ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

AVALIAÇÃO DO DESEMPENHO DE MÉTODOS DE ESTIMATIVA DA EVAPOTRANSPIRAÇÃO DE REFERÊNCIA PARA O MUNICÍPIO DE PRESIDENTE FIGUEIREDO, AM*

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**Parte retirado do trabalho de conclusão de curso "Avaliação de métodos de estimativa da evapotranspiração de referência e obtenção do balanço hídrico climatológico para o município de Presidente Figueiredo, Amazonas", Universidade Federal do Amazonas, defendido em 28 de abril de 2022.*

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1 RESUMO

A evapotranspiração é um processo de grande importância na determinação das necessidades hídricas de uma cultura, constatando períodos de excessos ou escassez de água, sendo fundamental para a elaboração do balanço hídrico climatológico, essencial no planejamento agrícola. Portanto, o objetivo foi comparar os métodos de Blaney-Criddle, Camargo, Hargreaves e Jensen-Haise com o método de Penman-Monteith, padrão FAO, para estimativa da evapotranspiração de referência para o município de Presidente Figueiredo, AM. Os dados meteorológicos utilizados foram obtidos na estação meteorológica automática de Presidente Figueiredo, compreendendo dados diários de uma série temporal de 10 anos. Os indicadores estatísticos utilizados foram, percentagem em relação ao método-padrão, erro-padrão de estimativa, erro-padrão de estimativa ajustado, índice de concordância, coeficiente de correlação, coeficiente de determinação e coeficiente de desempenho. A classificação do método de Jensen-Haise, Makkink, FAO 54 da Radiação e Blaney-Criddle-Frevert, foram satisfatórias ajustando melhor ao método padrão Penman-M FAO 56, com desempenho "ótimo", seguidos pelos métodos de Blaney-Criddle e Hargreaves-Samani tiveram desempenho "muito bom", e Thornthwaite com desempenho "mediano", devendo ser recomendados após ajustes locais. O modelo de Camargo apresentou desempenho "mau", não recomendado em razão da baixa exatidão e precisão em relação ao padrão.

Palavras-chave: Penman-Monteith, dados meteorológicos, irrigação.

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2 ABSTRACT

Evapotranspiration is a process of great importance in determining the water needs of a crop, noting periods of excess or scarce water, which is fundamental for the elaboration of the

Recebido em 03/12/2024 e aprovado para publicação em 12/12/2024
DOI: http://dx.doi.org/10.15809/irriga.2024v29p289-305

climatological water balance, an essential tool in agricultural planning. Therefore, the objective was to compare the Blaney-Criddle, Camargo, Hargreaves, and Jensen-Haise methods with the Penman–Monteith method, the FAO standard, for estimating the reference evapotranspiration for the municipality of Presidente Figueiredo, AM. The meteorological data used were obtained from the Presidente Figueiredo automatic meteorological station, comprising daily data from a 10-year time series. The statistical indicators used were percentage in relation to the standard method, standard error of estimate, standard error of adjusted estimate, concordance index, correlation coefficient, determination coefficient and performance coefficient. The classifications of the Jensen-Haise, Makkink, FAO 54 Radiation, and Blaney-Criddle-Frevert methods were satisfactory and better adjusted to the standard Penman-M FAO 56 method, with an 'optimal' performance, followed by the Blaney-Criddle and Hargreaves-Samani methods, which had a 'very good' performance, and Thornthwaite performed 'arerage', which should be recommended after local adjustments. Camargo's model presented a “bad” performance and was not recommended because of its low accuracy and precision in relation to the standard.

Keywords: Penman-Monteith, weather data, irrigation.

3 INTRODUCTION

Climate is still the most important variable in agricultural production, as climatic parameters influence all stages of the production chain, including soil preparation, sowing, crop growth, harvesting, storage, transportation and marketing (Ayoade, 2013).

Agriculture is the economic activity most dependent on edaphoclimatic and agrometeorological conditions, which involve the appropriate management of soil, water, climate, and water resources (Alencar *et al.*, 2016). Crop water consumption can be determined through direct measurements in the field or through indirect methods via empirical equations. Direct measurements, however, require sophisticated and expensive equipment, making empirical equations more practical and viable alternatives (Cavalcante Junior *et al*., 2011).

Over the years, several methods have been developed to estimate reference evapotranspiration (ETo), considering three main factors: the suitability of the method for regional climatic conditions, its simplicity of use and the availability of meteorological data (Carvalho *et al*., 2011).

The International Commission on Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO) recommend the Penman–Monteith method as the standard for calculating reference evapotranspiration from meteorological data (Allen; Pereira; Raes, 1998; Smith, 1991). This method represents an improvement over the original Penman model and has been widely validated by studies in Brazil and several regions of the world (Barros *et al.*, 2009; Jabloun; Sahli, 2008; Xu; Chen, 2005; Yoder; Odhiambo; Wright, 2005). However, its application is limited because of the need for a broad set of meteorological variables, which are often unavailable, especially in developing countries. Alternatively, empirical methods that require fewer variables are used, such as those of Blaney-Criddle, Hargreaves, Camargo and Jensen-Haise (Ayoade, 2013), which are particularly useful in tropical regions.

It is known that no ET estimation method is universally suitable for all climatic conditions without appropriate local or regional adjustments. Although several studies on ET models have been conducted in the Northeast, Central-West, Southeast, and South Regions of Brazil, few studies have focused on the North Region. Obtaining reliable ET data in this region is essential, considering that, according to Carvalho *et al. (2011),* one of the strategies for rationalizing water use in agriculture is to estimate crop evapotranspiration (ETc) from ET and the crop coefficient (Kc).

Thus, with the aim of providing simpler methods adjusted to the climatic conditions of the municipality of Presidente Figueiredo (AM), northern Brazil, this study aimed to evaluate the performance of indirect methods for estimating reference evapotranspiration—Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Thornthwaite-Camargo, FAO Radiation 54 and Blaney-Criddle-Frevert—and compare them with the standard Penman–Monteith FAO method.

4 MATERIALS AND METHODS

The research was developed on the basis of data from a conventional meteorological station, referring to a provisional normal from 2009--2018. The data were obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET, 2023), for the location of Presidente Figueiredo, AM (World Meteorological Organization - WMO: 81699), located at latitude 2.08499999° South, longitude 60.04888888° West, at an altitude of 92 meters.

According to the Köppen-Geiger climate classification, Presidente Figueiredo, Amazonas, has a humid tropical climate (Af), characterized by high annual rainfall, an average annual precipitation of 3,038 mm, and an average annual temperature of 25.5 °C (CLIMATE DATA, 2023). The meteorological variables considered in this investigation were dry bulb temperature; maximum, minimum, and mean air temperatures; maximum, minimum, and mean relative humidity; atmospheric pressure; sunshine (Allen; Pereira; Raes, 1998); and wind direction and speed. These variables are necessary for estimating daily reference evapotranspiration (ET_o) via the standard FAO-56 Penman–Monteith method, as well as the alternative methods evaluated: Blaney–Criddle, Hargreaves–Samani, Jensen–Haise, and Camargo.

The data were tabulated in electronic spreadsheets via Microsoft Excel software. The estimate of daily ET via the FAO-56 Penman–Monteith method is summarized in Equation (1), according to Allen, Pereira and Raes (1998).

$$ET_o = \frac{0{,}408\Delta(\mathrm{Rn}-\mathrm{G})+\gamma\left(\frac{900}{\mathrm{T}+273}\right)\mathrm{U}_2(\mathrm{e_s}-\mathrm{e_a})}{\Delta+\gamma(1+0{,}34\mathrm{U}_2)} \quad (1)$$

where ET_o is the reference potential evapotranspiration (mm d^{-1}); Δ is the slope of the saturation vapor pressure curve (kPa $°C^{-1}$); Rn is the daily net radiation (MJ m^{-2} d^{-1}); G is the ground heat flux (MJ m^{-2} d^{-1}); γ is the psychrometric constant (kPa $°C^{-1}$); T is the average air temperature (°C) (INMET, 2022); U_2 is the wind speed measured at a height of 2 m (ms^{-1}); e_s is the saturation vapor pressure (kPa); and e_a is the current vapor pressure of the air (kPa).

The pressure exerted by the saturating water vapor content (e.g., daily average) was obtained as a function of the saturation pressure of the maximum and minimum temperatures, described by Tetens' equations (2) and (3):

$$e_s = \frac{e^0(T_x)+e^0(T_n)}{2} \quad (2)$$

$$e^0 = 0{,}6108 * e^{\left(\frac{17{,}27*T}{237{,}3+T}\right)} \quad (3)$$

The current vapor pressure (e_a) was obtained via Equation (4) via the average relative humidity of the air.

$$e_a = \frac{e_s * UR_m}{100} \quad (4)$$

The slope of the vapor pressure curve was calculated via Equation (5).

$$\Delta = \frac{4098\left[0,6108 * e^{\left(\frac{17,27 * T_m}{237,3 + m}\right)}\right]}{(T_m + 237,3)^2} \quad (5)$$

The psychrometric constant was estimated from equations (6) and (7) or, when this is not possible, a tabulated value was adopted:

$$\gamma = \frac{C_p * p}{\varepsilon * \lambda} = 0,665 * 10^{-3} \quad (6)$$

$$P = 101,3\left(\frac{293 - 0,0065 * Z}{293}\right)^{5,26} \quad (7)$$

where Cp is the specific heat at constant pressure, 1.013x10 $^{-3}$ (MJ kg $^{-1}$ °C $^{-1}$); P is the atmospheric pressure (kPa); ε is the molecular weight coefficient of water vapor in dry air (-1, 0.622); λ is the latent heat of vaporization, 2.45 (MJ kg^{-1}); and Z is the altitude of the location (m).

The soil heat flux (G) for a period of one day or ten days under a grassy reference surface is relatively small, and the soil heat flux can be ignored (G≈0). The monthly period G was determined via Equation 8.

$$G_{mês,i} = 0,14\left(T_{mês,i} - T_{mês,i-1}\right) \quad (8)$$

where $T_{month,i}$ is the average monthly air temperature for month i (°C) and $T_{month,i-1}$ is the average monthly air temperature of the previous month i (°C).

The net radiation (R_n) is the difference between the net shortwave radiation (R_{ns}) and the net longwave radiation (R_{nl}), which was estimated via Equations (9) to (16).

$$R_n = R_{ns} - R_{nl} \quad (9)$$

$$R_{ns} = (1 - 0,23) * R_s \quad (10)$$

$$R_{nl} = \sigma\left(\frac{T_{x,k^4} + T_{n,k^4}}{2}\right)\left(0,34 - 0,14\sqrt{e_a}\right)\left(1,35\ \frac{R_s}{R_{so}} - 0,35\right) \quad (11)$$

$$R_{so} = (0,75 + 2X10^{-5} * Z)\ R_a \quad (12)$$

$$R_a = \frac{24\ (60)}{\pi}\ G_{sc}\ d_r(\omega_s\ sen\ \varphi\ sen\ \delta + \cos\varphi\cos\delta\ \ sen\ \omega_s) \quad (13)$$

$$d_r = 1 + 0,033\cos\left(\frac{2\pi}{365}\ J\right) \quad (14)$$

$$\delta = 0,409\ sen\left(\frac{2\pi}{365}J - 1,35\right) \quad (15)$$

$$\omega_s = cos^{-1}(-\tan\varphi * \tan\delta) \quad (16)$$

where R s is solar radiation (MJ m^{-2} day^{-1}); R a is air deposition at the top of the atmosphere (MJ m^{-2} day^{-1}); G sc is constant, 0.0820 (MJ m^{-2} min^{-1}); σ is the Stefan-Boltzmann constant, 4.903 x 10^{-9} (MJ m $^{-2}$ day^{-1}); R so is the solar irradiation on a cloudless day (MJ m^{-2} day^{-1}); Z is the altitude of the location (m); d r is the relative distance from Earth–Sun; J is the Julian day; δ is the solar declination (radians); Φis the local latitude (radians); ω_s is the angle of radiation at sunset (radians); $T_{x,k}$ is the maximum temperature observed during the 24-hour period (K); and $T_{n,k}$ is the minimum temperature observed during the 24-hour period (K).

The estimate of daily ET via the Blaney and Criddle (1950) method, known as Blaney-Criddle FAO 24, is summarized in Equation 17 (Pereira; Villa Nova; Sediyama, 1997).

$$ET_o = (0{,}457 * \mathrm{T} + 8{,}13) * \mathrm{p} * \mathrm{c} \quad (17)$$

where ET_o is the reference potential evapotranspiration (mm month $^{-1}$); T is the average air temperature (°C) (INMET, 2022); “p” is the monthly percentage of annual sunlight hours; and “c” is the regional coefficient of adjustment of the equation (Bernardo; Soares; Mantovani, 2006).

The estimate of daily ET via the Camargo method (1971) was calculated via Equation 18 (Pereira; Villa Nova; Sediyama, 1997; Pereira; Angelocci; Sentelhas, 2007).

$$ET_o = \mathrm{R_T} * \mathrm{T} * \mathrm{k_f} * \mathrm{ND} \quad (18)$$

where ET_o is the reference evapotranspiration (mm d $^{-1}$); R_T is the extraterrestrial solar radiation (mm d $^{-1}$ of equivalent evapotranspiration); T is the mean air temperature (°C) (INMET, 2022); kf is the adjustment factor that varies with the mean local annual temperature (kf = 0.01 for T < 23 °C; kf = 0.0105, for T = 24 °C; kf = 0.011, for T = 25 °C; kf = 0.0115, for T = 26 °C; and kf = 0.012, for T > 26 °C); and ND is the number of days in the analyzed period.

The estimate of daily ET via the method of Hargreaves and Samani (1985) was obtained via Equation (19).

$$ET_o = 0{,}0135 * KT * (T_m + 17{,}8) * R_a * 0{,}408 * (T_x - T_n)^{1/2} \quad (19)$$

where ET_o is the reference potential evapotranspiration (mm month^{-1}); KT is the global atmospheric transmissivity coefficient, whose value for an inland region is 0.162 and equal to 0.19 for a coastal region; T_m is the average air temperature (°C) (INMET, 2022); R_a is the radiation at the top of the atmosphere (MJ m^{-2} day^{-1}); T_x is the maximum air temperature (°C); and T_n is the minimum air temperature (°C).

The estimate of daily ET via the method of Jensen and Haise (1963) was obtained via Equation 20 (Pereira; Villa Nova; Sediyama, 1997).

$$ET_o = \mathrm{R_s}(0{,}0252 * \mathrm{T} + 0{,}078) \quad (20)$$

where ET_0 is the reference potential evapotranspiration (mm month^{-1}); Rs is the global solar radiation (mm d^{-1}); and T is the average air temperature (°C) (INMET, 2022).

The estimate of daily ET via the Thornthwaite method (1948) was obtained via Equation 21 (Pereira; Angelocci; Sentelhas, 2007).

$$ET_o = \mathrm{ET_P} * Cor \quad (21)$$

where ET_0 is the reference potential evapotranspiration (mm month^{-1}), ETP is the standard evapotranspiration (mm month^{-1}), and Cor is the evapotranspiration correction factor.

The estimate of daily ET via the Thornthwaite method (1948) simplified by Camargo (1962) was obtained via Equation 22 (Pereira; Angelocci; Sentelhas, 2007).

$$ET_o = 30 * \mathrm{ET_T} * Cor \quad (22)$$

where ET_o is the reference potential evapotranspiration (mm month $^{-1}$); ET_T is the daily potential evapotranspiration (mm d $^{-1}$); and Cor is the evapotranspiration correction factor.

The estimate of daily ET via the Makkink method (1957) was obtained via

Equation 23 (Turco; Perecin; Pinto Junior, 2008; Pereira; Villa Nova; Sediyama, 1997).

$$ET_o = (0{,}61 * R_s * W) - 0{,}12 \quad (23)$$

where ET_o is the reference potential evapotranspiration (mm d^{-1}); R_s is the measured or estimated global solar radiation, mm d^{-1}; and W is the weighting factor, estimated via the linear expressions proposed by Wilson and Rouse (1972) and Viswanadham, Silva Filho and Andre (1991) for wet bulb temperatures ranging from 0 to 16 °C and 16.1 to 32 °C, respectively.

The estimate of daily ET via the method of Blaney and Criddle (1950) adapted by Frevert; Hill; Braaten (1983) was obtained via Equation (24) (Fernandes *et al*., 2010).

$$ET_o = \mathrm{a} + \mathrm{b} * \mathrm{p}(0{,}457 * T + 8{,}13) \quad (24)$$

where ET_0 is the reference potential evapotranspiration (mm d^{-1}); "a" and "b" are the coefficients; "p" is the monthly percentage of annual sunlight hours; and T is the average air temperature (°C) (INMET, 2022).

ET estimates were analyzed via linear regression (Equations (25) to (29)), with the Blaney, Criddle Camargo, Hargreaves, Samani, Jensen, Haise, Thornthwaite, Makkink, FAO-24 radiation methods and the Blaney-Criddle-Frevert as independent variables (Xs), and the ET values were estimated via the Penman–Monteith–FAO 56 method.

$$\mathrm{Y} = \beta_0 + \beta_1 \mathrm{X} \quad (25)$$

where Y is the estimated value for empirical methods; β_0 is the angular coefficient; β_1 is the linear coefficient; and X is the value estimated by the standard Penman–Monteith method (FAO 56).

$$\beta_0 = Y - \beta_1 X \quad (26)$$

$$\beta_1 = \frac{S_{xy}}{S_{xx}} \quad (27)$$

$$S_{xy} = \sum (X_t - \bar{X})(Y_t - \bar{Y}) \quad (28)$$

$$S_{xx} = \sum (X_i - \bar{X})^2 \quad (29)$$

The Penman–Monteith–FAO 56 method and the empirical methods were performed on the basis of statistical indicators to observe the precision given by the correlation coefficient (r), which is associated with the deviation between the estimated and measured values, indicating the degree of dispersion of the data obtained in relation to the average, via Equation (30).

$$\mathrm{r} = \sqrt{\frac{[\sum(\mathrm{X_i} - X_m)(\mathrm{Y_i} - Y_m)]^2}{\sum(\mathrm{X_i} - X_m)^2 \sum(\mathrm{Y_i} - Y_m)^2}} \quad (30)$$

where X_i is the value estimated by the Penman–Monteith method FAO 56; X_m is the mean of the Penman–Monteith method FaO 56; Y_i is the estimated value of the evaluated method; and Y_m is the average of the evaluated methods.

The accuracy of the ET estimate in relation to the standard model was obtained by calculating the "d" index (Equation 31), which varies from 0 to 1 (Willmott; Ckleson; Davis, 1985).

$$\mathrm{d} = 1 - \left[\frac{\sum(\mathrm{Y_i} - \mathrm{X_i})^2}{\sum(|\mathrm{Y_i} - X_m| + |X_i - X_m|)^2}\right] \quad (31)$$

The safety or performance coefficient "c" (Table 1) was calculated as the product of red (c = r*d) (Camargo; Sentelhas, 1997).

Table 1. Performance coefficient values according to Camargo and Sentelhas (1997).

Value of "c"	Performance
> 0.85	Excellent
0.76 to 0.85	Very good
0.66 to 0.75	Good
0.61 to 0.65	Median
0.51 to 0.60	Terrible
0.41 to 0.50	Bad
≤ 0.40	Terrible

The quantification of the standard error of estimate (SEE) was obtained via equation 32, and the adjusted standard error of estimate (ASE) of the regression was obtained via equation 33 through the relationship of the mean values, expressed as a percentage (Equation 34). Standard errors are a measure of dispersion of observations around the regression line, adopting the same measure as the dependent variable; that is, they measure how far the dependent variable Y is from its predicted value (Stock; Watson, 2010).

$$\text{EPE} = \sqrt{\frac{\sum(X_i - Y_i)^2}{n-1}} \quad (32)$$

$$\text{EPE} = \sqrt{\frac{\sum(Y_i - \hat{Y})^2}{n-2}} \quad (33)$$

$$\% = \left(\frac{Y_i}{X_i}\right) * 100 \quad (34)$$

where X_i is the estimate of ET_o by the standard model (PM); Y_i is the estimate of ET_o obtained by each of the models evaluated; and n is the number of observations.

5 RESULTS AND DISCUSSION

Table 2 presents the monthly averages of the climatological variables—minimum, maximum, and mean temperatures; mean relative humidity; wind speed at 2 m; global solar radiation; and number of hours of sunlight—referring to the 10-year provisional normal (2009--2018) for the municipality of Presidente Figueiredo, AM. These data were used as a basis for estimating the reference potential evapotranspiration. The minimum (T_n) and maximum (T_x) temperatures varied between 25.73°C and 26.05 °C and between 26.72 °C and 27.09°C, respectively. The smallest total amplitude was observed at the minimum temperatures, with a variation of only 0.32 °C. Similar results were reported by Teixeira Filho, Barbosa, and Ferreira (2023), who reported the smallest thermal amplitude among the minimum temperatures for Manicoré, AM, with a value of 1.51°C. Barbosa *et al*. (2022), when studying Maués, AM also had the smallest minimum temperature, 0.94 °C. This low thermal amplitude of minimum temperatures is characteristic of regions of low latitude and altitude, as observed in Boa Vista, RR (Araújo; Conceição; Venancio, 2012). The average relative humidity remained above 74.96%, even in the months with the lowest rainfall.

With respect to wind speed (Table 2), no values above 1.0 ms^{-1} were recorded in any month, with the maximum value observed in March (0.71 ms^{-1}, equivalent to 2.54 km h^{-1}) and the minimum in May (0.44 ms^{-1}, or 1.58 km h^{-1}), remaining practically constant throughout the year. These values correspond to scale 1 of the Beaufort scale, characterized as "almost calm", a favorable condition for agricultural planning and decision-making in agricultural operations. This same characteristic was observed for the municipality of Maués, AM (Barbosa *et al.*, 2022).

Table 2. Monthly average minimum (T_n), maximum (T_x) and mean (T_m) air temperatures; mean relative humidity (RH_m); daily wind speed at 2 m height (U_2); daily global solar radiation (Q_g); and daily insolation (n), referring to the automatic station of Presidente Figueiredo, AM.

Months	**T_n**	**T_x**	**T_m**	**UR_m**	**U_2**	**Q_g**	**n**
		°C		**%**	**ms^{-1}**	**$MJ\ m^{-2}$**	**h**
January	25.73	26.72	26.23	82.38	0.56	12.38	1.95
February	25.78	26.82	26:30	82.22	0.69	11:30	1.12
March	26.10	27.15	26.63	81.92	0.71	12,10	1.77
April	25.80	26.79	26.29	84.07	0.53	10.93	1.44
May	25.65	26.63	26.14	85.16	0.44	11.34	2.20
June	25.61	26.76	26.19	83.01	0.49	13.17	3.66
July	25.45	26.65	26.05	81.80	0.49	14.05	3.88
August	25.34	26.68	26.01	74.96	0.62	13.84	3.14
September	26.50	27.80	27.15	78.11	0.54	15.54	3.92
October	26.73	27.96	27.35	78.30	0.54	14.86	3.55
November	26.55	27.69	27.12	80.09	0.53	13.92	3.15
December	26.05	27.09	26.57	81.90	0.56	13.18	2.67

Source: Author.

Table 3 presents the daily averages of reference evapotranspiration (ET) for the municipality of Presidente Figueiredo, AM, estimated by the evaluated methods, using the FAO 56 Penman–Monteith equation as a comparative standard. The Hargreaves-Samani, Makkink, and Blaney-Criddle-Frevert models underestimate ET in all months of the year, with differences between the mean values ranging from 1.29 mm d^{-1} in May (Hargreaves-Samani) to 2.80 mm d^{-1} in September (Makkink). In contrast, Carvalho and Delgado (2016), studying ET in the municipality of Ariquemes, RO, reported overestimation of ET in a region with an Aw climate type, according to the Köppen classification. Similarly, Araújo, Costa and Santos (2007) reported that, for Boa Vista, RR, the Thornthwaite and Hargreaves-Samani methods overestimate the standard method, whereas the Makkink method underestimates ET throughout the year.

Table 3. Averages of reference evapotranspiration (ET_o) estimated via the methods of Penman–Monteith [$ET_{o\,(PM)}$], Blaney-Criddle [$ET_{o\,(BC)}$], Camargo [$ET_{o\,(C)}$], Hargreaves-Samani [$ET_{o\,(HS)}$], Jensen-Haise [$ET_{o\,(JH)}$], Thornthwaite [$ET_{o\,(T)}$], Makkink [$ET_{o\,(M)}$], FAO 54 of Radiation [$ET_{o\,(R)}$] and Blaney-Criddle-Frevert [$ET_{o\,(BCF)}$] for Presidente Figueiredo, AM, 2009--2018.

Months	$ET_{o(P-M)}$	$ET_{o(B-C)}$	$ET_{o(C)}$	$ET_{o(H-S)}$	$ET_{o(J-H)}$	$ET_{o(T)}$	$ET_{o(M)}$	$ET_{o(R)}$	$ET_{o(B-C-F)}$
	mm d^{-1}								
Jan	2.72	2.79	4.81	1.47	3.73	4.50	2.18	3.07	2.07
Feb	2.60	2.91	4.91	1.53	3.42	4.50	1.98	2.80	1.94
Sea	2.73	2.76	4.87	1.52	3.70	4.58	2.14	3.01	2.10
Apr	2.45	2.75	4.54	1.38	3.30	4.46	1.91	2.71	1.89
May	2.43	2.80	4.24	1.29	3.41	4.40	1.98	2.80	1.98
June	2.73	3.19	4.18	1.37	3.97	4.41	2.32	3.26	2.32
Jul	2.91	3.13	4.34	1.46	4.21	4.37	2.48	3.47	2.39
Aug	3.02	2.99	4.62	1.64	4.14	4.38	2.44	3.42	2.46
Set	3.31	3.35	5.00	1.72	4.83	4.76	2.80	3.89	2.61
Out	3.24	3.19	5.01	1.67	4.65	4.84	2.68	3.74	2.60
Nov	3.05	3.20	4.87	1.57	4.33	4.79	2.49	3.49	2.43
Ten	2.90	2.97	4.76	1.47	4.02	4.62	2.34	3.28	2.24
Average	2.84	3.00	4.68	1.51	3.98	4.55	2.31	3.24	2.25
ME-PM *	-	0.16	1.84	-1.33	1.14	1.71	-0.53	0.40	-0.59

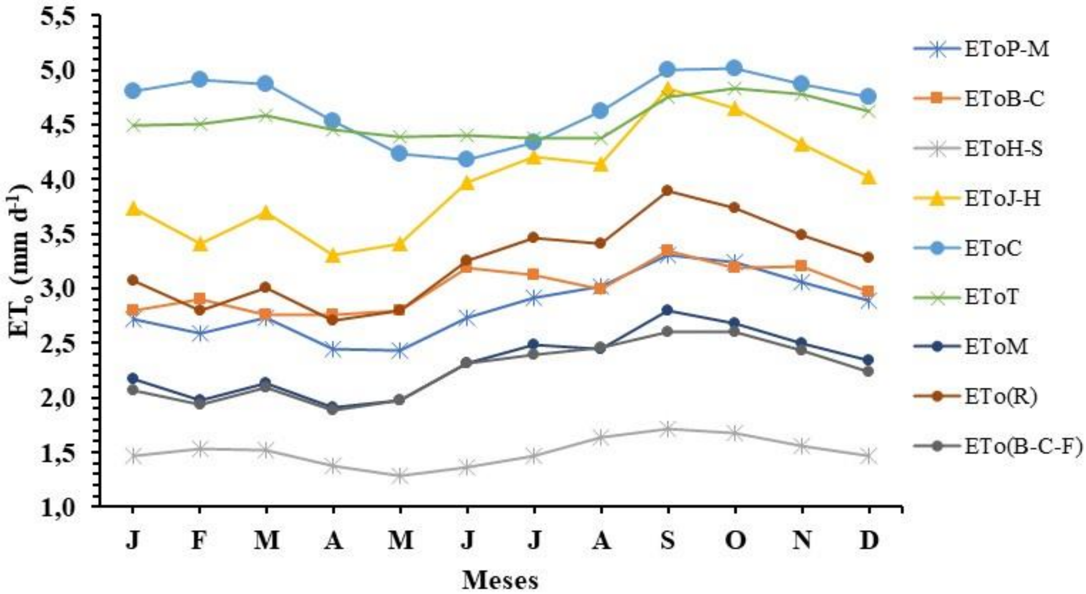
Source: Author. (*) Difference between the average reference evapotranspiration of the empirical methods and the average of the FAO-56 standard method.

In the FAO Bulletin 56, Allen *et al. (2006)* noted that the Hargreaves-Samani model tends to underestimate ET values under strong wind conditions (U_2 > 3 ms^{-1}) and overestimate them under conditions of high relative humidity. However, in Presidente Figueiredo, where the wind speed was always below 1 ms^{-1} and the relative humidity remained above 74%, the model underestimated the ET calculated by Penman–Monteith (Figure 1).

The other models overestimate the Penman–Monteith ET during all months of the year, with differences between the mean values ranging from 2.71 mm d^{-1} in April (FAO-24 radiation method) to 5.01 mm d^{-1} in October (Camargo method) (Table 3, Figure 1). These results corroborate those reported by Back (2008), Ferraz (2008), Carvalho and Delgado (2016), Souza and Sousa (2020), and Ferreira *et al*. (2020) and Teixeira Filho, Barbosa and Ferreira (2022), who also reported a tendency to overestimate reference potential evapotranspiration via the Blaney-Criddle, Camargo, Jensen-Haise, Thornthwaite, FAO-54 Radiation and Blaney-Criddle-Frevert methods throughout the year.

The Blaney-Criddle method was developed in the western United States, a semiarid region encompassing the states of New Mexico and Texas. For this reason, Doorenbos and Pruitt (1984) included a correction factor that allows the method to be applied in a variety of climatic conditions. Pereira, Villa Nova, and Sediyama (1997) noted that the Blaney-Criddle and Jensen-Haise methods were developed in semiarid regions of the United States, which explains the greater increase in ET observed in these models during months with less rainfall than during the rainiest months. This behavior was also observed in the regions of Presidente Figueiredo, Amazonas State; Maués, Amazonas State (Teixeira Filho; Barbosa; Ferreira, 2022); and Manicoré, Amazonas State (Teixeira Filho; Barbosa; Ferreira, 2023).

Figure 1. Average daily values for each month of ET estimated by the various models for the municipality of Presidente Figueiredo – AM

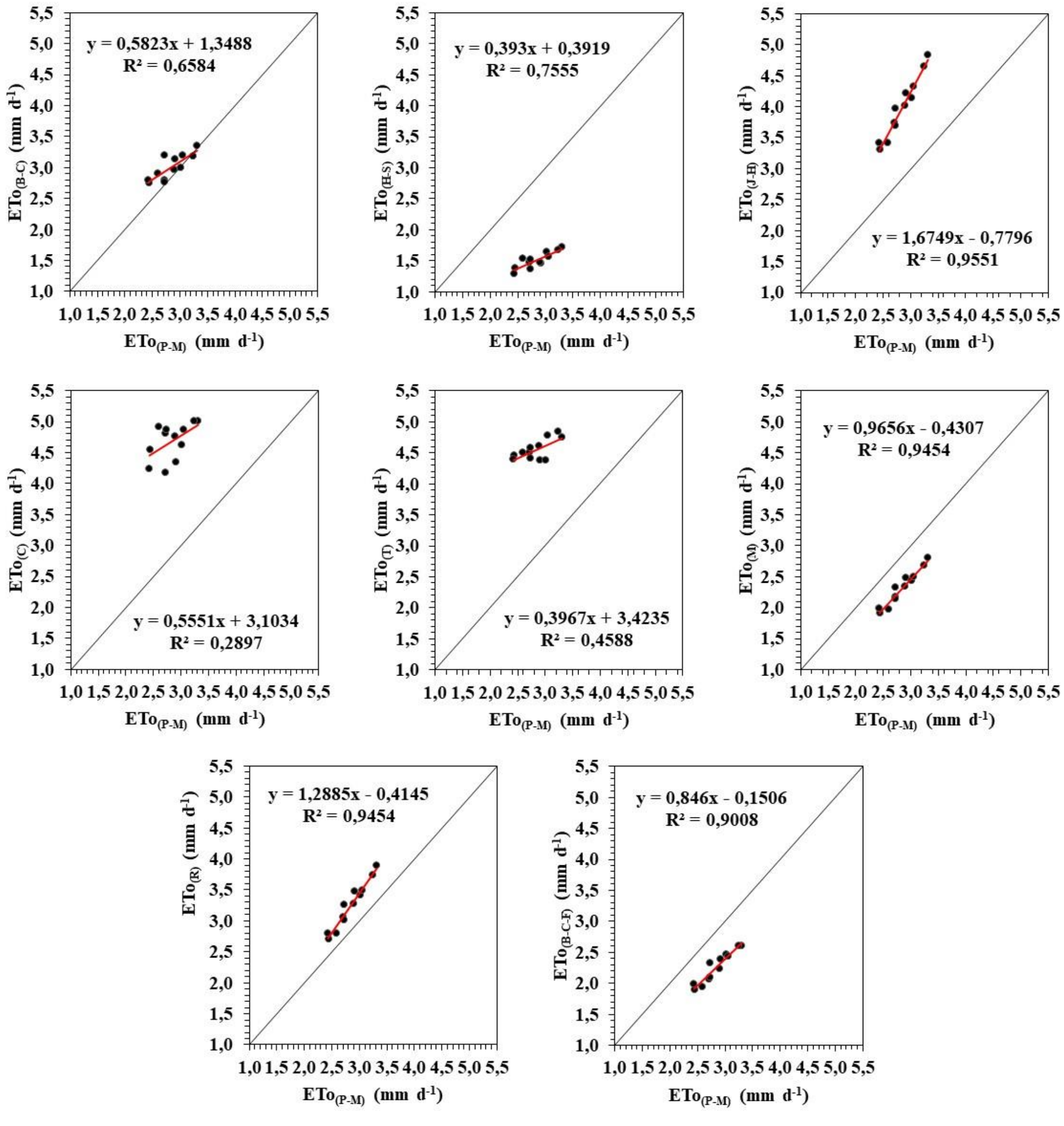


Source: Author.

Figure 2 presents the correlations of the monthly mean values of reference evapotranspiration (ET_o), in mm d^{-1}, estimated via the Penman–Monteith method and via the Blaney–Criddle, Camargo, Hargreaves–Samani, Jensen–Haise, Thornthwaite, Makkink, FAO Radiation 54 and Blaney–Criddle–Frevert methods. This analysis allows the methods studied to be evaluated in relation to the standard Penman–Monteith FAO 56 method. If the evaluated method presents results similar to those of Penman–Monteith, the regression line should coincide with the line y = x. If the regression line deviates from this line, the studied method presents differences in relation to the standard.

Among the models, the Jensen–Haise method (Figure 2) presented the best correlation for the studied period ($R^2 = 0.96$), whereas the Camargo model presented the worst correlation ($R^2 = 0.29$), as evidenced by the dispersion of the points in relation to the regression line. According to Sampaio (1998), the occurrence of a low coefficient of determination (R^2) makes the estimates unreliable, either because of the instability of the studied variable or because of the inadequate fit of the model to the observed data. This was confirmed by the t test, which presented a value of 1.78, lower than the tabulated t of 2.23 for 95% confidence.

Figure 2. Linear regression between reference evapotranspiration (ET_o, mm d^{-1}) values estimated by the Blaney-Criddle [ET_o (BC)], Camargo [ET_o (C)], Hargreaves-Samani [ET_o (HS)], Jensen-Haise [ET_o (JH)], Thornthwaite [ET_o (T)], Makkink [ET_o (M)], FAO Radiation Standard [ET_o (R)] and Blaney-Criddle-Frevert [ET_o (BCF)] methods, with the standard method, Penman–Monteith [ET_o (PM)], Presidente Figueiredo, AM.



Source: Author.

The Makkink method yielded the slope closest to 1 (+0.9656), followed by the Blaney-Criddle-Frevert (+0.8460), Blaney-Criddle (+0.5823), Camargo (+0.5551), Thornthwaite (+0.3967), Hargreaves-Samani (+0.3930), FAO Radiation 54 (+1.2885) and Jensen-Haise (+1.6749) methods. This finding indicates that the reference potential evapotranspiration estimated via empirical methods increases with increasing ET compared with the standard Penman–Monteith FAO 56 method. Furthermore, these coefficients show that, for each 1 mm d^{-1} of water evapotranspired according to the historical series considered, the ET estimated by the methods increases between 0.3967 mm d^{-1} and 1.6749 mm d^{-1}, on average. The Blaney–Criddle–Frevert method presented the linear coefficient closest to zero (-0.1506), followed by the FAO Radiation 54 (-0.4145), Makkink (-0.4307), Jensen–Haise (-0.7796), Hargreaves–Samani (+0.3919), Blaney–Criddle (+1.3488), Camargo (+3.1034) and Thornthwaite (+3.4235) methods.

The lowest values of the standard error of estimation (SEE) were observed in the Blaney-Criddle, FAO Radiation 54, Makkink and Blaney-Criddle-Frevert methods, corresponding to 0.24 mm d⁻¹, 0.44 mm d⁻¹, 0.56 mm d⁻¹ and 0.62 mm d⁻¹, respectively, which confirms the accuracy of these models in relation to the standard Penman–Monteith method. When the adjusted standard error of estimate (ASEO) was analyzed, the lowest values were obtained by the Hargreaves-Samani, Makkink, FAO-24 Radiation and Blaney-Criddle-Frevert models, with values of 0.11 mm d⁻¹, 0.07 mm d⁻¹, 0.09 mm d⁻¹ and 0.08 mm d⁻¹, respectively (Table 4). This confirms that the regression line fit the data of the investigated models very well, since the coefficients of determination presented high values. Furthermore, the standard error indicates that the dependent variable Y is close to its predicted value.

Table 4. Percentage in relation to the standard method (%), standard error of estimate (EPE), adjusted standard error of estimate (EPEA), concordance index (d), correlation coefficient (r), coefficient of determination (R²), coefficient of performance (c) and classification based on the coefficient of performance for the city of Presidente Figueiredo, AM.

Model	%	EPE	EPEA	d	r	R ²	w	Performance
		mm d ⁻¹						
Blaney-Criddle	105.72	0.24	0.13	1.00	0.81	0.66	0.81	Very good
Camargo	164.80	1.94	0.26	0.93	0.54	0.29	0.50	Bad
Hargreaves- Samani	53.10	1.40	0.07	0.88	0.87	0.76	0.77	Very good
Jensen- Haise	140.03	1.21	0.11	0.97	0.98	0.96	0.95	Excellent
Thornthwaite	160.22	1.80	0.13	0.94	0.68	0.46	0.64	Median
Makkink	81.40	0.56	0.07	0.99	0.97	0.95	0.96	Excellent
FAO-24 Radiation	114.26	0.44	0.09	0.99	0.97	0.95	0.97	Excellent
Blaney-Criddle- Frevert	79.30	0.62	0.08	0.98	0.95	0.90	0.93	Excellent

Source: Author.

An analysis of the data in Table 4 reveals that the Jensen–Haise (c = 0.95), Makkink (c = 0.96), FAO Radiation 54 (c = 0.97), and Blaney–Criddle–Frevert (c = 0.93) methods presented an "optimal" performance index. Similarly, Ferreira *et al.* (2020), when several methods for the municipality of Parintins, AM, were compared, the Jensen–Haise model was classified as "optimal" (c = 0.85). This suggests that water availability for the crop can be better defined by the interval in which the climate allows the plant to maintain a transpiration rate equal to the rate of water absorption by the roots, according to Penman–Monteith. As long as water absorption by a plant is maintained at the same rate as loss, there will be no water deficit (Visser, 1964). With the performance presented, these models can be used in the absence of data that allow the calculation of ET $_{\text{via the}}$ Penman–Monteith method.

The Blaney-Criddle and Hargreaves-Samani models (Table 4) presented "very good" performance, unlike Araújo *et al. (2007),* who obtained "excellent" performance (c = 0.92) for the Blaney–Criddle model in the Boa Vista–RR region. For the Manicoré region, AM, Teixeira Filho, Barbosa, and Ferreira (2023) reported that the Blaney-Criddle method (c = 0.51) presented "poor" performance. Ferreira *et al* . (2020) classified the Hargreaves method as "poor" in the municipality of Parintins, AM, while Barbosa *et al*. (2022) reported an "excellent" classification for the municipality of Maués, AM. Mendoza *et al*. (2016) classified the estimates of the Hargreaves-Samani method as "median" for the region of São Luís, MA, but highlighted that, among the methods that use temperature data, this method obtained the best performance, with c = 0.64.

The Thornthwaite model presented "average" performance, and the Camargo model presented "poor" performance. Souza and Sousa (2020) evaluated the Thornthwaite method (c = 0.64) as "average" and the Camargo method (c = 0.33) as "poor" for the Rio Branco region, AC. According to Santana *et al*. (2018), this unsatisfactory performance can be attributed to the simplicity of the equation, which results in the method being less accurate because of the reduced number of input parameters in the evapotranspiration estimate. In this context, if there is a delay in water absorption in relation to losses, deficits will arise that can irreversibly reduce potential crop production (Vaadia *et al*., 1961; Kramer, 1963).

6 CONCLUSIONS

The Haise, Makkink, FAO 54 Radiation and Blaney-Criddle-Frevert models showed the best fit to the Penman–Monteith FAO 56 standard method, with performance classified as "excellent", and are recommended for application in the municipality of Presidente Figueiredo, AM.

The Blaney-Criddle and Hargreaves-Samani models showed "very good" performance and are also recommended for the municipality of Presidente Figueiredo, AM.

Thornthwaite's model showed "average" performance and should be used only after specific local adjustments.

Compared with the standard method, Camargo's model performs poorly and is not recommended because of its low accuracy and precision.

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