ISSUES, REQUIREMENTS AND CHALLENGES IN SELECTING AND SPECIFYING A STANDARDIZED ET EQUATION

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Abstract

The ASCE Evapotranspiration in Irrigation and Hydrology Committee in cooperation with the Water Management Committee of the Irrigation Association has defined and established a standardized reference evapotranspiration (ET) equation. The purpose of the equation and standardized calculation of parameters is to bring a commonality to the methodology of reference ET and to the basis used to determine crop coefficients for both agricultural and landscape use. Issues and requirements in the selection and definition of the standardized procedure are that the procedure be understandable, defensible, accepted by science/engineering communities, relatively simple, and use existing and historical data and technology. The primary challenge was to select one or more equations that would satisfy the selection criteria. There have been traditionally two types of reference crops (grass and alfalfa) and six major reference equation types (Kimberly Penman, CIMIS[2] Penman, FAO Penman, ASCE Penman-Monteith, FAO-56 Penman-Monteith and NRCS Penman-Monteith) have evolved over the past thirty years, each having large groups of followers and related crop coefficients. In addition, the reference crop is a living crop and therefore changes in its height, leaf area, stage of growth, age, variety, stomatal feedback, and irrigation frequency impact its ET rate. Other challenges include a myriad of procedures used to predict net radiation, vapor pressure deficit and other equation parameters. Hourly and daily computation are both in common usage, therefore, it is important that hourly calculations, when summed for 24 hours agree relatively closely with calculations made on daily time steps.

Key Words
Reference Evapotranspiration, standardization, crop coefficients, crop water requirements

Introduction

In May 1999 the Irrigation Association (IA) formally requested that the American Society of Civil Engineers (ASCE) Evapotranspiration in Irrigation and Hydrology Committee define and establish a benchmark reference evapotranspiration (ET) equation. The purpose of the equation and standardized calculation procedures is to bring a commonality to the methodology of reference ET data and to the basis used to determine crop coefficients for both agricultural and landscape use. The committee, in association with some IA members, has held extensive discussions on the issues and requirements for a standardized reference ET formula and some of the challenges and problems in making the specifications. In addition, the committee has undertaken an intensive intercomparison of commonly used methods at forty-nine locations across the U.S (Itenfisu et al., 2000).

The primary issue is to select and specify a standardized equation(s) that serves the needs of a large group of users nationwide and that is compatible with current de facto standard equations and data sets, and that represents "reality" (i.e., measured ET from a reference crop) over the range of climates and regions within the nation. Other issues are whether one equation can span calculation timesteps ranging from less than one hour to one month with little modification and whether it can form a basis for computing crop coefficients from field measurements that allow the coefficients to be transferable, across the United States. Additional issues are whether a simplified equation is acceptable when the loss of accuracy is less than a few percent and whether

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[1] Members of the ASCE Task Committee on Standardization of Reference ET and/or the Water Management Committee of the Irrigation Association.
[2] CIMIS refers to California Irrigation Management and Information Service

it is important for the national standardization to follow an international standardization introduced by FAO in 1998. One last challenge is to present a fairly robust, yet simple procedure for converting crop coefficients between reference types to facilitate transfer of coefficients to new locations.

Issues and Requirements

Following are some of the issues and requirements that were discussed by the ASCE Task Committee on Standardization of Reference Evapotranspiration:

1. The selected ET computation procedure and resulting equations should facilitate determining crop coefficients for both agricultural and landscape usage.
   - Irrigation water management in urban areas is increasing in sophistication and information requirements. Substantial and widespread research is being conducted to quantify water requirements for various types of urban and residential land-covers. There is need for a reference ET basis that is easy to understand, visualize and apply using commonly available weather data and that is simplified for application by urban users who may lack a background in physical processes of energy balance and aerodynamic processes.
   - The visualization requirement suggests the need to include a grass reference basis for use in urban applications where turfgrass is a primary component.
   - It is desirable for landscape "cover" coefficients (K_c) to be transferable across a wide range of latitude and climate. Therefore, it is important that the adapted standardization be as accurate as possible over a wide range of climatic regions.

2. The selected ET computation procedure should apply to both tall (alfalfa) and short (grass) references. This issue and requirement narrows the number of equations that have direct application for both tall reference ET (ET_r) and short reference ET (ET_o) approximations.
   - For reasons already stated, ET_o has a long history of application in urban areas and for agriculture in much of the U.S. Alfalfa has a long history for agricultural application in the midwest and northwestern U.S. Families of crop coefficients have been developed for each reference type. Wide adoption of any standardization will require a method that is able to produce both ET_o and ET_r values that adequately represent each reference type.
   - Other methods that are tailored specifically for either ET_o or ET_r can be converted to the other reference type by multiplying by a conversion factor. However, there is substantial uncertainty in the ratio of ET_r/ET_o to use for conversion and how the ratio changes with location, time of year and with climate (Wright et al., 2000). Therefore, this approach to producing a method that is applicable to both ET_r and ET_o prediction was not recommended.

3. There are several methods that have been applied to both tall (alfalfa) and short (grass) reference surfaces.
   - The ASCE Penman-Monteith equation (ASCE PM), included within ASCE Manual 70, used algorithms for surface and aerodynamic resistance that were tailored to both grass and alfalfa references. These algorithms have had considerable review and application and are considered to produce relatively accurate estimates of ET_o and ET_r over a range of climates and locations. In addition, the PM equation includes parameterization of resistance components that have a physical basis. This facilitates changing these parameters to fit various surface conditions or characteristics or for tailoring the equation to better fit measured ET. This characteristic of the PM equation along with its didactic form increases its appeal.
   - The 1982 Kimberly Penman equation (Wright, 1982) includes a variable wind function that was developed to improve prediction of ET_r for the southern Idaho climate. The 1982 Kimberly Penman equation was demonstrated to have high predictive accuracy in other regions of the U.S. and worldwide in the analyses conducted for ASCE Manual 70. In 1996, Wright (1996) presented a variable wind function to use with the Kimberly Penman

equation for predicting ET_o. This form of the 1982 Kimberly Penman with grass wind function is referred to as the 1996 Kimberly Penman. Unfortunately, the 1996 Kimberly Penman was not included in the 1999 analyses conducted by ASCE (Walter et al., 2000; Itenfisu et al., 2000). In a recent analysis at an independent site near Bushland, Texas, the 1996 Kimberly Penman performed equally as well as the recommended ASCE standardized reference ET_o equation in predicting measured ET_o (Wright et al., 2000).

4. The ET computation procedure and resulting equation should have commonality and appeal to a wide range of users of reference ET data.
   - The intention of ASCE was to adapt and recommend a method or methods that have received widespread usage and testing. There was insufficient time or resources to launch a research study to develop or refine a new method. This would have required the assembly and analysis of a wide range of ET measurement data from locations in addition to those that have already been included in equation development (such as in ASCE Manual 70).
   - Although ASCE was careful to not allow international standardization and practice unduly influence practice within the U.S., there was some consideration given to current usage and practice within the international community. This included the recent release of FAO Irrigation and Drainage Paper No. 56 which adapted the FAO-56 Penman-Monteith equation as the sole ET_o reference method. The FAO-56 PM equation is a direct derivative of the ASCE PM equation. Therefore, all things being equal, there were some international grounds for adapting the ASCE PM equation as the standardized method.

5. The standardized method should be compatible with current de facto standard equations and data sets
   - Similar to the explanation provided above, the ASCE PM equation and implementation in the proposed standardization of ET_o closely resembles the FAO-56 PM equation. This is advantageous in providing for more “seamless” transfer of crop coefficients and other information developed in the U.S. that are based on reference ET.
   - The FAO-24 publication and various publications by the University of California and California Department of Water Resources contain a large number of crop coefficients that are based on ET_o. Therefore, it is important that the adopted standardization reproduce the ET_o that formed the basis of the published K_c information sufficiently close so that the large base of K_c information can be utilized with the new standardization with little or no modification. This was a primary supposition of FAO-56.
   - A family of alfalfa-based K_c’s developed by Wright (1982; Jensen et al., 1990) have received extensive use across the U.S. It is important to support the future usage of these K_c’s within a standardization framework.

6. The adapted equation or variations on the equation should span calculation timesteps ranging from less than one hour to one month.
   - Electronic data logging weather stations are becoming the norm. These systems are typically programmed to produce hourly and 24-hour summaries.
   - Computing ET on an hourly or shorter time step has advantages of improved accuracy in locations where large diurnal changes in wind speed and direction or cloudiness occur that are not typical of patterns at locations where daily ET methods have been developed. Once programmed into a computer or data logger, computation of hourly ET is relatively straightforward. Basically, the increase in effort is for quality control and assessment of much more information than required for daily summaries.
   - Even though hourly data are widely available and applied, it is important for the selected method(s) to apply to daily or even monthly summaries from historical periods. This is important in water rights work, irrigation water management, hydraulic design and in computing hydrologic water balances for historical time periods.

7. The adapted equation should provide for development of crop coefficients based on field measurements that are transferable across the United States.
   – Serious field measurement of ET represents an enormous investment in time and money. It is economically advantageous to leverage the past investments in quantifying ET demands for various agricultural and urban vegetation and landscapes at specific locations. Providing a reference ET basis that reproduces the reference basis and characterization of evaporative demand over a wide range of climate and latitude does this.

8. The adapted method should have a simplified and compact form (terms simplified and combined) that is traceable to a full form equation.
   – It is important to reduce any "intimidation factor" in the standardized method. Where possible and without the loss of accuracy, simplifications should be made to the finalized equation to facilitate its coding and debugging in computer programs and to enhance the process of teaching, presenting, and explaining the method.
   – The full, original form of the equation should be retained as background to assist in educating the user in the various physical processes that govern evapotranspiration. The full form should also be referred to for research applications or for derivation or refinement of the simplified, standardized forms in the future.

Challenges

The following are some of the challenges faced by the Task Committee (TC) in analyzing and implementing the various requirements summarized above:

1. There is a large array and diversity of ET methods that have been developed and applied over the history of the U.S. There is diversity in the specific type and form of ET equations applied in various states. These include:
   – "Modified" Penman equations
   – Forms of the Penman-Monteith equation
   – Forms of the Blaney-Criddle equation
   – Jensen-Haise equation
   – Hargreaves equation
   – Pan Evaporation (direct and using various "pan" coefficients)
   – Thornthwaite equation
   – Various radiation-based equations such as the Priestley-Taylor, Makkink, Turc, and FAO-24 equations

2. Six primary reference equations have attained substantial adoption and usage over the past 30 years:
   – 1982 Kimberly Penman (24-hour, alfalfa reference)
   – CIMIS Penman (hourly, grass reference)
   – FAO-24 Penman
   – ASCE Penman-Monteith (hourly or 24-hour, alfalfa or grass reference)
   – NRCS Penman-Monteith (24-hour grass reference)
   – FAO Penman-Monteith (special case of the ASCE PM for hourly or 24-hour, grass reference)
     – The NRCS and FAO Penman-Monteith methods are direct derivatives of the ASCE PM and vary primarily in how specific intermediate parameters are calculated.

3. Two different reference crops, alfalfa and clipped grass are used, with usage generally divided among western States.

4. There is presently no clear de facto standard equation in the U.S.
   - Many users concur with ASCE manual 70 procedures for calculating reference ET, however the ASCE procedures discuss a wide range of equations.
   - The Kimberly Penman equation and the ASCE Penman-Monteith (or FAO-PM) seem to have the widest application within the research and technical communities.
   - The CIMIS Penman equation was developed for hourly application and has no direct counterpart or procedure for application with daily or even monthly data.

5. There is no clear set of supporting equations for calculating net radiation, soil heat flux, and vapor pressure deficit
   - The three most widely used procedures for predicting net radiation from solar radiation measurements are the procedures by Wright (1982), by FAO-56 (essentially the procedure of Brunt (1932)), and the procedure of Dong et al., (1992) used by CIMIS. Associated with these methods, are basically three approaches for predicting short wave albedo:
     - The procedure by Wright (1982) uses albedo that varies with time of year to reflect the effect of sun angle. It employs coefficients for predicting the net emissivity of the atmosphere and surface that also vary with time of year.
     - The FAO-56 method uses a fixed albedo (0.23) and fixed coefficients for emissivity with the intention of more universal application around the world.
     - The procedure of Dong uses a sun-angle based prediction of albedo that is applied hourly. The equation was integrated for daily application by Martin and Gilley (1993).
     - Comparison of the three methods over all latitudes and seasons (R.G. Allen, 1997, unpublished analyses) has identified time periods or latitudes where the three methods for albedo agree and time periods and latitudes where they are significantly different. The time-based equation by Wright (1982) calculates values that are up to 0.08 (i.e., 25%) higher than estimates calculated using the method of Dong during spring, fall and winter for many latitudes. The fixed albedo (0.23) recommendation of FAO-56 predicts within 10% of Dong for all months for latitudes between -30 and +30 degrees and within 15% of Dong (i.e., +/- 0.03 albedo) for growing periods at all latitudes for 24-hour timesteps. It is uncertain whether Dong represents the more accurate estimate for albedo. More research and testing is needed to evaluate all three techniques.
     - There is uncertainty in computing net radiation and soil heat flux during nighttime. Prediction of cloudiness and its effect on prediction of net emissivity is uncertain.
     - The is additional uncertainty concerning computing sky emissivity across a wide range of weather conditions and during winter months
   - There is uncertainty as to the best means to predict soil heat flux (G). Allen and Wright (1997, unpublished analyses) and other members of the TC have shown that basing G for hourly periods as a function of R_n provides good results for reference surfaces. Allen and Wright and Wright et al. (2000) show that for daily timesteps, the air temperature based method originally proposed by Wright (1982) may worsen the prediction of ET_{ref} compared to using G=0 as proposed by FAO-56 for daily time steps.
   - Two traditional procedures have been used to predict mean saturation vapor pressure (e_s) for a 24-hour period when only daily or monthly weather data are available:
     - Apply the saturation vapor pressure function ($e^o(T)$) to the mean air temperature (i.e, $e_s = e^o(T_{mean})$).
     - Apply $e^o(T)$ to both daily maximum air temperature (T_{max}) and daily minimum air temperature (T_{min}) and average the two (i.e., $e_s = (e^o(T_{max}) + e^o(T_{min}))/2$).
     - ASCE Manual 70 demonstrated the advantage of averaging $e^o(T)$ from maximum and minimum air temperature, especially in arid climates. Allen et al. (1994) argued that any upward bias of this procedure helps to counteract daily predictions of ET that are based on daily averages of wind speed.

6. Even though the ASCE PM and Kimberly Penman methods have received relatively widespread usage across the U.S., neither equation has received widespread testing against

validated field measurements over a wide range of locations. Much of this is due to prohibitive costs for collecting and validating high quality ET measurement data and difficulty in making precise measurements.

- Based on analyses made to date, no equation exists that has demonstrated predictive accuracy that is within +/- 10% on a daily basis over a wide range in climates.
- Therefore, selection of the method for standardization had to be made based on other factors in addition to validation tests at a few locations.

7. Some state agencies use hourly computations for routine ET prediction and some use daily and monthly timesteps.
   - Many ET equations developed for application to daily timesteps produce estimates of ET from hourly computations that do not agree with estimates made on daily time steps when summed over 24 hours. Many times this has to do with non-linearity and phase incongruency associated with averaging weather data over 24-hour periods and averaging crop responses to climate over 24-hour periods (e.g. stomatal conductance). This is complicated by the fact that many of the common equations, including the Kimberly Penman and ASCE PM equation were developed using 24-hour data and have been less precisely defined for hourly applications.
   - A challenge is to select an equation that can be readily modified to be equally accurate at predicting ET for hourly (or shorter) timesteps and for 24-hour calculation time steps.

8. There is large diversity in sources of weather data, types of weather data, how data have been summarized, and environments associated with weather stations
   - A full "toolbox" of standardized procedures is needed to provide means for processing available weather data for a location into usable information for the standardized equation.
   - The toolbox must contain procedures for estimating missing data or for producing reference estimates using reduced parameters when data are missing.
   - The toolbox must contain procedures for estimating ET_o or ET_r at locations that are data short, i.e., some parameters (solar radiation, air temperature, wind speed or humidity are not measured). Options include:
     - Predict missing weather parameters based on other parameters or based on regional and/or long-term averages and then apply the full standardized equation
     - Apply a reference ET equation that requires only the data available, for example, the Hargreaves equation where local calibration is done by comparing the reduced equation to the standardized equation at locations in the region having full data sets.
   - The local environment and general "aridity" of the area surrounding a weather station (i.e., lack of transpiring vegetation) can impact readings of air temperature and humidity. Simple yet effective standardized procedures for adjusting for the effects of weather measurements from nonagricultural settings are needed, such as those proposed by Allen (1996) and by FAO-56 (Allen et al., 1998).
   - There is need to recommend procedures for characterizing and improving the integrity of weather data used in making ET computations.

9. There is a need to simplify terms if the simplifications result in insignificant amounts of error. The challenge is in balancing minimization of error and simplification of the standardized methods. Parameters evaluated by ASCE for impacts of simplification include:
   - Latent heat of vaporization (λ) varies as a weak function of air temperature and therefore varies slightly with time of day. Basing λ on average daily temperature typical of the growing season, for example 20 ^oC, produces a fixed value of λ=2.45 MJ/kg. This value does not deviate from actual values for λ by more than 2% even in winter time when mean air temperature is 0 ^oC.
   - Air density (ρ) is a function of air pressure and virtual air temperature. Virtual air temperature is a weak function of the ratio of vapor pressure to air pressure. If the latter

ratio is held constant, ρ can be expressed as a function of air temperature and pressure only, with pressure incorporated into the pyschrometric constant, γ, in the PM equation.
– Full expressions for aerodynamic resistance (r_a) generally include complex expressions for characterizing the effects of stability on eddy transfer. For reference surfaces, however, sensible heat exchange is generally small relative to flux of vapor so that boundary layer stability is near neutral and therefore stability corrections can be ignored with little error, even for hourly computations (Allen et al., 1996).
– Surface resistance (r_s) is a strong function of stomatal resistance of individual leaves. It is well known that r_s varies with environmental stresses such as air temperature, vapor pressure deficit and solar radiation so that the value for r_s changes with time of day (Allen et al., 1996). Some of these functions are poorly defined for grass and alfalfa crops especially for daily timesteps. For purposes of computing ET_r or ET_o using hourly timesteps where the intent is to sum ET_r or ET_o over 24-hour time periods, the absolute accuracy for each hour is of less concern than the accuracy of the summed daily total. Therefore, r_s for reference ET applications can generally be fixed over time for simplicity and consistency in application. In the standardization effort, unique, constant values for r_s were assigned for daytime and for nighttime periods for both tall and short references. These values were different from the 24-hour values (Walter et al., 2000).

10. Historically, the reference surface is a living crop having variation in time and location for height, leaf area, leaf morphology, stage of growth, age, and irrigation and/or precipitation frequency. These characteristics vary due to time and location and due to varietal differences. They may even vary from year to year due to changes in weather and stomatal response (Howell et al., 2000; Wright et al., 2000).
   – For purposes of establishing definitions for the reference surfaces that are consistent, constant and reproducible in regard to their impact on the reference ET estimate, the above characteristics need to be fixed in regard to height, leaf area, stomatal resistance, aerodynamic roughness, albedo, and underlying soil moisture.
   – In the Penman-Monteith equation as applied to a defined, constant reference, this implies fixing aerodynamic roughness and zero plane displacement as well as the value for r_s.
   – In the Penman equation as applied to a defined, constant reference, this implies fixing the coefficients in the wind function.
   – The penalty for fixing parameters is that the flexibility to vary parameters to fit observations is given up in exchange for consistency and reproducibility of the reference across locations and regions.
   – A subtle advantage of fixing terms in a standardized definition and procedure is that it may discourage development of localized reference methods that are based on faulty or biased measurements of ET or weather data. Errors and biases in ET measurements are prevalent. This places pressure on the method selected for standardization to adequately represent the reference ET condition over a wide range of weather and climatic conditions.

11. There is uncertainty in the ratios for ET_r/ET_o to be used in converting families of crop coefficients between reference types.
   – There is concern that ratios of ET_r/ET_o that are computed from the standardized equations may not reproduce ratios of ET_r/ET_o from field measurements.
   – Reasons for this are the lack of feedback in the common weather data set, errors in prediction of net radiation and soil heat flux and deviation of the standardized reference definition from the field measurements at a location (Wright et al., 2000).

12. There is uncertainty in the application of ET_r and ET_o equations during wintertime for both dormant and non-dormant conditions. Uncertainties include characterization of:
   – Net radiation due to impacts of daytime length, changes in albedo and low sun angle.
   – Surface resistance of living reference crops that deviate from the definition due to low temperatures, senescence or dormancy.

13. There is some uncertainty in how to incorporate impacts of unique diurnal patterns for wind speed into 24-hour calculation timesteps.

Summary and Conclusions

The issues, requirements and challenges listed represent the considerations that have been made by ASCE in directing efforts and technical work for selecting and establishing standardized procedures to compute reference evapotranspiration. Some issues and challenges have been difficult to assess or solve. Many of the decisions made or solutions found are less than perfect due to the nature of the physical processes being modeled and the randomness of nature in space and time. Presently, the ASCE Penman-Monteith has been selected by ASCE as the basis for the standardization with most supporting parameters based on FAO-56. It is anticipated that this standardization effort will continue to evolve with time as new information and procedures become available.

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