

ACCURACY OF ESTIMATED REFERENCE CROP EVAPOTRANSPIRATION

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ABSTRACT: Evapotranspiration from cool-season grasses is used as the reference for ET_0 . The requirements for local calibration for three equations for ET_0 recommended by the Food and Agriculture Organization of the United Nations (FAO) are shown for different climatic regions of California. Data from measured cool-season-grass evapotranspiration and Class A pan evaporation from sites located in large well-watered, irrigated grass pastures in three distinct climatic conditions are used to evaluate a method for estimating ET_0 that requires only measured values of maximum and minimum air temperatures. Mean temperature, minimum relative humidity, and solar radiation can all be estimated from maximum and minimum air temperatures. The equation for ET_0 that requires only temperature measurements may seem to be quite simple, but it is in reality a very comprehensive procedure incorporating most of the climatic interactions that influence the evaporative potential. The analysis of data from four lysimeter and Class A pan sites in California indicates that the temperature-range equation estimates ET_0 reasonably well in a large diversity of climates. The corrected Penman and other equations recommended by FAO are shown to usually overestimate ET_0 in various climatic regions of California.

INTRODUCTION

The user of reference crop evapotranspiration (ET_0) should know which crop or grass was used as a reference and the methods used to obtain or estimate the reference values. Cool-season grasses usually have significantly higher rates of evapotranspiration (ET) than warm-season grasses. For some varieties of alfalfa, maximum growth occurs at 15° to 20° C and for other varieties at 25° to 30° C. The actual ratio of ET of one grass to that of another depends upon the characteristics of the varieties being compared and upon climate (mainly upon temperature). The ET of grass is also influenced by vigor of growth, plant height, soil fertility, leaf area index, and the degree of water stress.

A review of values of ET of various grasses indicates that for similar conditions perennial ryegrass, the tall fescues, and Kentucky bluegrass have similar rates of ET . The ET of these cool-season grasses (ET_0G) is used as an index of ET_0 in this paper. Class A evaporation pan data (E_p) from large irrigated pasture area sites is also used as an index of ET_0 .

Due to the large sums being used to finance new irrigation developments and to the importance of irrigation in many developing countries, there is a need for a method that can be applied worldwide for estimating crop water requirements. Doorenbos and Puritt (1977) and Doorenbos and Kassam (1979) recommended four methods for estimating ET_0 and proposed crop coefficients to be multiplied by ET_0 in order to estimate potential crop evapotranspiration (ET_c). The methods they recommend for worldwide use are the following.

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TABLE 1. Lysimeter Locations and Descriptions: California

Station (1)	Northern latitude (2)	Western longitude (3)	Elevation (m) (4)	Lysimeter type (5)	Vegetation (6)
Arvin	35°03'	118°02'	133	Floating	Imp. pasture and grass
Davis	38°32'	121°46'	18	6.1 m diameter weighing	Alta fescue grass
Glenburn	41°03'	129°29'	1,010	1.8 m diameter floating	Imp. grass pasture
Lompoc	34°41'	120°21'	27	Hydraulic and/or electronic	Grass

1. A modified Blaney-Cridde (B-C) equation.
2. A radiation (RAD) method.
3. A corrected Penman (CPEN) equation.
4. A procedure using Class A pan evaporation (Ep).

The first three of the recommended FAO equations require measured or estimated values of four or more weather variables. Hargreaves et al. (1985) and Hargreaves and Samani (1985) proposed the use of an equation for ET_0 that requires only measured values of maximum and minimum temperature. The objective of this paper is to evaluate the accuracy or usefulness of the Hargreaves 1985 method of estimating ET_0 , and to determine the needs for local calibration prior to use with the crop coefficients proposed by Doorrenbos and Pruitt (1977), Doorrenbos and Kassam (1979), and by Snyder et al. (1987a,b).

DATA SOURCES

Monthly values of ET_{OG} , Ep , and climatic data are available for various locations in California from SDWR-113-3 of the California State Department of Water Resources (*Vegetative* 1975) and other sources. Four locations were selected where lysimeters and Class A evaporation pans were sited in large well-managed irrigated pastures. The locations and lysimeter descriptions are given in Table 1. Descriptions of the type of grass were less complete than desired and for Arvin and Glenburn the temperature range (TD), or mean maximum minus mean minimum temperatures, was taken from a nearby station with very similar climatic values.

Unfortunately, not all grasses are equivalent in water use, some lysimeters are less reliable than others, and management practices were not completely documented. However, in each case the values are considered to be typical of those from cool-season grasses in lysimeters located in adequately irrigated pasture areas. Since frost modifies the relationships of Ep and ET_{OG} to the climatic variables, only the months of active growth of grass (approximately the frost-free growing season) were used in this study.

ESTIMATING ET_0

Reference crop evapotranspiration (ET_0) is largely determined by the characteristics of the reference crop, solar radiation, air temperature, and ad-

vective energy. Advection is influenced by the interactions of temperature, relative humidity and/or vapor pressures, and wind. Hargreaves (1981) and Hargreaves et al. (1985) proposed the use of the average daily temperature range (*TD*) for estimating solar radiation. Richardson (1980, personal communication, 1988) developed a procedure for estimating average minimum monthly relative humidity (*RH*) in percentages from the average daily temperature range.

Maximum and minimum temperatures can be used to determine saturation vapor pressure, relative humidity, solar radiation, and mean air temperature. Wind also influences advection. However, advection can be positive or negative and the interactions of wind with temperature, relative humidity, vapor pressure deficit, etc., are difficult to estimate with equations. Since *TD* can be correlated with most of the climatic factors that influence advection, use of *TD* in an equation for estimating *ET₀* should provide a significant compensation for the influence of advective energy.

Temperature measurements should be from representative sites. Mean temperatures decrease about 5° C to 7° C per 1,000 m increase in elevation. *TD* may vary significantly with changes in elevation. Values are somewhat influenced by local topography, aspect, and exposure. Allen et al. (1983) found an average increase in air temperature in nonirrigated areas of from 0.9° C for May and October to 4.7° C for August over the average measured values in irrigated areas for various locations in Southern Idaho. A review of published temperature data from many locations indicates little difference in *TD* from irrigated and nonirrigated sites.

In consideration of the aforementioned relationships, the equation for *ET₀* or *ET_{0H}* used in this study appears simple but compensates for most of the important climatic factors that influence evapotranspiration, with the partial exception of advective energy. The equation for *ET_{0H}* proposed by Hargreaves et al. (1985) and Hargreaves and Samani (1985) can be written

$$ET_{0H} = 0.0023 \times RA \times (T^{\circ}C + 17.8) \times TD^{0.50} \dots\dots\dots (1)$$

in which *ET_{0H}* and *RA* are in the same units of equivalent water evaporation; *RA* = extraterrestrial radiation; and *TD* is in °C. For temperature in °F the equation becomes

$$ET_{0H} = 0.00094 \times RA \times T^{\circ}F \times TD^{0.50} \dots\dots\dots (2)$$

Eqs. 1 and 2 have been used with average values of *RA* and temperature for periods of time varying from 5 days to 1 month. The resulting values of *ET_{0H}* seem satisfactory for irrigation scheduling for most locations evaluated for these time periods. Attempts to date to develop a wind function or other corrections for these equations have been inconclusive.

For various design and other purposes it is desirable to know how much *ET₀* may vary from the mean. As part of this study, long records of monthly values of mean daily maximum and minimum temperatures at locations from 0.2° S to 48.5° N latitude were used with Eq. 2 to calculate *ET_{0H}* and the standard deviation of *ET_{0H}* (*SDET*). The standard deviations of monthly mean temperatures (*SDT*) from hundreds of locations, both north and south latitudes, were compared. These investigations resulted in the following conclusions.

1. *SDET* is equal to about 4.7% of *ET₀* for latitudes 10° N to 10° S.
2. *SDET* increases with latitude departure (*LD*) from 10° N or 10° S and is approximately equal to $ET_0 \times (0.047 + 0.0012 \times LD)$.
3. The maximum *SDET* at extreme latitudes is about 10% of *ET_{0H}*.

COMPARISONS AND RATIOS

Pruitt et al. (1987) used lysimeter-determined *ET₀* (*ET_{0G}*), 1–3 lysimeters per site; at nine locations, Class A pan evaporation (*E_p*) from 30 sites (one or more pans per site), and other weather measurements at various locations to develop calibration coefficients to be used with the B-C, RAD, and CPEN equations. These coefficients (see Table 2) are recommended for use in different regions of California. Arvin is in the San Joaquin Valley and Davis in the Sacramento Valley. These two large connecting valleys, comprising the Central Valley of California, have very similar climatic characteristics throughout. Glenburn is in a northeast mountain valley and Lompoc is located in the Santa Ynez Valley 8 mi (about 13 km) inland from the ocean. The lysimeters listed in Table 1 represent three significantly different climates. Snyder, Pruitt, and Shaw (1987) used the data and study by Pruitt et al. (1987) to determine reference evapotranspiration (*ET_{0S}*) for cool-season grasses that are not water stressed.

Table 3 is an attempt to evaluate the reliability of Eq. 1 in calculating *ET_{0H}*. For Glenburn, Eqs. 1 and 2 produce values of estimated *ET_{0H}* that exceed the measured grass evapotranspiration, except for the month of Au-

TABLE 2. Calibrated Coefficients to be Multiplied by Calculated *ET₀* Values for Three Equations

<i>E%</i> equation ^a (1)	March (2)	April (3)	May (4)	June (5)	July (6)	August (7)	September (8)	October (9)
(a) Northeast Mountain Valleys and Sierra Range								
B-C	—	—	0.99	0.98	0.96	0.94	0.92	—
RAD	—	—	0.85	0.87	0.88	0.89	0.88	—
CPEN	—	—	0.91	0.92	0.94	0.95	0.95	—
(b) Coastal Valley and Plants and Coastal Interior Valleys								
B-C	0.92	0.92	0.92	0.92	0.92	0.92	0.88	0.84
RAD	0.83	0.82	0.79	0.79	0.81	0.83	0.83	0.83
CPEN	0.74	0.74	0.74	0.74	0.76	0.79	0.79	0.77
(c) Sacramento Valley								
B-C	0.86	0.85	0.82	0.80	0.77	0.73	0.71	0.72
RAD	0.80	0.78	0.78	0.80	0.80	0.81	0.82	0.85
CPEN	0.71	0.69	0.71	0.71	0.71	0.70	0.71	0.72
(d) Davis (Using Weather Data Collected within 5-ha Irrigated Grass Field)								
B-C	0.85	0.90	0.96	0.92	0.88	0.82	0.77	0.74
RAD	0.74	0.76	0.80	0.86	0.85	0.79	0.78	0.79
CPEN	0.75	0.79	0.83	0.89	0.88	0.83	0.83	0.81

^aB-C, RAD, and CPEN are Blaney-Criddle, Radiation, and corrected Penman equations for *ET₀* from Doorenbos and Pruitt (1977).

TABLE 3. Ratios of Measured and Calculated Grass *ET* to Pan Evaporation and Comparisons of Calculated *ET₀* to Measured Grass *ET*

Ratio (1)	March (2)	April (3)	May (4)	June (5)	July (6)	August (7)	September (8)	October (9)	Mean (10)
(a) Arvin									
<i>ETOG^a/Ep^b</i>	0.82	0.75	0.81	0.74	0.82	0.88	0.88	0.90	0.82
<i>ETOH^c/Ep</i>	0.79	0.76	0.72	0.73	0.80	0.85	0.88	0.94	0.81
<i>ETOG/ETOH</i>	1.05	1.00	1.12	1.00	1.02	1.04	1.01	0.96	1.02
<i>ETOS^d/ETOH</i>	0.98	1.02	1.10	1.03	1.03	1.04	1.01	0.91	1.02
(b) Davis									
<i>ETOG/Ep</i>	0.74	0.72	0.77	0.78	0.78	0.78	0.76	0.73	0.76
<i>ETOH/Ep</i>	0.76	0.70	0.77	0.77	0.82	0.84	0.75	0.76	0.77
<i>ETOG/ETOH</i>	0.97	1.02	1.00	1.01	0.95	0.94	1.01	0.96	0.98
<i>ETOS/ETOH</i>	0.96	1.09	0.96	1.05	0.96	0.93	0.96	1.05	1.00
(c) Glenburn									
<i>ETOG/Ep</i>	—	—	0.70	0.79	0.74	0.96	0.86	—	0.81
<i>ETOH/Ep</i>	—	—	0.84	0.90	0.83	0.91	0.92	—	0.88
<i>ETOG/ETOH</i>	—	—	0.83	0.88	0.89	1.06	0.93	—	0.92
<i>ETOS/ETOH</i>	—	—	0.87	0.95	0.99	0.91	0.90	—	0.92
(d) Lompoc									
<i>ETOG/Ep</i>	0.78	0.72	0.67	0.61	0.57	0.64	0.59	0.59	0.65
<i>ETOH/Ep</i>	0.77	0.75	0.65	0.59	0.56	0.63	0.67	0.72	0.67
<i>ETOG/ETOH</i>	1.02	0.95	1.03	1.03	1.02	1.02	0.88	0.82	0.97
<i>ETOS/ETOH</i>	0.87	1.08	1.02	0.99	1.00	1.04	0.92	0.83	0.97

^a*ETOG* = measured cool-season grass lysimeter evapotranspiration.

^b*Ep* = Class A pan evaporation from well-watered and clipped irrigated grass sites.

^c*ETOH* = *ET₀* from Eq. 1 or Eq. 2.

^d*ETOS* = *ET₀* from Snyder, Pruitt, and Shaw (1987).

gust. The ratios of values estimated by the equations to Class A pan evaporation are also higher than for the other locations. Evapotranspiration by the grass in a lysimeter depends on the density of stand and the vigor of the growth required for representative values of evapotranspiration.

If it is assumed that during the last half of the growing season the lysimeter at Glenburn provides a reasonably good index of *ET₀* then Eq. 1, when used with the available temperature data, provides satisfactory estimates of *ET₀* at all four California lysimeter sites. The coefficients provided by Pruitt et al. (1987) indicate that the corrected Penman would probably overestimate *ET₀* and average 8% at Glenburn, 32% at Lompoc, 41% in typical locations in the Sacramento Valley, and 20% at Davis. Comparisons with the other two equations given by Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) are indicated in Table 2.

PRACTICAL APPLICATIONS

The temperature range (*TD*) can be used to estimate global solar radiation, minimum relative humidity, *ET₀*, and *Ep*. Since *TD* can be used to estimate

most of the various factors that have been used to estimate ET_0 , it seems logical to assume that an empirically derived equation that makes use of TD should require a minimum of local calibration.

Crop water requirements are estimated by multiplying ET_0 times crop coefficients. Crop coefficients for many commercial crops are given by Doorenbos and Pruitt (1977), Doorenbos and Kassam (1979), and Snyder et al. (1987a,b). These coefficients are widely used. They were developed principally from crop ET measured in California. The reference used was cool-season grass, principally Alta Fescue and perennial ryegrass. The comparisons in Table 3 indicate Eq. 1 to be appropriate for use with these crop coefficients. A need for local calibration is not indicated. The aforementioned crop coefficients may be less appropriate when used with lysimeter-determined ET from other grasses in significantly different climates.

In climates where irrigation is needed, Eq. 1 is indicated to provide a good index for irrigation scheduling, management, and design. Frequently, Eq. 1 will be the method of choice, due to the limited availability or reliability of the climatic data required for most other methods.

For locations with very high relative humidity and those months when rainfall is fairly adequate, Eq. 1 may significantly overestimate the potential evapotranspiration of cool-season grasses. This may be partially due to a significant water contribution from dew. However, for other climates there does not appear to be sufficient justification for local calibration of Eq. 1. When temperature data from an arid (nonirrigated) area are used to calculate ET_0 , the values will frequently be approximately equal to ET_0 plus one standard deviation when compared to those calculated with temperatures measured in a large irrigated area.

Irrigation design, scheduling, and management can be improved and simplified providing the following can be promoted.

1. That the use of cool-season grasses such as perennial ryegrass, the tall fescues, and the bluegrass be accepted as standard reference crops.
2. That the climatic data used in ET_0 estimations be collected from large irrigated areas or corrected for differences between arid-area and irrigated-area temperatures.
3. That the published data summaries include maximum and minimum temperatures and the temperature range (TD).
4. That the management of lysimeters be fully described, including density of stand, frequency and height of cutting, fertilizer applications, frequency of watering, rainfall amounts, and complete climatic data.

SUMMARY AND CONCLUSION

The cool-season grasses are recommended as the reference for ET_0 . The needs for local calibration of four methods for estimating ET_0 are explored and evaluated by comparisons to Class A pan evaporation from pans located in large well-watered irrigated areas and with measured cool-season grass lysimeter-measured evapotranspiration. A procedure that requires only measured values of maximum and minimum temperatures from sites well within large irrigated areas appears to require little or no local calibration. This is explained by the high degree of correlation of the temperature range (TD) with several other measurable climatic variables.

Maximum and minimum temperatures probably do not correlate with wind, but the other factors that relate to advection and to a given evaporative potential can be largely determined from maximum and minimum temperatures. The standard deviations of monthly values of ET_0 are linearly correlated with latitude. Due to a common lack of more complete climatic data and to the indicated reliability of ET_0 estimates, a procedure for estimating ET_0 from maximum and minimum air temperatures appears more suitable than most other methods for worldwide use for irrigation design, scheduling, and management.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

- ET_0 = reference-crop evapotranspiration with a cool-season grass as reference;
- LD = degrees of latitude departure from 10° N or 10° S;
- RA = extraterrestrial radiation in same units as ET_0 ;
- RH = average daily minimum relative humidity for month;

- SDET* = standard deviation of monthly *ET0*;
SDT = standard deviations of monthly temperature;
T ° C = monthly average temperature in °C;
TD = mean daily maximum temperature for month minus mean daily
minimum temperature for month;
T ° F = monthly average temperature in °F.