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AVALIAÇÃO DO DESEMPENHO DE MÉTODOS DE ESTIMATIVA DA EVAPOTRANSPIRAÇÃO DE REFERÊNCIA PARA O MUNICÍPIO DE ITACOATIARA, AM, PÓS PREENCHIMENTO DE FALHAS EM SÉRIES METEOROLÓGICAS*

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** Parte 2: Trabalho retirado do Relatório de Pesquisa de Pós-Doutorado "Preenchimento de falhas em observações meteorológicas importantes na estabilidade da modelagem de evapotranspiração potencial de referência para Município de Itacoatiara, AM", 2025/2026.*

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1 RESUMO

A distribuição espacial e temporal da disponibilidade hídrica de uma região é de extrema importância ao possibilitar o estabelecimento de diretrizes para a implantação de políticas de planejamento que venham a contribuir para o uso racional dos recursos hídricos disponíveis, minimizando as perdas. Vários autores salientam o papel da evapotranspiração de referência como variável componente do balanço hídrico, estimada com base em princípios físicos e, principalmente, em equações empíricas, visando suprir a ausência de dados por meio de medidas diretas em diferentes locais e condições meteorológicas distintas. Com base nas publicações sobre metodologias de preenchimento de falhas em dados meteorológicos, este estudo teve como objetivo avaliar a estimativa da evapotranspiração de referência pelos métodos de Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 da Radiação e Blaney-Criddle-Frevert, comparados ao método padrão de Penman-Monteith FAO 56. Estas falhas foram observadas em dados oriundos de uma estação meteorológica automática com normal provisória de 15 anos, obtidos do Banco de Dados Meteorológico para Ensino e Pesquisa do Instituto Nacional de Meteorologia em Itacoatiara, AM. Os resultados obtidos mostraram desempenho ótimo dos modelos de Makkink, Jensen-Haise, Blaney-Criddle-Frevert, FAO 24 da Radiação e Hargreaves-Samani, podendo ser adotados no planejamento de áreas agrícolas e no dimensionamento de sistemas de irrigação, o que otimiza o consumo de água, potencializa o aumento da produtividade das culturas e contribui para a segurança alimentar global.

Palavras-chave: Modelagem, uso racional de água, produção agrícola, agrometeorologia.

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PERFORMANCE EVALUATION OF METHODS FOR ESTIMATING POTENTIAL EVAPOTRANSPIRATION FOR THE MUNICIPALITY OF ITACOATIARA, AM AFTER FILLING GAPS IN METEOROLOGICAL DATA

2 ABSTRACT

The spatial and temporal distribution of water availability in a region is extremely important because it enables the establishment of guidelines for the implementation of planning policies that contribute to the rational use of available water resources and minimize undesirable losses. Several authors have highlighted the role of potential evapotranspiration as a component variable of the water balance, which is estimated on the basis of physical principles and mainly empirical equations to compensate for the absence of direct evapotranspiration measurements at different locations and under different meteorological conditions. On the basis of the published methodologies for filling gaps in meteorological data, the performance of indirect methods for estimating potential evapotranspiration was evaluated using the following methods: the Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, and FAO 24 methods and the Blaney-Criddle-Frevert method compared with the standard FAO 56 Penman–Monteith method. These geps were identified in data obtained from the automatic meteorological station, with a provisional normal of 15 years, from the Meteorological Database for Teaching and Research of the National Institute of Meteorology in Itacoatiara, AM. The results obtained revealed the optimal performance of the Makkink, Jensen–Haise, Blaney–Criddle–Frevert, FAO 24 Radiation and Hargreaves–Samani models, which can be applied in the design of agricultural planning and irrigation systems, contributing to improved water use efficiency and increased crop productivity.

Keywords: Modeling, rational use of water, agricultural production, agrometeorology.

3 INTRODUCTION

Water management aims to harmonize the natural supply with the needs of consumptive and nonconsumptive uses, without the risk of conflicts caused by reduced quantity, diseases due to deteriorated quality, or damage to species maintenance due to altered water dynamics (Christofidis, 2013). The study of the spatial and temporal distribution of water availability in a region is extremely important, as it allows the establishment of guidelines for the implementation of planning policies that contribute to the rational use of available water resources (Silva *et al.*, 2015).

In 1948, Thornthwaite introduced the term potential evapotranspiration (ETp) to designate the amount of water evaporated and transported from the soil when it has maximum water storage and when vegetation completely covers the soil, with the area being large enough to minimize the effects caused by local advection. In the case of water deficit in the soil, the potential condition is no longer reached, and its values are restricted, leading to a new condition called actual evapotranspiration (ETr), with a value lower than the potential. Actual evapotranspiration occurs when the soil moisture condition begins to decrease, causing a reduction in the rate of water transfer to the atmosphere, which then depends not only on the prevailing atmospheric conditions but also on the physical-hydric characteristics of the soil and the plant.

The evaporation and evapotranspiration processes of natural surfaces can be simulated on a physical basis by models that describe the effects of resistance to molecular and turbulent diffusion on the distribution of energy from the sun or the atmosphere. Both the planning of rainfed or irrigated agricultural areas and the forecasting of floods or the construction and operation of reservoirs require reliable evaporation and/or evapotranspiration data. However, this information, when obtained through direct measurements from different locations and under distinct meteorological conditions, is not available in sufficient quantity. Thus, estimates based on physical principles and, mainly, on empirical equations are used as alternatives to address this shortcoming (Tucci; Beltrame, 2013).

The transfer of water from a cultivated area, where soil moisture is not a limiting factor, occurs according to its potential intensity, and any variation is due solely to differences in meteorological conditions, including advection effects. According to Berlato and Molion (1981), the control exerted by vegetation occurs through its structure, affecting albedo, roughness, and the root system. As soil moisture decreases, restrictions on water transfer to the atmosphere occur, which then depend not only on meteorological conditions but also on the root system of the plants, as well as other characteristics, such as their phytosanitary status. This condition allows us to distinguish between potential and actual evapotranspiration. Reliable information on actual evapotranspiration is scarce and difficult to obtain, as it requires a long observation time and is costly. Potential evapotranspiration, on the other hand, can be obtained quickly and with sufficient precision from models based on physical laws and empirical relationships (Tucci; Beltrame, 2013).

Despite the importance of reference evapotranspiration as a component variable of the water balance, most research evaluating the performance of methods for filling gaps is concentrated on rainfall data (Brubacher; Oliveira; Guasselli, 2020; Srivastava). *et al.,* ., 2020), and low amounts of air temperature, relative humidity, atmospheric pressure, insolation, wind speed, and solar radiation data are available. One of the significant challenges when dealing with information collected from meteorological stations is the number of gaps (periods without measurement) found in the databases. Rainfall and hydrological gaps can occur because of technical/operational problems, such as the absence of an observer, instrumental failures, breaks in the communication line, or geographic location, for example, which can lead to incorrect interpretations if not corrected (Correa *et al*., 2021).

In the northern region, particularly in the state of Amazonas, despite the significant number of meteorological stations, there are gaps in observations because of operational failures or defects. Furthermore, the cities are geographically distant and difficult to access, hindering technical assistance for adjustments and corrections. In many cases, seeking alternatives to generate missing meteorological data to minimize errors in the modeling of fundamental variables would be a viable alternative.

This study aimed to evaluate and compare the performance of different indirect methods for estimating reference evapotranspiration (ETo)—Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 Radiation and Blaney-Criddle-Frevert—in relation to the standard Penman–Monteith FAO 56 method after the gaps in historical series of meteorological data in Itacoatiara, AM, were filled.

4 MATERIALS AND METHODS

This research was developed using data from the automatic weather station (A121), with a historical series from 2009 to 2023, obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET, 2025) for the locality of Itacoatiara, AM, which is located at a latitude of 3.1333° south and a longitude of 58.4828° west, at an altitude of 41.54 meters. According to Köppen and Geiger, the climate classification of Itacoatiara, AM, is tropical humid, " Af ". The average annual temperature is 26.8 °C, and the annual precipitation in this location is approximately 2750 mm (ClimateData, 2025).

The meteorological variables considered in this investigation were air temperature (maximum and minimum); relative air humidity (maximum and minimum); atmospheric pressure; insolation; photoperiod; wind speed; and solar radiation (global and extraterrestrial), which are necessary for daily ETo estimates using the standard method, FAO-56 Penman–Monteith, and the evaluated methods Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 Radiation, and Blaney-Criddle-Frevert. The values for these variables were tabulated using Microsoft Excel spreadsheets.

The gaps in the meteorological data for the variables air temperature (minimum and maximum, °C), relative air humidity (minimum, maximum, and average, %), average atmospheric pressure (kPa), and average wind speed (m $^{s^{-1}}$) identified in the series were filled using the within-station method, such as linear interpolation and moving average methods (Allen; Degaetano, 2001), which are based on hourly and daily information that is converted into monthly averages. Owing to the lack of complete data from neighboring stations (Table 1), which are located 150 km from the Itacoatiara Meteorological Station, gaps were filled using the within-station data interpolation method, in addition to using the easy-fit software. To complete the data in Easy-Fit, the Kolmogorov–Smirnov test was used because the data are nonparametric, as well as the WeatherMan/DSSAT v 4.8.5.0 program (Decision). Support System for Agrotechnology Transfer) for the generation of climate data by the WGEN model (Richardson; Wright, 1984; Hoogenboom *et al*., 2024). It is important to choose the methodology that best suits and meets the needs of the research, in accordance with the geographical and climatological reality in which the meteorological stations studied are located (Fante; Sant'anna Neto, 2016).

Table 1. Locations of the stations near Itacoatiara

Name	**UF**	**Latitude**	**Longitude**	**Distance**	**Altitude**	**Code**
		°		**km**	**m**	
Itacoatiara	AM	-3.13694444	-58.44277777	-	41.54	A121
Maues	AM	-3.39888888	-57.67388888	94.34	25.49	A122
Parintins	AM	-2.63916666	-56.75611111	198.26	18.72	A123
Urucará	AM	-2.53472221	-57.75805555	105.86	18.49	A124
Urubu River	AM	-2.6336111	-59,60055555	139.32	112.84	A125

Source: Authors (2025).

Daily ET estimates using the FAO-56 method (Perman–Monteith) are summarized in Equation 1 (Allen; Pereira; Raes, 1998).

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

where ET_o is the reference evapotranspiration (mm d^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa $°C^{-1}$), R_n is the net daily radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa $°C^{-1}$), T_{mc} is the compensated average air temperature (°C), 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 actual vapor pressure of the air (kPa).

The pressure exerted by the saturating water vapor content (e_s), average daily, is described by Equation (2) of Tetens (1930), and the air temperature (T_{ar}) is equal to the dry bulb thermometer temperature (T_s), which is similar to the wet bulb thermometer temperature (T_u) for the determination of "e_{su}". The actual vapor pressure (e_a) was obtained by the psychrometric equation 3.

$$e_s = 0{,}6108 * EXP^{\left(\frac{17{,}27*T_{ar}}{237{,}3+T_{ar}}\right)} \quad (2)$$

$$e_a = e_{su} - A\ P\ (T_s - T_u) \quad (3)$$

where A = 0.00080 $°C^{-1}$ for nonventilated psychrometers; A = 0.00067 $°C^{-1}$ for psychrometers with forced ventilation; and P is the local atmospheric pressure (kPa).

The slope of the vapor pressure curve was calculated using Equation 4.

$$\Delta = \frac{4098\left[0{,}6108*e^{\left(\frac{17{,}27*T_m}{237{,}3+T_m}\right)}\right]}{(T_m+237{,}3)^2} \quad (4)$$

where Tm is the average air temperature (°C).

The psychrometric constant was estimated from Equations (5) and (6), or when this was not possible, the tabulated value was adopted:

$$\gamma = \frac{C_p*P}{\varepsilon*\lambda} = 0{,}665 * 10^{-3} * P \quad (5)$$

$$P = 101{,}3\left(\frac{293-0{,}0065*Z}{293}\right)^{5{,}26} \quad (6)$$

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

The heat flux in the soil (G) for a period of one day or ten days under a grassy reference surface is relatively low and can be ignored (G≈0). For the monthly period, G is given by Equation 7.

$$G_{mês,i} = 0{,}14\left(T_{mês,i} - T_{mês,i-1}\right) \quad (7)$$

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

The radiation balance (Rn) is the difference between the shortwave radiation balance (Rns) and the longwave radiation balance (Rnl) and is estimated by Equations (8) to (16).

$$R_n = R_{ns} - R_{nl} \quad (8)$$

$$R_{ns} = (1 - 0{,}23) * Q_g \quad (9)$$

$$R_{nl} = \sigma\left(\frac{T_{x,k^4} + T_{n,k^4}}{2}\right)\left(0{,}34 - 0{,}14\sqrt{e_a}\right)\left(1{,}35\ \frac{Q_g}{R_{so}} - 0{,}35\right) \quad (10)$$

$$R_{so} = (0{,}75 + 2X10^{-5} * Z)\ Q_o \quad (11)$$

$$Q_o = \frac{24\ (60)}{\pi}\ G_{sc}\ d_r(\omega_s\ sen\ \varphi\ sen\ \delta + \cos\varphi \cos\delta\ \ sen\ \omega_s) \quad (12)$$

$$Q_g = Q_o \left[a + b\ \left(\frac{n}{N}\right)\right] \quad (13)$$

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

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

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

where Qg is the global solar radiation (MJ m $^{-2}$ d $^{-1}$) (Angström–Prescott, Equation 13); a = 0.25 and b = 0.50 (Bernardo; Soares; Mantovani, 2006); Qo a is the air transfer at the top of the atmosphere (MJ m $^{-2)}$ d $^{-1}$); G_{sc} is the solar constant, 0.0820 MJ m $^{-2}$ min $^{-1}$; σ is the Stefan–Boltzmann constant, 4.903 x 10 $^{-9}$ MJ m $^{-2}$ d $^{-1}$; and e R_{so} é ar adiment solar em um dia sem nuvens (MJ m $^{-2}$ d $^{-1}$). To convert 1 MJ m $^{-2}$ d $^{-1}$ into the equivalent evaporated water depth, multiply it by 0.408 and express the result in mm d $^{-1}$; Z is the altitude of the location (m); d_r is the relative Earth–Sun distance; J is the Julian day; δ is the solar declination (radians); Φ is the local latitude (radians); ω_s is the radiation angle 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).

Daily ET estimates using the Blaney and Criddle method (1950), known as the FAO Blaney–Criddle 24 method, are summarized in Equation 17 (Pereira; Villa Nova; Sediyama, 1997).

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

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

Daily ET estimates using the Camargo method (1971) were calculated using Equation 18 (Pereira; Villa Nova; Sediyama, 1997; Pereira; Angelocci; Sentelhas, 2007).

$$ET_o = \mathrm{Q_o} * \mathrm{T_m} * \mathrm{k_f} * \mathrm{ND} \quad (18)$$

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

Daily ET estimates using the Hargreaves and Samani (1985) method were obtained using Equation 19.

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

where ET_o is the reference 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), Q_o is the radiation at the top of the atmosphere (MJ m $^{-2}$ d $^{-1}$), T_x is the maximum air temperature (°C), and T_n is the minimum air temperature (°C).

Daily ET estimates using the Jensen–Haise method (Jensen; Haise, 1963) were obtained using Equation 20.

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

where ET_o is the reference evapotranspiration (mm month $^{-1}$), Q_g is the global solar radiation (mm d $^{-1}$) , and T_m is the average air temperature (°C).

Daily ET estimates using the Thornthwaite method (1948) were obtained using Equation 21.

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

where ET_o is the reference evapotranspiration (mm month $^{-1}$), ET_P is the standard evapotranspiration (mm month $^{-1}$), and Cor is the evapotranspiration correction factor.

Daily ET estimates using the Thornthwaite method (1948) simplified by Camargo (1962) were obtained using Equation 22.

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

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

Daily ET estimates using Makkink's method (1957) were obtained using Equation 23 (Pereira; Villa Nova; Sediyama, 1997; Turco; Perecin; Pinto Junior, 2008).

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

where ET_o is the reference evapotranspiration (mm d $^{-1}$); Q_g is the measured or estimated global solar radiation, mm d $^{-1}$; and W is the weighting factor, which is estimated using 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.

Daily ET estimates using the Blaney and Criddle method (1950) adapted from Frevert, Hill and Braaten (1983) were obtained using Equation 24 (Fernandes *et al.*, 2010).

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

where ET_o is the reference evapotranspiration (mm d $^{-1}$), "a" and "b" are the adjustment coefficients, "p" is the monthly percentage of annual hours of sunlight, and T_m is the average air temperature (°C).

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

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

where Y is the estimated value for the empirical methods, β1 is the slope coefficient, β0 is the y-intercept coefficient, and X is the value estimated by the standard Penman–Monteith–FAO method 56.

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

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

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

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

To verify whether the independent variable (X - Penman - Monteith - FAO 56) contributes to the prediction of the dependent variable (Y - empirical methods), the value of β1 was used $\hat{B}_1$to test if B1 = 0, assuming the hypothesis test: H0: β1 = 0; that is, there is no regression (X does not contribute to the prediction of Y); H1: β1 ≠ 0; that is, there is regression (X contributes to the prediction of Y).

Student's t-distribution with n-2 degrees of freedom, allowing for hypothesis testing. Thus, for a significance level of 5%, if the calculated t value is equal to or greater than the tabulated value, the null hypothesis is rejected, indicating that regression exists.

The Penman–Monteith–FAO–56 method and 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 mean, using Equation 30.

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

where X $_i$ is the value estimated by the Penman–Monteith FAO 56 method, X $_m$ is the average of the Penman–Monteith FAO 56 method, Y $_i$ is the estimated value of the evaluated method, and Y $_m$ is the average of the evaluated method.

The accuracy of the estimation of ET $_{relative}$ to that of the standard model was obtained by calculating the “d” index (Equation 31), which ranges from 0 to 1 (Willmott). *et al* ., 1985).

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

The safety or performance coefficient “c” (Table 2) was calculated as the product of red (c = r*d) (Camargo; Sentelhas, 1997).

Table 2. Performance coefficient values .

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

Source: Camargo and Sentelhas (1997)

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

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

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

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

where X $_i$ is the ET_o estimate by the standard model, FAO-56 Penman–Monteith; Y_i is the ET_o estimate obtained by each of the evaluated models; and en is the number of observations.

5 RESULTS AND DISCUSSION

The modeling of reference evapotranspiration, after estimates of flawed meteorological data using the organized-within-station method, which has the advantage of independence from data from other stations, was carried out on the basis of the relational discussions presented in Table 3. Planning agricultural areas and making decisions require reliable evaporation and evapotranspiration data.

The meteorological elements (Table 3) help to describe the average atmospheric conditions of the municipality of Itacoatiara, such that the maximum air temperature varied between 30.23 °C (April) and 33.97 °C (September) and the minimum between 23.80 °C (January) and 24.64 °C (October). The smallest total amplitude was observed for the minimum air temperature (0.84 °C). Barbosa *et al.* (2022) and Teixeira Filho, Barbosa and Ferreira (2023), when developing studies in Amazonian municipalities, observed a smaller total amplitude in the minimum temperature, whose values were equal to 0.94 °°C and 1.51 °C, respectively.

Table 3. Monthly average values of maximum (Tx) and minimum (Tn) air temperature, maximum (RHx) and minimum (RHn) relative air humidity, and wind speed at 2 m height (U2), global solar radiation (Qg) and insolation (n), after missing data (2009 to 2023) are filled in, Itacoatiara, AM

Months	T_x	T_n	UR_x	UR_n	U_2	Q_g	n
	°C		%		ms $^{-1}$	MJ m $^{-2}$ d $^{-1}$	h
J	30.70	23.80	92.71	62.65	0.72	13.42	4.40
F	30.28	23.82	93.39	65.85	0.70	14.47	3.53
M	30.47	23.89	93.56	65.71	0.71	15.98	4.14
THE	30.23	24.04	93.88	67.16	0.63	13.67	4.40
M	30.54	24.25	93.64	65.98	0.60	13.79	5.11
J	31.14	24.00	92.97	61.90	0.58	15.12	6.79
J	31.75	23.89	92.97	57.69	0.66	17.99	7.54
THE	33.08	24.18	90.88	50.49	0.81	19.62	8.24
S	33.97	24.58	89.17	48.93	0.85	19.36	7.88
THE	33.70	24.64	89.42	49.93	0.79	18.83	7.00
N	33.00	24.55	90.57	54.14	0.77	18.35	5.91
D	31.57	24.10	92.20	60.65	0.71	13.85	5.08

Source: Authors (2025)

The maximum relative humidity ranged from 89.17% (September) to 93.88% (April), and the minimum ranged between 48.93% (September) and 67.16% (April) (Table 3) in the Amazonian winter and summer, respectively. Even in the Amazonian summer, the local atmosphere had considerable humidity, indicating a lower demand for water for agricultural crops and, certainly, a lower atmospheric water deficit.

Pereira, Angelocci, and Sentelhas (2007) reported that the wind speed is also affected by the surface roughness created by obstacles (vegetation, buildings, mountainous terrain, etc.) and by the vertical distance above the surface where it is measured. The closer to the surface, the greater the effect of friction with the terrain, slowing the movement and decreasing the speed of air displacement. This blockage imposed by the surface causes higher-speed air bubbles to move downward, generating a sudden impulse in the air near the ground. This abrupt increase in the wind speed is called a gust. However, the wind at a height of two meters at the station (Table 3), with a minimum of 0.58 ms^{-1} (2.09 km h^{-1}, June) and a maximum of 0.85 ms^{-1} (3.06 km h^{-1}, September), suggests that the measured evapotranspiration was the main cause of the increased water loss from the plant to the atmosphere. According to the classification proposed on the Beaufort scale, these are the force 1 winds, which are in the almost calm category. This wind category can favor agricultural planning activities in the region, as well as decision-making in operations to be carried out in agriculture (Teixeira Filho; Barbosa; Ferreira, 2023). Teixeira Filho and Arruda (2024), evaluating the performance of Methods for estimating reference evapotranspiration for the municipality of Presidente Figueiredo, AM, verified that the wind speed was less than 1.0 ms^{-1} in all months of the year, 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, which corresponded to 1 on the Beaufort scale, characterized as “almost calm”, also presenting favorable conditions for agricultural planning and decision-making in agricultural operations.

Table 4 shows the daily averages of reference evapotranspiration (ETo) for the municipality of Itacoatiara, AM, for each empirical method evaluated in comparison with the FAO 56 Penman–Monteith method. The Makkink and FAO 24 Radiation models (Table 3, Figure 1) underestimated ETo during all months of the year, with differences between the average ETo values ranging from -0.56 to -0.78 mm d^{-1} and from -0.53 to -0.93 mm d^{-1}, respectively. This trend was also observed by Teixeira Filho and Braga (2023) for the Makkink and Blaney–Criddle–Frevest models, which underestimated ET during all months of the year, with differences between the average ET_o values varying between -0.40 and -0.49 mm d^{-1} and between -0.40 and -0.90 mm d^{-1}, respectively.

Table 4. Mean reference evapotranspiration (ETo, mm d $^{-1}$) was estimated by the standard Penman–Monteith method [ETo $_{(PM)}$], and by the empirical methods of Blaney–Criddle [ETo $_{(BC)}$], Camargo [ETo (C)], Hargreaves–Samani [ETo (HS], Jensen–Haise [ETo (JH), Thornthwaite [ETo (T], Makkink [ETo $_{(M)}$, FAO 24 Radiation [ETo $_{(R)}$] and Blaney–Criddle–Frevert [ETo (BC-F)], Itacoatiara, AM.

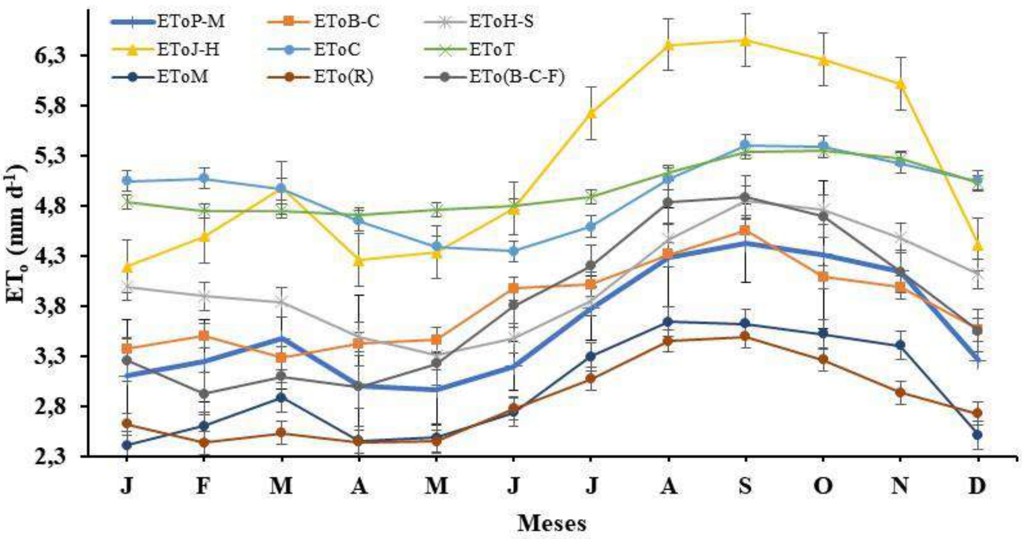
Months	ET_{oP-M}	ET_{oB-C}	ET_{oH-S}	ET_{oJ-H}	ET_{oC}	ET_{oT}	ET_{oM}	ET_{oR}	ET_{oB-CF}
J	3.10	3.37	3.99	4.19	5.04	4.83	2.41	2.62	3.25
F	3.25	3.50	3.89	4.49	5.07	4.74	2.60	2.43	2.92
M	3.47	3.28	3.84	4.98	4.96	4.75	2.88	2.53	3.09
A	3.00	3.42	3.49	4.25	4.64	4.70	2.45	2.44	2.99
M	2.96	3.46	3.31	4.33	4.38	4.76	2.48	2.44	3.22
J	3.19	3.97	3.48	4.77	4.34	4.80	2.74	2.77	3.80
J	3.77	4.01	3.85	5.72	4.59	4.89	3.29	3.07	4.20
A	4.28	4.31	4.46	6.40	5.06	5.13	3.64	3.45	4.83
S	4.42	4.55	4.85	6.45	5.40	5.33	3.62	3.49	4.88
O	4.31	4.08	4.76	6.25	5.38	5.34	3.51	3.26	4.69
N	4.14	3.98	4.48	6.02	5.22	5.27	3.40	2.93	4.14
D	3.25	3.56	4.12	4.41	5.04	5.02	2.51	2.72	3.55
Average	3.60	3.79	4.04	5.19	4.93	4.96	2.96	2.85	3.80
ME- PM (*)	-	0.19	0.45	1.59	1.33	1.37	-0.64	-0.75	0.20

Note: (*) **-** Difference between the average reference evapotranspiration (ETo) of the empirical methods ($_{EM}$) in relation to the FAO-56 Penman–Monteith standard method (PM). **Source:** Authors (2025)

The models that overestimated ET $_o$ (Table 4, Figure 1) were Hargreaves-Samani, Jensen-Haise, Camargo, and Thorthwaite in relation to the Penman–Monteith model in all months of the year, whose differences between the average values (minimum and maximum) varied between 0.34 and 0.43 mm d $^{-1,}$ 1.23 and 2.03 mm d $^{-1,}$ 1.38 and 0.98 mm d $^{-1,}$ and 1.74 and 0.92 mm d $^{-1}$, respectively. In the municipality of Benjamin Constant, Teixeira Filho and Braga (2023) also reported similar trends for the Hargreaves-Samani, Jensen-Haise, Camargo, Thorthwaite and FAO 24 Radiation models in relation to the Penman–Monteith model in all months of the year, whose differences between the average values (minimum and maximum) varied between 1.16 and 1.14 mm d $^{-1}$; 1.23 and 1.98 mm d $^{-1}$; 1.41 and 1.15 mm d $^{-1}$; 1.31 and 0.94 mm d $^{-1}$; and between 0.50 and 0.78 mm d $^{-1}$, respectively.

The Blaney–Criddle method overestimated ET in the months of January, February, April, May, June, July, August, September, and December, with variations between 0.31 and 0.13 mm d$^{-1.}$ Three underestimations were also observed in the months of March, equal to -0.20 mm $^{d^{-1}}$, October, equal to -0.23 mm d$^{-1,}$ and November, equal to -0.16 mm d^{-1} (Table 4, Figure 1). The Blaney–Criddle–Frevest method overestimated ET in the months of January, May, June, July, August, September, October, November, and December, which varied between -0.05 and 0.46 mm $^{d^{-1}}$. Four underestimations were also observed in the months of February, equal to -0.33 mm d $^{-1;}$ March, equal to -0.38 mm d $^{-1;}$ April, equal to -0.01 mm d $^{-1;}$ and November, equal to -0.01 mm d $^{-1}$ (Table 4, Figure 2). For Boa Vista, RR, Araújo, Costa and Santos (2007) verified an underestimation, in all months of the year, of evapotranspiration calculated by the standard Penman–Monteith method, which is different from what was verified in this research.

Figure 1. Monthly behavior of reference evapotranspiration, daily average - Itacoatiara, AM



Notice: ET_{oP-M} (Penman–Monteith), ET_{oB-C} (Blaney–Criddle), ET_{oC} (Camargo), ET_{oH-S} (Hargreaves–Samani), ET_{oJ-H} (Jensen–Haise), ET_{oT} (Thornthwaite), ET_{oT-C} (Thornthwaite–Camargo), ET_{oM} (Makink), ET_{oR} (FAO–24 Radiation) and ET_{oB-CF} (Blaney–Criddle–Frevert). **Source:** Authors (2025)

Ferraz (2008), Carvalho and Delgado (2016), Ferreira *et al* . (2020), Souza and Sousa (2020) and Barbosa *et al*. (2022), and Teixeira Filho and Braga (2023) verified a tendency to overestimate the potential reference evapotranspiration by the Blaney-Criddle, Camargo, Jensen-Haise, Thornthwaite and FAO 24 Radiation methods for all months of the year. Teixeira Filho and Braga (2023) report that this presupposes a trend in the behavior of these models adjusted to Penman–Monteith–FAO 56 in regions whose climate is classified in group A, according to the Köppen Climate Classification (1948), which Almeida (2016) characterized as areas with a megathermal, tropical rainy climate, with an average temperature of the coldest month greater than 18 °C and an average annual rainfall greater than 700 mm.

The degree of interrelationship between the independent variable, estimated by the Penman–Monteith–FAO 56 method, and the dependent variable, estimated by the Blaney–Criddle, Camargo, Hargreaves–Samani, Jensen–Haise, Thornthwaite, Makkink, FAO 24 Radiation, and Blaney–Criddle–Frevert methods, is shown in Figure 2. Therefore, a good fit between the variables involved should be associated with a small "total error," which implies that the correlation coefficient, the statistical measure that quantifies the degree of relationship between two or more variables, should be close to -1 or +1.

There is a functional relationship that explains a large part of the variation in ET_o (Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 Radiation and Blaney-Criddle-Frevert) in relation to ET_o estimated by the standard Penman–Monteith method. However, a portion of the variability of the models not explained by the standard method is attributed to chance, i.e., to random error. It is possible to establish (estimate) a functional relationship between the simplified ET_o (Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24

Radiation and Blaney-Criddle-Frevert) and the standard ET o (Penman–Monteith-FAO 56), describing how much the water loss of the standard method affects the other simplified methods. This implies variations in the water needs of arable crops and in the atmospheric balance, since a portion of the variability in empirical models, not explained by the standard method, will be attributed to chance, that is, to random error.

In Figure 2, Jensen–Haise presented the best correlation ($R^2 = 0.97$) for the period studied, and Camargo presented the worst correlation ($R^2 = 0.47$). According to Devore (2018), many x and y variables may appear to be related to each other but not in a deterministic way. In other words, the existence of a “good” regression model does not necessarily imply a cause-and-effect relationship or dependence between the variables.

The combined Jensen–Haise model shows excellent linear correlation ($R^2 = 0.97$), strong systematic overestimation (ME-PM = +1.59), and a high associated error (EPE = 1.70 mm d^{-1}), indicating that it is far from the standard model, even though it demonstrates excellent fit. In practice, this results in higher water consumption or, rather, oversizing of the water depth required in irrigation projects to meet the demand of the cultivated crop.

The overestimation by Jensen–Haise, a model that linearly combines radiation and temperature, can be explained by its inability to represent the aerodynamic term, that is, the contribution of wind to water evapotranspiration. In environments with low wind speed ($U^2 < 1$ ms^{-1}) and high humidity, such as in Itacoatiara, evapotranspiration is strongly limited by the vapor pressure deficit (VPD). Since Jensen–Haise does not incorporate the VPD, it overestimates water loss, especially in the drier months when the VPD is slightly higher. The high R^2, in this case, only indicates that the model follows the seasonality of radiation but has a systematic bias.

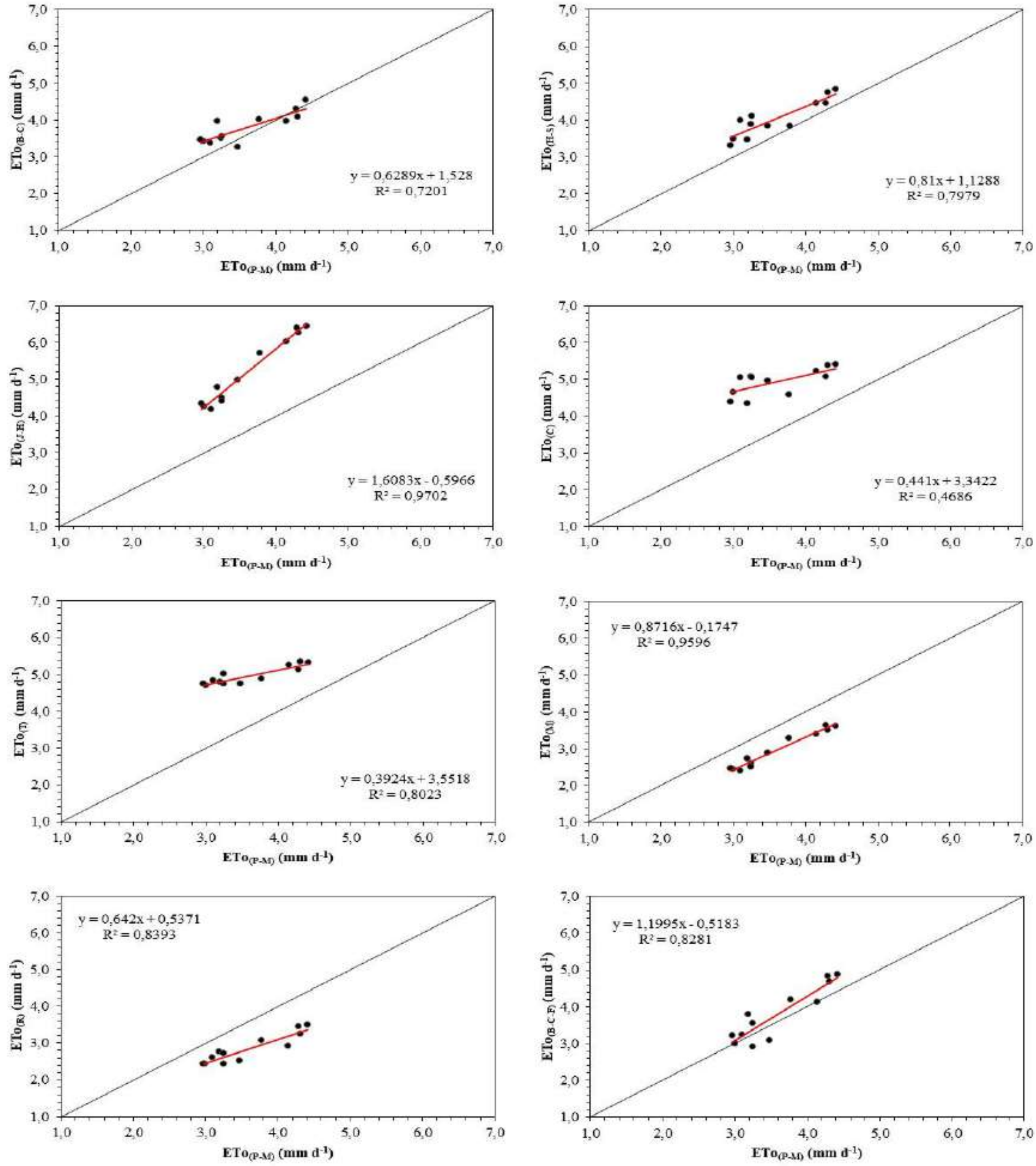
Thermal methods (Jensen–Haise and Thornthwaite) are sensitive to temperature; therefore, in humid climates, there is a tendency to overestimate them, as discussed in terms of the local conditions studied.

Camargo's model presented an observed t test value of 2.45, which was greater than the critical t value for 10 degrees of freedom, 2.23, at 95% confidence. Thus, the null hypothesis was rejected; that is, the test result is statistically significant, which demonstrates that the Penman–Monteith FAO 56 model affects the behavior of Camargo's model ($R^2 = 0.47$; Figure 2).

The slope of the regression line indicates how much the mean of Y varies as a consequence of a one-unit increase in the variable X. The slopes (Figure 2) of Thornthwaite (+0.3924), Camargo (+0.4410), Blaney-Criddle (+0.6289), FAO 24 Radiation (+0.6420), Hargreaves-Samani (+0.8100), Makkink (+0.8716), Blaney-Criddle-Frevert (+1,1995) and Jensen-Haise (+1,6083) indicate that for every 1 mm d^{-1} of water evapotranspiration, in the interval of the historical series considered, ETo increases on average between 0.3924 mm d^{-1} and 1.6083 mm d^{-1}.

The linear coefficient of the line is the point where the line intercepts the y-axis; thus, when x=0, y = n, the closest to zero was observed in the Makkink model (-0.1747), with the others as follows: Jensen-Haise (-0.5966), Blaney-Criddle-Frevert (-0.5183), FAO 24 Radiation (+0.5371), Hargreaves-Samani (+1.1288), Blaney-Criddle (+1.5280), Camargo (+3.3422), and Thornthwaite (+3.5518) (Figure 2).

Figure 2. Simple linear regression between the standard method (Penman–Monteith FAO 56) and the empirical methods studied for the Municipality of Itacoatiara, AM, 2009 to 2023.



Note: Empirical ET models: Blaney-Criddle [**ET $_{o\,(BC)}$**], Hargreaves- $_{Samani}$ [ET **o** $_{(HS)}$], Jensen-Haise [**ET $_{o\,(JH)}$**], Camargo [**ET $_{o\,(C}$**], Thornthwaite [**ET $_{o\,(T)}$**], Thornthwaite -Camargo [**ET $_{o\,(TC)}$**], Makkink [**ET $_{o\,(M)}$**], FAO 24 Radiation [**ET $_{o\,(R)}$**] and Blaney-Criddle-Frevest [**ET $_{o\,(BCF)}$**]; standard method: Penman–Monteith [**ET $_{o\,(PM)}$**].

The standard error of the estimate (Table 5) ranged from 0.36 to 1.70 mm d^{-1}, with the Blaney–Criddle, Makkink, Blaney–Criddle–Frevert, and Hargreaves–Samani models showing the lowest values, demonstrating their accuracy in relation to the ET$_0$ values $_{obtained}$ by the standard Penman–Monteith FAO 56 method. In other words, this error indicates how much the average of the dependent models can vary in relation to the standard model.

Table 5. Statistical indicators, Itacoatiara, AM

Models	%	EPE	EPEA	d	r	R^2	w	Performance
		mm d^{-1}						
Blaney-Criddle	105.38	0.36	0.23	1.00	0.85	0.72	0.85	Very good
Hargreaves- Samani	112.38	0.53	0.24	1.00	0.89	0.80	0.89	Excellent
Jensen- Haise	144.24	1.70	0.1645	0.96	0.99	0.97	0.95	Excellent
Camargo	137.05	1.45	0.27	0.97	0.68	0.47	0.67	Good
Thornthwaite	138.01	1.47	0.11	0.97	0.90	0.80	0.87	Excellent
Makkink	82.30	0.68	0.10	0.99	0.98	0.96	0.97	Excellent
FAO-24 Radiation	79.13	0.82	0.1640	0.98	0.92	0.84	0.90	Excellent
Blaney-Criddle-Frevest	105.54	0.39	0.32	1.00	0.91	0.83	0.91	Excellent

Note: Statistical indicators used in the evaluation of the methods: percentage in relation to the standard Penman–Monteith method (%), standard error of estimate (SEE, mm d^{-1}), adjusted standard error of estimate (ASE, mm d^{-1}), correlation coefficient (r), coefficient of determination (R^2), index of agreement (d), performance coefficient (c) and classification based on the performance coefficient. **Source**: Authors (2025)

The adjusted standard error of the estimate ranged from 0.10 to 0.32 mm d^{-1}, with the lowest values observed in the Makkink, Thornthwaite, FAO-24 Radiation, Jensen-Haise, Hargreaves-Samani, and Blaney-Criddle-Frevert models (Table 5), confirming that the regression line had an optimal fit to the data of the investigated models since the values of the coefficients of determination were high.

The Makkink (c = 0.97), Jensen–Haise (0.95), Blaney–Criddle–Frevert (0.91), FAO 24 Radiation (0.90), and Hargreaves–Samani (0.89) methods performed “optimally” (Table 5). Teixeira Filho and Braga (2023) and Teixeira Filho, Barbosa and Ferreira (2023), who evaluated the performance of reference evapotranspiration estimation methods for the municipalities of Benjamin Constant and Manicoré, AM, also reported that the Makkink (c = 0.98), FAO 24 Radiation (0.98), Jensen-Haise (0.95), Hargreaves-Samani (0.90), and Blaney-Criddle-Frevert (0.90) and Blaney-Criddle (0.85) models presented an “optimally” coefficient of performance. Ferreira *et al.* (2020) compared several methods for the municipality of Parintins, AM, and classified the Jensen–Haise model as having “optimal” performance (c = 0.85). Araújo Araújo, Costa and Santos *(2007), using the* Blaney–Criddle model for the locality of Boa Vista, RR, obtained “optimal” performance (c = 0.92). Mendoza, Menezes and Dias (2016) classified the estimates of the Hargreaves–Samani method as “median” for the region of São Luís, MA. However, the authors highlighted that, among the methods that use temperature data, this method obtained the best performance (c = 0.64).

As long as water absorption by the plant is maintained in the same proportion as loss, there will be no deficit (Visser, 1964). Since the Makkink, Jensen–Haise, Blaney–Criddle–Frevert, FAO 24 Radiation, and Hargreaves–Samani (0.89) models performed “optimally” (Table 5), they can be adopted in the absence of data that allow the calculation of $_{ET}$ using Penman–Monteith. Bernardo, Soares, and Mantovani (2006) state that the water requirement is the amount of water needed by the crop during a given period of time to avoid limiting its growth and production under local climatic conditions; that is, it is the amount of water needed to meet evapotranspiration and leaching of salts from the soil. In terms of the definition of water required by the crop, evapotranspiration constitutes the greatest and most important component.

The combined Makkink model, as well as the Jensen–Haise model, presents excellent linear correlation ($R^2 = 0.96$), a systematically consistent mean underestimate throughout the year (ME-PM

= -0.64), and a low associated error (EPE = 0.68 mm d^{-1}); that is, it is not far from the standard model, demonstrating an excellent fit. The absence of the aerodynamic term, low wind speed ($U^2 < 1$ ms^{-1}), and high relative humidity lead to underestimation, as does the existence of the "W" factor, which is not calibrated for the Amazonian climate and represents the fractional part of solar radiation used in ET_0 and varies with temperature and altitude; therefore, this factor deserves attention in future work.

The Blaney–Criddle–Frevert model showed "very good" performance, and the Camargo model showed "good" performance (Table 5). Souza and Sousa (2020) evaluated the Camargo method (c = 0.33) and reported "very poor" performance for the Rio Branco, AC region. The unsatisfactory performance of this method can be attributed to the simplicity of its equation, which provides less precision to the method, since it presents a reduced number of input parameters for the evapotranspiration estimate (Santana *et al.*, 2018).

According to Vaadia, Raney and Hagan (1961), and Kramer (1963), if there is a delay in water absorption relative to losses, deficits will arise that can irreversibly reduce the potential production of crops. Therefore, attention must be given to the choice of ETo estimation method, which may vary depending on the geographical location of the site where the agricultural project will be implemented.

6 CONCLUSION

Under the conditions in which this work was carried out, the following conclusions can be drawn:

- The results are valid within the uncertainties associated with the gap-filling method used, which requires further validation;
- Student's t-distribution with n-2 degrees of freedom and hypothesis testing can be performed. Thus, for a significance level of 5%, if the calculated "t" value is equal to or greater than the tabulated value, the null hypothesis is rejected, meaning that regression exists;
- Hypothesis tests revealed that the standard Penman–Monteith method contributes to the prediction of the empirical models studied;
- Makkink's method achieved the best overall performance. Although it showed the best annual performance, seasonal differences were observed, especially during the less rainy period;
- The Jensen–Haise, Blaney–Criddle–Frevert, and FAO 24 radiation methods were strongly correlated. Although Jensen–Haise and Blaney–Criddle–Frevert tended to overestimate, and the FAO 24 method tended to underestimate, they should be used with caution. The results refer to the local conditions analyzed, and further validation in other locations with similar climates is recommended.
- Further studies should evaluate the performance of these models in other locations within the Amazon region. When possible, the effects of seasonality on the models should be studied for a future recommendation of a regional model.

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