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DESEMPENHO DE MODELOS PARA ESTIMATIVA DA EVAPOTRANSPIRAÇÃO DE REFERÊNCIA NA MICRORREGIÃO DE TOMÉ AÇÚ-PA

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1 RESUMO

A estimativa da evapotranspiração de referência (ETo) é um parâmetro que permite o gerenciamento das atividades agrícolas de uma região e o uso racional dos recursos hídricos, possibilitando o cálculo do volume de água a ser aplicado. Objetivou-se neste trabalho, avaliar o desempenho de métodos empíricos para o cálculo da evapotranspiração de referência na microrregião de Tomé-Açu, no estado do Pará, Brasil. O desempenho dos modelos simplificados foi verificado por meio de regressão linear simples, utilizando os indicadores estatísticos *Mean Bias Error* (*MBE*), *Relative Mean Bias Error* (rMBE), *Root Mean Square Error* (*RMSE*) e *Relative Root Mean Square Error* (*rRMSE*). Os modelos que apresentam menor dispersão dos dados, em comparação com a equação padrão de Penman Monteith, foram Jensen-Haise, Hargreaves-Samani, Turc, Makkink e Priestley-Taylor. Ao análisar a acurácia dos modelos, verificou-se que os modelos de Hargreaves-Samani, Makkink e Camargo foram classificados como bons. Os métodos de Linacre, Blaney-Criddle e Jensen-Haise não são recomendados para a microrregião de Tomé-Açu. Na falta dos dados necessários para estimativa da evapotranspiração de referência pelo método padrão de Penman-Monteith – FAO 56, a equação que obteve melhor ajuste foi o modelo de Hargreaves-Samani, podendo ser aplicada para a região em estudo.

Palavras-chave: Região Norte, Penman-Monteith, Hargreaves-Samani.

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PERFORMANCE OF MODELS TO ESTIMATE THE REFERENCE EVAPOTRANSPIRATION IN THE TOMÉ AÇÚ-PA MICROREGION

2 ABSTRACT

The estimation of reference evapotranspiration (ETo) is a parameter that allows the management of agricultural activities in a region and the rational use of water resources, enabling the calculation of water volume to be applied. This study aimed to evaluate the performance of empirical methods to calculate the reference evapotranspiration in the microregion of Tomé-Açú, in the state of Pará, Brazil. The performance of the simplified models was verified through simple linear regression, using the statistical indicators Mean Bias Error (MBE), Relative Mean Bias Error (rMBE), Root Mean Square Error (RMSE), and Relative Root Mean Square Error (rRMSE). The models that presented lower data dispersion were Jensen-Haise, Hargreaves-Samani, Turc, Makkink, and Priestley-Taylor, compared to the standard equation of Penman-Monteith. When analyzing the accuracy of the models, the models of Hargreaves-Samani, Makkink, and Camargo were classified as good. The models of Linacre, Blaney-Criddle, and e Jensen-Haise are not recommended to the microregion of Tomé-Açu. In the lack of the necessary data to estimate the reference evapotranspiration by the standard method of Penman-Monteith - FAO 56, the equation that obtained the best adjust was the model of Hargreaves-Samani. Thus, it may be applied for the studied region.

Keywords: North Region, Penman-Monteith, Hargreaves-Samani.

3 INTRODUCTION

Recent climate change has the potential to have significant impacts on water resources globally. Among the many consequences of global warming is climate change, which alters regional weather patterns and consequently leads to changes in rainfall and evapotranspiration patterns (SOUZA FILHO *et al*., 2016).

Agriculture activities are heavily influenced by climate variations, which can affect crop productivity, crop management, and product quality. Extreme rainfall, hail, frost, or prolonged droughts can influence agricultural practices (DUARTE; WOLLMANN, 2017). This dependence is primarily due to the availability of soil water; however, this dependence can be mitigated through the use of irrigation.

Owing to increasing scarcity, rational management of water resources in irrigated agriculture, which requires knowledge about crop water consumption, is essential. Andrade *et al*. (2016) state that there are different processes applicable for adequate irrigation management, and among these, those that use the estimate of reference evapotranspiration (ETo) as a parameter stand out, such as in the proposal by Doorenbos and Pruitt (1977), in which the calculation of crop evapotranspiration (ETc) is obtained through the product between the evapotranspiration of a reference crop and a crop coefficient (Kc).

Evapotranspiration consists of the process of water loss from the soil through evaporation and transpiration by plants into the atmosphere. Therefore, it is an essential parameter for the hydraulic design of irrigation systems and water management

(OLIVEIRA *et al*., 2017). The Food and Agriculture Organization of the United Nations (FAO) recommends estimating ETo via the method proposed by Penman–Monteith, published in FAO Bulletin 56, which is used as a basis for estimating ETo and for calibrating existing models (ALLEN *et al*., 1998).

The Penman–Monteith equation (FAO-56) is recommended as a standard method for estimating ETo, but its use is limited because of the amount of information required by the model. The equation's input variables are not always available because of the investments required for the acquisition and maintenance of sensors (PALARETTI; MANTOVANI; SEDIYAMA, 2014a).

In the Penman–Monteith equation, there are simplified methods for determining ETo, which require fewer climatic variables. In the absence of climatic data for determining ETo via the standard method, the FAO Bulletin 56 recommends other methods, such as the model developed by Hargreaves-Samani, which can be used to determine ETo when only air temperature and solar radiation data are available (ALLEN *et al*., 1998). In the Amazon region, the distribution of meteorological stations is irregular; furthermore, there are limitations in obtaining data, such as the possibility of recording errors and/or difficult access for equipment maintenance, which limits the study of climatic variables (SOUTO; TAVARES; BELTRÃO, 2019).

Determining ETo is essential for designing irrigation projects and managing irrigation, as it allows us to determine crop water demand. Although irrigation is a widely used technology, particularly in regions experiencing water scarcity due to lower rainfall, in regions with greater rainfall, such as the state of Pará, this technique is used during periods of lower rainfall to supplement crop water demand. Therefore, studies on simplified methods for this region are crucial.

The municipality of Tomé-Açu is located in the Mesor region of Northeast Pará, in the microregion of the same name, and is considered one of the most important commercial agricultural development hubs in the state of Pará, in which irrigated cultivation systems are used (BELATO; SERRÃO, 2019).

Considering the importance of the Tomé-Açu region for the agricultural production of various crops, combined with the need for rational management of water resources, especially in irrigated agriculture, as well as the lack of information necessary to determine the actual water demand of crops, including ETo. Furthermore, empirical models are highly important in the study of ETo; however, it is interesting that research has led to theoretical/methodological innovations. Thus, the objective of this work was to evaluate the efficiency of empirical methods for calculating reference evapotranspiration in the Tomé–Açu microregion in the state of Pará.

4 MATERIALS AND METHODS

4.1 Study location and measurements

The climatological data from the conventional station of Tomé Açu (02° 24'S and 48°09'W), which is part of the Northeast Pará Mesoregion and refers to a period of 12 years (2007--2018), were obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET).

The municipality of Tomé-Açu is located in the central part of northeastern Pará, in the microregion of Tomé-Açu, between the geographic coordinates of 02°54'45" and 03°16'36" S and 47°55'38" and 48°26'44" W, with an altitude of 45 m and a surface area of approximately 5179 km². The microregion is formed by five (5) municipalities: Acará, Concórdia do Pará, Moju, Tailândia and Tomé-Açu (RODRIGUES *et al*., 2001; CORDEIRO *et al.*, 2017).

The municipality of Tomé Açu has a hot and humid climate, which fits the Ami climate type of the Köppen classification, with a well-defined dry season, with the month with the least rainfall of 60 mm and an average annual temperature of 26.4 °C (PACHÊCO; BASTOS; CREÃO, 2009).

4.2 Determining the models used in the research

Excel spreadsheets were used to tabulate the meteorological data. The ETo calculation was subsequently performed via the models of Penman - Monteith, Allen *et al.* (1998), Hargreaves and Samani (1985), Blaney and Criddle (1950), Camargo (1971), Priestley and Taylor (1972), Turc (1961), Makkink (1957), Jensen and Haise (1963) and Linacre (1977) described in Table 1. The tabulated data are daily data; therefore, the ETo (mm day $^{-1)}$ of each day of the evaluated years was estimated through the models described in equations 1, 2, 3, 4, 5, 6, 7, 8 and 9.

$$ETo\ (P\text{-}M) = \frac{0{,}408 * \Delta * (Rn - G) + Y * \frac{900}{Tméd + 273} * U_2 * (es - ea)}{\Delta + Y\,(1 + 0{,}34 * U_2)} \quad (1)$$

$$ETo\ (H\text{-}S) = 0{,}0023 * (Tméd + 17{,}8) * (Tmáx - Tmin)^{0{,}5} * Ra \quad (2)$$

$$ETo\ (B - C) = a + b * (\ p * (\ 0{,}46 * Tméd + 8{,}13\ )) \quad (3)$$

$$ETo\ (C) = F * Qo * Tméd * ND \quad (4)$$

$$ETo\ (P - T) = \frac{\alpha}{\lambda} * \frac{\Delta}{\Delta + \gamma} * (\ Rn - G\ ) \quad (5)$$

$$ETo\ (T) = 0{,}013 * \frac{Tméd}{Tméd + 15} * \frac{23{,}8856 * Rs + 50}{\lambda} \quad \text{para UR} \geq 50 \quad (6)$$

$$ETo\ (M) = 0{,}61 * \frac{\Delta}{\Delta + \gamma} * \frac{Rs}{\lambda} - 0{,}12 \quad (7)$$

$$ETo\ (J - H) = Rs\ (0{,}025 * Tméd + 0{,}078) \quad (8)$$

$$ETo\ (L) = \frac{500 \left(\frac{Tmed + 0{,}006 * h}{100 - \varphi}\right) + 15\ (Tméd - Tpo)}{(80 - Tméd)} \quad (9)$$

where Rn = net radiation, MJ m $^{-2}$ d $^{-1}$; G = ground heat flux, MJ m $^{-2}$ d $^{-1}$; Tméd = average air temperature in °C; U_2 = average daily wind speed at 2 m height (ms $^{-1}$); es = saturation vapor pressure (kPa); ea = true vapor pressure (kPa); Δ = tangent of the saturation vapor pressure curve, in kPa °C $^{-1}$; γ = psychometric constant, kPa °C; Tmáx = maximum air temperature, in °C; Tmin = minimum air temperature, in °C; Ra = extraterrestrial solar radiation, MJ m $^{-2}$ d $^{-1}$; p = percentage of possible sunlight hours in relation to the annual total, for a given month and latitude; URmin = minimum daily relative humidity (%); n = duration of daily sunshine (h); N = maximum possible duration of daily sunshine (h); F = adjustment factor that varies according to the average annual temperature of the location (F = 0.01 for T up to 23 °C; F = 0.0105 for T = 24 °C; F = 0.011 for T = 25 °C; F = 0.0115 for T = 26 °C and F = 0

Notably, the empirical equations have been validated for specific regions and climates, with the equations of Hargreaves and Samani (1985) for arid regions; Blaney and Criddle (1950) for semiarid regions; Camargo (1971) for arid and superhumid climates; Priestley and Taylor (1972) for upper arid regions; Turc (1961) for coastal and humid regions; Makkink (1957) for humid climatic conditions; Jensen and Haise (1963) for arid regions; and Linacre (1977) for subtropical and semiarid climates (FERNANDES *et al.*, 2010).

Considering the limited meteorological data available in the study region and the general variability among climate variables, validation studies for empirical models that utilize fewer climate variables are essential. Although not all equations are validated for the study region, the literature only mentions recommendations for their use. Therefore, in the absence of research and published data for specific regions, it is necessary to apply these equations to validate their use in a specific region, considering that the literature only describes recommended climatic regions for model applicability.

4.3 Model performance evaluation

The models were compared with the standard model that calculates ETo via the Penman–Monteith equation (ALLEN *et al*., 1998). The models were subsequently evaluated on the basis of the degree of correlation, followed by the statistical goodness-of-fit indicators mean bias error (MBE), relative mean bias error (rMBE%), root mean square error (RMSE), relative root mean square error (rRMSE%) and the Willmott concordance index (d). The indices were calculated via equations 1, 2, 3, 4 and 5 (STONE; SELLARS; KRESS, 1979; WILLMONTT, 1981; MA and IQBAL, 1984).

$$MBE = \frac{\sum_{i=1}^{n}(Si-Oi)}{n} \quad (10)$$

$$rMBE(\%) = 100* \frac{\frac{\sum_{i=1}^{n}(Si-Oi)}{n}}{\bar{o}} \quad (11)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(Si-Oi)^2}{n}\right]^{\frac{1}{2}} \quad (12)$$

$$rRMSE(\%) = 100* \left[\frac{\sum_{i=1}^{n}(Si-Oi)^2}{\bar{o}}\right]^{\frac{1}{2}} \quad (13)$$

$$d = 1- \frac{\sum_{i=1}^{n}(Si-Oi)^2}{\sum_{i=1}^{n}([Si-\bar{o}i]+[Oi-\bar{o}])} \quad (14)$$

where Si represents the estimated values at the ith time; Oi represents the measured values at the ith time; O represents the average measured values; and n represents the number of observations. The output unit is the same as the input variable tested mm day $^{-1}$ for BEM, RMSE or percentage (%) for rMBE and rRMSE.

The aforementioned statistical indices allow for assessments of the values found by the models and the values measured in the field. MBE indicates the tendency of models to underestimate (MBE < 1) or overestimate (MBE > 1) predicted values but does not provide information on the spread of the data. The RMSE provides information on the spread of the evaluated data. Willmott's d index can range from 0 to 1 and serves as an indicator of the accuracy of the evaluated model, with values closer to 1 indicating greater accuracy.

The rRMSE is used by some authors as a classification scale for different intervals to evaluate the accuracy of models (HEINEMANN *et al*. , 2012). The classification of the models can be excellent (rRMSE < 10%), good (10% ≤ rRMSE < 20%), acceptable (20% ≤ rRMSE < 30%) or poor (rRMSE ≥ 30%).

In this work, when the rRMSE is greater than or equal to 30%, the terminology "not acceptable" will be used because of better compliance with the technical term.

The statistical indices obtained for the present work were calculated through the development and execution of a *script* in the *software* Microcal™ Origin® version 6.0.

Considering the linear regression of Y with a random variable at time X, the null hypothesis (Ho) that there is no trend was tested via Student's t test with n-2 degrees of freedom. When a trend existed, the null hypothesis was rejected; this occurred when the calculated t was greater, in absolute value, than the critical value of the tabulated t, determined at a significance level of α. In this research, a significance level of 5% was used, with Student's t being calculated via Equation (6), as shown below:

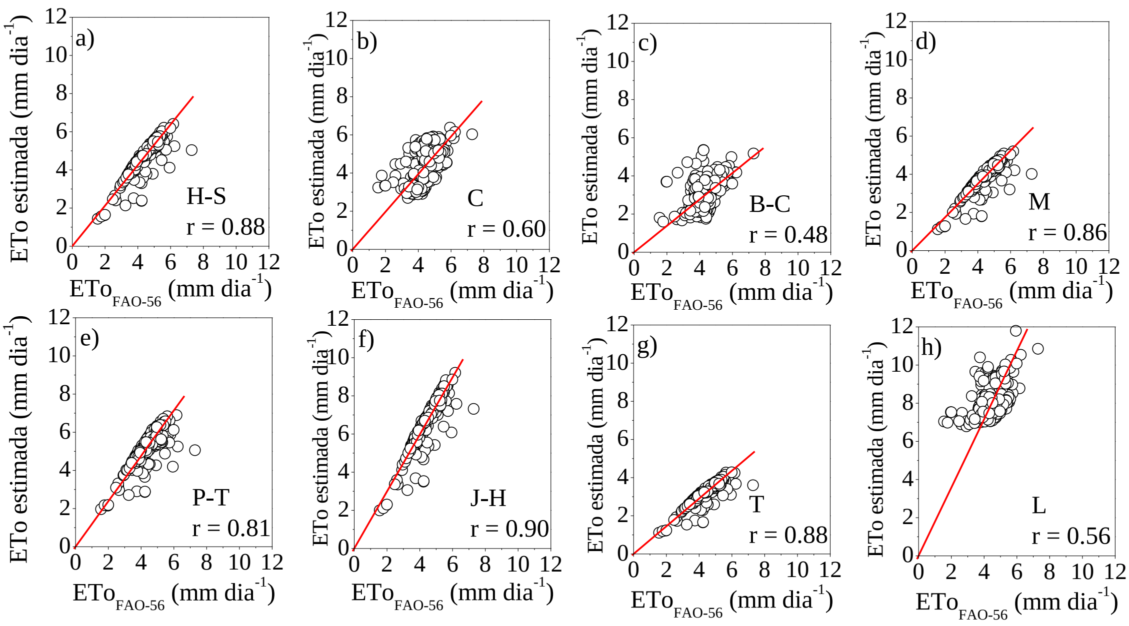
$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} = \frac{\beta 1}{S/\sqrt{SSx}} \qquad (15)$$

where n represents the sample size; r represents Pearson's correlation coefficient; s represents the standard deviation of the residuals; β1 represents the slope of the regression; and SSX represents the sum of the squares of the independent variable.

5 RESULTS AND DISCUSSION

In Figure 2 (a, b, c, d, e, f, g, h), the behavior of the ETo resulting from the simplified methods is presented in relation to the standard method, corresponding to the methods of Hargreaves and Samani, Camargo, Blaney and Criddle, Makkink, Priestley and Taylor, Jensen and Haise, Turc and Linacre, respectively.

Figure 2. Correlations between reference evapotranspiration (ETo) - FAO 56 estimated via the Penman–Monteith method and the evaluated models



Source: Prepared by the authors.

where *HS= Hargreaves and Samani, C= Camargo, BC= Blaney and Criddle, M= Makkink, PT= Priestley and Taylor, JH=Jensen and Haise, T= Turc and L= Linacre.*

The values of the correlation coefficients (r) for a, b, c, d, e, f, g, and h were 0.88, 0.60, 0.48, 0.86, 0.81, 0.90, 0.88 and 0.56, respectively. According to Pisani Júnior, Castro and Costa (2018), the correlation coefficient r aims to measure the degree of linear correlation between two quantitative variables, with values between -1 and 1 reflecting the intensity of a linear relationship between the data.

Thus, through correlation, the Jensen–Haise, Hargreaves–Samani, Turc, Makkink and Priestley and Taylor models presented greater correlations than did the standard model, and for these models, the values presented less dispersion of the data, with values closer to 1. The results corroborate those of Lobato (2019), who, when evaluating the same equations for northeastern Pará, reported values of r higher than 80%; however, for the Hargreaves–Samani equation, the author reported a value of 0.35. Similarly, Carvalho *et al. (2018) reported a value of 0.51 for or,* via the Hargreaves–Samani equation, in the state of Ceará.

The linacre and Blaney-Criddle methods presented the lowest r values, with values of 0.6, 0.56 and 0.48, respectively. Thus, these methods presented greater data dispersion in relation to the other methods, with values greater than 1, making them unreliable models for use in the absence of the necessary data for determining ETo via the standard method (Penman--Monteith FAO 56).

Souza and Sousa (2020), analyzing simplified equations in Rio Branco, AC, a city in Acre that has similar climatic characteristics to Tome Açu, reported low r values for the Linacre and Carmargo equations, corroborating the results of this research. Sanches *et al*. (2015), analyzing simplified equations for some regions of the state of Pará, reported that the Linacre methodology presented the worst fit compared with the standard method.

The Blaney-Criddle method showed low performance, as analyzed by r (0.48), as was reported by Lima *et al*. (2019), who analyzed simplified empirical equations compared with the Penman–Monteith equation for six different climates, reported an r of 0.41 in the correlation of simple linear regression with the Blaney equation. Criddle to Belém, PA.

The Camargo, Linacre, and Blaney-Criddle equations do not use solar radiation as input data, which can result in poor performance compared with the Penman–Monteith FAO-56 equation. Rigoni *et al* . (2013), when evaluating equations that use or do not use solar radiation, highlighted that the equations that presented a low correlation coefficient were those not based on radiation, corroborating the results of this research.

Like the Linacre model, the Blaney-Criddle model was developed to estimate the monthly ETo, and the Camargo model was developed for 10-- to 30-day periods. Therefore, the poor performance may be related to the fact that the models were used on a daily time scale rather than the monthly scale for which they were developed.

Thus, through regression analysis, the simplified Jensen–Haise method for the conditions studied proved to be the most suitable method for determining ETo, as among the methods evaluated, the method that came closest to the standard method presented ~~a~~ correlation coefficient (r) of 0.90.

Hallal *et al*. (2017) reported that methods that consider incident solar radiation on the surface to estimate ETo, such as the Jensen–Hayse method, performed better than the standard method (r = 0.81).

For the Student's t test with a 5% significance level, all simplified equations showed statistically significant trends with the standard model (Table 2).

Table 2. Performance indicators of the simplified equations of Hargreaves and Samani (HS), Camargo (C), Blaney and Criddle (BC), Makkink (M), Priestley and Taylor (PT), Jensen and Haise (JH), Turc (T) and Linacre (L) for the microregion of Tomé-Açu, PA

Models (ETo)	rMBE	MBE	rRMSE	RMSE	d	t
	(%)	(mm day $^{-1}$)	(%)	(mm day $^{-1}$)	(-)	(-)
HS	6.62	0.29	10.73	0.46	0.90	14.70*
W	-1.01	-0.04	18,17	0.79	0.74	1.04*
BC	-30.28	-1.31	34.50	1.49	0.43	34.29*
M	-12.41	-0.54	14.90	0.65	0.79	28.17*
PT	19.80	0.86	22.48	0.97	0.68	34.85*
JH	49.65	2.15	51.31	2.22	0.43	71.76*
T	-27.04	-1.17	28.22	1.22	0.55	62.69*
L	81.97	3.55	83.52	3.61	0.25	95.85*

Source: Prepared by the authors. rMBE*: relative mean bias error; MBE: mean bias error; rRMSE: relative root mean square error; RMSE: root mean square error; d: Willmott's Concordance Index; t: Student's t test (*Significant at 5% probability by Student's t test: t > t critical – Ho is rejected*).

The analysis of the models revealed that the Blaney-Criddle, Turc, Makkink and Camargo methods presented underestimations in relation to the standard method, with underestimations of -30.28, -27.04, -12.41 and -1.01%, respectively. This percentage represents -1.31, -1.17, -0.54 and -0.04 mm day $^{-1}$, indicating that, despite the Camargo method having underestimated the value compared with the standard method, such underestimation was much smaller than that of the other methods.

Underestimation of the data is a characteristic of the Makkink equation, with higher underestimation values found in drier periods than in wetter periods of the year. For these reasons, the Makkink model can be recommended for humid climate conditions and has the advantage of using only air temperature and solar radiation data (PALARETTI; MANTOVANI; SEDIYAMA, 2014b; CAVALCANTI JÚNIOR *et al*., 2011; FERNANDES *et al*., 2010).

For the Linacre, Jansen-Haise, Priestley-Taylor, and Hargreaves-Samani models, overestimation of values was observed in relation to the standard method, with overestimations of 3.55, 2.15, 0.86, and 0.29 mm day $^{-1}$, respectively. The Linacre and Jansen–Haise models presented the greatest overestimation. As in this work, Rocha *et al*. (2015) reported ETo values for Hargreaves-Samani, which overestimated the standard method, and Tanaka *et al*. (2016) reported results with overestimation for the Linacre method in the state of Mato Grosso.

For the RMSE indices for the evaluated models, the results obtained in increasing order were as follows: Hargreaves-Samani (0.46 mm day $^{-1}$), Makkink (0.65 mm day $^{-1}$), Camargo (0.79 mm day $^{-1}$), Priestley-Taylor (0.97 mm day $^{-1}$), Turc (1.22 mm day $^{-1}$), Blaney-Criddle (1.49 mm day $^{-1}$), Jansen-Haise (2.22 mm day $^{-1}$) and Linacre (3.61 mm day $^{-1}$).

When the classification scale for the rRMSE intervals was used to evaluate the accuracy of the models studied, the Blaney-Criddle, Jansen-Haise and Linacre models were classified as “not acceptable”, with rRMSE values of 34.5, 51.31 and 83.52%, respectively.

The Priestley-Taylor and Turc models were classified in this study for the data evaluated as "acceptable," with values of 22.48 and 28.22%, respectively. The

Hargreaves–Samani, Makkink, and Camargo models obtained "good" classification, with values of 10.73, 14.90, and 18.17%, respectively. Therefore, none of the equations were classified as "excellent" according to the classification of Heinemann *et al*. (2012).

In the evaluation of the models for Willmott's d index, the Hargreaves–Samani, Makkink, and Camargo equations showed the greatest agreement with the standard method, with values of 0.9, 0.79, and 0.74, respectively, and can thus be considered the most accurate methods for the data in question. The Blaney Criddle, Priestley and Taylor, Linacre, Jensen Haise, and Turc methods showed the lowest agreement with the standard method, with values ranging from 0.25--0.68.

Thus, the joint use of the tested statistical indicators allows us to make a more accurate assessment of the models' performance in relation to the standard method (SOUZA *et al*., 2011). Thus, the Camargo method presented a small underestimation (0.04 mm day $^{-1}$) and good agreement (d = 0.74) and was considered a good model for estimating the ETo na microregion of Tomé-Açu, PA.

Similarly, the Makkink model also showed low underestimation (0.54 mm day $^{-1}$) and good agreement (d = 0.79) and is also considered a good model for estimating ETo in the microregion of Tomé-Açu, PA, as well as the Hargreaves-Samani method (d = 0.90), which was also classified as a good model, presenting low overestimation (0.29 mm day $^{-1}$).

When analyzing simplified equations in the northern region of Brazil, Lobato (2019) reported good and poor performance for the Makkink and Jansen–Haise methods, respectively, confirming the results of this study. However, when evaluating the Hargreaves–Samani, Linacre, and Camargo equations, the author obtained an acceptable rating, differing from the results of this study, in which the Hargreaves–Samani method performed well and the Linacre method performed unacceptably.

Although the Hargreaves–Samani method overestimates ETo values in humid regions, the overestimation value in this study compared with the standard method was considered low, presenting a good fit between the estimated values and those calculated by the standard Penman–Monteith equation. Considering that the Hargreaves–Samani model requires smaller amounts of input data, in the absence of data for the use of the standard equation, the use of this method is recommended for estimating ETo. ETo in the study region.

6 CONCLUSIONS

The Hargreaves–Samani model obtained the best fit, being the most suitable for use in the Tomé–Açu microregion in the absence of the necessary data to estimate reference evapotranspiration via the standard Penman–Monteith method (FAO 56).

The use of the Linacre, Blaney–Criddle and Jensen–Haise models is not recommended for the Tomé–Açu microregion.

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