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AVALIAÇÃO DO DESEMPENHO DE MÉTODOS DE ESTIMATIVA DA EVAPOTRANSPIRAÇÃO POTENCIAL DE REFERÊNCIA PARA O MUNICÍPIO DE BENJAMIN CONSTANT, AMAZONAS (*)

ARISTÓTELES DE JESUS TEIXEIRA FILHO[1] E AMÓS FELIPE DE FARIA BATISTA BRAGA[2]

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[1] *Professor Associado do Instituto de Ciências Exatas e Tecnologia, Universidade Federal do Amazonas, Campus Itacoatiara, Av. Nossa Senhora do Rosário, 3863 - Bairro Tiradentes, Itacoatiara, Amazonas, Brasil, aristoteles@ufam.edu.br*

[2] *Estudante do Curso de Agronomia do Instituto de Ciências Exatas e Tecnologia, Universidade Federal do Amazonas, Campus Itacoatiara, Av. Nossa Senhora do Rosário, 3863 - Bairro Tiradentes, Itacoatiara, Amazonas, Brasil, fariafelipe964@gmail.com*

1 RESUMO

A disponibilidade de água para uma cultura pode ser melhor definida pelo intervalo em que o clima permitirá à planta manter uma razão de transpiração igual à razão de absorção de água pelas raízes. Assim, objetivou-se avaliar o desempenho dos métodos indiretos de estimativa da evapotranspiração de referência de Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 da Radiação e Blaney-Criddle-Frevert em comparação com o método padrão de Penman-Monteith. Os dados meteorológicos utilizados foram obtidos na estação meteorológica convencional de Benjamin Constant do Instituto Nacional de Meteorologia, compreendendo dados mensais da normal provisória de 10 anos. Os indicadores estatísticos utilizados foram: coeficiente de correlação, coeficiente de determinação, índice de exatidão e o coeficiente de segurança ou desempenho. Os métodos ajustados ao método padrão de Penman-Monteith com desempenho “ótimo” foram Makkink, FAO 24 da Radiação, Jensen-Haise, Hargreaves-Samani, Blaney-Criddle-Frevert e Blaney-Criddle, recomendados para o município de Benjamin Constant, AM. O modelo de Camargo apresentou desempenho “sofrível”, podendo ser recomendado após ajustes locais. Enquanto o modelo de Thornthwaite apresentou desempenho “mau”, não podendo ser recomendado em razão da baixa exatidão e precisão em relação ao método padrão.

Palavras-chave: Penman-Monteith, planejamento agrícola, tomada de decisão.

TEIXEIRA FILHO, A. de J.; BRAGA, A. F. DE F. B.

PERFORMANCE EVALUATION OF REFERENCE POTENTIAL EVAPOTRANSPIRATION ESTIMATION METHODS FOR THE CITY OF BENJAMIN CONSTANT, AMAZONAS

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2 ABSTRACT

Water availability for a crop can be best defined by the range in which the climate allows the plant to maintain a transpiration rate equal to the rate of water absorption by the roots. Thus, the objective was to evaluate the performance of the indirect reference evapotranspiration estimation methods of Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 of Radiation, and Blaney-Criddle-Frevert in comparison with the standard Penman–Monteith method. The meteorological data used were obtained from the Benjamin Constant conventional meteorological station of the National Institute of Meteorology, comprising monthly data from the 10-year provisional normal. The statistical indicators used were the correlation coefficient, determination coefficient, accuracy index, and safety or performance coefficient. The methods adjusted to the Penman–Monteith standard method with "optimal" performance were Makkink, FAO 54 of the Radiation, Jensen–Haise, Hargreaves–Samani, Blaney–Criddle–Frevert and Blaney–Criddle, recommended for the municipality of Benjamin Constant, AM. The Camargo model presented "sufferable" performance and can be recommended after local adjustments. The Thornthwaite model presented "poor" performance and cannot be recommended because of its low accuracy and precision compared with those of the standard method.

Keywords: Penman-Monteith, agricultural planning, decision making.

3 INTRODUCTION

The rate at which molecules are transferred from liquid to vapor and from vapor to liquid depends on the concentration of water vapor in the atmosphere in contact with the liquid surface. An atmosphere in equilibrium with the water surface is considered to be saturated with water vapor. The vapor pressure of the air in equilibrium with the water surface depends on the pressure and temperature of the system. In general, under normal pressure conditions, air can retain more vapor as its temperature increases (REICHARDT; TIMM, 2004). Thus, it is possible to use these concepts in planning and exploring agricultural crops, especially in rainfed areas, where there is greater demand from the atmosphere, and in forecasting droughts and floods.

The amount of water lost through evapotranspiration is the amount that must be replaced in the soil through the irrigation process in the absence of rain. Hence, the importance of your determination. It can be measured directly on the ground or indirectly in the atmosphere. Therefore, indirect measurements carried out in the atmosphere generally involve empirical formulas that relate evapotranspiration to available solar radiation, relative humidity, air temperature and wind (REICHARDT, 1978).

Currently, soil–water–plant and atmosphere interrelationships are being approached from the point of view of a physical continuum in which flow occurs from the highest to the lowest potential. Owing to the potential variability that occurs, especially in the soil, the evapotranspiration regime also presents extreme variability; hence, the introduction of potential evapotranspiration occurs when the soil has a high moisture content and when the plants that are vegetate have excellent development. vegetative (SILVA; DUARTE, 1980).

Water availability for a crop can be best defined by the range in which the climate allows the plant to maintain a transpiration rate equal to the rate of water absorption by the roots (VISSER, 1964). In this case, there will be no water deficit, as long as the harvested crop is maintained at its potential capacity, which, in practice, does not occur under normal atmospheric conditions. The soil–atmosphere relationship requires constant evaporative flows to maintain moisture. Furthermore, Vaadia *et al*. (1961) and Kramer (1963) reported that as long as water absorption by a plant is maintained at the same rate as loss, there will be no deficit. However, if there is a delay in absorbing losses, deficits will arise that can irreversibly reduce potential crop production.

The main purpose of irrigation is to prevent cultivated plants from suffering water deficits (SCALOPPI; VILLA NOVA; SALATI, 1978). Modeling evapotranspiration in a regionalized manner can enable the use of more robust equations that can meet the reality of rural producers and minimize water deficits in agricultural crops during the hottest hours of the day.

Bernardo, Soares and Mantovani (2006) reported that there are several methods for determining evapotranspiration, most of which estimate potential evapotranspiration (ETp), that is, that which occurs when there is no water deficiency in the soil that limits its use by plants. ETp varies from culture to culture, as expected, due to its intrinsic characteristics. This led to the need to define a reference crop (ETo) as the evapotranspiration of a hypothetical crop, such as Bataais grass, which covers the entire soil during active growth without water or nutritional restrictions (optimal development conditions).), with an average height of 0.12 m, albedo of 0.23 and surface resistance of 70 sm $^{-1}$.

Therefore, despite the existence of several models to estimate reference potential evapotranspiration, they are often used in climatic and agronomic conditions that are very different from those in which they were initially conceived. Therefore, it is extremely important to evaluate the degree of accuracy of these models before they are used in new conditions (OLIVEIRA *et al*., 2001).

The accurate estimation of ETo is essential for calculating the water needs of a crop, for scheduling irrigation needs and for the sustainable management of water resources (BARBOSA *et al*., 2022). In this context, determining the water needs of a crop is crucial for the planning and management of irrigated areas and for predicting agricultural production (FERREIRA *et al*., 2020).

A frequently used way to verify the efficiency of reference evapotranspiration estimation methods is through comparisons with the Penman–Monteith method, which is parameterized by the Food and Agriculture Organization of the United Nations (FAO) (TURCO; PERECIN; PINTO JÚNIOR, 2008).

The International Commission on Irrigation and Drainage (ICID) and the FAO consider the Penman–Monteith method as the standard for calculating reference evapotranspiration from meteorological data (ALLEN; PEREIRA; RAES, 1998; SMITH, 1991). However, its use is quite limited because many data that cannot be readily obtained are needed. As an alternative, particularly in developing countries in the tropics, equations with a smaller number of variables are used, such as those of Blaney-Criddle, Hargreaves, Camargo and Jensen-Haise (AYOADE, 2013).

According to Munhoz *et al*. (2012), only one study was found that addresses reference evapotranspiration for the northern region of Brazil, which was counted together with the Northeast Region. Recently, many articles have been published in the State of Amazonas (BARBOSA *et al*., 2022; FERREIRA *et al*., 2020). To contribute to the production of evapotranspiration data for the northern region and understand the importance of the topic and its application, this investigation aimed to evaluate the performance of indirect reference evapotranspiration estimation methods from

Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 of Radiation and Blaney-Criddle-Frevert compared with the FAO Penman–Monteith standard method.

4 MATERIALS AND METHODS

The research was developed on the basis of data from the conventional meteorological station of a provisional normal from 2008--2017, obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET, 2022) for the locality of Benjamin Constant, AM (World Meteorological Organization - WMO: 82410), latitude 4.378611° South and longitude 70.03° West, at 78.41 m altitude.

According to Köppen and Geiger, Benjamin Constant's climate classification, AM, is tropical, “ Af ”, with significant rainfall throughout the year, an average of 2,876 mm and an average annual temperature of 25.5 °C (CLIMATE -DATA. ORG, 2023).

The meteorological variables considered in this investigation were as follows: air temperature (dry bulb and wet bulb, maximum, minimum and compensated average); relative air humidity (minimum and average compensated); atmospheric pressure; heatstroke (ALLEN; PEREIRA; RAES, 1998); and photoperiod and wind speed. They were used to calculate daily ETo estimates via the standard FAO-56 Penman–Monteith method and the methods compared to it, which included the following methods: Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO-24 of Radiation and Blaney-Criddle-Frevert. The values for these variables were tabulated via Microsoft Excel spreadsheets.

The estimate of $_{\text{daily}}$ ET via the FAO-56 method (Penman–Monteith) was computed via Equation 1 (ALLEN; PEREIRA; RAES, 1998).

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

where ET_o is the reference potential evapotranspiration (mm d $^{-1}$); Δ is the slope of the saturation vapor pressure curve (kPa °C $^{-1}$); R_n is the daily net radiation (MJ m $^{-2}$ d $^{-1}$); G is the heat flux in the soil (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 $^{-1}$); $_s$ is the vapor saturation pressure (kPa); and e e e_a is the current vapor pressure of the air (kPa).

The daily average saturating water vapor content (e_s) was calculated according to Equation 2 of Tetens (1930), considering that the air temperature (T_{air}) was equal to the temperature of the dry bulb thermometer (T_s). Similarly, the temperature of the wet bulb thermometer (T_u) was used to determine the “e_{su}”. The vapor current pressure (e_a) was obtained via Equation 3.

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

$$e_a = es_u - A\,P\,(T_s - T_u) \qquad (3)$$

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

The slope of the saturation vapor pressure curve was calculated according to Equation (4).

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

where T_{mc} = average air temperature compensated at 2 m height, in °C.

The psychrometric constant was estimated from Equations 5 and 6, and when its calculation was not possible, the tabulated value was adopted.

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

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

where C_p is the specific heat at constant pressure, 1.013×10^{-3} (MJ kg $^{-1}$ °C $^{-1}$); P is the atmospheric pressure (kPa); ε is the molecular weight coefficient of dry air water vapor (-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 was calculated via Equation (7).

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

where T is the average monthly air temperature for month i (°C) and T is the average monthly temperature of the previous month ai (°C).

The radiation balance (Rn) is the difference between the shortwave radiation balance (Rns) and the longwave radiation balance (Rnl). Its calculation involves the use of Equations 8 to 16.

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

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

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

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

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

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

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

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

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

where Q_g represents global solar air deferral (MJ m $^{-2}$ day $^{-1}$); coefficients a = 0.25 and b = 0.50 (Bernardo; Soares; Mantovani, 2006); What a represents air adiation at the top of the atmosphere (MJ m $^{-2}$ day $^{-1}$); G_{sc} represents a constant, 0.0820 (MJ m $^{-2}$ min $^{-1}$); σ represents the Stefan–Boltzmann constant, 4.903 x 10 $^{-9}$ (MJ m $^{-2}$ day $^{-1}$); R represents air solar deferral on a cloudless day (MJ m $^{-2}$ day $^{-1}$); Z represents the altitude of the location (m); d r represents the Earth–Sun relative distance; J represents the Julian day; δ represents the solar declination (radians); Φ represents the local latitude (radians); ω_s represents the radiation angle at the time of sunset (radians); $T_{x,k}$ represents the maximum temperature observed during the 24-hour period (K); and $T_{n,k}$ represents the minimum temperature observed during the 24-hour period (K).

The estimate of daily ET via the Blaney and Criddle (1950) method was calculated via Equation 17 (PEREIRA; VILLA NOVA; SEDIYAMA, 1997).

$$ET_o = (0{,}457 * T_{mc} + 8{,}13) * \mathrm{p} * \mathrm{c} \qquad (17)$$

where ET is the reference potential evapotranspiration (mm month $^{-1}$); T $_{mc}$ is the compensated average air temperature (°C); “p” is the monthly percentage of annual hours of sunlight; and “c” is the regional adjustment coefficient of the equation (BERNARDO; SOARES; MANTOVANI, 2006).

The daily ET estimate via the Camargo method (1971) was calculated according to Equation 18 (PEREIRA; VILLA NOVA; SEDIYAMA, 1997; PEREIRA; ANGELOCCI; SENTELHAS, 2007).

$$ET_o = \mathrm{Q_o} * \mathrm{T_{mc}} * \mathrm{k_f} * \mathrm{ND} \qquad (18)$$

where ET $_o$ is the reference evapotranspiration (mm d $^{-1}$); Q is the extraterrestrial solar radiation (mm d $^{-1}$ of equivalent evapotranspiration); T $_{mc}$ is the compensated 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.

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

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

where ET 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 $_{mc}$ is the compensated average air temperature (°C); Q 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 Jensen and Haise (1963) method was obtained via Equation 20 (PEREIRA; VILLA NOVA; SEDIYAMA, 1997).

$$ET_o = \mathrm{R_s}(0{,}0252 * T_{mc} + 0{,}078) \qquad (20)$$

where ET $_o$ is the reference potential evapotranspiration (mm month $^{-1}$); Q $_g$ is the global solar radiation (mm d $^{-1}$); and T $_{mc}$ is the average air temperature (°C).

The estimate of daily ET via the Thornthwaite method (1948) was obtained via Equation 21 (PEREIRA; ANGELOCCI; SENTELHAS, 2007).

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

where ET0 is the reference potential evapotranspiration (mm month $^{-1}$), ETP is the standard evapotranspiration (mm month $^{-1}$), and color 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).

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

where ET $_o$ is the reference potential evapotranspiration (mm month $^{-1}$); ET $_T$ is the daily potential evapotranspiration (mm d $^{-1}$); and color is the evapotranspiration correction factor.

The estimate of daily ET via the Makkink method (1957) was obtained via Equation 23 (PEREIRA; VILLA NOVA; SEDIYAMA, 1997; TURCO; PERECIN; PINTO JR, 2008).

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

where ET $_o$ is the reference potential evapotranspiration (mm d $^{-1}$); Q $_g$ is the measured or estimated global solar radiation, mm d $^{-1}$; and W is the weighting factor, estimated via 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 FAO-24 radiation method, adapted from Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1994) via the Makkink (1957) method, was calculated via Equation (24).

$$ET_o = \mathrm{c\,W}\,Q_g \quad (24)$$

where ET0 is the reference potential evapotranspiration (mm d $^{-1}$); c is a parameter that is a function of relative air humidity and wind speed; and W is defined in Makkink's method.

The estimate of daily ET via the Blaney and Criddle (1950) method, adapted from Frevert, Hill and Braaten (1983) and referring to the Blaney–Criddle–Frevert method, was calculated via Equation 25 (FERNANDES *et al.*, 2010).

$$ET_o = \mathrm{a} + \mathrm{b} * \mathrm{p}(0{,}457 * T_{mc} + 8{,}13) \quad (25)$$

where ET $_o$ is the reference potential evapotranspiration (mm d $^{-1}$); “a” and “b” are the coefficients; “p” is the monthly percentage of annual hours of sunlight; and T $_{mc}$ is the average air temperature (°C).

ET estimates were analyzed via linear regression (Equations 26 to 30), with the Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, and FAO-24 radiation methods used as the dependent variable (Y). and Blaney-Criddle-Frevert, and as an independent variable (X), the ET values are estimated via the Penman–Monteith-FAO 56 method.

$$\mathrm{Y} = \beta_0 + \beta_1 \mathrm{X} \quad (26)$$

where Y is the estimated value for empirical methods; β $_1$ is the angular coefficient; β $_0$ is the linear coefficient; and X is the value estimated by the standard Penman–Monteith–FAO 56 method.

$$\beta_0 = Y - \beta_1 X \quad (27)$$

$$\beta_1 = \frac{S_{xy}}{S_{xx}} \quad (28)$$

$$S_{xy} = \sum(X_t - \bar{X})(Y_t - \bar{Y}) \quad (29)$$

$$S_{xx} = \sum(X_i - \bar{X})^2 \quad (30)$$

where S $_{xx}$ is the sum of squares of the independent variable (FAO standard model - 56 Penman–Monteith); S $_{xy}$ is the sum of the products of the models involved in the analysis; X $_t$ is the value of the independent variable; $\dot{X}$ is the mean of the independent variable; Y $_t$ is the value of the dependent variable (models in comparison); and $\bar{Y}$ is the mean of the variables of the compared model.

Using Equation 31, the correlations between the Penman–Monteith–FAO 56 method and the empirical methods were calculated, and the correlation coefficient (r) was calculated. This coefficient 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.

$$\mathrm{r} = \sqrt{\frac{[\sum(\mathrm{X_i} - X_m)(\mathrm{Y_i} - Y_m)]^2}{\sum(\mathrm{X_i} - X_m)^2 \sum(\mathrm{Y_i} - Y_m)^2}} \quad (31)$$

where X $_i$ is the value estimated via the Penman–Monteith FAO 56 method; X $_m$ is the mean of the Penman–Monteith FAO 56 method; Y $_i$ is the value estimated via the evaluated method; and Y $_m$ is the average of the evaluated methods.

The accuracy in estimating ET in relation to the standard model was obtained by calculating the index “d” (Equation 32), which varies from 0 to 1 (WILLMOTT; CKLESON; DAVIS, 1985).

$$d = 1 - \left[\frac{\sum(Y_i - X_i)^2}{\sum(|Y_i - X_m| + |X_i - X_m|)^2}\right] \qquad (32)$$

The safety coefficient or performance “c” (Table 1) was calculated by 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	Sufferable
0.41 to 0.50	Bad
≤ 0.40	Terrible

The quantification of the standard error of the estimate (EPE) was obtained via equation 33. The adjusted standard error of the estimate (EPEA) of the regression was calculated according to equation 34 and through the relationship of the mean values, expressed as a percentage (Equation 35). 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).

$$EPE = \sqrt{\frac{\sum(X_i - Y_i)^2}{n-1}} \qquad (33)$$

$$EPE = \sqrt{\frac{\sum(Y_i - \hat{Y})^2}{n-2}} \qquad (34)$$

$$\% = \left(\frac{Y_i}{X_i}\right) * 100 \qquad (35)$$

where X $_i$ is the ET estimate via the standard Penman–Monteith FAO 56 model; Y $_i$ is the ET estimate obtained via each of the models evaluated; and en is the number of observations.

5 RESULTS AND DISCUSSION

In the North Region, there are few studies on reference potential evapotranspiration. Aware that there is an insufficient amount of information on local meteorological variables and the relevance of this information for agronomic and agricultural planning in the city of Benjamin Constant, AM, a provisional normal was prepared with recent historical data (2008--2017), which include air temperature (minimum, maximum and compensated average), relative air humidity, wind speed at 2 meters above the local surface, global solar radiation and insolation (Table 2).

Table 2. Provisional normal from 2008--2017 in the municipality of Benjamin Constant, AM

Months	T_n	T_x	T_{mc}	UR_{mc}	U_2	Q_g	n
		°C		%	m s^{-1}	MJ m^{-2} d^{-1}	h
Jan.	22,75	31,16	26,11	89,78	0,45	15,04	3,52
Fev.	22,75	31,30	26,22	89,59	0,48	14,82	3,29
Mar.	22,68	31,74	26,35	89,52	0.45	15,03	3,70
Abr.	22.75	31,89	26,46	89,53	0.46	14,89	4,28
Me.	22,72	31,65	26,32	89,87	0.47	13,79	4,21
Jun.	22,14	31,43	25,89	89,81	0.51	12,87	3,69
Jul.	21,53	31,69	25,70	88,56	0,50	15,91	5,39
Ago.	21,77	32,80	26,25	87,20	0,47	18,40	6,27
Set.	22,16	33,16	26,63	85,73	0,53	18,97	6,10
Out.	22,69	32,75	26,73	86,58	0,50	16,94	4,77
Nov.	22,97	32,56	26.88	87.20	0.55	16.95	4.95
Ten.	22.93	31.86	26.44	88.58	0.45	14.38	3.28

Source: Authors (2024). Monthly mean minimum (T_n), maximum (T_x) and compensated mean (T_{mc}) temperatures; compensated mean relative humidity (RH_{mc}); wind speed (U_2); global solar radiation (Q_g); and insolation (n).

In the provisional normal (Table 2), it appears that the air temperature varied, with a minimum ranging between 21.53 °C (July) and 22.97 °C (November); the maximum between 31.16 °C (January) and 33.16 °C (September); and the offset average between 25.70 °C (July) and 26.88 °C (November). The lowest total amplitude was observed at the compensated mean temperature (1.18 °C). Unlike what was found in the present study for the municipality of Benjamin Constant, Am, both Barbosa *et al*. (2022), like Teixeira Filho, Barbosa and Ferreira (2023), when developing studies in Amazonian municipalities, reported a lower total amplitude in the minimum temperature, whose values were 0.94 °C and 1.51 °C, respectively.

The average relative humidity remained above 85.73% in the month of September (Table 2), even in the Amazonian summer, which demonstrates that the local atmosphere had high humidity, and under these conditions, the demand for water was lower, which would culminate in a lower demand for potential evapotranspiration.

The loss of water to the atmosphere can be increased by wind speed, which leads to an increase in evapotranspiration rates; however, the wind speed at a height of two meters did not reach 1.0 ms $^{-1}$, with its maximum speed being recorded in March, equal to 0.55 ms $^{-1}$ (1.98 km h $^{-1}$). The minimum, equal to 0.45 ms $^{-1}$ (1.62 km h $^{-1}$), was repeated in the months of January, March and December. Notably, this parameter fluctuated little throughout the year (Table 2). The minimum and maximum values fall on the Beaufort scale as winds of force 0 and 1, respectively, designated, in that order, calm and fog. According to Teixeira Filho, Barbosa and Ferreira (2023), these wind categories can favor agricultural planning activities in the region, as well as decision-making in operations to be carried out in agriculture.

The amount of water evapotranspired depends mainly on the plant, the soil and the climate, with the latter factor being predominant over the others, so that the amount of water required by a crop varies with the extent of the area covered by the plant and with the season. year (Bernardo; Soares and Mantovani, 2006). Table 3 shows the daily averages of reference evapotranspiration (ET) for the municipality of Benjamin Constant, AM, for each method evaluated in comparison with the FAO 56 Penman–Monteith method.

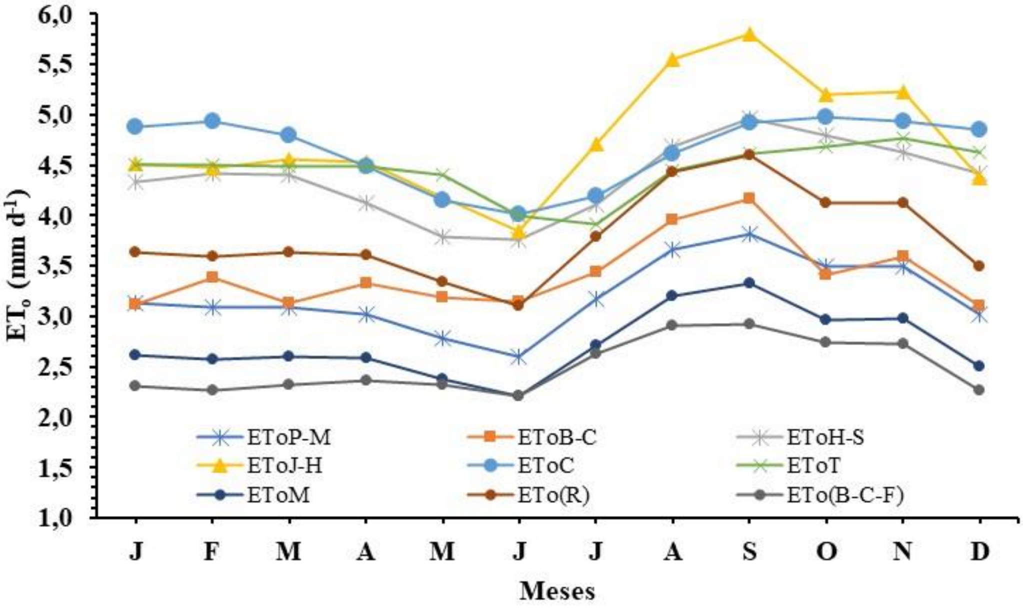
Table 3. Variation in daily average reference potential evapotranspiration ($_{ETo}$, mm d^{-1}) for the municipality of Benjamin Constant, AM

Months	**J**	**F**	**J**	**F**	**J**	**F**	**J**	**F**	**J**	**F**	**J**	**F**	**Average**	**ME-PM** *
$ET_{o\,(PM)}$	3.13	3.08	3.09	3.02	2.78	2.60	3.17	3.66	3.82	3.50	3.49	3.02	3.20	-
$ET_{o\,(BC)}$	3.12	3.39	3.12	3.33	3.18	3.15	3.43	3.96	4.17	3.41	3.58	3.10	3.41	0.21
$ET_{o\,(HS)}$	4.34	4.41	4.40	4.13	3.78	3.76	4.11	4.69	4.96	4.79	4.63	4.42	4.37	1.17
$ET_{o\,(JH)}$	4.52	4.47	4.55	4.53	4.17	3.84	4.71	5.56	5.80	5.20	5.23	4.37	4.74	1.55
$ET_{o\,(C)}$	4.88	4.93	4.79	4.48	4.15	4.01	4.19	4.61	4.92	4.97	4.94	4.85	4.64	1.45
$ET_{o\,(T)}$	4.49	4.49	4.49	4.48	4.41	4.00	3.92	4.44	4.61	4.68	4.76	4.63	4.45	1.25
$ET_{o\,(M)}$	2.61	2.57	2.60	2.59	2.38	2.20	2.71	3.20	3.33	2.97	2.97	2.49	2.72	-0.48
$ET_{o\,(R)}$	3.64	3.58	3.64	3.61	3.34	3.10	3.78	4.43	4.60	4.12	4.12	3.49	3.79	0.59
$ET_{o\,(BCF)}$	2.31	2.26	2.26	2.36	2.32	2.21	2,62	2,91	2,92	2,74	2,73	2,27	2,49	-0,71

Source: Authors (2024). $^{(*)}$ Difference between the reference evapotranspiration means of the empirical methods and the mean of the FAO-56 standard method. Methods of Penman–Monteith [$\mathbf{ET_{o\,(PM)}}$], Blaney-Criddle [$\mathbf{ET_{o\,(BC)}}$], Camargo [$\mathbf{ET_{o\,(C}}$], Hargreaves- Samani [$\mathbf{ET_{o\,(HS)}}$], Jensen-Haise [$\mathbf{ET_{o\,(JH)}}$], Thornthwaite [$\mathbf{ET_{o\,(T)}}$], Thornthwaite-Camargo [$\mathbf{ET_{o\,(TC)}}$], Makkink [$\mathbf{ET_{o\,(M)}}$], FAO 24 da Radiação [$\mathbf{ET_{o\,(R)}}$] and Blaney-Criddle-Frevest [$\mathbf{ET_{o\,(BCF)}}$].

The Makkink and Blaney-Criddle-Frevest models (Table 3, Figure 1) underestimate ET during all months of the year, with differences between the mean ET values varying between -0.40 and -0.49 mm d^{-1} in the Makkink method and between -0.40 and -0.90 in the Blaney-Criddle-Frevest method. In accordance with this investigation, Araújo, Costa and Santos (2007) reported that for Boa Vista, RR, an underestimation, in all months of the year, of evapotranspiration calculated via the standard Penman–Monteith method.

Figure 1. Variation in daily average reference potential evapotranspiration (ETo, mm d^{-1}) for the municipality of Benjamin Constant, AM.



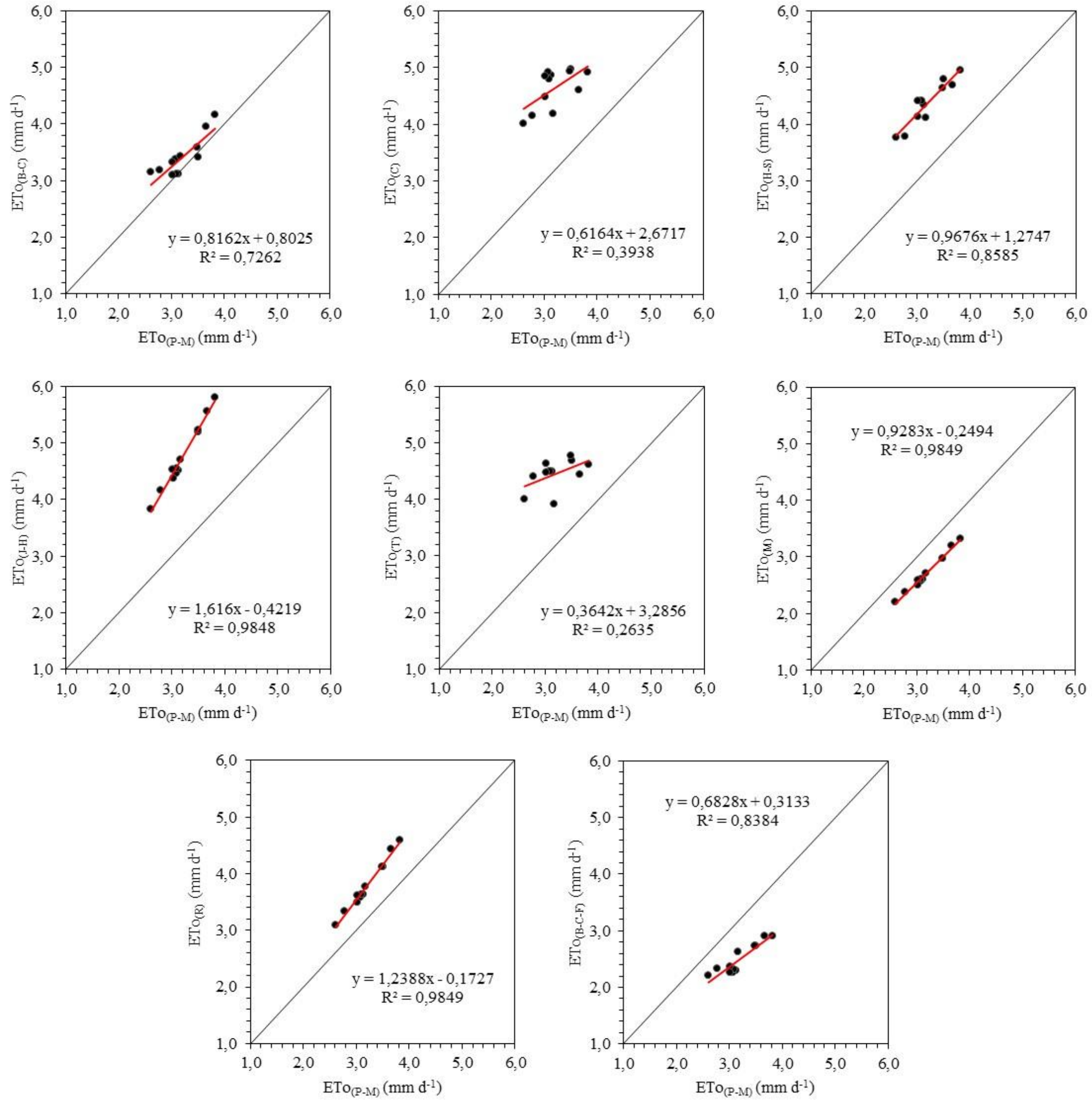
Source: Métodos de: Penman–Monteith [$\mathbf{ET_{o\,(PM)}}$], Blaney-Criddle [$\mathbf{ET_{o\,(BC)}}$], Camargo [$\mathbf{ET_{o\,(C}}$]), Hargreaves-Samani [$\mathbf{ET_{o\,(HS)}}$], Jensen- Haise [$\mathbf{ET_{o\,(JH)}}$], Thornthwaite [$\mathbf{ET_{o\,(T)}}$], Thornthwaite -Camargo [$\mathbf{ET_{o\,(TC)}}$], Makkink [$\mathbf{ET_{o\,(M)}}$], FAO 24 da Radiação [$\mathbf{ET_{o\,(R)}}$] e Blaney- Criddle-Frevest [$\mathbf{ET_{o\,(BCF)}}$].

The overestimation of ET was verified in 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 0.50 and 0.78 mm d^{-1}, respectively. For the Blaney–Criddle method, an overestimation of ET was observed in the months of February, March, April, May, June, July, August, September, November and December, which varied between 0.50 and 0.35 mm d^{-1}. Two underestimates were observed for the months of January, equal to -0.01 mm d$^{-1,}$ and for October, equal to -0.09 mm d^{-1} (Table 3, Figure 1).

In studies developed by Barbosa *et al*. (2022), Carvalho and Delgado (2016), Ferraz (2008), Ferreira *et al*. (2020) and Souza and Sousa (2020) in municipalities in the North Region, a tendency to overestimate the reference potential evapotranspiration was also observed via the Blaney-Criddle, Camargo, Jensen-Haise, Thornthwaite and FAO 24 Radiation methods during all months of the year. This presupposes a tendency in the behavior of these models adjusted to Penman–Monteith in regions whose climate is classified into group A according to the Köppen Climate Classification, which characterizes areas with a megathermal, rainy tropical climate, which have an average annual precipitation above 700 mm and an average temperature in the coldest month above 18 °C (ALMEIDA, 2016).

Correlation measures the degree of relationship between two variables, resulting in a mathematical equation that can be adopted or rejected if the adjustment is not recommended. Thus, the existence or absence of a functional relationship was measured between the monthly average ET values estimated via the Penman–Monteith–FAO 56 method and the methods of Blaney–Criddle, Camargo, Hargreaves–Samani, Jensen–Haise, Thornthwaite, Makkink, FAO 24 Radiation and Blaney–Criddle–Frevert (Figure 2).

Figure 2. Linear regression between the daily average reference potential evapotranspiration values ($_{\text{ETo}}$, mm d $^{-1}$) for the municipality of Benjamin Constant, AM



Font: Autores (2024). Models: Blaney-Criddle [**ET** **o (BC)**], Camargo [**ET** **o (C)**], Hargreaves- Samani [**ET** **o (HS)**], Jensen- Haise [**ET** **o (JH)**], Thornthwaite [**ET** **o (T)**], Thornthwaite -Camargo [**ET** **o (TC)**], Makkink [**ET** **o (M)**], FAO 24 da Radiação [**ET** **o (R)**] e Blaney-Criddle-Frevest [**ET** **o (BCF)**] eo method standardo Penman - Monteith [**ET** **o (PM)**].

In the functional relationship, we are interested in the function that explains a large part of the Blaney-Criddle, Camargo, Hargreaves-Samani, Jensen-Haise, Thornthwaite, Makkink, FAO 24 Radiation and Blaney-Criddle-Frevert variation in relation to the standard Penman–Monteith. However, a portion of the model variability not explained by the standard method will be attributed to chance, that is, to random error.

Among the models evaluated, Jensen-Haise, Makkink and FAO 24 of Radiation (Figure 2) presented the best correlations for the period studied (R^2 =

0.98), and the worst correlation (R ^{2} = 0.26) was from Thornthwaite, which presented pairs of scattered points on the regression line (Figure 2).

The Thornthwaite model presented an observed “t” test value of 1.68, which was lower than the critical “t” value for 10 degrees of freedom of 2.23 at 95% confidence. Thus, the null hypothesis is maintained; that is, there is no evidence that the Penman–Monteith FAO 56 model affects the behavior of the Thornthwaite model. In fact, the coefficient of determination (R ^{2} = 0.26) was low (Figure 2). The occurrence of a reduced coefficient of determination (R ^{2}) makes the proposed estimates unreliable, either because of the instability of the studied variable or because the tested model is not suitable for the dispersion of the observed results (SAMPAIO, 1998). Furthermore, although the use of this method is considered for humid regions, the fact that it is based only on temperature can lead to erroneous results, as temperature is not a good indicator of the energy available for evapotranspiration (PORTO, 1986).

The Samani method (Figure 2) presented the angular coefficient of the regression equation (+0.9676) closest to 1, followed by the Makkink (+0.9283), Blaney-Criddle (+0.8162), FAO 24 Radiation methods (+ 1.2388), Blaney-Criddle-Frevert (+ 0.6826), Camargo (+0.6164), Jensen-Haise (+1.6160) and Thornthwaite (+0.3642) methods (Figure 2). These coefficients indicate that for every 1 mm d $^{-1}$ of water evapotranspiration, in the interval of the historical series considered, the ET increases by an average of 0.3642 mm d $^{-1}$ and 1.6160 mm d $^{-1}$.

The linear coefficient of the line is the point at which the line intersects the y axis, so when x=0, y = n. Of the coefficients obtained, the closest to zero was observed in the FAO 24 Radiation model (-0.1727), followed by Makkink (-0.2494), Blaney-Criddle-Frevert (- 0.3133), Jensen-Haise (-0.4219), Blaney-Criddle (+0.8025), Hargreaves-Samani (+1.2747), Camargo (+2.6710) and Thornthwaite (+3.2856) (Figure 2).

Table 4 shows that the standard error of the estimate varied between 0.29 and 1.63 mm d $^{-1}$, with the Blaney-Criddle, Makkink, FAO 24 Radiation and Blaney-Criddle-Fvert models presenting the lowest values, which demonstrates their accuracy in relation to the ET values obtained via the standard Penman–Monteith method.

Table 4. Statistical coefficients analyzed for the municipality of Benjamin Constant, AM

Models	**%**	**EPE**	**EPEA**	**d**	**r**	**R2**	**w**	**Performance**
		mm d $^{-1}$						
Blaney-Criddle	106.72	0.29	0.19	1.00	0.85	0.73	0.85	Excellent
Camargo	145.22	1.54	0.29	0.96	0.63	0.39	0.60	Sufferable
Hargreaves - Samani	136.63	1.23	0.15	0.97	0.93	0.86	0.90	Excellent
Jensen- Haise	148.41	1.63	0.08	0.96	0.99	0.98	0.95	Excellent
Thornthwaite	139.20	1.35	0.23	0.97	0.51	0.26	0.50	Bad
Makkink	85.03	0.50	0.04	0.99	0.99	0.98	0.98	Excellent
FAO-24 of Radiation	118.48	0.63	0.06	0.99	0.99	0.98	0.98	Excellent
Blaney-Criddle-Frevest	78.09	0.75	0.11	0.98	0.92	0.84	0.90	Excellent

Source: Authors (2024). Percentage in relation to the standard Penman–Monteith method (%), standard error of estimate (EPE, mm d $^{-1}$), adjusted standard error of estimate (EPEA, mm d $^{-1}$), correlation coefficient (r), coefficient of determination (R²), agreement index (d), performance coefficient (c) and classification based on the performance coefficient.

The adjusted standard error of the estimate (EPEA) ranged from 0.04 to 0.29 mm d $^{-1}$, with the lowest values observed in Makkink, FAO-24 Radiation, Jensen-Haise, Blaney-Criddle-Frevert, Hargreaves-Samani and Blaney-Criddlle (Table 4). This confirms that the regression line fits very well with the data from the models investigated since the values of the determination coefficients are high. Furthermore, the standard error demonstrates that the dependent variable (tested models) is close to its predicted value.

The methods of Makkink (c = 0.98), FAO 24 of Radiation (0.98), Jensen-Haise (0.95), Hargreaves-Samani (0.90) and Blaney-Criddle-Frevert (0.90) and Blaney-Criddlle (0.85) presented excellent performance coefficients (Table 4). Teixeira Filho, Barbosa and Ferreira (2023), evaluating the performance of reference evapotranspiration estimation methods for the municipality of Manicoré, AM, also reported that the Hargreaves-Samani, Jensen-Haise and FAO-24 radiation models presented “large” coefficients of performance. Ferreira *et al* . (2020), when comparing several methods for the municipality of Parintins, AM also classified the Jensen–Haise model with “excellent” performance (c = 0.85). While Araújo, Costa and Santo (2007), using the Blaney-Criddle model for the location of Boa Vista, RR, also obtained “excellent” performance (c = 0.92).

Unlike the present study, Mendoza, Menezes and Dias (2016) classified the Hargreaves–Samani method estimates as “average” 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).

Visser (1964) stated that, as long as water absorption by a plant is maintained in proportion to loss, there will be no deficit. Like the Makkink, FAO 24 Radiation, Jensen-Haise, Hargreaves-Samani, Blaney-Criddle-Frevert and Blaney-Cleddle models achieve excellent performance (Table 4) and can be used in the absence of data that allow the calculation of the ET $_{or}$ by Penman–Monteith.

Camargo's model showed “poor” performance, and Thornthwaite's model showed “poor” performance (Table 4). Souza and Sousa (2020) evaluated Thornthwaite's method (c = 0.64) as “average” performance and Camargo's method (c = 0.33) as “terrible” performance for the region of Rio Branco, AC. The unsatisfactory performance of this method can be attributed to the simplicity of its equation, which results in less precision, as it presents a reduced number of input parameters for estimating evapotranspiration (SANTANA *et al*., 2018). Thus, if there is a delay in water absorption in relation to losses, deficits will arise that can irreversibly reduce the potential production of crops (VAADIA *et al*., 1961; KRAMER, 1963).

Importantly, if there is a delay in water absorption in relation to losses, deficits will arise that can irreversibly reduce the potential production of crops (VAADIA *et al*., 1961; KRAMER, 1963). Therefore, care must be taken when choosing the method for estimating ET, which may vary depending on the location.

6 CONCLUSION

The methods that were best adjusted to the standard Penman–Monteith method were Makkink, FAO 24 Radiation, Jensen– Haise, Hargreaves– Samani, Blaney–Criddle–Frevert and Blaney–Criddlle, which presented “excellent” performance for the municipality of Benjamin Constant, AM.

Camargo's model showed “poor” performance and can be recommended after local adjustments.

Thornthwaite's model showed “poor” performance and cannot be recommended due to its low accuracy and precision in relation to the standard method.

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