RESEARCH

Reference evapotranspiration estimates based on minimum meteorological variable requirements of historical weather data

Antonio J. Steidle Neto[1*], João C.F. Borges Júnior[1], Camilo L.T. Andrade[2], Daniela C. Lopes[1], and Priscilla T. Nascimento[1]

Reference evapotranspiration (ET_0) is critical for agricultural and urban planning, irrigation scheduling, regional water balance studies, and agroclimatological zoning. The objective of this study was to estimate ET_0 based on methods with minimum meteorological variable requirements and on empirical models to predict solar radiation. These alternative methods were compared to the FAO Penman-Monteith method by using more than 80 yr of historical weather data. Alternative methods were adapted from the standard FAO Penman-Monteith or Priestley-Taylor methods, which allow estimating ET_0 when fewer meteorological variables are available. The Hargreaves-Samani method was also analyzed. The mean absolute error, index of agreement, correlation coefficient, and confidence index were used to compare the alternative methods. Results showed that alternative methods based on the maximum and minimum temperatures, sunshine hours, and/or wind speed are appropriate for estimating ET_0 in the region under study.

Key words: FAO Penman-Monteith, meteorological variables, reference evapotranspiration, solar radiation models.

INTRODUCTION

Accurately estimating evapotranspiration is very important for water resources and watershed management, as well as in agricultural and hydrological studies. It is especially applied to estimate crop water requirements and support irrigation scheduling and drought management (Raziei and Pereira, 2013). Evapotranspiration has also often been used to identify regions prone to drought, and it is an important field of research related to climate changes (Croitoru et al., 2013). Crop evapotranspiration quantification must frequently be preceded by the determination of reference evapotranspiration (ET_0), which has been defined by Doorenbos and Pruitt (1977) as the rate of evapotranspiration from an extensive area covered with grass that is 0.08 to 0.15 m tall, uniform, actively growing, completely shading the ground, and under adequate soil-water conditions. Allen et al. (1998) elaborated on the concept of ET_0 by referring it to a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and albedo of 0.23.

[1]Universidade Federal de São João del-Rei, Campus Sete Lagoas, Rodovia MG 424, km 47, Sete Lagoas, 35701-970, Minas Gerais, Brasil. *Corresponding author (antonio@ufsj.edu.br).
[2]Embrapa Milho e Sorgo, Rodovia MG 424, km 45, Sete Lagoas, 35702-098, Minas Gerais, Brasil.
Received: 21 October 2014.
Accepted: 26 April 2015.
doi:10.4067/S0718-58392015000400014

Reference evapotranspiration (ET_0) can be obtained by direct and accurate techniques with special equipment, such as lysimeters, or estimated indirectly by mathematical models to provide good results (Alves Sobrinho et al., 2011). However, constructing and maintaining lysimeters is very costly, which restricts their use in research institutions; however, they are justifiably applicable for regional calibration of evapotranspiration models and to evaluate water balance models (Xu and Chen, 2005; Melo and Fernandes, 2012). The FAO Penman-Monteith method has been reported as providing consistent ET_0 values in many regions and climates (Allen et al., 2006); it has long been accepted worldwide as an excellent ET_0 estimator when compared with other methods (Cai et al., 2007). Although this method has performed excellently, it requires many meteorological variables; this imposes a barrier to its widespread use, especially among small farmers who lack the economic resources to purchase automatic meteorological stations (Borges Júnior et al., 2012). The application of ET_0 models with fewer meteorological variable requirements is recommended under situations where weather data sets are incomplete. However, before these models can be used to estimate ET_0 for a given region, they must be evaluated against either lysimeter measurements or the FAO Penman-Monteith method (Tabari et al., 2013). Gong et al. (2006) performed a sensitivity analysis of the FAO Penman-Monteith variables and pointed out the great influence of solar radiation in accurately estimating ET_0. Availability of solar radiation measurements has proven to be spatially and temporally inadequate for many applications; this has led to research studies focused on estimating this important variable (Belcher and DeGaetano, 2007). Empirical formulas have been developed to estimate solar radiation using some normal observations from meteorological stations, such as maximum and minimum temperatures, sunshine hours, cloud, precipitation, latitude, and elevation (Yin et al., 2008).

The present study was carried out to estimate reference evapotranspiration (ET_0) based on methods with minimum meteorological variable requirements and on empirical models to predict solar radiation. These methods were compared with the FAO Penman-Monteith method by using more than 80 yr of weather data for the region of Sete Lagoas, State of Minas Gerais, Brazil.

MATERIALS AND METHODS

Climate database

Daily climate data were collected by a conventional meteorological station of the National Institute of Meteorology (INMET) in Sete Lagoas (19°48' S, 44°17' W; 732 m a.s.l.), Minas Gerais, Brazil. The region's climate is characterized as rainy tropical with dry winters and a rainy season from October to March. According to Panoso et al. (2002), the climate is humid mesothermal (Cwa) according to Köppen's classification.

Historical climate data from 1927 to 2010 were tabulated on electronic spreadsheets. The following meteorological variables were considered: maximum temperature (T_{max}), minimum temperature (T_{min}), duration of sunshine (n), wind speed at 10 m height (U_{10}), and mean relative humidity (RH). Pluvial precipitation (P) was also considered to characterize the local climate. Liquid-in-glass thermometers used to measure maximum and minimum temperatures and non-aspirated psychrometer used to measure air relative humidity were manufactured by R. Fuess (Berlin, Germany). Duration of sunshine was determined with a Campbell-Stokes sunshine recorder (Negretti & Zambra, London, UK). Wind speed was measured with a cup-anemometer (Henry J. Green, New York, USA) and pluvial precipitation was counted with a Ville de Paris rain gauge (I-H, São Paulo, Brazil).

The values of T_{max} were collected at 00:00 UTC and T_{min} at 12:00 UTC as a routine procedure. The value of T_{med} was expressed as the mean of daily T_{max} and T_{min}. Mean RH was obtained by summing the values measured at 12:00, 18:00, and twice at 24:00 UTC, and dividing this sum by four. Wind speed was adjusted to a 2 m height as proposed by Allen et al. (1998). Accumulated daily pluvial precipitation was collected at 12:00 UTC.

A consistency analysis was performed on the meteorological variable data with electronic spreadsheet functions to remove all inconsistent data. Visual analysis of graphs relating the variables to time was also used as a complementary tool. Data gaps of 1 to 3 d were filled with the mean values of the day before and after. The historical database size was reduced by discarding missing days when there was a lack of data for more than three consecutive days. Generally, discards were 1.3% of the total of 30 681 d, resulting in a database of 30 295 d.

Pluvial precipitation data were analyzed separately since these data were recorded once a day and exclusions would result in information losses when analyzing monthly values. The historical series of pluvial precipitation included the years 1926 to 2011. Data from January to April 1926 were excluded from the series due to missing information. The same occurred for December 1926, August 1935, and from August to December 2011. Pluvial precipitation values were only used in the climate characterization of the region under study.

Following recommendations by Allen (2013), wind speed was limited to more than 0.5 m s^{-1}. This recommendation accounts for the effects of boundary layer instability and air buoyancy to promote the exchange of surface vapor when wind speed is low. Thus, the wind speed limitation in the ET_0 equation improves estimation accuracy under very low wind speed conditions (Allen, 2013).

Methods to estimate reference evapotranspiration

The standard FAO Penman-Monteith method (Allen et al., 1998) was applied on the electronic spreadsheet to calculate ET_0, as well as the following alternative methods: Method 1: Priestley-Taylor (Jensen et al., 1990; Palumbo et al., 2011) with air temperature and duration of sunshine as input data; Method 2: Hargreaves-Samani (Jensen et al., 1990; Bachour et al., 2013); Methods 3, 5, 7, and 9: Priestley-Taylor with procedures that allow applying the method when only air temperature is available; Methods 4, 6, 8, and 10: FAO Penman-Monteith procedures that allow applying the method when only air temperature and wind speed are available. In these methods, saturation vapor pressure and actual vapor pressure were estimated from T_{max} and T_{min} as recommended by Allen et al. (1998) for situations where air humidity data are lacking or are of questionable quality.

The standard FAO Penman-Monteith method is based on the following equation (Allen et al., 1998; Palumbo et al., 2011; Bachour et al., 2013):

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\dfrac{900}{T_{med} + 273}\,U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \qquad [1]$$

where ET_0 is the reference evapotranspiration (mm d^{-1}), Δ is the slope of the vapor pressure curve (kPa $^oC^{-1}$), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa $°C^{-1}$), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and T_{med} is the mean daily air temperature at 2 m height (°C).

The Priestley-Taylor equation, developed in Australia, is expressed as (Jensen et al., 1990; Palumbo et al., 2011; Allen, 2013):

$$ET_0 = 1.26\ \frac{\Delta}{\Delta + \gamma}\ (R_n - G) \qquad [2]$$

The Hargreaves-Samani method requires only temperature data and is based on the following equation (Jensen et al., 1990; Fooladmand and Haghighat, 2007; Bachour et al., 2013):

$$ET_0 = 0.0023\ R_a\,(T_{max} - T_{min})^{0.5}\,(T_{med} + 17.8) \qquad [3]$$

where R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}).

Net radiation (R_n) is the major factor influencing evapotranspiration, and is an essential input data in the Penman-Monteith model (Blonquist et al., 2010) and other models such as Priestley-Taylor (Cristea et al., 2013). Net radiation was obtained from the difference between incoming net shortwave radiation (R_{ns}) and outgoing net longwave radiation (R_{nl}) according to Allen et al. (1998). Estimates of solar radiation (R_s), required for calculating R_{ns} and R_{nl}, were calculated by the Angstrom radiation model (Equation [4]). It was used in the standard FAO Penman-Monteith model and in the alternative Priestley-Taylor method (method 1).

$$\frac{R_s}{R_a} = a_s + b_s\left[\frac{n}{N}\right] \qquad [4]$$

where R_s is solar radiation (MJ m^{-2} d^{-1}); a_s and b_s are regression coefficients (dimensionless); n is the duration of sunshine (h); and N is daylight hours (h). The R_a values were calculated following the procedures described by Allen et al. (1998); the latitude of the region under study was taken into account, as well as the daily estimate of N. The a_s and b_s values were assumed to be equal to 0.25 and 0.50, respectively, as suggested by Allen et al. (1998).

Models to estimate solar radiation

Several empirical equations to obtain the R_s/R_a term of Equation [4] were evaluated with the objective of applying it in ET_0 methods when the duration of sunshine (n) is not available to estimate R_s. Results of applying these equations were compared with the results obtained by the Angstrom radiation model (Equation [4]). These evaluations consisted in statistical analysis based on the mean absolute error and correlation coefficient. Four alternatives were selected; air temperature was the only input variable that was measured, while the other variables were predicted:

Hargreaves model: $$\frac{R_s}{R_a} = k_1\sqrt{T_{max} - T_{min}} \qquad [5]$$

Modified Hargreaves model: $$\frac{R_s}{R_a} = k_2\sqrt{T_{max} - T_{min}} + k_3 \qquad [6]$$

Borges Júnior model:

$$\frac{R_s}{R_a} = \sqrt{\frac{T_{max}}{N}}\left[k_4\,(T_{max} - T_{min})^3 + k_5\left(\frac{T_{min}}{T_{max}}\right)^2 + k_6\,T_{med} + k_7\right]^2 \qquad [7]$$

Steidle Neto model: $$\frac{R_s}{R_a} = k_8 + k_9\left(\frac{e_s - e_a}{N}\right) + k_{10}\,W \qquad [8]$$

where k_1 to k_{10} are adjustment coefficients and W is precipitable water (cm). The adjustment coefficients in Equations [5] to [8] were obtained from computational procedures aimed at minimizing the mean absolute error related to the R_s/R_a daily ratio calculated by Equation [4].

Equation [5] refers to the Hargreaves radiation model (Allen et al., 1998; Todorovic et al., 2013). Equation [6] is Equation [5] with an additional linear coefficient (k_3). The Borges Júnior radiation model (Equation [7]) includes different relationships between T_{max} and T_{min}, as well as a general coefficient given by the square root of the T_{max}/N ratio. The Borges Júnior model was derived by considering the already observed high correlation between R_s and T_{max} and between R_a and N. In addition, an improved R_s/R_a prediction was expected by including the terms T_{max}-T_{min}, T_{min}/T_{max}, and T_{med} in the model.

When Equations [6] and [7] were applied, and a value was determined to be less than 0.25, the R_s/R_a ratio was equal to 0.25. This was done even though approximately 25% of solar radiation intercepted by the top of the atmosphere even in very cloudy days can reach the terrestrial surface mainly as diffuse radiation (Allen et al., 1998).

The Steidle Neto radiation model (Equation [8]) was derived by modifying the Angstrom formula (Equation [4]). The duration of sunshine (n) was substituted by vapor pressure deficit (e_s - e_a). Additionally, a representative variable of the total amount of water vapor in the zenithal direction, between the terrestrial surface and the top of the atmosphere, was included in this model. The proposition of an empirical radiation model that incorporates variables related to water vapor present in the atmosphere is justifiable because this gas is responsible for solar radiation absorption in different spectra wavelengths, thus attenusting solar radiation intercepted by the terrestrial surface.

Precipitable water (W), associated with solar radiation absorption by water vapor, was calculated from an exponential model (Iqbal, 1983):

$$W = 0.493\left(\frac{e_a}{e_s}\right)\left[\exp\left(26.23 - \frac{5416}{T_{med} + 273.15}\right)\right](T_{med} + 273.15)^{-1} \qquad [9]$$

Estimates of saturation vapor pressure (e_s) and actual vapor pressure (e_a) in Equations [8] and [9] were obtained from T_{max} and T_{min} as recommended by Allen et al. (1998).

The ET_0 estimation methods, R_s/R_a estimation models, and climate variables required in the equations are summarized in Table 1.

Comparison of method

When evaluating the performance of alternative methods compared with the standard FAO Penman-Monteith method, the following statistical indices were used: mean absolute error (MAE), root mean square error (RMSE), systematic root mean square error (RMSEs), unsystematic root mean square error (RMSEu), systematic and

Table 1. The reference evapotranspiration (ET_0) estimation methods, R_s/R_a estimation models, and required climate variables.

	Method to estimate ET_0	Model to estimate R_s/R_a	Required climate variables			
			T_{med}	RH	U_2	n
Standard	FAO Penman-Monteith	Angstrom	X	X	X	X
1	Priestley-Taylor	Angstrom	X			X
2	Hargreaves-Samani	-	X			
3	Priestley-Taylor	Hargreaves	X			
4	FAO Penman-Monteith	Hargreaves	X		X	
5	Priestley-Taylor	Modified Hargreaves	X			
6	FAO Penman-Monteith	Modified Hargreaves	X		X	
7	Priestley-Taylor	Borges Júnior	X			
8	FAO Penman-Monteith	Borges Júnior	X		X	
9	Priestley-Taylor	Steidle Neto	X			
10	FAO Penman-Monteith	Steidle Neto	X		X	

R_s/R_a: ratio between solar radiation and extraterrestrial radiation; T_{med}: mean air temperature; RH: mean relative humidity; U_2: wind speed at 2 m height; n: duration of sunshine.

unsystematic proportions of mean square error (MSEs and MSEu), index of agreement (d), confidence index (C), correlation coefficient (r), and determination coefficient (R^2). Additionally, linear and angular coefficients of regression (a_r and b_r, respectively) were also considered in the evaluation of the models. The following equations were used to calculate the indices (Willmott, 1982; Camargo and Sentelhas, 1997; Willmott and Matsuura, 2005; Todorovic et al., 2013):

$$MAE = N_d^{-1} \sum_{i=1}^{N_d} \left| P_i - O_i \right| \quad [10]$$

$$RMSE = MSE^{0.5} = \left[N_d^{-1} \sum_{i=1}^{N_d} (P_i - O_i)^2 \right]^{0.5} \quad [11]$$

$$RMSEs = MSEs^{0.5} = \left[N_d^{-1} \sum_{i=1}^{N_d} (\hat{P}_i - O_i)^2 \right]^{0.5} \quad [12]$$

$$RMSEu = MSEu^{0.5} = \left[N_d^{-1} \sum_{i=1}^{N_d} (\hat{P}_i - P_i)^2 \right]^{0.5} \quad [13]$$

$$d = 1 - \frac{\sum_{i=1}^{N_d} (P_i - O_i)^2}{\sum_{i=1}^{N_d} \left(\left| P_i - \bar{O} \right| + \left| O_i - \bar{O} \right| \right)^2} \quad [14]$$

$$C = d\, r \quad [15]$$

where N_d is the number of data pairs; P_i is the ET_0 value obtained by one of the methods on a daily scale (mm); O_i is the ET_0 value estimated by the standard FAO Penman-Monteith method on a daily scale (mm); MSE is the mean square error (mm^2); MSEs is the systematic mean square error (mm^2); $\hat{P}_i$ is the Pi estimator based on the linear regression model (mm); MSEu is the unsystematic mean square error (mm^2); and $\bar{O}_i$ is the mean of the O_i values (mm).

The confidence index (Equation [15]) was obtained from the correlation coefficient (r) and d. It was used to classify each method performance according to Camargo and Sentelhas (1997). Besides the indices described above, means, maximums, minimums, standard deviations (S_d), and coefficients of variation (CV) were calculated. Plots of the linear regressions were also used to support the comparison of the methods.

The RMSEs and RMSEu indices were used to try to identify systematic and non-systematic components of RMSE. For the regression models, the MSEs/MSE and MSEu/MSE ratios represent the systematic and non-systematic components, respectively. The square roots of MSEs and MSEu have the P_i and O_i units, mm. They are shown together with MAE and RMSE to help in the analysis as suggested by Willmott (1982).

RESULTS AND DISCUSSION

The monthly means of the historical weather data are shown in Table 2. A smaller annual amplitude was observed for T_{max} (3.7 °C) than T_{min} (7.2 °C), thus implying an annual amplitude of 5.4 °C in the T_{med} monthly means. The mean annual air temperature was 21.8 °C. Although the number of daylight hours was low during the winter months, high values of duration of sunshine were verified from June to August because of low cloudiness during this period. Mean annual pluvial precipitation was 1346 mm with a coefficient of variation of 22.9%.

Mean monthly ET_0 obtained from the standard FAO Penman-Monteith method did not exceed 4.3 mm (Table 2). However, the maximum ET_0 value for the standard method was greater than 8 mm d^{-1} (Table 4). Two different seasons could be observed when analyzing monthly means (Table 2). There is a warm, humid, and rainy season (October to March) and a dry season (April to September) with considerably lower pluvial precipitation. The highest monthly ET_0 means were recorded from September to March and were directly influenced by the high solar radiation available during this period.

The adjustment coefficients (k_1 to k_{10}) of Equations [5] to [8] are displayed in Table 3. Coefficients were truncated at the fourth significant digit. The k_1 coefficient value (0.1656 °$C^{-0.5}$), obtained by minimizing the mean absolute error in the Hargreaves model for the Sete Lagoas region, is very similar to the one ($k_{Rs} \approx 0.16$ °$C^{-0.5}$) recommended by Allen et al. (1998) for interior locations where land areas dominate and air masses are not strongly influenced

Table 2. Monthly means of climate variables determined from historical daily weather series (1927-2010) for Sete Lagoas, Minas Gerais, Brazil.

Month	T_{max}	T_{min}	T_{med}	n	RH	U_{10}	P	ET_0
	——— °C ———			h	%	m s^{-1}	mm	mm
January	29.1	18.2	23.7	6.3	77.6	1.54	265.3	4.2
February	29.6	18.1	23.9	7.1	76.4	1.51	172.4	4.3
March	29.3	17.8	23.6	7.0	77.0	1.44	155.6	3.9
April	28.3	16.1	22.2	8.0	75.7	1.42	58.0	3.4
May	26.9	13.4	20.1	8.3	73.8	1.37	21.7	2.8
June	26.1	11.5	18.8	8.6	71.5	1.41	7.8	2.5
July	26.0	11.1	18.5	8.8	67.4	1.66	9.1	2.8
August	27.7	12.3	20.0	9.1	61.3	1.91	8.6	3.5
September	28.9	14.9	21.9	7.5	61.3	2.08	36.4	4.1
October	29.2	16.9	23.0	6.6	67.0	1.94	99.7	4.2
November	28.5	17.7	23.1	5.9	74.4	1.76	208.1	4.1
December	28.2	18.2	23.2	5.4	78.7	1.65	303.3	3.9

T_{max}: maximum air temperature; T_{min}: minimum air temperature; T_{med}: mean air temperature; n: duration of sunshine; RH: mean relative humidity; U_{10}: wind speed at 10 m height; P: pluvial precipitation; ET_0: reference evapotranspiration calculated by FAO Penman-Monteith method.

Table 3. Values and units of the adjustment coefficients of the R_s/R_a ratio estimation models.

k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}
0.1656	0.2432	-0.2916	-2.582×10^{-5}	-0.9690	0.01121	0.7300	0.4160	3.911	-0.06811
°C$^{-1/2}$	°C$^{-1/2}$	-	h$^{1/4}$ °C$^{-13/4}$	h$^{1/4}$ °C$^{-1/4}$	h$^{1/4}$ °C$^{-5/4}$	h$^{1/4}$ °C$^{-1/4}$	-	h kPa^{-1}	cm^{-1}

R_s/R_a: ratio between solar radiation and extraterrestrial radiation.

by large water bodies. The inclusion of a linear coefficient (k_3) in the modified Hargreaves model (Equation [6]) in relation to the Hargreaves model (Equation [5]) resulted in an approximate increase of 47% in the k_2 coefficient value compared with the k_1 coefficient.

Comparisons between ET_0 estimation methods on a daily time scale are shown in Tables 4 and 5 and Figures 1, 2, 3, 4 and 5. Regarding mean ET_0 values, the percentile deviations obtained with methods 1 to 10 varied from 3% (method 10) to 22% (method 2) when compared with the FAO Penman-Monteith method. On the other hand, the coefficients of variation of the evaluated methods fluctuated from 24% (method 2) to 32% (method 1). Table 5 was generated with data from Table 4 and shows the ranking of the methods based on four different performance evaluation criteria. The indices considered as criteria in Table 5 include precision and accuracy and are widely used in model performance studies (Willmott, 1982; Camargo and Sentelhas, 1997; Willmott and Matsuura, 2005; Borges Júnior et al., 2012; Melo and Fernandes, 2012; Cristea et al., 2013; Todorovic et al., 2013; Kisi, 2014). The criteria used to compare the methods greatly affect the rank.

The rank generated by MAE is equal to those obtained by MSE and RMSE (Tables 4 and 5). Willmott and Matsuura (2005) pointed out that MAE is unambiguous and the most natural measure of the mean error magnitude. These authors considered that MAE should be used as the basis for all dimensioned evaluations and inter-comparisons of model performance. The same authors referred to RMSE as a non-appropriate parameter for evaluating model performance because it changes with the variability of the error squares in the data set. This parameter also varies depending on MAE and the square root of the comparison number. While the dimensioned statistics (MAE, RMSE, MSE, and d) are related to the accuracy concept, the regression and correlation coefficients are associated with the precision concept. The rank obtained by the regression coefficient (R^2) in Table 5 is identical to the one obtained by the correlation coefficient (r).

Table 4. Indices for the different reference evapotranspiration (ET_0) estimation methods using the FAO Penman-Monteith method as a reference.

	Method										
	FAO PM	1	2	3	4	5	6	7	8	9	10
Maximum ET_0, mm	8.43	7.66	8.33	7.42	8.69	8.05	9.11	7.08	7.85	9.23	9.89
Minimum ET_0, mm	1.10	1.39	0.80	1.28	0.88	1.37	1.15	1.37	1.15	1.50	1.12
Mean ET_0, mm	3.66	4.09	4.47	4.17	3.90	4.02	3.79	4.02	3.79	3.99	3.77
S_d, mm	1.13	1.31	1.07	1.20	1.00	1.21	1.04	1.21	1.05	1.17	1.02
CV, %	31	32	24	29	26	30	28	30	28	29	27
MAE, mm		0.534	0.862	0.699	0.451	0.583	0.399	0.550	0.368	0.574	0.408
d (dimensionless)		0.935	0.809	0.839	0.916	0.891	0.937	0.901	0.943	0.893	0.934
r (dimensionless)		0.942	0.839	0.771	0.869	0.837	0.889	0.856	0.900	0.835	0.885
C (dimensionless)		0.880	0.679	0.647	0.795	0.745	0.833	0.771	0.848	0.745	0.827
MSE, mm^2		0.391	1.057	0.887	0.372	0.587	0.288	0.533	0.263	0.552	0.292
RMSE, mm		0.626	1.028	0.942	0.610	0.766	0.536	0.730	0.513	0.743	0.541
MSEs, mm^2		0.198	0.719	0.304	0.129	0.147	0.060	0.144	0.055	0.135	0.065
MSEu, mm^2		0.194	0.338	0.583	0.243	0.440	0.227	0.388	0.208	0.417	0.227
RMSEs, mm		0.445	0.848	0.551	0.359	0.384	0.245	0.380	0.234	0.368	0.255
RMSEu, mm		0.440	0.581	0.764	0.493	0.663	0.477	0.623	0.456	0.646	0.477
MSEs/MSE, %		51	68	34	35	25	21	27	21	25	22
MSEu/MSE, %		49	32	66	65	75	79	73	79	75	78
b_r (dimensionless)		1.088	0.793	0.817	0.763	0.895	0.819	0.912	0.831	0.865	0.799
a_r (dimensionless)		0.110	1.572	1.179	1.105	0.749	0.795	0.690	0.752	0.827	0.850
R^2, mm^2		0.887	0.705	0.595	0.754	0.700	0.791	0.733	0.810	0.697	0.783

S_d: standard deviation; CV: coefficient of variation; MAE: mean absolute error; d: index of agreement; r: correlation coefficient; C: confidence index; MSE: mean square error; RMSE: root mean square error; MSEs: systematic mean square error; MSEu: unsystematic mean square error; RMSEs: systematic root mean square error; RMSEu: unsystematic root mean square error; a_r and b_r: linear and angular coefficients of regression; R^2: coefficient of determination.

Table 5. Rank of reference evapotranspiration (ET_0) estimation methods considering mean absolute error (MAE), index of agreement (d), correlation coefficient (r) and confidence index (C) as criteria.

	Rank	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°
Rank criteria	MAE	8	6	10	4	1	7	9	5	3	2
	d	8	6	1	10	4	7	9	5	3	2
	r	1	8	6	10	4	7	2	5	9	3
	C	1	8	6	10	4	7	5 and 9	---	2	3

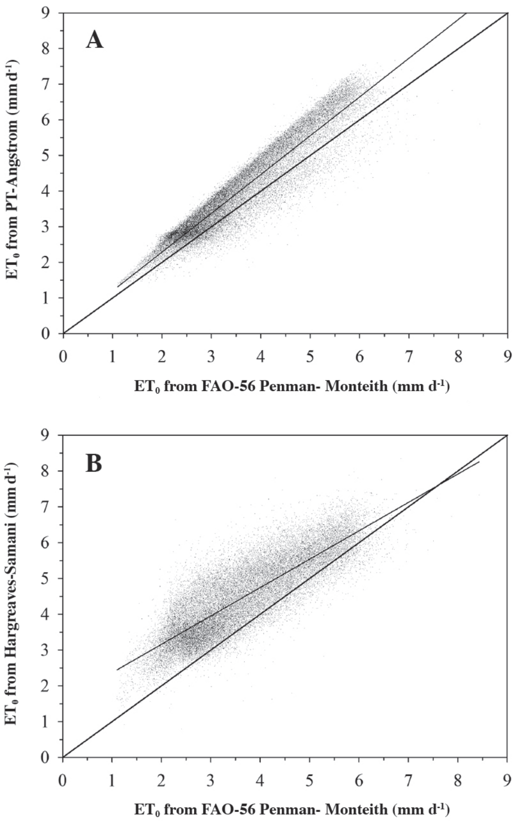

Figure 1. Comparison between reference evapotranspiration (ET_0) on a daily time scale estimated by the Priestley-Taylor method using Angstrom radiation model (A) and Hargreaves-Samani method (B) compared with the standard FAO Penman-Monteith method.

Method 8, which requires air temperature and wind speed data, had the lowest MAE and d, and also had the second largest r and confidence index (C). This indicates some improvement in the ET_0 estimations by incorporating the T_{max}/N and T_{min}/T_{max} ratios and the T_{med} component into the equation used to determine R_s/R_a (Equation [7]) when compared with the models in which only the difference between T_{max} and T_{min} (Equations [5] and [6]) were considered.

Based on criteria r and C, the method which uses the Priestley-Taylor equation to calculate ET_0 and the Angstrom radiation equation to calculate R_s/R_a (method 1) was the best. This method requires air temperature and solar radiation data. Fietz and Fisch (2009) successfully used this method in the Dourados region, Mato Grosso do Sul State, Brazil; they obtained a C value of 0.78, which is lower than the one found in the present study. These authors also observed overestimation trends and attributed them to the fact that 70% of the ET_0 values were obtained from data collected during the rainy period. Given this, it is recommended that the coefficient value (1.26) in the Priestley-Taylor equation be reduced. Additionally, the authors related the overestimation trend to soil heat flux density, which was negligible. The superior performance of method 1, using the confidence index (C) as the criterion, can be confirmed by analyzing Figure 1, as well as the linear and angular coefficients a_r and b_r, respectively (Table 4). While the angular coefficient value was closer to 1, the linear coefficient had the lowest absolute value (0.110) among all the evaluated models. Suleiman and Hoogenboom (2007), in a study in the State of Georgia, USA, found d values varying from 0.95 to 0.99 when comparing the Priestley-Taylor and FAO Penman-Monteith methods; they reported a performance of the Priestley-Taylor method that was better than the one obtained in the present study. It is important to note that these authors did not use values of duration of sunshine to estimate solar radiation. Instead, solar radiation was measured with pyranometers in meteorological stations.

When comparing Figures 2 to 5 analyzing the a_r and b_r regression coefficients (Table 4), it is possible to note that, independently of the radiation model used to estimate the R_s/R_a ratio, the Priestley-Taylor method generally had linear coefficients closer to 0 (zero) and angular coefficients closer to 1 (one) when compared with the standard FAO Penman-Monteith method.

Regarding the methods which require only air temperature data, it can be observed in Table 5 that they

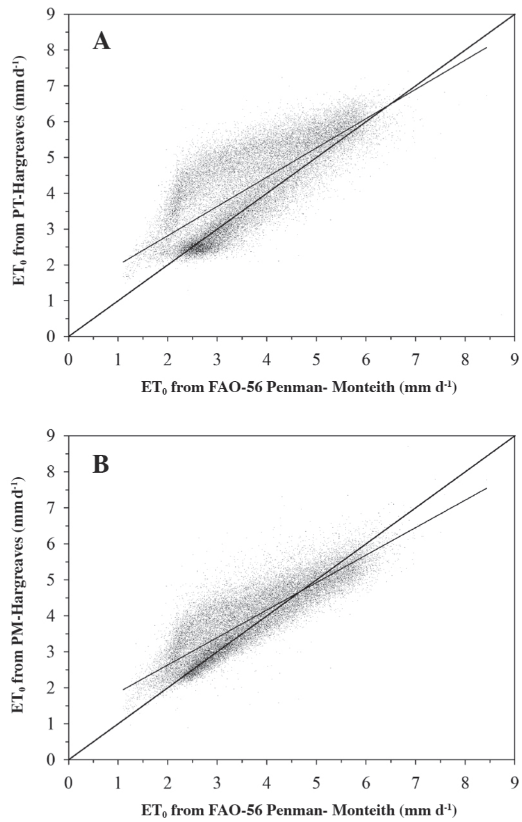

Figure 2. Comparison between reference evapotranspiration (ET_0) on a daily time scale estimated by the Priestley-Taylor method (A) and Penman-Monteith method (B), both using the Hargreaves radiation model, and compared with the standard FAO Penman-Monteith method.

always occupied the last positions in the ranking probably because only one meteorological variable was used to calculate ET_0, and the effects of solar radiation, wind speed, and RH were not considered. The best performance was obtained by combining the Priestley-Taylor method and the Borges Júnior radiation model (method 7). The calibration of the coefficients of Equation [3] can considerably improve method 2 (Hargreaves-Samani) performance as observed by Fooladmand and Haghighat (2007), Trajkovic (2007) and Borges Júnior et al. (2012). This expectation was increased when the methods that only depend on air temperature were considered; this resulted in the second highest value of r in method 2. It also provided the highest ratio between MSEs and MSE when compared with all the methods under study (Table 4). Bachour et al. (2013) commented that the Hargreaves-Samani method often tends to systematically overestimate or underestimate ET_0 unless regional calibration is performed. Todorovic et al. (2013) highly recommend testing and calibrating the Hargreaves-Samani against the FAO Penman-Monteith method under different Mediterranean climates and geographic-orographic conditions when good quality data sets are available.

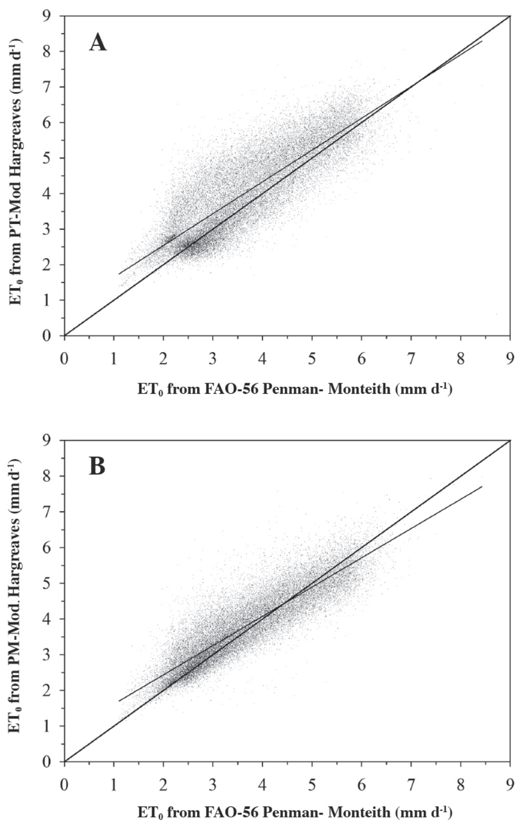

Figure 3. Comparison between reference evapotranspiration (ET_0) on a daily time scale estimated by the Priestley-Taylor method (A) and Penman-Monteith method (B), both using the modified Hargreaves radiation model, and compared with the standard FAO Penman-Monteith method.

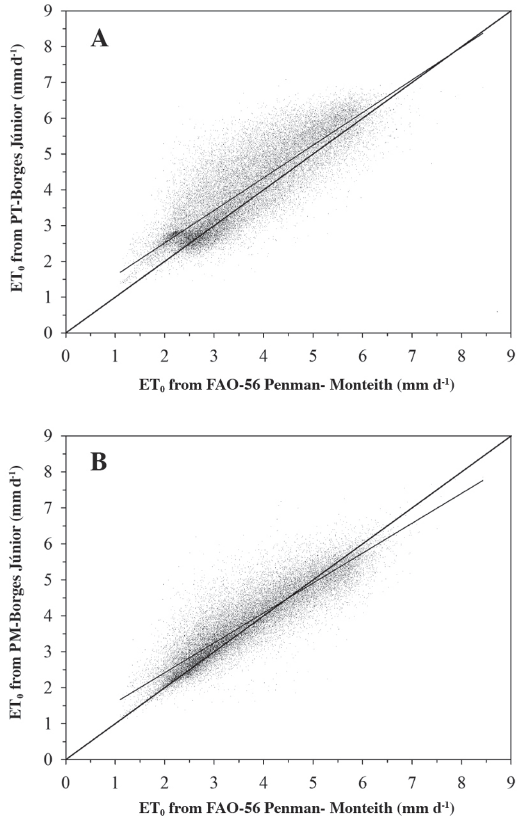

Figure 4. Comparison between reference evapotranspiration (ET_0) on a daily time scale estimated by the Priestley-Taylor method (A) and Penman-Monteith method (B), both using the Borges Júnior radiation model, and compared with the standard FAO Penman-Monteith method.

Borges Júnior et al. (2012) obtained reductions of 69% to 25% and 52% to 15% in the systematic portion of MSE for dry and rainy periods, respectively, after calibrating the coefficients and exponents of Equation [3] when estimating ET_0 from meteorological data of a district of the Agrest region of Pernambuco State (Brazil).

Willmott (1982) affirms that RMSEs should be close to zero in a good model, while RMSEu should be close to RMSE with the aim of representing the main trends of observed values, which, in the present study, are the values estimated by the standard FAO Penman-Monteith method. In this regards, methods 8, 6, and 10 had the best results (Table 4).

Classes of the percentile frequencies of deviation between the ET_0 daily values obtained by each one of the alternative methods and the standard FAO Penman-Monteith method are shown in Table 6. Considering all the methods, deviations were between -3.1 and 4.4 mm d^{-1} that were distributed in 16 classes. In general, overestimation trends were observed in all the evaluated methods with respect to the standard method. The highest overestimation percentiles (91.6% of 30 295 ET_0 daily values) were obtained by method 2 (Hargreaves-Samani).

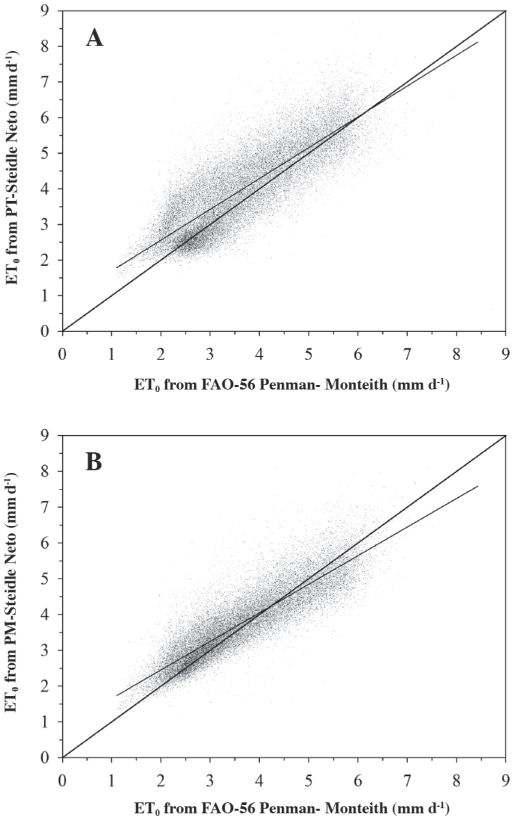

Figure 5. Comparison between reference evapotranspiration (ET_0) on a daily time scale estimated by the Priestley-Taylor method (A) and Penman-Monteith method (B), both using the Steidle Neto radiation model, and compared with the standard FAO Penman-Monteith method.

On the other hand, the lowest overestimation percentile of ET_0 was verified by method 10 (59.1%). When considering only the deviations between 0 and 1 mm d^{-1}, the highest concentration was observed in method 1 (75.4% of 30 295 ET_0 daily values).

The best equilibrium between underestimations (40.9%) and overestimations (59.1%) was found in method 10. Among the methods requiring only air temperature data, the most equilibratory situation was verified by method 9 with 33% underestimations and 67% overestimations. Although considerable amplitude in daily deviations was observed in the 30 295 ET_0 daily values estimated by each method, most of the data was concentrated between the deviations from -1 to 1 mm d^{-1} (Table 6). The highest deviation concentrations in this interval were verified in methods 8 (93.8%), 10 (93.4%), and 6 (93.3%), while the lowest was observed in method 2 (63.8%). Among the methods requiring only air temperature data, the highest deviation concentration in this interval was verified for method 7 (83.8%) followed by methods 9 (82.0%) and 5 (81.1%).

CONCLUSIONS

When air temperature and wind speed are available for the region under study, the best reference evapotranspiration estimates were achieved when the FAO Penman-Monteith equation was combined with the Borges Júnior empirical model to estimate the R_s/R_a ratio (method 8). When air temperature and duration of sunshine are available, the best performance was obtained by the Priestley-Taylor method using the Angstrom radiation model (method 1).

Regarding the methods requiring only air temperature data, the best performance was obtained by combining the Priestley-Taylor method and the Borges Júnior radiation model (method 7). Comparisons between models to estimate the R_s/R_a ratio from solar radiation data measured with pyranometers will be done in the future with the objective of improving the evaluation of the models.

Table 6. Percentile frequencies for deviation classes obtained when comparing reference evapotranspiration (ET_0) estimated by different methods with the standard FAO Penman-Monteith method.

	Method									
Deviation class[1] (mm d^{-1})	1	2	3	4	5	6	7	8	9	10
-3.5 < de ≤ -3.0	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.003	0.000	0.007
-3.0 < de ≤ -2.5	0.007	0.007	0.000	0.010	0.003	0.003	0.007	0.003	0.007	0.003
-2.5 < de ≤ -2.0	0.007	0.007	0.013	0.003	0.010	0.030	0.023	0.040	0.010	0.036
-2.0 < de ≤ -1.5	0.063	0.020	0.066	0.033	0.116	0.119	0.139	0.185	0.152	0.178
-1.5 < de ≤ -1.0	0.472	0.188	0.588	0.390	0.881	1.013	0.868	0.970	1.102	1.631
-1.0 < de ≤ -0.5	2.895	1.119	5.308	5.578	6.466	7.741	4.932	6.163	7.351	8.770
-0.5 < de ≤ 0.0	12.398	7.070	24.294	32.035	24.592	31.563	22.165	31.494	24.341	30.322
0.0 < de ≤ 0.5	36.125	23.080	27.087	33.474	29.609	38.511	34.979	42.423	29.361	38.561
0.5 < de < 1.0	39.280	32.524	15.785	17.429	20.462	15.471	21.707	13.682	20.987	15.781
1.0 < de ≤ 1.5	8.698	21.895	12.151	8.708	11.570	4.275	9.926	3.710	12.111	3.608
1.5 < de ≤ 2.0	0.050	10.510	10.107	1.977	5.011	0.964	3.902	1.027	3.611	0.815
2.0 < de ≤ 2.5	0.007	2.974	4.011	0.300	1.023	0.234	1.066	0.248	0.763	0.208
2.5 < de ≤ 3.0	0.000	0.492	0.551	0.046	0.218	0.053	0.244	0.043	0.158	0.056
3.0 < de ≤ 3.5	0.000	0.102	0.036	0.013	0.036	0.017	0.040	0.007	0.036	0.017
3.5 < de ≤ 4.0	0.000	0.010	0.000	0.003	0.000	0.003	0.000	0.003	0.003	0.007
4.0 < de ≤ 4.5	0.000	0.003	0.003	0.000	0.003	0.000	0.003	0.000	0.007	0.000
Total (%)	100	100	100	100	100	100	100	100	100	100

[1]Negative values indicate underestimation and positive values indicate overestimation.

ACKNOWLEDGEMENTS

The authors would like to thank the National Institute of Meteorology (INMET) of Brazil for providing the historical weather data used in this study.

LITERATURE CITED

Allen, R.G. 2013. REF-ET: Reference evapotranspiration calculation software for FAO and ASCE standardized equations. Moscow, Idaho, United States. Available at http://extension.uidaho.edu/kimberly/files/2013/03/Ref-ET-V3.1-Users-Manual.pdf (accessed January 2014).

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper nr 56. 300 p. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Allen, R.G., W.O. Pruitt, J.L. Wright, T.A. Howell, F. Ventura, R. Snyder, et al. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ET_0 by the FAO56 Penman-Monteith method. Agricultural Water Management 81:1-22. doi:10.1016/j.agwat.2005.03.007.

Alves Sobrinho, T., D.B.B. Rodrigues, P.T.S. Oliveira, L.C.S. Rebucci, e C.A. Pertussatti. 2011. Estimativa da evapotranspiração de referência através de redes neurais artificiais. Revista Brasileira de Meteorologia 26:197-203.

Bachour, R., W.R. Walker, A.F. Torres-Rua, and M. McKee. 2013. Assessment of reference evapotranspiration by the Hargreaves method in the Bekaa Valley, Lebanon. Journal of Irrigation and Drainage Engineering 139:933-938. doi:10.1061/(ASCE)IR.1943-4774.0000646.

Belcher, B.N., and A.T. DeGaetano. 2007. A revised empirical model to estimate solar radiation using automated surface weather observations. Solar Energy 81:329-345. doi:10.1016/j.solener.2006.07.003.

Blonquist, J.M., R.G. Allen, and B. Bugbee. 2010. An evaluation of the net radiation sub-model in the ASCE standardized reference evapotranspiration equation: Implications for evapotranspiration prediction. Agricultural Water Management 97:1026-1038. doi:10.1016/j.agwat.2010.02.008.

Borges Júnior, J.C.F., R.J. Anjos, T.J.A. Silva, J.R.S. Lima, e C.L.T. Andrade. 2012. Métodos de estimativa da evapotranspiração de referência diária para a microrregião de Garanhuns, PE. Revista Brasileira de Engenharia Agrícola e Ambiental 16:380-390. doi:10.1590/S1415-43662012000400008.

Cai, J., Y. Liu, T. Lei, and L.S. Pereira. 2007. Estimating reference evapotranspiration with the FAO Penman-Monteith equation using daily weather forecast messages. Agricultural and Forest Meteorology 145:22-35. doi:10.1016/j.agrformet.2007.04.012.

Camargo, A.P., e P.C. Sentelhas. 1997. Avaliação do desempenho de diferentes métodos de estimativa da evapotranspiração potencial no estado de São Paulo, Brasil. Revista Brasileira de Agrometeorologia 5:89-97.

Cristea, N.C., S.K. Kampf, and S.J. Burges. 2013. Revised coefficients for Priestley-Taylor and Makkink-Hansen equations for estimating daily reference evapotranspiration. Journal of Hydrologic Engineering 18:1289-1300. doi:10.1061/(ASCE)HE.1943-5584.0000679.

Croitoru, A.E., A. Piticar, C.S. Dragotă, and D.C Burada. 2013. Recent changes in reference evapotranspiration in Romania. Global and Planetary Change 111:127-132. doi:10.1016/j.gloplacha.2013.09.004.

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. Irrigation and Drainage Paper nr 24. 156 p. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Fietz, C.R., e G.F. Fisch. 2009. Avaliação de modelos de estimativa do saldo de radiação e do método de Priestley-Taylor para a região de Dourados, MS. Revista Brasileira de Engenharia Agrícola e Ambiental 13:449-453. doi:10.1590/S1415-43662009000400012.

Fooladmand, H.R., and M. Haghighat. 2007. Spatial and temporal calibration of Hargreaves equation for calculating monthly ET_0 based on Penman-Monteith method. Irrigation and Drainage 56:439-449. doi:10.1002/ird.305.

Gong, L., C.-Y. Xu, D. Chen, S. Halldin, and Y.D. Chen. 2006. Sensitivity of the Penman-Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. Journal of Hydrology 329:620-629. doi:10.1016/j.jhydrol.2006.03.027.

Iqbal, M. 1983. An introduction to solar radiation. 390 p. Academic Press, Don Mills, Ontario, Canada.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and irrigation water requirements. 332 p. American Society of Civil Engineers, New York, USA.

Kisi, O. 2014. Comparison of different empirical methods for estimating daily reference evapotranspiration in Mediterranean climate. Journal of Irrigation and Drainage Engineering 140(1). doi:10.1061/(ASCE)IR.1943-4774.0000664.

Melo, G.L., and A.L.T. Fernandes. 2012. Evaluation of empirical methods to estimate reference evapotranspiration in Uberaba, State of Minas Gerais, Brazil. Engenharia Agrícola 32:875-888. doi:10.1590/S0100-69162012000500007.

Palumbo, A.D., D. Vitale, P. Campi, and M. Mastrorilli. 2011. Time trend in reference evapotranspiration: analysis of a long series of agrometeorological measurements in Southern Italy. Irrigation and Drainage Systems 25:395-411. doi:10.1007/s10795-012-9132-7.

Panoso, L.A., D.P. Ramos, e M. Brandão. 2002. Solos do Campo Experimental da Embrapa Milho e Sorgo: suas características e classificação no novo sistema brasileiro, Brazil. Available at http://www.cnps.embrapa.br/publicacoes/pdfs/bpd05_2002_milho_sorgo.pdf (accessed January 2014).

Raziei, T., and L.S. Pereira. 2013. Estimation of ET_0 with Hargreaves-Samani and FAO-PM temperature methods for a wide range of climates in Iran. Agricultural and Water Management 121:1-18. doi:10.1016/j.agwat.2012.12.019.

Suleiman, A.A., and G. Hoogenboom. 2007. Comparison of Priestley-Taylor and FAO-56 Penman-Monteith for daily reference evapotranspiration estimation in Georgia. Journal of Irrigation and Drainage Engineering 133:175-182. doi:10.1061/(ASCE)0733-9437(2007)133:2(175).

Tabari, H., M.E. Grismer, and S. Trajkovic. 2013. Comparative analysis of 31 reference evapotranspiration methods under humid conditions. Irrigation Science 31:107-117. doi:10.1007/s00271-011-0295-z.

Todorovic, M., B. Karic, and L.S. Pereira. 2013. Reference evapotranspiration estimate with limited weather data across a range of Mediterranean climates. Journal of Hydrology 481:166-176. doi:10.1016/j.jhydrol.2012.12.034.

Trajkovic, S. 2007. Hargreaves versus Penman-Monteith under humid conditions. Journal of Irrigation and Drainage Engineering 133:38-42. doi:10.1061/(ASCE)0733-9437(2007)133:1(38).

Willmott, C.J. 1982. Some comments on the evaluation of model performance. Bulletin American Meteorological Society 30:1309-1310.

Willmott, C.J., and K. Matsuura. 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research 30:79-82. doi:10.3354/cr030079.

Xu, C.-Y., and D. Chen. 2005. Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. Hydrological Processes 19:3717-3734. doi:10.1002/hyp.5853.

Yin, Y., S. Wu, D. Zheng, and Q. Yang. 2008. Radiation calibration of FAO-56 Penman-Monteith model to estimate reference crop evapotranspiration in China. Agricultural Water Management 95:77-84. doi:10.1016/j.agwat.2007.09.002.