 s h^{-1} for ET in mm h^{-1} .

The aerodynamic resistance, applied for neutral stability conditions, is:

$$r_a = \frac{\ln \left[\frac{z_w - d}{z_{om}} \right] \ln \left[\frac{z_h - d}{z_{oh}} \right]}{k^2 u_z} \quad (B.2)$$

where

r_a	= aerodynamic resistance [$s\ m^{-1}$],
z_w	= height of wind measurements [m],
z_h	= height of humidity and or air temperature measurements [m],
d	= zero plane displacement height [m], $= 0.67\ h$
z_{om}	= roughness length governing momentum transfer [m], $= 0.123\ h$
z_{oh}	= roughness length for transfer of heat and vapor [m], $= 0.0123\ h$
k	= von Karman's constant, $0.41\ [-]$,
u_z	= wind speed at height z [$m\ s^{-1}$]
h	= mean height of the vegetation [m].

Bulk surface resistance is:

$$r_s = \frac{r_l}{LAI_{active}} \quad (B.3)$$

where

r_s	= (bulk) surface resistance [$s\ m^{-1}$],
r_l	= effective stomatal resistance of a well-illuminated leaf [$s\ m^{-1}$],
LAI_{active}	= active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)]

For ASCE calculations for dense vegetation, LAI_{active} is calculated as:

$$LAI_{active} = 0.5\ LAI \quad (B.4)$$

where

LAI	= leaf area index [m^2 of leaf per m^2 of soil surface = dimensionless]
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For clipped grass:

$$LAI = 24\ h \quad (B.5)$$

For alfalfa:

$$LAI = 5.5 + 1.5\ \ln(h) \quad (B.6)$$

where

h	= vegetation height [m]
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In the “full-form” ASCE Penman-Monteith method, the following “full-form” ancillary equations are used. Many of these have been simplified for use with the ET_{sz} form of the Penman-Monteith equation and are listed in the main text.

Latent Heat of Vaporization (λ)¹

$$\lambda = 2.501 - (2.361 \times 10^{-3}) T_{\text{mean}} \quad (\text{B.7})$$

where:

$$\begin{aligned} \lambda &= \text{latent heat of vaporization [MJ kg}^{-1}\text{]} \\ T_{\text{mean}} &= \text{mean air temperature for the time interval [}^{\circ}\text{C]} \end{aligned}$$

The value of the latent heat varies only slightly over normal temperature ranges. For ET_{SZ} , a single value is taken: $\lambda = 2.45 \text{ MJ kg}^{-1}$. The inverse of λ is presented as 0.408.

Atmospheric Pressure (P)²

Mean atmospheric pressure for a location is predicted from site elevation using a lapse-based integration of the universal gas law:

$$P = P_o \left(\frac{T_{K_o} - \alpha_1 (z - z_o)}{T_{K_o}} \right)^{\frac{g}{\alpha_1 R}} \quad (\text{B.8})$$

where:

$$\begin{aligned} P &= \text{atmospheric pressure at elevation } z \text{ [kPa]} \\ P_o &= \text{atmospheric pressure at reference level (sea level = 101.3) [kPa]} \\ z &= \text{weather site elevation [m]} \\ z_o &= \text{elevation at reference level (i.e., sea level = 0) [m]} \\ g &= \text{gravitational acceleration} = 9.807 \text{ [m s}^{-2}\text{]} \\ R &= \text{specific gas constant} = 287 \text{ [J kg}^{-1} \text{K}^{-1}\text{]} \\ \alpha_1 &= \text{constant lapse rate of moist air} = 0.0065 \text{ [K m}^{-1}\text{]} \\ T_{K_o} &= \text{reference temperature [K] at pressure } P_o \text{ and elevation } z_o. \end{aligned}$$

List (1984) defined $P_o = 101.3 \text{ kPa}$, $z_o = 0 \text{ m}$ and $T_{K_o} = 288 \text{ K}$ for the U.S. and International Standard Atmospheres,. However, Smith et al., (1991) recommended

¹ Reference: Harrison (1963)

² Reference: List (1984), Burman *et al.* (1987)

using a reference temperature of $T_{\text{mean}} = 20\text{ }^{\circ}\text{C}$ to represent mean daytime conditions during growing seasons, so that:

$$T_{K0} = 293\text{ K} \quad (\text{B.9})$$

Using $T_{K0} = 293\text{ K}$ from equation (B.9), equation (B.8) becomes equation 3 of the main text. The difference in prediction of P using $T_{K0} = 288$ and $T_{K0} = 293\text{ K}$ is less than 0.7% for elevations less than 3000 m.

Air Density (ρ_a)³

$$\rho_a = \frac{1000 P}{T_{Kv} R} = 3.486 \frac{P}{T_{Kv}} \quad (\text{B.10})$$

where:

$$\begin{aligned} \rho_a &= \text{air density [kg m}^{-3}\text{]} \\ R &= \text{specific gas constant} = 287 \text{ [J kg}^{-1} \text{ K}^{-1}\text{]} \\ T_{Kv} &= \text{mean virtual temperature for period [K]} \end{aligned}$$

$$T_{Kv} = T_K \left(1 - 0.378 \frac{e_a}{P} \right)^{-1} \quad (\text{B.11})$$

where:

$$\begin{aligned} T_K &= \text{mean absolute temperature [K]} : T_K = 273.16 + T_{\text{mean}} \text{ [}^{\circ}\text{C]} \\ e_a &= \text{actual vapor pressure [kPa]} \end{aligned}$$

In derivation of the ET_{sz} equation, equation (B.11) was reduced to $T_{Kv} \approx 1.01 (T_{\text{mean}} + 273)$ that holds for most conditions. T_{mean} is set equal to mean daily temperature for 24-hour calculation time steps.

Psychrometric Constant (γ)⁴

The psychrometric constant, γ , is used in the numerator and denominator of the standardized Penman-Monteith equation:

³ Reference: Smith *et al.* (1991)

⁴ Reference: Brunt (1952)

$$\gamma = \frac{c_p P}{\varepsilon \lambda} \quad (\text{B.12})$$

where:

$$\begin{aligned} \gamma &= \text{psychrometric constant [kPa } ^\circ\text{C}^{-1}] \\ c_p &= \text{specific heat of moist air} = 1.013 \times 10^{-3} \text{ [MJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}] \\ P &= \text{atmospheric pressure [kPa]} \\ \varepsilon &= \text{ratio of the molecular weight of water vapor/dry air ("epsilon")} \\ &\quad (\varepsilon = 0.622 \text{ for standard, dry air}) \\ \lambda &= \text{latent heat of vaporization [MJ kg}^{-1}] \quad (\lambda = 2.45 \text{ MJ kg}^{-1} \text{ for} \\ &\quad \text{standardized calculations}) \end{aligned}$$

The simplification of $\lambda = 2.45 \text{ MJ kg}^{-1}$ in equation B.12 and reduction results in Eq. 4 for the ET_{SZ} equation. This simplification causes less than 2% error in γ over the range of $0 < T_{\text{mean}} < 40 \text{ } ^\circ\text{C}$ and less than 1% error over the range of $11 < T_{\text{mean}} < 31 \text{ } ^\circ\text{C}$. This translates into errors in ET_{OS} and ET_{RS} that are generally less than 0.2%.

Soil Heat Flux Density (G) for hourly periods⁵

The full equation for hourly G, on which equations 66 and 67 for ET_{SZ} are based, is:

$$G_{\text{hr}} = K_G \exp(-0.5 \text{ LAI}) R_n \quad (\text{B.13})$$

where

$$\begin{aligned} K_G &= 0.4 \text{ during daytime (defined as when } R_n > 0) \\ K_G &= 2.0 \text{ during nighttime (defined as when } R_n \leq 0) \\ \text{LAI} &= \text{leaf area index [dimensionless]} \end{aligned}$$

Units for G_{hr} and R_n are the same.

⁵ Reference: Choudhury et al. (1987), Choudhury (1989)

Wind Speed Adjustment for Measurement Height

To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m for use in all combination equations, a logarithmic wind speed profile is used. The exception is Eq. B.1 for the full-form Penman-Monteith equation above, which uses the actual wind speed and actual measurement height in calculating r_a as in Eq. B.2:

$$u_2 = u_z \frac{\ln\left(\frac{2-d}{z_{om}}\right)}{\ln\left(\frac{z_w-d}{z_{om}}\right)} \quad (B.14)$$

where

- u_2 = wind speed at 2 m above ground surface [m s^{-1}],
- u_z = measured wind speed at z_w m above ground surface [m s^{-1}],
- z_w = height of measurement above ground surface [m],
- d = zero plane displacement height for the weather site vegetation, m, ($d = 0.67 h$)
- z_{om} = aerodynamic roughness length for the weather site vegetation, m, ($z_{om} = 0.123 h$)

This equation serves as the basis for Equations 33 and 63 of the text, where for 0.12 m tall grass, (B.14) reduces to:

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (B.14b)$$

Allen and Wright (1997) described procedures for adjusting wind speed measured over and down-wind of non-grassed surfaces to account for differences between the vegetation at the measurement surface and the vegetation type for the reference. The Allen-Wright procedures are recommended where the vegetation upwind of the measurement site is aerodynamically different from clipped grass or full-cover alfalfa or where the “full” Penman-Monteith equation (B.1) is applied to vegetation other than the two reference types. The following (B.14c) is a special application of (B.14) for the case where wind speed is measured over and downwind of approximately 0.5 m tall alfalfa and is to be adjusted to an equivalent speed at 2 m height over grass for use in the standardized equation for ET_{os} or ET_{rs} . In this situation, the d and z_{om} in

the numerator of (B.14) are set to 0.08 m and 0.062 m, representing d for clipped grass and z_{om} for alfalfa. However, the d and z_{om} in the denominator of (B.14) are set to 0.335 m and 0.062 m, representing values for alfalfa. This “hybrid” combination of using d for both grass and alfalfa in (B.14c) is required because coefficients used in the standardized ET_{rs} equation (1) presume that wind is measured over and downwind of grass (typical of weather stations), even for the tall reference (see Table 2 of the main text). Using these substitutions, (B.14) reduces to:

$$u_2 = u_z \frac{\ln\left(\frac{2 - 0.08}{0.062}\right)}{\ln\left(\frac{z_w - 0.335}{0.062}\right)} = u_z \frac{3.44}{\ln(16.3 z_w - 5.42)} \quad (B.14c)$$

Equation (B.14c) is used to adjust wind speed measured over alfalfa for use in calculating ET_{os} and ET_{rs} . This adjustment is necessary because the formulation of ET_{rs} was made expecting weather measurements collected over clipped grass. The process and application with ET_{os} and ET_{rs} assumes that temperature and humidity data are measured over clipped grass or that the impact of measurement of these parameters over some other surface, including alfalfa, does not significantly impact the measurements. This is generally a good assumption for well-watered vegetation.

FAO-56 PENMAN-MONTEITH METHOD

The FAO-56 Penman-Monteith equation is a grass reference equation that was derived from the ASCE equations (B.1 – B.6) by fixing $h = 0.12$ m for clipped grass and by assuming measurement heights of $z_w = 2$ m and $z_h = 2$ m and using $\lambda = 2.45$ MJ kg⁻¹. The result is an equation that defines the reference evapotranspiration from a hypothetical grass surface having a fixed height of 0.12 m, bulk surface resistance of 70 s m⁻¹, and albedo of 0.23. For 24-hour time steps:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (B.15)$$

where

ET_o	=	grass reference evapotranspiration [mm day ⁻¹],
R_n	=	net radiation at the crop surface [MJ m ⁻² day ⁻¹],
G	=	soil heat flux density [MJ m ⁻² day ⁻¹],
T	=	mean daily air temperature at 2 m height [°C],
u_2	=	wind speed at 2 m height [m s ⁻¹],
e_s	=	saturation vapor pressure [kPa],
e_a	=	actual vapor pressure [kPa],
$e_s - e_a$	=	vapor pressure deficit [kPa],
Δ	=	slope of saturation vapor pressure temperature relationship [kPa °C ⁻¹],
γ	=	psychrometric constant [kPa °C ⁻¹].

The FAO-56 Penman-Monteith equation for hourly time steps assumes that $r_s = 70$ s m⁻¹ so that:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e_s(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (B.16)$$

where

ET_o	=	grass reference evapotranspiration [mm h ⁻¹],
R_n	=	net radiation at the crop surface [MJ m ⁻² h ⁻¹],
G	=	soil heat flux density [MJ m ⁻² h ⁻¹],
T_{hr}	=	mean hourly air temperature at 2 m height [°C],
u_2	=	wind speed at 2 m height [m s ⁻¹],

$e_s(T_{hr})$	=	saturation vapor pressure function at (T_{hr}) [kPa],
e_a	=	actual vapor pressure [kPa],
$e_s(T_{hr}) - e_a$	=	saturation vapor pressure deficit [kPa],
Δ	=	slope vapor pressure curve [kPa °C ⁻¹],
γ	=	psychrometric constant [kPa °C ⁻¹].

OTHER PENMAN EQUATIONS

The classical form of the Penman equation (Penman, 1948, 1956, 1963) is:

$$ET = \left(\frac{\Delta}{\Delta + \gamma} (R_n - G) + K_w \frac{\gamma}{\Delta + \gamma} (a_w + b_w u_2) (e_s - e_a) \right) / (\lambda \rho_w) \quad (B.17)$$

where:

K_w	=	is a units constant
a_w and b_w	=	are wind function coefficients
u_2	=	wind speed at 2 m, [m s ⁻¹]
λ	=	latent heat of vaporization, MJ kg ⁻¹ ,
ρ_w	=	density of water, [Mg m ⁻³] (taken as 1.0 Mg m ⁻³)

All other terms and definitions are the same as those used for the Penman-Monteith equation. Parameter $K_w = 6.43$ for ET in mm d⁻¹ and $K_w = 0.268$ for ET in mm hour⁻¹. The a_w and b_w terms are empirical wind coefficients that have often received local or regional calibration and apply to a specific reference type of crop or surface.

THE 1963 PENMAN METHOD

The values for a_w and b_w for the original Penman equation, first applied by Penman (1948) to open water and implicitly to grass, and later by Penman (1963) to clipped grass were $a_w = 1.0$ and $b_w = 0.537$, respectively, for wind speed in m s⁻¹, $e_s - e_a$ in kPa and grass ET₀ in mm d⁻¹. The equations were intended for use with daily computations. In task committee comparisons, R_n for the 1963 Penman equation was calculated similar to Eq. 15-18, and saturation vapor pressure was based on only mean daily air temperature rather than on T_{max} and T_{min} following Penman. For hourly applications, G was predicted using Eq. 66 and 67 and, for daily applications, G was predicted using Eq. 30.

THE KIMBERLY PENMAN METHOD.

The 1982 Kimberly Penman method (Wright, 1982,) uses B.17, with wind coefficients that vary with time of year. In addition, the coefficients used for computation of net radiation and the method to predict 24-hour soil heat flux are unique to the Kimberly method.

The 1982 Kimberly Penman equation was developed from intensive studies of evapotranspiration at Kimberly, Idaho using measurements of full-cover alfalfa ET from precision weighing lysimeters (Wright and Jensen 1972; Wright 1981; Wright 1982; Wright 1988). For grass ET_o , the 1996 Kimberly wind function was developed by Wright (1996) from five years of weighing lysimeter data from well-managed and well-fertilized clipped fescue grass having high leaf area and maintained at 0.08 to 0.15 m height.

The Kimberly Penman and associated wind functions were intended for application with 24-hour time steps ($K_w = 6.43$). The form and all units and definitions are the same as those in Eq. B.17. The Kimberly wind function coefficients a_w and b_w for alfalfa vary with time of year and are computed for ET_r as (Wright 1987, pers. comm. and Jensen et al. 1990):

$$a_w = 0.4 + 1.4 \exp \left(- \left[\left(\frac{J - 173}{58} \right)^2 \right] \right) \quad (B.18)$$

$$b_w = 0.605 + 0.345 \exp \left(- \left[\left(\frac{J - 243}{80} \right)^2 \right] \right) \quad (B.19)$$

where J is the day of the year. For latitudes south of the equator, one should use J' in place of J , where $J' = (J - 182)$ for $J \geq 182$ and $J' = (J + 182)$ for $J < 182$. The $(e_s - e_a)$ term in the 1982 and 1996 Kimberly Penmans is computed the same as for the Penman-Monteith equation (e_s is computed at both maximum and minimum temperatures).

In the original (Wright, 1982) definition for the 1982 Kimberly Penman equation, net long wave radiation was computed for Kimberly as:

$$R_{nl} = \sigma \left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] \left(a_1 + b_1 \sqrt{e_a} \right) \left(a_c \frac{R_s}{R_{so}} + b_c \right) \quad (B.20)$$

where

$$\begin{aligned} R_{nl} &= \text{net outgoing longwave radiation [MJ m}^{-2} \text{ d}^{-1}\text{]}, \\ \sigma &= \text{Stefan-Boltzmann constant [4.901 10}^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}\text{]}, \\ T_{K \max} &= \text{maximum absolute temperature during the 24-hour period [K} \\ &= ^\circ\text{C} + 273.16\text{]}, \\ T_{K \min} &= \text{minimum absolute temperature during the 24-hour period [K} \\ &= ^\circ\text{C} + 273.16\text{]}, \\ e_a &= \text{actual vapor pressure [kPa]}, \\ R_s/R_{so} &= \text{relative shortwave solar radiation (limited to } \leq 1.0\text{)}, \\ R_s &= \text{measured or calculated solar radiation [MJ m}^{-2} \text{ d}^{-1}\text{]}, \\ R_{so} &= \text{calculated clear-sky radiation [MJ m}^{-2} \text{ d}^{-1}\text{]}. \end{aligned}$$

Eq. B.20 has the same form as used for Eq. 17 of the ET_{sz} procedure. However, coefficients a_1 , b_1 , a_c and b_c have different values.

Parameter a_1 for alfalfa at Kimberly (42 ° N) is:

$$a_1 = 0.26 + 0.1 \exp\left(-[0.0154 (J - 180)]^2\right) \quad (B.21)$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19. Parameter $b_1 = -0.139$ in Wright (1982).

Wright (1982) predicted a_c and b_c as:

$$\begin{aligned} a_c &= 1.126 \quad \text{and} \quad b_c = -0.07 \quad \text{for} \quad R_s / R_{so} > 0.7 \\ a_c &= 1.017 \quad \text{and} \quad b_c = -0.06 \quad \text{for} \quad R_s / R_{so} \leq 0.7 \end{aligned} \quad (B.22)$$

Wright (1982) predicted albedo as:

$$\alpha = 0.29 + 0.06 \sin[(J + 96) / 57.3] \quad (B.23)$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19.

Soil heat flux for 24-hour periods is predicted for the alfalfa reference of Wright (1982) using the difference between mean air temperature of the current day and the mean air temperature of the previous three days:

$$G_{24} = 0.38 \left(T_{\text{mean}} - \sum_{i=1}^3 T_{\text{mean } i} / 3 \right) \quad (\text{B.24})$$

where G_{24} is 24-hour soil heat flux in $\text{MJ m}^{-2} \text{d}^{-1}$, T_{mean} is mean air temperature on the current day and $T_{\text{mean } i}$ is the mean air temperatures of the previous three days. Equation B.24 may not predict well under all conditions. In a study on 24-hour heat flux at Kimberly and Logan, Utah, Allen and Wright (unpublished research, 1996) found that using $G=0$ for 24-hour periods under alfalfa and grass produced less error relative to measured G than using Eq. B.24. For hourly applications, G was predicted using Eq. 66 and 67.

THE CIMIS PENMAN METHOD.

Pruitt (Pruitt and Doorenbos 1977) developed a_w and b_w for predicting grass ET_0 for hourly periods for a clipped grass reference. These coefficients have been adopted for standard ET_0 estimation in the California Irrigation Management Information Service (CIMIS) (Snyder and Pruitt, 1985, Snyder and Pruitt, 1992). The result is the "CIMIS" Penman ET_0 equation where $a_w = 0.29$ and $b_w = 0.53$ for $R_n > 0$ and $a_w = 1.14$ and $b_w = 0.40$ for $R_n \leq 0$. These coefficients are applied hourly using Eq. B.17 where $ET_0 = \text{mm hour}^{-1}$, $R_n = \text{MJ m}^{-2} \text{hour}^{-1}$, and $K_w = 0.268$.

The net radiation calculation for the CIMIS method as applied by CIMIS is similar to that by Dong et al.(1992) and is different than that applied during the Task Committee study. In the Task Committee application and evaluation, R_n for the CIMIS Penman equation was computed using Eq. 42-47 of the text. The decision to

use the standardized R_n was based on concern for potential over-sensitivity in the CIMIS routines during the prediction of R_{nl} when R_s/R_{so} is close to 1.0.

Standard CIMIS calculations assume $G = 0$, although G in hourly applications should normally be considered. In the Task Committee analyses using the CIMIS Penman equation, G was set equal to $G = 0$ to be consistent with standard CIMIS usage.

FAO-24 PENMAN METHOD.

The FAO-24 Penman method (Doorenbos and Pruitt, 1977) was applied for daily timesteps only using net radiation as computed in the FAO-24 publication. In the FAO-24 Penman, $a_w = 1.0$ and $b_w = 0.862$ for u_2 in m s^{-1} and vapor pressure in kPa and radiation in $\text{MJ m}^{-2} \text{d}^{-1}$. R_n for the FAO-24 Penman equation is calculated similar to Eq. 15-18, except that only mean daily air temperature is used in place of $T_{\max}$ and $T_{\min}$. Saturation vapor pressure is based only on mean daily air temperature. The FAO-24 “correction” (coefficient “c”) was applied using the regression equation reported by Allen and Pruitt (1991).

THE 1985 HARGREAVES METHOD

The 1985 Hargreaves method (Hargreaves and Samani, 1985 and Hargreaves et al. 1985) requires only maximum and minimum daily air temperature and can be applied on 24-hour, weekly, 10-day, or monthly time steps. It has the form:

$$ET_o = 0.0023(T_{\max} - T_{\min})^{0.5} (T_{\text{mean}} + 17.8) R_a \quad (\text{B.25})$$

where:

- ET_o = grass reference ET, mm d⁻¹
- $T_{\max}$ = maximum daily air temperature, °C
- $T_{\min}$ = minimum daily air temperature, °C
- T_{mean} = mean daily air temperature, $T_{\text{mean}} = (T_{\max} + T_{\min}) / 2$
- R_a = extraterrestrial radiation, mm d⁻¹ (see Eq. 21 – 29 in main text)
(R_a in mm d⁻¹ = R_a in MJ m⁻² d⁻¹ / 2.45).

APPENDIX C

EXAMPLE CALCULATIONS FOR DAILY AND HOURLY STANDARDIZED REFERENCE EVAPOTRANSPIRATION

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INTRODUCTION

The following examples demonstrate application of the standardized ET_{sz} equation and supporting calculations for daily and hourly time periods. These examples provide a standardized set of calculations for checking computer software. Various software programs are available for making the calculations for the equations presented in this standardization statement, as a means of comparing against other computer software. These standardized software programs include the REF-ET software available from the University of Idaho (<http://www.kimberly.uidaho.edu/ref-et/>) and the ETo spreadsheets by Snyder (2000). The REF-ET software is Windows-based and can read a wide range of file formats and unit types.

The location selected for this example application is an agricultural weather site near Greeley, CO¹ operated by the Northern Colorado Water Conservation District. The weather station utilizes electronic, automated equipment and is situated above irrigated grass having an expanse of approximately 50 x 50 m. Surroundings beyond the grassed weather surface are irrigated residential turf and agriculture. The technical data in Table C-1 describe the weather station.

Additional constants for the Greeley site that are a part of the standardized calculations are listed in Table C-2 along with the equation number used for the calculation.

Example calculation results are presented in the following sections for daily (i.e., 24-hour) and hourly timesteps. Calculated values can be compared with computations by user software programs to confirm accuracy of the programs.

¹ Data were provided courtesy of Mr. Mark Crookston and Mr. Brent Mecham of the Northern Colorado Conservancy District, Loveland, CO.

Table C-1. Characteristics of the Greeley, Colorado weather station

Attribute	Value
Latitude	40.41 degrees N
Longitude	104.78 degrees W
Elevation	1462.4 m
Anemometer height	3 m
Height of air temperature and RH meas.	1.68 m
Longitude of center of time zone	105 degrees W
Type of surface at weather station	irrigated grass
Height of vegetation of weather station	0.12 m

Table C-2. Calculation constants for the Greeley, Colorado weather station

Variable	Equation(s)	Value
Mean atmospheric pressure	3	85.17 kPa
Psychrometric Constant (γ)	4	0.0566 kPa °C ⁻¹
K _{ab} for predicting R _{so}	19, 20	0.779
Multiplier for adjusting wind speed to 2 m height	33	0.921
Latitude in radians	22	0.7053 radians

DAILY CALCULATION TIMESTEP

Calculation results for daily time steps are presented in Table C-3 for 10 days in July, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. Columns 3 - 7 of Table C-3 are the original weather data reported for the station. Average daily vapor pressure, e_a , was reported for the Greeley station. These values were calculated inside the electronic data logging system at the weather site throughout the course of a day using measured air temperature and relative humidity (via equations 37 and 41), and an average vapor pressure for the day was calculated. An equivalent dew-point temperature for each day was calculated from daily e_a using Eq. D.7 of Appendix D.

INTEGRITY OF DATA

Daily solar radiation data for the complete year 2000 are plotted in Figure D-2 for Greeley, along with clear sky R_{so} envelopes that were determined using Eq. 19 and by also using the more detailed procedure of Appendix D. The good agreement between measured R_s for cloud-free days and the computed R_{so} curves supports using the solar radiation data.

The daily mean dew-point temperature, computed from daily mean vapor pressure, was plotted against daily minimum air temperature as shown in Figure D-9a of Appendix D, and computed daily maximum relative humidity and daily minimum relative humidity are plotted in Figure D-9b. Based on the guidelines of Appendix D, the humidity and air temperature data for the Greeley location during 2000 were judged to be of good integrity and representative of a well-watered, agricultural (i.e., “reference ET”) condition.

Daily mean wind speed data were plotted vs. day of year as described in Appendix D. The wind speed appeared to follow a typical distribution with ranges and averages typical of agricultural areas. No comparisons using an independent anemometer or using wind speed data from a nearby weather station were made to confirm the accuracy of the wind data.

CALCULATIONS OF VARIABLES AND STANDARDIZED REFERENCE EVAPOTRANSPIRATION

Table C-3 contains calculations required for computation of ET_{sz} for daily time steps for the 10 day period at Greeley, Colorado. ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns of the table.

Table C-3. Measured data, calculations, and ET_{os} and ET_{rs} for daily time steps for July 1-10, 2000 near Greeley, Colorado.

Month	Day	Data from Weather Station					Day of Year	T_{mean}	Δ	$e^o(T_{max})$	$e^o(T_{min})$	e_s	wind @2m
		T_{max}	T_{min}	vapor press. e_a	R_s	wind @3m							
		$^{\circ}C$	$^{\circ}C$	kPa	$MJ\ m^{-2}\ d^{-1}$	$m\ s^{-1}$		$^{\circ}C$	$kPa\ ^{\circ}C^{-1}$	kPa	kPa	kPa	$m\ s^{-1}$
							Eq. 25	Eq. 3	Eq. 5	Eq. 7	Eq. 7	Eq. 6	Eq. 33
7	1	32.4	10.9	1.27	22.4	1.94	183 ^a	21.7 ^b	0.1585	4.88	1.31	3.09	1.79
7	2	33.6	12.2	1.19	26.8	2.14	184	22.9	0.1692	5.21	1.42	3.31	1.97
7	3	32.6	14.8	1.40	23.3	2.06	185	23.7	0.1762	4.91	1.69	3.30	1.90
7	4	33.8	11.8	1.18	29.0	1.97	186	22.8	0.1684	5.27	1.39	3.33	1.81
7	5	32.7	15.9	1.59	27.9	2.98	187	24.3	0.1820	4.94	1.81	3.37	2.74
7	6	36.3	15.8	1.58	29.2	2.37	188	26.0	0.1990	6.03	1.79	3.91	2.18
7	7	35.5	16.7	1.13	23.2	2.43	189	26.1	0.1996	5.78	1.9	3.84	2.24
7	8	34.4	18.3	1.38	22.1	1.95	190	26.4	0.2027	5.45	2.11	3.78	1.80
7	9	32.7	15.1	1.38	26.5	1.75	191	23.9	0.1781	4.94	1.72	3.33	1.61
7	10	32.7	15.7	1.59	27.7	2.31	192	24.2	0.1809	4.95	1.78	3.37	2.13

^a Year 2000 was a leap year.

^b T_{mean} was calculated from T_{max} and T_{min} following standardized procedure (Eq. 2). These values differ slightly from T_{mean} computed from hourly averages.

Table C-3. Continued.

Month	Day	$T_{k \max}$	$T_{k \min}$	d_r	declin.	sunset hr	R_a	R_{so}	R_s/R_{so}	R_{nl}	R_n	ET_{os}	ET_{rs}
		K	K		radians	radians	$MJ\ m^{-2}\ d^{-1}$			$MJ\ m^{-2}\ d^{-1}$	$MJ\ m^{-2}\ d^{-1}$	$mm\ d^{-1}$	$mm\ d^{-1}$
				Eq. 23	Eq. 24	Eq. 28	Eq. 21	Eq. 20		Eq. 17	Eq. 15	Eq. 1	Eq. 1
7	1	305.6	284.1	0.9670	0.4017	1.941	41.63	32.43	0.691	3.96	13.31	5.71	7.34
7	2	306.8	285.4	0.9670	0.4003	1.939	41.58	32.39	0.827	5.45	15.20	6.71	8.68
7	3	305.8	288.0	0.9670	0.3988	1.938	41.53	32.36	0.720	4.15	13.78	5.98	7.65
7	4	307.0	285.0	0.9671	0.3972	1.936	41.48	32.32	0.897	6.14	16.19	6.86	8.73
7	5	305.9	289.1	0.9671	0.3954	1.934	41.43	32.27	0.864	5.15	16.33	7.03	9.07
7	6	309.5	289.0	0.9671	0.3936	1.932	41.37	32.23	0.906	5.67	16.83	7.50	9.60
7	7	308.7	289.9	0.9672	0.3916	1.930	41.31	32.18	0.721	4.71	13.15	7.03	9.56
7	8	307.6	291.5	0.9673	0.3895	1.928	41.25	32.13	0.688	4.02	13.00	6.16	7.99
7	9	305.9	288.3	0.9674	0.3873	1.925	41.18	32.08	0.826	5.16	15.27	6.20	7.68
7	10	305.9	288.9	0.9674	0.3850	1.923	41.11	32.02	0.865	5.15	16.15	6.61	8.28

HOURLY CALCULATION TIMESTEP

Calculation results for hourly time steps are presented in Table C-4 for a 31-hour period spanning from 1600 hours on July 1 to 2200 hours on July 2, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. The 31-hour period was selected to contain both nighttime and daytime conditions and to illustrate how the cloudiness function value (based on R_s/R_{s0}) is selected for nighttime periods and periods of low sun angle.

Columns 4 - 7 of Table C-4 are the original weather data reported for the station. Average hourly vapor pressure, e_a , was reported in the data set. The e_a data were calculated inside the electronic data logging system at the weather site using measured air temperature and relative humidity (via equations 37 and 41) on an hourly or shorter basis.

INTEGRITY OF DATA

Integrity of the solar radiation, humidity, air temperature and wind data was assessed for daily timesteps as discussed in the previous section. Solar radiation data were additionally assessed for the hourly time steps by plotting measured R_s vs. computed clear sky R_{s0} envelopes as illustrated in Figure D-3 of Appendix D. The good agreement between measured hourly R_s for cloud-free conditions and the computed R_{s0} curves supports using the solar radiation data.

**CALCULATION OF VARIABLES AND STANDARDIZED REFERENCE
EVAPOTRANSPIRATION**

Table C-4 contains calculations of variables that are required for computation of the standardized reference evapotranspiration for hourly time steps for the 31-hour period at Greeley, Colorado. Calculations for the standardized reference ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns of the table.

Notes concerning the calculation of the variables in Table C-4 are the following:

- The beginning and ending times for each hourly period, expressed in radians (ω_1 and ω_2) were limited to the sunset hour angle as recommended in Eq. 57.
- The ratio R_s/R_{s0} was limited to $0.3 < R_s/R_{s0} \leq 1.0$ as recommended following Eq. 45.
- The cloud function, f_{cd} , during nighttime periods and periods of low sun angle, was set equal to the value $f_{cd \beta > 0.3}$ calculated for the period prior to when the sun angle at the center of a period decreased to below 0.3 radians, as recommended in the text (Eq. 45-46). The substituted value $f_{cd \beta > 0.3}$ for f_{cd} during the dusk, nighttime and dawn periods is bolded in Table C-4.

The soil heat flux was calculated according to reference type and daytime or nighttime period using Eq. 65 and 66.

- The reference ET calculated for some nighttime hours is negative. In practice, the user may wish to set negative values to zero before summing over the 24-hour period. However, in some situations, negative hourly computed ET_{os} or ET_{rs} may indicate the condensation of vapor during periods of early morning dew and

should therefore be registered as negative during the summing of 24-hour ET. In other situations, negative hourly ET_{os} or ET_{rs} during nighttime reflect the uncertainties in some parameter estimates, including R_n , and assumptions implicit to the combination equation. In general, the impact of negative hourly values on ET summed over daily periods is less than a few percent.

Table C-4. Measured data, calculations, and ET_{os} and ET_{rs} for hourly time steps for July 1-2, 2000 near Greeley, Colorado.

Month	Day	Hour	Data from Weather Station				Day of Year	Δ	$e_s = e^o(T_{hr})$	wind @2m	$T_{k \text{ max}}$
			T_{hr} °C	vapor pressure e_a kPa	R_s $MJ \text{ m}^{-2} \text{ h}^{-1}$	wind speed @3m m s^{-1}					
							Eq. 52	Eq. 36	Eq. 37	Eq. 67	K
7	1	1600	30.9	1.09	2.24	4.07	183 ^a	0.2545	4.467	3.75	304.1
7	1	1700	31.2	1.15	1.65	3.58	183	0.2583	4.544	3.30	304.4
7	1	1800	29.1	1.21	0.34	1.15	183	0.2326	4.029	1.06	302.3
7	1	1900	28.3	1.21	0.32	3.04	183	0.2234	3.846	2.80	301.5
7	1	2000	26.0	1.13	0.08	2.21	183	0.1987	3.361	2.04	299.2
7	1	2100	22.9	1.20	0.00	1.04	183	0.1690	2.792	0.96	296.1
7	1	2200	20.1	1.35	0.00	0.58	183	0.1455	2.353	0.53	293.3
7	1	2300	19.9	1.35	0.00	0.95	183	0.1440	2.324	0.87	293.1
7	1	2400	18.4	1.32	0.00	0.30	183	0.1327	2.116	0.28	291.6
7	2	100	16.5	1.26	0.00	0.50	184	0.1194	1.877	0.46	289.7
7	2	200	15.4	1.34	0.00	1.00	184	0.1123	1.750	0.92	288.6
7	2	300	15.5	1.31	0.00	0.68	184	0.1129	1.761	0.63	288.7
7	2	400	13.5	1.26	0.00	0.69	184	0.1008	1.547	0.64	286.7
7	2	500	13.2	1.24	0.03	0.29	184	0.0991	1.517	0.27	286.4
7	2	600	16.2	1.31	0.46	1.24	184	0.1174	1.842	1.14	289.4
7	2	700	20.0	1.36	1.09	1.28	184	0.1447	2.338	1.18	293.2
7	2	800	22.9	1.39	1.74	0.88	184	0.1690	2.792	0.81	296.1
7	2	900	26.4	1.25	2.34	0.72	184	0.2028	3.442	0.66	299.6
7	2	1000	28.2	1.17	2.84	1.52	184	0.2223	3.824	1.40	301.4
7	2	1100	29.8	1.03	3.25	1.97	184	0.2409	4.195	1.81	303.0
7	2	1200	30.9	1.02	3.21	2.07	184	0.2545	4.467	1.91	304.1
7	2	1300	31.8	0.98	3.34	2.76	184	0.2660	4.701	2.54	305.0
7	2	1400	32.5	0.87	2.96	2.90	184	0.2753	4.891	2.67	305.7
7	2	1500	32.9	0.86	2.25	3.10	184	0.2808	5.002	2.85	306.1
7	2	1600	32.4	0.93	1.35	2.77	184	0.2740	4.863	2.55	305.6
7	2	1700	30.2	1.14	0.88	3.41	184	0.2458	4.292	3.14	303.4
7	2	1800	30.6	1.27	0.79	2.78	184	0.2507	4.391	2.56	303.8
7	2	1900	28.3	1.27	0.27	2.95	184	0.2234	3.846	2.72	301.5
7	2	2000	25.9	1.17	0.03	3.27	184	0.1977	3.342	3.01	299.1
7	2	2100	23.9	1.20	0.00	2.86	184	0.1782	2.966	2.63	297.1

^a Year 2000 was a leap year.

Table C-4. Continued.

Mont h	Day	Hour	d_r	declin.	sunset hr angle (ω_s)	time at mid point	time corr. (S_c)	solar time angle (ω)	ω_1	ω_2	R_a	R_{so}
				radians	radians	hours	hours	radians	radians	radians	$\text{MJ m}^{-2} \text{h}^{-1}$	$\text{MJ m}^{-2} \text{h}^{-1}$
			Eq. 50	Eq. 51	Eq. 59	--	Eq. 57	Eq. 55	Eq. 53	Eq. 54	Eq. 48	Eq. 47
7	1	1600	0.9670	0.4017	1.941	15.5	-0.0618	0.904	0.773	1.035	3.26	2.54
7	1	1700	0.9670	0.4017	1.941	16.5	-0.0618	1.166	1.035	1.297	2.52	1.96
7	1	1800	0.9670	0.4017	1.941	17.5	-0.0618	1.428	1.297	1.558	1.68	1.31
7	1	1900	0.9670	0.4017	1.941	18.5	-0.0618	1.689	1.558	1.820	0.81	0.63
7	1	2000	0.9670	0.4017	1.941	19.5	-0.0618	1.951	1.820	1.941	0.09	0.07
7	1	2100	0.9670	0.4017	1.941	20.5	-0.0618	2.213	1.941	1.941	0.00	0.00
7	1	2200	0.9670	0.4017	1.941	21.5	-0.0618	2.475	1.941	1.941	0.00	0.00
7	1	2300	0.9670	0.4017	1.941	22.5	-0.0618	2.737	1.941	1.941	0.00	0.00
7	1	2400	0.9670	0.4017	1.941	23.5	-0.0618	2.998	1.941	1.941	0.00	0.00
7	2	100	0.9670	0.4003	1.939	0.5	-0.0649	-3.024	-1.939	-1.939	0.00	0.00
7	2	200	0.9670	0.4003	1.939	1.5	-0.0649	-2.762	-1.939	-1.939	0.00	0.00
7	2	300	0.9670	0.4003	1.939	2.5	-0.0649	-2.500	-1.939	-1.939	0.00	0.00
7	2	400	0.9670	0.4003	1.939	3.5	-0.0649	-2.238	-1.939	-1.939	0.00	0.00
7	2	500	0.9670	0.4003	1.939	4.5	-0.0649	-1.977	-1.939	-1.846	0.05	0.04
7	2	600	0.9670	0.4003	1.939	5.5	-0.0649	-1.715	-1.846	-1.584	0.72	0.56
7	2	700	0.9670	0.4003	1.939	6.5	-0.0649	-1.453	-1.584	-1.322	1.59	1.24
7	2	800	0.9670	0.4003	1.939	7.5	-0.0649	-1.191	-1.322	-1.060	2.43	1.90
7	2	900	0.9670	0.4003	1.939	8.5	-0.0649	-0.929	-1.060	-0.799	3.19	2.49
7	2	1000	0.9670	0.4003	1.939	9.5	-0.0649	-0.668	-0.799	-0.537	3.81	2.97
7	2	1100	0.9670	0.4003	1.939	10.5	-0.0649	-0.406	-0.537	-0.275	4.26	3.32
7	2	1200	0.9670	0.4003	1.939	11.5	-0.0649	-0.144	-0.275	-0.013	4.49	3.50
7	2	1300	0.9670	0.4003	1.939	12.5	-0.0649	0.118	-0.013	0.249	4.51	3.51
7	2	1400	0.9670	0.4003	1.939	13.5	-0.0649	0.380	0.249	0.510	4.29	3.34
7	2	1500	0.9670	0.4003	1.939	14.5	-0.0649	0.641	0.510	0.772	3.87	3.01
7	2	1600	0.9670	0.4003	1.939	15.5	-0.0649	0.903	0.772	1.034	3.26	2.54
7	2	1700	0.9670	0.4003	1.939	16.5	-0.0649	1.165	1.034	1.296	2.52	1.96
7	2	1800	0.9670	0.4003	1.939	17.5	-0.0649	1.427	1.296	1.558	1.68	1.31
7	2	1900	0.9670	0.4003	1.939	18.5	-0.0649	1.689	1.558	1.819	0.81	0.63
7	2	2000	0.9670	0.4003	1.939	19.5	-0.0649	1.950	1.819	1.939	0.09	0.07
7	2	2100	0.9670	0.4003	1.939	20.5	-0.0649	2.212	1.939	1.939	0.00	0.00

Table C-4. Continued.

Month	Day	Hour	sun angle β	R_s/R_{s0}	cloud func. f_{cd}	$f_{cd} \beta > 0.3$	R_{nl}	R_n	G_{os}	G_{rs}	ET_{os}	ET_{rs}
			radians				$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$mm\ h^{-1}$	$mm\ h^{-1}$
			Eq. 62	(w/ Eq. 47)	Eq. 45, 46	---	Eq. 44	Eq. 42	Eq. 65	Eq. 66	Eq. 1	Eq. 1
7	1	1600	0.757	0.881	0.840		0.284	1.441	0.144	0.058	0.61	0.82
7	1	1700	0.558	0.842	0.787		0.262	1.009	0.101	0.040	0.48	0.66
7	1	1800	0.361	0.260	0.055 ^b	0.055 ^c	0.017	0.244	0.024	0.010	0.14	0.19
7	1	1900	0.171	0.506	0.055		0.017	0.229	0.023	0.009	0.22	0.35
7	1	2000	-0.007	1.173 ^d	0.055		0.017	0.044	0.004	0.002	0.12	0.21
7	1	2100	-0.167	--	0.055		0.016	-0.016	-0.008	-0.003	0.04	0.06
7	1	2200	-0.302	--	0.055		0.015	-0.015	-0.007	-0.003	0.01	0.02
7	1	2300	-0.401	--	0.055		0.015	-0.015	-0.007	-0.003	0.02	0.04
7	1	2400	-0.456	--	0.055		0.015	-0.015	-0.007	-0.003	0.01	0.01
7	2	100	-0.460	--	0.055		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	200	-0.410	--	0.055		0.014	-0.014	-0.007	-0.003	0.01	0.02
7	2	300	-0.314	--	0.055		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	400	-0.183	--	0.055		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	500	-0.024	0.731	0.055		0.014	0.009	0.001	0.000	0.01	0.01
7	2	600	0.153	0.815	0.055		0.014	0.340	0.034	0.014	0.10	0.12
7	2	700	0.342	0.879	0.836		0.223	0.616	0.062	0.025	0.19	0.23
7	2	800	0.538	0.918	0.889		0.244	1.096	0.110	0.044	0.32	0.37
7	2	900	0.737	0.941	0.920		0.278	1.524	0.152	0.061	0.46	0.52
7	2	1000	0.933	0.956	0.940		0.299	1.888	0.189	0.076	0.60	0.70
7	2	1100	1.113	0.980	0.973		0.331	2.171	0.217	0.087	0.72	0.85
7	2	1200	1.242	0.917	0.888		0.308	2.164	0.216	0.087	0.73	0.88
7	2	1300	1.250	0.952	0.935		0.332	2.239	0.224	0.090	0.79	0.97
7	2	1400	1.129	0.885	0.845		0.315	1.964	0.196	0.079	0.74	0.93
7	2	1500	0.952	0.747	0.658		0.248	1.485	0.148	0.059	0.62	0.81
7	2	1600	0.757	0.531	0.367		0.134	0.905	0.091	0.036	0.44	0.60
7	2	1700	0.558	0.449	0.256		0.084	0.593	0.059	0.024	0.35	0.52
7	2	1800	0.361	0.604	0.465	0.465 ^c	0.147	0.461	0.046	0.018	0.29	0.42
7	2	1900	0.171	0.427	0.465		0.143	0.065	0.006	0.003	0.17	0.29
7	2	2000	-0.007	0.444	0.465		0.143	-0.120	-0.060	-0.024	0.10	0.14
7	2	2100	-0.168	--	0.465		0.138	-0.138	-0.069	-0.028	0.07	0.10

^b The value 0.055 for f_{cd} is due to a lower limit placed on R_s/R_{s0} of 0.3 (Eq. 45).

^c The value calculated for $f_{cd \beta > 0.3}$ each afternoon occurred at 1800 hours because this is the last time period when $\beta > 0.3$ radians (Eq. 46).

^d The value of $R_s/R_{s0} = 1.173$ at 2000 hours must be limited to ≤ 1.0 in Eq. 45.

Table C-4. Continued, showing R_{so} computed using Eq. D.1 – D.4 of Appendix D.

Month	Day	Hour	Precip. water (W)	$\sin \beta$	K_B ($w/K_t = 1.0$)	K_D	R_{so} (opt. meth.)
			mm	--	--	--	$\text{MJ m}^{-2} \text{h}^{-1}$
			Eq. D.3	Eq. D.6	Eq. D.2	Eq. D.4	Eq. D.1
7	1	1600	15.1	0.6869 ^e	0.632	0.123	2.46
7	1	1700	15.8	0.5296	0.579	0.142	1.81
7	1	1800	16.5	0.3535	0.486	0.175	1.11
7	1	1900	16.5	0.1706	0.296	0.243	0.44
7	1	2000	15.6	-0.0067	0.000	0.180	0.02
7	1	2100	16.4	-0.1663	0.000	0.180	0.00
7	1	2200	18.2	-0.2972	0.000	0.180	0.00
7	1	2300	18.2	-0.3907	0.000	0.180	0.00
7	1	2400	17.8	-0.4402	0.000	0.180	0.00
7	2	100	17.1	-0.4437	0.000	0.180	0.00
7	2	200	18.1	-0.3987	0.000	0.180	0.00
7	2	300	17.7	-0.3093	0.000	0.180	0.00
7	2	400	17.1	-0.1815	0.000	0.180	0.00
7	2	500	16.9	-0.0242	0.000	0.180	0.01
7	2	600	17.7	0.1520	0.261	0.256	0.37
7	2	700	18.3	0.3350	0.466	0.182	1.03
7	2	800	18.7	0.5124	0.561	0.148	1.73
7	2	900	17.0	0.6722	0.620	0.127	2.38
7	2	1000	16.1	0.8033	0.655	0.114	2.93
7	2	1100	14.4	0.8969	0.679	0.105	3.34
7	2	1200	14.3	0.9466	0.688	0.102	3.55
7	2	1300	13.8	0.9490	0.691	0.101	3.57
7	2	1400	12.5	0.9039	0.689	0.102	3.40
7	2	1500	12.4	0.8145	0.673	0.108	3.02
7	2	1600	13.2	0.6868	0.640	0.119	2.48
7	2	1700	15.7	0.5295	0.579	0.141	1.81
7	2	1800	17.2	0.3533	0.483	0.176	1.11
7	2	1900	17.2	0.1702	0.293	0.244	0.44
7	2	2000	16.1	-0.0072	0.000	0.180	0.02
7	2	2100	16.4	-0.1669	0.000	0.180	0.00

^eThe $\sin(\beta)$ can also be computed as the sine of β computed earlier in this table.

APPENDIX D

WEATHER DATA INTEGRITY ASSESSMENT AND STATION SITING

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INTRODUCTION

Most automated weather stations (AWS) measure the primary variables affecting ET: solar radiation, air temperature, wind speed and humidity, and therefore provide relatively complete data for predicting ET as compared to manually-operated weather stations measuring only air temperature that were routinely used in the past. An AWS measures temperature, humidity and wind speed within the dynamic boundary overlying the ground surface. Properties of this boundary layer characterize the energy balance at the surface and are used to predict the ET rate. As studies in southern Idaho by Burman et al. (1975) have shown, the lower level of the atmosphere changes when going from desert to a patchwork of irrigated and non-irrigated fields. Humidity, temperature and wind speed variables change when entering an irrigated field surrounded by dry or poorly irrigated fields. It is important, when making calculations of ET_{sz} , that weather measurements are accurate and that the weather measurements reflect the environment that is defined by the reference surface.

WEATHER DATA INTEGRITY ASSESSMENT

Quality and accuracy of the The standardized ASCE reference ET equation (ET_{sz}) is dependent on the quality of the weather data. Weather data must be screened before use in any ET equation, including the standardized equation, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. When weather measurements are determined to be faulty, they can be adjusted or corrected using a justifiable and defensible procedure, or the user may elect to replace perceived faulty data with estimates. This Appendix reviews some general procedures that may prove useful when assessing the integrity and representativeness of weather data used for ET_{ref} calculation. Procedures for estimating data in situations where data are shown to be of poor quality or are missing are summarized in Appendix E.

WEATHER STATION SITING

When possible, meteorological data used for estimating ET_{ref} should be measured over and downwind of vegetation that approximates the reference surface. This is important because the standardized ET_{ref} equation was developed for use with meteorological data collected primarily over and downwind of dense, fully transpiring grass or similar vegetation exhibiting behavior similar to the definition of the reference surface condition. Feedback exists between the boundary layer above the surface and the surface, so that the energy balance and evaporation at the surface impacts temperature and humidity of the air layer above. Ideally, weather stations should be centered within large, nearly level expanses of uniform vegetation that are supplied with sufficient water through precipitation and/or irrigation to support ET near maximum levels. The preferred vegetation for the site is clipped grass. However, alfalfa or a grass-legume pasture maintained at a height of less than 0.5 m may also serve as an effective vegetation for the site. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. A station may be located on the periphery of a vegetated field provided the station is located downwind of the field during daytime hours and that vegetation is shorter than about 0.5 m so as to not impact the wind measurement. In an ideal setting, the well-watered vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available, and that often some nonvegetated areas or roadways will be present near the station.

Meteorological data sets obtained from true reference settings are generally difficult to come by. Often, weather stations are located over or adjacent to: 1) annual row crops that proceed through a distinct annual growth (and cover) cycle, or 2) range and/or pasture land that is subject to seasonal deficits in soil moisture and within the vicinity of small buildings and roadways. Many urban weather stations fail both the underlying surface requirement and the recommended separation distance from

obstacles. Failure of a weather station site to meet the definition of a reference condition described above does not preclude use of the data for estimation of ET_{ref} . However, data from such a station should be examined carefully before use, and may, in some cases, require adjustment to make the data more representative of reference conditions. New weather stations installed for the express purpose of estimating ET_{ref} should be located in sites that closely approximate the reference conditions outlined above.

It is the intent of this document to encourage the use of weather data and to site weather stations that adhere to the preferred guidelines. When weather data are not from an agricultural or reference environment and are shown to be substantially impacted by the lack of local ET, the user should be willing to adjust the data using procedures of this Appendix and other publications or to abandon the use of the data.

Weather stations should be isolated from nearby obstacles and obstructions that can impede airflow and/or shade the site. The recommended horizontal separation distance from such obstacles should exceed 10 times the height of the obstacle. Fences used to protect the station from unwanted intrusions by animals should be made of a porous fencing material (e.g., woven wire or chain link); fence height should not extend above the height of the anemometer.

DATA QUALITY CONTROL

Meteorological data sets acquired for the purposes of estimating ET_{ref} should be subjected to a number of quality control checks prior to use.

The first and most important quality control check involves contacting the source of the weather data to obtain information on:

1. Siting of the weather station.
2. Type and exposure of meteorological sensors employed at the station.
3. Procedures used to maintain and calibrate sensors.

4. Quality control procedures performed and/or data adjustments already performed on the data.
5. Availability of shorter interval data sets (e.g., hourly) to aid the overall QC process.
6. The station operator's experience and/or recommendations pertaining to use of the data for ET_{ref} assessment.

Recommendations pertaining to station siting were discussed in the opening section of this appendix. The types of sensors employed and their exposure (e.g., height of installation or type of radiation shelter) provide insight into expected error levels for specific measurements, and may identify measurements requiring some form of adjustment (e.g., height adjustment for wind speed).

Procedures used to maintain and calibrate meteorological sensors are of extreme importance. Maintenance can be divided into non-technical and technical categories. Non-technical maintenance activities include site maintenance (e.g., mowing, irrigation, and fence repair); cleaning sensors; and leveling radiation sensors and rain gauges. Technical maintenance involves repair and replacement of sensors and equipment, and represents an important component of the overall calibration process. Technical maintenance should be based on the concept of preventive maintenance; that is, replacement of sensors and equipment before their performance degrades. On-site calibration can be performed at regular intervals by comparing sensors with calibrated sensors that are taken to the site for inter-comparison purposes. The operator of the station should provide both the technical and non-technical maintenance protocols and schedule logs either on request basis or on a public web site.

ASAE has recently adopted Engineering Practice 505: "Measurement and Reporting Practices for Automatic Agricultural Weather Stations" (ASAE, 2004). This standard provides specifications for sensor accuracy, resolution, placement and monitoring, as well as intervals and procedures for sensor maintenance and calibration.

It is always advisable to investigate the various quality control (QC) routines that have been employed on the data set by the operator of the station. Data from weather stations operated as part of a weather network are generally subjected to some form of QC assessment (e.g., Snyder et al., 1985; Stanhill, 1992; Meek and Hatfield, 1994; Snyder et al., 1996; Shafer et al., 2000). Common QC assessments include comparing incoming parameters against relevant physical extremes (e.g., relative humidity >100%); using statistical techniques to identify extreme or anomalous values; and comparing data with neighboring stations. Some networks flag questionable data while other networks may replace questionable data with estimated values. The user should be aware, however, that QC procedures of some networks contain rather broad or coarse data range assessments, so that application of a QC procedure does not necessarily provide valid data.

Seeking the advice of the station operator regarding the fitness of a given meteorological data set for ET_{ref} assessment is always advisable. The operator should have considerable insight into whether station sites approach reference conditions, and if not, suggestions on how to correct or adjust either the raw meteorological data or the final ET_{ref} values. Subsequent sections of this document provide procedures for assessing the integrity of meteorological data sets used in the computation of ET_{ref} . Possible procedures for adjusting data to better reflect reference conditions are suggested. While these procedures are applicable in many circumstances, they are by no means a universal solution to all potential problems with meteorological data. Users of the standardized ASCE Penman-Monteith reference ET equation are encouraged to seek local input regarding the subject of assessment and correction of meteorological data for use in computation of ET_{ref} .

SOLAR RADIATION

Solar radiation data can be screened by plotting measurements against clear sky R_{so} envelopes for hourly or daily timesteps. Generally, the best estimates of R_{so} should be used, which may require applying equations that include the influence of sun

angle, turbidity, atmospheric thickness, and precipitable water, for example, Eq. D.1 – D.6 that are presented in the following section. For daily data sets, one can plot measured R_s and computed R_{so} against the day of the year (see Figure 1 in the text and Figure D-1 following). For hourly data, one can plot measured R_s and computed R_{so} against time of day, one day at a time, for perhaps five to ten selected “clear sky” days (Figure D-2).

After creating the R_s and R_{so} plots, the user can observe whether measured R_s “bumps” up against the clear sky envelope some of the time (i.e., on cloud-free days for daily data or during cloud-free hours for hourly data). R_s will fall below the clear sky curve on cloudy or hazy days and during times when the atmosphere is more turbid than under conditions of clean air. Conditions of relatively clean air occur following cleansing rain or snow showers. The transmissivity of the atmosphere and thus R_{so} can shift by several percent from day to day due to changes in water vapor, particulate matter and aerosols, which are all net absorbers of solar radiation. If the “upper” values of measured R_s lie routinely above or below the computed R_{so} curve by more than 3 to 5%, then the user should scrutinize the maintenance and calibration of the R_s sensor. Improper calibration, leveling errors, the presence of contaminants on the sensor (e.g., dust, salt, or bird droppings), or electrical problems can cause R_s to deviate from R_{so} on clear days. “Abrupt” changes in the clear-day relationship between R_s and R_{so} generally indicate: 1) accumulation or removal of contaminants from the sensor; 2) change in sensor level; 3) change in sensor calibration; 4) sensor replacement; or 5) problem with wiring or data-acquisition system. Pyranometer maintenance records, if available, may help explain changes in the relationship between R_s and R_{so} and aid decisions related to data adjustment. Occasionally, R_s during hourly periods may exceed R_{so} due to reflection of sunlight from nearby clouds.

Values of R_s that are consistently above or below R_{so} on clear days can be adjusted by dividing R_s by the average value of R_s/R_{so} on clear days. This adjustment should be used with appropriate caution as the procedure assumes: 1) computed values for

R_{so} are correct; 2) clear days can be effectively identified (for example, during midseason at Greeley in Fig. D-1 following, there is a substantial period having no completely cloud-free days); and 3) the factor causing R_s to deviate from R_{so} is static over time. The R_{so} curves computed by Eq. D.1-D.6 following or by Eq. 19 and 20 in the main body of the report are not “perfect.” They assume clean air and common relationships between the diffuse and beam components of short wave radiation along with typical spectral densities within the short wave band. Identification of clear days can be difficult in cloud prone areas, especially if hourly R_s data are not available to aid in the assessment process. Finally, many of the factors causing R_s to deviate from R_{so} , including leveling errors and contaminant accumulation (See Stanhill, 1992), may not be static over time.

DETAILED PROCEDURE FOR CLEAR-SKY SHORT WAVE RADIATION (R_{so})

A simplified procedure for estimating R_{so} was given in the main text as Eq. 19 and 48. A more complex and generally more accurate procedure involves considering the effects of sun angle and water vapor on absorption of short wave radiation and by separating the components of beam and diffuse radiation, so that:

$$R_{so} = (K_B + K_D) R_a \quad (D.1)$$

where:

- K_B = the clearness index for direct beam radiation [unitless]
- K_D = the transmissivity index for diffuse radiation [unitless]
- R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{d}^{-1}$] or [$\text{MJ m}^{-2} \text{h}^{-1}$]

The following equation for K_B , extended from Majundar et al., (1972) by Allen (1996) and Allen et al., (1998), is applied here with improved coefficients developed from the Task Committee evaluation of solar radiation data from many of the sites evaluated for ET_{os} and ET_{rs} :

$$K_B = 0.98 \exp \left[\frac{-0.00146 P}{K_t \sin \beta} - 0.075 \left(\frac{W}{\sin \beta} \right)^{0.4} \right] \quad (D.2)$$

where:

- K_t = turbidity coefficient [unitless], $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t \leq 0.5$ for extremely turbid, dusty or polluted air.
- P = atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]
- β = angle of the sun above the horizon [radians]
- W = precipitable water in the atmosphere [mm]

The value for K_t may vary with time of year and with cleansing of the atmosphere by precipitation. General values for K_t for a region can be determined using a pristine pyranometer that has a calibration traceable to the national or international solar standard. In general, for routine prediction of R_n and R_{so} envelopes, $K_t = 1.0$ is recommended. The value for β can be calculated using Eq. D.5 (daily) and Eq. D.6 (hourly). The “sin β ” in Eq. D.2 should be limited to ≥ 0.01 for computational stability.

Precipitable water is predicted as:

$$W = 0.14 e_a P + 2.1 \quad (D.3)$$

where:

- W = precipitable water in the atmosphere [mm]
- e_a = actual vapor pressure of the air (at approximately 2 m) [kPa]
- P = atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]

The diffuse radiation index is estimated from K_B (following Allen, 1996):

$$\begin{aligned} K_D &= 0.35 - 0.36 K_B & \text{for } K_B \geq 0.15 \\ K_D &= 0.18 + 0.82 K_B & \text{for } K_B < 0.15 \end{aligned} \quad (D.4)$$

For clear sky conditions, K_B is always > 0.15 for daily data and is nearly always > 0.15 for hourly periods, even those close to sunrise and sunset. Therefore, generally

K_D for use in R_{so} can be computed as $K_D = 0.35 - 0.36 K_B$, ignoring the second conditional of Eq. D.4.

For daily (24-hour) time periods, the average value of β , weighted according to R_a , can be approximated from Allen (1996) as:

$$\sin \beta_{24} = \sin \left[0.85 + 0.3 \varphi \sin \left(\frac{2\pi}{365} J - 1.39 \right) - 0.42 \varphi^2 \right] \quad (D.5)$$

where:

- β_{24} = average β during the daylight period, weighted according to R_a
[radians]
- φ = latitude [radians]
- J = day of the year [unitless]

The “ $\sin \beta_{24}$ ” variable is to be used in place of $\sin \beta$ in Eq. D.2 and represents the weighted average sun angle during daylight hours. The value for β_{24} should be limited to ≥ 0 .

For hourly or shorter periods the sun angle β is calculated as:

$$\sin \beta = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \quad (D.6)$$

where:

- φ = latitude [radians]
- δ = solar declination (“delta”)[radians]
- ω = solar time angle at the midpoint of the hourly or shorter period
[radians]

The user is cautioned that the R_{so} estimate is a theoretical approximation, and that there may be reasons why measured R_s for cloud-free periods deviates from the R_{so} curve. These reasons include air turbidity and haziness caused by dust and aerosols, nearly invisible clouds high overhead, and late afternoon clouding.

Daily measured R_s is plotted in Fig. D-1 for a full year at two CIMIS weather stations in the Imperial Valley of California. R_{so} has been calculated using two methods: Eq. 19 of the text and Eq. D.1 – D.5 of this appendix. Eq. 19 is a simplified procedure, where R_{so} is computed as a constant fraction of R_a , with the constant predicted from site elevation. In the case of Imperial Valley, which is at or below sea level, the constant is about 0.75 for both stations. Comparison of the R_{so} curves with measured R_s from Calipatria, California (Figure D-1a) indicates that the pyranometer was measuring about 12% low on clear-sky days through about day 200. At around day 200, the sensor was replaced, and readings for clear-sky days increased to about 5 to 10% higher than the R_{so} curves. R_s data from the nearby Seeley weather station (about 40 km to the SW) during the same year did not exhibit this shift in data. Therefore, for the Calipatria data for year 1999, the data user would be encouraged to contact the data collector and provider for information concerning pyranometer calibration and the user may wish to pursue options for applying some sort of correction to the data, for example, by multiplying R_s by about 1.12 for days prior to day 200 and by about 0.95 for days following day 200. The user could also consider substituting data from the nearby Seeley station. The more theoretical R_{so} curve from Eq. D.1-D.5 exceeded the more simple R_{so} curve from Eq. 19 by a few percent during mid summer at Seeley and Calipatria, and fit the measured R_s on clear-sky days more closely at Seeley during mid-summer (Fig. D-1b). R_s measured at Seeley on some of the clear-sky days during spring and fall routinely lay a few percent above the R_{so} curves. This indicates that the pyranometer calibration may have been a few percent high or that the theoretical R_{so} curve is a few percent low for this location. The data user may wish to investigate the pyranometer calibration at this site and perhaps conduct an independent assessment of clear-sky R_s using an accurate pyranometer having calibration traceable to the National Standard housed with the Solar Radiation Research Laboratory (<http://srri.nrel.gov/bms/>) located in the National Renewable Energy Laboratory (NREL) at Golden, CO (<http://www.NREL.GOV/>). However, agreement between measured R_s and R_{so} at Seeley appears to be good enough for application in the standardized equations without any adjustment or correction.

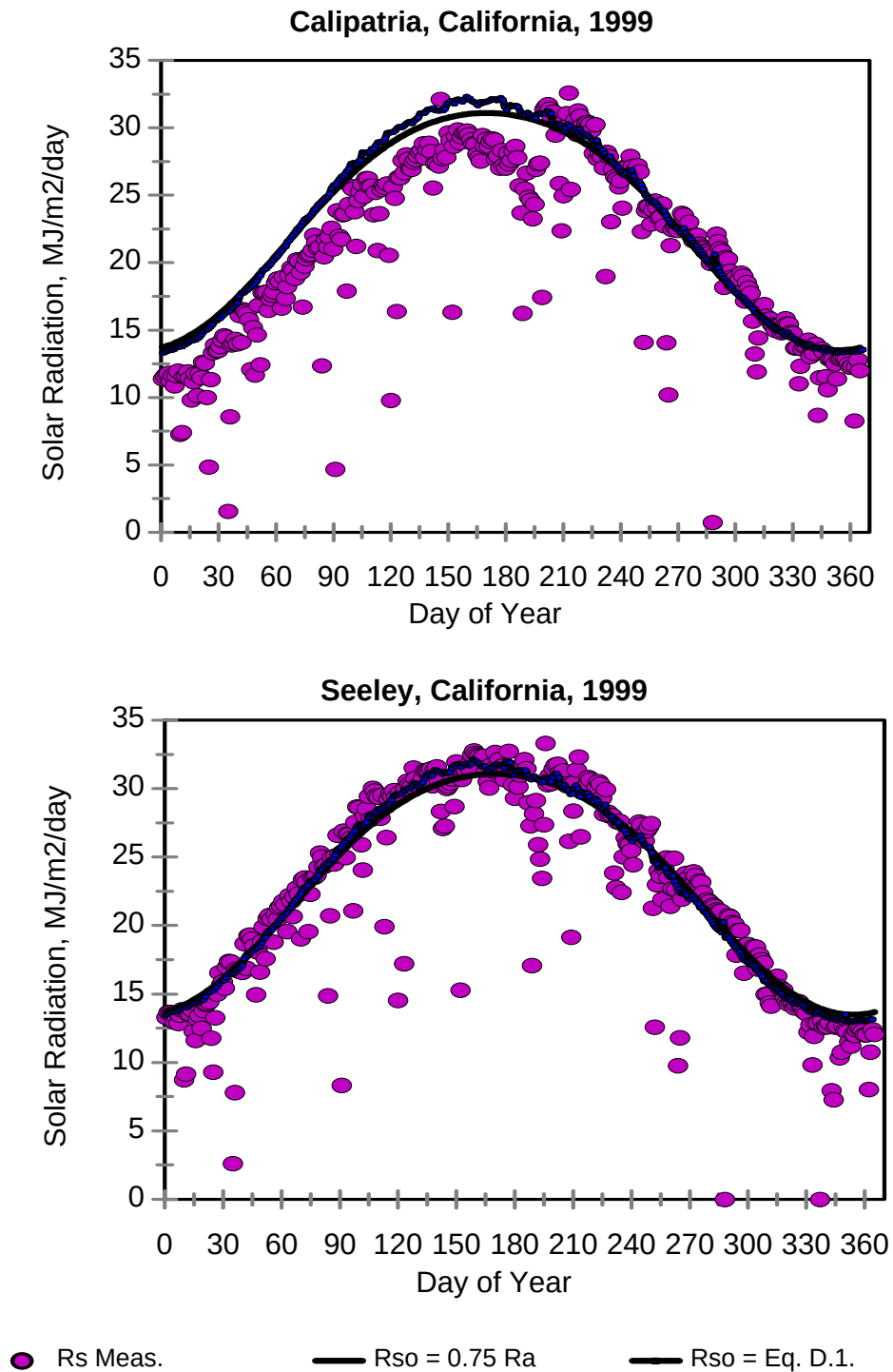


Figure D-1. Daily Measured R_s and Calculated R_{s0} using Eq. 19 of the text and using Eq. D.1 – D.5 for Calipatria (top) and Seeley (bottom), California CIMIS stations in the Imperial Valley during 1999.

A few unreasonably low values of R_s are shown in Figure D-1a and b, where measured R_s was reported as less than $0.1 R_a$. Generally, the lower bound for 24-hour R_s is about $0.2 R_a$. The very low values probably occurred due to sensor or datalogger malfunction or during site maintenance. Missing or faulty data should be substituted by data from surrounding stations as described in Appendix E.

A third set of daily measured R_s is plotted in Fig. D-2 for a full year at Greeley, Colorado. Both R_{s0} curves (Eq. 19 and Eq. D.1-D.5) follow the upper bound of measured R_s quite well for the Greeley data. Agreement is good throughout the year, except for the late spring – early summer period, when there were no days having completely clear conditions. This was confirmed by scanning records of hourly R_s , which indicated that essentially all days at Greeley during late spring – early summer were subject to afternoon clouding during 2000. This example is included to caution the data user that sometimes deviation of measured R_s from the R_{s0} curve for extended periods may be real and valid. The good agreement between measured R_s for cloud-free days and the computed R_{s0} curve for winter, early spring and fall periods supports using the solar radiation data from this weather station for the year shown. The R_{s0} curve computed using Eq. D.1 – D.5 dropped a small amount below the R_{s0} curve from Eq. 19 during summer (day 180 on) due to increased absorption by relatively higher humidity levels of the atmosphere during this period.

Figure D-3 illustrates a comparison of hourly measured solar radiation with R_{s0} computed using the simple method of Eq. 47 of the text and using the more complicated method described above, Eq. D.1-D.6. The data are from the agricultural weather station near Greeley, Colorado, and data from only two days in August are shown. August 5 had a brief period of cloudiness at around 0800 and then some cloudiness during the afternoon. August 6 was essentially a cloud-free day. The R_s data from August 6 compared well with both R_{s0} methods throughout the day. The measured data plotted slightly higher than the simpler R_{s0} estimate from Eq. 47 during the morning hours and slightly below the R_{s0} estimate during the afternoon. This may hint of a slight error in the level of the instrument or in the time setting for

the data-logger clock. In general, the solar radiation data appear to be of excellent quality and calibration.

Plotting hourly measured R_s against the theoretical R_{so} can be helpful in detecting errors or shifts in the reported times associated with the data set (i.e., errors in datalogger time clocks). Plotting of data can also provide an indication of a lack of level of the instrument. Shifts in time and lack of instrument level can both cause measured R_s to plot out of phase with the theoretical R_{so} curve

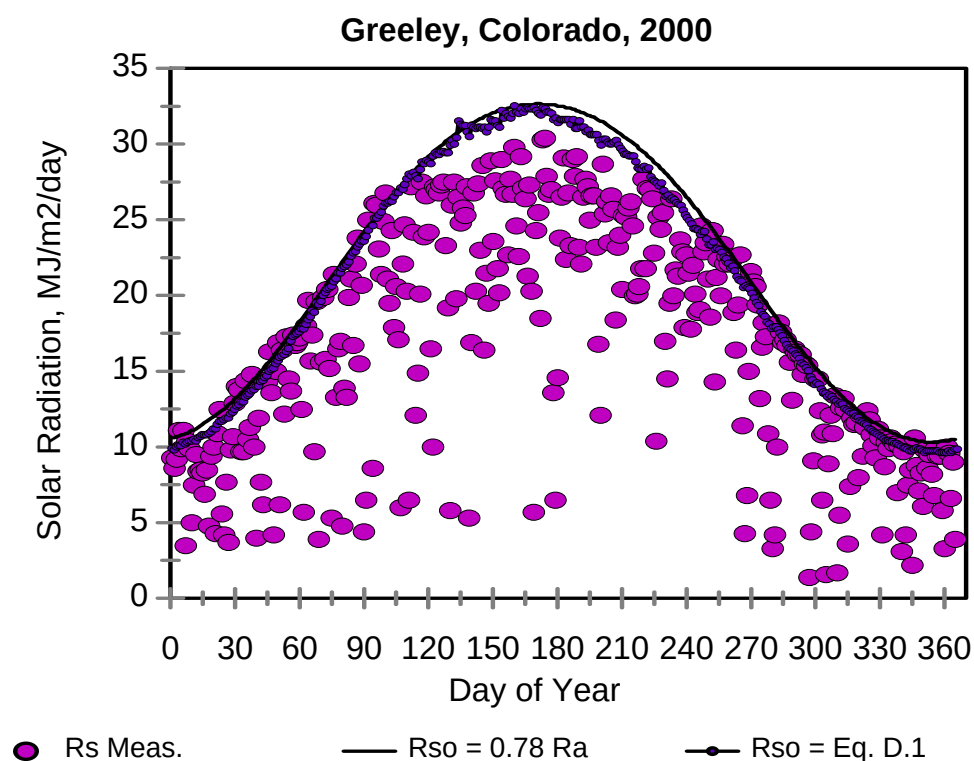


Figure D-2. Daily Measured R_s and Calculated R_{so} using Eq. 19 of the text and using Eq. D.1 – D.5 for Greeley, Colorado during 2000.

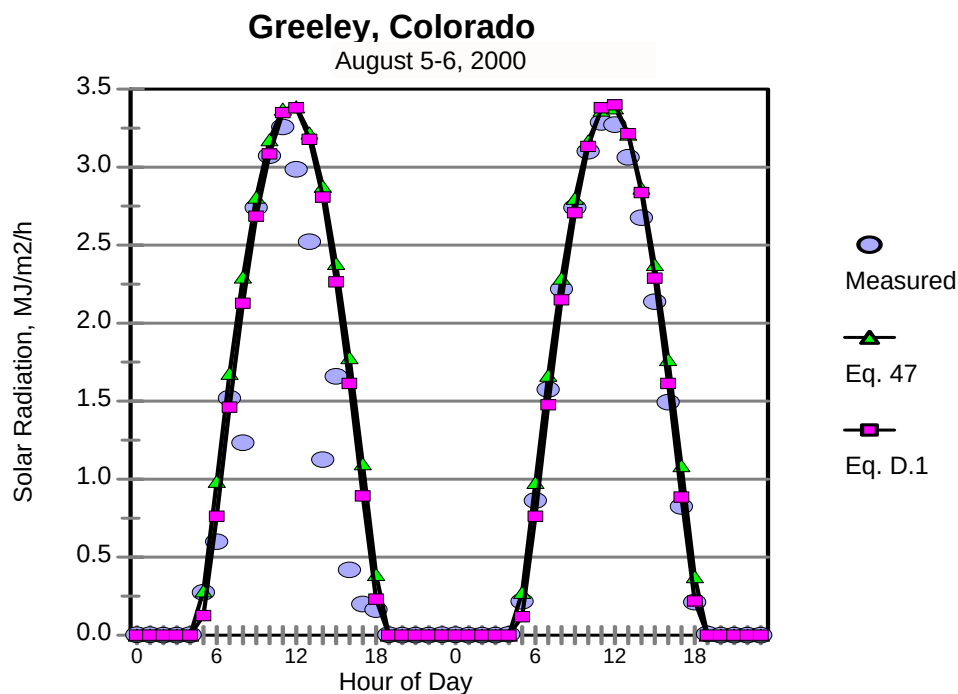


Figure D-3. Hourly measured solar radiation and clear-sky envelopes for two days in August, 2000 near Greeley, Colorado.

NET RADIATION

Where net radiation data are measured, values can be compared with R_n estimated from solar radiation as a means of integrity assessment. One should not expect measured R_n to exactly agree with estimated R_n . However, significant variation between the two should be cause for a closer investigation of the measured data. Some net radiometers do not accurately measure the long wave component of net radiation. In addition, the R_n measurement should be made over a well-watered surface of clipped grass or full-cover alfalfa so that albedo is similar to that defined for ET_{sz} . A shift in the relationship between measured and estimated R_n may reflect a change in the quality or condition of the surface at the measurement site. Other

measurement related factors that can shift the relationship between measured and estimated R_n include scratched or dirty radiometer domes, an off-level sensor, or condensation of moisture inside domes of the R_n sensor.

Figure D-4 shows hourly measured net radiation and net radiation calculated using the standardized net radiation procedure for one day at Kimberly, Idaho. Agreement between measured and calculated R_n is judged to be very good, even during nighttime periods.

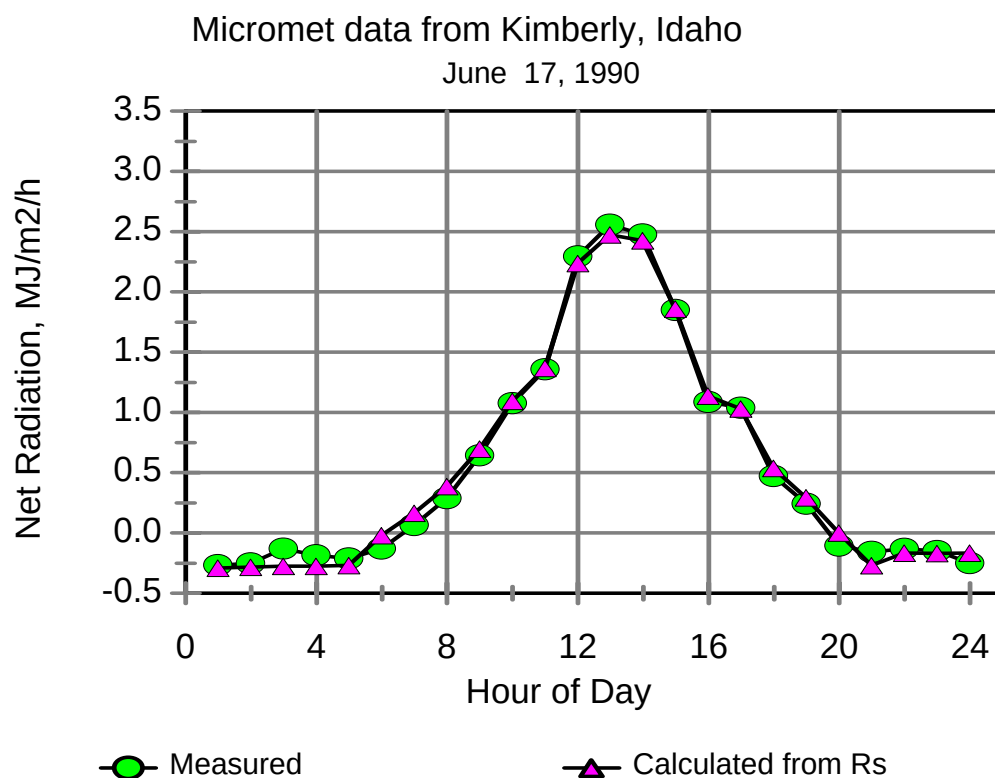


Figure D-4. Measured and calculated hourly net radiation for one day at Kimberly, Idaho over clipped grass (R_n was calculated using Eq. 42-44). Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly.

HUMIDITY AND AIR TEMPERATURE

RELATIVE HUMIDITY

Humidity and air temperature data should be screened to identify questionable or erroneous data. A portion of the screening process involves the user having a sense of what are reasonable and unreasonable values. For example, relative humidity (RH) values chronically lower than 5 to 10% in arid regions and 30% in subhumid regions are uncommon and may indicate problems with the sensor. Similarly, RH values in excess of 100% do not occur in the natural environment and may indicate that the sensor is out of calibration. The accuracy of most modern-day electronic RH sensors is generally within $\pm 5\%$ RH (ASAE, 2004); thus, recorded RH values in excess of 105% provide good evidence that the sensor is out of calibration.

All RH values in excess of 100% should be set equal to 100% prior to use in the ET_{sz} computation process. Use of this simple adjustment procedure, however, does not alleviate sensor calibration errors in recorded RH data that lie below 100%. Some type of proportional adjustment to all data may be warranted. One should use RH data sets containing values in excess of 100% with caution. Furthermore, RH values in excess of 100%, if not accompanied by a QC flag, may indicate that the data set has not been subjected to rigorous QC.

If hourly data are available, it is advisable to examine the diurnal variation of RH on selected days to ensure that RH approaches maximum and minimum levels during the coolest and warmest portions of the day, respectively. Hourly time series of RH should also be examined for the presence of spikes and spurious values of RH that may indicate sensor malfunction. Finally, one should check RH data on several days having heavy and/or sustained precipitation events or when dew or fog events are known to have occurred. Relative humidity should approach 90-100% during a

sustained precipitation, fog, or dew event, and should approach 100% in the evening hours following a heavy rain event.

DEW-POINT TEMPERATURE

Dew-point temperature (T_{dew}), as calculated from RH, may be reported in lieu of RH in some data sets. Any errors in RH will affect e_a (since $e_a = \text{RH} * e_s(T)/100$), and thus the computed T_{dew} . Values for daily average or early morning T_{dew} should be compared to minimum temperatures (T_{min}). In humid regions, the T_{dew} measurement will approach T_{min} on many days. Exceptions occur on days that feature a change in air mass (e.g., frontal passage), or that have high winds and/or cloudiness at night. T_{dew} may approach T_{min} in arid and semiarid environments if nighttime winds are light and measurements are made over a surface exhibiting behavior similar to the reference definition (i.e., sufficient evaporation to cause evaporative cooling). It is not uncommon in arid and semiarid regions to have T_{dew} 2 to 5 °C lower than T_{min} under reference conditions (see discussion below) but well below T_{min} if the measurement site is subjected to local aridity. If daily average T_{dew} regularly exceeds T_{min} , then the humidity sensor may be out of calibration. Such data should be examined closely and possibly adjusted prior to use (see Appendix E).

When it is not observed, T_{dew} can be computed from e_a by¹

$$T_{\text{dew}} = \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)} \quad (\text{D.7})$$

where:

T_{dew} = dew point temperature [°C]
 e_a = actual vapor pressure [kPa]

Figure D-5 illustrates the use of comparisons between T_{min} and T_{dew} and use of plots of daily RH_{max} and RH_{min} to detect errors in hygrometer data from an AWS in SE

¹ Reference: Bosen (1958); Jensen *et al.* (1990)

Colorado. The large shifts in mean daily T_{dew} relative to T_{min} at days 15 and 200 are obvious. Following day 200, the data began to follow an expected pattern and relationship with T_{min} , with T_{dew} in close proximity to T_{min} . Similar obvious shifts in RH_{max} and RH_{min} are apparent also (bottom plot of Figure D-5). During the last half of the year, values for RH_{max} exceeded 100% by a small amount. However, these errors in RH are considered to be small relative to those occurring during the first part of the year, where the T_{dew} data required substantial correction. Daily RH_{min} after day 200 regularly fell below 10%, which is considered to be very low reading for a reference site. This reflects a relatively “harsh” evaporative environment. The proximity of T_{dew} to T_{min} during the same period indicated the general presence of an evaporative surface.

Figure D-6 shows T_{dew} and T_{min} for the same station and year as in Figure D-5, but following correction of T_{dew} using the following relationship:

$$T_{\text{dew}} = T_{\text{min}} - (T_{\text{min}} - T_{\text{dew}})_{\text{station 2}} \quad (\text{D.8})$$

where $(T_{\text{min}} - T_{\text{dew}})_{\text{station 2}}$ is the measured difference on the same day between T_{min} and T_{dew} at an AWS about 50 km distant. The use of $(T_{\text{min}} - T_{\text{dew}})_{\text{station 2}}$ preserved the difference observed between T_{min} and T_{dew} at the adjacent station, and therefore the relative dryness of the air mass, but adjusted for differences in minimum daily air temperature between the two sites. The resulting plots of T_{min} and T_{dew} in Fig. D-6 illustrate good continuity of the relationship between T_{min} and T_{dew} for the corrected period (days 15 – 200) and original observations following day 200. The occasionally low values for T_{dew} during days 15 – 200 were present in the data set for station 2.

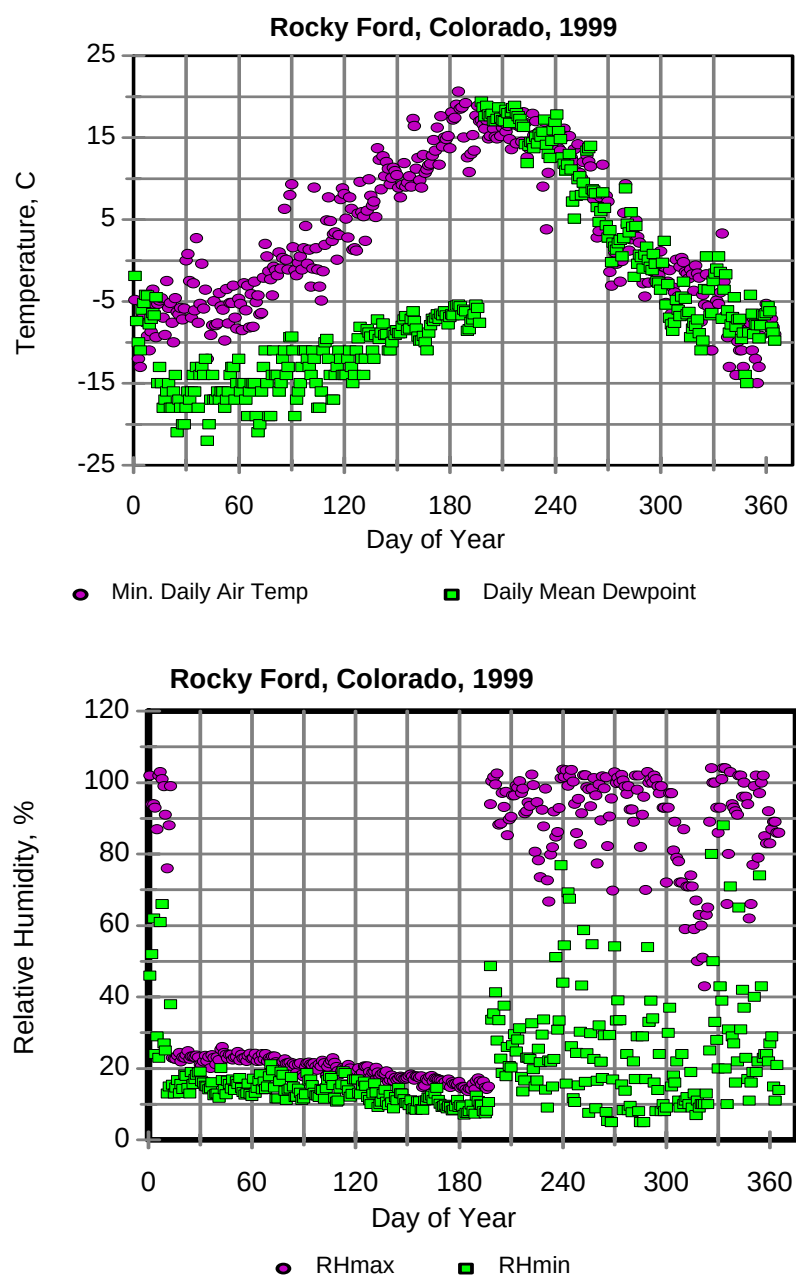


Figure D-5. Measured daily minimum air temperature and mean daily dewpoint temperature (top) and daily maximum and minimum relative humidity (bottom) recorded for Rocky Ford, Colorado during 1999.

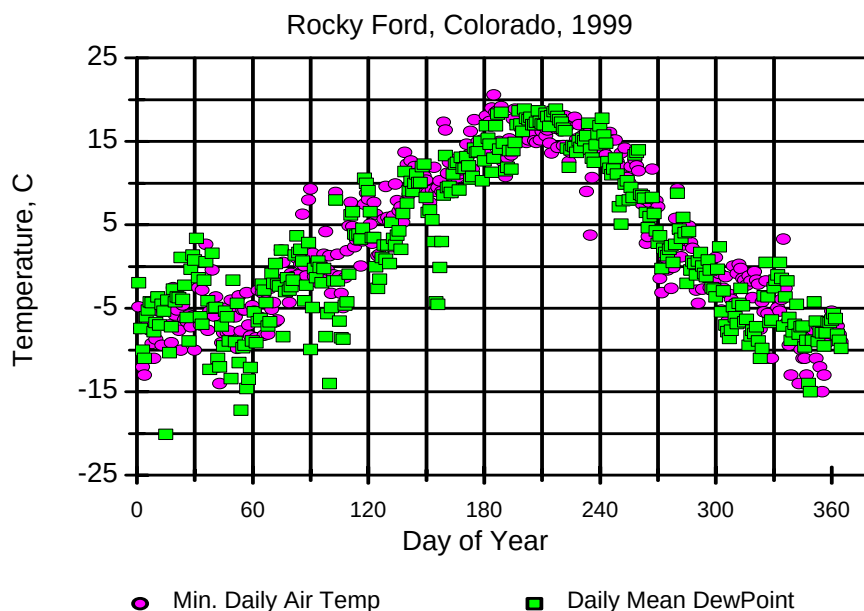


Figure D-6. Measured daily minimum air temperature and mean daily dewpoint temperature for Rocky Ford, Colorado during 1999, where T_{dew} for days 15 to 200 was replaced by estimates using Eq. D-8.

Plots of hourly or shorter period T_{dew} data may assist in identifying problems in T_{dew} data. Dew point and vapor pressure are relatively conservative parameters and often exhibit little change over a day, especially in humid regions. Often, T_{dew} will increase somewhat during midmorning due to evaporation of water and increased capacity for the air to contain vapor (see for example, Fig. D-7 and D-10). Dew point will then stabilize or decline slightly during the mid-day hours as the vapor near the surface gets mixed into a progressively deeper boundary layer. Hourly variation in T_{dew} is greater in semiarid and arid settings, especially in areas prone to strong regional advection, where T_{dew} can drop substantially during afternoon as warm, dry air from outside an irrigated area “breaks into” the boundary layer established over the irrigated area. However, large changes in T_{dew} during the day, except under circumstances such as a change in air mass (e.g., frontal activity or sea/land breeze) or large change in wind direction, could signal an error or bias in the T_{dew} measurement. It is common in the western Great Plains of the U.S. to have distinct

drylines, which extend either N-S or NE-SW. A dryline, which is an atmospheric transition zone having large gradients in vapor content, may move during the day, with larger T_{dew} values in front of the dryline (typically the eastern side) and with substantially smaller T_{dew} values behind the dryline (typically the western side). Allen (1996) provided illustrative plots of hourly T_{dew} data and expected trends over time. Comparison of hourly T_{dew} to T over a 24-hour period is illustrated in Figure D-7.

AIR TEMPERATURE

In general, air temperature is the simplest and most consistent weather parameter to measure and the parameter most likely to be of highest quality, provided it is measured in a reference-type of environment. Air temperature extremes in a data set should be compared to historical record extremes, if such data are available for locations near the site. Temperatures that routinely exceed the recorded extremes for a region indicate a problem with either the sensor or with the radiation shield used to house the sensor. Sensors mounted in non-aspirated radiation shields may produce erroneously high temperatures on days having light winds due to solar heating of the shield (Gill, 1983). Consistently hot temperatures from a sensor mounted in an aspirated radiation shield may indicate problems with the ventilation system. An effective check for spuriously high or low temperature extremes is to compare the average of the daily extremes (T_{max} and T_{min}) with the mean daily temperature as averaged by the data logger for the day. Many automated weather stations now generate a recorded average temperature for the 24-hr period that can be used in this comparison. Differences between the average computed from the temperature extremes and the recorded 24-hr average for the day will generally run within 2 °C. Data should be subjected to closer scrutiny on days when the two averages deviate by more than 3 °C. Precipitation events, air mass changes, and unusual wind conditions can cause deviations in excess of 3 °C.

When hourly temperature data are available, it is advisable to plot the diel (hourly) temperature trend on selected dates to ensure that temperatures attain maximum and minimum values at the appropriate time of the day. For most locations, minimum temperatures occur shortly before sunrise, and maximum temperatures occur in mid-afternoon (1400-1600). It is also important to examine diel temperature profiles for spikes or spurious temperatures that could indicate a malfunctioning sensor.

Figure D-7 illustrates hourly measurements of both air temperature and dewpoint temperature during a single day over a grassed surface near Kimberly, Idaho. Measurements were made using electronic instrumentation and dual measurements using independent systems from different manufacturers were used for purposes of data back-up and redundancy. The two air temperature sensors (TC = thermocouple

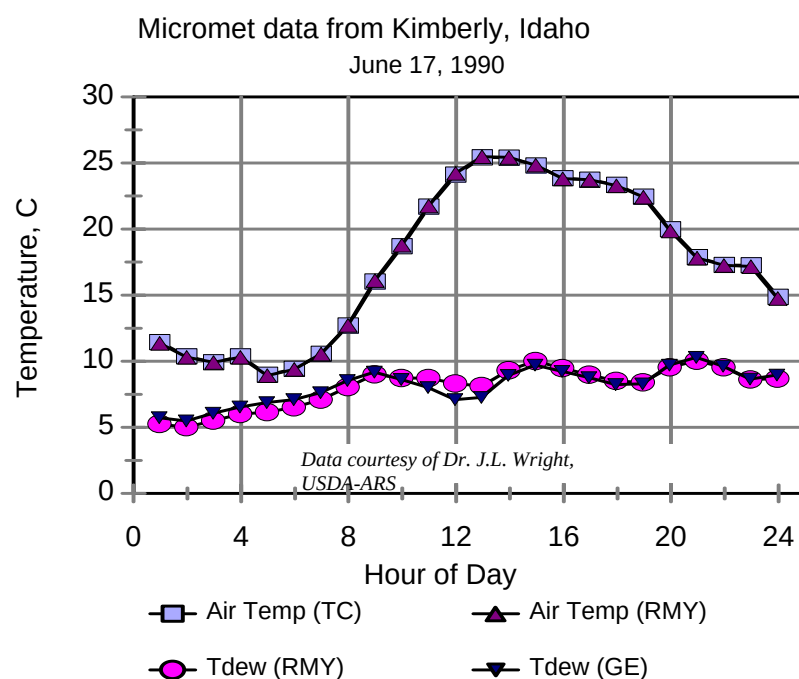


Figure D-7. Hourly air temperature and measured dewpoint temperature from dual sensor systems near Kimberly, Idaho, July 17, 1990. Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly, Idaho.

and RMY = RM Young chilled mirror system) tracked each other consistently throughout the 24-hour period. The two dewpoint temperature measurements (RMY = RM Young chilled mirror system and GE = General Eastern chilled mirror system) tracked each other closely throughout the period. The closeness of the data measurements from two independent, colocated systems is useful in confirming the accuracy of the data and the proper functioning of both instrument systems. In addition to validation of the air temperature and measured dewpoint temperatures, the data in Fig. D-7 show that minimum daily air temperature, recorded as 9.0 °C at about 5 am was about 3 °C above the dewpoint temperature (6.2 °C) measured at the same time. This difference is in line with that expected from a well-watered reference environment as discussed in the following section.

IMPACT OF NON-REFERENCE WEATHER STATION SITE ON TEMPERATURE AND HUMIDITY

Temperature and humidity data that pass QC checks still may not be advisable for use in estimating ET_{ref} . The moisture status of the underlying surface impacts both temperature and humidity due to the energy balance and impacts of evaporative cooling. Therefore, data collected away from well-watered vegetation (e.g., at airports or over dry, paved, and fallow surfaces) can be negatively influenced by the local aridity, especially in arid and semiarid climates. Data from dry or urban settings may cause overestimation of ET_{os} or ET_{rs} due to air temperature measurements that are too high and humidity measurements that are too low, relative to the reference condition. Under these “arid” measurement conditions, the ET_{os} and ET_{rs} calculations may reflect ET demand of the “ambient,” “non-reference” environment, for instance where average net rainfall plus irrigation is substantially less than ET_o or ET_r , so that air temperature is elevated. However, these estimates of ET_{os} and ET_{rs} may overpredict the ET_{os} and ET_{rs} that would occur for a well-watered setting. An extreme example of the impact of local aridity on ET_{os} was observed in a study near Parker, AZ, (Brown, 2001) where weather stations were installed in adjacent 15-ha fields containing irrigated alfalfa and fallow ground. Data from each station were used to

estimate ET_{os} using the ET_{sz} equation. Monthly totals of ET_{os} computed using the fallow station data set exceeded similar ET_{os} totals computed using the alfalfa data set by 18-26% during months of June through September (Figure D-8).

Often, an assessment of RH , T_{dew} , and e_a can indicate whether meteorological data were collected in a reference type of environment. Under reference conditions, daily RH_{max} generally exceeds 90% and may approach 100% during early morning hours, provided skies are clear and winds are light (Allen, 1996). Minimum temperatures under these circumstances will approach T_{dew} . One can therefore plot and then visually scan plots of RH_{max} or average (or early morning) T_{dew} and T_{min} as a function of time to determine if humidity data reflect the reference condition.

For example, Figure D-9a shows daily T_{min} and T_{dew} for the year 2000 for the agricultural weather station near Greeley, Colorado. Mean daily T_{dew} (calculated from daily average measured vapor pressure) follows T_{min} relatively closely throughout the year, and is generally within a few degrees Celsius of T_{min} . Figure D-9b shows daily maximum and minimum RH for 2000 at Greeley. The RH_{max} tends toward 90 to 100% during many days. Minimum relative humidity (RH_{min}) runs a little below the expected 25 to 35% range for a reference setting in a semi-arid environment (Allen et al., 1983; Allen 1996, Allen et al., 1996). Overall, the humidity and air temperature data at Greeley during 2000 are judged to be relatively accurate and reflective of a “reference” condition.

If RH_{max} is consistently below 80% for a substantial portion of the growing season record, or if T_{dew} deviates more than 3–4 °C less than T_{min} for a substantial portion of the growing season record, then the humidity data should be subjected to further scrutiny. Among the factors to investigate are: 1) type, maintenance, and calibration of the RH or T_{dew} equipment; 2) presence of cloudiness or wind flow at night, which tend to reduce RH_{max} ; 3) that the site may not be representative of well-watered conditions; and 4) that the region has characteristically very dry air so that irrigated areas are subject to substantial advection of hot, dry air, for example in Imperial

Valley, CA, and portions of Arizona and New Mexico. Historically, humidity has been among the most difficult routine meteorological parameters to accurately measure. The quality of RH measurements has improved in recent years due to improvements in sensor technology. Prior to 1990, many agricultural weather networks used polystyrene humidity sensors. These sensors degraded rather quickly in agricultural environments (Howell et al., 1984; Brown et al., 1987), and RH measurement errors in excess of 5% RH were common under the best of circumstances (Brown et al., 1987). Most networks now utilize thin-film capacitance RH sensors that are stable for periods in excess of one year and accurate to within 2-3% RH if properly maintained and calibrated (Tanner, 2001).

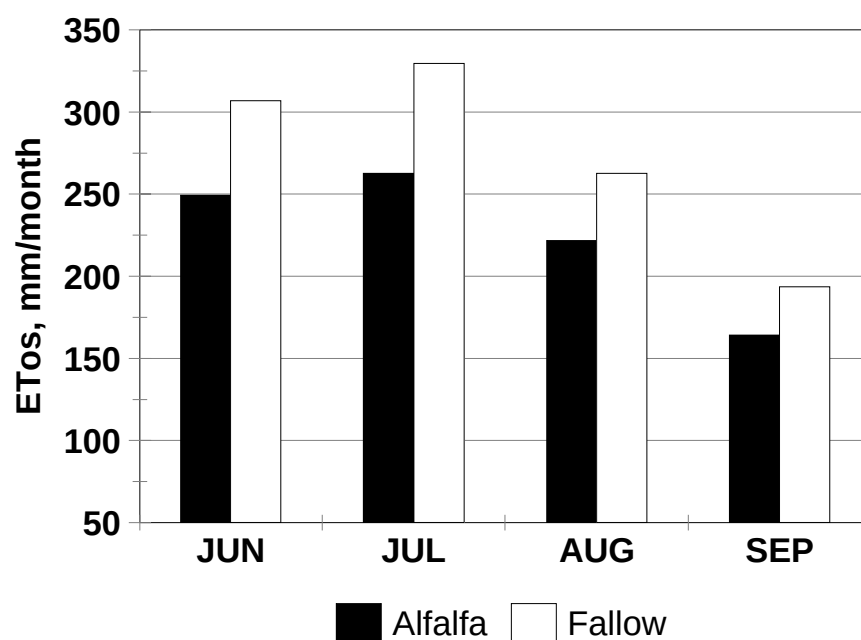


Figure D-8. ET_{os} by month for the summer of 2000 at Parker, AZ computed using meteorological data collected under reference (alfalfa) and non-reference (fallow) conditions.

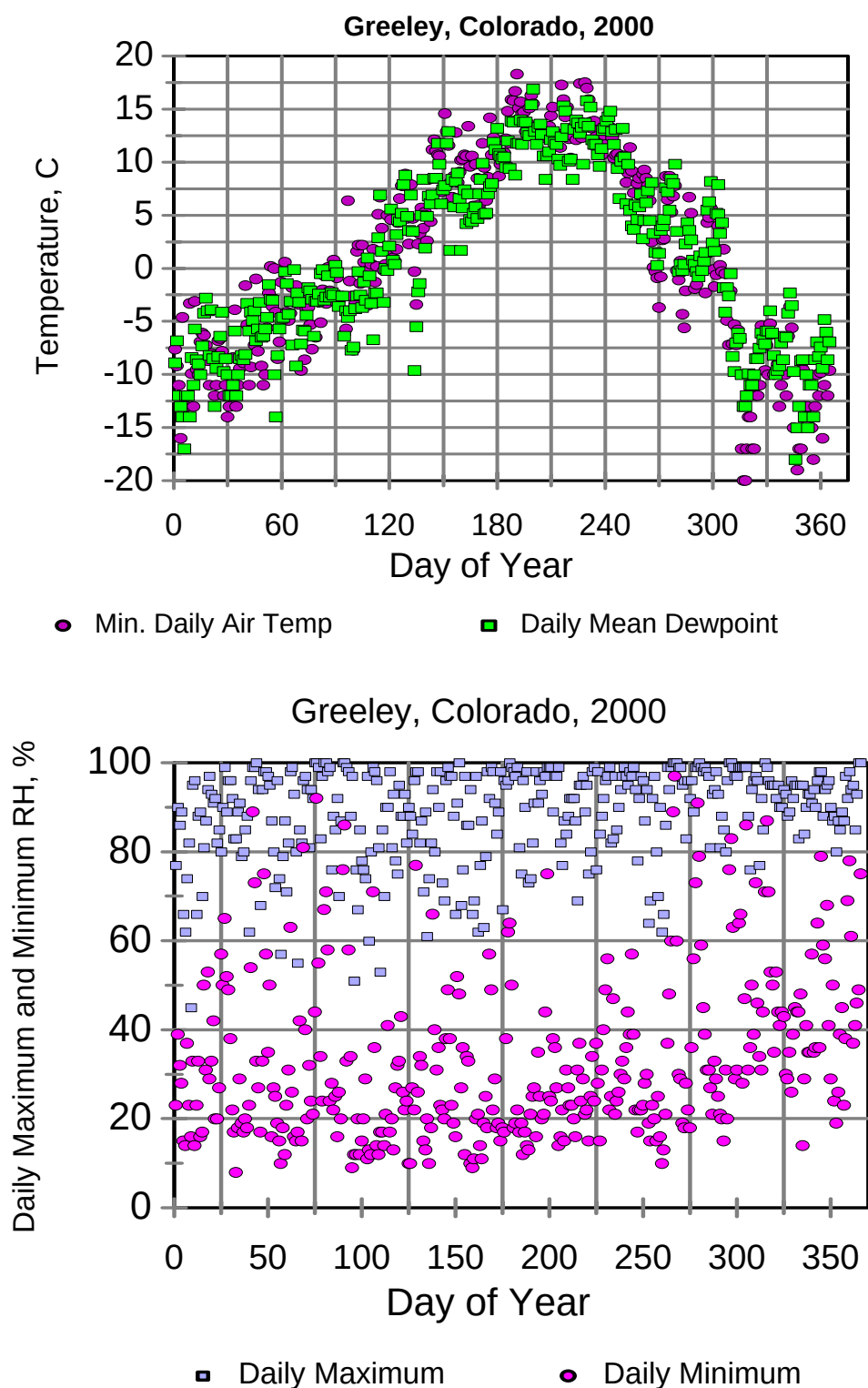


Figure D-9. a) Daily minimum air temperature and daily mean dew point temperature vs. day of the year and b) daily maximum and daily minimum relative humidity vs. day of the year for Greeley, Colorado, during 2000.

Psychrometers, dewcells, and chilled mirror hygrometers can provide high quality humidity data, as shown in Fig. D-7, provided the sensors receive proper maintenance and are operated within the design range. These sensors are not in widespread use for general climate monitoring in remote, automated weather stations due to cost and maintenance factors. The RH and T_{dew} assessments described here may not be effective at identifying data representative of a suitable reference environment in regions prone to cloudiness and large nighttime winds. Cloudiness lowers net loss of long-wave radiation at night, which inhibits cooling and may prevent T_{min} from approaching T_{dew} at night. High nighttime wind speed enhances the transfer of sensible heat and dry air to the surface, slowing the rate of cooling and preventing full humidification of the atmospheric boundary layer above well-watered surfaces.

Often, dewpoint temperature is consistent between locations having similar surface conditions. For example, Fig. D-10 shows hourly dewpoint temperatures for four Agrimet weather stations (data from U.S. Bureau of Reclamation) in southern Idaho that are up to 140 km apart. The recorded dewpoint temperatures and their trend during the day are largely consistent. The four stations (Rexburg, Montevideo, Ashton, and Aberdeen) are situated in irrigated agricultural settings. Dewpoint data taken from a desert weather station (Flint Creek, Idaho, lat. 42.08°, long. 112.18°) is substantially lower, averaging 11 °C below the average for the four Agrimet stations. Air temperature at Flint Creek averaged 4 °C above the Agrimet stations over the 24-hour period. The impact of aridity on both dewpoint temperature and air temperature at Flint Creek is obvious and is manifested in erroneously high ET_{ref} estimates if applied without correction.

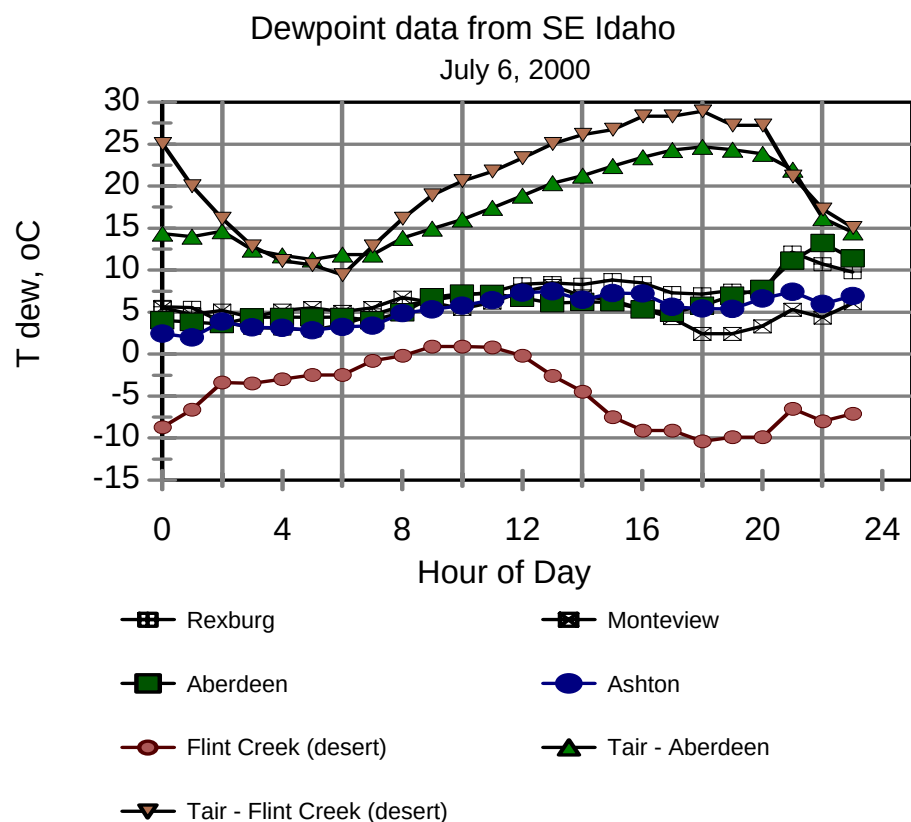


Figure D-10. Hourly dewpoint from four irrigated regions of southeast Idaho and from a desert weather station (Flint Creek) on July 6, 2000. Also shown are air temperatures at Aberdeen and Flint Creek.

Adjustment of temperature and/or humidity data may be warranted when the weather station site is known to be in a local environment that substantially departs from a reference condition and assessment of humidity data indicates that the aridity is impacting the weather data. Allen and Pruitt (1986) and Allen (1996) suggested simple, empirical adjustment procedures to make "non-reference" weather data more representative of well-watered reference conditions. Allen and Gichuki (1989) and Ley et al. (1996) suggested more sophisticated approaches. Annex 6 of FAO-56 includes procedures for evaluating and adjusting humidity and air temperature data for aridity of the weather station site.

ESTIMATING T_{DEW} USING T_{MIN}

Often, substituting $T_{dew} = T_{min} - K_o$ for measured T_{dew} , (i.e., using Eq. E.1 of Appendix E), can improve estimates of daily ET_{os} and ET_{rs} when data are from a non-reference, arid setting. In arid and semiarid regions, it is best to check with the source of weather data to determine if K_o values have been developed for the area. For example, in Arizona the value of K_o was found to vary from 2 to 5 °C over the course of a year. When local information on K_o is not available, a K_o in the range of 2 to 4 °C is recommended for semiarid and arid regions (Allen, 1996). In humid regions where T_{dew} approaches T_{min} on most nights, K_o is set equal to 0 °C. Some irrigated areas in very dry, advective climates can have extended periods during which T_{min} is more than 5 °C above T_{dew} . These areas include portions of SE California, southern Arizona and New Mexico. Caution should be exercised in the specification of K_o .

Using minimum air temperature measurements from a non-reference setting to predict dew point temperature using K_o with Eq. E.1 of Appendix E may tend to overestimate the true T_{dew} and e_a that would have occurred under reference conditions. This occurs because measured T_{min} is higher in the dry setting than in a reference setting and thus T_{dew} based on $T_{min} - K_o$ where T_{min} is elevated due to aridity may be somewhat overpredicted. However, because e_s in the Penman-Monteith equation will be predicted using the same T_{min} values used to predict T_{dew} , e_s and e_a will be essentially equally “inflated.” Therefore, the $e_s - e_a$ difference in the standardized ET_{ref} equation in general will approximate the $e_s - e_a$ difference anticipated for the reference condition. As a consequence, a more accurate estimate for ET_{os} or ET_{rs} may result than if the actual measurement of T_{dew} from the arid setting had been used. When humidity is adjusted using $T_{dew} = T_{min} - K_o$, no further adjustment is generally needed to the air temperature data set to account for effects of aridity of the weather measurement site.

Use of the $T_{dew} = T_{min} - K_o$ adjustment may produce a slight upward bias in computed net radiation (R_n). The adjustment when T_{min} is impacted by station

aridity inflates e_a above levels expected for reference conditions. This error in e_a causes atmospheric long-wave radiation to be overestimated, which in turn causes a 1 to 3% overestimation in R_n . This impact is considered to be relatively minor.

DISCUSSION

The impacts of aridity upon data collected at an automated weather station received considerable consideration and deliberation by Task Committee members. The availability of experimental data that were collected specifically for evaluating impacts of aridity on weather data was a constraint. Brown (2001) data, however, demonstrate that significant error in predicted ET_{sz} can occur under very arid conditions. The magnitude of expected error under more moderate climates and the typical patchwork of irrigated and non-irrigated fields should be less.

Important questions concern the magnitude of errors in ET_{sz} associated with non-ideal sites (i.e., those lacking substantial transpiring vegetation). How well does a station represent the average expected ET over an adjacent irrigated green crop? The TC has attempted to provide guidelines for the user of AWS data to adjust for, or evaluate, the probable error associated with data from an AWS based on the data it provides. Making a simple check by substituting dew point based on minimum air temperature minus a constant will indicate if there is a potential problem. Analysis of $T_{min}-T_{dew}$ relationship from nearby stations can provide valuable insight as to whether data are representative of the reference condition.

WIND SPEED

Accuracy of wind speed measurements is difficult to assess unless duplicate instruments are used. Nevertheless, one should visually inspect wind records for the presence of consistently low wind speed values that may indicate a malfunctioning or failed anemometer or the presence of ice if air temperatures are near or below 0 °C. Consistent and low wind speeds can indicate dirty anemometer bearings that will increase the anemometer wind speed threshold and might eventually seize and stop the anemometer altogether. Wind speeds from failed anemometers will usually appear as small, constant values (less than 0.5 m s⁻¹ or the wind speed threshold for a new anemometer) if the anemometer is monitored with a data logger. With a failed anemometer, recorded maximum and mean wind speeds will often have the same values and be equal to any numerical offset in the calibration equation.

Maximum wind speed data, if available, can assist in the assessment of low wind speed data, with a gust factor (ratio of maximum wind speed (m s⁻¹) to mean daily wind speed (m s⁻¹)) serving as a useful index. If plotting the gust factor over time indicates a period of excessively large values, then the anemometer may be malfunctioning. For example, Figure D-11a shows data from an anemometer that was malfunctioning between Day 109 to 117 due to bearing contamination. Gust factors often increase as contamination increases the friction in the bearings. The increasing bearing friction has a greater impact on cup rotation at small as opposed to large wind speeds and thus causes an increase in the ratio of maximum to mean wind speed. The gust factor will exhibit a sudden drop to 1.0 when the anemometer seizes or fails electronically. The data analyst must be cautious, however, in interpretation of a gust factor, because some weather periods can have more gusty, turbulent air flow than others.

Any appreciable period having daily mean wind speeds of less than 1.0 m s^{-1} should be viewed with caution. Aside from exceptionally calm periods or anemometer problems, other possible reasons for daily wind speeds of less than 1.0 m s^{-1} would include excessive vegetation height at the station or the presence of blocking structures in the nearby landscape (e.g., solid fences or buildings).

Data from a nearby station may also assist in the assessment of wind speeds at a particular site. In some cases, winds at two nearby locations are related which indicates the ratio of the wind speeds at the two locations will remain nearly constant. By plotting this ratio over time, one can identify a problem anemometer. A sudden and consistent change in the ratio often indicates a failed anemometer; a gradual change in ratio may indicate growing contamination in the bearings (Figure D-11b).

As an illustration of comparing wind speed data from two or more locations, daily wind speed data from three neighboring CoAgMet AWS stations located in the Arkansas River Valley of Colorado are plotted in Figure D-12a. The Vineland and Avondale stations are within 15 km (10 miles) of one another and the Rocky Ford station is about 60 km (40 miles) further east. All stations are located in agricultural environments and wind was measured at 2 m above the ground. The similarity in wind speed records is apparent. The Vineland station had some fields of corn planted near the weather station during 1995 (personal commun., R.Allen, 2001) that impeded wind speed measurements during late summer. This is evident in viewing the daily wind plot in Figure D-12a, where daily wind speeds for Vineland fell below those at Avondale and Rocky Ford from day 190 through day 270. Ratios of wind speed for Vineland to wind speed at Rocky Ford show a similar pattern (Figure D-12b), with ratios routinely falling below 0.7 during the period from day 210 through day 270 when the corn crop was tallest. Ratios of wind speed for Avondale to Rocky Ford followed a consistent average of 1.0 all year, as is expected, with some inconsistencies during winter months. This example illustrates the use of data from neighboring stations to discern shifts or anomalies in a data set.

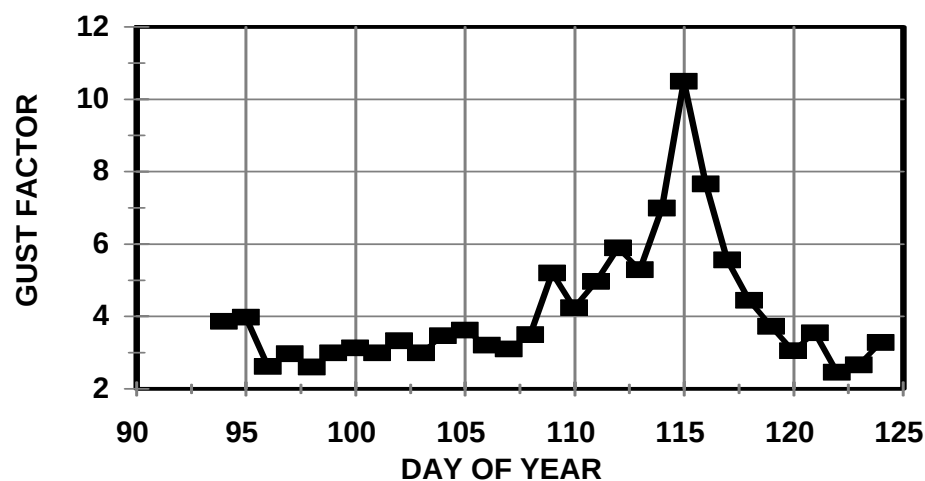


Figure D-11.a) Plot showing the increase in the gust factor at Eloy, AZ during a period when an anemometer was failing due to bearing contamination.

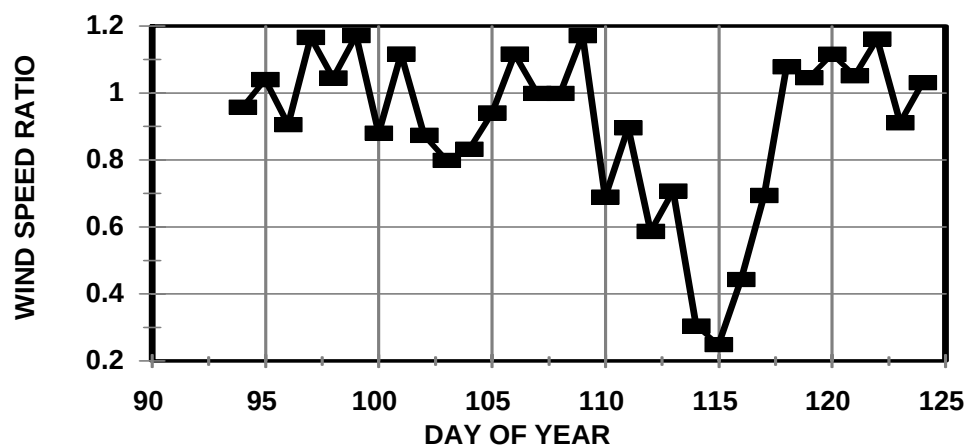


Figure D-11b) Ratio of daily mean wind speeds at Eloy, AZ to those at Maricopa, AZ during the period of anemometer failure described in a).

A good preventive maintenance program is required to keep anemometers functioning at peak performance levels. Weather station anemometers should be replaced with newly reconditioned (new bearings) and calibrated anemometers at regular intervals. An annual replacement in light to normal wind regions or semi-annual replacement in windy regions should be considered for anemometers located in agricultural settings. Some providers of weather data employ a standard practice of replacing anemometers on a regularly scheduled basis. The replacement schedule is typically based on local experience or recommendations of the manufacturer and may be as short as six months. ASAE (2004) provides detailed recommendations on periodic sensor maintenance. An alternative technique for evaluating anemometers involves redundancy in instrumentation and requires placement of a second anemometer² of the same design, but with fresh bearings, at the weather station for a three or four day period at least once each year, and comparing recorded values. Variations between recordings can signal a need to replace bearings, switches, or other parts.

Wind speeds over non-reference surfaces may exhibit a systematic upward bias relative to wind speeds measured over reference surfaces. Vegetation in excess of the recommended reference-surface height will impose a greater frictional drag on the near surface atmosphere and reduce wind speed relative to the reference condition. Smooth, dry surfaces will generate an opposite bias; wind speeds over these surfaces will generally be higher than those measured over reference surfaces. Allen and Wright (1997) have suggested procedures for adjusting non-reference wind speed data to better represent reference conditions; however, these procedures are somewhat complicated and have not been validated for a wide range of conditions.

² If a second data logger is used to record the temporary anemometer, one should be careful to synchronize data logger clocks. Also, one should be careful that adjacent anemometers do not interfere with one another's wind stream.

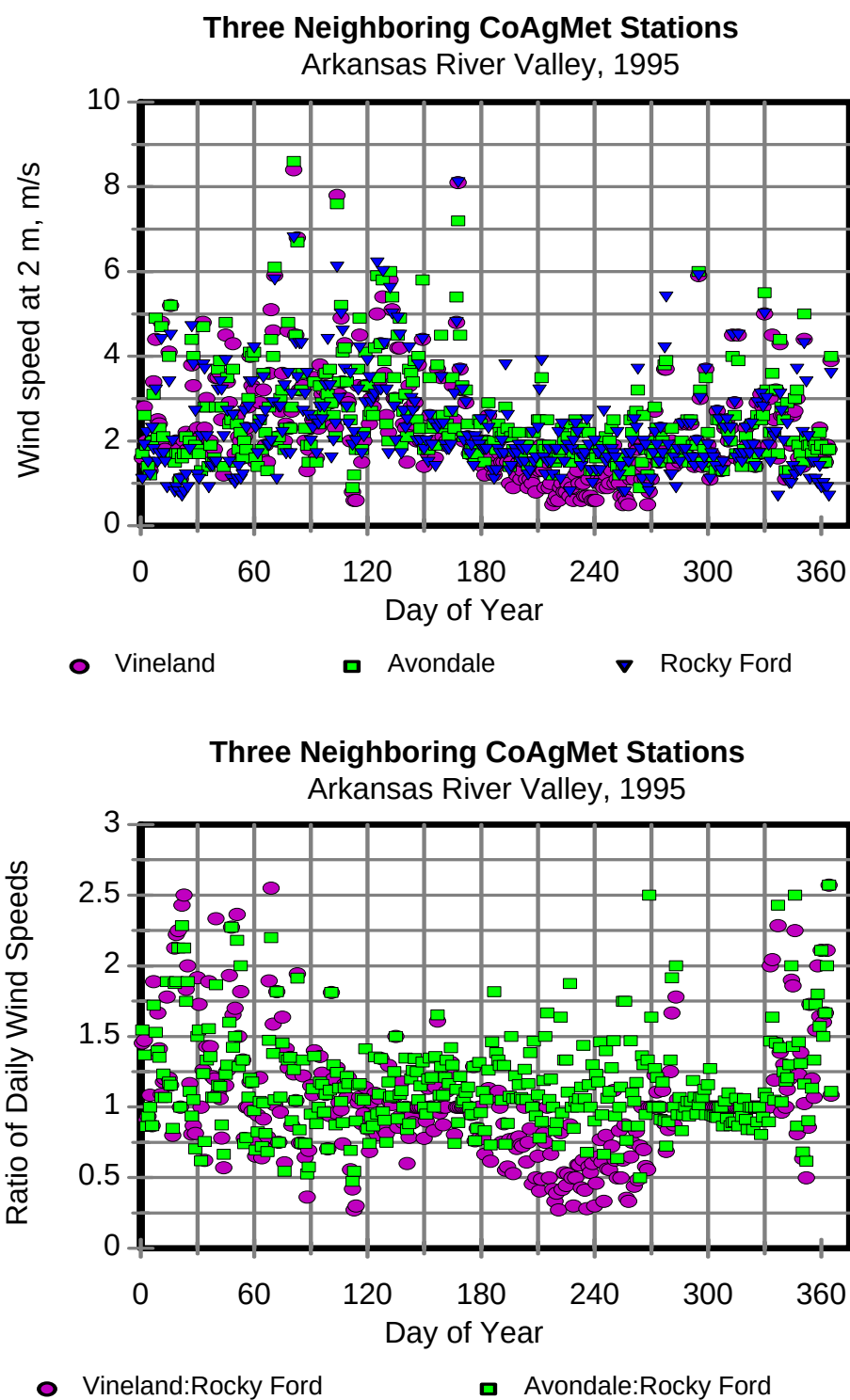


Figure D-12 Daily mean wind speeds recorded at three neighboring AWS stations in SE Colorado during 1995 (a) and ratios of wind speeds to those at Rocky Ford for the same stations (b).

APPENDIX E

ESTIMATING MISSING CLIMATIC DATA

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INTRODUCTION

The calculation of reference evapotranspiration with the standardized ASCE Penman-Monteith reference ET equation requires air temperature, vapor pressure, radiation, and wind speed data. The climate data should reflect the environment within the area for which an estimate of ET is required. If some of the required weather data are missing or do not accurately represent an irrigated site/region or are erroneous, then it may be possible that data can be estimated in order to apply the equation. The quality of calculated reference ET values depend on the quality and completeness of weather data. If the estimated data for missing periods are reasonably representative of a site within an irrigated area, then it is likely that the reference ET values from the standardized equation calculated with these data will be more reliable than reference ET estimates made using other more empirical ET methods. This appendix provides procedures for estimating solar radiation, vapor pressure, and wind speed data when they are missing or of questionable quality. Users should employ some type of “flagging” procedure to clearly identify data that have been estimated.

MINIMUM DATA REQUIREMENTS

Many of the suggested procedures for estimating missing data rely upon measured maximum and minimum air temperatures. Daily maximum and minimum air temperature, or at the very least, daily mean air temperatures are considered to be the absolute minimum data requirements necessary to apply the standardized Penman-Monteith method. In situations where solar radiation, humidity and wind speed data are available, but air temperature data are missing, temperature may be estimated from a nearby weather station site using some form of regression or interpolation/extrapolation procedure. Estimated temperature data should not be used at a site if the temperature data are subsequently used to estimate humidity and solar radiation data, as the resulting ET_{ref} would essentially have been calculated using no local data.

ESTIMATING MISSING HUMIDITY DATA

Where daily humidity data are missing or are of questionable quality, vapor pressure, e_a , can be estimated for the reference environment by assuming that dew-point temperature (T_{dew}) is near the daily minimum air temperature (T_{min}):

$$T_{\text{dew}} = T_{\text{min}} - K_o \quad (\text{E.1})$$

where K_o is approximately 2 to 4 °C in dry (semiarid and arid) climates and K_o is approximately 0 °C in humid to subhumid climates. Background on this relationship is discussed in Appendix D and an illustration of the trend for close proximity between T_{dew} and T_{min} is provided. Further discussion and caveats of this relationship are given in Allen (1996) and Allen et al., (1998).

An alternative to applying Eq. E.1 is to assume that relative humidity, RH, approaches 90 to 100% during early morning hours (before sunrise) over well-watered (i.e. reference) settings (as illustrated in Figure D-2b), so that the assumption that $\text{RH}_{\text{max}} \sim 90\%$ or $\text{RH}_{\text{max}} \sim 100\%$ can be employed. Daily vapor pressure is then calculated using the estimated RH_{max} and measured T_{min} in Eq. 12 of the text.

When humidity data are available from a nearby station, for example within 100 km, the user may elect to predict T_{dew} for a site having no humidity data or having faulty data using Eq. D.8 of Appendix D. This relationship presumes that differences between T_{dew} and T_{min} are similar between stations. Similar results and estimates of humidity can be obtained by transferring RH measurements between locations and calculating e_a using the transferred RH data and local air temperature (using Eq. 7 and 11-13 or Eq. 37 and 41 in the text). It is recommended that similarity in relationships between T_{dew} and T_{min} or in RH be confirmed using temporary measurement of humidity or by analysis of data from adjacent stations.

By definition, reference ET_{OS} , or ET_{RS} , is ET from an extensive surface of well-watered vegetation. Therefore, when humidity data are available from only a site that is known to deviate substantially from a reference environment, then use of “adjusted” dew-point temperature in the standardized PM equation may produce more reliable and representative reference ET than those obtained using the original humidity data from the non-reference site. Further information and recommendations on coping with impacts of weather station environment are given in Appendix D. The user should “flag” any estimated humidity data and describe the procedures that were used.

ESTIMATING MISSING RADIATION DATA

Solar Radiation Data Derived From Observed Sunshine Hours

If observed hours of sunshine are measured, solar radiation for 24-hour and longer time periods can be calculated using the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (E.2)$$

where

- R_s = solar or shortwave radiation [$\text{MJ m}^{-2} \text{ day}^{-1}$],
- n = actual duration of sunshine [hour],
- N = maximum possible duration of sunshine or daylight hours [hour],
- n/N = relative sunshine duration [-],
- R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{ day}^{-1}$] (Eq. 21 to 29 in the text),
- a_s = constant expressing the fraction of extraterrestrial radiation reaching the earth’s surface on overcast days (when $n = 0$),
- b_s = constant expressing the additional fraction of extraterrestrial radiation reaching the earth’s surface on a clear day,
- $a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth’s surface on a clear day (when $n = N$).

R_s is expressed in Eq. E.2 in $\text{MJ m}^{-2} \text{ day}^{-1}$ for R_a in $\text{MJ m}^{-2} \text{ day}^{-1}$. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month),

the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ from FAO-24 and FAO-56 are recommended.

The potential daylight hours, N , are given by:

$$N = \frac{24}{\pi} \omega_s \quad (\text{E.3})$$

where ω_s is the sunset hour angle in radians and is calculated using Eq. 27 or 28 in the text.

Solar Radiation Data From a Nearby Weather Station

For 24-hour and longer time periods, solar radiation can be relatively similar over large areas. Similarity in solar radiation depends on (i) the size of the region; (ii) the air masses governing rainfall and cloudiness being nearly identical within the region; and (iii) the physiography of the region being nearly homogenous. Differences in relief strongly influence the movement of air masses and development of cloud systems, so that these should be negligible if radiation data are to be transferred between locations.

Generally, daily calculations of reference ET using estimated radiation data are justified when utilized as a sum or as an average over a multiple-day period so that differences due to frontal activity tend to average out. This is the case for the computation of total evapotranspiration demand between successive irrigations or when planning irrigation schedules. Under these conditions, the relative error for one day may be compensated by an error for another day within the time period. Daily ET estimates should not be utilized as true daily estimates but used only to compute averages over the period under consideration.

Solar Radiation Data Derived From Air Temperature

Solar radiation can be estimated based on an empirical equation derived using the difference between maximum and minimum air temperature and extraterrestrial solar

radiation. The difference between the maximum and minimum air temperature is related to the degree of cloud cover at a location. Clear-sky conditions result in higher air temperatures during the day (i.e., $T_{\max}$) than under cloudy conditions because the atmosphere is transparent to incoming solar radiation. Clear-sky conditions result in relatively lower air temperatures during nighttime (i.e., $T_{\min}$) than under cloudy conditions because less outgoing long-wave radiation is absorbed and reemitted by the atmosphere. On the other hand, under overcast conditions, $T_{\max}$ is often lower than for clear days because a significant portion of the incoming solar radiation never reaches the earth's surface and is absorbed and reflected by the clouds. Similarly, $T_{\min}$ will be relatively higher because cloud cover acts as an absorbing and reemitting blanket and therefore decreases the net outgoing long-wave radiation. Therefore, the difference between the maximum and minimum air temperature ($T_{\max} - T_{\min}$) can be used as an indicator of the fraction of extraterrestrial radiation that reaches the earth's surface. This principle has been utilized by Hargreaves and Samani (1982) to develop estimates of ET_0 using only air temperature data.

The Hargreaves-Samani style of radiation prediction formula has the form:

$$R_s = k_{Rs} \sqrt{(T_{\max} - T_{\min})} R_a \quad (E.4)$$

where

- R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
- $T_{\max}$ = maximum air temperature [$^{\circ}\text{C}$],
- $T_{\min}$ = minimum air temperature [$^{\circ}\text{C}$],
- k_{Rs} = adjustment coefficient (0.16 .. 0.19) [$^{\circ}\text{C}^{-0.5}$].

The adjustment coefficient k_{Rs} is empirical and differs for 'interior' or 'coastal' regions¹:

¹ The values presented here for k_{Rs} are based on work by Hargreaves and Samani (1982) and Allen (1995) and were reported in FAO-56.

- for ‘interior’ locations, defined as where the local land mass dominates and air masses are not strongly influenced by a large water body, $k_{RS} \cong 0.16$;
- for ‘coastal’ locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, $k_{RS} \cong 0.19$.

R_s predicted by Eq. E.4 should be limited to $\leq R_{s0}$ which is the R_s for a cloud-free day. The temperature difference method is recommended for locations where it is not appropriate to import radiation data from a regional station, either because homogeneous climate conditions do not occur, or because data for the region are lacking. For island conditions, the methodology is not appropriate due to moderating effects of the surrounding water body. Allen (1997) provides examples for applying Eq. E.4 to predict daily and monthly values for solar radiation and procedures for site specific auto-calibration of k_{RS} .

MISSING WIND SPEED DATA

Wind Speed Data From a Nearby Weather Station

Extrapolating wind speed data from a nearby agricultural weather station, as for radiation data, relies on the assumption that the airflow is relatively similar within a relatively ‘homogeneous’ region. There is generally relatively large variation in wind speed through the course of a day, which can translate into substantial differences in concurrent measurements of wind speed at two locations. However, when averaged over times periods of one day or longer, differences between locations become smaller.

Data from a weather station may be extrapolated to a nearby location where ET_{ref} is to be predicted if the governing air masses are of the same origin and where the same weather frontal systems govern the regional air flow. The surrounding relief of the two locations should be similar. In areas having large differences in relief, density-induced “drainage” of air and shielding and direction of air movement by relief can

cause substantial differences in observed wind speed over relatively short distances. Where short periods of wind data are available for the location, ratios of wind speed between two locations can be established and used to estimate wind data for the data-short location.

Wind speed data from airports in the U.S. typically are measured at a height of 10 m. In arid and semiarid areas, the airport anemometer is often surrounded by non-irrigated, short grass. Measured wind speed adjusted from a height of 10 m to 2 m using the logarithmic wind profile will typically exceed the wind speed over an irrigated area during the growing season because of large differences in vegetation roughness and the damping effect caused by the heat sink as water evaporates.

When extrapolating wind speed data from another station, trends in other meteorological parameters and relief should be compared. Strong winds are often associated with low relative humidity and light winds are common with high relative humidity. Thus, trends in variation of daily maximum and minimum relative humidity should be similar in both locations. In mountainous areas, data should not be extrapolated from the nearest station but from nearby stations with similar elevation, surrounding vegetation, and exposure to the dominant winds. The pairing of stations may vary from one season to another, depending on the dominant winds.

Empirical Estimates of Monthly Wind Speed

The variation in average wind speed between monthly periods is often relatively small and fluctuates around average values. Therefore, in situations of no, or faulty, wind speed data, monthly values of wind speed may be estimated based on general information available for the regional climate, taking seasonal changes into account. Or, if regional information is unavailable, general values for wind speed suggested in Table E-1 can be employed. Caution should be exercised.

TABLE E-1**General classes of wind speed data (taken from FAO-56)**

Description	mean wind speed at 2 m
light wind	... $\leq 1.0 \text{ m s}^{-1}$
light to moderate wind	1–3 m s^{-1}
moderate to strong wind	3–5 m s^{-1}
strong wind	... $\geq 5.0 \text{ m s}^{-1}$

A preliminary value of 2 m s^{-1} can be used as a first estimate of 2-m wind speed for an agricultural setting. This value is based on an average computed from over 2 000 weather stations around the globe (Allen et al., 1998).

In general, estimated wind speed at 2 m should be limited to about $u_2 \geq 0.5 \text{ m s}^{-1}$ when used to calculate standardized reference ET. This lower limit accounts for the influence of boundary layer instability caused by buoyancy of air in promoting exchange of heat and vapor at the surface when air is calm. This effect occurs when the wind speed is small and buoyancy of warm air induces air exchange at the surface.

As with humidity and solar radiation data, estimated wind speed data should be flagged in the data set and the user should describe procedures that were used to make the estimates.

MISSING MAXIMUM OR MINIMUM AIR TEMPERATURE DATA

Some weather data sets contain daily mean air temperature summaries, but do not contain values for maximum and minimum air temperature. Daily maximum and minimum air temperatures are used in the standardized reference ET procedure for calculating net radiation and the saturation vapor pressure. During the process of calculating daily ET_{ref} using data sets where T_{max} and T_{min} are not available, but

where daily mean air temperature and solar radiation data are available, accuracy of calculations for net radiation and saturation vapor pressure can be improved by estimating values for $T_{\max}$ and/or $T_{\min}$ by inverting Eq. E.4 and solving for $T_{\max} - T_{\min}$:

$$(T_{\max} - T_{\min}) = \left(\frac{R_s}{k_{Rs} R_a} \right)^2 \quad (\text{E.5a})$$

where

- R_s = measured solar radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
- R_a = extraterrestrial radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
- $T_{\max}$ = maximum air temperature [$^{\circ}\text{C}$],
- $T_{\min}$ = minimum air temperature [$^{\circ}\text{C}$],
- k_{Rs} = adjustment coefficient, defined previously [$^{\circ}\text{C}^{-0.5}$].

Values for $T_{\max}$ and/or $T_{\min}$ can be estimated using $T_{\max} - T_{\min}$ from E.5a as:

$$T_{\max} = T_{\text{mean}} + \frac{(T_{\max} - T_{\min})}{2} \quad (\text{E.5b})$$

$$T_{\min} = T_{\text{mean}} - \frac{(T_{\max} - T_{\min})}{2} \quad (\text{E.5c})$$

The estimated values for $T_{\max}$ and $T_{\min}$ should be clearly identified in the data set as estimated values.

APPENDIX F

SUMMARY OF

REFERENCE EVAPOTRANSPIRATION COMPARISONS

BY THE

TASK COMMITTEE

The following tables summarize intercomparisons between various reference evapotranspiration equations that were used by the Task Committee in formulating recommendations for the standardization. The summaries include comparisons for hourly calculation timesteps (summed to daily totals and labeled as “sum of hourly”) and for daily calculation timesteps. Table F-1 summarizes weather station location information for the sites and years investigated. Table F-2 summarizes statistics for ratios of each method against the ASCE-PM (full-form ASCE Penman-Monteith method) where the ASCE-PM method, applied daily, served as the comparison basis in all cases. The methods summarized in Table F-2 are the FAO-56 Penman-Monteith, the Standardized ASCE-PM, the 1963 Penman, the Hargreaves, and the 1982 Kimberly Penman. These methods are defined in Appendix B.

Tables F-3 to F-10 summarize ratios of computations by the various reference equations to computations by the daily ASCE-PM method (as the comparison basis) by location. Ratios are summarized for sum-of-hourly compared to daily timesteps and for daily timesteps compared to daily timesteps. The tables also compare “within method” comparisons of sum-of-hourly to daily calculations. Comparisons are given for both reference types (short and tall), where specific methods or coefficients applied vary with reference surface type. The reference methods summarized in Tables F-3 to F-10 include various forms of the ASCE Penman-Monteith method and applications of the ASCE Penman-Monteith equation using different coefficients or parameter calculations. These forms and variations are defined in Appendix B, pages 1-4. It is noted that in Tables F-6 and F-10, sum-of-hour calculations are compared against sum-of-hour calculations by the ASCE-PM, applied hourly using surface resistance values from ASCE manual 70 (70 s m^{-1} for ET_0 and 45 s m^{-1} for ET_p). The Task committee, however, recommends the use of smaller resistance values for hourly or shorter time steps during daytime to provide predictions that are commensurate with daily calculation time steps, as is done for the standardized method. The smaller values for resistance increase the sum-of-hour predictions by the ASCE-PM method by about 5% as shown in Tables F-4 and F-8.

Table F-1. Summary of weather station sites used in the study (listed from east to west longitude).

Site- Year Index	State	SITE	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Mean Annual Precip.	Years (19--)	Peak-Month Mean ASCE-PM ET _o (mm d ⁻¹)	
								Year 1	Year 2
1	NY	Willsboro	73.38	44.38	43	760	98	3.79	
2, 3	NY	Valatie	73.68	42.43	76	910	97 98	3.90	3.89
4, 5	NY	Ithaca	76.45	42.45	123	910	97 98	3.82	3.88
6	SC	Florence	79.81	34.24	40	1120	86	5.91	
7	FL	Fort Pierce	80.44	27.57	7	1422	99	4.68	
8, 9	FL	Lake Alfred	81.89	28.03	46	1270	98 99	5.66	4.88
10, 11	GA	Blairsville	83.93	34.84	584	1307	97 98	4.48	4.63
12, 13	GA	Griffin	84.28	33.26	282	1447	97 98	5.05	5.99
14, 15	GA	Attapulgus	84.49	30.76	37	1460	97 98	4.54	6.29
16	IL	Bondville	88.37	40.00	213	1008	99	5.18	
17	IL	Belleville	89.88	38.52	133	974	99	5.53	
18	IL	Monmouth	90.73	40.92	229	942	99	5.23	
19, 20	OK	Wister	94.68	34.98	143	1188	97 98	5.13	6.03
21, 22	NE	Mead	96.30	41.08	366	743	97 98	5.15	4.57
23, 24	OK	Marena	97.21	36.06	331	889	97 98	5.63	6.84
25, 26	NE	Clay Center	98.08	40.31	552	685	97 98	5.46	5.15
27, 28	OK	Apache	98.29	34.91	440	757	97 98	6.59	8.60
29, 30	NE	Champion	101.43	40.22	1029	482	97 98	6.64	6.18
31, 32	OK	Goodwell	101.60	36.60	996	447	97 98	8.56	9.68
33, 34	TX	Bushland	102.05	35.11	1170	505	97 98	7.36	9.34
35, 36	TX	Dalhart	102.32	36.20	1228	467	97 98	6.44	7.30
37, 38	CO	Ovid	102.45	40.97	1089	448	98 99	5.50	6.08
39, 40	CO	Rocky Ford	104.00	38.00	1274	279	97 99	7.08	8.02
41, 42	CO	Wiggins	104.06	40.31	1367	353	97 98	5.88	5.93
43	CO	Fort Collins	105.00	40.60	1527	383	95	5.58	
44, 45	CO	Loveland	105.11	40.40	1540	406	97 98	5.59	5.30
46, 47	CO	Center	106	38	2348	178	97 99	5.62	5.96
48, 49	CO	Colton	106	39	2743	279	82 83	4.65	4.69
50, 51	CO	Portis	106	39	2895	279	82 83	4.38	4.30
52, 53	CO	Fruita	109	39	1377	228	97 99	7.87	6.75
54, 55	CO	Yellow Jacket	109	37	2252	406	97 99	5.92	5.96
56, 57	AZ	Tucson	110.94	32.28	713	300	97 98	8.54	8.21
58, 59	ID	Ashton	111.47	44.03	1615	430	97 98	4.96	5.70
60, 61	UT	Logan	111.80	41.60	1350	433	89 90	6.21	5.77
62, 63	AZ	Phoenix Encanto	112.10	33.48	335	175	97 98	7.49	7.60
64, 65	MT	St. Ignatius	114.10	47.31	896	360	97 98	4.52	5.27
66, 67	MT	Creston	114.13	48.19	899	390	97 98	4.16	4.73
68, 69	MT	Ronan	114.28	47.54	927	380	97 98	4.31	4.70
70, 71	ID	Twin Falls	114.35	42.61	1195	222	97 98	5.69	6.44
72, 73	ID	Parma	116.93	43.80	703	237	97 98	5.66	6.10
74	WA	Paterson	119.49	45.94	109	152	98	6.65	
75	CA	Fresno	119.70	36.80	103	269	98	7.11	
76	WA	Gramling	119.73	46.29	386	178	98	7.42	
77	WA	Roza	119.73	46.29	343	178	98	5.96	
78	CA	Santa Maria	120.40	35.00	82	314	98	4.42	
79	CA	Davis	121.80	38.50	18	461	98	6.71	
80	WA	Puyallup	122.30	47.10	61	1016	98	3.48	
81	WA	Grayland	124.00	46.78	2	2032	98	2.78	
82		Haga	124.50	42.50	9	1778	99	3.32	

Table F-2. Statistical summary of the comparisons between various reference ET methods, using growing-season results from 82 site-years of daily and 76 site-years of hourly data.

METHOD	RATIO				RMSD (mm d ⁻¹)				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	
Daily ET _o vs. Daily ASCE-PM ET _o									
FAO56-PM	1.004	0.982	0.994	0.006	0.155	0.005	0.039	0.035	0.8
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
1963 Penman	1.201	0.995	1.072	0.036	0.772	0.167	0.430	0.092	10.4
Hargreaves	1.430	0.791	1.057	0.127	2.235	0.439	0.927	0.308	22.2
Daily ET _r vs. Daily ASCE-PM ET _r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
1982 Kim Penman	1.118	0.892	0.988	0.043	1.706	0.169	0.662	0.267	12.2
Sum-of-Hourly ET _o vs. Daily ET _o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.043	0.901	0.958	0.032	0.829	0.197	0.365	0.137	8.5
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
1963 Penman	1.182	0.955	1.047	0.036	1.373	0.185	0.429	0.179	8.9
Sum-of-Hourly ET _r vs. Daily ET _r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
1982 Kim Penman	1.054	0.910	0.976	0.032	1.008	0.322	0.539	0.071	10.1
Sum-of-Hourly ET _o vs. Daily ASCE-PM ET _o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.041	0.896	0.952	0.034	0.889	0.200	0.389	0.152	8.9
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
1963 Penman	1.225	1.039	1.124	0.043	1.186	0.326	0.684	0.152	16.3
CIMIS Penman	1.220	0.969	1.080	0.047	0.966	0.290	0.579	0.137	13.9
Sum-of-Hourly ET _r vs. Daily ASCE-PM ET _r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41
1982 Kim Penman	1.138	0.855	0.963	0.059	1.923	0.416	0.759	0.304	13.8

ASCE Standardized Reference Evapotranspiration Equation

Table F-3. Ratio of method Daily ET_o to Daily ASCE-PM ET_o

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ET _o (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON												
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ET _{os} (YR)	F56 PM (YR)	F24 Pen (YR)	1963 Pen (YR)	1985 Harg (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ET _{os} (GS)	F56 PM (GS)	F24 Pen (GS)	1963 Pen (GS)	1985 Harg (GS)	
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	1.000	0.999	0.995	0.994	0.986	0.986	0.986	1.193	1.119	1.019	1.000	0.999	0.994	0.991	0.986	0.986	0.985	1.184	1.104	0.998	
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	1.000	0.999	0.995	0.994	0.988	0.988	0.987	1.206	1.105	0.984	1.000	0.999	0.994	0.989	0.987	0.987	0.987	1.204	1.098	0.962	
AZ	Tucson	1997	713	32.28	110.94	300	8.54	1.000	0.999	0.996	0.991	0.986	0.986	0.985	1.153	1.025	0.902	1.000	0.999	0.995	0.988	0.986	0.986	0.985	1.166	1.034	0.902	
AZ	Tucson	1998	713	32.28	110.94	300	8.21	1.000	0.999	0.997	0.991	0.987	0.987	0.987	1.188	1.031	0.944	1.000	0.999	0.996	0.987	0.987	0.987	0.986	1.211	1.045	0.947	
CA	Davis	1998	18	38.50	121.80	461	6.71	1.000	0.998	0.998	0.984	0.989	0.983	0.989	1.217	1.064	1.033	1.000	0.998	0.998	0.985	0.989	0.989	0.988	1.242	1.062	1.003	
CA	Fresno	1998	103	36.80	119.70	269	7.11	1.000	0.999	0.998	0.982	0.990	0.990	0.989	1.217	1.064	1.066	1.000	0.999	0.997	0.980	0.989	0.989	0.989	1.262	1.067	1.015	
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	1.000	0.998	1.000	0.982	0.993	0.993	0.993	1.177	1.077	1.143	1.000	0.998	1.000	0.977	0.995	0.995	0.995	1.215	1.098	1.158	
CO	Center	1997	2348	38.00	106.00	178	5.62											1.000	0.998	1.001	0.970	1.002	1.002	1.001	1.207	1.062	1.000	
CO	Center	1999	2348	38.00	106.00	178	5.96											1.000	0.998	1.001	0.975	1.001	1.001	1.001	1.224	1.066	0.925	
CO	Colton	1982	2743	39.00	106.00	279	4.65											1.000	0.998	1.003	0.958	1.004	1.004	1.003	1.171	1.051	1.075	
CO	Colton	1983	2743	39.00	106.00	279	4.69											1.000	0.998	1.003	0.965	1.005	1.005	1.003	1.164	1.027	1.048	
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58	1.000	0.998	1.000	0.974	0.991	0.991	0.986	1.109	1.013	1.032	1.000	0.998	1.000	0.967	0.992	0.992	0.989	1.159	1.047	1.115	
CO	Fruita	1997	1274	38.00	104.00	228	7.83											1.000	0.998	0.998	0.981	1.001	1.001	0.999	1.211	1.038	0.922	
CO	Fruita	1999	1274	38.00	104.00	228	6.75											1.000	0.999	0.999	0.974	1.002	1.002	1.000	1.183	1.043	1.059	
CO	Loveland	1997	1540	40.40	105.11	406	5.59	1.000	0.999	1.001	0.969	0.996	0.996	0.995	1.161	1.073	1.063	1.000	0.999	1.000	0.965	0.996	0.996	0.995	1.175	1.079	1.092	
CO	Loveland	1998	1540	40.40	105.11	406	5.30	1.000	0.999	1.001	0.970	0.995	0.995	0.994	1.138	1.070	1.041	1.000	0.999	1.000	0.965	0.995	0.995	0.994	1.158	1.081	1.083	
CO	Ovid	1998	1089	40.97	102.45	448	5.5	1.000	0.998	0.999	0.979	0.978	0.978	0.978	1.144	1.007	0.942	1.000	0.998	0.998	0.976	0.982	0.982	0.982	1.223	1.051	0.997	
CO	Ovid	1999	1089	40.97	102.45	448	6.08	1.000	0.998	0.999	0.978	0.978	0.978	0.978	1.136	0.999	0.931	1.000	0.998	0.999	0.973	0.982	0.982	0.982	1.191	1.042	1.007	
CO	Portis	1982	2895	39	106	279	4.03											1.000	0.998	1.003	0.957	1.006	1.006	0.998	1.196	1.075	1.028	
CO	Portis	1983	2895	39	106	279	4.21											1.000	0.998	1.003	0.961	1.006	1.006	0.999	1.206	1.084	1.039	
CO	Rocky Ford	1997	1274	38	104	279	7.08											1.000	0.999	0.998	0.978	1.000	1.000	0.998	1.098	1.016	0.960	
CO	Rocky Ford	1999	1274	38	104	279	8.02											1.000	0.999	0.999	0.973	0.999	0.999	0.998	1.059	1.044	0.918	
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	1.000	0.998	1.000	0.977	0.980	0.980	0.980	1.134	1.004	0.957	1.000	0.998	0.999	0.974	0.983	0.983	0.982	1.171	1.025	1.002	
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	1.000	0.998	1.000	0.979	0.980	0.980	0.980	1.138	0.998	0.951	1.000	0.998	0.999	0.976	0.983	0.983	0.982	1.191	1.028	0.991	
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94											1.000	0.999	1.000	0.969	0.997	0.997	0.997	0.994	1.156	1.080	0.993
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01											1.000	0.998	1.000	0.971	0.997	0.997	0.997	0.994	1.171	1.089	0.907
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	1.000	0.999	0.996	0.984	0.996	0.996	0.997	1.145	1.043	1.071	1.000	0.999	0.995	0.981	0.995	0.995	0.996	1.167	1.047	1.069	
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	1.000	0.999	0.996	0.984	0.997	0.997	0.997	1.150	1.041	1.094	1.000	0.999	0.996	0.982	0.996	0.996	0.997	1.162	1.046	1.102	
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	1.000	0.998	0.996	0.987	0.997	0.997	0.997	1.180	1.078	1.056	1.000	0.999	0.996	0.982	0.996	0.996	0.997	1.195	1.083	1.077	
GA	Attapulugus	1997	37	30.761	84.4853	1460	4.54	1.000	0.999	0.998	0.974	0.999	0.999	0.998	1.197	1.104	1.261	1.000	0.999	0.997	0.975	0.998	0.998	0.998	1.213	1.108	1.266	
GA	Attapulugus	1998	37	30.761	84.4853	1460	6.29	1.000	0.999	0.997	0.971	0.998	0.998	0.998	1.202	1.100	1.295	1.000	0.999	0.996	0.973	0.996	0.996	0.997	1.221	1.098	1.264	
GA	Blairsville	1997	584.3	34.839	83.928	1307	4.48	1.000	0.999	1.001	0.955	1.004	1.004	1.001	1.196	1.126	1.309	1.000	0.999	1.001	0.961	1.003	1.003	1.001	1.215	1.131	1.326	
GA	Blairsville	1998	584.3	34.839	83.928	1307	4.63	1.000	0.999	1.000	0.960	1.002	1.002	1.000	1.188	1.092	1.241	1.000	0.999	0.999	0.965	1.001	1.001	0.999	1.209	1.096	1.242	
GA	Griffin	1997	281.9	33.262	84.284	1447	5.05	1.000	0.998	0.999	0.972	1.001	1.001	0.999	1.213	1.091	1.092	1.000	0.999	0.998	0.975	0.999	0.999	0.998	1.231	1.095	1.107	
GA	Griffin	1998	281.9	33.262	84.284	1447	5.99	1.000	0.999	0.998	0.973	0.998	0.998	0.998	1.228	1.103	1.157	1.000	0.999	0.997	0.974	0.998	0.998	0.998	1.239	1.103	1.151	
ID	Ashton	1997	1615	44.03	111.47	430	4.96	1.000	0.998	1.001	0.967	0.998	0.998	0.997	1.196	1.078	0.929	1.000	0.998	1.001	0.966	0.998	0.998	0.997	1.208	1.071	0.946	
ID	Ashton	1998	1615	44.03	111.47	430	5.70	1.000	0.998	1.001	0.967	0.998	0.998	0.997	1.167	1.053	0.966	1.000	0.998	1.001	0.970	0.998	0.998	0.997	1.183	1.043	0.971	
ID	Parma	1997	703	43.80	116.93	237	5.66	1.000	0.999	1.000	0.977	0.997	0.997	0.997	1.181	1.074	1.037	1.000	0.999	1.000	0.977	0.997	0.997	0.997	1.195	1.075	1.036	
ID	Parma	1998	703	43.80	116.93	237	6.10	1.000	0.999	1.000	0.972	0.997	0.997	0.997	1.187	1.080	1.054	1.000	0.999	1.000	0.976	0.997	0.997	0.997	1.207	1.082	1.069	
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	1.000	0.998	1.000	0.977	0.996	0.996	0.996	1.184	1.055	0.899	1.000	0.998	0.999	0.975	0.996	0.996	0.996	1.208	1.057	0.927	
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	1.000	0.998	1.000	0.970	0.996	0.996	0.996	1.175	1.056	0.922	1.000	0.998	0.999	0.971	0.997	0.997	0.996	1.200	1.057	0.952	
IL	Belleville	1999	133	38.52	89.88	974	5.53	1.000	0.999	0.999	0.980	1.000																

ASCE Standardized Reference Evapotranspiration Equation

Table F-3. Ratio of method Daily ETo to Daily ASCE-PM ETo, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	YEARLY SUMMARY										GROWING SEASON									
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	EToS (YR)	F56 PM (YR)	F24 Pen (YR)	1963 Pen (YR)	1985 Harg (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	EToS (GS)	F56 PM (GS)	F24 Pen (GS)	1963 Pen (GS)	1985 Harg (GS)
IL	Monmouth	1999	229	40.92	90.73	942	5.23	1.000	0.998	0.999	0.979	1.001	1.001	0.998	1.206	1.085	0.981	1.000	0.998	0.998	0.969	0.999	0.999	0.998	1.245	1.106	1.054
MT	Creston	1997	899	48.19	114.13	390	4.16	1.000	0.999	1.002	0.948	1.001	1.001	0.999	1.170	1.107	1.090	1.000	0.999	1.001	0.955	1.000	1.000	0.999	1.188	1.098	1.108
MT	Creston	1998	899	48.19	114.13	390	4.73	1.000	0.999	1.001	0.955	1.000	1.000	0.998	1.155	1.078	1.109	1.000	0.999	1.001	0.965	0.999	0.999	0.998	1.176	1.072	1.138
MT	Ronan	1997	927	47.54	114.28	380	4.31	1.000	0.999	1.002	0.948	1.001	1.001	0.999	1.178	1.122	1.096	1.000	0.999	1.001	0.955	1.001	1.001	1.000	1.193	1.113	1.117
MT	Ronan	1998	927	47.54	114.28	380	4.70	1.000	0.999	1.001	0.952	1.000	1.000	0.999	1.174	1.117	1.146	1.000	0.999	1.001	0.961	1.000	1.000	0.999	1.195	1.114	1.175
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	1.000	0.999	1.002	0.951	1.000	1.000	0.999	1.173	1.097	1.058	1.000	0.999	1.001	0.959	1.000	1.000	0.999	1.196	1.094	1.080
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	1.000	0.999	1.001	0.958	0.998	0.998	0.997	1.154	1.066	1.004	1.000	0.999	1.000	0.967	0.998	0.998	0.997	1.173	1.060	1.036
NE	Champion	1997	1029	40.22	101.43	482	6.64	1.000	0.998	0.998	0.978	0.985	0.985	0.985	1.144	0.993	0.906	1.000	0.998	0.998	0.972	0.988	0.988	0.987	1.208	1.031	0.986
NE	Champion	1998	1029	40.22	101.43	482	6.18	1.000	0.998	0.999	0.973	0.986	0.986	0.986	1.110	0.978	0.929	1.000	0.998	0.998	0.973	0.987	0.987	0.987	1.179	1.012	0.980
NE	Clay Center	1997	552	40.31	98.08	685	5.46	1.000	0.998	0.998	0.971	0.989	0.989	0.988	1.157	1.035	1.008	1.000	0.998	0.998	0.967	0.991	0.991	0.990	1.229	1.075	1.081
NE	Clay Center	1998	552	40.31	98.08	685	5.15	1.000	0.998	0.998	0.967	0.989	0.989	0.989	1.122	1.030	1.053	1.000	0.998	0.997	0.968	0.990	0.990	0.990	1.184	1.055	1.091
NE	Mead	1997	366	41.08	96.30	743	5.15	1.000	0.998	0.998	0.968	0.989	0.989	0.989	1.165	1.056	1.080	1.000	0.998	0.998	0.966	0.990	0.990	0.990	1.209	1.075	1.130
NE	Mead	1998	366	41.08	96.30	743	4.57	1.000	0.998	0.998	0.967	0.990	0.990	0.989	1.129	1.047	1.094	1.000	0.998	0.997	0.967	0.991	0.991	0.991	1.180	1.068	1.125
NY	Ithaca	1997	123	42.45	76.45	914	3.9	1.000	0.998	1.000	0.944	1.005	1.005	0.999	1.176	1.117	1.221	1.000	0.998	1.000	0.953	1.003	1.003	1.000	1.201	1.117	1.259
NY	Ithaca	1998	123	42.45	76.45	914	3.89	1.000	0.998	1.000	0.948	1.003	1.003	0.999	1.162	1.107	1.223	1.000	0.998	1.000	0.955	1.002	1.002	0.999	1.192	1.113	1.263
NY	Valatie	1997	76	42.43	73.68	914	3.82	1.000	0.999	1.001	0.939	1.005	1.005	1.001	1.185	1.153	1.329	1.000	0.999	1.001	0.947	1.003	1.003	1.001	1.198	1.148	1.356
NY	Valatie	1998	76	42.43	73.68	914	3.88	1.000	0.999	1.001	0.944	1.004	1.004	1.001	1.160	1.129	1.328	1.000	0.999	1.000	0.951	1.002	1.002	1.000	1.172	1.121	1.336
NY	Willsboro	1998	43	44.38	73.38	762	3.79	1.000	0.998	1.001	0.944	1.004	1.004	1.000	1.171	1.123	1.155	1.000	0.999	1.000	0.951	1.002	1.002	1.000	1.194	1.126	1.188
OK	Apache	1997	440	34.91	98.29	757	6.59	1.000	0.998	0.997	0.982	0.988	0.988	0.988	1.223	1.070	0.878	1.000	0.998	0.996	0.976	0.989	0.989	0.989	1.272	1.089	0.923
OK	Apache	1998	440	34.91	98.29	757	8.60	1.000	0.998	0.996	0.983	0.985	0.985	0.984	1.187	1.044	0.839	1.000	0.998	0.994	0.982	0.985	0.985	0.983	1.213	1.043	0.832
OK	Goodwell	1997	996	36.60	101.60	447	8.56	1.000	0.998	0.997	0.984	0.984	0.984	0.984	1.143	0.993	0.792	1.000	0.998	0.996	0.978	0.986	0.986	0.985	1.191	1.014	0.848
OK	Goodwell	1998	996	36.60	101.60	447	9.68	1.000	0.998	0.997	0.986	0.983	0.983	0.982	1.105	0.975	0.758	1.000	0.998	0.996	0.982	0.983	0.983	0.982	1.142	0.995	0.791
OK	Marena	1997	331	36.06	97.21	889	5.63	1.000	0.998	0.998	0.977	0.989	0.989	0.989	1.208	1.075	0.963	1.000	0.998	0.997	0.973	0.991	0.991	0.991	1.253	1.093	0.992
OK	Marena	1998	331	36.06	97.21	889	6.84	1.000	0.999	0.996	0.977	0.987	0.987	0.986	1.184	1.064	0.960	1.000	0.999	0.995	0.976	0.986	0.986	0.986	1.215	1.068	0.960
OK	Wister	1997	143	34.98	94.68	1188	5.13	1.000	0.999	0.999	0.965	0.994	0.994	0.993	1.181	1.105	1.249	1.000	0.999	0.997	0.966	0.994	0.994	0.994	1.203	1.104	1.231
OK	Wister	1998	143	34.98	94.68	1188	6.09	1.000	0.999	0.997	0.973	0.990	0.990	0.990	1.196	1.100	1.209	1.000	0.999	0.996	0.975	0.990	0.990	0.989	1.224	1.096	1.200
OR	Haga	1999	9	42.50	124.50	1778	3.32	1.000	1.000	1.004	0.933	1.008	1.008	1.004	1.058	1.063	1.125	1.000	1.000	1.004	0.948	1.007	1.007	1.004	1.062	1.043	1.051
SC	Florence	1986	40	34.24	79.81	1120	5.91	1.000	0.999	0.998	0.971	0.998	0.998	0.998	1.189	1.116	0.985	1.000	0.999	0.997	0.974	0.998	0.998	0.997	1.195	1.110	0.999
TX	Bushland	1997	1170	35.11	102.05	505	7.36	1.000	0.997	0.998	0.983	0.993	0.993	0.993	1.203	1.039	0.815	1.000	0.998	0.997	0.976	0.994	0.994	0.994	1.259	1.060	0.892
TX	Bushland	1998	1170	35.11	102.05	505	9.34	1.000	0.998	0.997	0.985	0.992	0.992	0.992	1.162	1.010	0.793	1.000	0.998	0.996	0.983	0.992	0.992	0.992	1.186	1.019	0.811
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	1.000	0.998	0.999	0.980	0.998	0.998	0.994	1.178	1.016	0.948	1.000	0.998	0.998	0.980	0.997	0.997	0.994	1.211	1.031	0.974
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	1.000	0.998	0.998	0.980	0.996	0.996	0.994	1.138	0.990	0.948	1.000	0.998	0.998	0.979	0.995	0.995	0.993	1.170	1.007	0.967
UT	Logan	1989	1350	41.60	111.80	433	6.21											1.000	0.999	1.000	0.974	0.997	0.997	0.996	1.189	1.029	1.102
UT	Logan	1990	1350	41.60	111.80	433	5.77											1.000	0.999	1.000	0.971	0.998	0.998	0.997	1.156	1.022	1.182
WA	Gramling	1998	386	46.29	119.73	178	7.42											1.000	0.998	0.997	0.980	0.988	0.988	0.987	1.197	1.045	0.878
WA	Grayland	1998	2	46.78	124.00	2032	2.78											1.000	0.998	1.001	0.957	1.003	1.003	1.000	1.213	1.201	1.166
WA	Paterson	1998	109	45.94	119.49	152	6.65											1.000	0.998	0.998	0.979	0.990	0.990	0.990	1.236	1.068	1.072
WA	Puyallup	1998	61	47.10	122.30	1016	3.48											1.000	0.999	1.001	0.943	0.999	0.999	0.998	1.151	1.119	1.430
WA	Roza	1998	343	46.29	119.73	178	5.96											1.000	0.999	0.999	0.978	0.991	0.991	0.991	1.233	1.083	1.048
	Average							1.000	0.998	0.999	0.971	0.994	0.994	0.993	1.171	1.065	1.041	1.000	0.999	0.999	0.971	0.995	0.995	0.994	1.195	1.072	1.057
	Minimum							1.000	0.997	0.995	0.933	0.978	0.978	0.978	1.058	0.975	0.758	1.000	0.998	0.994	0.943	0.982	0.982	0.982	1.059	0.995	0.791
	Maximum							1.000	1.000	1.004	0.994	1.008	1.008	1.004	1.228	1.153	1.329	1.000	1.000	1.004	0.991	1.007	1.007	1.004	1.272	1.201	1.430

ASCE Standardized Reference Evapotranspiration Equation

Table F-4. Ratio of Hourly Sum ETo to Daily ETo (within Method)

								YEARLY									GROWING SEASON								
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	1.005	1.033	1.031	1.028	1.003	1.042	1.031	1.003	1.069	0.992	1.018	1.015	1.013	0.990	1.027	1.016	0.990	1.052
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	0.994	1.027	1.024	1.021	0.993	1.034	1.025	0.993	1.059	0.984	1.013	1.011	1.009	0.982	1.020	1.012	0.982	1.042
AZ	Tucson	1997	713	32.28	110.94	300	8.54	0.988	1.020	1.017	1.012	0.987	1.041	1.019	0.987	1.073	0.992	1.021	1.018	1.015	0.991	1.042	1.019	0.991	1.057
AZ	Tucson	1998	713	32.28	110.94	300	8.21	0.980	1.016	1.013	1.009	0.979	1.032	1.015	0.979	1.069	0.986	1.020	1.017	1.015	0.984	1.035	1.018	0.984	1.052
CA	Davis	1998	18	38.50	121.80	461	6.71	0.938	0.998	0.995	0.997	0.938	1.014	0.997	0.938	1.047	0.940	0.997	0.994	0.994	0.939	1.007	0.996	0.940	1.042
CA	Fresno	1998	103	36.80	119.70	269	7.11	0.970	1.014	1.011	1.014	0.969	1.024	1.013	0.969	1.052	0.973	1.014	1.011	1.011	0.972	1.024	1.012	0.972	1.043
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	0.939	1.006	1.004	1.003	0.939	1.005	1.006	0.940	1.055	0.948	1.017	1.015	1.014	0.948	1.012	1.016	0.949	1.046
CO	Center	1997	2348	38.00	106.00	178	5.62										0.967	1.018	1.016	1.011	0.964	1.028	1.015	0.964	1.066
CO	Center	1999	2348	38.00	106.00	178	5.96										0.967	1.023	1.021	1.014	0.964	1.038	1.020	0.965	1.084
CO	Colton	1982	2743	39.00	106.00	279	4.65																		
CO	Colton	1983	2743	39.00	106.00	279	4.69																		
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58																		
CO	Fruita	1997	1274	38.00	104.00	228	7.83										0.985	1.033	1.029	1.012	0.978	1.031	1.026	0.977	1.107
CO	Fruita	1999	1274	38.00	104.00	228	6.75										0.995	1.034	1.031	1.014	0.989	1.033	1.028	0.991	1.102
CO	Loveland	1997	1540	40.40	105.11	406	5.59	0.995	1.027	1.024	1.021	0.993	1.041	1.025	0.993	1.087	0.987	1.016	1.014	1.010	0.985	1.026	1.014	0.985	1.057
CO	Loveland	1998	1540	40.40	105.11	406	5.30	0.992	1.024	1.021	1.019	0.990	1.039	1.022	0.991	1.082	0.989	1.021	1.018	1.016	0.987	1.029	1.019	0.987	1.055
CO	Ovid	1998	1089	40.97	102.45	448	5.5	0.930	0.984	0.981	0.981	0.933	1.008	0.987	0.933	1.088	0.956	1.009	1.006	1.006	0.957	1.024	1.010	0.958	1.053
CO	Ovid	1999	1089	40.97	102.45	448	6.08	0.918	0.976	0.973	0.972	0.922	1.000	0.979	0.922	1.088	0.946	1.003	1.001	1.002	0.947	1.017	1.004	0.947	1.042
CO	Portis	1982	2895	39	106	279	4.03																		
CO	Portis	1983	2895	39	106	279	4.21																		
CO	Rocky Ford	1997	1274	38	104	279	7.08										1.047	1.079	1.075	1.052	1.041	1.081	1.073	1.043	1.182
CO	Rocky Ford	1999	1274	38	104	279	8.02										1.032	1.060	1.057	1.039	1.028	1.064	1.055	1.037	1.142
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	0.950	0.995	0.993	0.988	0.954	1.021	1.000	0.954	1.104	0.956	0.999	0.997	0.992	0.959	1.019	1.002	0.959	1.074
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	0.947	0.996	0.993	0.990	0.951	1.015	1.000	0.951	1.103	0.961	1.007	1.004	1.001	0.962	1.020	1.009	0.963	1.071
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94										0.959	1.002	1.000	0.998	0.960	1.014	1.003	0.962	1.056
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01										0.968	1.019	1.017	1.014	0.965	1.016	1.016	0.967	1.063
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	0.899	0.944	0.941	0.943	0.895	0.942	0.940	0.896	0.998	0.904	0.946	0.943	0.944	0.900	0.943	0.942	0.901	0.993
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	0.905	0.947	0.944	0.942	0.901	0.943	0.942	0.902	1.000	0.909	0.948	0.945	0.943	0.905	0.945	0.944	0.905	0.994
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	0.947	1.006	1.004	0.981	0.943	1.008	1.001	0.945	1.052	0.942	0.999	0.997	0.980	0.938	1.001	0.994	0.939	1.038
GA	Attapulgis	1997	37	30.7612	84.4853	1460	4.54	0.903	0.944	0.943	0.946	0.899	0.943	0.940	0.900	0.967	0.909	0.947	0.945	0.946	0.905	0.945	0.943	0.906	0.958
GA	Attapulgis	1998	37	30.7612	84.4853	1460	6.29	0.903	0.942	0.940	0.946	0.899	0.941	0.938	0.900	0.960	0.906	0.943	0.941	0.944	0.902	0.941	0.938	0.903	0.955
GA	Blairsville	1997	584.3	34.8388	83.928	1307	4.48	0.959	0.993	0.990	0.994	0.954	0.992	0.988	0.956	1.002	0.973	1.005	1.002	1.004	0.968	1.002	1.000	0.970	1.000
GA	Blairsville	1998	584.3	34.8388	83.928	1307	4.63	0.921	0.965	0.962	0.968	0.916	0.963	0.960	0.918	0.993	0.927	0.971	0.968	0.971	0.923	0.968	0.966	0.925	0.987
GA	Griffin	1997	281.9	33.2623	84.284	1447	5.05	0.899	0.945	0.943	0.944	0.896	0.945	0.941	0.897	0.990	0.905	0.950	0.948	0.949	0.901	0.949	0.946	0.902	0.983
GA	Griffin	1998	281.9	33.2623	84.284	1447	5.99	0.916	0.958	0.956	0.961	0.912	0.957	0.954	0.913	0.985	0.918	0.960	0.957	0.960	0.914	0.958	0.956	0.915	0.983
ID	Ashton	1997	1615	44.03	111.47	430	4.96	0.968	1.024	1.022	1.017	0.967	1.047	1.022	0.967	1.087	0.961	1.013	1.011	1.009	0.959	1.034	1.011	0.959	1.070
ID	Ashton	1998	1615	44.03	111.47	430	5.70	0.942	1.001	0.998	0.997	0.941	1.010	0.999	0.941	1.068	0.941	0.997	0.994	0.992	0.939	1.005	0.995	0.939	1.064
ID	Parma	1997	703	43.80	116.93	237	5.66	0.990	1.027	1.024	1.028	0.987	1.039	1.024	0.987	1.088	0.985	1.020	1.017	1.017	0.982	1.031	1.017	0.982	1.075
ID	Parma	1998	703	43.80	116.93	237	6.10	0.980	1.019	1.016	1.022	0.977	1.029	1.016	0.977	1.076	0.982	1.021	1.018	1.020	0.978	1.027	1.017	0.979	1.073
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	0.956	1.000	0.997	0.995	0.954	1.024	0.999	0.954	1.074	0.958	0.999	0.996	0.994	0.956	1.018	0.997	0.956	1.058
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	0.946	0.987	0.984	0.984	0.945	1.011	0.985	0.945	1.061	0.951	0.992	0.990	0.989	0.949	1.008	0.990	0.949	1.050
IL	Belleville	1999	133	38.52	89.88	974	5.53	0.997	1.040	1.037	1.031	0.993	1.037	1.036	0.994	1.062	0.988	1.028	1.025	1.023	0.984	1.025	1.024	0.985	1.026
IL	Bondville	1999	213	40.05	88.37	1008	5.18	0.957	1.012	1.010	1.007	0.953	1.009	1.008	0.955	1.060	0.961	1.016	1.014	1.014	0.958	1.014	1.012	0.959	1.027

ASCE Standardized Reference Evapotranspiration Equation

Table F-4. Ratio of Hourly Sum ETo to Daily ETo (within Method), continued.

								YEARLY									GROWING SEASON								
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ET _o (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PM _r f (YR)	ASCE PM _r th (YR)	ET _o (YR)	F56 PM (YR)	1963 Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PM _r f (GS)	ASCE PM _r th (GS)	ET _o (GS)	F56 PM (GS)	1963 Pen (GS)
IL	Monmouth	1999	229	40.92	90.73	942	5.23	0.940	0.988	0.986	0.983	0.937	0.986	0.984	0.938	1.049	0.944	0.995	0.993	0.994	0.940	0.994	0.991	0.941	1.017
MT	Creston	1997	899	48.19	114.13	390	4.16	0.969	1.020	1.019	1.030	0.966	1.026	1.018	0.967	1.048	0.970	1.019	1.017	1.021	0.967	1.023	1.016	0.968	1.048
MT	Creston	1998	899	48.19	114.13	390	4.73	0.971	1.019	1.017	1.027	0.969	1.024	1.017	0.969	1.062	0.975	1.024	1.021	1.024	0.972	1.023	1.021	0.972	1.063
MT	Ronan	1997	927	47.54	114.28	380	4.31	0.996	1.037	1.035	1.047	0.993	1.042	1.033	0.994	1.057	0.997	1.035	1.033	1.037	0.994	1.037	1.032	0.995	1.055
MT	Ronan	1998	927	47.54	114.28	380	4.70	1.001	1.035	1.033	1.042	0.997	1.041	1.032	0.999	1.063	1.002	1.038	1.035	1.037	0.999	1.037	1.035	1.000	1.060
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	0.978	1.012	1.010	1.017	0.976	1.024	1.010	0.977	1.037	0.979	1.014	1.012	1.014	0.977	1.020	1.012	0.977	1.034
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	0.965	0.987	0.985	0.990	0.963	1.009	0.985	0.964	1.036	0.966	0.992	0.990	0.989	0.963	1.003	0.990	0.964	1.038
NE	Champion	1997	1029	40.22	101.43	482	6.64	0.931	0.991	0.989	0.982	0.932	1.019	0.992	0.932	1.116	0.945	1.003	1.000	0.997	0.944	1.018	1.002	0.944	1.068
NE	Champion	1998	1029	40.22	101.43	482	6.18	0.917	0.971	0.968	0.961	0.918	0.996	0.971	0.918	1.106	0.934	0.989	0.986	0.982	0.934	1.004	0.988	0.934	1.070
NE	Clay Center	1997	552	40.31	98.08	685	5.46	0.907	0.975	0.973	0.974	0.907	0.993	0.975	0.907	1.075	0.929	0.996	0.994	0.996	0.928	1.004	0.995	0.928	1.038
NE	Clay Center	1998	552	40.31	98.08	685	5.15	0.886	0.950	0.948	0.953	0.886	0.965	0.950	0.886	1.047	0.906	0.967	0.964	0.967	0.906	0.977	0.966	0.906	1.025
NE	Mead	1997	366	41.08	96.30	743	5.15	0.936	0.998	0.996	0.995	0.936	1.021	0.998	0.936	1.080	0.943	1.006	1.003	1.002	0.942	1.017	1.005	0.943	1.049
NE	Mead	1998	366	41.08	96.30	743	4.57	0.921	0.978	0.976	0.975	0.921	0.998	0.977	0.921	1.066	0.928	0.983	0.981	0.981	0.927	0.994	0.982	0.927	1.035
NY	Ithaca	1997	123	42.45	76.45	914	3.9	0.977	1.031	1.029	1.038	0.972	1.035	1.026	0.975	1.077	0.983	1.044	1.041	1.045	0.978	1.043	1.039	0.981	1.071
NY	Ithaca	1998	123	42.45	76.45	914	3.89	0.976	1.029	1.027	1.033	0.972	1.032	1.025	0.974	1.071	0.979	1.037	1.035	1.036	0.975	1.037	1.033	0.977	1.059
NY	Valatie	1997	76	42.43	73.68	914	3.82	1.017	1.046	1.044	1.055	1.014	1.045	1.042	1.015	1.064	1.018	1.045	1.043	1.048	1.014	1.042	1.041	1.015	1.053
NY	Valatie	1998	76	42.43	73.68	914	3.88	1.001	1.035	1.033	1.046	0.997	1.034	1.031	0.998	1.055	0.997	1.031	1.029	1.034	0.994	1.029	1.027	0.995	1.042
NY	Willsboro	1998	43	44.38	73.38	762	3.79	0.985	1.019	1.017	1.027	0.983	1.022	1.016	0.983	1.046	0.985	1.022	1.020	1.023	0.982	1.023	1.019	0.983	1.033
OK	Apache	1997	440	34.91	98.29	757	6.59	0.925	0.977	0.975	0.974	0.925	1.010	0.977	0.925	1.047	0.935	0.987	0.985	0.986	0.933	1.007	0.986	0.934	1.016
OK	Apache	1998	440	34.91	98.29	757	8.60	0.933	0.977	0.975	0.976	0.932	1.007	0.976	0.933	1.039	0.943	0.982	0.980	0.981	0.942	1.008	0.981	0.942	1.020
OK	Goodwell	1997	996	36.60	101.60	447	8.56	0.920	0.972	0.969	0.962	0.921	1.008	0.972	0.921	1.085	0.924	0.975	0.972	0.971	0.923	1.000	0.974	0.923	1.042
OK	Goodwell	1998	996	36.60	101.60	447	9.68	0.922	0.967	0.964	0.957	0.922	1.007	0.967	0.922	1.085	0.935	0.976	0.973	0.971	0.934	1.010	0.976	0.934	1.047
OK	Marena	1997	331	36.06	97.21	889	5.63	0.938	0.992	0.990	0.993	0.938	1.012	0.991	0.938	1.055	0.943	0.994	0.992	0.994	0.941	1.006	0.992	0.942	1.024
OK	Marena	1998	331	36.06	97.21	889	6.84	0.946	0.992	0.989	0.995	0.945	1.014	0.991	0.945	1.050	0.949	0.991	0.988	0.991	0.948	1.007	0.989	0.948	1.026
OK	Wister	1997	143	34.98	94.68	1188	5.13	1.004	1.043	1.040	1.047	1.002	1.050	1.040	1.002	1.076	0.989	1.026	1.022	1.028	0.986	1.026	1.022	0.987	1.041
OK	Wister	1998	143	34.98	94.68	1188	6.09	1.013	1.053	1.050	1.056	1.010	1.064	1.050	1.010	1.079	1.002	1.043	1.039	1.042	0.999	1.045	1.039	0.999	1.053
OR	Haga	1999	9	42.50	124.50	1778	3.32																		
SC	Florence	1986	40	34.24	79.81	1120	5.91	0.973	1.007	1.005	1.008	0.970	1.025	1.004	0.970	1.060	0.975	1.010	1.008	1.007	0.972	1.022	1.008	0.973	1.051
TX	Bushland	1997	1170	35.11	102.05	505	7.36	0.894	0.944	0.942	0.935	0.894	0.982	0.944	0.893	1.036	0.903	0.956	0.954	0.953	0.902	0.979	0.955	0.902	1.002
TX	Bushland	1998	1170	35.11	102.05	505	9.34	0.904	0.951	0.949	0.941	0.903	0.987	0.950	0.902	1.045	0.917	0.961	0.959	0.954	0.915	0.995	0.959	0.915	1.033
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	0.913	0.976	0.973	0.967	0.909	0.970	0.971	0.911	1.084	0.917	0.977	0.974	0.971	0.912	0.971	0.972	0.915	1.059
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	0.920	0.979	0.976	0.973	0.915	0.973	0.974	0.918	1.091	0.931	0.986	0.983	0.982	0.926	0.979	0.981	0.928	1.072
UT	Logan	1989	1350	41.60	111.80	433	6.21										0.996	1.042	1.039	1.037	0.993	1.045	1.039	0.994	1.112
UT	Logan	1990	1350	41.60	111.80	433	5.77										0.987	1.036	1.032	1.032	0.984	1.032	1.033	0.984	1.110
WA	Gramling	1998	386	46.29	119.73	178	7.42										0.910	0.944	0.942	0.941	0.910	0.976	0.944	0.910	1.003
WA	Grayland	1998	2	46.78	124.00	2032	2.78										0.930	1.017	1.016	1.014	0.927	1.009	1.014	0.928	1.020
WA	Paterson	1998	109	45.94	119.49	152	6.65										0.947	0.991	0.988	0.990	0.946	1.006	0.990	0.946	1.041
WA	Puyallup	1998	61	47.10	122.30	1016	3.48										1.007	1.049	1.046	1.050	1.005	1.047	1.046	1.006	1.064
WA	Roza	1998	343	46.29	119.73	178	5.96										0.984	1.021	1.018	1.019	0.983	1.033	1.020	0.984	1.058
	Average							0.951	0.997	0.995	0.995	0.949	1.009	0.995	0.950	1.057	0.960	1.005	1.002	1.001	0.957	1.012	1.002	0.958	1.047
	Minimum							0.886	0.942	0.940	0.935	0.886	0.941	0.938	0.886	0.960	0.903	0.943	0.941	0.941	0.900	0.941	0.938	0.901	0.955
	Maximum							1.017	1.053	1.050	1.056	1.014	1.064	1.050	1.015	1.116	1.047	1.079	1.075	1.052	1.041	1.081	1.073	1.043	1.182

ASCE Standardized Reference Evapotranspiration Equation

Table F-5. Ratio of Hourly Sum ETo to Daily ASCE-PM ETo

Site	Year	State	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON											
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
Phoenix	1997	AZ	335	33.48	112.10	175	7.49	1.005	1.032	1.025	1.022	0.990	1.028	1.016	0.989	1.196	1.074	0.992	1.017	1.009	1.004	0.976	1.013	1.001	0.976	1.161	1.061
Phoenix	1998	AZ	335	33.48	112.10	175	7.60	0.994	1.026	1.019	1.015	0.981	1.021	1.012	0.981	1.171	1.064	0.984	1.012	1.005	0.998	0.970	1.008	0.998	0.969	1.144	1.059
Tucson	1997	AZ	713	32.28	110.94	300	8.54	0.988	1.019	1.013	1.002	0.973	1.027	1.003	0.973	1.100	1.001	0.992	1.020	1.013	1.003	0.977	1.027	1.004	0.976	1.093	1.008
Tucson	1998	AZ	713	32.28	110.94	300	8.21	0.980	1.015	1.009	1.000	0.966	1.019	1.000	0.966	1.103	1.008	0.986	1.019	1.012	1.002	0.972	1.021	1.004	0.971	1.099	1.021
Davis	1998	CA	18	38.50	121.80	461	6.71	0.938	0.996	0.993	0.981	0.927	0.996	0.984	0.927	1.115	1.044	0.940	0.995	0.992	0.980	0.929	0.995	0.983	0.929	1.107	1.050
Fresno	1998	CA	103	36.80	119.70	269	7.11	0.970	1.012	1.009	0.996	0.959	1.013	1.001	0.959	1.119	1.050	0.973	1.012	1.008	0.995	0.962	1.013	1.000	0.962	1.113	1.060
Santa Maria	1998	CA	82	35.00	120.40	314	4.42	0.939	1.004	1.004	0.984	0.933	0.999	0.998	0.933	1.136	1.087	0.948	1.015	1.014	0.991	0.943	1.007	1.010	0.944	1.149	1.127
Center	1997	CO	2348	38.00	106.00	178	5.62											0.967	1.017	1.017	0.980	0.966	1.030	1.016	0.966	1.132	1.097
Center	1999	CO	2348	38.00	106.00	178	5.96											0.967	1.021	1.022	0.989	0.966	1.039	1.020	0.965	1.156	1.124
Colton	1982	CO	2743	39.00	106.00	279	4.65																				
Colton	1983	CO	2743	39.00	106.00	279	4.69																				
Fort Collins	1995	CO	1527	40.60	105.00	383	5.58																				
Fruita	1997	CO	1274	38.00	104.00	228	7.83											0.985	1.031	1.028	0.993	0.979	1.031	1.025	0.977	1.149	1.132
Fruita	1999	CO	1274	38.00	104.00	228	6.75											0.995	1.033	1.030	0.987	0.991	1.035	1.029	0.991	1.150	1.116
Loveland	1997	CO	1540	40.40	105.11	406	5.59	0.995	1.026	1.025	0.989	0.989	1.037	1.020	0.988	1.167	1.084	0.987	1.015	1.014	0.975	0.981	1.022	1.009	0.980	1.141	1.089
Loveland	1998	CO	1540	40.40	105.11	406	5.30	0.992	1.023	1.022	0.988	0.985	1.033	1.016	0.985	1.158	1.061	0.989	1.020	1.018	0.980	0.982	1.024	1.013	0.982	1.141	1.076
Ovid	1998	CO	1089	40.97	102.45	448	5.5	0.930	0.982	0.980	0.960	0.913	0.986	0.964	0.913	1.096	1.024	0.956	1.007	1.004	0.982	0.940	1.006	0.990	0.940	1.107	1.066
Ovid	1999	CO	1089	40.97	102.45	448	6.08	0.918	0.974	0.972	0.951	0.901	0.978	0.956	0.902	1.087	1.020	0.946	1.001	0.999	0.971	0.931	1.000	0.986	0.931	1.108	1.074
Portis	1982	CO	2895	39	106	279	4.03																				
Portis	1983	CO	2895	39	106	279	4.21																				
Rocky Ford	1997	CO	1274	38	104	279	7.08											1.047	1.078	1.074	1.029	1.041	1.080	1.071	1.041	1.201	1.152
Rocky Ford	1999	CO	1274	38	104	279	8.02											1.032	1.058	1.055	1.011	1.027	1.063	1.053	1.034	1.192	1.135
Wiggins	1997	CO	1367	40.31	104.06	353	5.88	0.950	0.993	0.992	0.965	0.935	1.000	0.978	0.935	1.109	1.046	0.956	0.998	0.996	0.966	0.942	1.001	0.983	0.942	1.101	1.065
Wiggins	1998	CO	1367	40.31	104.06	353	5.93	0.947	0.994	0.993	0.969	0.932	0.995	0.979	0.932	1.101	1.037	0.961	1.005	1.003	0.978	0.946	1.003	0.990	0.946	1.100	1.063
Yellow Jacket	1997	CO	2252	37.00	109.00	406	5.94											0.959	1.001	1.000	0.968	0.957	1.011	0.998	0.957	1.141	1.093
Yellow Jacket	1999	CO	2252	37.00	109.00	406	6.01											0.968	1.017	1.017	0.985	0.962	1.012	1.011	0.961	1.158	1.099
Lake Alfred	1998	FL	46	28.03	80.89	1250	6.08	0.899	0.943	0.938	0.929	0.892	0.938	0.935	0.894	1.041	1.002	0.904	0.944	0.938	0.926	0.896	0.938	0.936	0.898	1.039	1.016
Lake Alfred	1999	FL	46	28.03	80.89	1250	5.23	0.905	0.946	0.941	0.927	0.898	0.940	0.938	0.900	1.041	1.017	0.909	0.947	0.941	0.926	0.901	0.941	0.939	0.903	1.040	1.028
St. Pierce	1999	FL	7	27.57	80.44	1422	4.99	0.947	1.004	1.000	0.968	0.940	1.005	0.996	0.942	1.135	1.142	0.942	0.997	0.993	0.963	0.934	0.997	0.989	0.936	1.124	1.143
Attapulgus	1997	GA	37	30.761	84.4853	1460	4.54	0.903	0.943	0.941	0.921	0.898	0.942	0.938	0.899	1.067	1.027	0.909	0.946	0.942	0.922	0.903	0.943	0.940	0.904	1.061	1.043
Attapulgus	1998	GA	37	30.761	84.4853	1460	6.29	0.903	0.941	0.937	0.919	0.897	0.939	0.935	0.898	1.056	1.022	0.906	0.942	0.937	0.918	0.899	0.937	0.934	0.900	1.049	1.029
Blairsville	1997	GA	584.3	34.839	83.928	1307	4.48	0.959	0.992	0.991	0.950	0.958	0.996	0.991	0.957	1.128	1.080	0.973	1.004	1.003	0.964	0.970	1.005	1.002	0.970	1.131	1.105
Blairsville	1998	GA	584.3	34.839	83.928	1307	4.63	0.921	0.964	0.962	0.929	0.918	0.965	0.961	0.918	1.084	1.037	0.927	0.970	0.967	0.936	0.924	0.969	0.966	0.924	1.082	1.055
Griffin	1997	GA	281.9	33.262	84.284	1447	5.05	0.899	0.943	0.942	0.918	0.896	0.945	0.940	0.896	1.080	1.022	0.905	0.949	0.947	0.925	0.900	0.948	0.944	0.901	1.076	1.038
Griffin	1998	GA	281.9	33.262	84.284	1447	5.99	0.916	0.957	0.953	0.935	0.911	0.955	0.951	0.912	1.087	1.043	0.918	0.959	0.955	0.935	0.912	0.956	0.953	0.913	1.084	1.052
Ashton	1997	ID	1615	44.03	111.47	430	4.96	0.968	1.022	1.023	0.984	0.966	1.044	1.019	0.964	1.171	1.111	0.961	1.011	1.012	0.974	0.957	1.032	1.007	0.956	1.145	1.103
Ashton	1998	ID	1615	44.03	111.47	430	5.70	0.942	0.999	0.998	0.964	0.939	1.008	0.996	0.938	1.125	1.065	0.941	0.995	0.994	0.962	0.937	1.003	0.991	0.937	1.110	1.066
Parma	1997	ID	703	43.80	116.93	237	5.66	0.990	1.026	1.025	1.004	0.984	1.036	1.020	0.984	1.168	1.067	0.985	1.019	1.017	0.993	0.979	1.028	1.012	0.979	1.155	1.076
Parma	1998	ID	703	43.80	116.93	237	6.10	0.980	1.018	1.016	0.994	0.974	1.026	1.012	0.974	1.163	1.073	0.982	1.020	1.017	0.996	0.976	1.024	1.014	0.976	1.161	1.090
Twin Falls	1997	ID	1195	42.61	114.35	222	5.69	0.956	0.998	0.997	0.973	0.951	1.020	0.993	0.951	1.133	1.050	0.958	0.997	0.995	0.969	0.953	1.014	0.991	0.953	1.118	1.062
Twin Falls	1998	ID	1195	42.61	114.35	222	6.44	0.946	0.985	0.984	0.955	0.942	1.008	0.980	0.941	1.120	1.038	0.951	0.991	0.989	0.961	0.946	1.005	0.985	0.946	1.110	1.053
Belleville	1999	IL	133	38.52	89.88	974	5.53	0.997	1.039	1.036	1.010	0.993	1.038	1.035	0.993	1.176	1.124	0.988	1.027	1.023	0.994	0.982	1.023	1.021	0.983	1.147	1.138
Bondville	1999	IL	213	40.05	88.37	1008	5.18	0.957	1.011	1.009	0.985	0.954	1.010	1.007	0.953	1.157	1.099	0.961	1.015	1.012	0.985	0.956	1.012	1.009	0.957	1.140	1.123

ASCE Standardized Reference Evapotranspiration Equation

Table F-5. Ratio of Hourly Sum ET_o to Daily ASCE-PM ET_o, continued.

Site	Year	State	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	YEARLY SUMMARY										GROWING SEASON									
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
Monmouth	1999	IL	229	40.92	90.73	942	5.23	0.940	0.986	0.985	0.963	0.938	0.987	0.984	0.936	1.137	1.072	0.944	0.993	0.991	0.963	0.939	0.992	0.989	0.939	1.125	1.102
Creston	1997	MT	899	48.19	114.13	390	4.16	0.969	1.019	1.020	0.977	0.967	1.026	1.017	0.966	1.160	1.086	0.970	1.018	1.019	0.975	0.967	1.023	1.015	0.967	1.151	1.106
Creston	1998	MT	899	48.19	114.13	390	4.73	0.971	1.018	1.018	0.981	0.968	1.024	1.015	0.968	1.145	1.070	0.975	1.023	1.022	0.988	0.971	1.022	1.019	0.971	1.140	1.089
Ronan	1997	MT	927	47.54	114.28	380	4.31	0.996	1.036	1.037	0.992	0.994	1.043	1.033	0.993	1.186	1.110	0.997	1.034	1.035	0.990	0.995	1.038	1.031	0.994	1.174	1.125
Ronan	1998	MT	927	47.54	114.28	380	4.70	1.001	1.034	1.034	0.991	0.998	1.041	1.031	0.997	1.187	1.100	1.002	1.037	1.036	0.996	0.999	1.037	1.033	0.998	1.181	1.118
St. Ignatius	1997	MT	896	47.31	114.10	360	4.52	0.978	1.010	1.011	0.968	0.977	1.024	1.009	0.976	1.138	1.061	0.979	1.013	1.013	0.972	0.977	1.020	1.011	0.976	1.131	1.081
St. Ignatius	1998	MT	896	47.31	114.10	360	5.27	0.965	0.986	0.985	0.948	0.962	1.007	0.982	0.961	1.105	1.016	0.966	0.991	0.990	0.957	0.962	1.002	0.987	0.961	1.101	1.034
Champion	1997	NE	1029	40.22	101.43	482	6.64	0.931	0.989	0.987	0.961	0.919	1.003	0.975	0.918	1.108	1.037	0.945	1.001	0.998	0.970	0.932	1.006	0.988	0.932	1.101	1.062
Champion	1998	NE	1029	40.22	101.43	482	6.18	0.917	0.968	0.966	0.935	0.905	0.981	0.955	0.905	1.082	1.017	0.934	0.987	0.983	0.955	0.922	0.991	0.974	0.922	1.084	1.044
Clay Center	1997	NE	552	40.31	98.08	685	5.46	0.907	0.973	0.971	0.945	0.897	0.982	0.962	0.897	1.112	1.045	0.929	0.994	0.991	0.963	0.919	0.994	0.984	0.919	1.115	1.082
Clay Center	1998	NE	552	40.31	98.08	685	5.15	0.886	0.948	0.946	0.921	0.876	0.955	0.938	0.876	1.078	1.017	0.906	0.965	0.962	0.936	0.897	0.967	0.955	0.897	1.081	1.053
Mead	1997	NE	366	41.08	96.30	743	5.15	0.936	0.996	0.994	0.964	0.926	1.009	0.985	0.925	1.140	1.084	0.943	1.004	1.001	0.968	0.933	1.007	0.993	0.933	1.127	1.102
Mead	1998	NE	366	41.08	96.30	743	4.57	0.921	0.976	0.974	0.943	0.912	0.988	0.966	0.912	1.116	1.059	0.928	0.981	0.978	0.948	0.919	0.985	0.972	0.919	1.105	1.079
Ithaca	1997	NY	123	42.45	76.45	914	3.9	0.977	1.030	1.030	0.980	0.977	1.041	1.030	0.975	1.203	1.140	0.983	1.042	1.042	0.996	0.981	1.047	1.041	0.980	1.196	1.159
Ithaca	1998	NY	123	42.45	76.45	914	3.89	0.976	1.027	1.027	0.980	0.975	1.036	1.027	0.973	1.186	1.134	0.979	1.035	1.034	0.989	0.977	1.039	1.032	0.976	1.179	1.154
Valatie	1997	NY	76	42.43	73.68	914	3.82	1.017	1.045	1.045	0.991	1.019	1.050	1.046	1.016	1.227	1.147	1.018	1.045	1.044	0.992	1.017	1.045	1.044	1.016	1.208	1.160
Valatie	1998	NY	76	42.43	73.68	914	3.88	1.001	1.035	1.034	0.987	1.001	1.038	1.035	0.999	1.191	1.122	0.997	1.030	1.029	0.983	0.996	1.031	1.028	0.995	1.168	1.133
Willsboro	1998	NY	43	44.38	73.38	762	3.79	0.985	1.017	1.018	0.969	0.987	1.027	1.019	0.984	1.175	1.094	0.985	1.021	1.020	0.973	0.984	1.025	1.020	0.983	1.164	1.117
Apache	1997	OK	440	34.91	98.29	757	6.59	0.925	0.975	0.973	0.957	0.914	0.998	0.964	0.914	1.120	1.057	0.935	0.985	0.981	0.962	0.924	0.997	0.973	0.924	1.106	1.077
Apache	1998	OK	440	34.91	98.29	757	8.60	0.933	0.975	0.970	0.959	0.919	0.992	0.960	0.918	1.084	1.015	0.943	0.981	0.974	0.963	0.927	0.992	0.964	0.927	1.064	1.011
Goodwell	1997	OK	996	36.60	101.60	447	8.56	0.920	0.969	0.967	0.947	0.906	0.992	0.955	0.906	1.078	1.003	0.924	0.973	0.969	0.950	0.910	0.986	0.958	0.909	1.057	1.010
Goodwell	1998	OK	996	36.60	101.60	447	9.68	0.922	0.965	0.961	0.944	0.906	0.989	0.948	0.905	1.058	0.981	0.935	0.974	0.969	0.953	0.919	0.993	0.957	0.918	1.042	0.984
Marena	1997	OK	331	36.06	97.21	889	5.63	0.938	0.990	0.987	0.971	0.928	1.001	0.979	0.928	1.135	1.070	0.943	0.992	0.988	0.967	0.932	0.996	0.982	0.933	1.119	1.091
Marena	1998	OK	331	36.06	97.21	889	6.84	0.946	0.990	0.986	0.972	0.932	1.000	0.976	0.932	1.117	1.043	0.949	0.990	0.983	0.968	0.935	0.993	0.975	0.935	1.095	1.048
Wister	1997	OK	143	34.98	94.68	1188	5.13	1.004	1.042	1.038	1.011	0.995	1.043	1.033	0.996	1.188	1.131	0.989	1.025	1.020	0.993	0.980	1.020	1.016	0.981	1.149	1.129
Wister	1998	OK	143	34.98	94.68	1188	6.09	1.013	1.053	1.047	1.029	1.000	1.055	1.039	1.000	1.186	1.118	1.003	1.042	1.035	1.017	0.989	1.035	1.028	0.989	1.155	1.117
Haga	1999	OR	9	42.50	124.50	1778	3.32																				
Florence	1986	SC	40	34.24	79.81	1120	5.91	0.973	1.006	1.003	0.979	0.968	1.023	1.001	0.968	1.182	1.086	0.975	1.009	1.005	0.981	0.970	1.020	1.004	0.970	1.167	1.095
Bushland	1997	TX	1170	35.11	102.05	505	7.36	0.894	0.941	0.940	0.919	0.887	0.975	0.935	0.886	1.076	1.005	0.903	0.954	0.951	0.930	0.897	0.973	0.947	0.896	1.062	1.023
Bushland	1998	TX	1170	35.11	102.05	505	9.34	0.904	0.948	0.946	0.927	0.896	0.979	0.940	0.895	1.055	0.980	0.917	0.959	0.955	0.938	0.908	0.987	0.949	0.907	1.053	0.992
Dalhart	1997	TX	1228	36.20	102.32	467	6.44	0.913	0.974	0.972	0.949	0.907	0.968	0.967	0.906	1.101	1.040	0.917	0.975	0.972	0.951	0.909	0.968	0.967	0.910	1.092	1.048
Dalhart	1998	TX	1228	36.20	102.32	467	7.30	0.920	0.977	0.974	0.954	0.912	0.969	0.968	0.912	1.080	1.012	0.931	0.984	0.980	0.961	0.921	0.974	0.974	0.922	1.079	1.026
Logan	1989	UT	1350	41.60	111.80	433	6.21											0.996	1.041	1.039	1.009	0.990	1.042	1.035	0.990	1.144	1.082
Logan	1990	UT	1350	41.60	111.80	433	5.77											0.987	1.035	1.032	1.002	0.982	1.030	1.030	0.982	1.135	1.080
Gramling	1998	WA	386	46.29	119.73	178	7.42											0.910	0.942	0.939	0.922	0.898	0.964	0.930	0.898	1.049	0.969
Grayland	1998	WA	2	46.78	124.00	2032	2.78											0.930	1.015	1.017	0.971	0.929	1.011	1.014	0.927	1.225	1.220
Paterson	1998	WA	109	45.94	119.49	152	6.65											0.947	0.989	0.986	0.969	0.937	0.996	0.979	0.937	1.112	1.042
Puyallup	1998	WA	61	47.10	122.30	1016	3.48											1.007	1.048	1.048	0.990	1.004	1.047	1.045	1.003	1.191	1.157
Roza	1998	WA	343	46.29	119.73	178	5.96											0.984	1.019	1.017	0.996	0.975	1.024	1.009	0.974	1.146	1.072
Average								0.951	0.995	0.993	0.967	0.944	1.003	0.988	0.943	1.127	1.059	0.960	1.004	1.001	0.973	0.952	1.007	0.996	0.952	1.124	1.080
Minimum								0.886	0.941	0.937	0.918	0.876	0.938	0.935	0.876	1.041	0.980	0.903	0.942	0.937	0.918	0.896	0.937	0.930	0.896	1.039	0.969
Maximum								1.017	1.053	1.047	1.029	1.019	1.055	1.046	1.016	1.227	1.147	1.047	1.078	1.074	1.029	1.041	1.080	1.071	1.041	1.225	1.220

ASCE Standardized Reference Evapotranspiration Equation

Table F-6. Ratio of method Hourly Sum ETo to Hourly Sum ASCE PMD ETo

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	YEARLY SUMMARY										GROWING SEASON									
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrF (YR)	ASCE PMrRh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrF (GS)	ASCE PMrRh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	0.974	1.000	0.993	0.990	0.959	0.996	0.985	0.958	1.158	1.040	0.975	1.000	0.992	0.987	0.960	0.996	0.984	0.959	1.141	1.043
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	0.969	1.000	0.994	0.989	0.957	0.996	0.987	0.956	1.141	1.038	0.971	1.000	0.993	0.985	0.958	0.995	0.986	0.957	1.130	1.046
AZ	Tucson	1997	713	32.28	110.94	300	8.54	0.970	1.000	0.995	0.984	0.956	1.008	0.985	0.955	1.080	0.983	0.973	1.000	0.993	0.983	0.958	1.007	0.984	0.957	1.072	0.989
AZ	Tucson	1998	713	32.28	110.94	300	8.21	0.966	1.000	0.995	0.985	0.952	1.004	0.986	0.952	1.087	0.994	0.968	1.000	0.993	0.983	0.954	1.003	0.985	0.953	1.079	1.003
CA	Davis	1998	18	38.50	121.80	461	6.71	0.942	1.000	0.997	0.985	0.931	1.001	0.988	0.931	1.119	1.048	0.945	1.000	0.997	0.984	0.933	1.000	0.988	0.933	1.112	1.055
CA	Fresno	1998	103	36.80	119.70	269	7.11	0.958	1.000	0.997	0.984	0.947	1.001	0.989	0.947	1.105	1.038	0.962	1.000	0.996	0.983	0.950	1.001	0.988	0.950	1.099	1.047
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	0.935	1.000	0.999	0.980	0.929	0.994	0.994	0.929	1.131	1.082	0.934	1.000	0.999	0.976	0.929	0.992	0.995	0.929	1.132	1.110
CO	Center	1997	2348	38.00	106.00	178	5.62											0.951	1.000	1.000	0.964	0.950	1.013	0.999	0.950	1.114	1.079
CO	Center	1999	2348	38.00	106.00	178	5.96											0.947	1.000	1.001	0.968	0.946	1.018	0.998	0.945	1.132	1.101
CO	Colton	1982	2743	39.00	106.00	279	4.65											0.955	1.000	0.997	0.963	0.949	1.000	0.994	0.947	1.115	1.098
CO	Colton	1983	2743	39.00	106.00	279	4.69																				
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58																				
CO	Fruita	1997	1274	38.00	104.00	228	7.83											0.955	1.000	0.997	0.963	0.949	1.000	0.994	0.947	1.115	1.098
CO	Fruita	1999	1274	38.00	104.00	228	6.75											0.963	1.000	0.997	0.956	0.959	1.002	0.996	0.959	1.113	1.080
CO	Loveland	1997	1540	40.40	105.11	406	5.59	0.970	1.000	0.999	0.965	0.964	1.011	0.994	0.964	1.137	1.057	0.972	1.000	0.998	0.956	0.966	1.005	0.994	0.965	1.119	1.081
CO	Loveland	1998	1540	40.40	105.11	406	5.30	0.970	1.000	0.999	0.966	0.963	1.011	0.993	0.963	1.132	1.037	0.969	1.000	0.997	0.960	0.962	1.003	0.993	0.962	1.114	1.058
CO	Ovid	1998	1089	40.97	102.45	448	5.5	0.947	1.000	0.998	0.978	0.930	1.004	0.982	0.930	1.116	1.043	0.950	1.000	0.997	0.975	0.934	0.999	0.983	0.934	1.099	1.059
CO	Ovid	1999	1089	40.97	102.45	448	6.08	0.943	1.000	0.999	0.977	0.926	1.005	0.982	0.926	1.117	1.047	0.943	1.000	0.998	0.974	0.928	1.002	0.984	0.928	1.112	1.061
CO	Portis	1982	2895	39	106	279	4.03																				
CO	Portis	1983	2895	39	106	279	4.21																				
CO	Rocky Ford	1997	1274	38	104	279	7.08											0.972	1.000	0.997	0.955	0.966	1.003	0.994	0.966	1.115	1.070
CO	Rocky Ford	1999	1274	38	104	279	8.02											0.975	1.000	0.997	0.956	0.970	1.004	0.995	0.970	1.126	1.072
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	0.956	1.000	0.999	0.972	0.941	1.007	0.984	0.941	1.116	1.053	0.958	1.000	0.998	0.965	0.945	1.002	0.986	0.945	1.104	1.078
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	0.952	1.000	0.999	0.975	0.937	1.001	0.984	0.937	1.107	1.043	0.956	1.000	0.997	0.971	0.941	0.997	0.985	0.941	1.093	1.064
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94											0.958	1.000	0.999	0.967	0.956	1.010	0.997	0.956	1.139	1.092
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01											0.952	1.000	1.000	0.968	0.946	0.995	0.994	0.945	1.139	1.080
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	0.954	1.000	0.994	0.985	0.946	0.995	0.992	0.948	1.104	1.063	0.957	1.000	0.994	0.980	0.949	0.993	0.991	0.951	1.100	1.076
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	0.957	1.000	0.995	0.980	0.950	0.994	0.992	0.951	1.101	1.076	0.960	1.000	0.994	0.978	0.951	0.993	0.991	0.953	1.098	1.086
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	0.943	1.000	0.996	0.964	0.936	1.000	0.992	0.938	1.130	1.137	0.945	1.000	0.995	0.966	0.936	0.999	0.991	0.939	1.127	1.146
GA	Attapulgus	1997	37	30.76	84.4853	1460	4.54	0.958	1.000	0.997	0.977	0.952	0.999	0.994	0.953	1.131	1.089	0.961	1.000	0.996	0.975	0.954	0.996	0.993	0.955	1.121	1.102
GA	Attapulgus	1998	37	30.76	84.4853	1460	6.29	0.960	1.000	0.996	0.977	0.953	0.997	0.993	0.954	1.122	1.086	0.962	1.000	0.995	0.975	0.954	0.995	0.992	0.956	1.114	1.093
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.48	0.967	1.000	0.999	0.958	0.966	1.004	0.999	0.965	1.137	1.089	0.969	1.000	0.999	0.960	0.966	1.001	0.998	0.966	1.126	1.100
GA	Blairsville	1998	584.3	34.84	83.928	1307	4.63	0.955	1.000	0.998	0.964	0.953	1.001	0.997	0.952	1.125	1.076	0.957	1.000	0.997	0.966	0.953	0.999	0.996	0.953	1.116	1.088
GA	Griffin	1997	281.9	33.26	84.284	1447	5.05	0.953	1.000	0.998	0.973	0.950	1.002	0.996	0.950	1.144	1.083	0.954	1.000	0.997	0.975	0.949	0.999	0.995	0.949	1.134	1.094
GA	Griffin	1998	281.9	33.26	84.284	1447	5.99	0.957	1.000	0.996	0.977	0.952	0.998	0.994	0.953	1.136	1.090	0.957	1.000	0.996	0.975	0.951	0.997	0.994	0.953	1.131	1.098
ID	Ashton	1997	1615	44.03	111.47	430	4.96	0.948	1.000	1.001	0.963	0.945	1.022	0.997	0.944	1.146	1.087	0.949	1.000	1.000	0.963	0.945	1.017	0.996	0.945	1.130	1.097
ID	Ashton	1998	1615	44.03	111.47	430	5.70	0.943	1.000	1.000	0.965	0.940	1.009	0.997	0.939	1.127	1.067	0.947	1.000	0.999	0.965	0.943	1.007	0.996	0.942	1.114	1.080
ID	Parma	1997	703	43.80	116.93	237	5.66	0.965	1.000	0.999	0.979	0.959	1.009	0.994	0.959	1.139	1.040	0.967	1.000	0.997	0.971	0.960	1.003	0.993	0.961	1.127	1.065
ID	Parma	1998	703	43.80	116.93	237	6.10	0.963	1.000	0.998	0.976	0.957	1.008	0.994	0.957	1.143	1.055	0.964	1.000	0.996	0.972	0.958	1.001	0.993	0.958	1.132	1.076
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	0.958	1.000	0.999	0.975	0.953	1.022	0.995	0.953	1.135	1.053	0.961	1.000	0.999	0.974	0.955	1.020	0.995	0.955	1.128	1.066
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	0.961	1.000	0.999	0.969	0.956	1.023	0.995	0.956	1.137	1.054	0.959	1.000	0.999	0.970	0.954	1.016	0.995	0.954	1.126	1.065
IL	Belleville	1999	133	38.52	89.88	974	5.53	0.960	1.000	0.997	0.972	0.956	0.999	0.996	0.956	1.132	1.082	0.961	1.000	0.996	0.968	0.955	0.996	0.994	0.957	1.117	1.107
IL	Bondville	1999	213	40.05	88.37	1008	5.18	0.947	1.000	0.998	0.975	0.944	0.999	0.997	0.943	1.145	1.087	0.947	1.000	0.997	0.971	0.942	0.997	0.994	0.943	1.124	1.107

ASCE Standardized Reference Evapotranspiration Equation

Table F-6. Ratio of method Hourly Sum ETo to Hourly Sum ASCE PMD ETo, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETto (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON											
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrF (YR)	ASCE PMrth (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrF (GS)	ASCE PMrth (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
IL	Monmouth	1999	229	40.92	90.73	942	5.23	0.953	1.000	0.999	0.976	0.951	1.001	0.998	0.949	1.153	1.087	0.950	1.000	0.997	0.970	0.945	0.999	0.995	0.946	1.133	1.110
MT	Creston	1997	899	48.19	114.13	390	4.16	0.951	1.000	1.001	0.958	0.949	1.007	0.998	0.948	1.139	1.066	0.952	1.000	1.001	0.959	0.949	1.006	0.998	0.949	1.136	1.086
MT	Creston	1998	899	48.19	114.13	390	4.73	0.954	1.000	1.000	0.964	0.951	1.006	0.997	0.950	1.125	1.051	0.952	1.000	1.000	0.966	0.949	1.000	0.997	0.948	1.118	1.065
MT	Ronan	1997	927	47.54	114.28	380	4.31	0.962	1.000	1.001	0.958	0.959	1.007	0.997	0.959	1.145	1.071	0.962	1.000	1.001	0.959	0.960	1.006	0.997	0.959	1.142	1.089
MT	Ronan	1998	927	47.54	114.28	380	4.70	0.967	1.000	1.000	0.958	0.964	1.006	0.997	0.964	1.148	1.063	0.965	1.000	0.999	0.961	0.962	1.001	0.997	0.962	1.141	1.078
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	0.968	1.000	1.001	0.958	0.967	1.013	0.998	0.966	1.126	1.050	0.966	1.000	1.001	0.960	0.964	1.009	0.998	0.964	1.121	1.065
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	0.979	1.000	1.000	0.961	0.976	1.022	0.996	0.975	1.121	1.031	0.973	1.000	0.999	0.965	0.969	1.011	0.996	0.969	1.113	1.043
NE	Champion	1997	1029	40.22	101.43	482	6.64	0.942	1.000	0.998	0.972	0.929	1.015	0.986	0.929	1.121	1.049	0.943	1.000	0.997	0.969	0.931	1.004	0.987	0.931	1.100	1.060
NE	Champion	1998	1029	40.22	101.43	482	6.18	0.947	1.000	0.998	0.966	0.934	1.013	0.986	0.934	1.117	1.050	0.947	1.000	0.996	0.968	0.934	1.004	0.987	0.934	1.098	1.058
NE	Clay Center	1997	552	40.31	98.08	685	5.46	0.933	1.000	0.998	0.972	0.922	1.010	0.989	0.922	1.144	1.075	0.935	1.000	0.997	0.969	0.925	1.000	0.989	0.925	1.122	1.089
NE	Clay Center	1998	552	40.31	98.08	685	5.15	0.934	1.000	0.998	0.972	0.924	1.007	0.989	0.924	1.137	1.073	0.939	1.000	0.997	0.970	0.929	1.003	0.989	0.929	1.121	1.091
NE	Mead	1997	366	41.08	96.30	743	5.15	0.939	1.000	0.998	0.968	0.929	1.013	0.989	0.929	1.145	1.088	0.940	1.000	0.997	0.964	0.930	1.003	0.990	0.930	1.123	1.098
NE	Mead	1998	366	41.08	96.30	743	4.57	0.944	1.000	0.998	0.966	0.934	1.012	0.990	0.934	1.144	1.085	0.946	1.000	0.997	0.966	0.936	1.004	0.990	0.936	1.125	1.100
NY	Ithaca	1997	123	42.45	76.45	914	3.9	0.949	1.000	1.000	0.951	0.949	1.011	1.000	0.947	1.168	1.107	0.944	1.000	0.999	0.953	0.943	1.004	0.998	0.942	1.148	1.121
NY	Ithaca	1998	123	42.45	76.45	914	3.89	0.950	1.000	1.000	0.953	0.949	1.008	0.999	0.947	1.155	1.104	0.947	1.000	0.999	0.955	0.945	1.003	0.997	0.944	1.138	1.121
NY	Valatie	1997	76	42.43	73.68	914	3.82	0.974	1.000	1.000	0.948	0.975	1.005	1.001	0.972	1.174	1.097	0.975	1.000	0.999	0.947	0.974	1.000	0.999	0.974	1.154	1.116
NY	Valatie	1998	76	42.43	73.68	914	3.88	0.967	1.000	1.000	0.954	0.967	1.003	1.000	0.966	1.151	1.084	0.969	1.000	0.998	0.952	0.967	1.000	0.998	0.967	1.130	1.106
NY	Willsboro	1998	43	44.38	73.38	762	3.79	0.968	1.000	1.001	0.953	0.970	1.009	1.002	0.967	1.155	1.076	0.964	1.000	1.000	0.952	0.963	1.004	0.999	0.962	1.137	1.103
OK	Apache	1997	440	34.91	98.29	757	6.59	0.949	1.000	0.997	0.981	0.937	1.023	0.988	0.937	1.148	1.084	0.949	1.000	0.996	0.977	0.937	1.012	0.988	0.938	1.123	1.093
OK	Apache	1998	440	34.91	98.29	757	8.60	0.957	1.000	0.995	0.983	0.942	1.018	0.985	0.941	1.112	1.040	0.962	1.000	0.993	0.982	0.946	1.012	0.983	0.945	1.084	1.031
OK	Goodwell	1997	996	36.60	101.60	447	8.56	0.949	1.000	0.997	0.977	0.935	1.023	0.985	0.934	1.112	1.035	0.950	1.000	0.996	0.976	0.935	1.013	0.985	0.935	1.087	1.038
OK	Goodwell	1998	996	36.60	101.60	447	9.68	0.955	1.000	0.997	0.978	0.939	1.026	0.983	0.939	1.097	1.017	0.960	1.000	0.995	0.978	0.943	1.019	0.983	0.942	1.069	1.010
OK	Marena	1997	331	36.06	97.21	889	5.63	0.948	1.000	0.997	0.980	0.937	1.011	0.989	0.937	1.146	1.080	0.950	1.000	0.996	0.975	0.940	1.004	0.989	0.940	1.128	1.100
OK	Marena	1998	331	36.06	97.21	889	6.84	0.955	1.000	0.995	0.982	0.942	1.010	0.986	0.941	1.128	1.054	0.959	1.000	0.993	0.978	0.944	1.003	0.985	0.944	1.106	1.059
OK	Wister	1997	143	34.98	94.68	1188	5.13	0.964	1.000	0.996	0.970	0.955	1.001	0.991	0.956	1.140	1.086	0.965	1.000	0.995	0.969	0.956	0.995	0.991	0.957	1.121	1.102
OK	Wister	1998	143	34.98	94.68	1188	6.09	0.963	1.000	0.995	0.976	0.950	1.002	0.987	0.950	1.127	1.062	0.962	1.000	0.993	0.975	0.949	0.992	0.986	0.949	1.108	1.072
OR	Haga	1999	9	42.50	124.50	1778	3.32	0.904	1.000	1.002	0.955	0.905	1.033	1.001	0.906	1.427	1.425	0.887	1.000	1.001	0.955	0.887	1.011	1.000	0.884	1.418	1.436
SC	Florence	1986	40	34.24	79.81	1120	5.91	0.967	1.000	0.997	0.973	0.963	1.017	0.995	0.963	1.175	1.080	0.966	1.000	0.996	0.972	0.961	1.011	0.995	0.961	1.156	1.085
TX	Bushland	1997	1170	35.11	102.05	505	7.36	0.950	1.000	0.999	0.976	0.943	1.036	0.993	0.942	1.143	1.068	0.947	1.000	0.996	0.975	0.940	1.019	0.992	0.939	1.113	1.073
TX	Bushland	1998	1170	35.11	102.05	505	9.34	0.953	1.000	0.997	0.978	0.944	1.033	0.991	0.944	1.113	1.034	0.957	1.000	0.996	0.979	0.947	1.030	0.990	0.947	1.099	1.035
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	0.937	1.000	0.998	0.974	0.931	0.994	0.993	0.930	1.131	1.068	0.940	1.000	0.997	0.975	0.933	0.993	0.992	0.933	1.120	1.075
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	0.941	1.000	0.997	0.976	0.933	0.991	0.991	0.933	1.105	1.036	0.945	1.000	0.996	0.977	0.936	0.989	0.990	0.936	1.097	1.043
UT	Logan	1989	1350	41.60	111.80	433	6.21											0.956	1.000	0.998	0.970	0.950	1.001	0.994	0.950	1.100	1.041
UT	Logan	1990	1350	41.60	111.80	433	5.77											0.954	1.000	0.997	0.969	0.949	0.995	0.995	0.949	1.097	1.043
WA	Gramling	1998	386	46.29	119.73	178	7.42											0.966	1.000	0.997	0.979	0.954	1.023	0.988	0.953	1.113	1.029
WA	Grayland	1998	2	46.78	124.00	2032	2.78											0.916	1.000	1.002	0.957	0.916	0.997	1.000	0.914	1.208	1.202
WA	Paterson	1998	109	45.94	119.49	152	6.65											0.957	1.000	0.997	0.980	0.947	1.007	0.989	0.947	1.124	1.053
WA	Puyallup	1998	61	47.10	122.30	1016	3.48											0.961	1.000	1.000	0.944	0.958	0.998	0.997	0.957	1.136	1.104
WA	Roza	1998	343	46.29	119.73	178	5.96											0.966	1.000	0.997	0.977	0.956	1.005	0.990	0.956	1.124	1.052
	Average							0.954	1.000	0.998	0.971	0.947	1.008	0.992	0.947	1.136	1.069	0.955	1.000	0.997	0.969	0.948	1.003	0.992	0.948	1.123	1.082
	Minimum							0.904	1.000	0.993	0.948	0.905	0.991	0.982	0.906	1.080	0.983	0.887	1.000	0.992	0.944	0.887	0.989	0.983	0.884	1.069	0.989
	Maximum							0.979	1.000	1.002	0.990	0.976	1.036	1.002	0.975	1.427	1.425	0.975	1.000								

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY							GROWING SEASON						
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50		1.000	0.999	0.995	0.996	0.984	0.984	0.948	1.000	0.999	0.994	0.993	0.983	0.983	0.972
AZ	Phoenix	1998	335	33.48	112.10	175	9.67		1.000	0.999	0.996	0.995	0.986	0.986	0.954	1.000	0.999	0.995	0.991	0.985	0.985	0.979
AZ	Tucson	1997	713	32.28	110.94	300	11.37		1.000	0.999	0.997	0.993	0.986	0.986	0.858	1.000	0.999	0.996	0.992	0.985	0.985	0.892
AZ	Tucson	1998	713	32.28	110.94	300	10.93		1.000	0.999	0.997	0.993	0.988	0.988	0.876	1.000	0.999	0.996	0.990	0.987	0.987	0.914
CA	Davis	1998	18	38.50	121.80	461	8.55		1.000	0.999	0.999	0.988	0.989	0.989	0.962	1.000	0.999	0.998	0.989	0.989	0.989	0.975
CA	Fresno	1998	103	36.80	119.70	269	9.09		1.000	0.999	0.998	0.986	0.989	0.989	0.963	1.000	0.999	0.997	0.988	0.988	0.988	0.984
CA	Santa Maria	1998	82	35.00	120.40	314	5.11		1.000	0.999	1.000	0.986	1.000	1.000	0.959	1.000	0.999	1.000	0.982	0.996	0.996	1.017
CO	Center	1997	2348	38.00	106.00	178	7.24									1.000	0.999	1.002	0.977	1.002	1.002	0.973
CO	Center	1999	2348	38.00	106.00	178	7.73									1.000	0.998	1.001	0.982	1.003	1.003	0.976
CO	Colton	1982	2743	39.00	106.00	279	5.85									1.000	0.999	1.003	0.968	1.006	1.006	1.007
CO	Colton	1983	2743	39.00	106.00	279	5.91									1.000	0.999	1.003	0.973	1.006	1.006	1.006
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76		1.000	0.999	1.001	0.980	0.986	0.986	0.905	1.000	0.999	1.000	0.970	0.988	0.988	0.999
CO	Fruita	1997	1274	38.00	104.00	228	10.45									1.000	0.999	0.999	0.986	0.994	0.994	0.966
CO	Fruita	1999	1274	38.00	104.00	228	9.06									1.000	0.999	0.999	0.980	0.994	0.994	0.950
CO	Loveland	1997	1540	40.40	105.11	406	6.68		1.000	0.999	1.001	0.975	1.002	1.002	0.952	1.000	0.999	1.000	0.971	1.000	1.000	1.008
CO	Loveland	1998	1540	40.40	105.11	406	6.45		1.000	0.999	1.001	0.976	1.001	1.001	0.936	1.000	0.999	1.000	0.972	0.998	0.998	0.996
CO	Ovid	1998	1089	40.97	102.45	448	7.12		1.000	0.999	1.000	0.985	0.974	0.974	0.886	1.000	0.999	0.999	0.982	0.974	0.974	0.953
CO	Ovid	1999	1089	40.97	102.45	448	7.55		1.000	0.998	1.000	0.984	0.975	0.975	0.876	1.000	0.999	0.999	0.980	0.976	0.976	0.948
CO	Portis	1982	2895	39	106	279	4.74									1.000	0.999	1.003	0.967	1.008	1.008	1.021
CO	Portis	1983	2895	39	106	279	5									1.000	0.999	1.004	0.969	1.009	1.009	1.040
CO	Rocky Ford	1997	1274	38	104	279	9.44									1.000	0.999	0.999	0.984	1.007	1.007	0.944
CO	Rocky Ford	1999	1274	38	104	279	11.37									1.000	0.999	0.999	0.981	1.007	1.007	0.924
CO	Wiggins	1997	1367	40.31	104.06	353	7.30		1.000	0.999	1.000	0.983	0.975	0.975	0.893	1.000	0.999	1.000	0.980	0.975	0.975	0.950
CO	Wiggins	1998	1367	40.31	104.06	353	7.67		1.000	0.999	1.000	0.984	0.975	0.975	0.897	1.000	0.999	1.000	0.982	0.975	0.975	0.954
CO	Yellow Jacket	1997	2252	37.00	109.00	406	7.60									1.000	0.999	1.000	0.976	0.997	0.997	0.989
CO	Yellow Jacket	1999	2252	37.00	109.00	406	7.70									1.000	0.999	1.001	0.978	0.999	0.999	0.961
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51		1.000	0.999	0.996	0.988	1.004	1.004	0.942	1.000	0.999	0.996	0.985	1.002	1.002	0.977
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12		1.000	0.999	0.997	0.987	1.004	1.004	0.924	1.000	0.999	0.996	0.985	1.003	1.003	0.949
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81		1.000	0.999	0.997	0.990	1.005	1.005	0.960	1.000	0.999	0.996	0.986	1.003	1.003	0.992

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY							GROWING SEASON						
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulugus	1997	37	30.76	84.485	1460	5.02		1.000	0.999	0.998	0.979	1.005	1.005	0.959	1.000	0.999	0.998	0.979	1.003	1.003	1.007
GA	Attapulugus	1998	37	30.76	84.485	1460	7.68		1.000	0.999	0.997	0.976	1.003	1.003	0.984	1.000	0.999	0.997	0.978	1.002	1.002	1.018
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.85		1.000	0.999	1.001	0.962	1.009	1.009	0.993	1.000	0.999	1.001	0.965	1.007	1.007	1.051
GA	Blairsville	1998	584.3	34.84	83.928	1307	5.27		1.000	0.999	1.000	0.968	1.008	1.008	0.958	1.000	0.999	0.999	0.971	1.006	1.006	1.005
GA	Griffin	1997	281.9	33.26	84.284	1447	5.9		1.000	0.999	0.999	0.978	1.008	1.008	0.921	1.000	0.999	0.998	0.980	1.006	1.006	0.966
GA	Griffin	1998	281.9	33.26	84.284	1447	7.27		1.000	0.999	0.998	0.978	1.005	1.005	0.981	1.000	0.999	0.997	0.978	1.004	1.004	1.002
ID	Ashton	1997	1615	44.03	111.47	430	6.01		1.000	0.998	1.001	0.976	1.010	1.010	0.969	1.000	0.998	1.001	0.974	1.008	1.008	0.984
ID	Ashton	1998	1615	44.03	111.47	430	7.04		1.000	0.999	1.001	0.976	1.009	1.009	0.973	1.000	0.999	1.001	0.978	1.007	1.007	0.987
ID	Parma	1997	703	43.80	116.93	237	6.89		1.000	0.999	1.000	0.982	1.004	1.004	0.966	1.000	0.999	1.000	0.982	1.003	1.003	0.988
ID	Parma	1998	703	43.80	116.93	237	7.29		1.000	0.999	1.000	0.978	1.004	1.004	0.971	1.000	0.999	1.000	0.981	1.003	1.003	1.006
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53		1.000	0.999	1.000	0.984	1.008	1.008	0.938	1.000	0.999	1.000	0.982	1.005	1.005	0.978
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19		1.000	0.999	1.000	0.978	1.006	1.006	0.931	1.000	0.999	1.000	0.979	1.004	1.004	0.975
IL	Belleville	1999	133	38.52	89.88	974	5.76		1.000	0.999	0.999	0.983	1.007	1.007	0.980	1.000	0.999	0.998	0.975	1.003	1.003	1.049
IL	Bondville	1999	213	40.05	88.37	1008	5.66		1.000	0.999	0.999	0.983	1.010	1.010	0.944	1.000	0.999	0.998	0.977	1.006	1.006	0.996
IL	Monmouth	1999	229	40.92	90.73	942	5.87		1.000	0.999	0.999	0.984	1.011	1.011	0.953	1.000	0.999	0.998	0.976	1.007	1.007	1.016
MT	Creston	1997	899	48.19	114.13	390	4.84		1.000	0.999	1.002	0.958	1.009	1.009	0.978	1.000	0.999	1.002	0.964	1.007	1.007	1.017
MT	Creston	1998	899	48.19	114.13	390	5.78		1.000	0.999	1.001	0.965	1.007	1.007	0.961	1.000	0.999	1.001	0.972	1.005	1.005	1.009
MT	Ronan	1997	927	47.54	114.28	380	4.89		1.000	0.999	1.002	0.957	1.008	1.008	0.998	1.000	0.999	1.002	0.962	1.006	1.006	1.041
MT	Ronan	1998	927	47.54	114.28	380	5.42		1.000	0.999	1.001	0.961	1.006	1.006	0.993	1.000	0.999	1.001	0.968	1.004	1.004	1.047
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40		1.000	0.999	1.002	0.962	1.008	1.008	0.956	1.000	0.999	1.001	0.967	1.007	1.007	1.006
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43		1.000	0.999	1.001	0.968	1.005	1.005	0.936	1.000	0.999	1.000	0.975	1.004	1.004	0.989
NE	Champion	1997	1029	40.22	101.43	482	8.71		1.000	0.998	0.999	0.984	0.991	0.991	0.882	1.000	0.998	0.998	0.979	0.989	0.989	0.949
NE	Champion	1998	1029	40.22	101.43	482	8.19		1.000	0.998	0.999	0.981	0.990	0.990	0.876	1.000	0.999	0.998	0.980	0.988	0.988	0.939
NE	Clay Center	1997	552	40.31	98.08	685	6.69		1.000	0.998	0.999	0.979	0.995	0.995	0.921	1.000	0.999	0.998	0.975	0.993	0.993	0.986
NE	Clay Center	1998	552	40.31	98.08	685	6.52		1.000	0.998	0.999	0.976	0.994	0.994	0.925	1.000	0.999	0.998	0.976	0.992	0.992	0.973
NE	Mead	1997	366	41.08	96.30	743	6.50		1.000	0.999	0.999	0.976	0.993	0.993	0.921	1.000	0.999	0.998	0.974	0.992	0.992	0.978
NE	Mead	1998	366	41.08	96.30	743	5.54		1.000	0.999	0.999	0.975	0.993	0.993	0.926	1.000	0.999	0.998	0.974	0.992	0.992	0.977
NY	Ithaca	1997	123	42.45	76.45	914	4.44		1.000	0.999	1.001	0.954	1.013	1.013	0.971	1.000	0.999	1.001	0.961	1.010	1.010	1.032
NY	Ithaca	1998	123	42.45	76.45	914	4.39		1.000	0.999	1.001	0.957	1.011	1.011	0.970	1.000	0.999	1.000	0.962	1.008	1.008	1.036
NY	Valatie	1997	76	42.43	73.68	914	4.03		1.000	0.999	1.002	0.945	1.009	1.009	1.042	1.000	0.999	1.001	0.951	1.006	1.006	1.107
NY	Valatie	1998	76	42.43	73.68	914	4.14		1.000	0.999	1.001	0.950	1.008	1.008	1.014	1.000	0.999	1.001	0.955	1.006	1.006	1.069
NY	Willsboro	1998	43	44.38	73.38	762	4.24		1.000	0.999	1.001	0.953	1.011	1.011	0.962	1.000	0.999	1.001	0.958	1.008	1.008	1.029

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr, continued.

									YEARLY SUMMARY						GROWING SEASON								
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)	
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ET (ASCE PM) - mm															
OK	Apache	1997	440	34.91	98.29	757	8.36		1.000	0.998	0.998	0.987	0.991	0.991	0.920	1.000	0.998	0.996	0.982	0.989	0.989	0.986	
OK	Apache	1998	440	34.91	98.29	757	11.47		1.000	0.999	0.996	0.988	0.985	0.985	0.882	1.000	0.999	0.995	0.987	0.981	0.981	0.908	
OK	Goodwell	1997	996	36.60	101.60	447	12.07		1.000	0.998	0.998	0.989	0.989	0.989	0.878	1.000	0.999	0.997	0.984	0.986	0.986	0.934	
OK	Goodwell	1998	996	36.60	101.60	447	14.03		1.000	0.998	0.998	0.991	0.986	0.986	0.858	1.000	0.998	0.996	0.987	0.983	0.983	0.894	
OK	Marena	1997	331	36.06	97.21	889	6.67		1.000	0.999	0.998	0.983	0.991	0.991	0.917	1.000	0.999	0.997	0.979	0.990	0.990	0.993	
OK	Marena	1998	331	36.06	97.21	889	8.64		1.000	0.999	0.997	0.983	0.986	0.986	0.908	1.000	0.999	0.995	0.982	0.983	0.983	0.955	
OK	Wister	1997	143	34.98	94.68	1188	5.59		1.000	0.999	0.999	0.971	0.994	0.994	0.985	1.000	0.999	0.998	0.971	0.993	0.993	1.056	
OK	Wister	1998	143	34.98	94.68	1188	7.40		1.000	0.999	0.997	0.979	0.988	0.988	0.949	1.000	0.999	0.996	0.980	0.986	0.986	0.998	
OR	Haga	1999	9	42.50	124.50	1778	3.33		1.000	1.000	1.004	0.935	1.009	1.009	1.000	1.000	1.000	1.004	0.949	1.008	1.008	1.015	
SC	Florence	1986	40	34.24	79.81	1120	7.05		1.000	0.999	0.998	0.978	1.006	1.006	0.925	1.000	0.999	0.997	0.980	1.004	1.004	0.976	
TX	Bushland	1997	1170	35.11	102.05	505	9.88		1.000	0.998	0.998	0.988	1.004	1.004	0.902	1.000	0.998	0.997	0.983	1.000	1.000	0.967	
TX	Bushland	1998	1170	35.11	102.05	505	13.27		1.000	0.998	0.998	0.989	1.001	1.001	0.887	1.000	0.998	0.997	0.988	0.999	0.999	0.916	
TX	Dalhart	1997	1228	36.20	102.32	467	8.33		1.000	0.998	0.999	0.986	1.005	1.005	0.904	1.000	0.999	0.999	0.985	1.003	1.003	0.940	
TX	Dalhart	1998	1228	36.20	102.32	467	10.96		1.000	0.999	0.999	0.986	1.003	1.003	0.887	1.000	0.999	0.998	0.985	1.001	1.001	0.923	
UT	Logan	1989	1350	41.60	111.80	433	7.69									1.000	0.999	1.000	0.980	1.003	1.003	0.990	
UT	Logan	1990	1350	41.60	111.80	433	7.06									1.000	0.999	1.000	0.978	1.003	1.003	1.013	
WA	Gramling	1998	386	46.29	119.73	178	10.21									1.000	0.999	0.998	0.986	0.991	0.991	0.951	
WA	Grayland	1998	2	46.78	124.00	2032	2.96									1.000	0.999	1.002	0.963	1.025	1.025	1.118	
WA	Paterson	1998	109	45.94	119.49	152	8.65									1.000	0.999	0.998	0.985	0.992	0.992	0.993	
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									1.000	0.999	1.001	0.951	1.000	1.000	1.050	
WA	Roza	1998	343	46.29	119.73	178	7.40									1.000	0.999	0.999	0.983	0.992	0.992	0.989	
	Average								1.000	0.999	0.999	0.977	0.999	0.999	0.939	1.000	0.999	0.999	0.977	0.998	0.998	0.988	
	Minimum								1.000	0.998	0.995	0.935	0.974	0.974	0.858	1.000	0.998	0.994	0.949	0.974	0.974	0.892	
	Maximum								1.000	1.000	1.004	0.996	1.013	1.013	1.042	1.000	1.000	1.004	0.993	1.025	1.025	1.118	

ASCE Standardized Reference Evapotranspiration Equation

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method)

									YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50		0.976	1.004	1.001	0.998	1.002	1.051	1.031	1.003	0.975	1.001	0.998	0.996	1.002	1.049	1.028	0.998
AZ	Phoenix	1998	335	33.48	112.10	175	9.67		0.966	1.000	0.997	0.993	0.990	1.041	1.024	0.996	0.969	1.000	0.997	0.995	0.994	1.043	1.025	0.993
AZ	Tucson	1997	713	32.28	110.94	300	11.37		0.957	0.982	0.979	0.974	0.983	1.052	1.009	0.997	0.973	0.995	0.992	0.989	1.001	1.067	1.023	0.999
AZ	Tucson	1998	713	32.28	110.94	300	10.93		0.948	0.982	0.978	0.974	0.972	1.039	1.007	0.989	0.970	1.001	0.998	0.996	0.995	1.060	1.028	0.994
CA	Davis	1998	18	38.50	121.80	461	8.55		0.905	0.975	0.973	0.973	0.922	1.010	0.994	0.953	0.912	0.979	0.977	0.976	0.930	1.016	0.998	0.953
CA	Fresno	1998	103	36.80	119.70	269	9.09		0.945	0.993	0.991	0.990	0.962	1.032	1.011	0.970	0.955	0.998	0.995	0.994	0.973	1.040	1.016	0.970
CA	Santa Maria	1998	82	35.00	120.40	314	5.11		0.905	0.991	0.989	0.984	0.911	0.994	0.998	0.978	0.930	1.024	1.021	1.018	0.940	1.023	1.034	0.986
CO	Center	1997	2348	38.00	106.00	178	7.24										0.934	0.995	0.993	0.988	0.945	1.028	1.006	0.968
CO	Center	1999	2348	38.00	106.00	178	7.73										0.930	0.994	0.992	0.986	0.940	1.034	1.005	0.977
CO	Colton	1982	2743	39.00	106.00	279	5.85																	
CO	Colton	1983	2743	39.00	106.00	279	5.91																	
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																	
CO	Fruita	1997	1274	38.00	104.00	228	10.45										0.954	1.007	1.004	0.992	0.952	1.010	1.005	0.999
CO	Fruita	1999	1274	38.00	104.00	228	9.06										0.964	1.006	1.003	0.991	0.962	1.011	1.004	0.997
CO	Loveland	1997	1540	40.40	105.11	406	6.68		0.967	0.999	0.997	0.992	0.978	1.036	1.010	0.997	0.975	1.005	1.003	0.999	0.986	1.037	1.016	0.984
CO	Loveland	1998	1540	40.40	105.11	406	6.45		0.965	0.995	0.993	0.989	0.979	1.037	1.010	0.993	0.979	1.013	1.010	1.008	0.993	1.045	1.027	0.988
CO	Ovid	1998	1089	40.97	102.45	448	7.12		0.896	0.953	0.951	0.949	0.914	1.007	0.973	0.968	0.942	1.000	0.997	0.997	0.961	1.045	1.020	0.981
CO	Ovid	1999	1089	40.97	102.45	448	7.55		0.885	0.947	0.945	0.943	0.903	1.001	0.967	0.960	0.934	1.001	0.999	1.000	0.951	1.040	1.019	0.971
CO	Portis	1982	2895	39	106	279	4.74																	
CO	Portis	1983	2895	39	106	279	5																	
CO	Rocky Ford	1997	1274	38	104	279	9.44										1.013	1.041	1.038	1.022	1.007	1.046	1.035	1.042
CO	Rocky Ford	1999	1274	38	104	279	11.37										1.001	1.022	1.019	1.007	0.996	1.030	1.017	1.054
CO	Wiggins	1997	1367	40.31	104.06	353	7.30		0.907	0.954	0.951	0.946	0.925	1.009	0.973	0.970	0.928	0.973	0.970	0.967	0.946	1.022	0.992	0.965
CO	Wiggins	1998	1367	40.31	104.06	353	7.67		0.903	0.956	0.954	0.949	0.921	1.001	0.976	0.964	0.932	0.984	0.981	0.978	0.951	1.024	1.003	0.967
CO	Yellow Jacket	1997	2252	37.00	109.00	406	7.60										0.932	0.981	0.979	0.977	0.955	1.024	1.005	0.991
CO	Yellow Jacket	1999	2252	37.00	109.00	406	7.70										0.944	0.999	0.997	0.995	0.942	0.993	0.997	0.999
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51		0.872	0.928	0.925	0.924	0.868	0.924	0.923	0.920	0.889	0.939	0.936	0.936	0.884	0.935	0.934	0.919
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12		0.877	0.928	0.925	0.922	0.872	0.923	0.922	0.944	0.887	0.935	0.933	0.930	0.882	0.931	0.930	0.945
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81		0.944	1.015	1.012	0.994	0.940	1.019	1.010	0.994	0.945	1.016	1.014	1.001	0.941	1.020	1.012	0.988

ASCE Standardized Reference Evapotranspiration Equation

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method), continued.

StateSiteYearElevation (m)LatitudeLongitudeMean Annual Precip (mm)Peak-MonthMean Daily ETr (ASCE PM) - mm									YEARLY SUMMARY								GROWING SEASON							
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.485	1460	5.02	0.873	0.925	0.923	0.924	0.869	0.924	0.921	0.922	0.891	0.940	0.938	0.939	0.887	0.938	0.936	0.918	
GA	Attapulgus	1998	37	30.76	84.485	1460	7.68	0.875	0.925	0.922	0.926	0.870	0.924	0.920	0.917	0.887	0.935	0.932	0.935	0.883	0.933	0.930	0.912	
GA	Blairsville	1997	584	34.84	83.928	1307	4.85	0.926	0.971	0.968	0.970	0.921	0.971	0.965	0.950	0.954	0.999	0.996	0.998	0.949	0.997	0.993	0.952	
GA	Blairsville	1998	584	34.84	83.928	1307	5.27	0.885	0.941	0.939	0.942	0.880	0.940	0.936	0.934	0.902	0.959	0.956	0.959	0.898	0.957	0.954	0.932	
GA	Griffin	1997	282	33.26	84.284	1447	5.9	0.869	0.919	0.917	0.916	0.866	0.918	0.915	0.934	0.884	0.936	0.935	0.934	0.880	0.933	0.933	0.934	
GA	Griffin	1998	282	33.26	84.284	1447	7.27	0.896	0.947	0.944	0.947	0.892	0.945	0.942	0.942	0.904	0.955	0.953	0.954	0.900	0.953	0.951	0.944	
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.933	0.992	0.990	0.985	0.942	1.042	1.002	0.979	0.936	0.993	0.991	0.990	0.947	1.043	1.004	0.974	
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.898	0.963	0.961	0.958	0.906	0.993	0.972	0.941	0.903	0.966	0.963	0.961	0.912	0.995	0.975	0.938	
ID	Parma	1997	703	43.80	116.93	237	6.89	0.954	0.994	0.991	0.991	0.968	1.035	1.008	0.982	0.959	0.995	0.992	0.992	0.973	1.037	1.009	0.980	
ID	Parma	1998	703	43.80	116.93	237	7.29	0.951	0.993	0.990	0.992	0.962	1.030	1.005	0.982	0.958	1.003	1.000	1.001	0.970	1.032	1.015	0.981	
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.918	0.959	0.957	0.953	0.929	1.017	0.970	0.963	0.930	0.968	0.965	0.963	0.942	1.021	0.980	0.961	
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.911	0.946	0.944	0.943	0.923	1.008	0.959	0.957	0.923	0.963	0.961	0.960	0.936	1.012	0.977	0.956	
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.994	1.044	1.042	1.034	0.989	1.041	1.040	1.028	1.011	1.065	1.062	1.060	1.007	1.062	1.061	1.022	
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.936	0.999	0.997	0.993	0.931	0.991	0.995	1.008	0.962	1.032	1.029	1.030	0.958	1.026	1.027	1.020	
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.916	0.964	0.962	0.958	0.912	0.957	0.959	0.968	0.939	1.000	0.997	0.998	0.935	0.996	0.995	0.974	
MT	Creston	1997	899	48.19	114.13	390	4.84	0.949	1.017	1.015	1.022	0.957	1.035	1.025	0.987	0.961	1.026	1.024	1.028	0.968	1.042	1.034	0.986	
MT	Creston	1998	899	48.19	114.13	390	5.78	0.947	1.005	1.003	1.010	0.957	1.029	1.015	0.983	0.956	1.019	1.016	1.019	0.966	1.031	1.029	0.977	
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.977	1.029	1.027	1.035	0.985	1.051	1.037	1.004	0.987	1.038	1.035	1.039	0.994	1.053	1.045	0.999	
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.978	1.021	1.019	1.025	0.987	1.045	1.031	0.995	0.987	1.034	1.031	1.033	0.996	1.047	1.044	0.988	
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.945	0.979	0.977	0.980	0.954	1.016	0.988	0.967	0.954	0.992	0.990	0.990	0.962	1.017	1.000	0.965	
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.924	0.937	0.935	0.935	0.937	0.995	0.949	0.945	0.927	0.950	0.947	0.945	0.939	0.990	0.961	0.938	
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.899	0.963	0.960	0.955	0.916	1.022	0.981	0.969	0.926	0.993	0.990	0.989	0.944	1.037	1.012	0.968	
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.883	0.941	0.938	0.933	0.900	0.997	0.959	0.954	0.914	0.976	0.973	0.970	0.932	1.021	0.995	0.961	
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.880	0.959	0.957	0.956	0.893	1.000	0.973	0.958	0.920	1.002	1.000	1.002	0.933	1.029	1.017	0.966	
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.857	0.935	0.933	0.934	0.870	0.969	0.949	0.930	0.892	0.966	0.964	0.965	0.906	0.996	0.981	0.941	
NE	Mead	1997	366	41.08	96.30	743	6.50	0.919	0.992	0.990	0.988	0.934	1.042	1.008	0.992	0.942	1.018	1.016	1.016	0.957	1.053	1.034	0.989	
NE	Mead	1998	366	41.08	96.30	743	5.54	0.904	0.966	0.964	0.962	0.918	1.014	0.981	0.972	0.926	0.991	0.990	0.990	0.939	1.026	1.006	0.975	
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.976	1.035	1.034	1.040	0.971	1.041	1.031	1.021	0.989	1.061	1.059	1.063	0.984	1.061	1.056	1.018	
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.977	1.037	1.035	1.039	0.972	1.041	1.033	1.020	0.989	1.060	1.057	1.059	0.985	1.060	1.055	1.012	
NY	Valatie	1997	76	42.43	73.68	914	4.03	1.028	1.061	1.059	1.070	1.023	1.060	1.057	1.037	1.042	1.076	1.074	1.079	1.037	1.072	1.072	1.028	
NY	Valatie	1998	76	42.43	73.68	914	4.14	1.006	1.051	1.048	1.060	1.002	1.051	1.047	1.024	1.016	1.062	1.059	1.065	1.013	1.060	1.058	1.011	
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.985	1.018	1.016	1.023	0.982	1.024	1.015	1.012	0.995	1.036	1.034	1.037	0.992	1.038	1.033	1.004	

ASCE Standardized Reference Evapotranspiration Equation

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method), continued.

								YEARLY SUMMARY								GROWING SEASON								
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36		0.904	0.953	0.951	0.949	0.920	1.028	0.971	0.971	0.930	0.985	0.982	0.983	0.947	1.043	1.003	0.974
OK	Apache	1998	440	34.91	98.29	757	11.47		0.916	0.955	0.953	0.952	0.938	1.035	0.979	0.977	0.937	0.971	0.969	0.969	0.962	1.048	0.998	0.982
OK	Goodwell	1997	996	36.60	101.60	447	12.07		0.885	0.933	0.931	0.925	0.904	1.013	0.954	0.950	0.902	0.954	0.952	0.950	0.924	1.022	0.976	0.945
OK	Goodwell	1998	996	36.60	101.60	447	14.03		0.887	0.927	0.924	0.918	0.908	1.015	0.950	0.955	0.912	0.948	0.945	0.943	0.936	1.033	0.974	0.958
OK	Marena	1997	331	36.06	97.21	889	6.67		0.923	0.982	0.979	0.982	0.939	1.036	0.999	0.998	0.947	1.008	1.005	1.007	0.963	1.049	1.025	0.993
OK	Marena	1998	331	36.06	97.21	889	8.64		0.934	0.982	0.979	0.983	0.955	1.044	1.004	0.996	0.950	0.994	0.992	0.995	0.973	1.051	1.018	0.991
OK	Wister	1997	143	34.98	94.68	1188	5.59		1.015	1.062	1.059	1.068	1.025	1.093	1.073	1.057	1.020	1.068	1.065	1.071	1.028	1.084	1.077	1.023
OK	Wister	1998	143	34.98	94.68	1188	7.40		1.021	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.026	1.079	1.075	1.079	1.044	1.108	1.098	1.052
OR	Haga	1999	9	42.50	124.50	1778	3.33																	
SC	Florence	1986	40	34.24	79.81	1120	7.05		0.957	0.989	0.987	0.988	0.975	1.045	1.008	1.005	0.966	1.003	1.000	1.000	0.984	1.049	1.022	1.002
TX	Bushland	1997	1170	35.11	102.05	505	9.88		0.859	0.904	0.903	0.896	0.875	0.985	0.921	0.921	0.882	0.936	0.934	0.932	0.899	0.997	0.953	0.925
TX	Bushland	1998	1170	35.11	102.05	505	13.27		0.870	0.910	0.908	0.902	0.889	0.994	0.930	0.927	0.891	0.929	0.927	0.924	0.912	1.013	0.951	0.933
TX	Dalhart	1997	1228	36.20	102.32	467	8.33		0.873	0.944	0.942	0.935	0.868	0.934	0.940	0.950	0.886	0.955	0.952	0.948	0.881	0.944	0.950	0.946
TX	Dalhart	1998	1228	36.20	102.32	467	10.96		0.882	0.948	0.945	0.942	0.877	0.937	0.943	0.952	0.903	0.965	0.962	0.961	0.898	0.953	0.960	0.954
UT	Logan	1989	1350	41.60	111.80	433	7.69										0.943	0.987	0.983	0.981	0.955	1.021	0.999	0.961
UT	Logan	1990	1350	41.60	111.80	433	7.06										0.935	0.987	0.984	0.982	0.944	1.006	0.997	0.951
WA	Gramling	1998	386	46.29	119.73	178	10.21										0.875	0.900	0.899	0.897	0.895	0.979	0.921	0.910
WA	Grayland	1998	2	46.78	124.00	2032	2.96										0.931	1.048	1.047	1.048	0.915	1.017	1.030	1.003
WA	Paterson	1998	109	45.94	119.49	152	8.65										0.922	0.973	0.970	0.970	0.939	1.019	0.991	0.951
WA	Puyallup	1998	61	47.10	122.30	1016	3.92										1.011	1.073	1.070	1.077	1.019	1.077	1.081	1.024
WA	Roza	1998	343	46.29	119.73	178	7.40										0.958	0.994	0.991	0.991	0.976	1.041	1.012	0.980
	Average								0.926	0.977	0.975	0.974	0.936	1.010	0.987	0.975	0.944	0.996	0.993	0.992	0.953	1.022	1.005	0.976
	Minimum								0.857	0.904	0.903	0.896	0.866	0.918	0.915	0.917	0.875	0.900	0.899	0.897	0.880	0.931	0.921	0.910
	Maximum								1.028	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.042	1.079	1.075	1.079	1.044	1.108	1.098	1.054

ASCE Standardized Reference Evapotranspiration Equation

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	0.976	1.003	0.996	0.994	0.986	1.034	1.014	0.951	0.975	1.000	0.992	0.988	0.985	1.031	1.009	0.971
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	0.966	0.999	0.993	0.988	0.976	1.026	1.010	0.950	0.969	0.999	0.992	0.986	0.979	1.027	1.009	0.972
AZ	Tucson	1997	713	32.28	110.94	300	11.37	0.957	0.981	0.976	0.967	0.970	1.037	0.995	0.855	0.973	0.994	0.987	0.981	0.986	1.051	1.007	0.891
AZ	Tucson	1998	713	32.28	110.94	300	10.93	0.948	0.981	0.975	0.967	0.961	1.026	0.994	0.867	0.970	1.000	0.994	0.986	0.982	1.046	1.013	0.908
CA	Davis	1998	18	38.50	121.80	461	8.55	0.905	0.974	0.972	0.961	0.912	0.999	0.982	0.916	0.912	0.978	0.975	0.965	0.919	1.004	0.985	0.928
CA	Fresno	1998	103	36.80	119.70	269	9.09	0.945	0.992	0.989	0.976	0.951	1.021	0.999	0.934	0.955	0.996	0.992	0.982	0.961	1.027	1.003	0.955
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	0.905	0.990	0.990	0.970	0.911	0.995	0.997	0.938	0.930	1.023	1.021	1.000	0.936	1.018	1.029	1.003
CO	Center	1997	2348	38.00	106.00	178	7.24									0.934	0.993	0.994	0.965	0.946	1.030	1.006	0.942
CO	Center	1999	2348	38.00	106.00	178	7.73									0.930	0.993	0.994	0.968	0.942	1.037	1.006	0.953
CO	Colton	1982	2743	39.00	106.00	279	5.85																
CO	Colton	1983	2743	39.00	106.00	279	5.91																
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																
CO	Fruita	1997	1274	38.00	104.00	228	10.45									0.954	1.006	1.003	0.978	0.947	1.005	0.999	0.966
CO	Fruita	1999	1274	38.00	104.00	228	9.06									0.964	1.005	1.002	0.971	0.957	1.006	0.997	0.947
CO	Loveland	1997	1540	40.40	105.11	406	6.68	0.967	0.998	0.998	0.967	0.980	1.038	1.011	0.949	0.975	1.004	1.003	0.971	0.986	1.037	1.015	0.991
CO	Loveland	1998	1540	40.40	105.11	406	6.45	0.965	0.994	0.994	0.965	0.980	1.038	1.009	0.929	0.979	1.012	1.010	0.979	0.992	1.043	1.025	0.984
CO	Ovid	1998	1089	40.97	102.45	448	7.12	0.896	0.952	0.950	0.935	0.890	0.981	0.946	0.858	0.942	0.999	0.996	0.979	0.936	1.018	0.993	0.935
CO	Ovid	1999	1089	40.97	102.45	448	7.55	0.885	0.946	0.945	0.928	0.880	0.975	0.941	0.842	0.934	1.000	0.997	0.976	0.929	1.016	0.995	0.942
CO	Portis	1982	2895	39.00	106.00	279	4.74																
CO	Portis	1983	2895	39.00	106.00	279	5																
CO	Rocky Ford	1997	1274	38.00	104.00	279	9.44									1.013	1.040	1.037	1.005	1.014	1.054	1.041	0.984
CO	Rocky Ford	1999	1274	38.00	104.00	279	11.37									1.001	1.021	1.018	0.987	1.003	1.038	1.024	0.974
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	0.907	0.952	0.952	0.930	0.902	0.983	0.947	0.866	0.928	0.972	0.970	0.948	0.923	0.996	0.966	0.916
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	0.903	0.955	0.954	0.934	0.898	0.975	0.950	0.865	0.932	0.983	0.981	0.961	0.927	0.998	0.977	0.922
CO	Yellow Jacke	1997	2252	37.00	109.00	406	7.60									0.932	0.980	0.979	0.954	0.952	1.022	1.001	0.980
CO	Yellow Jacke	1999	2252	37.00	109.00	406	7.70									0.944	0.998	0.998	0.973	0.941	0.992	0.995	0.960
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	0.872	0.927	0.922	0.912	0.871	0.927	0.925	0.866	0.889	0.938	0.932	0.922	0.886	0.937	0.936	0.898
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	0.877	0.927	0.922	0.910	0.875	0.927	0.925	0.872	0.887	0.935	0.929	0.916	0.885	0.933	0.932	0.897
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	0.944	1.014	1.009	0.984	0.944	1.024	1.014	0.954	0.945	1.015	1.010	0.987	0.944	1.024	1.014	0.981

ASCE Standardized Reference Evapotranspiration Equation

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr, continued.

StateSiteYear			Elevation (m)LatitudeLongitudeMean Annual Precip (mm)Peak-Month Mean Daily ETr (ASCE PM) - mm					YEARLY SUMMARY								GROWING SEASON							
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.49	1460	5.02	0.873	0.925	0.922	0.904	0.873	0.929	0.925	0.884	0.891	0.939	0.936	0.919	0.890	0.941	0.938	0.925
GA	Attapulgus	1998	37	30.76	84.49	1460	7.68	0.875	0.924	0.920	0.904	0.873	0.927	0.923	0.902	0.887	0.934	0.929	0.914	0.885	0.935	0.932	0.928
GA	Blairsville	1997	584	34.84	83.93	1307	4.85	0.926	0.970	0.970	0.934	0.930	0.980	0.974	0.943	0.954	0.999	0.997	0.964	0.955	1.004	1.000	1.001
GA	Blairsville	1998	584	34.84	83.93	1307	5.27	0.885	0.940	0.939	0.912	0.888	0.948	0.943	0.894	0.902	0.958	0.956	0.931	0.903	0.963	0.959	0.937
GA	Griffin	1997	282	33.26	84.28	1447	5.9	0.869	0.918	0.917	0.896	0.873	0.925	0.922	0.860	0.884	0.936	0.933	0.915	0.886	0.939	0.937	0.903
GA	Griffin	1998	282	33.26	84.28	1447	7.27	0.896	0.946	0.942	0.926	0.896	0.950	0.946	0.925	0.904	0.954	0.950	0.934	0.903	0.957	0.954	0.947
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.933	0.991	0.991	0.961	0.951	1.052	1.010	0.949	0.936	0.992	0.992	0.964	0.954	1.052	1.011	0.958
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.898	0.962	0.962	0.935	0.914	1.002	0.979	0.916	0.903	0.964	0.964	0.940	0.919	1.003	0.981	0.925
ID	Parma	1997	703	43.80	116.93	237	6.89	0.954	0.993	0.991	0.973	0.971	1.039	1.011	0.949	0.959	0.994	0.992	0.974	0.975	1.040	1.011	0.968
ID	Parma	1998	703	43.80	116.93	237	7.29	0.951	0.992	0.990	0.970	0.966	1.034	1.008	0.954	0.958	1.002	1.000	0.982	0.972	1.035	1.017	0.987
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.918	0.957	0.957	0.938	0.936	1.025	0.976	0.903	0.930	0.966	0.965	0.946	0.946	1.026	0.984	0.940
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.911	0.945	0.945	0.922	0.929	1.014	0.964	0.892	0.923	0.962	0.960	0.939	0.940	1.016	0.980	0.933
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.994	1.043	1.041	1.016	0.996	1.048	1.046	1.008	1.011	1.064	1.060	1.033	1.009	1.064	1.063	1.072
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.936	0.998	0.996	0.977	0.941	1.001	1.003	0.952	0.962	1.031	1.028	1.006	0.963	1.032	1.032	1.016
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.916	0.962	0.961	0.943	0.922	0.967	0.968	0.923	0.939	0.998	0.996	0.974	0.941	1.002	1.001	0.990
MT	Creston	1997	899	48.19	114.13	390	4.84	0.949	1.015	1.017	0.980	0.965	1.045	1.033	0.965	0.961	1.025	1.025	0.990	0.975	1.049	1.040	1.002
MT	Creston	1998	899	48.19	114.13	390	5.78	0.947	1.004	1.004	0.975	0.963	1.036	1.021	0.945	0.956	1.018	1.017	0.991	0.971	1.037	1.034	0.985
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.977	1.028	1.029	0.991	0.992	1.059	1.044	1.001	0.987	1.037	1.037	1.000	1.001	1.060	1.051	1.040
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.978	1.020	1.020	0.985	0.993	1.052	1.036	0.988	0.987	1.033	1.032	0.999	1.000	1.051	1.047	1.034
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.945	0.978	0.979	0.942	0.962	1.024	0.995	0.924	0.954	0.991	0.991	0.957	0.968	1.024	1.005	0.971
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.924	0.936	0.935	0.905	0.942	1.000	0.953	0.885	0.927	0.949	0.947	0.922	0.942	0.993	0.964	0.928
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.899	0.961	0.959	0.940	0.908	1.013	0.970	0.855	0.926	0.991	0.988	0.968	0.934	1.026	0.999	0.919
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.883	0.940	0.938	0.915	0.891	0.987	0.948	0.836	0.914	0.975	0.971	0.951	0.920	1.009	0.982	0.903
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.880	0.957	0.956	0.936	0.889	0.995	0.966	0.882	0.920	1.001	0.998	0.976	0.927	1.021	1.008	0.952
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.857	0.933	0.931	0.911	0.865	0.963	0.941	0.860	0.892	0.965	0.962	0.942	0.898	0.988	0.972	0.916
NE	Mead	1997	366	41.08	96.30	743	6.50	0.919	0.991	0.989	0.965	0.928	1.035	1.000	0.913	0.942	1.017	1.014	0.989	0.949	1.045	1.024	0.967
NE	Mead	1998	366	41.08	96.30	743	5.54	0.904	0.965	0.963	0.938	0.911	1.007	0.973	0.900	0.926	0.990	0.987	0.964	0.932	1.017	0.997	0.953
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.976	1.034	1.035	0.992	0.984	1.055	1.043	0.991	0.989	1.060	1.060	1.021	0.994	1.072	1.066	1.051
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.977	1.036	1.035	0.994	0.983	1.053	1.043	0.989	0.989	1.059	1.057	1.019	0.993	1.068	1.062	1.048
NY	Valatie	1997	76	42.43	73.68	914	4.03	1.028	1.061	1.061	1.011	1.033	1.070	1.066	1.081	1.042	1.076	1.075	1.027	1.044	1.079	1.078	1.138
NY	Valatie	1998	76	42.43	73.68	914	4.14	1.006	1.050	1.050	1.007	1.011	1.060	1.055	1.038	1.016	1.061	1.060	1.017	1.018	1.066	1.063	1.081
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.985	1.017	1.018	0.974	0.993	1.035	1.025	0.974	0.995	1.035	1.035	0.993	0.999	1.046	1.040	1.034

ASCE Standardized Reference Evapotranspiration Equation

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	0.904	0.952	0.949	0.937	0.912	1.019	0.961	0.893	0.930	0.983	0.978	0.965	0.937	1.032	0.991	0.960
OK	Apache	1998	440	34.91	98.29	757	11.47	0.916	0.954	0.949	0.941	0.924	1.019	0.963	0.882	0.937	0.970	0.963	0.957	0.944	1.029	0.978	0.908
OK	Goodwell	1997	996	36.60	101.60	447	12.07	0.885	0.932	0.930	0.915	0.894	1.002	0.942	0.834	0.902	0.952	0.948	0.936	0.911	1.008	0.961	0.883
OK	Goodwell	1998	996	36.60	101.60	447	14.03	0.887	0.925	0.922	0.910	0.895	1.001	0.934	0.819	0.912	0.947	0.942	0.932	0.920	1.015	0.955	0.856
OK	Marena	1997	331	36.06	97.21	889	6.67	0.923	0.980	0.978	0.965	0.931	1.027	0.989	0.913	0.947	1.007	1.002	0.986	0.953	1.038	1.013	0.985
OK	Marena	1998	331	36.06	97.21	889	8.64	0.934	0.981	0.976	0.966	0.941	1.029	0.988	0.905	0.950	0.993	0.987	0.976	0.956	1.033	1.000	0.947
OK	Wister	1997	143	34.98	94.68	1188	5.59	1.015	1.061	1.058	1.037	1.019	1.086	1.066	1.025	1.020	1.068	1.062	1.039	1.021	1.076	1.069	1.081
OK	Wister	1998	143	34.98	94.68	1188	7.40	1.021	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.026	1.079	1.075	1.079	1.044	1.108	1.098	1.052
OR	Haga	1999	9	42.50	124.50	1778	3.33																
SC	Florence	1986	40	34.24	79.81	1120	7.05	0.957	0.988	0.985	0.966	0.981	1.052	1.013	0.929	0.966	1.002	0.998	0.980	0.988	1.053	1.025	0.978
TX	Bushland	1997	1170	35.11	102.05	505	9.88	0.859	0.902	0.902	0.885	0.879	0.989	0.923	0.831	0.882	0.934	0.931	0.916	0.899	0.997	0.952	0.894
TX	Bushland	1998	1170	35.11	102.05	505	13.27	0.870	0.909	0.906	0.892	0.890	0.996	0.930	0.823	0.891	0.927	0.924	0.912	0.911	1.012	0.948	0.855
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	0.873	0.943	0.941	0.922	0.872	0.938	0.943	0.859	0.886	0.953	0.951	0.934	0.884	0.947	0.951	0.889
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	0.882	0.947	0.944	0.929	0.880	0.939	0.944	0.845	0.903	0.964	0.960	0.947	0.899	0.954	0.960	0.881
UT	Logan	1989	1350	41.60	111.80	433	7.69									0.943	0.986	0.984	0.961	0.958	1.024	1.001	0.952
UT	Logan	1990	1350	41.60	111.80	433	7.06									0.935	0.986	0.984	0.959	0.947	1.009	0.999	0.963
WA	Gramling	1998	386	46.29	119.73	178	10.21									0.875	0.899	0.897	0.885	0.886	0.970	0.911	0.865
WA	Grayland	1998	2	46.78	124.00	2032	2.96									0.931	1.047	1.049	1.009	0.938	1.043	1.055	1.121
WA	Paterson	1998	109	45.94	119.49	152	8.65									0.922	0.971	0.969	0.955	0.932	1.011	0.982	0.944
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									1.011	1.072	1.071	1.024	1.019	1.077	1.080	1.075
WA	Roza	1998	343	46.29	119.73	178	7.40									0.958	0.993	0.990	0.974	0.968	1.033	1.003	0.969
	Average							0.926	0.976	0.974	0.952	0.935	1.009	0.984	0.917	0.944	0.995	0.992	0.970	0.951	1.020	1.002	0.963
	Minimum							0.857	0.902	0.902	0.885	0.865	0.925	0.922	0.819	0.875	0.899	0.897	0.885	0.884	0.933	0.911	0.855
	Maximum							1.028	1.069	1.066	1.072	1.039	1.113	1.088	1.081	1.042	1.079	1.075	1.079	1.044	1.108	1.098	1.138

ASCE Standardized Reference Evapotranspiration Equation

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	0.972	1.000	0.993	0.990	0.983	1.030	1.010	0.948	0.975	1.000	0.992	0.988	0.985	1.031	1.010	0.971	
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	0.967	1.000	0.994	0.989	0.977	1.027	1.010	0.951	0.970	1.000	0.993	0.987	0.979	1.028	1.010	0.973	
AZ	Tucson	1997	713	32.28	110.94	300	11.37	0.975	1.000	0.995	0.986	0.989	1.057	1.014	0.872	0.979	1.000	0.993	0.987	0.992	1.057	1.013	0.896	
AZ	Tucson	1998	713	32.28	110.94	300	10.93	0.967	1.000	0.995	0.986	0.980	1.047	1.014	0.884	0.969	1.000	0.993	0.986	0.982	1.046	1.013	0.908	
CA	Davis	1998	18	38.50	121.80	461	8.55	0.929	1.000	0.998	0.987	0.936	1.026	1.008	0.941	0.933	1.000	0.997	0.987	0.940	1.027	1.008	0.949	
CA	Fresno	1998	103	36.80	119.70	269	9.09	0.952	1.000	0.997	0.984	0.959	1.029	1.007	0.942	0.959	1.000	0.996	0.985	0.965	1.031	1.006	0.958	
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	0.913	1.000	0.999	0.979	0.920	1.004	1.007	0.947	0.910	1.000	0.999	0.978	0.916	0.996	1.006	0.981	
CO	Center	1997	2348	38.00	106.00	178	7.24									0.940	1.000	1.001	0.972	0.952	1.036	1.013	0.948	
CO	Center	1999	2348	38.00	106.00	178	7.73									0.936	1.000	1.001	0.975	0.949	1.044	1.013	0.960	
CO	Colton	1982	2743	39.00	106.00	279	5.85																	
CO	Colton	1983	2743	39.00	106.00	279	5.91																	
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																	
CO	Fruita	1997	1274	38.00	104.00	228	10.45									0.948	1.000	0.997	0.972	0.941	0.999	0.993	0.960	
CO	Fruita	1999	1274	38.00	104.00	228	9.06									0.959	1.000	0.997	0.967	0.952	1.001	0.993	0.942	
CO	Loveland	1997	1540	40.40	105.11	406	6.68	0.969	1.000	1.000	0.969	0.982	1.040	1.013	0.951	0.970	1.000	0.998	0.963	0.980	1.029	1.010	0.997	
CO	Loveland	1998	1540	40.40	105.11	406	6.45	0.971	1.000	0.999	0.971	0.985	1.044	1.015	0.935	0.968	1.000	0.998	0.967	0.979	1.029	1.012	0.979	
CO	Ovid	1998	1089	40.97	102.45	448	7.12	0.941	1.000	0.998	0.982	0.935	1.030	0.994	0.901	0.943	1.000	0.997	0.981	0.937	1.020	0.994	0.936	
CO	Ovid	1999	1089	40.97	102.45	448	7.55	0.935	1.000	0.999	0.981	0.930	1.031	0.994	0.890	0.934	1.000	0.998	0.980	0.929	1.023	0.995	0.918	
CO	Portis	1982	2895	39	106	279	4.74																	
CO	Portis	1983	2895	39	106	279	5																	
CO	Rocky Ford	1997	1274	38	104	279	9.44									0.974	1.000	0.997	0.966	0.976	1.014	1.001	0.946	
CO	Rocky Ford	1999	1274	38	104	279	11.37									0.980	1.000	0.997	0.967	0.982	1.016	1.002	0.953	
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	0.952	1.000	0.999	0.976	0.947	1.033	0.995	0.910	0.954	1.000	0.998	0.973	0.949	1.023	0.995	0.952	
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	0.945	1.000	0.999	0.978	0.940	1.021	0.994	0.906	0.949	1.000	0.998	0.977	0.944	1.015	0.994	0.944	
CO	Yellow Jacket	1997	2252	37.00	109.00	406	7.60									0.951	1.000	0.999	0.973	0.971	1.042	1.021	1.000	
CO	Yellow Jacket	1999	2252	37.00	109.00	406	7.70									0.946	1.000	1.000	0.975	0.943	0.994	0.997	0.962	
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	0.941	1.000	0.994	0.984	0.940	1.001	0.999	0.935	0.947	1.000	0.993	0.982	0.945	0.999	0.997	0.957	
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	0.946	1.000	0.995	0.982	0.944	1.000	0.998	0.941	0.950	1.000	0.994	0.981	0.947	0.999	0.997	0.960	
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	0.931	1.000	0.996	0.970	0.931	1.010	1.000	0.941	0.931	1.000	0.995	0.972	0.930	1.008	0.999	0.966	

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.485	1460	5.02	0.944	1.000	0.997	0.978	0.944	1.004	1.001	0.956	0.949	1.000	0.996	0.978	0.947	1.001	0.999	0.984	
GA	Attapulgus	1998	37	30.76	84.485	1460	7.68	0.946	1.000	0.995	0.978	0.945	1.003	0.998	0.976	0.950	1.000	0.994	0.978	0.947	1.000	0.997	0.993	
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.85	0.955	1.000	0.999	0.962	0.958	1.010	1.004	0.972	0.956	1.000	0.999	0.965	0.957	1.006	1.001	1.002	
GA	Blairsville	1998	584.3	34.84	83.928	1307	5.27	0.941	1.000	0.998	0.969	0.944	1.008	1.003	0.951	0.942	1.000	0.997	0.971	0.943	1.005	1.001	0.977	
GA	Griffin	1997	281.9	33.26	84.284	1447	5.9	0.947	1.000	0.998	0.976	0.951	1.008	1.004	0.937	0.945	1.000	0.997	0.978	0.947	1.004	1.002	0.965	
GA	Griffin	1998	281.9	33.26	84.284	1447	7.27	0.947	1.000	0.996	0.979	0.947	1.004	1.000	0.978	0.948	1.000	0.996	0.979	0.947	1.003	0.999	0.992	
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.941	1.000	1.001	0.970	0.960	1.062	1.020	0.958	0.942	1.000	1.000	0.972	0.960	1.054	1.018	0.971	
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.934	1.000	1.000	0.972	0.951	1.042	1.018	0.953	0.937	1.000	0.999	0.973	0.953	1.038	1.017	0.967	
ID	Parma	1997	703	43.80	116.93	237	6.89	0.961	1.000	0.998	0.980	0.978	1.047	1.018	0.956	0.962	1.000	0.997	0.977	0.976	1.033	1.015	0.999	
ID	Parma	1998	703	43.80	116.93	237	7.29	0.959	1.000	0.998	0.978	0.974	1.043	1.016	0.962	0.957	1.000	0.996	0.976	0.969	1.026	1.013	1.005	
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.959	1.000	1.000	0.979	0.978	1.071	1.020	0.944	0.962	1.000	0.999	0.979	0.980	1.067	1.019	0.962	
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.963	1.000	0.999	0.976	0.983	1.073	1.020	0.943	0.958	1.000	0.999	0.976	0.976	1.059	1.019	0.963	
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.952	1.000	0.998	0.974	0.954	1.004	1.002	0.966	0.950	1.000	0.996	0.971	0.949	1.000	0.999	1.007	
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.938	1.000	0.999	0.979	0.943	1.003	1.005	0.954	0.933	1.000	0.997	0.976	0.934	1.001	1.001	0.985	
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.952	1.000	0.999	0.979	0.958	1.005	1.006	0.959	0.940	1.000	0.997	0.975	0.943	1.004	1.002	0.991	
MT	Creston	1997	899	48.19	114.13	390	4.84	0.935	1.000	1.001	0.965	0.951	1.029	1.017	0.951	0.936	1.000	1.001	0.967	0.951	1.027	1.016	0.973	
MT	Creston	1998	899	48.19	114.13	390	5.78	0.943	1.000	1.000	0.971	0.959	1.032	1.017	0.941	0.937	1.000	1.000	0.973	0.952	1.018	1.016	0.963	
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.950	1.000	1.001	0.963	0.965	1.029	1.015	0.973	0.951	1.000	1.000	0.965	0.964	1.026	1.014	0.994	
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.958	1.000	1.000	0.965	0.973	1.031	1.015	0.969	0.953	1.000	0.999	0.967	0.966	1.017	1.014	0.993	
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.967	1.000	1.001	0.964	0.984	1.047	1.017	0.946	0.963	1.000	1.001	0.966	0.978	1.039	1.016	0.965	
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.988	1.000	1.000	0.967	1.006	1.069	1.019	0.946	0.975	1.000	0.999	0.971	0.991	1.046	1.016	0.973	
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.936	1.000	0.998	0.979	0.945	1.054	1.010	0.890	0.935	1.000	0.997	0.977	0.942	1.036	1.008	0.927	
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.940	1.000	0.998	0.974	0.948	1.050	1.009	0.889	0.937	1.000	0.997	0.976	0.944	1.035	1.007	0.926	
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.919	1.000	0.999	0.977	0.928	1.039	1.009	0.921	0.919	1.000	0.997	0.976	0.926	1.021	1.008	0.952	
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.918	1.000	0.998	0.976	0.926	1.032	1.009	0.922	0.924	1.000	0.997	0.976	0.931	1.024	1.007	0.949	
NE	Mead	1997	366	41.08	96.30	743	6.50	0.928	1.000	0.998	0.974	0.937	1.045	1.009	0.922	0.927	1.000	0.997	0.973	0.934	1.028	1.008	0.951	
NE	Mead	1998	366	41.08	96.30	743	5.54	0.937	1.000	0.998	0.972	0.945	1.044	1.008	0.933	0.935	1.000	0.997	0.973	0.941	1.027	1.007	0.962	
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.943	1.000	1.000	0.959	0.951	1.020	1.008	0.959	0.934	1.000	0.999	0.961	0.939	1.010	1.005	0.998	
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.943	1.000	1.000	0.960	0.949	1.016	1.006	0.955	0.935	1.000	0.998	0.962	0.938	1.008	1.003	0.998	
NY	Valatie	1997	76	42.43	73.68	914	4.03	0.969	1.000	1.000	0.953	0.974	1.009	1.005	1.019	0.970	1.000	0.999	0.951	0.971	1.003	1.002	1.065	
NY	Valatie	1998	76	42.43	73.68	914	4.14	0.958	1.000	0.999	0.959	0.962	1.009	1.004	0.988	0.960	1.000	0.999	0.957	0.961	1.005	1.001	1.028	
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.969	1.000	1.000	0.958	0.976	1.018	1.008	0.957	0.958	1.000	0.999	0.958	0.962	1.009	1.004	1.009	

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month	Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
									ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	0.950	1.000	0.997	0.984	0.959	1.071	1.010	0.939	0.946	1.000	0.996	0.982	0.954	1.050	1.008	0.977	
OK	Apache	1998	440	34.91	98.29	757	11.47	0.960	1.000	0.995	0.986	0.969	1.068	1.009	0.924	0.966	1.000	0.993	0.986	0.973	1.060	1.008	0.936	
OK	Goodwell	1997	996	36.60	101.60	447	12.07	0.949	1.000	0.997	0.982	0.959	1.075	1.011	0.894	0.947	1.000	0.996	0.982	0.956	1.058	1.009	0.927	
OK	Goodwell	1998	996	36.60	101.60	447	14.03	0.958	1.000	0.996	0.983	0.968	1.082	1.010	0.885	0.963	1.000	0.994	0.984	0.971	1.072	1.009	0.904	
OK	Marena	1997	331	36.06	97.21	889	6.67	0.942	1.000	0.997	0.984	0.949	1.048	1.008	0.932	0.941	1.000	0.996	0.980	0.947	1.031	1.007	0.979	
OK	Marena	1998	331	36.06	97.21	889	8.64	0.952	1.000	0.996	0.985	0.960	1.050	1.008	0.923	0.956	1.000	0.994	0.983	0.963	1.040	1.006	0.953	
OK	Wister	1997	143	34.98	94.68	1188	5.59	0.956	1.000	0.996	0.977	0.960	1.023	1.004	0.966	0.955	1.000	0.995	0.974	0.956	1.008	1.001	1.012	
OK	Wister	1998	143	34.98	94.68	1188	7.40	0.955	1.000	0.995	0.982	0.961	1.030	1.006	0.941	0.951	1.000	0.993	0.980	0.955	1.013	1.003	0.974	
OR	Haga	1999	9	42.50	124.50	1778	3.33	0.881	1.000	1.003	0.966	0.891	1.051	1.011	1.213	0.854	1.000	1.002	0.966	0.860	1.013	1.007	1.238	
SC	Florence	1986	40	34.24	79.81	1120	7.05	0.968	1.000	0.997	0.978	0.993	1.065	1.026	0.940	0.964	1.000	0.996	0.978	0.986	1.051	1.023	0.976	
TX	Bushland	1997	1170	35.11	102.05	505	9.88	0.952	1.000	0.999	0.981	0.974	1.096	1.022	0.921	0.945	1.000	0.996	0.980	0.963	1.067	1.019	0.957	
TX	Bushland	1998	1170	35.11	102.05	505	13.27	0.957	1.000	0.997	0.982	0.980	1.096	1.023	0.906	0.961	1.000	0.996	0.984	0.983	1.092	1.023	0.922	
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	0.925	1.000	0.998	0.978	0.925	0.995	1.000	0.911	0.929	1.000	0.998	0.980	0.927	0.994	0.998	0.933	
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	0.931	1.000	0.997	0.981	0.929	0.992	0.997	0.892	0.937	1.000	0.996	0.982	0.933	0.989	0.996	0.913	
UT	Logan	1989	1350	41.60	111.80	433	7.69									0.956	1.000	0.998	0.975	0.971	1.039	1.016	0.962	
UT	Logan	1990	1350	41.60	111.80	433	7.06									0.948	1.000	0.998	0.973	0.960	1.023	1.013	0.976	
WA	Gramling	1998	386	46.29	119.73	178	10.21									0.973	1.000	0.997	0.984	0.986	1.079	1.013	0.962	
WA	Grayland	1998	2	46.78	124.00	2032	2.96									0.889	1.000	1.002	0.964	0.896	0.996	1.008	1.072	
WA	Paterson	1998	109	45.94	119.49	152	8.65									0.949	1.000	0.997	0.984	0.959	1.040	1.011	0.972	
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									0.944	1.000	1.000	0.956	0.951	1.005	1.008	1.003	
WA	Roza	1998	343	46.29	119.73	178	7.40									0.965	1.000	0.998	0.981	0.975	1.041	1.010	0.976	
	Average							0.948	1.000	0.998	0.976	0.956	1.034	1.009	0.942	0.948	1.000	0.997	0.975	0.955	1.025	1.007	0.972	
	Minimum							0.881	1.000	0.993	0.953	0.891	0.992	0.994	0.872	0.854	1.000	0.992	0.951	0.860	0.989	0.993	0.896	
	Maximum							0.988	1.000	1.003	0.990	1.006	1.096	1.026	1.213	0.980	1.000	1.002	0.988	0.992	1.092	1.023	1.238	