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COMPARISONS OF MEASURED AND ESTIMATED DAILY POTENTIAL EVAPOTRANSPIRATION IN A HUMID REGION*

L.H. PARMELE and J.L. MCGUINNESS

Agricultural Research Service, U.S. Department of Agriculture, Northeast Watershed Research Center, University Park, Pa. (U.S.A.)

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ABSTRACT

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Daily totals of continuous micrometeorological measurements made over one of the monolith lysimeters at Coshocton, Ohio were used during the summers of 1968 and 1969 to test the application of various meteorological methods for computing daily potential evapotranspiration (PET). Evapotranspiration from corn and clover was at or near potential during the two periods of observation. Estimates of PET made with various versions of the combination equation that utilized measured net or solar radiation were superior to estimates made with the other methods tested. A daily value of net radiation was a good measure of evapotranspiration when conditions were at potential. In one version of the combination equation we utilized "true" crop roughness parameters, which gave a good fit with the clover data but over-predicted potential ET for corn by 44%.

A modified combination equation developed at Coshocton, Ohio for predicting actual ET was tested with data independent from that used in the derivation. The successful application of this equation, during both potential and nonpotential conditions, adds confidence that it could be used to estimate actual daily ET in the humid northeastern United States from climatic data.

INTRODUCTION

Many aspects of water resources planning are not as critical in humid areas as in the more arid regions. Estimates of water use, for instance, can be much less precise in humid regions where available water supplies are generally adequate. This is why most of the work in evapotranspiration is being done in subhumid and arid regions.

However, pressures on the currently adequate water resources of humid areas are increasing. Hydrologic design and performance prediction of a watershed will most likely be based on a complete and continuous hydrologic model.

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Thus, there will be demands for increased accuracy in the measurement and estimation of evapotranspiration (ET). Parmele (1972) has shown that errors in ET input to mathematical watershed models cannot be neglected and that an accurate prediction of ET amounts is prerequisite for a complete representation of the hydrologic system.

This study deals mainly with the estimation of potential evapotranspiration (PET), since in a humid region many well-watered crops and soils will evaporate at or near potential rates. McGuinness and Bordne (1972) compared several methods for estimating PET from routine climatic measurements with data obtained from a lysimeter-derived "standard" PET curve as an aid in selecting appropriate estimating methods for humid areas. Fourteen methods of computing daily PET from general climatic data were compared for the entire year. The methods of Kohler et al. (1955), Kohler and Richards (1962), Jensen and Haise (1963), Christiansen (1966, 1968), Blaney-Criddle (Soil Conservation Service, USDA, 1967), pan evaporation, and Penman (1948) all provided a good fit with the lysimeter-derived PET curve.

Of the climatic data used by McGuinness and Bordne (1972), solar radiation was transposed from off-site stations and used with other climatic data to estimate net radiation. In our present study, we used detailed "on-site" micrometeorological data collected during two growing seasons when soil moisture conditions were nonlimiting. This paper deals with the estimation of daily potential evapotranspiration using the various methods found satisfactory by McGuinness and Bordne (1972) and the comparison of these values with daily ET under nonlimiting soil moisture conditions as measured by a weighing lysimeter.

Details of the computation of PET for the various methods was given by McGuinness and Bordne (1972). The Blaney-Criddle method (Soil Conservation Service, USDA, 1967) uses only mean daily air temperature as an input, the Jensen-Haise (1963) method uses solar radiation along with air temperature, and the Christiansen (1966) method utilizes any climatic data available for the site.

Of the combination methods, the Penman (1948) equation was used with an empirical wind function applicable to a short grass with a roughness coefficient of approximately 1.0 cm:

$$f(u) = 0.35 + 0.0035\, u_2 \tag{1}$$

In this equation, u_2 is wind movement at the 2-m height in miles per day. The Van Bavel (1966) version of the combination method differs from the Penman version in that: (a) the net radiation is measured; (b) a correction is made for soil heat flow; and (c) the aerodynamic term is derived from the log wind profile theory of Thornthwaite and Holzman (1942) as:

$$B_{\mathrm{v}} = \frac{\rho \epsilon K^2}{p} \frac{u_a}{[\ln (z_a/z_0)]^2} \tag{2}$$

where ρ is the density of air, ϵ is the water—air molecular weight ratio, K is the Von Karman constant, p is the ambient pressure, u_a is the windspeed at height a, z_a is the height above the surface at which temperature, humidity, and wind are measured, and z_0 is the roughness parameter. The Penman, Van Bavel, and Weather Bureau methods require measurements of temperature, humidity, wind, and radiation.

Mustonen and McGuinness (1968) used the Weather Bureau method and soil moisture data to develop an empirical equation for predicting actual ET. In addition, the single measurement of net radiation was tested as a predictor of PET.

FACILITIES AND EQUIPMENT

The experimental site was developed near Watershed 109 at the U.S. Department of Agriculture, North Appalachian Experimental Watershed at Coshocton, Ohio. During the summers of 1968 and 1969, micrometeorological data were collected hourly over weighing lysimeter Y102C. The lysimeter was not irrigated and thus represented the natural evapotranspiration demand and soil conditions. Data were collected continuously from June 23 to July 26, 1968 and from August 1 to September 14, 1968 over a first-year mixed meadow of red clover, alfalfa, and timothy. In 1969, data were collected over corn from July 24, when the crop was about 240 cm high and continued until harvest on October 16.

The weighing lysimeter used to measure ET directly has been described (Harrold and Dreibelbis, 1958, 1967). The automatic weighing mechanism records weight changes in the 65-ton mass to an accuracy equivalent to approximately 0.01 inch of water over the lysimeter surface area. Daily ET was determined from the weight change from midnight to midnight, after allowances were made for precipitation, percolation and run-off.

On site climatic measurements were made with carefully calibrated micrometeorological type equipment. Wind speed was measured at 1 and 2 m above the crop surface with sensitive cup anemometers. Air temperature and humidity was measured with an aspirated psychrometer system modeled after that developed by Lourence and Pruitt (1969). Incoming solar and net radiation was measured with an Epply pyranometer and 2 Fritschen net radiometers. Beckman and Whitley soil heat flux plates 5 cm below the soil surface measured soil heat flux. Hourly or half-hourly integrations of the above measurements were summed to provide a daily total or average for each variable.

Data were also collected from the Coshocton, Ohio climatological station to provide daily values of maximum and minimum temperatures, dew point temperature, Class A pan evaporation and wind movement, windspeed at 2 ft. above the surface and precipitation. Measurements were made of soil moisture inside the lysimeter by a series of fiberglass gypsum resistance blocks and the neutron probe. These data were interpolated to a daily basis.

Since the original computation of McGuinness and Bordne (1972) utilized radiation data from Wooster, Ohio about 30 miles north, daily incoming solar radiation values were tabulated from that location for comparison.

The Van Bavel formula requires a measure of the aerodynamic roughness parameter z_0. Unfortunately, methods used to evaluate z_0 are subject to shortcomings and require sensitive instrumentation. However, this parameter can be expressed as a function of crop height, since it is mainly plant geometric properties that influence z_0 (Lemon, 1965; Tanner, 1968). Determination of z_0 equal to 10 cm for corn in 1969 was estimated on the basis of wind profile parameters measured over corn of equal height at Ithaca, N.Y. (Lemon, 1965). This transformation is possible because of the similarity in leaf area index (LAI) between the corn at Ellis Hollow, N.Y. and that corn crop used in this study. The value of z_0 for the meadow grass in 1968 was assumed to be 1.0 throughout the test (McGuinness and Bordne, 1972).

RESULTS

Results of the daily computations using on-site meteorological measurements for the mixed meadow data, 1968, are given in Table I. The percent difference column measures the difference between the average computed and lysimeter values. For the Blaney-Criddle method, the percent difference is computed as (100) (0.211 - 0.168)/0.168 = 25.6%. For the May—October 1968 growing season, precipitation was 18.79 inches, 1.46 inches below normal, and lysimeter ET totaled 27.46 inches.

Calculations were also made for the 1968 mixed meadow season using off-site climatic data. Air temperature, dew point temperature, and windspeed were measured at a climatological plot about 800 ft. east of the lysimeter. Solar radiation values were from Wooster, Ohio about 30 miles north of the North Appalachian Experimental Watershed, and net radiation was estimated from techniques described by Penman (1948). Results are given in Table II.

For the corn year in 1969, the results of computations are given in two groups in Table III. From July 25 through September 5, growing conditions were judged to be at or near potential. After September 5, plant physiological changes and inadequate soil moisture began to limit plant response. Precipitation from May through October was 25.43 inches, more than 5 inches above normal, and lysimeter ET totalled 20.72 inches.

USWB Class A pan evaporation as computed from on-site meteorological measurements was compared with values measured at the climatological plot about 800 ft. east of the lysimeter. Results for various periods are given in Table IV.

DISCUSSION

For actual ET rates to equal or approach potential ET rates, it is necessary to have an adequate supply of water available for evaporation and transpiration. The 1968 growing season precipitation was below normal, and ET was

TABLE I

Correlation and regression statistics for measured versus computed daily evapotranspiration (ET) for mixed meadow grass at Coshocton, Ohio using 1968 on site meteorological data (6/23—9/14/68)*

Calculation method	Avg. calc. daily ET (in./day)	Diff. from lysimeter (%)	Intercept a (in./day)	Slope b (in./day)	Standard error (in./day)	Correlation coefficient r
Blaney-Criddle	0.211	+25.6	0.072	0.451	0.061	0.31
Jensen-Haise	0.177	+ 5.4	0.030	0.780	0.034	0.85
Christiansen	0.226	+34.5	0.016	0.814	0.043	0.74
Penman	0.149	-11.3	0.025	0.956	0.036	0.82
Van Bavel	0.163	- 3.0	0.034	0.820	0.039	0.81
W.B. Class A Pan	0.171	+ 1.8	0.040	0.750	0.033	0.86
W.B. lake	0.127	-24.4	0.044	0.977	0.032	0.87
Net radiation	0.159	- 5.4	0.032	0.838	0.038	0.80
Mustonen-McGuinness	0.151	-10.1	0.043	0.834	0.031	0.88

*Average ET by lysimeter = 0.168 inch/day for n = 70.

TABLE II

Correlation and regression statistics for measured versus computed daily evapotranspiration (ET) for mixed meadow grass at Coshocton, Ohio using 1968 general climatic data (6/23—9/14/68)*

Calculation method	Avg. calc. daily ET (in./day)	Diff. from lysimeter (%)	Intercept a (in./day)	Slope b (in./day)	Standard error (in./day)	Correlation coefficient r
Blaney-Criddle	0.221	+31.5	0.015	0.286	0.063	0.24
Jensen-Haise	0.193	+14.9	0.084	0.435	0.058	0.43
Christiansen	0.215	+28.0	0.023	0.673	0.042	0.76
Penman	0.163	− 3.0	0.105	0.385	0.061	0.30
Van Bavel	0.181	+ 7.7	0.090	0.428	0.060	0.37
W.B. Class A Pan	0.187	+11.3	0.032	0.725	0.048	0.66
W.B. lake	0.138	−17.9	0.061	0.774	0.053	0.57
Mustonen-McGuinness	0.164	− 2.4	0.064	0.634	0.054	0.56

*Average ET by lysimeter = 0.168 inch/day for n = 70.

TABLE III

Correlation and regression statistics for measured versus computed daily evapotranspiration (ET) for corn (240 cm high) at Coshocton, Ohio using 1969 on site meteorological data

Calculation method	Avg. calc. daily ET (in./day)	Diff. from lysimeter (%)	Intercept a (in./day)	Slope b (in./in)	Standard error (in./day)	Correlation coefficient r
Average ET by lysimeter = 0.165 in./day for n = 43 (July 25—Sept.5, 1969)						
Blaney-Criddle	0.208	+ 26.1	0.004	0.768	0.059	0.33
Jensen-Haise	0.185	+ 12.1	-0.036	1.065	0.030	0.89
Christiansen	0.190	+ 15.2	0.006	0.829	0.034	0.84
Penman	0.154	- 6.7	-0.019	1.199	0.035	0.90
Van Bavel (z_0 = 10 cm)	0.237	+ 43.6	0.008	0.655	0.036	0.84
W.B. Class A Pan	0.177	+ 7.3	0.024	0.870	0.024	0.92
W.B. lake	0.132	- 20.0	0.000	1.237	0.028	0.90
Net radiation	0.163	- 1.2	-0.012	1.059	0.032	0.87
Mustonen-McGuinness	0.178	+ 7.9	0.019	0.819	0.019	0.95
Average ET by lysimeter = 0.067 in./day for n = 25 (Sept. 6—Sept. 30, 1969)						
Blaney-Criddle	0.114	+ 70.1	0.035	0.326	0.029	0.34
Jensen-Haise	0.104	+ 55.2	0.017	0.468	0.020	0.76
Christiansen	0.143	+113.4≤	0.009	0.404	0.019	0.79
Penman	0.106	+ 58.2	0.004	0.591	0.016	0.84
Van Bavel (z_0 = 10 cm)	0.213	+225.4≤	0.024	0.195	0.022	0.67
W.B. Class A Pan	0.119	+ 77.6	0.020	0.394	0.020	0.76
W.B. lake	0.084	+ 25.4	0.021	0.541	0.019	0.79
Net radiation	0.109	+ 62.7	0.001	0.591	0.015	0.87
Mustonen-McGuinness	0.077	+ 14.9	0.019	0.629	0.014	0.90

TABLE IV

Correlation and regression statistics for measured versus computed daily Class A pan evaporation (E_p) for Coshocton, Ohio using 1968 and 1969 on site meteorological data

Period	No. of days	Avg. pan E_p meas. (in./day)	Avg. pan E_p calc. (in./day)	Diff. from meas. E_p (%)	Intercept a (in./day)	Slope b (in./in)	Standard error (in./day)	Correlation coefficient r
6/23—9/9/68	57	0.181	0.181	0.0	0.027	0.855	0.030	0.89
7/25—9/5/69	31	0.157	0.168	+7.0	0.011	0.867	0.033	0.86
9/9—9/30/69	23	0.109	0.114	+4.6	0.016	0.815	0.021	0.92
7/25—9/30/69	54	0.136	0.145	+6.6	0.012	0.854	0.028	0.90
all 1968 and 69	111	0.160	0.164	+2.5	0.015	0.882	0.030	0.90

almost 9 inches in excess of precipitation. However, because of the deep rooting of the meadow grass and the relatively high ET rates observed during August and September, it is doubtful that soil moisture was seriously limiting transpiration.

Precipitation during the 1969 growing season was more than 5 inches above normal and almost 5 inches in excess of ET for the same period. Evapotranspiration dropped off during September and October because changes in corn plant physiology limited growth and transpiration. Albedo of the corn changed from a daily mean of 0.184 during the July 25 — September 5 period to 0.175 after September 5, indicating some change in plant optical properties.

To evaluate the data in Tables I—IV, one must consider several factors simultaneously. The "best" method is the one with the lowest absolute difference, and intercept closest to zero, a slope closest to 1.0, the smallest standard error, and the highest correlation coefficient. Such a non-pareil method was not found.

Table I and the top section of Table III show that the two methods that do not use radiation measurements, Blaney-Criddle and Christiansen, are not as efficient estimators of daily ET as the remaining methods. The Mustonen-McGuinness method performed well, as might be expected since it was developed at this site. The Penman, USWB pan and Jensen-Haise equations were satisfactory for most of the factors considered. The Van Bavel version of the combination equation compared favorably with the lysimeter for the period of observations over the mixed meadow grass.

There was excellent agreement between the daily net radiative flux and lysimeter ET for both crops, Tables I and III. Tanner and Pelton (1960) found that, in Wisconsin, net radiation alone agreed better with measured evaporation from irrigated alfalfa than did three different combination-type equations. Graham and King (1961) reported that daily net radiation was highly correlated with measured ET from corn when conditions for potential ET existed.

The same calculations for 1968 were made using general station climatic data and transposed daily solar radiation. Although the means of the various estimating techniques were not changed appreciably (compare Tables I and II), the degree of fit on a day-by-day basis dropped considerably from that achieved with on-site climatic measurements. The standard error of estimate nearly doubled to approximately 1/3 the average daily ET. This decrease in accuracy is probably the result of transposing solar radiation from Wooster, Ohio and estimating net radiation.

Computations for the second period of 1969, Table III, show that no method of calculating PET provided a good fit with observed ET when plant physiological changes and soil moisture began to limit plant response. Net radiation exceeded lysimeter evapotranspiration by 63% during this period. Only computations of actual ET with the Mustonen-McGuinness equation provide a reasonable fit with the observed data.

It can be seen from Table III for the period of July 25 to September 5, 1969 that the Van Bavel formula overcomputed the mean daily ET by 43.6% and exceeded measured net radiation by about the same amount. It is difficult to conceive of potential ET exceeding net radiation in a humid region by the amount shown in Table III. Even though five other methods did overestimate the lysimeter measure, the error was not as large as that obtained with the Van Bavel formula.

It would be easy to account for this disagreement by assuming that corn has a much higher stomatal resistance than the mixed meadow grass. The surface diffusion resistance r_s, a measure of the degree of unsaturation within the canopy, is a means of defining the resistance to evaporation by the crop and soil system (Szeicz and Long, 1969). Computed ET could be made to match the lysimeter measure if a diffusion resistance term was incorporated into eq. 6 as suggested by Monteith (1965).

The use of the log profile wind function in the combination equation has been criticized because of the high increase in sensitivity of the aerodynamic term as the magnitude of z_0 increases. Parmele (1968), Jensen et al. (1969) and Rosenberg (1969) all report failure of the combination equation with the aerodynamic term used by Van Bavel (1966). For crops over 30 inches high, Jensen (1969) found it necessary to "calibrate" eq.2 by varying the z_0 value until the PET estimate agreed with the lysimeter measure. Sellers (1964) has indicated that unreasonably high ET estimates have been obtained using simple aerodynamic logarithmic profile methods over tall crops.

If an adjustment similar to that used by Jensen (1969) were applied to the corn data for July 25 to September 5, 1969, the z_0 value necessary to achieve agreement with the lysimeter would be 1.0 cm, which is a roughness parameter usually appropriate for short grass. This value of z_0 is similar to "adjusted" z_0 values reported by Jensen, but is inconsistent with aerodynamic theory where z_0 has been found to range from 10 to 25 cm for corn (Lemon, 1965). Correction of eq.2, for diabatic profiles as suggested by Tanner (1968) would only increase the error between estimated and observed lysimeter flux rates for the period in question.

The modified combination equation of the Weather Bureau did well in estimating daily potential ET for both the mixed meadow and corn crops. To check the representativeness of the calculations with the USWB pan evaporation equation, daily computed values of pan evaporation were compared with measured Class A pan evaporation at the Coshocton station and these results were presented in Table IV. There is an excellent fit for the 1968 data and only a slight overcomputation for 1969 (6.6%). For both years, a 2.5% overcomputation of observed pan evaporation and a correlation coefficient of 0.90 is a good indication that the data used in the calculations were representative for Coshocton conditions.

McGuinness and Bordne (1972) found that computed pan evaporation (43.35 inches) for a year compared favorably with total ET as measured by the lysimeter (40.14 inches). Thus it appears that a measure or estimate of class A pan evaporation may be a good estimate of potential ET and ET under non-limiting moisture conditions in the humid eastern U.S. The concept proposed by Kohler and Richards (1962) that PET could be considered equal to free water or lake evaporation is unacceptable. The Weather Bureau lake relationship undercomputed observed ET by 20—25% when conditions were assumed to be a potential. Similar failure of the Weather Bureau lake evaporation equation was reported by McGuinness and Bordne (1972).

CONCLUSIONS

The result of the daily potential ET calculations and the general agreement of these estimates with the lysimeter values of ET, indicate that evapotranspiration was at potential from the two crops during the periods of observation. If ET were not at potential, then the estimated values would overcompute the lysimeter ET.

The Weather Bureau (Kohler, 1955) equation with an empirical wind function appeared to provide the most consistent and reliable estimates of daily evapotranspiration. The Van Bavel (1966) version of the combination equation did well in estimating ET from the short mixed meadow grass. The Penman (1948) equation using measured net radiation and an empirical wind function did almost as well as the modified combination equation of the Weather Bureau.

Estimates of PET with the Van Bavel equation using a z_0 term based on wind profile or crop height was unsatisfactory for estimating potential ET over corn. Two possible alternate conclusions can be drawn. For corn: (1) there is a resistance to water vapor transport within the corn plant in spite of high soil water content; or (2) the log profile wind function is unsatisfactory for application in the combination equation with tall crops such as corn.

Measured daily net radiation was a good measure of daily potential ET when soil water was non-limiting. The simple measure of net radiation predicted daily PET for both crops as well as the improved combination equations and better than the empirical methods.

Where only daily incoming solar radiation and mean air temperature data are available, the Jensen-Haise equation appears to be satisfactory for general daily PET estimates. This equation gave an excellent fit with daily PET from a mixed meadow grass, but overcomputed by 15% PET for corn. Modification of the coefficients may be necessary for application to corn in a humid region.

The successful application of the Mustonen-McGuinness equation using data independent from that used in the derivation of the equation gives confidence that this method can be used to estimate actual ET rates in the eastern United States from general climatic data on a daily basis or longer. Of course, it is necessary to have some continuous measure or estimate of soil moisture in the top meter of soil. Part of the strength of this approach is the high correlation between free water evaporation and potential evapotranspiration.

The Blaney-Criddle equation and the Christiansen equation were inadequate for daily ET estimates. Transposing the solar radiation data seriously limited all of the methods tested, and estimates of PET using general climatic data were unsatisfactory on a daily basis. Accurate daily estimates of PET in humid areas appear to require on-site micrometeorological data.

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