Watershed Evapotranspiration Estimated by the Combination Method

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WITHIN the hydrologic cycle of a watershed, evapotranspiration (ET) is second only to precipitation in the movement of water. It is a complex process driven by meteorologic variables, limited by plant and soil characteristics and available soil moisture, and strongly related to other hydrologic processes such as infiltration, soil moisture storage and redistribution, percolation, and crop moisture stress. To adequately model the hydrologic cycle, we must first be able to closely estimate daily actual ET under natural rainfall regimes.

Several methods are available for estimating watershed ET, but most are largely empirical and require considerable local calibration (ASAE 1966). For hydrologic research, it is desirable to use a method which has a physical basis and which will provide daily ET estimates that have a minimum of variation from actual ET. During recent years, the combination energy budget-aerodynamic equation developed by Penman (1948) has been modified and verified (Tanner and Pelton 1960, Van Bavel 1966) such that it is primarily a physically based model for defining potential ET.

Under natural rainfall regimes, actual ET is often less than the potential ET. To estimate actual ET, the potential for ET is usually first determined and then those processes which limit the amount of water actually returned to the atmosphere are considered. Thus, daily potential ET, considered in this report, is an important key to the development of actual watershed ET. A companion paper describes a rational model for estimating actual ET by considering crop and soil moisture effects (Saxton et al. 1974). Additional details of both papers have been presented by Saxton (1972).

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The objective of this study was to develop procedures and techniques for estimating daily potential ET of agricultural watersheds by the combination method. The study was conducted from March through November for 3 yr, 1969-1971, on watersheds in corn and brome grass crops. In this paper, we (a) discuss the requirements of meteorologic measurements used in the combination equation, (b) show that wind profile parameters cannot satisfactorily be estimated by reported relationships, but we present a method of estimating values for the complete wind profile term, and (c) compare calculated potential ET values for corn and brome grass with pan evaporation and net radiation.

COMBINATION METHOD

The combination energy budget-aerodynamic equation used for calculating potential ET was the same as that reported by van Bavel (1966). It is:

$$PET = \left[\epsilon R_n + \frac{7.12\, d_a U_a}{\left[\ln\left(\frac{Z_a - d}{Z_o}\right)\right]^2}\right] / \left[(1+\epsilon)\, 583\right] \quad \ldots\ldots\ldots\ldots\ [1]$$

where:

- PET = potential evapotranspiration cm day^{-1}
- ϵ = slope of psychrometric saturation line over psychrometric constant
- R_n = net radiation cal $cm^{-2} day^{-1}$
- d_a = vapor pressure deficit mb
- U_a = horizontal wind movement at elevation Z_a km day^{-1}
- Z_a = anemometer height above soil cm
- d = wind profile displacement height cm
- Z_o = wind profile roughness height cm

The numerical constants in the equation represent unit conversions plus standard values of air density (1.168 x 10^{-3} g cm^{-3}), heat of vaporization (583 cal g^{-1}), von Karman coefficient (0.41), barometric pressure (1,000mb), psychrometric constant (0.66 mb°C^{-1}), and water/air molecular ratio (0.622). A complete derivation of this equation was presented by Saxton (1972).

INSTRUMENTATION

Corn and brome grass research watersheds near Treynor, Iowa (Saxton et al. 1971) were each instrumented to obtain daily values of the variables in equation [1] except for those related to the wind profile. The two sets of sensors were maintained approximately 1 m above the soil, or 1 m above the top of the crop canopy when a canopy was present, and were located on either side and about 60 m (200 ft) from a common watershed boundary separating corn and brome grass watersheds. The sensors over corn were mounted on a vertically movable cradle attached to a stationary tower; those over grass were permanently positioned.

Net radiation was measured with miniature net radiometers (Fritschen 1960, Fritschen 1965) which were recorded individually on strip-chart recorders with mechanical integrators. Air temperature was sensed by ventilated thermocouples, air humidity by ventilated lithium-chloride dew cells, and wind travel by 3-cup aluminum anemometers. These sensors over both crops were continuously recorded by a multipoint strip-chart recorder. Measurements were made from about March 15 to December 1 during 1969, 1970, and 1971. A class A evaporation pan, located about 300 m (1,000 ft) from the sensors, was read each day.

DATA

Daily net radiation was summarized from sunup to sunup. Nighttime outgoing radiation was assumed to compensate for the previous day's soil heat storage, which was not measured.

Wind travel only during daylight hours was used because air movement contributes to potential ET in proportion to vapor pressure deficit, which becomes nearly zero during most nights at the Treynor, Iowa location. The necessity for correspondence of wind travel

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and vapor pressure deficit was previously shown by Tanner and Pelton (1960). An average daylight (0600 to 1800 hr) vapor pressure deficit was obtained by calculating vapor pressure deficits from air temperature and dew probe readings at 0600, 1000, 1400, and 1800 hr; these vapor deficits were then weighted by 1, 2, 2, and 1, respectively. A study of 24 days showed that these weighted averages very closely approximated daily averages computed from readings at 1-hr intervals.

ESTIMATING WIND PROFILE PARAMETERS

It was not feasible to measure wind profiles for obtaining representative d and Z_o values. Several locations would have been required to sample the spatial variation over the watersheds, and the data and computations would have been too voluminous. In addition, the wind profile theory contains assumptions that are questionable when applied to undulating topography with tall crops and open canopies. However, the wind profile parameters provide an important modifier to the wind travel measurements and need to be adequately represented for each anemometer situation.

Values of d and Z_o, in cm, were first estimated by the relationships

$$d = 0.7\ (\%\ \text{canopy}/100)\ (H) \qquad [2]$$

$$\log_{10} Z_o = -0.98 + \log_{10} H \quad \text{(grass)} \qquad [3]$$

$$\log_{10} Z_o = -1.6 + 1.1 \log_{10} H \quad \text{(corn)} \qquad [4]$$

where

H = crop height in cm.

The equation for d was derived to give values similar to those reported by Lemon (1963) and Szeicz et al. (1969), and the Z_o equations were from several data sources summarized by Szeicz et al. (1969). These estimated values were also adjusted to account for the wind bending and streamlining the plant canopy with increasing velocities (Lemon 1963 and Szeicz et al. 1969). Estimated brome grass Z_o values averaged 1 to 2 cm during the growing season, but the wind effects resulted in daily variations of ±0.5 cm. For corn, estimated Z_o values were near 0 in May, 0 to 2 cm in June, 2 to 6 cm in July, and 6 to 16 cm in August and through October.

Potential ET values (PET) calculated with these estimated wind parameter values compared unfavorably with pan evaporation and net radiation (expressed in equivalent cm of water). Ratios of net radiation/PET and pan evaporation/PET for grass were both about 0.75, with a slight trend of higher-to-lower values throughout the year. For corn, the same two ratios had a strong annual trend from about 1.5 in the spring to 0.5 in the fall.

The ratio values with net radiation were expected to be about 0.85 to 1.15. Net radiation usually exceeds potential ET by 10 to 20 percent when water is not limiting and little advection occurs (Graham and King 1961, Parmele and McGuinness 1974, Tanner 1957 and Tanner and Pelton 1960). When moisture is limiting, the air temperature, and thus vapor pressure deficit, will rise and higher potential ET values will result. If advection occurs, the potential ET may exceed net radiation (van Bavel 1966). Pan evaporation usually exceeds potential ET by about 20 percent (Veihmeyer 1964); thus the pan-over-potential ET ratio values were expected to be about 1.2. Compared with these expectations based on the results of others, our calculated potential ET values for brome grass were slightly high, but the values for corn were too small in the spring and too large in the fall.

Additional unsatisfactory ratio values and trends were obtained for several subsequent sets of calculations using reduced- and no- wind effects on Z_o and d. A review of all data and the estimated wind parameters indicated that the d or Z_o values were in error. It was concluded that equations 2, 3, and 4 for estimating wind profile parameters could not be applied to our situation of a nonisothermic boundary layer over medium-to-tall crops on undulating watershed surfaces.

ESTIMATING A WIND PROFILE TERM

A second method for estimating the wind profile term of equation [1] were which the entire wind profile term of equation [1]

$$[\ln(\frac{Z_{a-d}}{Z_o})]^2 \qquad [5]$$

was replaced by a single term, W, and an annual distribution of daily W values was estimated. By using measured values for all other variables in equation [1], values of W were determined such that the average potential ET values calculated for 1969 were nearly equal to net radiation and about 20 percent less than pan evaporation; thus, the ratio trends were consistent throughout the 1969 study period with those expected. The estimated W values were varied gradually in response to observed physical changes that would alter the wind profile; for example, grass height increase beneath the stationary anemometer.

Only the 1969 data were used for the W determinations. Then, these W values were applied to the two subsequent years' data. For corn, the 1969 W values were used unaltered and with equal success for 1970 and 1971. For brome grass, the 1969 values were adjusted to account for observed crop height differences and a shift in anemometer height in mid-1970.

Example values for the wind profile term W are shown in Fig. 1 for 1969 corn, along with field observations of crop height and canopy. The anemometer was 140 cm above the top of the crop on a west-facing, 12-percent slope and midway between two level terraces which are about 30 meters (100 ft) apart. Similar data are shown in Fig. 2 for brome grass during 1970. This anemometer was 55 cm above the soil surface before June 26 and 135 cm after June 26. It was on an east-facing, 10-percent slope, and the fetch was unlimited except that corn was grown about 50 meters (150 ft) upslope (west).

COMPARING WIND ESTIMATES

The W values were used in the final and most realistic potential ET calculations, However, values of the roughness height, Z_o, that would have given the estimated W values were calculated for comparison with those Z_o values first estimated by equations [3] and [4]. Displacement height, d, was first estimated by equation [2]; then values of Z_o were calculated by setting W equal to equation [5] and applying the known values of Z_a, d, and W. These calculated d and Z_o values are shown in Figs. 1 and 2. These Z_o values contrasted sharply to those first estimated by equations [3] and [4]. Values for grass ranged from 0.2 to 0.4 cm compared with first estimates of 1 to 2 cm. Values for August corn were about 2 cm compared with earlier estimates of 6 to 16 cm. These differences indicate that the earlier Z_o estimates were in error by several

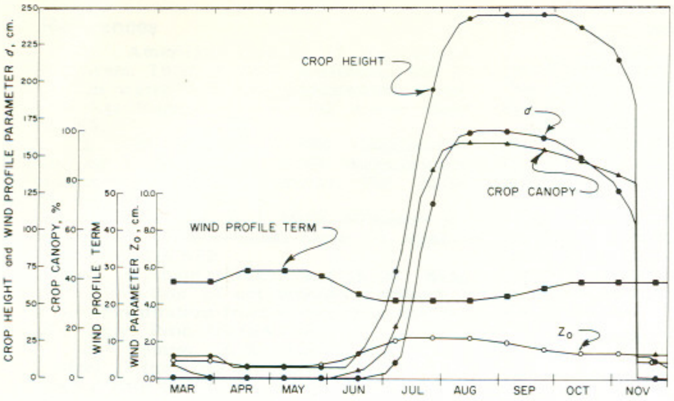

FIG. 1 Crop and wind profile parameters for corn during 1969.

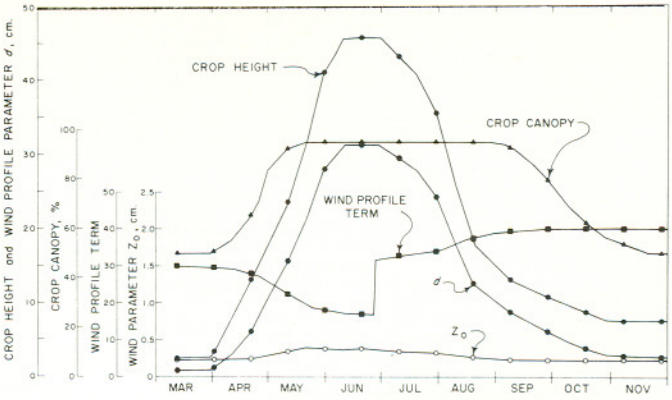

FIG. 2 Crop and wind profile parameters for brome grass during 1970.

hundred percent. A sensitivity analysis of equation [1] showed that about 10 percent of any Z_o error would be transferred to the PET values during the mid-year and 20 to 30 percent during the spring and fall when the aerodynamic term becomes more important. Therefore, these Z_o errors were significant, or even dominant, when this large.

These wind profile considerations showed that equations reported in literature (Lemon 1963, Szeicz et al. 1969) could not be reliably used for estimating wind profile parameters for tall crops on undulating watersheds for a complete growing season. Parmele and McGuinness (1974) also reported unrealistic potential ET values for corn using a Z_o value of 10 cm. We found that, once realistic W values representing the entire wind prodile term of equation [1] were estimated for the growing season, they could be applied for subsequent years for the same crop and anemometer setting. Although empirical, this method of modifying the aerodynamic portion of equation [1] has the advantages over constants used by others (Parmele and McGuinness 1974, Penman 1948, Ritchie 1972) in that seasonal variations of the wind profile and turbulent exchange caused by crop growth can be accounted for and wind travel measurements can be modified to account for the anemometer height by using estimates based on equation [5].

CALCULATED POTENTIAL ET RESULTS

The daily potential ET values shown in Fig. 3 are typical of those obtained by applying the observed data and estimated wind profile term to equation [1]. Although estimating the wind profile term influenced the average potential ET magnitudes, the daily and annual variation was primarily determined by the observed values of net radiation, vapor pressure deficit, and wind travel.

The accumulative values of Fig. 4 show a reasonably smooth trend despite the day-to-day variation demonstrated in Fig. 3. This is the effect, of course, that allows averages to be used for potential ET estimates for periods of a week or longer with moderate success. Although the wind parameters were estimated such that the 1969 potential ET values would approximately equal the net radiation values, the 1970 potential ET values (Fig. 4) were more than net radiation. We believe that this was due to more advected energy in 1970 than in 1969. The meteorological data and pan evaporation amounts also indicated this difference.

Both net radiation and computed potential ET were similar for the corn and grass crops as shown by the monthly summary in Table 1. A comparison of daily potential ET values for corn versus grass for 266 days during 1969 gave

$$\begin{aligned} \text{PET (corn)} &= 0.03 + 0.93\ \text{PET (grass)} \\ R^2 &= 0.92 \\ S_{y \cdot x} &= 0.07\ \text{cm} \\ \bar{x} &= 0.38\ \text{cm} \end{aligned}$$

Similar results were obtained for the other two study years.

Crops can only affect potential ET by their influence on the meteorologic variables. This effect would mostly be through net radiation because local cover conditions would have only minor effects on the wind movement and vapor pressure deficit at the heights measured. Although there was some deviation of net radiation over the two crops, particularly during bare soil conditions on the cornland, these were quite small and had little overall effect. A linear correlation of daily net radiation for 256 days, March through November 1970, gave

$$\begin{aligned} R_n\ \text{(corn)} &= 16.4 + 0.97\ R_n\ \text{(grass)} \\ R^2 &= 0.96 \\ S_{y \cdot x} &= 22\ \text{cal cm}^{-2} \\ \bar{x} &= 118\ \text{cal cm}^{-2} \end{aligned}$$

Similar results were obtained for the other two study years, which suggest that a single net radiation measurement

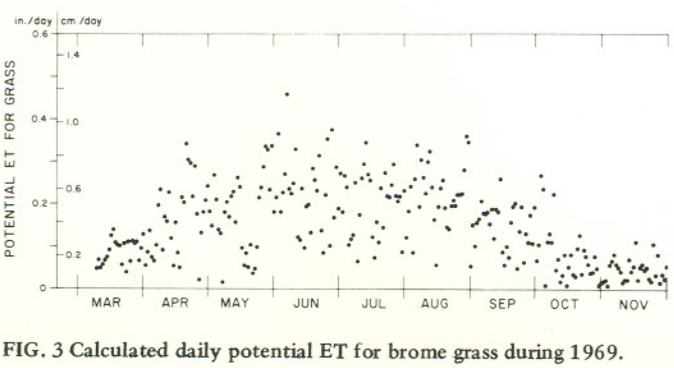

FIG. 3 Calculated daily potential ET for brome grass during 1969.

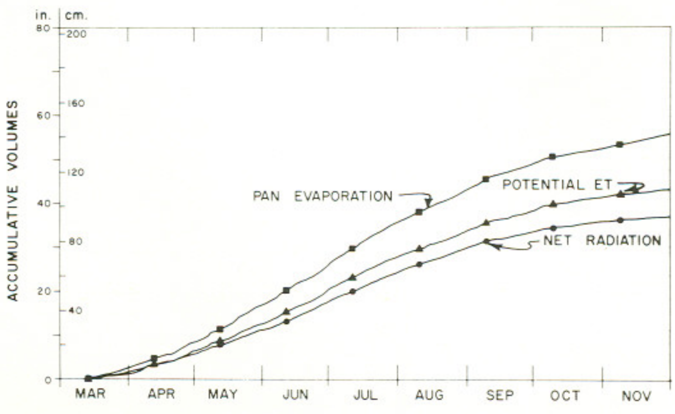

FIG. 4 Calculated daily potential ET and related variables for corn during 1970.

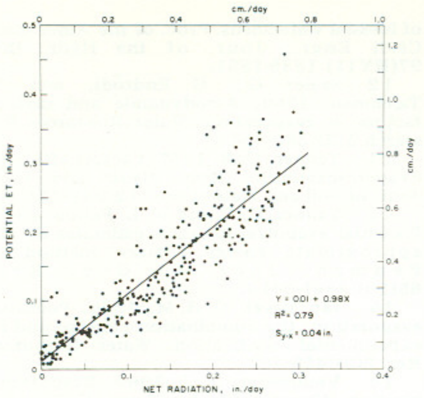

FIG. 5 Computed potential ET for brome grass during 1969 versus measured net radiation expressed as equivalent water depth.

could have been used for both crops with minimal error.

Comparisons of calculated daily potential ET with daily net radiation and daily pan evaporation, shown in Figs. 5 and 6, respectively, contain the effect of the estimated wind profile term; however, the daily variation is related mostly to the measured meteorological variables. The scatter in the comparison with net radiation (Fig. 5) shows the effect of the aerodynamic variabes, because the potential ET values, calculated by equation [1], depend on the net radiation plus the wind travel and vapor pressure deficit. There is less scatter in the comparison with pan evaporation (Fig. 6) than with net radiation (Fig. 5) because pan evaporation responds to both radiation and aerodynamic variables. This was even more apparent with the 1970 data when more advected energy apparently occurred.

Even though the estimated wind profile term W played a significant role in the seasonal and annual amounts, close correlation of observed daily pan evaporation amounts with calculated daily potential ET values (Fig. 6) substantiates the common practice of estimating potential ET amounts by adjusting observed pan evaporation. Monthly ratio values of PET/pan evaporation, shown in Table 1, indicate that the ratio of potential ET over pan evaporation probably varies during the year, but the trend is somewhat inconsistent.

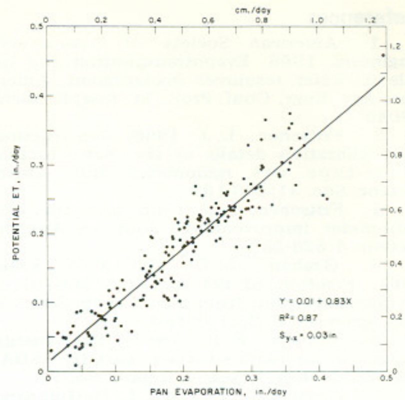

FIG. 6 Calculated potential ET for brome grass during 1969 versus observed pan evaporation.

SUMMARY

Meteorological variables used in the combination potential ET equation (van Bavel 1966) were measured over corn and grass watersheds during March through November for 3 years. It was shown that the measured wind travel must correspond to the period represented by the average vapor pressure deficit. It was neither theoretically nor practically feasible to measure wind profile parameters on the undulating watersheds. Estimates of these parameters, based on previously reported relationships, gave unreasonable potential ET values. A method was devised to give practical results by estimating an annual distribution of values for the complete wind profile term of the combination equation. These values were determined for both corn and brome grass by using 1 year's data; then they were applied to data of the other two study years. Although this method was empirical, it was related to wind profile theory and it provided realistic potential ET values by the combination equation.

The calculated daily potential ET values were very similar for the corn and grass watersheds because the immediate land surfaces had only minor effects on the meteorological variables. Wind travel and vapor deficits at the 1-m height were primarily determined by regional conditions, and net radiation was generally so similar over the two crops that a single measurement could have been used with minimal error. Good correlations of daily potential ET with daily pan evaporation substantiated the common practice of estimating potential ET by adjusting pan evaporation.

TABLE 1. MONTHLY SUMMARY OF PAN EVAPORATION, NET RADIATION, AND CALCULATED POTENTIAL ET

Month	Crop	Pan evap.*	Net rad.	PET	PET/Pan evap.	Pan evap.	Net rad.	PET	PET/Pan evap.	Pan evap.	Net rad.	PET	PET/Pan evap.
		cm	cm†	cm		cm	cm	cm		cm	cm	cm	
		1969				1970				1971			
March‡	Grass	7.6e§	6.9	5.2		6.3e	4.0	3.3		2.3e	2.4	2.6	
	Corn		8.1	5.8			4.3	3.0			2.5	3.0	
April	Grass	15.7	11.7	12.5	0.80	15.1	8.7	13.5	0.89	17.4	12.5	13.3	0.76
	Corn		12.1	13.0			10.0	13.2			11.9	14.1	
May	Grass	15.1	13.1	14.0	0.92	21.7	14.0	18.7	0.86	16.7	13.6	13.5	0.81
	Corn		14.3	14.9			14.4	16.0			13.0	13.6	
June	Grass	20.4	16.3	17.4	0.85	23.3	15.6	21.1	0.91	25.2	17.9	19.5	0.77
	Corn		16.0	17.1			16.4	19.9			16.9	19.9	
July	Grass	17.7	16.6	16.0	0.90	24.3	16.1	17.6	0.72	21.0	17.3	17.2	0.81
	Corn		16.9	15.4			16.6	18.5			19.0	20.1	
Aug.	Grass	18.3	16.0	17.2	0.93	18.7	14.6	14.7	0.79	18.6	15.2	15.0	0.81
	Corn		16.4	16.2			14.2	15.0			14.8	15.2	
Sept.	Grass	11.7	10.0	11.2	0.95	14.6	9.2	10.6	0.72	16.2	10.6	12.5	0.77
	Corn		10.1	10.0			9.2	11.8			10.3	14.3	
Oct.	Grass	9.6	4.9	6.2	0.65	8.7	4.8	6.2	0.71	11.3	6.2	7.5	0.66
	Corn		5.5	7.2			5.6	7.6			6.4	9.2	
Nov.	Grass	8.4e	1.7	3.5		8.4e	1.5	2.8		8.6e	2.5	3.2	
	Corn		2.8	4.7			2.7	4.2			3.2	4.1	
TOTAL	Grass	124.5	97.2	103.2		141.1	88.5	108.5		137.3	98.1	104.3	
	Corn		102.2	104.3			93.4	109.2			98.0	113.5	

* Class A pan approximately 300 m (1,000 ft) from meteorologic sensors, not associated with a crop

† Equivalent depth of water based on 583 cal g^{-1} and 1 g cm^{-3}.

‡ Beginning dates were March 9, 1969, March 13, 1970, and March 25, 1971.

§ Indicates estimated values.

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