ESTIMATION OF REFERENCE EVAPOTRANSPIRATION BY A MODIFIED BOWEN METHOD

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SUMMARY: The sustainability of irrigated agriculture depends primarily on efficient water use. Efficient irrigation decisions are function of potential atmospheric demand, which are expressed by reference evapotranspiration (ET_o). In general, all ET_o estimation methods refer to daily values including night evaporation losses, which are only substantial for a few days after rain or irrigation. We propose a method for estimating ET_o, based on the local energy balance from limited meteorological data monitored in an automated weather station throughout daylight periods. To validate the current method, climatic data and lysimetric measurements from Piracicaba, São Paulo, Brazil were used. Regression analyses revealed that a modified Bowen method provided results similar to the Penman-Monteith method and with measurements made by weighing lysimeters. Given the high coefficients of determination and ease of estimation, the method is recommended for assessment of crop water use at other sites.

KEYWORDS: energy balance, modeling, light period.

INTRODUCTION

Until recently, irrigation recommendations were often based on the concept of reference evapotranspiration (ET_o) defined as the water use by a uniform, actively growing, full-cover grass sward or alfalfa canopy with an unrestricted water supply. The daily water requirements of other crops are then estimated by adjusting ET_o via a series of multiplicative crop factors that purport to account for differences between the crop of interest and the reference crop. Differences for arable crops include incomplete ground cover as well as phenological stage of development (DOORENBOS & PRUITT, 1977; CSSRI, 2000 and ALLEN et al., 1994).

Compared to the Penman-Monteith equation, the Priestley-Taylor formula may have operational limits (McANENEY & ITIER, 1996) since it empirically proposes a coefficient of proportionality between evaporation and available energy. Despite this apparent limitation, the Priestley-Taylor equation has substantial experimental support, especially in humid regions (PRIESTLEY & TAYLOR, 1972; PEREIRA et al., 1997).

The estimate of maximum crop evapotranspiration is an important factor to be considered in agricultural planning and has been a research field that has involved studies related to irrigation management and agrometeorology all over the world. The reference or potential evapotranspiration (ET_o) needs to be determined to provide knowledge of crop water requirements. It is desirable to have a method that estimates ET_o with accuracy and from easily obtained meteorological data. Irrigation planning and decision making at a field scale are done based on calculations of crop evapotranspiration (ET_c).

Estimates of ET_o refer to potential evapotranspiration for daily increments. The nocturnal losses of soil evaporation that will be significant for a few days after rainfall or irrigation are taken into account. Usually methods that make use of daily mean values of air temperature, relative humidity, and wind speed do not depict very well the physical reality of evaporative water loss and for the soil surface might mask the actual behavior of the aforementioned meteorological variables. In the current work we have developed an estimation method to calculate the reference evapotranspiration (ET_o) on a diurnal basis throughout the light period, aiming at quantifying only the daytime values of evapotranspiration, which are often more representative of the water vapor transference process to the atmosphere for a given agricultural ecosystem.

THEORETICAL BACKGROUND

The classical theory related to the partition of net radiation (Rn) into the different natural processes presupposes that under natural conditions of water supply a part of Rn might be transformed into latent heat for evaporation and evapotranspiration (λE), part into sensible heat to the atmospheric air (H), and part into energy storage (A), and in compliance with energy conservation principle it is known that:

$$Rn = \lambda E + H + A \quad (1)$$

By the end of a diurnal cycle we can assume that A is negligible as well as consider that λE and H return from the surface to the atmosphere as transpiration and sensible heat fluxes (heating of humid air). Bowen ratio (BOWEN, 1926) was defined by the following relationship:

$$\beta = H/\lambda E = \gamma/S \quad (2)$$

In equation 2 the terms signify:

S is the slope of water vapor saturation pressure as a function of mean air temperature ($kPa.^{o}C^{-1}$); γ is the psychrometric coefficient (= $0.063 kPa.^{o}C^{-1}$), being determined by means of the following expression:

$$\gamma = \frac{Cp\ P}{0{,}622\ \lambda} \quad (3)$$

where Cp is the air sensible heat flux (= 1.013 $kJ.kg^{-1}$); P is the local atmospheric pressure (kPa); and λ is the water vaporization latent heat (= 2.45 $MJ.kg^{-1}$).

Substituting (2) in (1) we have:

$$Rn = \lambda E\ (S + \gamma)/S \quad (4)$$

Defining $\frac{S+\gamma}{S}$ as $\frac{1}{W}$, and substituting it in (4) we will have:

$$E = W\frac{Rn}{\lambda} \quad (5)$$

In this calculation procedure a method denominated modified Bowen (ET_oBm) is proposed, whose difference from equation 5 refers to the substitution of W value, usually determined at mean air temperature, for the value of W*, obtained as a function of the average between the dry and wet temperatures monitored by a psychrometer, as proposed by MONTEITH (1965), with the adjustment being extremely dependent on air temperature and relative humidity (VILLA NOVA et al., 2002).

The equation that defines the calculation of the potential or reference evapotranspiration by the proposed method and denominated here as modified Bowen will be expressed by:

$$EToBm = \alpha * W * \frac{Rn - G}{\lambda} \quad (6)$$

where ET_oBm is the potential evapotranspiration estimated by the modified Bowen method throughout light periods ($kg.m^{-2}.day^{-1}$ = $mm.day^{-1}$); Rn is the radiation balance at surface ($MJ.m^{-2}.day^{-1}$); G is the sensible heat flux density in the soil ($MJ.m^{-2}.day^{-1}$); $W* = S*/S*+\gamma$ is a weighing factor for the effect of solar radiation on evapotranspiration that depends on air temperature, relative humidity and psychrometric coefficient; α* is the adjustment parameter for the proposed method - similar to the Priestley-Taylor parameter (PRIESTLEY & TAYLOR, 1972); and λ defined as above. The term W* is then defined by the relationship:

$$W* = \frac{S*}{S*+\gamma} \quad (7)$$

where S* is the slope of water vapor saturation pressure as a function of the average temperature between dry and wet bulbs (Tdw). Tabular values of Tdw and S* calculated by VILLA NOVA et al. (2002) were utilized in the calculation of W* as a function of local latitude, air temperature and relative humidity.

The final equation representative of the current method in this study resulting from the substitution of α^*, which assumed the mean value of 1.037, and λ in equation 5 is given by:

$$ EToBm = \frac{1.037\, W^* \,(\mathrm{Rn - G})}{\lambda} $$

Or yet, being $\lambda = 2.45$ MJ.kg^{-1}

$$ EToBm = 0.423\, W^* \,(Rn - G) \text{ ------------------------------------- (8)} $$

MATERIALS AND METHODS

A set of potential evapotranspiration data was collected by PEREIRA (1998) at Piracicaba, State of São Paulo, Brazil (Latitude 22°42'S, Longitude 47°38'W and Altitude 596m), at the Experiment Station of Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo - ESALQ/USP throughout the period from 1 August to 24 September 1996, totaling 45 days was used for determination of the mean value of W*. The reference evapotranspiration (ET_o) was obtained in one weighing lysimeter with three load cells (Omega Eng., model LCCA-2K, capacity of 910 kg and accuracy of 0.037%), two drainage lysimeters and two sub-irrigation lysimeters with the same dimensions of load cells-based evapotranspirometer, at 0.65m-depth, 1.20m-long and 0.85m-wide cultivated with bahiagrass sward (*Paspalum notatum* F.) as described by SILVA et al., 1999. A 10m-fetch field adjacent to the lysimeters was managed in such a way to keep the grass sward uniform and actively-growing with a height between 0.08 and 0.15m by means of periodical cuttings. An unrestricted amount of water was continuously supplied by a drip irrigation system to both lysimeter areas and adjacent field so that evapotranspiration occurred at a representative rate, as recommended by DOORENBOS & PRUITT (1977) and ALLEN (1994).

Daily soil water potential readings were made from four digital tensiometers installed in each lysimeter at 15 and 30cm-depth. The soil water suction corresponding to field capacity at the drainage lysimeters was determined directly in the field whenever water drainage within the profile ceased after the soil was saturated.

Throughout the period of data collection, a field calibration procedure on the load cell system was adopted in order to check out its responsiveness. ET_o was calculated and recorded every 30 minutes from data measured each second by a data logger (model CR10, Campbell Scientific, Inc. Logan, Utah) hooked up to three load cells of a weighing lysimeter. The daily mean reference evapotranspiration measured by a weighing lysimeter adopted as a standard for evaluating the performance of other kinds of lysimetres (SILVA, 1999) was used to validate the modified Bowen method.

For validation of the modified Bowen method, sets of data of daily air mean temperature and relative humidity, net radiation, sensible heat flux in the soil monitored by an automatic weather station and lysimetric measurements collected by PEREIRA (1998) throughout the period between September and December 1996 (46 available days of observation), and by MAGGIOTTO (1996) between December 1995 and May 1996 (31 available days of observation) were used. Two comparison criteria were adopted to assess the proposed estimate model performance. A simple linear regression was made between the daily values of ET_o calculated by the modified Bowen method and those measured by weighing lysimeters with load cells. The estimates obtained by the modified Bowen method were also compared to that of the Penman-Monteith method.

RESULTS AND DISCUSSION

Determination of W*

W* values are presented as a function of the observed daily mean values of air temperature (T in degrees Celcius) and relative humidity (RH%) for altitudes from 0 to 1000 meters and from 1000 and 2000 meters, respectively (Tables 1 and 2). Parameter corrections from the average temperature between dry and wet bulbs of a psychrometer, according to MONTEITH (1965), is a function of S* calculated by VILLA NOVA et al. (2002) and is dependent on γ and local atmospheric pressure, as shown above in equation 3.

TABLE 1. Values of W* as a function of the observed daily mean air temperature and relative humidity for altitudes from 0 to 1000 meters.

Altitudes between 0 and 1000 meters									
Relative Humidity (%)									
Temperature (^oC)	45	50	55	60	65	70	75	80	85
10	0.532	0.535	0.539	0.542	0.545	0.548	0.551	0.554	0.557
11	0.546	0.549	0.552	0.556	0.559	0.562	0.565	0.568	0.571
12	0.560	0.563	0.566	0.569	0.573	0.576	0.579	0.582	0.585
13	0.573	0.576	0.580	0.583	0.586	0.589	0.593	0.596	0.599
14	0.586	0.589	0.593	0.596	0.599	0.603	0.606	0.609	0.613
15	0.599	0.602	0.606	0.609	0.612	0.616	0.619	0.622	0.626
16	0.612	0.615	0.618	0.622	0.625	0.629	0.632	0.635	0.639
17	0.624	0.628	0.631	0.634	0.638	0.641	0.645	0.648	0.651
18	0.636	0.640	0.643	0.647	0.650	0.653	0.657	0.660	0.663
19	0.648	0.652	0.655	0.659	0.662	0.665	0.669	0.672	0.675
20	0.660	0.663	0.667	0.670	0.674	0.677	0.680	0.684	0.687
21	0.671	0.675	0.678	0.682	0.685	0.688	0.692	0.695	0.698
22	0.682	0.686	0.689	0.693	0.696	0.699	0.703	0.706	0.709
23	0.693	0.697	0.700	0.704	0.707	0.710	0.714	0.717	0.720
24	0.704	0.707	0.711	0.714	0.717	0.721	0.724	0.727	0.730
25	0.714	0.717	0.721	0.724	0.728	0.731	0.734	0.737	0.740
26	0.724	0.727	0.731	0.734	0.737	0.741	0.744	0.747	0.750
27	0.734	0.737	0.740	0.744	0.747	0.750	0.753	0.756	0.760
28	0.743	0.746	0.750	0.753	0.756	0.759	0.762	0.766	0.769
29	0.752	0.756	0.759	0.762	0.765	0.768	0.771	0.774	0.777
30	0.761	0.764	0.768	0.771	0.774	0.777	0.780	0.783	0.786

TABLE 2. Values of W* as a function of the observed daily mean air temperature and relative humidity for altitudes from 1000 to 2000 meters.

Altitudes between 1000 and 2000 meters									
	Relative Humidity (%)								
Temperature (^oC)	45	50	55	60	65	70	75	80	85
10	0.569	0.572	0.575	0.578	0.582	0.585	0.588	0.591	0.594
11	0.582	0.585	0.589	0.592	0.595	0.599	0.602	0.605	0.608
12	0.595	0.599	0.602	0.605	0.609	0.612	0.615	0.619	0.622
13	0.608	0.612	0.615	0.619	0.622	0.625	0.629	0.632	0.635
14	0.621	0.625	0.628	0.631	0.635	0.638	0.641	0.645	0.648
15	0.634	0.637	0.641	0.644	0.647	0.651	0.654	0.657	0.661
16	0.646	0.649	0.653	0.656	0.660	0.663	0.666	0.670	0.673
17	0.658	0.661	0.665	0.668	0.672	0.675	0.678	0.682	0.685
18	0.670	0.673	0.677	0.680	0.683	0.687	0.690	0.693	0.697
19	0.681	0.685	0.688	0.691	0.695	0.698	0.701	0.705	0.708
20	0.692	0.696	0.699	0.702	0.706	0.709	0.712	0.716	0.719
21	0.703	0.706	0.710	0.713	0.717	0.720	0.723	0.726	0.729
22	0.714	0.717	0.720	0.724	0.727	0.730	0.733	0.737	0.740
23	0.724	0.727	0.731	0.734	0.737	0.740	0.743	0.747	0.750
24	0.734	0.737	0.740	0.744	0.747	0.750	0.753	0.756	0.759
25	0.743	0.747	0.750	0.753	0.756	0.759	0.763	0.766	0.769
26	0.753	0.756	0.759	0.762	0.766	0.769	0.772	0.775	0.778
27	0.762	0.765	0.768	0.771	0.774	0.777	0.780	0.783	0.786
28	0.771	0.774	0.777	0.780	0.783	0.786	0.789	0.792	0.795
29	0.779	0.782	0.785	0.788	0.791	0.794	0.797	0.800	0.803
30	0.787	0.790	0.793	0.796	0.799	0.802	0.805	0.808	0.810

Estimation of the parameter α*

For estimation α* 45 days of lysimetric measurements of ET_o and readings of meteorological elements collected by PEREIRA (1998) during the period comprised between 1 August and 24 September 1996 were taken into consideration. The mean value of α* was 1.037 for the period in question (Table 3).

TABLE 3. Values of Priestley-Taylor parameter modified by the proposed method (α*) obtained by means of equation 5 from data collected by Pereira (1998).

Date	**Rn** *($MJ.m^{-2}.d^{-1}$)*	**G** *($MJ.m^{-2}. d^{-1}$)*	**Rn - G** *($MJ. m^{-2}.d^{-1}$)*	**W***	**ET_o** *($mm.d^{-1}$)*	**α***
August/1	9.91	0.68	9.23	0.678	2.10	0.822
2	10.80	0.73	10.07	0.652	2.10	0.784
3	10.15	0.71	9.44	0.659	2.05	0.807
4	10.92	0.91	10.01	0.675	2.89	1.048
5	10.95	0.74	10.21	0.680	2.99	1.055
6	9.99	0.73	9.26	0.676	2.48	0.971
7	9.54	0.81	8.73	0.693	2.42	0.980
8	9.49	0.81	8.68	0.704	2.68	1.075
9	8.25	0.59	7.66	0.721	2.48	1.100
11	7.60	0.63	6.97	0.674	2.21	1.153
12	9.21	0.76	8.45	0.685	2.26	0.957
13	10.73	0.87	9.86	0.710	2.32	0.812
15	9.91	0.58	9.33	0.680	2.65	1.023
16	12.49	0.43	12.06	0.634	2.85	0.913
17	11.99	0.79	11.20	0.667	3.04	0.997
18	12.00	0.80	11.20	0.672	3.05	0.993
19	12.32	0.78	11.54	0.683	3.10	0.964
21	12.31	0.82	11.49	0.704	3.37	1.021
22	11.42	0.88	10.54	0.714	3.14	1.022
23	11.89	0.86	11.03	0.714	3.45	1.073
24	12.61	0.82	11.79	0.707	3.39	0.996
25	12.69	0.87	11.82	0.711	3.55	1.035
26	12.35	0.89	11.46	0.730	3.74	1.095
27	11.23	0.87	10.36	0.740	3.97	1.269
28	10.06	0.84	9.22	0.722	3.00	1.104
29	10.01	0.62	9.39	0.712	2.61	0.956
30	11.19	0.81	10.38	0.734	3.72	1.196
31	12.47	0.57	11.90	0.739	4.30	1.198

Date	Rn $(MJ.m^{-2}.d^{-1})$	G $(MJ.m^{-2}. d^{-1})$	Rn - G $(MJ. m^{-2}.d^{-1})$	W*	ET_o $(mm.d^{-1})$	α*
September/2	12.50	0.70	11.80	0.704	3.38	0.997
4	8.67	0.53	8.14	0.693	2.72	1.181
7	14.11	0.88	13.23	0.696	3.74	0.995
12	10.38	0.55	9.83	0.677	2.85	1.049
13	13.48	1.06	12.42	0.707	3.18	0.887
14	14.32	0.97	13.35	0.717	4.45	1.139
15	14.49	0.89	13.60	0.714	4.18	1.055
17	10.86	0.38	10.48	0.699	3.52	1.177
18	14.08	0.46	13.62	0.674	3.86	1.030
19	15.03	0.82	14.21	0.698	4.41	1.089
20	14.28	0.92	13.36	0.711	4.14	1.068
22	14.39	0.79	13.60	0.740	5.02	1.222
23	13.54	0.83	12.71	0.748	4.52	1.165
24	12.04	0.65	11.39	0.734	3.72	1.090

Validation of the proposed method

The first validation of the modified Bowen method was a comparison between values of potential evapotranspiration measured by weighing lysimeters with load cells and those estimated by the proposed methodology, taking into account an independent series of data monitored by PEREIRA (1998) at Piracicaba, State of São Paulo, Brazil, throughout the period between 26 September and 9 December 1996, totaling 46 available days of observation. A second validation was performed with the aim of confirming the feasibility of the method through a study of simple linear regression between measured and estimated values of ET_o, taking into consideration lysimetric and radiometric data collected by MAGGIOTTO (1996) at the same site for a span from 23 December 1995 to 16 May 1996, amounting to a total of 31 completely independent observations.

The lysimetric measurements made by PEREIRA (1998) and MAGGIOTTO (1996) and the estimates of ET_o obtained by the modified Bowen and Penman-Monteith methods were closely correlated with coefficients of determination greater than 0.90 (Figures 1 through 6).

ET_o estimated by the modified Bowen method was closely related to the classical Penman-Monteith method, as well as to ET_o measured by weighting lysimeters from experimental data obtained by PEREIRA (1998). The modified Bowen method was accurate given an R^2 value of

0.903 as well as the dispersion of the data from comparison between estimates and measurements around the 1:1 line (Figure 2). The modified Bowen model also shows results very similar to estimates obtained by Penman-Monteith equation (Figure 3). By comparing the performance of the modified Bowen method in study with that one of Penman-Monteith method (Figure 1) it is possible to verify that there is a fairly consistent agreement between methods, statistically confirmed by an R^2 value of 0.961 and by an extremely small dispersion of the data around the 1:1 line. This indicates the feasibility of the modified Bowen method when a larger number of meteorological elements are not available to assess the potential demand at a given site. Given the slopes of the regression line observed in Figures 1 through 3 we may infer that the modified Bowen method corresponded to 96.75% of ET_o calculated by the classical method of Penman-Monteith. Both methods underestimated water use by less than 3%. The modified Bowen method had satisfactory performance at the site in study with a high degree of accuracy.

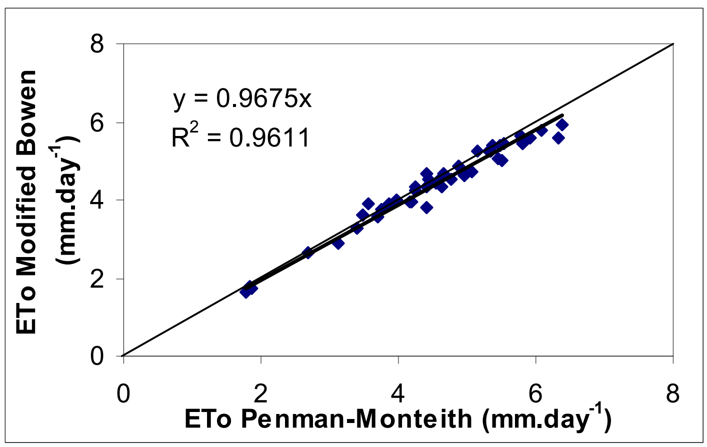

FIGURE 1. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Pereira (1998).

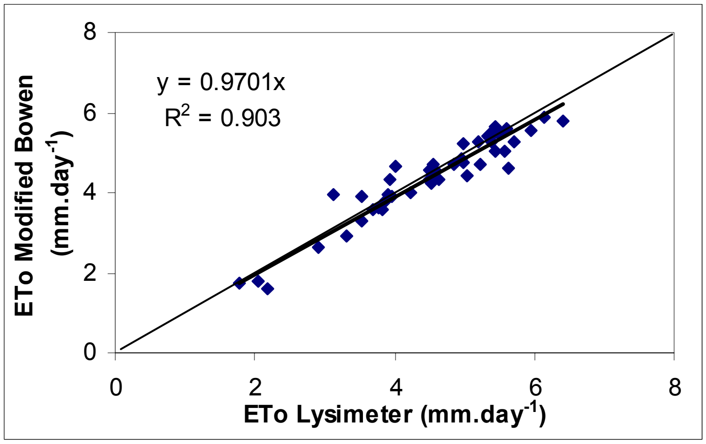

FIGURE 2. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Pereira (1998).

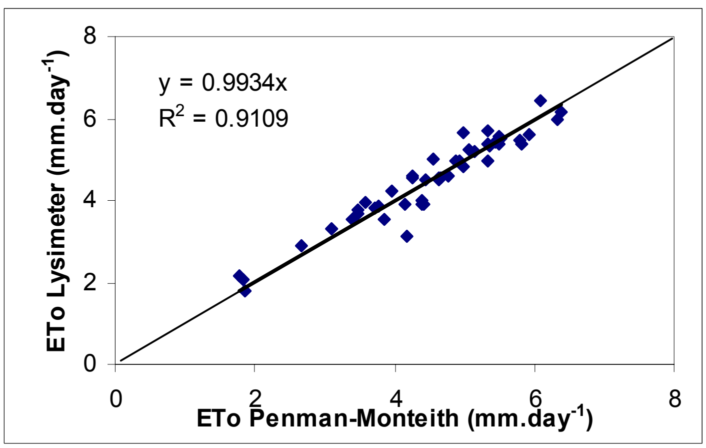

FIGURE 3. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the Penman-Monteith method for light periods. Experimental data collected by Pereira (1998).

Figures 4 through 6 show the validation of the proposed modified Bowen method from analysis of experimental data obtained by MAGGIOTTO (1996). Figure 4 reveals a pronounced agreement between the considered estimation methods of ET_o, which can be demonstrated by a coefficient of determination of 0.989 and by an evident coincidence degree between the trend line and 1:1 line as the regression line is forced to pass by origin (b = 0.973), standing out once more the feasibility of the proposed method in studies developed to evaluate crop water requirements.

The modified Bowen and Penman-Monteith estimation methods of potential demand were closely related with lysimetric measurements ($R^2 > 0.949$) (Figures 5 and 6). The modified Bowen method tended slightly to overestimate evapotranspiration by about 5%, whereas the Penman-Monteith method underestimated atmospheric demand at a rate close to 7%.

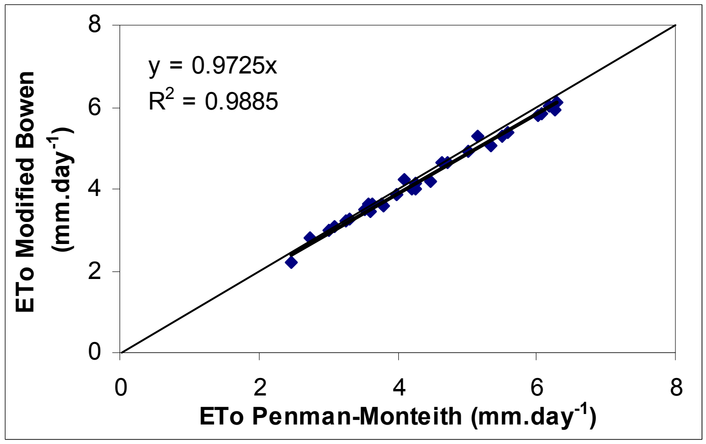

FIGURE 4. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Maggiotto (1996).

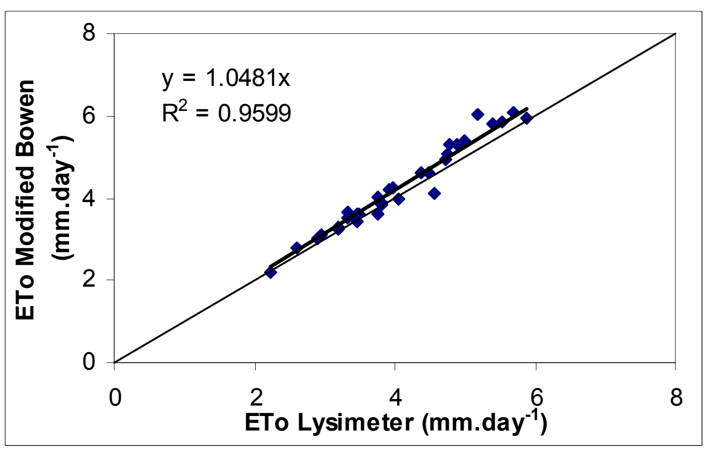

FIGURE 5. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Maggiotto (1996).

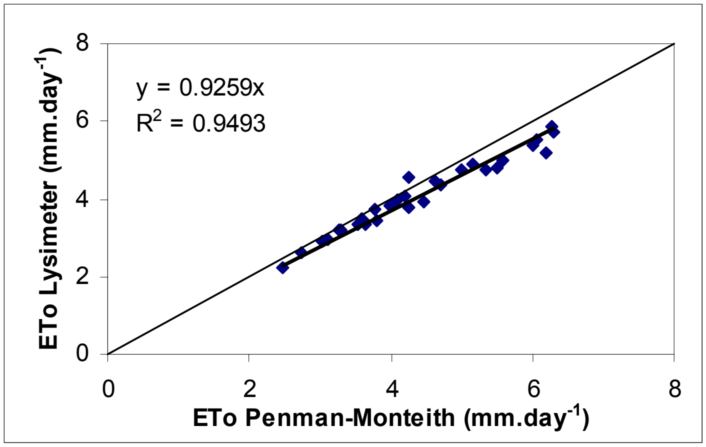

FIGURE 6. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand measured by a weighting lysimeter for light periods. Experimental data collected by Maggiotto (1996).

Although several states and counties in the USA have a network of computerized weather stations that measure the important environmental variables that govern water loss and predict crop evapotranspiration, in many developing countries there is no such a system to provide the users with information regarding the actual water loss from well-watered grass crop. Thus, the reference evapotranspiration has to be determined in compliance with available climatic elements in a given site, since it has been proven to be very useful in estimating actual crop water needs.

One of the factors that will give one some knowledge for scientific irrigation scheduling is daily estimates of crop water use. The Pacific Northwest AgriMet system uses the 1982 Kimberly-Penman evapotranspiration model combined with locally derived plant growth stage information to produce estimates of daily crop consumptive water use (PALMER, 2004).

All the theoretical background involved in the Penman-Monteith method to calculate ET_o is unquestionable and should be considered by a satellite-based network of automated agricultural weather stations to provide information at farmer levels. However, its limitation is related to a large number of environmental variables that are necessary to determine ET_o, In addition to such a point, the lack of computerized weather station systems available to monitor the atmospheric parameters in many developing localities justifies other alternative methods for determining ET_o as a function of a minor number of input data with a precision compatible to either lysimetric measurements or Penman-Monteith estimates.

CONCLUSIONS

Under local climatic conditions of the experiment, a modified Bowen method (ET_oBm) - gave estimates practically identical to those obtained by the classical Penman-Monteith method. The modified Bowen method had the added advantage of simplifying ET_o calculation, leaving out information related to wind speed, making use of only net radiation, mean air temperature and mean relative humidity in daily basis. For the climatic conditions for the site in this study, the method when compared to potential evapotranspiration measurements obtained by weighing lysimeters showed high statistical accuracy. The modified Bowen method was a feasible alternative to evaluate standard reference evapotranspiration. By means of the theoretical development of the current method, based on equations of net radiation, it might be precisely employed in other climatic regions.

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