Empirical Methods of Estimating or Predicting Evapotranspiration Using Radiation

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PREDICTIONS of evapotranspiration are basic parameters for the engineer or agronomist involved in planning and developing water resources. Estimates of evapotranspiration are also used extensively in assessing the irrigation water-management efficiency of existing projects, future project drainage requirements, and the magnitude of deep percolation losses under existing management practices. Water delivered to farms and fields must provide for evapotranspiration and unavoidable percolation beyond the root zone due to unsaturated flow caused by gravity. The first is dependent on meteorological conditions and the vegetative characteristics of the crop when water is not limiting. The second is dependent on management such as the amount of excess water applied by rainfall or irrigation, or the moisture level maintained, and it is not directly dependent on meteorological conditions. Actually the relative amount of deep percolation between irrigations under common practices is more apt to be inversely rather than directly related to evapotranspiration. Measurement of irrigation water delivered to an area and surface runoff, coupled with reliable estimates of evapotranspiration, provide the most practical estimates of deep percolation under existing management systems. Full utilization of water resources will require more reliable estimates of evapotranspiration in the future, and these estimates must not include deep percolation.

Empirical methods are used for estimating or predicting evapotranspiration when (a) inadequate meteorological and soil-crop data are available to apply complete rational equations based on the physical processes involved, (b) the absolute accuracy of the data needed may be adequate using simple empirical equations that require much less time and effort to solve, and (c) complete rational equations often require greater technical ability and experience in meteorology, physics and agronomy than many users of evapotranspiration data have or can justify attaining.

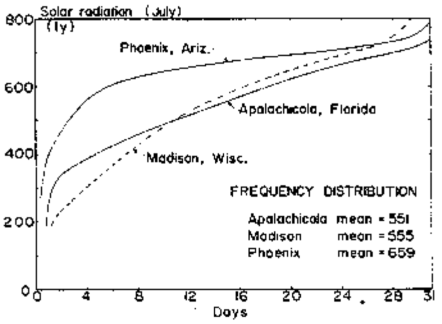

FIG. 1 Expected frequency of daily solar radiation in July.

Rationally developed empirical methods of estimating or predicting evapotranspiration, using either net or solar radiation as the primary variable, approximate solutions based on the conservation of energy or "energy balance." Energy balance has repeatedly been shown to be a reliable and conservative method of determining evapotranspiration for periods of time as short as one hr. Empirical methods using radiation are more reliable for both short and long-time periods than those using meteorological parameters that are not a measure of available energy, or basic components of energy balance or mass transfer equations. However, qualified technicians have little justification in using empirical methods when the basic meteorological parameters such as net radiation, vapor pressure and temperature gradients, wind speed at a prescribed elevation above the crop or over a standard surface, and soil heat flux are available. Preceding papers presented at this conference clearly demonstrated that reliable, rational equations are available for estimating or predicting evapotranspiration when these parameters are known.

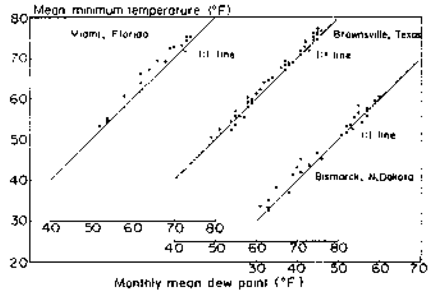

FIG. 2 Monthly mean minimum air temperatures and monthly mean dew point temperatures.

Several combination-type equations requiring three or four meteorological parameters may involve some empiricism and perhaps also fall in the category of this paper. However, the basic concept of the combination method was summarized in the preceding paper. Examples of methods requiring some empirical coefficients are those proposed by Penman in 1948, Ferguson in 1952, Budyko in 1956, and Slatyer and McIlroy in 1961 (1, 3, 14, 19)*. Stanhill in 1962 (20) approximated the aerodynamic component of the combination equation using atmometers.

Energy Balance and Combination Equations

Energy balance and combination equations for the soil-crop surface are presented to clarify the notation used and as a review of basic concepts. Only the major components are shown.

$$LE = (1 - r)R_s - R_{e\,t} - A - G \quad [1]$$

where $(1 - r)R_s - R_{e\,t} = R_n$ . . [2]

thus $LE = R_n - A - G$ . . . . . [3]

In these equations LE is latent heat, r is reflectance or albedo of the surface, R_s is direct and diffuse solar radiation (short wave), A is sensible heat flux to the air (negative for heat flux from the air), G is sensible heat flux to the ground (negative for heat flux from the ground), $R_{e\,t}$ is the net long wave or thermal radiation from the ground and plant surfaces to the atmosphere, and R_n is net radiation (short and long wave). Solutions of equation [1] or [3] (rate of evapotranspiration) require the determination or calculation of the components on the right side. A detailed review of energy-balance concepts can be found in numerous recent publications such as those by Budyko (1), Tanner (23), Tanner and Lemon (24), Jensen and Haise (10), Rijtema (18), and Waggoner et al (28).

Combination equations generally are of the form

$$LE = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} f(z_0, d)\, u(e_s - e_a) \quad [4]$$

where Δ is the slope of the saturation vapor pressure-temperature curve, de/dT; γ is the psychrometric constant; z_0 is the surface roughness length, d is the displacement of the zero plane of

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* Numbers in parentheses refer to the appended references.

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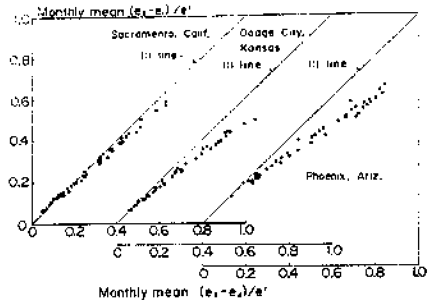

FIG. 3 Monthly mean humidity as indicated by difference between saturation vapor pressure at mean maximum air temperature, e_2, and mean minimum air temperature, e_1, as compared to $(e_2 - e_d)$ where e_d is the saturation vapor pressure at monthly mean dew point temperature. $e' = 70$ mb.

wind velocity in relation to the ground surface, u is wind speed, e_s is the saturation vapor pressure of the air, and e_d is the actual vapor pressure of the air. The parameters $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ are air-temperature weighting factors whose sum is 1.0. A summary of these terms is presented in Table 1. Most combination equations assume that $G = 0$ or negligible.

Empirical Radiation Equations

Empirical radiation equations that are rationally developed can be expected to resemble equations [1], [3], or [4]. Most would be simplified to fit one of the following forms:

$$LE = K_c\ \phi_1\ R_n \quad \ldots\ldots\ldots \quad [5]$$

$$LE = K_c\ \phi_2\ R_s \quad \ldots\ldots\ldots \quad [6]$$

$$LE = K_c\ \phi_3\ R_A \quad \ldots\ldots\ldots \quad [7]$$

in which K_c is a crop coefficient, R_A is extraterrestrial solar radiation, and ϕ_1, ϕ_2, and ϕ_3 are net radiation, solar radiation, and extraterrestrial radiation coefficients, respectively. The products $\phi_1 R_n$, $\phi_2 R_s$, and $\phi_3 R_A$ generally represent potential evapotranspiration or the upper limit of evapotranspiration that can occur from agricultural crops in either humid or arid areas surrounded by sufficient buffer area so that the "clothesline" effect is small or negligible. The width of the buffer strip required may be only 100 ft or less for most short, dense field crops. The crop coefficient accounts for the period of leaf-area development, minor differences between field crops when an effective full crop canopy exists, $(K_c \cong 1.0)$, and the maturation stages of growth. Effective full-crop canopy may not mean complete ground cover, but sufficient leaf areas so as not to limit evapotranspiration.

When $K_c = 1.0$, equations [5], [6], and [7] can be rearranged to assess the factors involved in the various coefficients. For example, the net radiation and solar radiation coefficients for daily totals represent the following terms:

$$\phi_1 = \frac{LE}{R_n} = 1.0 - \frac{A + G}{R_n} \quad \ldots \quad [8]$$

$$\phi_2 = \frac{LE}{R_s} = 1 - r - \frac{R_{e\,t}}{R_s} - \frac{A + G}{R_s} \quad \ldots\ldots\ldots \quad [9]$$

When considering daily totals, the value of ϕ_1 will be approximately 1.0 when the algebraic sum of A and $G \cong 0$. The value of ϕ_2 at this time will be $1 - r - R_{e\,t}/R_s$ or about $0.75 - R_{e\,t}/R_s$ since the reflectance is about 0.25 for most crops. A summary of observed ϕ_1 and ϕ_2 values will be presented in a later section.

Limitations of Empirical Equations

The major limitation of any empirical equation for estimating evapotranspiration is that its constants may not be applicable in other climatic regimes without calibration. Most empirical equations contain only one meteorological parameter, or at least not all of the basic parameters. Therefore, calibration does not assure the same reliability in different climatic regimes unless the equation contains the meteorological parameters controlling or closely related to evapotranspiration. For example, in arid areas sensible heat from vast dry, unirrigated areas often contributes part of the daily heat energy for evapotranspiration (warm air advection). This seldom occurs at significant magnitudes in humid areas. The daily rise in air temperature is a measure of the radiant energy reaching the earth's surface on a regional basis that was *not* utilized in evapotranspiration. Therefore, an empirical equation with air temperature as the main parameter would not be as reliable for short-period estimates in humid areas as in arid areas. In contrast, since radiant energy is the main source of heat energy in both areas, empirical equations with a radiation term can be applied with more confidence in either area when calibrated. The larger variability in day-to-day radiation in semihumid and humid areas, oftentimes with small changes in air temperature, is further evidence that radiation is more important than air temperature in estimating evapotranspiration under these conditions. The expected frequency of daily solar radiation in July for three locations is presented in Fig. 1 which illustrates that daily solar radiation is expected to deviate only ± 10 percent from the long-time mean two-thirds of the month at Phoenix, Ariz. In contrast, the expected deviation at the Florida location is ± 24 percent, and in Wisconsin ± 32 percent.

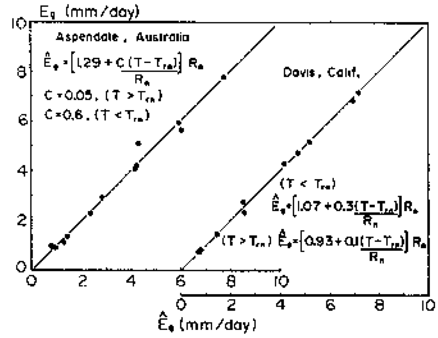

FIG. 4 Example procedure for correcting the net radiation coefficient, ϕ_1, using the mean air temperature—net radiation lag.

These examples illustrate that "calibration" of an empirical equation may be necessary to assure its accuracy when used under climatic conditions that are significantly different than those under which the equation was derived. Also, the short-period accuracy of an empirical equation may not be the same under vastly different climatic conditions even though the equation is "calibrated." The accuracy of an empirical equation being used in another climatic regime will depend on which meteorological parameters are used.

TABLE 1. SUMMARY OF $\Delta/(\Delta + \gamma)$, $\gamma/(\Delta + \gamma)$ AND Δ/γ VS T

Air temperature deg C	deg F	$\frac{\Delta}{\Delta + \gamma}$	$\frac{\gamma}{\Delta + \gamma}$	$\frac{\Delta}{\gamma}$
1	33.8	0.417	0.583	0.72
5	41	0.478	0.522	0.92
10	50	0.552	0.448	1.23
15	59	0.621	0.379	1.64
20	68	0.682	0.318	2.15
25	77	0.735	0.265	2.78
30	86	0.781	0.219	3.57
35	95	0.819	0.181	4.53
40	104	0.851	0.149	5.70

Computed from Smithsonian Meteorological Tables, 6th edition, 1958, equation [2], page 365, and Table 103, page 372.

Estimating Meteorological Parameters

Frequently the major justification for using a less reliable estimating or prediction equation is that limited meteorological data are available for the site in question. Actually, if a needed meteorological parameter is estimated and a more rational equation used, the accuracy of the estimated or predicted evapotranspiration is often greatly improved.

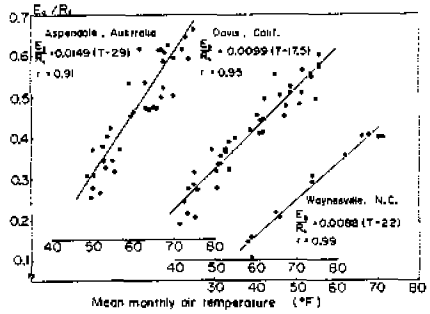

FIG. 5 Observed increase in the ratio of evapotranspiration from grass to solar radiation, ϕ_2, as mean air temperature increases.

Several procedures for estimating solar radiation have been satisfactorily used for many yrs. Estimates based on clear-day values and the percentage of daily sunshine are generally the most reliable (10). Solar radiation can also be reliably extrapolated between widely separated points of measurement in arid areas (9). Similarly, estimates of net radiation based on a linear relationship with solar radiation are very reliable in arid areas.

Mean dew-point temperatures also can be extrapolated between climatic stations and used with most empirical equations requiring dew points. When dew-point temperatures are not available, they can be estimated using minimum air temperatures in humid or cool, semihumid areas (6) from which a saturation vapor-pressure value, e_1, can be obtained (Fig. 2). The relationship between $(e_2 - e_1)$ and $(e_2 - e_d)$ is essentially linear in both arid and humid areas (Fig. 3). Therefore $(e_2 - e_d)$ can be estimated for individual months using a linear relationship derived using two points. These two points can be obtained from mean data for January and July in the northern hemisphere which are commonly available (maximum, minimum, and dew-point temperatures). If dew-point data are not available, then saturation vapor pressure at minimum temperatures could be used with e_2 as an index of humidity. This index would underestimate $(e_2 - e_d)$ by as much as 25 percent in arid areas as shown in Fig. 3. A summary of $(e_2 - e_1)$ vs $(e_2 - e_d)$ for additional locations is presented in Table 2. The excellent correlation is due to the use of e_2 in both variables, and since the saturation vapor pressure-temperature relationship is nonlinear, differences between minimum temperature and dew-point temperature have small effects.

Net Radiation Coefficients

Numerous studies have shown that net radiation accounts for most of the variability in evapotranspiration when soil water and vegetative cover are not limiting. The minimum value of ϕ_1 will be about $\Delta/(\Delta + \gamma)$ (19). Generally ϕ_1 will be near 1.0 in semihumid to humid areas with a small "loop" effect occurring during the season because of the lag in sensible heat in the air and soil. Simple linear-regression equations derived from observed data for a given area such as those presented by Tanner (23) and Pruitt (15) can be used to estimate evapotranspiration. Pruitt presented two regression equations – one for the period of increasing sensible-heat storage in the air and soil and the other for the period of decreasing sensible heat. In areas where advection is severe, short-period values of ϕ_1 often exceed 1.0 and may reach 1.8 as illustrated by the data of Fritschen (4), McIlroy and Angus (12), Pruitt (15), and van Bavel (27). Thus ϕ_1 cannot be assumed constant in a given area, nor can it be assumed to be near 1.0 for all areas for estimating purposes. If complete meteorological data are available, then one of the combination equations (with calibration) could be used to obtain good estimates of potential evapotranspiration when net radiation is known. Other procedures must be used when supporting meteorological data are inadequate, or the basic meteorological data also must be estimated.

The energy balance components affecting the magnitude of ϕ_1 in equation [5] are A and G. During the period when soil and air temperatures are increasing, part of the daily net radiation on a regional basis is converted to sensible heat in the air and soil. The opposite occurs when air and soil temperatures are decreasing. Therefore, one would expect a "loop" effect in the value of ϕ_1 on a regional basis due to the thermal lag of the soil and air mass. This loop effect could be related to $1.0 - C(dT/dt)/R_n$ in humid areas where T is mean daily air temperature, t is time, and C is a coefficient representing a "specific heat capacity" for the air and soil as related to the mean rate of air-temperature change measured at shelter height. In irrigated areas, or areas where warm-air advection may significantly affect ϕ_1, the above relationship would probably require separate coefficients for the periods when regional sensible heat is increasing and when regional sensible heat is decreasing. However, under these conditions C may not be constant and the entire equation would become more complex. If an empirically derived relationship is to be used, it must be an extremely simple relationship to justify its use over more rational equations. One such relationship is as follows:

$$\phi_1 = \frac{LE}{R_n} = 1 - C\,\frac{T - T_m}{R_n} + \phi_4 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{[10]}$$

where T is mean air temperature, T_m is mean air temperature for a given value of R_n at a given location if no "loop effect" exists. Therefore, T_m can be obtained from a linear relationship between mean air temperature and net radiation in January and July when $dT/dt \cong 0$. ϕ_4 is a dimensionless local calibration constant or a variable that may be related to some other climatic parameters such as vapor-pressure deficit and wind speed. When ϕ_4 is considered a constant, its magnitude can be evaluated when $dT/dt \cong 0$ which normally occurs in January and the latter part of July in the northern hemisphere. Equation [10] was evaluated using grass evapotranspiration data from McIlroy and Angus (12) and Pruitt (16) (Fig. 4). The weighted mean value of ϕ_4 for Aspendale, Australia was 0.29. Combining the constants results in a simple "calibrated" prediction equation for potential evapotranspiration from grass using net radiation and air temperature as shown in Fig. 4. These modifications essentially removed the loop effect shown by McIlroy and Angus when using the mean value of $\phi_1 = 1.2$.

A similar analysis was made using mean grass data from California (16). In this case ϕ_4 was -0.07 when T was increasing or $T < T_m$ and 0.04 when $T > T_m$. Substitution in equation [10] resulted in the equations shown in Fig. 4. These equations removed most of the loop effect present using the mean value of $\phi_2 = 0.98$.

An evaluation of these equations for estimating evapotranspiration for indi-

TABLE 2. SUMMARY OF REGRESSION EQUATIONS FOR MONTHLY MEAN VALUES OF $(e_2 - e_1)/e'$ VS $(e_2 - e_d)/e'$*

Location	a	b	Correlation coefficient
Bismarck, N.D.	0.008	0.948	0.998
Yakima, Wash.	0.011	0.906	0.996
Brownsville, Tex.	0.023	0.874	0.997
Sacramento, Calif.	0.015	0.892	0.998
Fresno, Calif.	0.032	0.824	0.996
Dodge City, Kans.	0.022	0.774	0.996
Yuma, Ariz.	0.020	0.729	0.998
Grand Junction, Colo.	0.018	0.706	0.997
Phoenix, Ariz.	0.047	0.689	0.994

* $\dfrac{e_2 - e_1}{e'} = a + b\,\dfrac{(e_2 - e_d)}{e'}$

$e' = 70$ mb

vidual months resulted in a standard error of 0.5 mm per day for both Aspendale and Davis. The standard error using $\phi_1 = 1.2$ for Aspendale was 0.62 mm per day, and when using $\phi_1 = 0.98$, the standard error was 0.75 mm per day for Davis. The temperature lag adjustment improves the estimates. However, if sufficient data are available to estimate R_n, one can seldom justify using this approach over one of the combination equations since very little additional data are needed.

Solar Radiation Coefficients

The value of ϕ_2, as shown in equation [9], will be about $0.75 - R_{e\,t}/R_s$ in July and January in humid areas at which time (mean daily) $A + G \cong 0$. Since $R_{e\,t}/R_s$ generally decreases with increasing solar radiation, an increase in ϕ_2 is expected as R_s increases. This increase can be predicted by estimating $R_{e\,t}$. An adjustment for the lag in sensible heat in the air and soil could also be incorporated as was done for ϕ_1. In addition, another adjustment must be made in areas where warm-air advection may occur since $A + G \neq 0$ for individual irrigated fields in July. If all of these adjustments had to be made independently, the resulting empirical equation would be cumbersome to use, and large errors may result when inexperienced personnel used this procedure. Instead, since the air temperature *vs* solar radiation lag reflects the lag in sensible heat stored in the soil and air, air temperature generally increases on a regional basis with increasing R_s and since the magnitude of advection is partially related to air temperature, one would expect a general increase in ϕ_2 as mean air temperature increases. This increase was apparent in evapotranspiration data obtained throughout western USA, Jensen and Haise (10). Mean monthly lysimeter data from Aspendale, Australia, McIlroy and Angus (12); Davis, Calif., Pruitt (16); Waynesville, North Carolina, [Fry et al (5) and Gilbert and van Bavel (7) as summarized by Stephens (21)], are presented in Fig. 5 to illustrate the linear relationship of ϕ_2 vs mean air temperature. The magnitude of E_g/R_s is greater under more arid conditions as is the slope of the regression equations. Mean air-temperature data reported for Aspendale by McIlroy and Angus is the mean of 09:00 and 15:00 hour observations. The normal mean air temperature computed from the maximum and minimum would be lower and the slope of the regression equation in Fig. 5 would be even greater. The Aspendale site is adjacent to Port Phillip Bay which would influence the air temperature-radiation relationship, and the lysimeters were irrigated up to four times per day which may have resulted in unusually high evapotranspiration rates for grass. A similar regression equation was obtained at Davis using mean air temperature at the Sacramento, Calif., airport. However, since the air temperature is higher at the airport, the coefficient was 0.0091 instead of 0.0099. The intercept of the *x* axis was about the same (17 F) and the correlation coefficient was 0.97. Therefore, it is not essential that air temperature be measured over the field, however, the coefficients may be slightly different.

Several regression equations for estimating evapotranspiration and some single-day values are presented in Fig. 6 to illustrate the differences due to climate and crops. The length of the lines represent the range of data used or variations in air temperature in the area where the data were obtained. The equation by Makkink (11) is about as good as Penman's equation for 10-day means in the Netherlands (17). The three equations for grass reflect primarily climatic differences. The regression equation by Jensen and Haise (10) represents data from crops other than grass and may reflect the influence of the roughness and leaf area of the crop. The alfalfa data from van Bavel (27) are single-day values in Arizona. The two high points represent severe advective conditions. These and several other estimating equations are summarized in Table 3. There are other estimating procedures that involve solar radiation such as those presented by Olivier (13) and Thompson (25). Turc's (26) equation generally will fall in the same area as the others in Fig. 6, except that the curve tends to flatten as T increases. The general humidity of a region and degree of warm-air advection appear to be the major climatic factors influencing variation in the slope of the lines in Fig. 6. The coefficient C in Grassi's (8) equation is a product of several dimensionless coefficients representing such parameters as air temperature, crop stage of growth, cloud cover, etc. A detailed summary of more recent developments in using this general equation for estimating evaporation from water surfaces is presented by Christiansen (2).

The major advantages of empirical equations using solar radiation are simplicity, "calibration" for an area is not difficult, and estimates have sufficient reliability for most engineering or water-management applications. Solar radiation is measured at a large number of locations throughout the world. Mean values can be estimated for most areas using clear-day or extraterrestrial val-

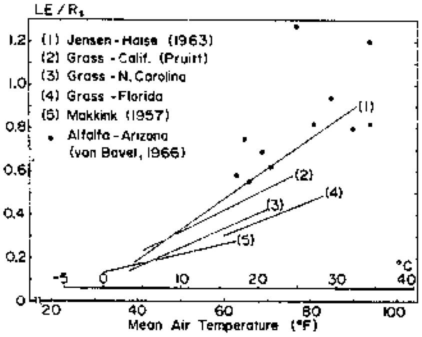

FIG. 6 Empirical regression equations relating the solar radiation coefficient, ϕ_2, to mean air temperature, and observed single day values for alfalfa in Arizona.

TABLE 3. SUMMARY OF SOME EMPIRICAL SOLAR RADIATION EQUATIONS

Equation	Units			Crop or estimate of potential and data source area
	E	T	R_s	
Makkink (1957)				
$\hat{E}_g = 0.61 \dfrac{\Delta}{\Delta + \gamma} R_s - 0.12$	mm per day,	*a*,	mm per day	Grass, Netherlands
Turc (1961)				
$\hat{ET}_p = 0.013 \left(\dfrac{T}{T + 15}\right)(R_s + 50)$	mm per 10 days,	deg C,	lys	Potential *ET*, primarily western Europe, 10-day totals, and monthly values where relative humidity, *h*, is < 50 percent
$\hat{ET}_p = 0.40 \left(\dfrac{T}{T + 15}\right)(R_s + 50) \left(1 + \dfrac{50 - h}{70}\right)$	mm per mo,	deg C,	lys	
Jensen-Haise (1963)				
$\hat{ET}_p = (0.014\,T - 0.37)\,R_s$	*b*,	deg F,	c	Potential *ET*, western USA
$\hat{ET}_p = (0.025\,T + 0.08)\,R_s$	*b*,	deg C,	c	
Stephens-Stewart (1963)				
$\hat{E}_g = (0.0082\,T - 0.19)\,R_s$	*b*,	deg F,	c	Grass, Florida
Grassi (1964)				
$\hat{ET}_p = K_t\,C\,R_s$	*b*,	deg F,	c	All crops, western USA
Stephens (1966)				
$\hat{E}_g = (0.0088\,T - 0.19)\,R_s$	*b*,	deg F,	c	Grass, North Carolina

a, see table 1.
b, depends on R_s units.
c, equivalent depth of evaporation, *i.e.*, mm per day, in. per day, etc.

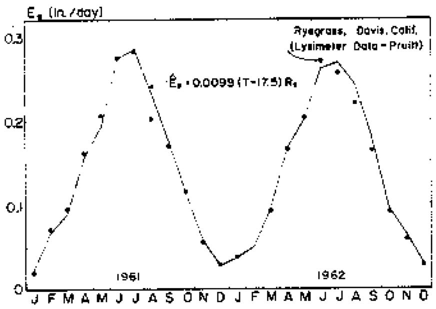

FIG. 7 A comparison of estimated evapotranspiration from grass using a calibrated empirical solar radiation—mean air temperature equation with measured evapotranspiration.

ues and percent of sunshine or cloud cover (10). Also interpolation between locations separated by several hundred miles usually provides adequate estimates except where orographic features may create localized cloud cover variations (9). The second major advantage is that solar radiation equations, properly calibrated, give estimates that are in phase with measured values as illustrated in Fig. 7 using mean monthly data.

A summary of the standard error for daily, mean 5-day, mean 10-day, and mean monthly estimates using only T and R_s for Davis, California, is presented in Table 4. The standard error during the summer months ranges from about 0.015 in. per day for monthly means to 0.035 for daily values. The coefficient of variability for these months ranges from 6 to 15 percent. The standard error increases during the fall months largely because of windy, high advection days. Since wind is not a variable in the estimating equation used, only that portion of advected energy related to mean air temperature is considered. Wind speed could easily be incorporated in an estimating equation for arid areas when standard wind speed data are available. Solar radiations equations are also reliable in humid areas. Stephens and Stewart (22) found that a solar radiation equation gave more reliable estimates in humid areas of Florida than temperature methods.

One problem associated with a solar radiation – air temperature relationship is the determination of the slope of the regression line, or the mean temperature coefficient, and the intercept of the temperature axis, T_x, for new areas. There are three possible procedures for doing this: (a) calibrate the equation using accurately measured ET data collected throughout the season from an area having similar climatic conditions; (b) calibrate using January and July data, or use July data in the northern hemisphere and data near the beginning and end of the growing season, and (c) relate the temperature coefficient and temperature intercept to one or more climatic factors that are related to humidity.

An example of the last procedure for estimating ϕ_2, when very limited data are available, is as follows:

$$\phi_2 = C_T(T - T_x) \quad \ldots\ldots \quad [11]$$

where C_T is a temperature coefficient normally determined as a constant for a given area. Preliminary data indicate that C_T can be estimated if only air-temperature data are available using the following expression and temperature data during the month of maximum mean air temperature. In tropical areas having dry and rainy periods, coefficients should be derived for each period.

$$C_T = \frac{1}{C_1 + C_2\, C_H} \quad \ldots\ldots \quad [12]$$

where

$$C_H = \frac{37.5 \text{ mm Hg}}{e_2 - e_1} = \frac{50 \text{ mb}}{e_2 - e_1} \quad \ldots\ldots \quad [13]$$

The value of 50 mb or 37.5 mm Hg. is about the maximum value found anywhere for $(e_2 - e_1)$. Thus the smallest value of $C_H \cong 1$. (C_2 = 13 F or 7.3 C depending on the scale used.)

The intercept of the temperature axis, T_x, increases as the slope of the line increases and as humidity increases. T_x can be estimated using the following equation derived from data in the western United States, North Carolina, and Florida ($C_H < 2.8$).

$$T_x = -9 + 1.8\, C^2_H + 2400\, C_T \quad \ldots\ldots \quad [14]$$

for use with mean air temperature in deg F and

$$T_x = -23 + C^2_H + 750\, C_T \quad . \quad [15]$$

for use with mean air temperature in deg C. Thus an estimate of potential evapotranspiration can be obtained using the following equations with mean air temperature in deg F or C.

$$\hat{ET}_p = \frac{T - T_x}{48 + 13\, C_H} R_s \ (T \text{ in deg F}) \quad \ldots\ldots \quad [16]$$

$$\hat{ET}_p = \frac{T - T_x}{27 + 7.3\, C_H} R_s \ (T \text{ in deg C}) \quad \ldots\ldots \quad [17]$$

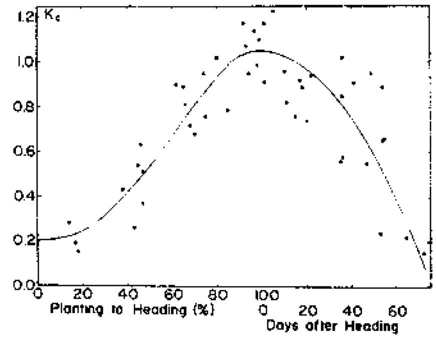

FIG. 8 An example of a crop coefficient curve relating evapotranspiration at various growth stages of grain sorghum to estimated potential evapotranspiration.

Equations [16] and [17] should be used only when mean air temperature is above 50 F or 10 C. Below this temperature the estimates for short grass should be used.

Estimates for well-watered short grass can be obtained by using C_1 = 85 F or 47 C.

When estimates or predictions of evapotranspiration are needed for various stages of crop development, then potential evapotranspiration obtained using equations [16] or [17], or a combination equation, can be multiplied by a crop coefficient K_c.

$$\hat{ET} = K_c\, \hat{ET}_p \quad \ldots\ldots \quad [18]$$

A typical example of the variation expected in a crop coefficient is indicated in Fig. 8. The data points represent observed evapotranspiration values. The magnitude near planting will be influenced by the frequency of rainfall that may keep the soil surface moist for longer periods of the time. The curve for grain sorghum was obtained in semi-arid to arid areas where the soil surface dries rapidly after an irrigation. Similar curves for about 15 different crops will be available within a yr from the author.

Summary and Conclusions

An analysis of empirical equations for estimating or predicting evapotranspiration using radiation is presented. Factors affecting the use, reliability and application of these equations to new areas are discussed. Estimates of me-

TABLE 4. SUMMARY OF STANDARD ERROR OF EVAPOTRANSPIRATION ESTIMATES FOR GRASS AT DAVIS, CALIF., JULY 1959 TO JUNE 1963
(Data courtesy of W. O. Pruitt)

Month	Mean (in. per day)	Standard error (in. per day)			
		Daily	5-day means	10-day means	Monthly mean
January	0.029	0.015	0.009	} 0.006	} 0.006
February	0.073	0.024	0.018		
March	0.092	0.024	0.013	} 0.012	} 0.032
April	0.149	0.023	0.015		
May	0.192	0.030	0.018	} 0.019	} 0.010
June	0.269	0.039	0.028		
July	0.273	0.025	0.017	} 0.021	} 0.021
August	0.220	0.033	0.029		
September	0.176	0.026	0.032	} 0.025	} 0.030
October	0.117	0.033	0.026		
November	0.059	0.019	0.011	} 0.007	} 0.004
December	0.033	0.018	0.009		

teorological parameters or extrapolation between widely separated points of measurements enable more rational empirical equations to be used even when climatic data are not readily available.

Empirical equations using radiation as the primary variable provide adequate and reliable estimates of evapotranspiration for most engineering purposes when limited meteorological data are available. Their use does not require much skill, and the time and effort required are minimal. The estimates or predictions approximate the energy balance equation. Empirical methods using radiation generally provide more reliable estimates than those based on air temperature as the primary variable, and are simple to use.

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