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Richard G. Allen, Marvin E. Jensen, James L. Wright, and Robert D. Burman

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ABSTRACT

Many forms of the Penman combination equation have been proffered for estimating daily evapotranspiration (ET) by the agricultural reference crops grass and alfalfa (*Medicago sativa* L.). This study was conducted to evaluate popular forms of the Penman equation, and to develop and evaluate general relationships for estimating daily average values of canopy and aerodynamic resistance parameters required by the Penman-Monteith equation. For simplicity and ease of use, resistance relationships were expressed as linear and logarithmic functions of mean plant height. The Penman-Monteith and other forms of the Penman equation were compared at 11 international lysimeter sites, with the Penman-Monteith method and a Penman equation with variable wind function developed at Kimberly, ID providing the best estimates of reference ET across the sites. Ratios of computed alfalfa to grass reference ET during peak months at various locations averaged 1.32, and ranged from 1.12 to 1.43. Values of computed ratios were related to local wind and humidity conditions. The development of relationships for canopy and aerodynamic resistances as functions of reference crop height allowed use of the Penman-Monteith equation in an operational mode, and improved transferability of this resistance form of the Penman equation to a wide variety of climates.

MANY SOIL water budgets require estimation of ET on a daily basis. Because ET is the primary component of the soil water balance, accuracy in ET estimation is usually paramount to accuracy in soil water accounting, irrigation system design and management, crop yield simulation, and hydrologic studies. A common procedure for estimating ET from a well-watered agricultural crop is to first estimate reference ET from a standard surface and to then apply an appropriate empirical crop coefficient such as those presented by Doorenbos and Pruitt (1977), and Wright (1981, 1982). However, several types and forms of reference ET equations appear in the literature, each of which provide estimates of reference ET that differ from the others (Penman, 1948, 1963; Jensen and Haise, 1963; Wright and Jensen, 1972; Wright, 1982; Doorenbos and Pruitt, 1977; Hargreaves et al., 1985). This paper summarizes development of resistance formulations that support the use of the more physically based Penman-Monteith equation (Monteith, 1965) and comparison of common forms of the Penman equation at eleven international lysimeter sites. Developed relationships enable ET predictions from reference crop surfaces of varying height.

Transpiration of water requires the diffusion of water vapor through stomates of plant leaves. Since leaves function as resistors to vapor diffusion and operate in parallel over the ground surface, as leaf area increases bulk stomatal resistance (or canopy resistance) decreases. Various researchers have reported measurements of minimum values of leaf stomatal resistance (van Bavel and Ehrler, 1968; Szeicz et al., 1973; Monteith, 1981; and Sharma, 1985). Monteith (1965), Hatfield (1985), and Choudhury (1983) reported observations of instantaneous values of canopy resistance (r_c), which appeared to vary inversely with net radiation. Hatfield et al. (1987) offered a hypothesis linking values of stomatal resistance to leaf temperature, where resistances of many plants under well-watered conditions are maintained at maximum levels (closed stomates) until leaf temperatures increase to levels that promote optimum enzymatic activity. Beyond these temperatures, stomates open to increase evaporative cooling of leaves. Idso et al. (1987) discussed potential problems involved in determination of stomatal resistance with conventional leaf chamber porometers.

Surface roughness affects the rate of momentum transfer from air above a crop canopy into the canopy, where it is dissipated by friction within small eddies. An increase in roughness increases the generation of eddy turbulence, which in turn increases momentum transfer and eddy diffusion of heat and water vapor. Businger (1956), and Penman and Long (1960) were among the first to include the logarithmic eddy diffusion function into the wind term of the Penman combination equation. Monteith (1965) combined the use of the logarithmic eddy diffusion function and canopy resistance into the Penman-Monteith combination equation of the form:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho\, c_p\, (e_a - e_d)/r_a}{\Delta + \gamma\, (1 + r_c/r_a)} \qquad [1]$$

where λET is the vapor flux density (MJ m^{-2} t^{-1}), R_n is net radiation flux density to the plant canopy (MJ m^{-2} t^{-1}), G is soil heat flux density (MJ m^{-2} t^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), ρ is the density of the air (kg m^{-3}), c_p is specific heat of the air (MJ kg^{-1} °C^{-1}), e_a is the saturation vapor pressure at the current air temperature (kPa), e_d is the saturation vapor pressure at the dewpoint temperature (actual vapor pressure of the air, kPa), r_a is the aerodynamic resistance to vapor and heat diffusion (t m^{-1}), γ is the psychrometric constant (kPa °C^{-1}), and r_c is the bulk stomatal (canopy) resistance (t m^{-1}). Variabl t is the time scale for which the vapor flux is to b estimated. Evapotranspiration in mm t^{-1} is calculate by dividing λET by the latent heat of vaporization (λ which has units of MJ kg^{-1}.

For estimation of reference ET on a daily avera basis, the Penman-Monteith equation can be writt as:

$$\lambda ET = \frac{\Delta(R_n - G) + 86400\, \rho\, c_p\, (e_a - e_d)/r_a}{\Delta + \gamma\, (1 + r_c/r_a)}$$

where λET, R_n, and G have units of MJ m^{-2} d^{-1}, r_a and r_c have units of s m^{-1}. The 86 400 term conv resistance time units from seconds to days. Th

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R.G. Allen, Dep. of Agric. and Irrig. Eng., Utah State Univ., Logan, UT 84322-4105; M.E. Jensen, Colorado Inst. for Irrig. Manage., Colorado State Univ., Ft. Collins, CO 80523; J.L. Wright, USDA-ARS, Box 186, Rt. 1, Kimberly, ID 83341; and R.D. Burman, Dep. Agric. Eng., Univ. of Wyoming, Laramie, WY 82071. This investigation was supported by the Utah Agric. Exp. Stn. Received 28 Dec. 1987. *Corresponding author.

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term in Eq. [2] was calculated as the average of saturation vapor pressures at maximum and minimum air temperatures in this study. All other variables are defined as in Eq. [1].

MATERIALS AND METHODS

Equations of Interest

Aerodynamic Resistance

The aerodynamic resistance to heat transfer from the surface to height z was approximated under neutral stability conditions similar to Garratt and Hicks (1973), and Brutsaert and Stricker (1979) as:

$$r_a = \frac{\left[ln\left(\frac{z_m - d}{z_{om}}\right)\right]\left[ln\left(\frac{z_h - d}{z_{oh}}\right)\right]}{k^2 \, u_z} \qquad [3]$$

where r_a has units of s m^{-1}, z_m is the height of the wind measurement (m), z_h is the height of the air and humidity measurements above the ground surface (m), d is the zero plane displacement height of the measurement surface (m), z_{om} is the roughness length for momentum transfer (m), z_{oh} is the roughness length of the vegetation for vapor and heat transfer (m), k is the von Karman constant for turbulent diffusion (0.41), and u_z is wind speed (m s^{-1}) at height z.

The roughness length for momentum transfer, z_{om}, includes the effects of bluff body (pressure) forces, which do not have a similar analogy in heat and vapor transfer. As a result the apparent roughness length for heat and vapor transfer will generally be less than that for momentum (Brutsaert, 1982). Thom (1972, 1975), Thom and Oliver (1977), and Campbell (1977) suggested estimating the value of z_{oh} as $0.2z_{om}$, whereas, measurements by Chamberlain (1966), Monteith (1973), and Brutsaert (1979, 1982) indicated that the value of z_{oh} can be approximated as $0.1z_{om}$.

Brutsaert (1975) suggested that the surface roughness parameter z_{om} is related to the mean height (h_c) of a crop canopy by the relationship $h_c/z_{om} = 3 \cdot e$, where e is the natural number. Based on these relationships, the roughness parameters for aerodynamic transfer of momentum and heat to a crop can be estimated as:

$$z_{om} = 0.123h_c \qquad [4]$$

and

$$z_{oh} = 0.0123h_c \qquad [5]$$

where h_c is the mean height of vegetation (m). Plate (1971), Monteith (1981), and Brutsaert (1982) recommended estimation of the zero plane displacement height as:

$$d = 0.67h_c \qquad [6]$$

where d and h_c are in meters.

Canopy Resistance

Canopy resistances for well-watered, actively growing reference crops were approximated by dividing the minimum stomatal resistance per single leaf area by the effective leaf area indices of the canopies. Szeicz and Long (1969) recommended considering only one half of the leaf area as being effective in evaporation from a fully developed crop, since typically the upper half of the canopy of a dense crop absorbs the majority of net radiation and is, therefore, more active in vapor and heat transport than is the lower half. Wright and Lemon (1966), Tanner and Fuchs (1968), and Lemon and Wright (1969) observed that the majority of carbon dioxide exchange occurred within the top one half of a dense crop canopy. Vapor exchange through stomates within the canopy is governed by processes similar to carbon dioxide, with similar flux gradient profiles (Wright and Brown, 1967; van Bavel and Ehrler, 1968). The use of one half of the total leaf area in estimating r_c helped to compensate for the use of 24-hr averages of weather and resistance parameters (Allen, 1986). The one-half factor also agrees with observations of effectiveness of leaf area in transpiration as summarized by Allen et al. (1985).

Average daily values for r_c were estimated as:

$$r_c = \frac{r_l}{0.5 \text{ LAI}} \qquad [7]$$

where r_l is an average minimum daytime value of stomatal resistance for a single leaf, which was approximated as 100 s m^{-1} for alfalfa and grass canopies (Monteith, 1965; Monteith, 1981; and Sharma, 1985), LAI is the leaf area index, and r_c is bulk stomatal resistance in s m^{-1}. Equation [7] does not consider effects of temperature or net radiation on the value of r_c, as reported relationships have been contradictory, and is, therefore, best suited for daily average values of r_c rather than for shorter time periods.

Leaf area indices (LAI) vary with time, height, and cultural practices. In estimating reference ET from a grass or alfalfa reference surface, the major variable related to leaf area is height, although many types of grasses can differ significantly in physiological composition and structure. For a clipped grass less than 0.15 m in height, LAI was approximated as

$$\text{LAI} = 24h_c \qquad [8]$$

where h_c is mean grass height (m). This linear function agrees with Loomis and Williams (1969) for ryegrass and with observations of clipped alta fescue at Kimberly, ID (Wright, personal communication, 1987). For alfalfa or tall grass hay harvested only periodically, LAI was approximated as

$$\text{LAI} = 5.5 + 1.5 \times \ln(h_c) \qquad [9]$$

where h_c is mean canopy height (m) and h_c is greater than 0.03 m. The logarithmic relationship in Eq. [9] describes stem extension with less leaf development with increasing height. Equation [9] predicted an LAI of 4.5 for 0.5 m tall alfalfa.

The utility of Eq. [8] and [9] is the ability to approximate r_c of a reference crop for varying height using an easily identifiable parameter. The use of Eq. [2] through [9] to estimate reference ET requires only measurement of daily values of maximum and minimum air temperature, solar radiation, dewpoint temperature, wind speed, and height of the reference crop being estimated. Supporting equations for estimating net radiation, soil heat flux, and intermediate parameters are included in the appendix.

Empirical Forms of the Penman Wind Function

The general form of the Penman combination equation is:

$$\lambda \text{ET} = \frac{\Delta(R_n - G) + \gamma \, 6.43 \, f(u) \, (e_a - e_d)}{\Delta + \gamma} \qquad [10]$$

where λET is grass or alfalfa reference ET in MJ m^{-2} d^{-1}. All other parameters have units as previously defined. The constant 6.43 in Eq. [10] is a residual term from the original Penman equation (Penman, 1948), which was based on a constant value of λ of 2.45 MJ kg^{-1}. Doorenbos and Pruitt (1977) recommended a constant of 6.61 in place of 6.43 in Eq. [10].

The wind function $f(u)$ is an empirical expression of the form:

$$f(u) = (a_w + b_w u_2) \qquad [11]$$

where u_2 is wind speed in m s^{-1} at 2 m above the ground, and a_w and b_w are empirical coefficients. Penman (1948, 1963) recommended the use of 1.0 and 0.537 for a_w and b_w for clipped grass, Doorenbos and Pruitt (1977) in the FAO-24 report recommended the use of 1.0 and 0.864 for clipped grass, and Wright and Jensen (1972) recommended the use of 0.75 and 0.993 for a_w and b_w (1972 Kimberly Penman equation) for full cover alfalfa. Both the Penman, and Doorenbos and Pruitt wind functions required the calculation of the mean daily vapor pressure deficit ($e_a - e_d$) using saturation vapor pressure at the mean daily air temperature, whereas the alfalfa-based Kimberly and Penman-Monteith equations required mean daily saturation vapor pressure (e_a) to be calculated as the average of saturation vapor pressures at maximum and at minimum daily air temperature.

Wright (personal communication, 1987) derived an improved form of the Wright (1982) variable wind function by using the normal probability density function equation to approximate the change in a_w and b_w coefficients for an alfalfa reference with time of season at Kimberly, ID. The new forms of a_w and b_w are:

$$a_w = 0.4 + 1.4\exp[-([J-173]/58)^2] \qquad [12]$$

$$b_w = \{0.007 + 0.004\exp[-([J-243]/80)^2]\}(86.4) \qquad [13]$$

where J is the day of year. Equation [12] and [13] produce minimum, asymptotic values of a_w and b_w during winter months, whereas, the previous polynomial equations for a_w and b_w by Wright (1982) predicted unreasonable values during winter months. Both sets of equations produce approximately equivalent values of a_w and b_w from April to October. In southern altitudes, the values of J in Eq. [12] and [13] should be incremented or decremented by 183. Equations [10] and [11], with a_w and b_w calculated with Eq. [12] and [13], are collectively termed the 1982 Kimberly Penman equation in this paper.

The FAO-24 form of the Penman method multiplies the right hand side of Eq. [10] by a correction factor (c), the value of which is a function of maximum daily relative humidity, daytime (0700 to 1900 h) wind speed, daily total solar radiation, and ratio of daytime to nighttime wind speed. The value of the FAO-24 correction factor can be interpolated from tables presented in the FAO-24 publication (Doorenbos and Pruitt, 1977). In this study, the value of the correction factor was estimated using a regression on the FAO-24 tables developed by Frevert et al. (1983). This equation overestimated values of the correction factor, as compared with the FAO-24 tables, by an average of 3% for all sites and months evaluated in this study, and by an average of 4% for peak months at all sites. The largest difference between the regression and tabular values occurred for Davis, CA data, where the ratio of daytime to nighttime wind speed was 1.2. At this location, tabular values of the correction factor were overestimated by 10% during the peak month of July and by an average of 6% over all months.

Wind speeds were converted to equivalent speeds at the 2 m height for use by the empirical wind functions by accounting for the roughness of the measurement surface as follows:

$$W_2 = W_{z_m} \frac{\ln\left(\dfrac{2-d}{z_{om}}\right)}{\ln\left(\dfrac{z_m-d}{z_{om}}\right)} \qquad [14]$$

where W_2 and W_{zm} are wind speeds at the 2 m and z_m heights, and z_m, d, and z_{om} and h_c are in meters.

An additional equation was developed to adjust recorded wind speeds to compensate for differences in roughness and height between reference crops and weather measurement surfaces. This adjustment may be necessary when wind speeds are measured over surfaces such as grass, which have roughness characteristics or heights that are different from those of the reference crop to which an aerodynamic ET equation has been calibrated. Equation [15] was developed by manipulating Eq. [14] and by making the assumption that wind speeds at some height above a weather measurement surface are outside of the equilibrium boundary layer established over that surface and are, therefore, independent of the characteristics of the weather measurement surface. Wind speeds at this height are instead functions of an integration of surface roughness and heights over a larger, hopefully agricultural, area comprised of a mixture of crop types. For areas having average field sizes of 10 to 15 ha, the average height of the wind profile interface between that of the measurement surface and that of the surrounding area is generally in the neighborhood of 3.5 m, based on an assumption of a 1:50 growth rate in height of the equilibrium boundary layer (z_{ebl}). Therefore, the adjustment to wind speed to obtain a closer estimate of the wind speed at the z height, which would have occurred if the measurement had been made over the reference crop, is the following:

$$W_{z_{ref}} = W_{z_w} \frac{\ln\left(\dfrac{z_{ebl}-d_w}{z_{om_w}}\right) \ln\left(\dfrac{z-d_{ref}}{z_{om_{ref}}}\right)}{\ln\left(\dfrac{z_{ebl}-d_{ref}}{z_{om_{ref}}}\right) \ln\left(\dfrac{z-d_w}{z_{om_w}}\right)} \qquad [15]$$

where W_{zref} is the adjusted wind speed that would have occurred over the reference surface and W_{zw} is the recorded wind speed at the weather measurement site. Variables z_{omref} and z_{omw} are the values of z_{om} for the reference crop and weather measurement surfaces, respectively, and d_{ref} and d_w are zero plane displacements of the reference crop and weather measurement surfaces, respectively. Parameter z_{ebl} should have a value of about 3.5 to 4 m, depending on the scale of field sizes of the region.

The multiplier computed using Eq. [15] to adjust winds measured at 2 m height over 0.12 m grass to corresponding wind speeds that would have occurred at a 2 m height over 0.5 m alfalfa when z_{ebl} = 3.5 m is 0.94. The value 0.94 indicates that wind speeds measured over 0.5 m alfalfa would typically be about 6% less than wind speeds measured over 0.12 m grass. This difference would likely cause a difference of 3 to 4% in an estimate by a Penman or a Penman-Monteith combination equation in arid or semiarid areas. Equation [15] should only be used when the measurement height z is less than the value of z_{ebl}.

Observational Techniques

Data used in method comparisons were selected from publications by or personal communications with investigators working at locations where lysimeter data for well-watered grass or alfalfa were available, along with adequate supporting meteorological data. The evaluations were based on monthly and daily averages of ET, and all relevant meteorological data. Monthly comparisons were made to allow inclusion of data from additional sites. A description of lysimeter sites, climates, and locations evaluated is presented in Table 1. Lysimeter sites selected ranged from 30 m below sea level to 2774 m above sea level, and latitudes ranged from 38°S at Aspendale, Australia to near the equator in Yangambi, Zaire to 56°N at Copenhagen, Denmark. A description of the lysimeter vegetation types and general irrigation practices is presented in Table 2. Portions of this analysis are described in detail by Jensen et al. (1989).

Penman equations applied to data at the lysimeter sites included the 1963 Penman (Penman, 1963), the FAO-24 Corrected Penman (the equation estimate is multiplied by an empirical correction factor), the 1972 Kimberly Penman, the 1982 Kimberly Penman (Wright, 1982), and the Penman-Monteith (Eq. [2] through [9]). The reference estimates by the empirical wind function equations were adjusted to reflect the type of lysimeter reference (alfalfa or grass) by multiplying by an approximate alfalfa-grass conversion ratio of 1.15, which is the peak ratio of alfalfa to grass ET recommended by Doorenbos and Pruitt (1977) for a dry climate with low wind. The ratio of alfalfa to grass reference ET varies largely with vapor pressure deficit and wind speed, as indicated by the Penman-Monteith method using Eq. [2], [3], and [7], where the ratio of alfalfa to grass may range from 1 for conditions of high humidity and very low wind to > 1.5 for conditions of low humidity and very high wind. The 1.15 ratio does not reflect the diversity of grass and alfalfa varieties and heights at the various lysimeter sites, and was intended only to be a first step in addressing the differences among references and equation estimates to allow evaluation of all reference equations at all sites.

Heights of lysimeter vegetation and heights of vegetation of weather measurement surfaces, which were used in calculation of parameters for the Penman-Monteith equation, are listed in Table 3. These heights were based on ranges published with the original data or by personal communication, when available. Where no information concerning vegetation height were available, heights were estimated according to general cultural practices and climates of the areas. Lysimeter locations where specific ranges of vegetation heights were unavailable, and were therefore estimated, were Scottsbluff, South Park, and Yangambi. General ranges of heights and/or cutting dates were available for Coshocton, Kimberly, and Brawley. Net radiation was estimated at all sites except at Davis and Copenhagen where reliable measurements were available.

RESULTS AND DISCUSSION

Comparative Analyses of Monthly Average Estimates

Estimated daily reference ET averaged over peak months at lysimeter locations are listed in Table 4. Large variations between locations and climates are apparent. Peak months and general aridity categorizations of the 11 monthly lysimeter sites are included in Table 5. Evapotranspiration estimates from all 11 lysimeter locations, which were averaged over individual months, are compared with lysimeter measurements in Fig. 1 to 5. Location of points close to the 1:1 line indicate agreement between method estimates and lysimeter measurements.

Standard errors of estimate (SEE) (mm d^{-1}) were computed from monthly average ET estimates at each lysimeter location for all months and peak months, and are listed in Table 6. Standard errors of estimate were calculated as:

$$\mathrm{SEE} = \left(\frac{\Sigma(Y-\hat{Y})^2}{n-2}\right)^{0.5} \qquad [16]$$

where Y was observed (lysimeter-measured) ET, $\hat{Y}$ was either ET estimated directly by the ET equations or ET estimates adjusted by regression analysis, and n was the number of observations. Average SEEs for the ET methods for all months of record over all locations

Table 1. Lysimeter locations, periods of record, and principal references.

Site	Lat.	Elevation m	Years data	Period	Months per growing season	Principal references
Aspendale, Australia	38 °S	3	3	1959–61	12	McIlroy and Angus (1963)
Brawley, CA, USA	34 °N	−30	1	1971	8	LeMert, R.D. (pers. comm., 1973)
Copenhagen, Denmark	56 °N	28	11	1955–66	8	Jensen, S.E. and Aslyng, H.C. (pers. comm., 1972)
Coshocton, OH, USA	40 °N	360	3	1977–79	9	Harlukowicz, T.J. (pers. comm., 1984)
Davis, CA, USA	39 °N	16	4 3	1959–63† 1967–69‡	12	Pruitt, W.O. (pers. comm., 1971)
Kimberly, ID, USA	42 °N	1195	3	1969–71	7	Wright, J.L. (pers. comm., 1985)
Lompoc, CA, USA	35 °N	26	4	—	12	Nixon, P.R. (pers. comm., 1971)
Scottsbluff, NE, USA	42 °N	1280	1	1977	4	Weiss, A. (pers. comm., 1981)
Seabrook, NJ, USA	39 °N	37	10	1949–59	12	Mather, J.R. (pers. comm., 1967)
South Park, CO, USA	39 °N	2774	1	1969	4	Kruse and Haise (1974)
Yangambi, Zaire	0 °N	487	1	1959	12	Bernard and Frére (1959) and Pruitt, W.O. (pers. comm., 1986).

† Period of record used in monthly analyses.
‡ Period of record used in daily analyses.

Table 2. Lysimeter vegetation and water management.

Site	Vegetative description	Irrigation
Aspendale	Clover and perennial rye grass maintained at 0.06 to 0.1 m.	Often daily
Brawley	Alfalfa, harvested as hay, weather measured over 0.12 m grass.	Normal commercial irrigation†
Copenhagen	Dense clover-grass maintained at 0.12 to 0.14 m height.	Watered on 30-mm deficit
Coshocton	Grass-legume, harvested as hay, weather measured over 0.15 m grass.	Natural rainfall only†‡
Davis	Perennial rye grass, 1959–63. Alta fescue grass, 1964–68, mowed weekly to 0.10 m.	Watered on 50% depletion
Kimberly	Alfalfa, harvested as hay, weather measured over 0.12 m grass.	Normal commercial irrigation†
Lompoc	Perennial rye grass maintained at 0.06 to 0.15 m.	Weekly and less frequent
Scottsbluff	Alfalfa, harvested as hay.	Normal commercial irrigation†
Seabrook	Clipped rye grass.	Daily by sprinkling
South Park	Native meadow, harvested as hay.	Very shallow water table†‡
Yangambi	*Brachiari Mutica* grass.	Drainage lysimeter

† Periods of regrowth after cutting were not used in developing the mean reference ET curves for these sites.
‡ Periods of significant moisture stress were not used in developing the mean reference ET curve for these sites.

ranged from 0.36 mm d^{-1} for the Penman-Monteith method to 1.16 mm d^{-1} for the FAO-24 Corrected Penman. Over all locations average standard errors of estimate for ET methods for peak months only ranged from 0.52 mm d^{-1} for the Penman-Monteith method to 1.53 mm d^{-1} for the FAO-24 Corrected Penman (Table 6). Values of SEE were large for the latter method

Table 3. Vegetation heights used in reference estimates with the Penman-Monteith method.

Location	Month	Height of lysimeter vegetation (m)	Height of weather surface vegetation (m)
Aspendale	All	0.10	0.10
Brawley	April	0.50	0.12
	May	0.40	0.12
	June	0.45	0.12
	July	0.50	0.12
	August	0.50	0.12
	September	0.30	0.12
	October	0.25	0.12
	November	0.25	0.12
Copenhagen	All	0.12	0.12
Coshocton	March	0.07	0.07
	April	0.10	0.10
	May	0.25	0.15
	June	0.25	0.15
	July	0.25	0.15
	August	0.20	0.15
	September	0.20	0.15
	October	0.15	0.15
	November	0.10	0.10
Davis	All	0.12	0.12
Kimberly	April	0.25	0.12
	May	0.40	0.12
	June	0.60	0.12
	July	0.50	0.12
	August	0.40	0.12
	September	0.40	0.12
	October	0.20	0.12
Lompoc	All	0.09	0.09
Seabrook	All	0.12	0.12
Scottsbluff	June	0.50	0.50
	July	0.50	0.50
	August	0.45	0.45
	September	0.50	0.50
South Park	May	0.12	0.12
	June	0.35	0.35
	July	0.35	0.35
Yangambi	All	0.25	0.25

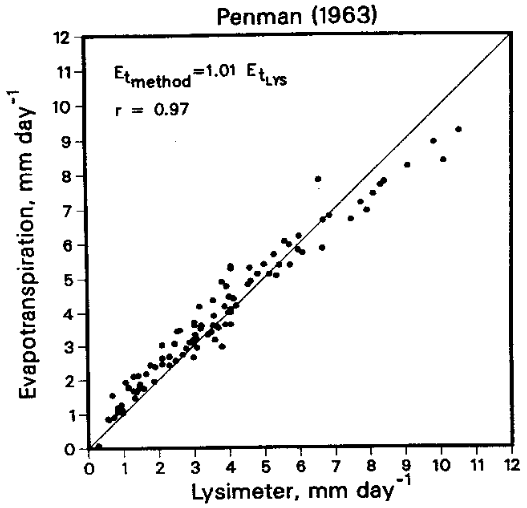

Fig. 1. Estimated monthly average reference ET using the Penman (1963) equation vs. monthly average measurements at 11 lysimeter locations.

Table 4. Average ET estimates† and lysimeter measurements, mm d^{-1}, for peak‡ months.

	Penman (1963)	1972 Kimberly Penman	1982 Kimberly Penman	FAO-24 Corrected Penman	Penman-Monteith	Lysimeter
Aspendale	7.2	7.6	8.0	9.5	6.3	7.7
Brawley	9.2	9.9	10.9	11.2	10.4	10.5
Copenhagen	3.7	3.8	3.9	4.8	3.0	3.0
Coshocton	4.4	4.3	4.6	5.3	4.4	4.1
Davis	6.8	7.3	8.0	8.9	6.7	6.9
Kimberly	7.0	7.4	8.0	8.8	7.8	7.9
Lompoc	5.3	5.1	5.3	6.5	4.2	4.1
Scottsbluff	8.4	8.9	9.3	9.7	9.9	10.1
Seabrook	5.4	5.8	6.0	6.8	5.1	5.4
South Park	3.6	3.7	4.0	4.3	4.1	4.1
Yangambi	3.6	3.4	3.1	4.2	3.5	3.9
All locations	5.9	6.1	6.5	7.3	6.0	6.2

† Equation estimates have been adjusted for the reference type of the lysimeter.

‡ Peak months for each location are listed in Table 5.

Table 5. Categorization of arid and humid lysimeter sites.

Arid†	Peak month
Aspendale	January
Brawley	June
Davis	July
Kimberly	July
Scottsbluff	June
South Park	July
Humid‡	**Peak month**
Copenhagen	June
Coshocton	June
Lompoc	June
Seabrook	July
Yangambi	March

† Arid locations were classified as those locations at which the mean daily relative humidity of the peak month was less than 60%.

‡ Humid locations were classified as those locations at which the mean daily relative humidity of the peak month was 60% or greater.

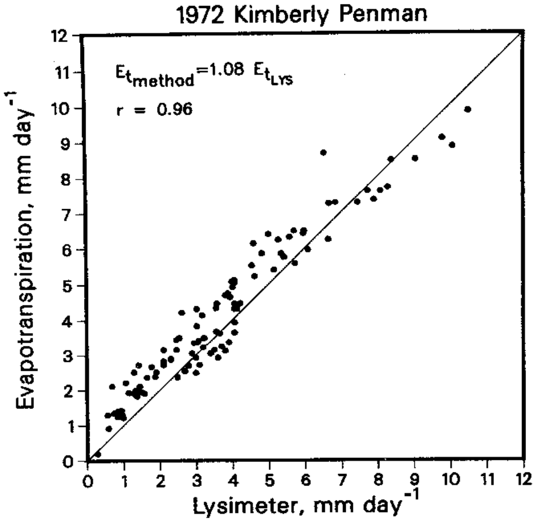

Fig. 2. Estimated monthly average reference ET using the 1972 Kimberly Penman equation vs. monthly average measurements at 11 lysimeter locations.

due its nearly consistent overestimation. A small amount (about 20%) of the overestimation by the FAO-24 Corrected Penman was caused by the use of the regression equation by Frevert et al. (1983) to estimate the correction factor, as opposed to using interpolated values from FAO-24 tables.

Linear regression analysis was performed on the monthly average estimates with lysimeter ET as the dependent variable and the ET estimate as the independent variable. Regression through the origin was used with the form:

$$E_{t_{lys}} = b\, E_{t_{method}} \qquad [17]$$

The use of regression through the origin was selected to evaluate the goodness of fit between ET equation estimates and lysimeter measurements, as both values should theoretically approach the origin when actual ET is zero. Regression through the origin was justified by testing for the significance of the Y-intercept. In all cases, the Y-intercept was not statistically different from zero, as determined by using the F test with 1 and $n-1$ degrees of freedom. Results of the analysis are presented in Table 7 for ET estimates averaged over all months at individual sites.

Standard errors of estimate calculated for ET estimates adjusted by regression are presented in Table 8. These values indicate the potential accuracy of the ET equations in predicting lysimeter ET when any linear

Table 6. Standard errors of estimate† of ET methods‡ in mm d^{-1} as compared with lysimeter measurements.§

	Penman (1963)	1972 Kimberly Penman	1982 Kimberly Penman	FAO-24 Correct. Penman	Penman-Monteith
Aspendale	0.33	0.49	0.45	1.25	0.65
Brawley	0.97	1.11	0.57	1.47	0.44
Copenhagen	0.64	0.76	0.67	1.28	0.11
Coshocton	0.40	0.58	0.33	0.79	0.26
Davis	0.39	0.88	0.68	1.57	0.36
Kimberly	0.69	0.91	0.24	1.17	0.25
Lompoc	0.97	0.95	0.79	1.75	0.33
Scottsbluff	1.34	0.94	0.66	0.73	0.53
Seabrook	0.54	1.11	0.73	1.52	0.48
South Park	0.67	0.64	0.44	0.53	0.27
Yangambi	0.24	0.41	0.52	0.44	0.32
Arid Locations	0.58	0.73	0.48	1.17	0.41
Humid Locations	0.57	0.75	0.59	1.17	0.31
All Locations	0.57	0.74	0.53	1.16	0.36
Peak Months, Arid	1.22	0.81	0.72	1.47	0.72
Peak Months, Humid	0.84	0.83	1.09	2.02	0.37
Peak Months, All	0.95	0.72	0.79	1.53	0.52

† Values are standard errors of estimate for ET estimates that have not been adjusted by regression.

‡ Equation estimates have been adjusted for the reference type of the lysimeter.

§ Unless noted, all statistics are for monthly average values over entire seasons of record.

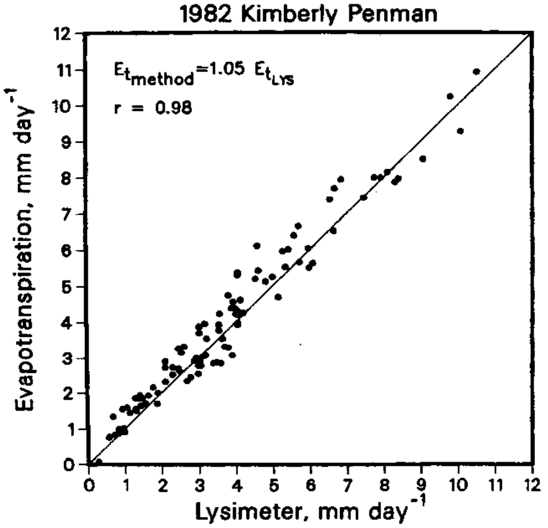

Fig. 3. Estimated monthly average reference ET using the 1982 Kimberly Penman equation vs. monthly average measurements at 11 lysimeter locations.

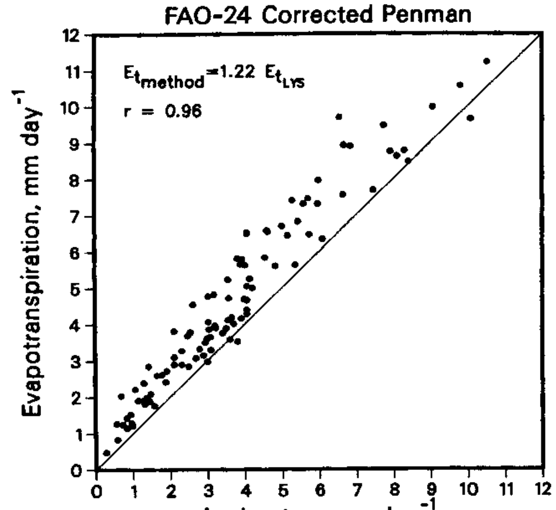

Fig. 4. Estimated monthly average reference ET using the FAO-24 Corrected Penman equation vs. monthly average measurements at 11 lysimeter locations.

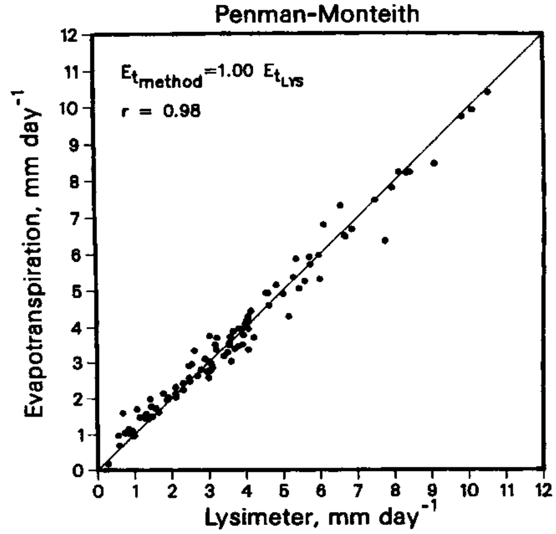

Fig. 5. Estimated monthly average reference ET using the Penman-Monteith equation vs. monthly average measurements at 11 lysimeter locations.

biases (i.e., chronic over- or underprediction) were removed.

Table 7. Regression coefficients (*b*)† and correlation coefficients (*r*) for regression through the origin of lysimeter measurements vs. equation estimates.‡§

	Penman (1963)	1972 Kimberly Penman	1982 Kimberly Penman	FAO-24 Correct. Penman	Penman-Monteith
Aspendale	*b* 0.98	0.93	0.97	0.79	1.14
	r 0.99	0.99	0.98	1.00	0.99
Brawley	*b* 1.05	0.99	0.99	0.89	1.01
	r 0.95	0.92	0.98	0.93	0.99
Copenhagen	*b* 0.78	0.75	0.77	0.64	0.97
	r 0.99	0.99	0.99	0.99	1.01
Coshocton	*b* 0.93	0.91	0.94	0.82	0.94
	r 0.97	0.93	0.98	0.97	0.99
Davis	*b* 0.95	0.86	0.87	0.75	0.97
	r 0.99	0.98	1.00	1.00	0.99
Kimberly	*b* 1.07	0.96	0.98	0.88	1.00
	r 0.95	0.83	0.99	0.92	0.99
Lompoc	*b* 0.78	0.79	0.82	0.66	0.95
	r 0.98	0.96	0.96	0.98	0.97
Scottsbluff	*b* 1.12	1.08	1.05	0.97	0.98
	r 0.97	0.98	0.98	0.96	0.98
Seabrook	*b* 0.90	0.78	0.84	0.70	0.95
	r 0.98	0.95	0.99	0.97	0.97
South Park	*b* 1.08	1.02	1.00	0.94	1.03
	r 0.31	0.41	0.51	0.40	0.82
Yangambi	*b* 1.02	1.11	1.14	0.90	1.07
	r 0.86	0.87	0.76	0.86	0.87
Arid Locations	*b* 1.04	0.96	0.98	0.86	1.01
	r 0.98	0.96	0.99	0.97	0.99
Humid Locations	*b* 0.88	0.85	0.89	0.73	0.98
	r 0.94	0.89	0.93	0.92	0.97
All locations	*b* 0.99	0.93	0.95	0.82	1.00
	r 0.97	0.96	0.98	0.96	0.99
Peak Month, Arid	*b* 1.12	1.06	0.98	0.90	1.04
	r 0.98	0.97	0.96	0.92	0.97
Peak Month, Humid	*b* 0.91	0.91	0.88	0.74	1.02
	r 0.74	0.75	0.57	0.65	0.93
Peak Month, All	*b* 1.07	1.03	0.96	0.86	1.03
	r 0.96	0.97	0.96	0.93	0.99

† Upper lines are *b* coefficients for regression through the origin. Lower lines are *r* coefficients.

‡ Unless noted, all statistics are for monthly average values over entire seasons of record.

§ Equation estimates have been adjusted for the reference type of the lysimeter.

Table 8. Standard errors of estimate of ET methods† in mm d^{-1} as compared with lysimeter measurements after adjustment of ET estimates using regression through the origin.‡

	Penman (1963)	1972 Kimberly Penman	1982 Kimberly Penman	FAO-24 Corrected Penman	Penman-Monteith
Aspendale	0.32	0.35	0.43	0.23	0.32
Brawley	0.86	1.11	0.56	0.99	0.43
Copenhagen	0.16	0.15	0.13	0.16	0.09
Coshocton	0.31	0.49	0.24	0.33	0.14
Davis	0.30	0.42	0.18	0.18	0.32
Kimberly	0.50	0.85	0.21	0.59	0.25
Lompoc	0.24	0.32	0.31	0.24	0.29
Scottsbluff	0.60	0.49	0.45	0.67	0.49
Seabrook	0.39	0.59	0.28	0.44	0.44
South Park	0.53	0.63	0.44	0.41	0.23
Yangambi	0.23	0.23	0.30	0.23	0.23
Arid Locations	0.54	0.70	0.45	0.68	0.41
Humid Locations	0.41	0.56	0.47	0.48	0.30
All Locations	0.57	0.67	0.49	0.65	0.36
Peak Months, Arid	0.55	0.59	0.70	1.02	0.62
Peak Months, Humid	0.67	0.65	0.82	0.76	0.36
Peak Months, All	0.81	0.70	0.73	1.00	0.47

† Equation estimates have been adjusted for the reference type of the lysimeter.

‡ Unless noted, all statistics are for monthly values over entire seasons of record.

Summary statistics and ranking of ET methods over arid, humid, and all lysimeter locations are included in Table 9. The Penman-Monteith method with aerodynamic and canopy resistances estimated using Eq. [3], [7], [8], and [9] had the lowest values of SEE and highest correlation coefficients. Average standard errors of estimate for the Penman-Monteith method were 0.52 and 0.36 mm d^{-1} for peak months and all months, respectively over all 11 lysimeter locations. The 1982 Kimberly Penman (Wright, 1982) had the second best performance overall, with a standard error of estimate for peak months of 0.79 mm d^{-1} and standard error of estimate for all months of 0.53 mm d^{-1}. The 1963 Penman wind function had an average SEE of 0.95 mm d^{-1} during peak months.

Daily Comparisons

Activities such as irrigation scheduling, crop yield simulation, hydrological modeling, and irrigation system sizing often require ET estimates for periods of 1 d. Because calculation of ET using monthly averages of weather data may not adequately indicate the ability of an ET method to estimate daily ET, a separate analysis was made of methods on a daily estimation basis.

Three lysimeter locations were selected for which sufficient daily weather and lysimeter measurements were available to evaluate equation performances over 3-yr periods. These locations were Kimberly, Coshocton, and Davis. Values of daily net radiation were estimated at the three sites using Eq. [22]. All method estimates used in the daily analysis, besides the Penman-Monteith, were adjusted for lysimeter vegetation type using the 1.15 multiplier. Values of lysimeter vegetation heights used in the Penman-Monteith method at the three sites were interpolated from monthly average values listed in Table 3.

Summary statistics and rankings of daily methods are listed in Table 10. Standard errors of estimate in this table were calculated in the same manner as in the monthly analysis using Eq. [16]. Additional statistics for each month of analysis are presented in Jensen et al. (1989). In general, the 1982 Kimberly Penman and the Penman-Monteith methods had the most consistency in the values of the regression coefficient, *b*, from month to month. However, the 1982 Kimberly Penman, after being divided by 1.15 at Davis to convert to a grass reference, overestimated grass lysimeter ET by about 20% at that location. The FAO-24 Corrected Penman equation overestimated daily ET early and late in irrigation seasons and overestimated daily reference ET at Davis by about 30 to 40%. About one quarter of the overestimation by the FAO-24 Corrected Penman at Davis was caused by the regression equation (Frevert et al., 1983) used to calculate the correction factor.

Standard errors of estimate for daily estimates in Table 10 were generally 0.1 to 0.3 mm d^{-1} greater in value than were standard errors of estimate for monthly average estimates (Table 6). The increase in values of SEE for daily estimates is apparent in Fig. 6, 7, and 8, which show daily ET estimates by the Penman-Monteith vs. lysimeter measurements at Kimberly, Coshocton, and Davis. The increases in SEE were due to the presence of more extreme combinations of weather parameters in the daily data set as compared

Table 9. Summary of statistics and ranking of ET equations for monthly average estimates.†

		All months					Peak month					Weighted
Rank	Method	%‡	SEE§	b¶	r#	ASEE††	%	SEE	b	r	ASEE	SEE‡‡
					Arid locations							
1	Penman-Monteith	99†	0.41	1.01	0.99	0.41	96	0.72	1.04	0.97	0.62	0.49‡‡
2	1982 Kimberly Penman	103	0.48	0.98	0.99	0.45	102	0.72	0.98	0.96	0.70	0.54
3	Penman (1963)	98	0.58	1.04	0.98	0.54	89	1.22	1.12	0.98	0.55	0.70
4	1972 Kimberly Penman	106	0.73	0.96	0.96	0.70	95	0.81	1.06	0.97	0.59	0.73
5	FAO-24 Corrected Penman	118	1.17	0.86	0.97	0.68	111	1.47	0.90	0.92	1.02	1.10
					Humid locations							
1	Penman-Monteith	104	0.31	0.98	0.97	0.30	98	0.37	1.02	0.93	0.36	0.32
2	Penman (1963)	114	0.57	0.88	0.94	0.41	109	0.84	0.91	0.74	0.67	0.60
3	1982 Kimberly Penman	110	0.59	0.89	0.93	0.47	111	1.09	0.88	0.57	0.82	0.69
4	1972 Kimberly Penman	118	0.75	0.85	0.89	0.56	109	0.83	0.91	0.75	0.65	0.71
5	FAO-24 Corrected Penman	135	1.17	0.73	0.92	0.48	134	2.02	0.74	0.65	0.76	1.14
					All locations							
1	Penman-Monteith	101	0.36	1.00	0.99	0.36	97	0.52	1.03	0.99	0.47	0.40
2	1982 Kimberly Penman	107	0.53	0.95	0.98	0.49	107	0.79	0.96	0.96	0.73	0.59
3	Penman (1963)	106	0.57	0.99	0.97	0.57	99	0.95	1.07	0.96	0.81	0.67
4	1972 Kimberly Penman	112	0.74	0.93	0.96	0.67	102	0.72	1.03	0.97	0.70	0.72
5	FAO-24 Corrected Penman	127	1.16	0.82	0.96	0.65	122	1.53	0.86	0.93	1.00	1.10

† All equation estimates have been adjusted for the reference type of the lysimeter.

‡ Average percentage of lysimeter measurements.

§ Standard error of estimate for ET estimates in mm d^{-1} that have not been adjusted by regression.

¶ Regression coefficient (slope) for regression through the origin of lysimeter vs. equation estimates (Eq. [17]).

Correlation coefficient for regression through the origin of lysimeter vs. equation estimates.

†† Standard error of estimate for ET estimates in mm d^{-1} that have been adjusted by regression through the origin.

‡‡ Weighted standard error of estimate calculated as 0.7(0.67(col 4) + 0.33(col 7)) + 0.3(0.67(col 9) + 0.33(col 12)).

Table 10. Summary of statistics and ranking of ET equations for daily estimates at Kimberly, ID, Coshocton, OH, and Davis, CA.†

		All months				Peak month				Weighted
Rank	Method	SEE‡	b§	r¶	ASEE#	SEE††	b	r	ASEE	SEE
1	Penman-Monteith	0.77	0.98	0.92	0.75	0.70	1.04	0.80	0.66	0.74
2	1982 Kimberly Penman	0.88	0.94	0.92	0.73	1.03	0.96	0.80	0.64	0.85
3	Penman (1963)	0.95	0.99	0.90	0.83	0.88	1.07	0.81	0.63	0.88
4	1972 Kimberly Penman	1.09	0.92	0.88	0.92	0.92	1.04	0.81	0.62	0.97
5	FAO-24 Corrected Penman	1.22	0.84	0.91	0.79	1.34	0.87	0.80	0.65	1.09

† All equation estimates have been adjusted for the reference type of the lysimeter.

‡ Standard error of estimate for ET estimates in mm d^{-1} which have not been adjusted by regression.

§ Regression coefficient (slope) for regression through the origin of lysimeter vs. equation estimates.

¶ Correlation coefficient for regression through the origin of lysimeter vs. equation estimates.

Standard error of estimate for ET estimates in mm d^{-1} which have been adjusted by regression through the origin.

†† Weighted standard error of estimate calculated as 0.7(0.67(col3) + 0.33(col 6)) + 0.3(0.67(col 7) + 0.33(col 10)).

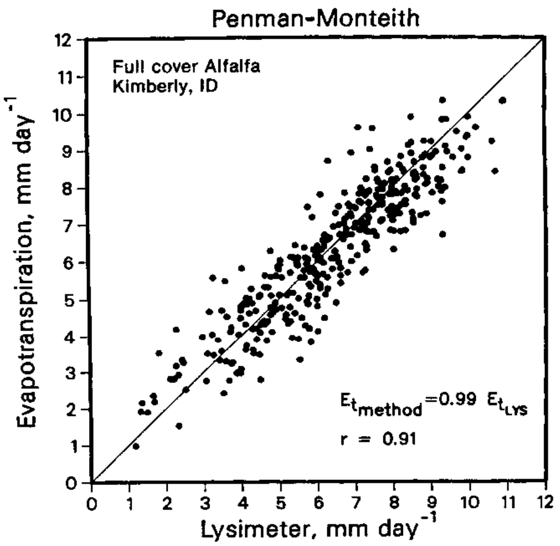

Fig. 6. Estimated daily reference ET using the Penman-Monteith equation vs. daily measurements at Kimberly, ID.

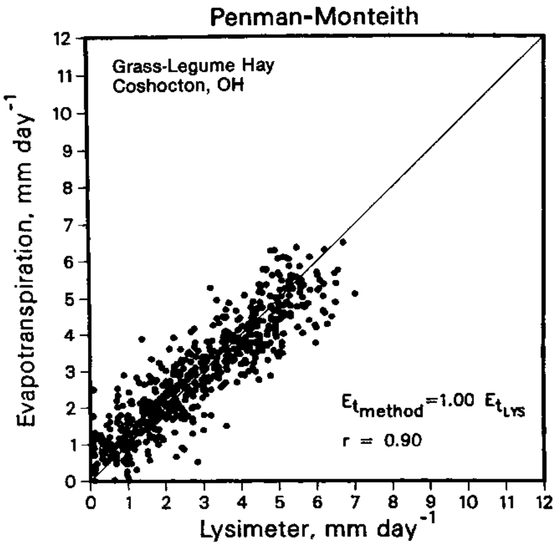

Fig. 7. Estimated daily reference ET using the Penman-Monteith equation vs. daily measurements at Coshocton, OH.

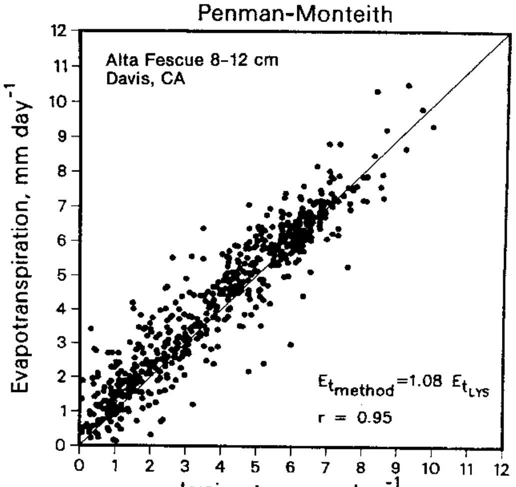

Fig. 8. Estimated daily reference ET using the Penman-Monteith equation vs. daily measurements at Davis, CA.

with the monthly data set where variabilities in parameters were reduced due to averaging over longer periods. Other variability in the daily analyses was caused by the use of estimated values of daily net radiation rather than measured values due to missing or incomplete data sets. This likely increased differences between measured and estimated lysimeter ET on a daily basis.

Monthly Average Estimates

Reference ET estimates using combination equation methods were well correlated with lysimeter measurements at 10 of 11 sites. In general, the combination methods with the empirical wind functions tended to slightly overestimate reference ET at the more arid locations and tended to significantly overestimate in the more humid climates (average percentage of lysimeter measurements was 120). A portion of this overestimation occurred during months of low ET, as average percentages of lysimeter-measured ET for peak months were 98 and 114, for the arid and humid locations, respectively. Some of the overestimation by the empirical wind functions may have been due to low heights and LAI of grass vegetation at several of the humid locations (Table 3) relative to vegetation heights to which a majority of the Penman wind functions were calibrated. This effect is evidenced by the goodness of fit at the majority of sites by the Penman-Monteith method in which surface roughnesses and LAI (affecting bulk stomatal resistance) described the conditions at each lysimeter. This emphasizes the importance and need for standardization of maintenance heights in reference lysimeters and in equation calibration.

In addition to lysimeter cover and height maintenance, other reasons for overestimation or underestimation by the combination methods include the problem of using daily or monthly averages of vapor pressure deficit, wind, radiation, and air temperature in the equations. In reality, these parameters are often significantly out of phase with one another during the course of a diurnal cycle, thereby weighting cumulative ET demands over a 24-h period disproportionately, as predicted, using daily or monthly averages. This problem in diurnal phasing of air and atmospheric properties can be corrected by performing ET calculations on an hourly or shorter time scale.

Daily Estimates

The Penman-Monteith method had the lowest standard errors of estimate for daily estimates over all months and also for peak months. Estimates by the 1982 Kimberly Penman method, adjusted for lysimeter reference type, were about 15% higher than lysimeter measurements, thereby increasing values of computed SEE. However, estimates by the 1982 Kimberly Penman, when adjusted by regression, had lower standard errors than the Penman-Monteith estimates. Some of the overestimation by the 1982 Kimberly Penman would have been reduced if a value of 1.2 or 1.25 had been used to adjust from an alfalfa to a grass reference for the Davis type of climate rather than 1.15.

As in the monthly statistical analysis, the values of SEE for the FAO-24 Corrected Penman method exceeded values from other forms of the combination equation due to the chronic overestimation. Values of *b* and SEE in Table 10 indicate that if estimates by the FAO-24 Corrected Penman were multiplied by about 0.85 to better approximate a grass reference, this equation would potentially be second only to the Penman-Monteith and 1982 Kimberly Penman equations in performance and accuracy in predicting daily ET at the three lysimeter sites.

Standardization of Vegetation Heights for Reference Equations

Reference ET is generally that from either a cool-season clipped grass or full cover alfalfa. Reference ET from clipped grass (ET_o) has been defined by Doorenbos and Pruitt (1977) as ET from a crop of short, evenly clipped grass 0.08–0.15 m tall, completely shading the ground, never short of water, and having uniform fetch. Reference ET from alfalfa (ET_r) has been defined similarly by Jensen et al. (1970) for alfalfa greater than 0.3 m in height.

Typically ET from grass (ET_o) may be only 75 to 90% of that from alfalfa (ET_r) under arid conditions. Wright (Jensen et al., 1989) reported average ratios of alfalfa reference ET to clipped ryegrass ET of about 1.28 at Kimberly, ID. Pruitt (Doorenbos and Pruitt, 1977) recommended a peak alfalfa to grass ratio of 1.05 in humid areas of light to moderate wind, 1.15 in dry areas with light to moderate wind, and 1.25 for dry areas with strong wind. Grass varieties are often adaptable to more diverse climates and locations than alfalfa, although there can be significant differences in ET by grass due to differences in variety, season, and height. Marsh et al. (1980) and Hargreaves (1983) noted differences in ET rates between warm and cool season grasses, and between clipped and non-clipped surfaces. Wright (personal communication, 1986) noted differences in water use between alfalfa varieties at Kimberly, ID.

The definitions of grass and alfalfa reference ET include specification of fixed ranges or lower limits of grass and alfalfa heights. Results of the analysis of leaf area and roughness relationships presented in this paper indicate that values of grass and alfalfa heights of about 0.12 m and 0.50 m, respectively, approximate reference conditions for the two reference types during peak periods at Davis, Copenhagen, and Kimberly. However, because an alfalfa height bias may be built into alfalfa-based crop coefficients (Wright, 1981, 1982) due to their development in a northern, temperate climate, the practitioner may wish to vary the height of alfalfa (as shown for Kimberly in Table 3) in the Penman-Monteith or energy balance equations when computing alfalfa references to approximate average heights of alfalfa with time in the specific local area.

When mean monthly data at the 11 monthly sites were evaluated with the Penman-Monteith method, with values of r_a and r_c estimated for 0.5 m tall alfalfa and 0.12 m tall grass (Eq. [3], and [7] through [9]), ratios of ET_r to ET_o for the two standard reference heights averaged 1.32 ($ET_o/ET_r = 0.76$). Ratios of alfalfa to grass reference ET for peak months, as predicted by the Penman-Monteith method, are listed in Table 11 for each lysimeter site. Values of these ratios are about 5% greater than those reported by Wright (personal communication, 1985) and are about 10% greater than the ranges recommended by Pruitt (Doorenbos and Pruitt, 1977). Ratios of ET_r/ET_o were typically lowest at the humid, low wind locations (Coshocton, Lompoc, and Yangambi). Ratios of ET_r/ET_o were high at Seabrook (1.39 avg.) due to high wind speeds (3.5 m s^{-1} avg.) and moderate vapor pressure deficits.

Table 11. Ratios of alfalfa reference ET estimates by the Penman-Monteith method to grass reference ET estimates by the Penman-Monteith method at arid and humid lysimeter sites.

Arid	Peak Month	Average†
Aspendale	1.34	1.37
Brawley	1.34	1.34
Davis	1.31	1.38
Kimberly	1.32	1.37
Scottsbluff	1.37	1.34
South Park	1.24	1.30
Humid	Peak Month	Average
Copenhagen	1.28	1.35
Coshocton	1.22	1.29
Lompoc	1.17	1.25
Seabrook	1.35	1.39
Yangambi	1.13	1.12

† Seasonal average weighted according to monthly average lysimeter measurements.

One of the limitations of the preceding analysis of reference ratios is the assumption that weather measurements above each reference surface were identical at each lysimeter location. In practice, the wind, temperature, and vapor profiles above a grass surface will generally have different shapes and gradients as compared with an alfalfa surface. These differences tend to decrease the differences in measured ET between the reference types. Therefore, the 1.35 ratio of alfalfa to grass is probably 5 to 10% greater than what would be found in practice at the various locations. The preceding analysis used the same zero plane displacement of the weather measurement surface for both reference estimates.

Standard Equations

For fixed reference height and weather measurement heights, Eq. [2] can be combined with fixed estimates of r_c and roughness heights from Eq. [3], and [7] through [9] to provide equations for standard references. For a 0.5 m tall alfalfa reference crop with all measurements at 2 m above the ground surface,

$$\lambda ET_r = \frac{\Delta(R_n - G) + 4680\ \rho\ c_p\ k^2\ u\ (e_a - e_d)}{\Delta + \gamma(1 + 2.42\ k^2\ u)} \quad [18]$$

and for a 0.12 m tall grass reference crop with all measurements at 2 m above the ground surface,

$$\lambda ET_o = \frac{\Delta(R_n - G) + 2480\ \rho\ c_p\ k^2\ u\ (e_a - e_d)}{\Delta + \gamma(1 + 1.99\ k^2\ u)} \quad [19]$$

If additional simplifications are made to the preceding equations, they can be reexpressed as:

$$\lambda ET_r = \frac{\Delta(R_n - G) + \gamma(\frac{5360}{T} - 4.02)\ u\ (e_a - e_d)}{\Delta + \gamma(1 + 0.407\ u)} \quad [20]$$

for 0.5 m tall alfalfa and

$$\lambda ET_o = \frac{\Delta(R_n - G) + \gamma(\frac{2830}{T} - 2.13)\ u\ (e_a - e_d)}{\Delta + \gamma(1 + 0.334\ u)} \quad [21]$$

for 0.12 m grass where T is mean air temperature in degrees Kelvin. Units of λET, R_n and G in Eq. [18] through [21] are in MJ m^{-2} d^{-1}, e_a and e_d are in kPa, Δ and γ have units of kPa $°C^{-1}$, c_p has the value of 1.01×10^{-3} MJ kg^{-1} $°C^{-1}$, and u is in m s^{-1}. Equations [18] through [21] are approximately equivalent to the use of Eq. [2] through [9].

CONCLUSIONS

In general, the inclusion of simple procedures to approximate the effects of vegetation leaf area and height on surface roughness and bulk stomatal (canopy) resistance into the Penman-Monteith equation appear to improve the application of reference ET to a wide variety of climates and locations. The algorithms presented for r_c should be used only for daily or longer term estimates, as diurnal values of r_c may change with temperature or net radiation. The Penman-Monteith equation provided best estimates of daily and monthly average reference ET and was the most consistent across all locations evaluated, followed by the 1982 Kimberly Penman and 1963 Penman equations. The FAO Penman estimated about 15 to 20% higher than lysimeter measurements at most locations.

Reference estimates and measurements are both sensitive to canopy height. Therefore, standard heights of perhaps 0.12 m and 0.5 m for clipped grass and alfalfa references, respectively, should be used for method calibration or testing. Ratios of alfalfa to grass reference ET as predicted by the Penman-Monteith method averaged between 1.2 and 1.35. Variation among ratios of alfalfa to grass reference ET at the various locations evaluated indicates that alfalfa may be a more desirable reference than grass, as its height and roughness approximate those of most agricultural crops.

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APPENDIX

Estimation of Daily Net Radiation

Where net radiation was not measured, daily values were estimated from solar radiation, air temperature and vapor pressure according to a general relationship (Penman, 1948) modified by Wright (1982) as:

$$R_n = [(1-\alpha)R_s - \sigma\frac{(T^4_{\text{maxk}} + T^4_{\text{mink}})}{2} \times (a_1 - 0.139\sqrt{e_d})\,(a\frac{R_s}{R_{so}} + b)] \quad [22]$$

where R_n is daily net radiation (MJ m^{-2} d^{-1}), α is albedo (reflectance) of the surface (0.23 to 0.30 for green plants), R_s is measured short wave (global) radiation (MJ m^{-2} d^{-1}), σ is the Stephan-Boltzman constant (4.903×10^{-9} MJ m^{-2} d^{-1} K^{-4}), T_{maxk} is maximum daily air temperature (K), T_{mink} is minimum daily air temperature (K), e_d is saturation vapor pressure at the dewpoint temperature (kPa), R_{so} is clear sky short wave radiation (R_s with no clouds) (MJ m^{-2} d^{-1}), and a_1, a, b are empirical coefficients.

Albedo in Eq. [22] was estimated according to Wright (1982) for an alfalfa crop in a northern temperate climate as:

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

where J is the day of the year (1 to 365) and the sine argument is in radians. The empirical coefficients in Eq. [22] were estimated according to Wright (1982) as:

$$a_1 = 0.26 + 0.1\, e-[0.0154(J - 180)]^2 \quad [24]$$

and for $R_s/R_{so} > 0.7$ (few clouds), $a = 1.126$ and $b = -0.07$, and for $R_s/R_{so} < 0.7$ (cloudy), $a = 1.017$ and $b = -0.06$. The value of a_1 predicted by Eq. [24] was limited to $\leqslant 4$ during late fall and winter months. In southern latitudes, the values of J in Eq. [23] and [24] were incremented or decremented by 183.

R_{so} (clear sky solar radiation) was estimated as:

$$R_{so} = 0.75\, R_a \quad [25]$$

where R_a is extraterrestrial radiation (at outside of atmosphere) in MJ m^{-2} d^{-1}. This relationship was determined by Allen (R.G. Allen, 1988, unpublished data) to predict R_{so} at seven locations in California, Utah, and southern Idaho ranging in elevation from 16 to 3000 m. It also agrees with clear sky relationships for both humid and arid regions summarized by Linacre (1967) and Doorenbos and Pruitt (1977).

Daily values of extraterrestrial radiation were estimated using an integrated equation by Duffie and Beckman (1980), which produces values in agreement with the Smithsonian Meteorological Tables (List, 1984) over a wide range of latitudes:

$$R_a = (24(60)/\pi)G_{sc}d_r\,[(\omega_s)\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)] \quad [26]$$

where all trigonometric functions are in radians, and ϕ is the latitude of the station in radians, G_{sc} is the solar constant (MJ m^{-2} min^{-1}), d_r is the relative distance of the earth from the sun, ω_s is the sunset hour angle (radians), and δ is the declination of the sun (radians). The International Association of Meteorology and Atmospheric Physics (IAMAP) determined G_{sc} to be 0.08202 MJ m^{-2} min^{-1} (1367 W m^{-2}) (London and Frohlich, 1982). The other parameters in Eq. [26] were calculated as follows:

$$\delta = 0.4093 \sin(2\pi(284 + J)/365) \quad [27]$$

$$d_r = 1 + 0.033 \cos(2\pi\, J/365) \quad [28]$$

$$\omega_s = \arccos(-\tan(\phi)\tan(\delta)) \quad [29]$$

or alternatively, for computer languages without built-in inverse cosine functions, as:

$$\omega_s = \pi/2 - \arctan((-\tan(\phi)\tan(\delta))/(1-\tan^2(\phi)\tan^2(\delta))^{1/2}) \quad [30]$$

The argument of the inverse functions in Eq. [29] and [30] must be limited for latitudes > 55 ° due to numeric instability. In winter it must be $\leqslant 2.0$, and if less than -1.0 during summer, it must be set equal to $(\tan(\phi)\tan(\delta) - 2.0)$.

Supporting Equations

Average daily soil heat flux was approximated (Wright and Jensen, 1972) as:

$$G = (T_a - T_p)\, c_s \quad [31]$$

where T_a is average daily air temperature at the z height (°C) and T_p is the average daily air temp (°C) for the previous 3 d. Parameter c_s is the general heat conductance for the soil surface, equal to about 0.38 MJ m^{-2} d^{-1} $°C^{-1}$ for a silt loam soil.

Saturation vapor pressure (e^o) in kPa at temperature T (°C) was calculated using the method of Tetens (1930):

$$e^o = \exp\left[\frac{16.78\, T - 117}{T + 237.3}\right] \quad [32]$$

Equation [32] yields estimates of saturation vapor pressure which are within 0.1% of the Goff-Gratch formulation (List, 1984) for temperatures ranging from 0 to 50 °C. Slope of the saturation vapor pressure function was calculated by taking the derivative of Eq. [32]

(Erpenbeck, 1981, M.S. thesis, Washington State University):

$$\Delta = \frac{4098\, e^o}{(T + 237.3)^2} \qquad [33]$$

The psychrometric constant, γ, (kPa °C^{-1}) was calculated as:

$$\gamma = \frac{c_p\, P}{\epsilon\, \lambda} \qquad [34]$$

where c_p is the specific heat of moist air at constant pressure (1.01×10^{-3} MJ kg^{-1} °C^{-1}), P is atmospheric pressure (kPa), ϵ is the ratio of molecular weights of air to water (0.622), and λ is the latent heat of vaporization (MJ kg^{-1}), which was calculated according to Harrison (1963) as:

$$\lambda = 2.50 - (2.361 \times 10^{-3})\, T_a \qquad [35]$$

where T_a is air temperature (°C).

Atmospheric density (ρ) was calculated using the following set of equations based on virtual temperature (T_v) and the ideal gas law:

$$T_v = \frac{T}{1 - 0.378\, \frac{e_d}{P}} \qquad [36]$$

$$\rho = \frac{1000\, P}{T'_v\, R} \qquad [37]$$

where T_v and T have units of K, ρ has units of kg m^{-3}, and R is the specific gas constant for dry air (286.9 J kg^{-1} K^{-1}). Virtual temperature represents the temperature of a dry air parcel with heat content equivalent to a similar moist parcel.

The ideal gas law was used to estimate mean atmospheric pressure by assuming a constant temperature lapse rate. The resulting equation for P (Burman et al., 1987) was:

$$P = P_o \left[\frac{T_o - \alpha\,(z - z_o)}{T_o} \right]^{g/(\alpha R)} \qquad [38]$$

where P_o and T_o are known atmospheric pressure (kPa) and absolute temperature (K) at elevation z_o (m), and P is the desired pressure estimate at elevation (altitude) z. Parameter α is the assumed constant adiabatic lapse rate, normally taken as either 0.0065 K m^{-1} for saturated air or about 0.01 K m^{-1} for dry air. The specific gas constant for dry air can be used for R with negligible error. Equation [38] is also relatively insensitive to the value for α for elevations between 0 and 7000 m. Gravitational acceleration (g) equals 9.8 m s^{-2}. Values for P_o, T_o, and z_o were set to those for the standard atmosphere at sea level, which are 101.3 kPa, 288 K, and 0 m, respectively (List, 1984).

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