ASCE'S STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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ABSTRACT

The ASCE Evapotranspiration in Irrigation and Hydrology Committee (ASCE-ET) is recommending for the intended purpose of establishing uniform evapotranspiration (ET) estimates and transferable crop coefficients, *two standardized* reference evapotranspiration *surfaces*: (1) a short crop (similar to grass) and (2) a tall crop (similar to alfalfa), and *one standardized* reference evapotranspiration *equation*. The equation is a simplified ASCE-Penman Monteith equation. The equation with appropriate constants is used to calculate standardized reference ET, short (ET_{os}) or standardized reference ET, tall (ET_{rs}). A constant in the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). A 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).

The standardized reference evapotranspiration surfaces and equation will provide:

1. A standardized calculated evaporative demand that can be used in developing transferable crop coefficients.
2. A clear methodology for practicing engineers to use for estimating reference ET.
3. More universal hourly equations that will provide better comparisons between summed hourly reference ET and daily reference ET.

The equation was selected based on the criteria that it would be understandable, defensible, accepted by science/engineering communities, simple, and would enable using existing data and technology. Based upon comparisons to lysimeter data and calculated reference evapotranspiration using 1982 Kimberly Penman, FAO-56 Penman, and ASCE Penman Monteith, ASCE-ET found the standardized reference ET equation to be sufficiently accurate to recommend its use for calculation of reference ET, the development of crop coefficients, and estimation of crop evapotranspiration. ASCE recommends using the symbols K_{co} for crop coefficients to be used with short crop reference ET_{os}, and K_{cr} for crop coefficients to be used with tall crop reference ET_{rs}.

Key Words:
Reference Evapotranspiration Equations

INTRODUCTION

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. The purpose of the equation is to bring commonality to the various reference ET equations and crop coefficients now in use.

The request to ASCE-ET was transmitted in a letter from IA's Executive Director. IA envisioned an equation that would be accepted by the U.S. scientific community, engineers, courts, policy makers, and end users. An equation that would be applicable to agricultural and landscape irrigation and

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1. Members of the American Society of Civil Engineers, Standardization of Reference Evapotranspiration Task committee and/or the Irrigation Association Water Management Committee.

facilitate the use and transfer of crop and landscape coefficients was requested. In addition, IA requested guidelines for using the equation in regions where climatic data are limited. Also, IA requested that ASCE-ET recommend methods for incorporating existing crop and landscape coefficients and existing reference ET calculations.

ASCE-ET Meetings

In response to IA, ASCE-ET committee members met three different times to discuss the issues. ASCE-ET met with members of IA's Water Management Committee in Denver, Colorado on May 25 and 26, 1999. At the Denver meeting attendees reviewed in detail the IA request. It was decided in Denver that the equation would be labeled the ASCE Standardized Reference Evapotranspiration Equation. In August 1999, ASCE-ET held its annual meeting in Seattle, Washington, and the ASCE Task Committee on Standardization of Reference Evapotranspiration (TC) was formed. Additionally, equations were selected by ASCE-ET to be evaluated as candidate standardized reference ET equations. The third meeting held November 18 and 19, 1999 in Phoenix, Arizona involved TC members only (although some TC members are members of the ASCE-ET committee and/or the IA water management committee). The purpose of that meeting was two-fold: (1) to evaluate the results of evapotranspiration estimates calculated using thirteen 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 on after the Phoenix meeting, an extensive amount of e-mail communication between ASCE-ET and TC members shared opinions and data on several of the technical issues that needed to be standardized for incorporation into the standardized reference equation. Several issues such as the calculation of net radiation, latent heat of vaporization, and measurement units for meteorological data were discussed by e-mail for several weeks.

Additional Motivations for Implementation

1. A standardized equation or equations will provide a standardized calculated evaporative demand that can be used in developing transferable coefficients.
2. Numerous reference crop equations have been developed and published which have created some confusion for practitioners as to which equation to use. For example, the TC evaluated seven basic reference evapotranspiration equations that calculate reference evapotranspiration for grass, alfalfa, or both.
3. The crop coefficient times reference ET procedure for estimating crop ET will be more readily adopted by the private sector and federal and state agencies if a scientific body recommends a standardized methodology.
4. Both the public and private sectors are now operating automated weather stations that calculate reference ET directly, and guidance as to which equation to use is needed.
5. Some reference crop equations have not worked well in coastal areas, and better hourly equations are needed.
6. Calculated hourly ET when summed for a 24-hour period should approximate calculated daily ET.

Criteria

The TC established several criteria for the selection of the equation. The criteria were that the product should be understandable, defensible, accepted by science/engineering communities, simple, enable use of existing data and technology, and 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. Additionally, the equation should be a derivation of accepted methods as described in Jensen et al. (1990), Allen et al. (1989), Allen et al. (1994), and Allen et al. (1996). Simplification of an accepted method without significant loss of accuracy was an important element of the criteria. Lastly, but of equal importance, the equation should be able to use existing hourly and/or daily data, and the sums of hourly calculated ET should closely approximate daily computed ET values.

Definition of the Equation

In its early discussions, ASCE-ET concluded that use of the term *standard* or *benchmark* 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. At the Denver meeting prior to testing of equations, ASCE-ET and IA members decided that two *standardized* reference ET surfaces along with *standardized* computational procedures were most appropriate for meeting the IA request. The two standardized reference ET surfaces to be adopted would be (1) a short crop (similar to grass) and (2) a tall crop (similar to alfalfa). Additionally, the TC recognized the need to have both hourly and daily reference ET equations.

Equations Evaluated

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

- ASCE-Penman Monteith (grass w/ h=0.12 m and alfalfa w/ h=0.50 m), Jensen et al. (1990)
- FAO-56 Penman Monteith (grass), Allen et al.(1998)
- Kimberly Penman (alfalfa), Wright (1982)
- CIMIS Penman (grass), Snyder and Pruitt (1985)
- NRCS Chapter 2 Penman Monteith (grass), Martin and Gilley (1993)
- Hargreaves (grass) Hargreaves (1985)

In their many years of research and practical experience, TC members have found that the ASCE Penman Monteith (ASCE-PM) equation, when applied using aerodynamic and surface resistance algorithms presented in Jensen et al. (1990), to match the particular reference type (0.12 m grass and 0.50 m alfalfa), provided accurate ET estimates compared with measured ET using a lysimeter with a reference crop. Since measured reference lysimeter ET data are limited worldwide and especially within the United States, the TC selected the ASCE-PM reference ET values as the measure against which to evaluate the proposed equations. The form of the ASCE-PM is:

$$ET = \left(\frac{\Delta(R_n - G) + K_{time}\,\rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right) / \lambda \qquad (1)$$

where:

ET = reference evapotranspiration(mm d^{-1} or mm h^{-1}),
R_n = net radiation (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}),
G = soil heat flux (MJ m^{-2} d^{-1} or MJ m^{-2} 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 (MJ kg^{-1} $^oC^{-1}$),
Δ = slope of the saturation vapor pressure temperature relationship (kPa $^oC^{-1}$),
γ = psychrometric constant (kPa $^oC^{-1}$),
r_s = (bulk) surface resistance (s m^{-1}),
r_a = aerodynamic resistance (s m^{-1}),
λ = latent heat of vaporization (MJ kg^{-1}), and
K_{time} = a unit conversion (86,400 s d^{-1} for ET in mm d^{-1} and 3600 s h^{-1} for ET in mm h^{-1}).

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 1. More detail is provided in Allen et al. (2000).

Table 1. Reference Evapotranspiration Equations and Procedures Evaluated

Abbreviation	Method or Procedure	Description
R_n 56	Net radiation	Net radiation calculated using FAO-56 procedures, Allen et al. (1998)
R_n Wright	Net radiation	Net radiation calculated using Wright (1982) procedure
G 56	Soil heat flux	Soil heat flux calculated using FAO-56 procedures, Allen et al. (1998)
ASCE-PM	ET_o & ET_r	ASCE-Penman Monteith, Jensen et al. (1990) w/Rn56, G56, r_a & r_s = F(ht)
FAO-56-PM	ET_o	ASCE-PM w/ ht = 0.12 m, r_s = 70 s/m and albedo = 0.23, R_n 56, G = 0, λ = 2.45 MJ kg^{-1}, Allen et al. (1998)
ASCE-PMD	ET_o & ET_r	ASCE-PM, r_a = f(ht), 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 = 30s/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, Wright (1982)
1982-Kpen	ET_r	1982 Kimberly Penman, Wright (1982 & 1987)
FAO24-Pen	ET_o	FAO24 Modified Penman, Doorenbos and Pruitt (1977)
1963-Pen	ET_o	1963 Version of Penman, Penman (1963)
1985-Harg	ET_o	1985 Version of Hargreaves, Hargreaves et al. (1985)
ASCE-PMrf	ET_o & ET_r	ASCE-PM, reduced form: R_n56, G56, ET_o rs = 70 s m^{-1}; ET_r rs = 45 s m^{-1}; ET_o zw & zh = 2 m; ET_r zw & zh = 1.5 m, d = 0.8 m.
ASCE-PMrfh	ET_o & ET_r	ASCE-PM reduced form hourly only: ET_o rs = 50 s m^{-1}; ET_r rs = 30 s m^{-1}.
CIMIS-Pen	ET_o	CIMIS Penman (hourly) with FAO-56 Rn and G = 0, Snyder and Pruitt (1985)

Issues Addressed

By careful examination of Table 1, it can be seen 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 use of a constant (2.45 MJ kg^{-1}) for the latent heat of vaporization (λ) was evaluated not only for how it changed with temperature, but the impact of that change on ET. The adoption of set values for surface and aerodynamic resistance occurred only after intense review and discussion by e-mail between TC members. The matter was also re-addressed at the Phoenix meeting. 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 criteria established.

Description of Evaluation

The evaluation was accomplished in part by using REF-ET, a software program capable of calculating reference ET by using up to 15 of the more common methods, Allen (1999). Allen modified the software to incorporate the 12 ET_o equations and 8 ET_r equations the TC selected for its initial evaluation. It was later modified again for testing the recommended reference ET equation. REF-ET was provided to TC members who had volunteered to calculate ET_o and ET_r using meteorological data within their region. The significant benefit of using REF-ET was that the output was standardized, which improved the efficiency of the analysis. At the Phoenix meeting, the TC was able to evaluate results of reference evapotranspiration estimates at 36 sites within the states of Arizona, California, Colorado, Idaho, Montana, Nebraska, Oklahoma, Oregon, South Carolina, Texas, Utah, and Washington. The elevation of the sites varied from 2 to 2,895 meters. Mean annual precipitation amounts ranged from 152 to 2,032 mm. Following the Phoenix meeting, data from the states of Florida, Georgia, Illinois, and New York were added to the analysis.

The results of REF-ET from all the sites were provided to Itenfisu et al. (2000). They compiled the information and conducted several equation-to-equation comparisons. The key comparisons were daily ET versus daily ASCE-PM, summed hourly ET versus daily ASCE-PM, and summed hourly ET versus daily ET (same method). The comparisons were made for both ET_o and Et_r. Itenfisu and Elliott analyzed the ratio of each equation's ET estimate to that of ASCE-PM, the Root Mean Square Difference (RMSD), and the RMSD as a percentage of ASCE-PM. For each of the site years, the statistics were summarized for growing season and, if available, the full year.

At the meeting in Phoenix, the TC spent the better part of two days reviewing and discussing the results of the 61 site-years of data. A detailed discussion of the results is presented in Itenfisu et al. (2000). Based upon that review and the extensive sharing of information prior to the meeting, the TC agreed upon the form of the standardized reference evapotranspiration equation.

Recommendation

The TC recommends that two Standardized Reference Evapotranspiration surfaces can be modeled using a Standardized Reference Evapotranspiration Equation with appropriate constants and standardized computational procedures be adopted. The surfaces/equations 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 grass).
>
> Standardized Reference Evapotranspiration Equation, Tall (ET_{rs}): 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. As a part of the standardization, the "full" form of the Penman-Monteith equation, Jensen et al. (1990), 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_{os} or ET_{rs}) 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 2 presents the form of the Standardized Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table 2 provides values for the constants C_n and C_d.

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (2)$$

where:

ET_{ref} = short (ET_{os}) or tall (ET_{rs}) standardized reference crop evapotranspiration (mm day^{-1} for daily time steps or mm hour^{-1} for hourly time steps),
R_n = calculated 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}), and
e_s = mean saturation vapor pressure at 1.5 to 2.5-m height (kPa),
e_s daily = 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 (kPa °C^{-1}),
γ = psychrometric constant (kPa °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 2. Values for C_n and C_d in Equation 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}

Briefly, C_n and C_d are based upon simplifying several terms within the ASCE-PM and limited rounding. The simplified terms are summarized in Table 3. Equations associated with calculation of required parameters in Equation 2, the detailed derivation of the constants in Table 2 and simplification of the terms listed in Table 3 are explained in more detail in Allen et al., (2000).

Table 3. ASCE Penman Monteith Terms Standardized for Standardized Reference Evapotranspiration Equations

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 of wind measurements, z_w	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m
Lambda	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}
R_n to predict daytime	> 0	> 0
R_n to predict nighttime	≤ 0	≤ 0

The standardized equation has been presented to IA in a brief four-page report. More detailed report and journal articles will be prepared containing specifics and referring to available publications for additional details.

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_{os} or ET_{rs}). It is recommended that the abbreviation for crop coefficients developed for use with ET_{os} be denoted as Kc_o and the abbreviation for crop coefficients developed for use with ET_{rs} be denoted as Kc_r. ET_c is to be calculated as shown in equation 3.

$$ET_c = Kc_o * ET_{os} \quad \underline{or} \quad ET_c = Kc_r * ET_{rs} \qquad (3)$$

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