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COMPARISON OF METHODS FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION: AN APPROACH TO THE MANAGEMENT OF WATER RESOURCES WITHIN AN EXPERIMENTAL BASIN IN THE BRAZILIAN CERRADO

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ABSTRACT: This study aimed to compare methods for estimating reference evapotranspiration using an experimental basin in the Brazilian Cerrado, for water management purposes. For that, we estimated daily reference evapotranspiration over a certain period (time series between 1982 and 2012) through different empirical methods. These methods consisted of Blaney-Criddle (BC), Hargreaves & Samani (HS), ASCE Penman-Monteith (ASCE- PM), Penman (1948/1963) (PO), Priestley-Taylor (PT), which were all compared to the standard Penman-Monteith FAO-56 (PM-FAO56). Based on statistics, ASCE- PM, P and BC methods should be recommended for cerrado areas, either in rainy or dry seasons. After these, the PT also stood out. Among the less complex methods, based on temperature and energy data, PT method is recommended whether climatological data are scarce either in rainy or dry seasons. Yet, HS reached the greatest errors, a broad data spread and low estimate accuracy, but showing better performance in dry periods, thus remaining under restricted use.

KEYWORDS: Evapotranspiration, Methods, Penman-Monteith FAO-56.

INTRODUÇÃO

Evapotranspiration (ET) is an essential factor in weather and water cycles. It has significant hydrological, agricultural and ecological implications. This process uses nearly three-fifths of annual solar radiation, available globally towards the Earth's surface (WANG & DICKINSON, 2012). Moreover, it is a key element in water balance, so its estimate is of vital importance for water resources and for forecasting drought periods (LINGLING et al., 2013). FALAMARZIA et al. (2014) studied this factor through neural networks in regions of climate-data scarcity.

Characterizing the climate-related water demand is highly important for expansion of irrigated farmland over the Brazilian cerrado regions. Such knowledge enables enhancing land use by rational use of available water resources. As irrigation systems are developed, implementation of guidelines and policies on water resources are needed to ensure sustainable investments over time (MEINZEN-DICK, 2014).

Climatic water deficit provides knowledge on local water availability. By accounting this factor, ET is a variable which quantifies water loss from surface to the atmosphere. The soil surface is often fully covered by grass and has no water restriction, for its maximum evaporating potential - reference ET for grassy surfaces. Among various requirements, a successful water use in irrigation depends mainly on a precise knowledge on crop water demand. Therefore, proper weighting is of utmost interest, particularly by using crop coefficients (Kc). These coefficients are determined based on crop evapotranspiration (ETc) and reference evapotranspiration (ET_0). Lately, some studies have been conducted to determine ETc using direct methods, especially weighing lysimeters, which are calibrated to the standard Penman-Monteith model (FAO-56) (FIGUERÊDO et al., 2009; MELO et al., 2013).

In a study aimed at checking the effect of input data of the Penman-Monteith model, provided by FAO-56 standard, a sensitivity analysis of this model was made for each micro-region of Minas

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Gerais state, Brazil. The authors underscored solar radiation as the input element to be measured precisely (LEMOS FILHO et al., 2010). By means of multivariate statistics, RUHOFF et al. (2009) investigated which elements had influence on ET in a cerrado region. They found three components influencing differently this process: i) energy supply - global incident radiation and net radiation (40%); ii) local atmospheric circulation - humidity, wind speed and atmospheric pressure (24%) and iii) vegetation cover (10%).

Several methods for estimating ET are encountered in the literature. Such calculations may be direct or indirect, being also adaptive to various parts of the globe. Meanwhile these methods are not simple, since they require numerous climatological data for their appropriate determination. This way, using less complex methods in areas with scarce or even lack of other available methods to increase precision, becomes an attractive option.

Against this background, this study aimed to evaluate five different empirical methods for estimating ET_0, comparing them to the standard Penman-Monteith by FAO-56. For that, we assessed daily evapotranspiration using a ten-day scale throughout dry and rainy periods, with a view to improve management of water resources.

MATERIAL AND METHODS

The monitored area monitored refers to the Buriti Vermelho river basin. It is located in the southeastern Federal District, Brazil. Figure 1 displays the georeferenced coordinates between 15°53'30" and 15°55'56" south latitude and 47°23'53" west longitude (UTM Zone 23/ SAD 69 datum). According to Köppen, local climate is classified as tropical climate (Aw), with dry winters (May to October) and rainy summers (November to April). The drainage area of the basin is of near 10 square kilometers (RODRIGUES et al., 2009).

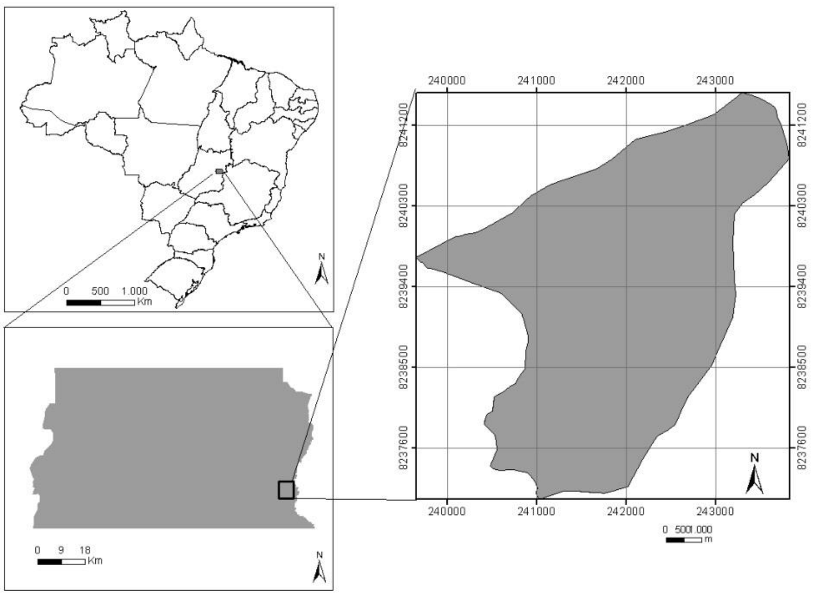


FIGURE 1. Location map of the experimental area of Buriti Vermelho river basin.

Regarding land use, several crops are grown such as forage plants, extensive farming of beans and corn, central-pivot irrigated wheat areas, soybean drylands, vegetables and lemon orchard, which are irrigated by various systems, besides a riparian forest. These are representing features of a cerrado land concerning farming practices, land use and vegetation covers. The basin instrumentation was implemented by the Research Center for Agriculture in Cerrado (CPAC), using a daily dataset from 1982 to 2012.

As exemplified in Figure 2, simulation and method were carried out using the database above cited. Reference evapotranspiration (ET_0) was determined based on the five methods and compared to the standard method (Penman-Monteith - FAO-56), as listed in Table 1. Reference evapotranspiration was predicted with the support of the computational tool Reference Evapotranspiration Calculator REF–ET (ALLEN, 2010) simulated the methods, which were:

(i) PRIESTLEY & TAYLOR (1972) - PT, stands for a simplification of PENMAN equation (1948), approaching solely the adiabatic term multiplied by a coefficient (α) - percentage of average contribution from the aerodynamic term of Penman equation;

(ii) HARGREAVES & SAMANI (1985) - HS, which considers latitude as well as maximum, minimum and average daily temperature;

(iii) BLANEY & CRIDDLE (1950) - BC;

(iv) PENMAN original (1948/1963) - PO;

(v) ASCE Penman-Monteith – ASCE-PM, stands for a full version of the Penman-Monteith equation (JENSEN et al.,1990);

(vi) Penman-Monteith method by FAO-56 (comparison parameter) - standard.

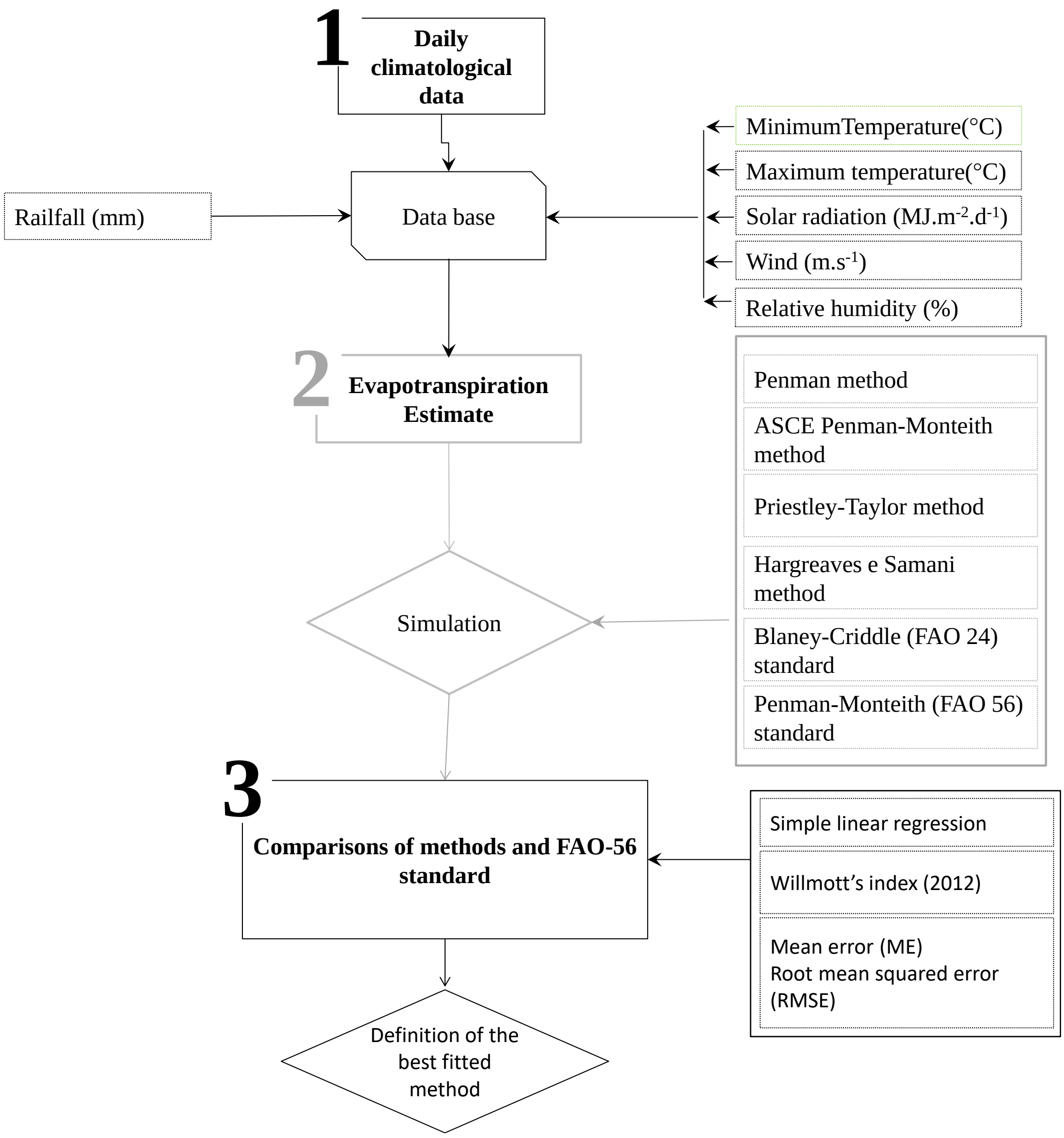


FIGURE 2. Flowchart of simulations and comparisons of the different methods.

For comparisons, we used the simple linear regression: $y = bx + a$, in which the reference evapotranspiration (ET_0) stands for the independent variable, estimated by the Penman-Monteith method (FAO-56); thus, the dependent variable is the reference evapotranspiration estimated by the different empirical methods. Daily data were divided into two seasons - dry and rainy, for a detailed analysis of the equations.

TABLE 1. Methods used for estimating the reference evapotranspiration.

Type	Method	Equation
Energy based	PRIESTLEY & TAYLOR (1972)	$ET_o = \frac{\alpha . W(R_n - G)}{\lambda}$
	HARGREAVES & SAMANI (1982)	$ET_o = a\ R_a\ TD^{1/2}\ (T_a + 17,8)$
Temperature based	BLANEY & CRIDDLE (1950)	$ETo = kp\ (0.46\ T_a + 8.13)$
Mass-transfer based	PENMAN (1948;1963)	$ET_o = 0.35(1 + 0.98/100U_2)(e_s - e_a)$
Compound	ASCE Penman-Monteith	$ET_o = \left(\frac{[\Delta(Rn - G)] + K_{time}\rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right) / \lambda$
	Penman-Monteith (ALLEN *et al*., 1998)	$ET_o = \frac{[0.408 \times \Delta \times (Rn - G)] + \left[\gamma \times \frac{900}{T + 273} \times U_2 \times (e_s - e_a)\right]}{\Delta + [\gamma \times (1 + 0.34 \times U_2)]}$

Footnote: Et_0 – reference evapotranspiration (mm.d^{-1}); R_n – net radiation (MJ.m^{-2}.d^{-1}); G – heat flow in soil (MJ.m^{-2}.d^{-1}); T – average daily temperature (°C); γ – psychrometric constant (kPa.°C^{-1}); Δ – vapor pressure curve tangent line as function of temperature (kPa°C^{-1}); U_2 – daily wind speed at 2 m (m.s^{-1});(es-ea) – vapor pressure deficit (kPa); es – air saturation vapor pressure (kPa); ea – actual vapor pressure (kPa); ρa – air average density at constant pressure (kg m^{-3}); cp – air specific heat, (MJ kg^{-1} C^{-1}); rs – surface roughness (m s-1);ra – aerodynamic resistance (s m^{-1}); λ – vaporization latent heat (MJ kg^{-1}); K_{time} – unit conversion, (86,400 s d^{-1} for ET in mm d^{-1} and 3,600 h s^{-1} for ET in mm h^{-1}); TD – current temperature variation (°C), T_{max} –T_{min}; a – non-dimensional coefficient – 0.0023; R_a – extraterrestrial solar radiation above the atmosphere on the 15th day of each month (MJ.m^{-2}.d^{-1}); T_a – average daily temperature (T_{max}+T_{min})/2; k – monthly coefficient dependent on vegetation, place and year season; p – percentage of maximum daily insolation (N) in relation to the theoretical insolation time of the year (4,380 h); W – weighting factor = Δ/Δ+γ; wherein, Δ vapor pressure curve slope; α – 1.26
Source: Adapted from LINGLING et al., 2013.

To assess model performance, we correlated the estimated values to those of the standard method using the coefficient of determination (r²) of the linear regression. As statistical indicators, the following indices were used: a) agreement index (d) by WILLMOTT et al. (2012) which varies from 0 to 1, according to [eq. (1)]; b) the mean error (ME) through [eq. (2)]; and the root mean square error (RMSE) through the [eq. (3)].

$$d = 1 - \frac{\sum_{i=1}^{n} \left| X_{standard,i} - X_{model,i} \right|}{2\sum_{i=1}^{n} \left| X_{Standard,i} - \overline{X}_{Standart,i} \right|} \quad (1)$$

$$ME = \frac{1}{n} \sum_{i=1}^{n} \left(X_{Standard,i} - X_{model,i} \right) \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(X_{Standard,i} - X_{model,i} \right)^2} \quad (3)$$

In which,

d - Willmott's agreement index (2012);

$X_{model,i}$ – reference evapotranspiration, estimated method, mm d^{-1};

$X_{standard,i}$ – reference evapotranspiration, standard method - Penman-Monteith (FAO-56), mm.d^{-1};

$\overline{X}_{standard,i}$ – mean values of ET_o, standard method - Penman-Monteith (FAO-56), mm d^{-1},

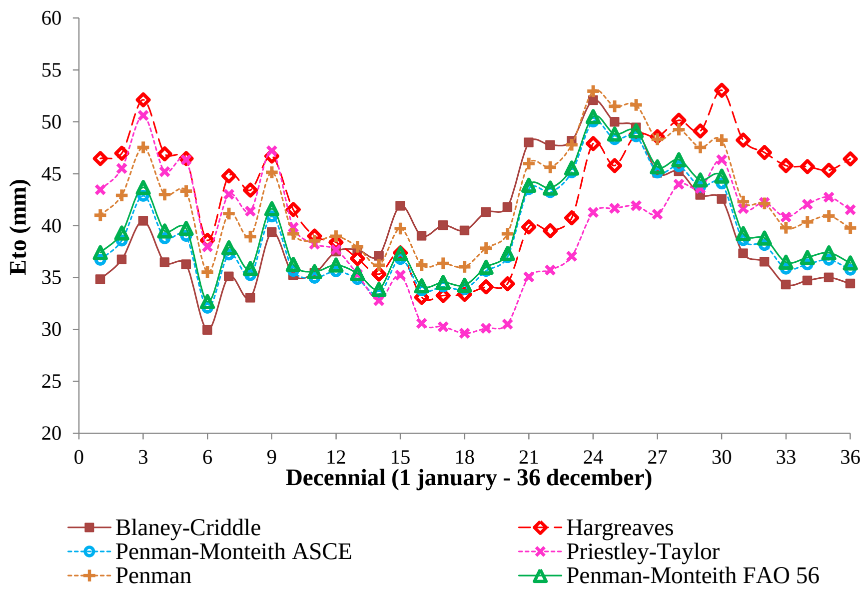
n – Number of observations.

RESULTS AND DISCUSSION

Figure 3a shows the averages of ET0 simulations in decennial scale. By contrasting PO, ASCE-PM, PT, BC and HS against the standard (FAO-56), it becomes evident that the less complex methods BC and HS, which use temperature and solar radiation, had conflicting data. While BC underestimates the potential ET in the rainy season, from 1 to 10 and from 31 to 36 decennials in the dry period (decennial 11 to 31) shows overestimated data. HS overestimated ET in the rainy season, being most suitable for dry periods (decennial 15 to 26). In this period, the relationship between the standard method and HS is 0.89 to 0.99, both for the decennial 23. Therefore, both methods showed insufficient data for cerrado, since this area has a distinctive climate where only temperature and extraterrestrial solar radiation data are insufficient given the cloudy rainy periods.

PRIESTLEY & TAYLOR (1972) exhibited similar behavior; overestimating in rainy seasons (decennials 1 to 13 and 29 to 36) and underestimating in dry ones (decennial 14 to 28). On the other side, the empirical methods PO and ASCE- PM performed similarly to the standard Penman-Monteith (FAO-56).

(a)



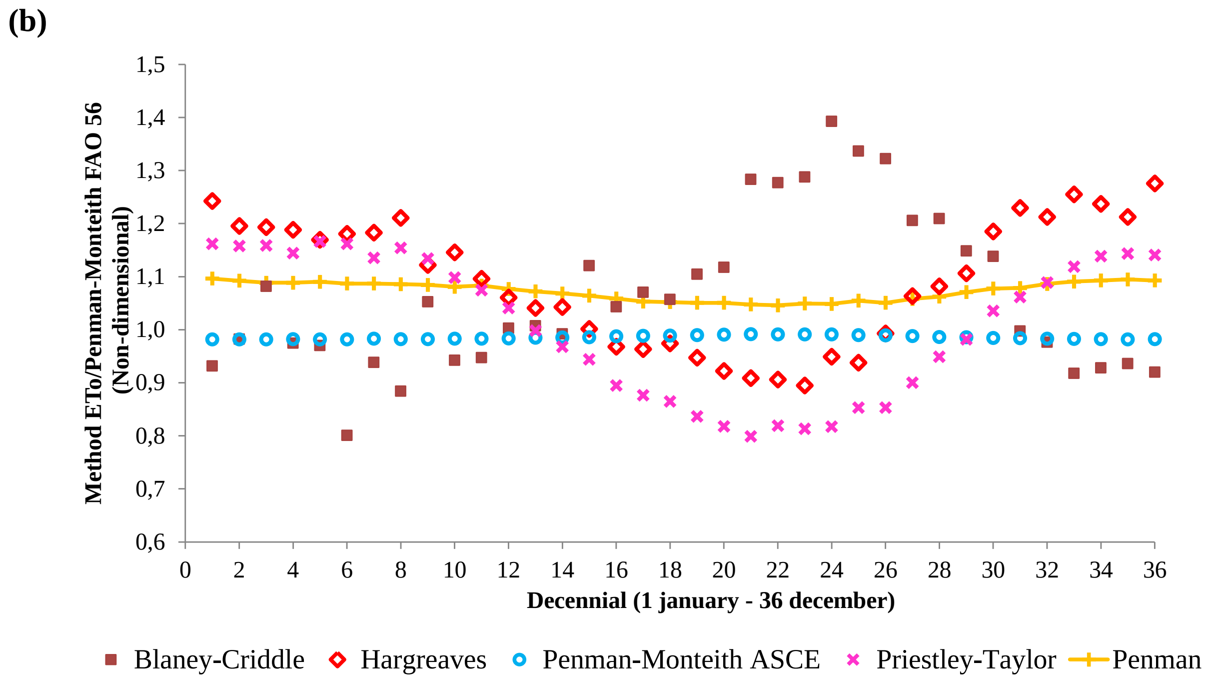


FIGURE 3. (a) Decennial averages for ET_0 estimated by different methods (b) decennial relationship between Penman-Monteith (FAO-56) and the other methods.

Figure 3b highlights two periods of distinct behavior for the relationship between the methods and the standard one. The rainy season is divided into two stages: the first starts at the first lasting to the 15th decennial, reoccurring between 25th and 36th ten-day period. In this last period, HS, PT and PO overestimated ET by about 20%, 15% and 9%, respectively, compared to the standard. Within the same period, BC underestimated by 5% the standard model, and ASCE-PM showed to be quite compatible to the standard. The second is the dry season, starting at 16 and extending up to 24 decennial. In this period, ASCE-PM and PO were compatible to the standard method. Conversely, BC FAO 24 overestimated by nearly 10% the standard method within the same period. PT and HS, in contrast, presented underestimation of 18% and 9% respectively.

ET estimating methods might consider the period of analysis, if it is a dry or rainy season. PO and ASCE-PM were satisfactory in any period. For a detailed analysis, the models were analyzed separately, one for dry season between May and October (decennials 13 to 30), and another for rainy season, which was made at two characteristic periods in the year; the first from January to April (decennials 1 to 12) and a second from November to December (decennials 31 to 36).

The analysis show daily data separating dry and rainy period:

For dry season, the less complex methods (BC, HS and PT) showed to be based on the agreement index (d) 0.78, 0.63 and 0.62, and on the coefficient of determination (r^2) 0.89, 0.49 and 0.61, respectively, as shown in Table 4. However, the most complex methods, involving greater amount of climatological variables, showed results consistent with the standard one. These complex methods, PO, and ASCE- PM, showed their performance by the agreement index (d) 0.85 and 0.97, respectively, approaching the model for fit to a 1: 1 line.

TABLE 2. Comparative analysis of the empirical methods to estimate daily potential evapotranspiration compared to the standard Penman-Monteith - FAO-56 (mm), for the dry period.

	n	b	a	r^2	d	RMSE	EM
ASCE Penman-Monteith	5704	0.9941	0.0233	0.9997	0.97	0.05	0.00
Penman 1948/1963	5704	1.0051	0.2166	0.9873	0.85	0.27	0.07
Priestley-Taylor	5704	0.6463	1.0000	0.6064	0.62	0.81	0.66
Hargreaves e Samani	5704	0.5952	1.6724	0.4909	0.63	0.75	0.57
Blaney-Criddley FAO 24	5704	0.9641	0.3923	0.8901	0.78	0.42	0.18

Nota: a e b - linear regression coefficients, r^2 - Coefficients of determination, d - Willmott´s index, ME- mean error, RMSE- Root mean squared error, n -number of data

Mean error (ME) and the root of mean squared error (RMSE) were calculated for the five methods against the standard, as observed in equations 2 and 3. The smallest MS and RMSE were seen for ASCE- PM, with values of 0.00 mm.d-1 and 0.05 mm.d-1, respectively. Oppositely, the highest were observed for PT, being of 0.66 mm.d-1 and 0.81mm.d-1, respectively.

The less complex methods BC and HS showed respectively coefficient of determinations (r^2) of 0.89 and 0.49 mm.d-1, EM of 0.18 and 0.66 mm.d-1, RMSE of 0.42 and 0.81 mm mm.d-1. In the light of these results, if compared to the standard method and by the absence of historical series of climatological data, we should recommend BC, emphasizing it as ideal during droughts in the study area.

While agreement index (d) was near one, as expected, for PO, ASCE- PM and BC; it showed intermediate values for PT and HS.

In general, HS showed a poor performance identified by a specific indicator and other statistical indicators. However, in the dry season and with limited data availability, it can be used, but always minding the model error.

From the daily ET0 historical series, we can highlighted a linear correlation trend in the scattering diagram, as shown in Figures 4a, 4b and 4e, respectively for the ASCE- PM - r^2 = 0.9997, PO - r^2 = 0.9873 and BC - r^2 = 0.8934. These results indicate that the correlation between this model and the standard is explained by a significant coefficient of determination. The accuracy of the values estimated by these three underscored methods, through concordance Willmott's agreement index, were above 0.89, of a maximum value of one.

Figure 4c and 4d represent respectively HS and PT, which showed a linear correlation with r^2 values of 0.60 and 0.49, respectively. The accuracy of the average values through Willmott's index were higher than 0.62, being thus intermediate.

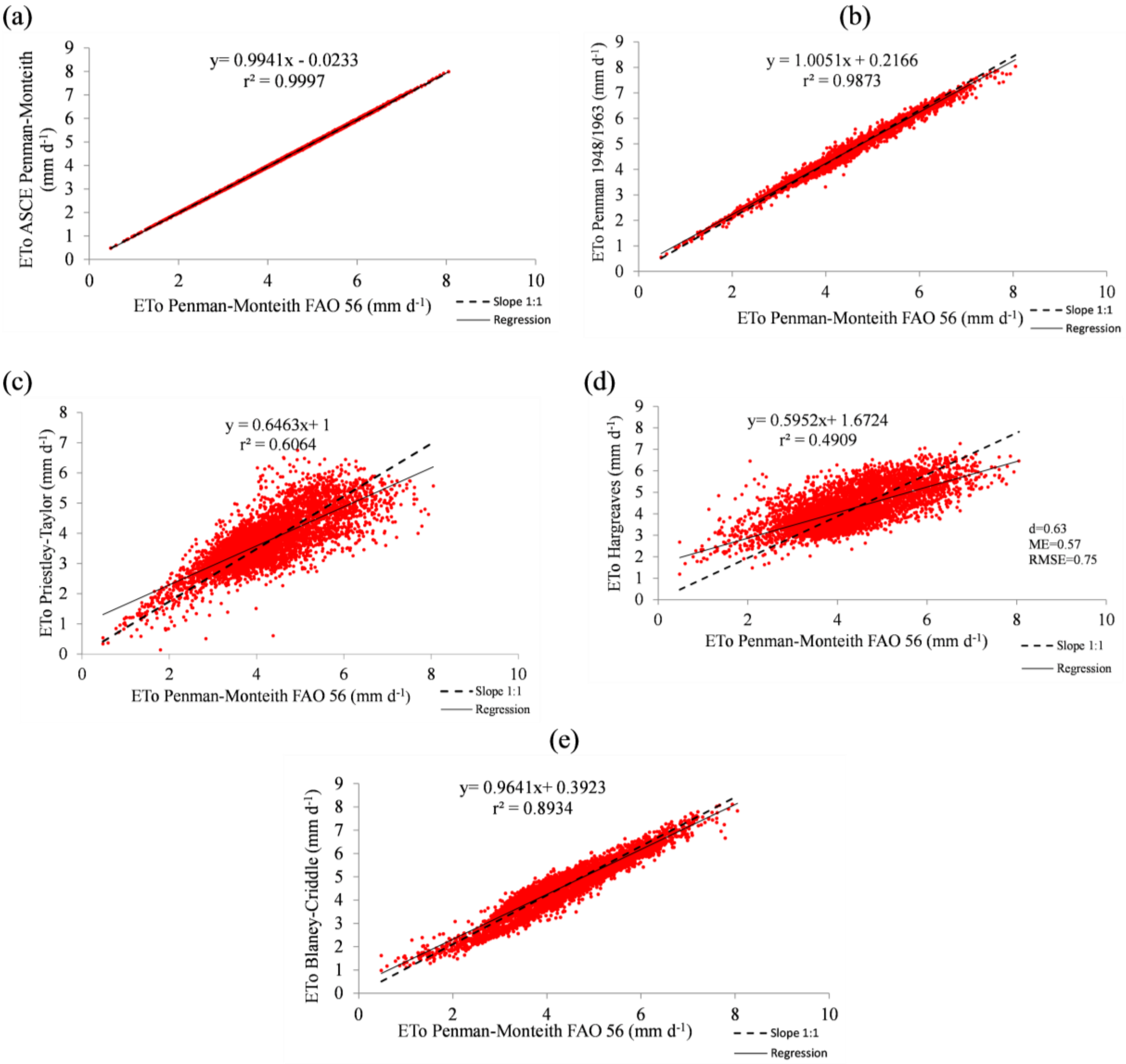


FIGURE 4. Linear regression for the different methods of daily reference evapotranspiration compared to the standard PM-FAO56, for the dry period.

The reference evapotranspiration can be estimated either by Penman or ASCE- PM method, regarded as satisfying tools for water management in the Buriti Vermelho river basin. However, BC, as a less complex method with satisfactory performance, is recommended in the shortage or lack of sufficient climatological data.

Oliveira et al. (2005) carried out a study in Goiânia - GO and observed that the best ET estimate during the dry season (April to September) was reached by the Penman method, compared to the standard by FAO-56; while for the rainy season (October to March), BC showed results close to the data found in our study.

DONOHUE et al. (2010) analyzed the recent ET changes in Australia, using five different equations; they reported temporal-spatial differences concerning the studied methods, pointing out that methods based only on temperature variables tend to overestimate or even underestimate ET values, without following a pattern.

During the dry season, PT and HS had the highest model errors, with mean values of 0.39 mm.d^{-1} and 1.15 mm.d^{-1} respectively and RMSE of 0.63 and 1.07 mm.d^{-1}. All of the methods had low MEs, but HS showed the highest one, as presented in Table 3.

TABLE 3. Comparative analysis of the empirical methods for estimating potential daily evapotranspiration compared to the standard Penman-Monteith - FAO-56 (mm), for the rainy season.

	n	b	a	r^2	d	RMSE	ME
ASCE Penman-Monteith	5557	0.9794	0.0121	0.9999	0.96	0.07	0.01
Penman 1948/1963	5557	1.0533	0.1314	0.9948	0.80	0.35	0.12
Priestley-Taylor	5557	1.0248	0.3839	0.8851	0.68	0.63	0.39
Hargreaves e Samani	5557	0.5302	2.5803	0.5281	0.48	1.07	1.15
Blaney-Criddley FAO 24	5557	0.9686	-0.0881	0.9482	0.84	0.33	0.11

Nota: a e b - linear regression coefficients, r^2 - Coefficients of determination, d - Willmott´s index, ME- mean error, RMSE- Root mean squared error, n -number of data

Figure 5 shows a low data dispersion in the rainy season for the comparisons. This behavior is explained by r^2 above 0.88 for ASCE-PM Monteith (Figure 5a), Penman (Figure 5b), PT (Figure 5c) and BC (Figure 5e); however, HS (Figure 5d) achieved less significant data.

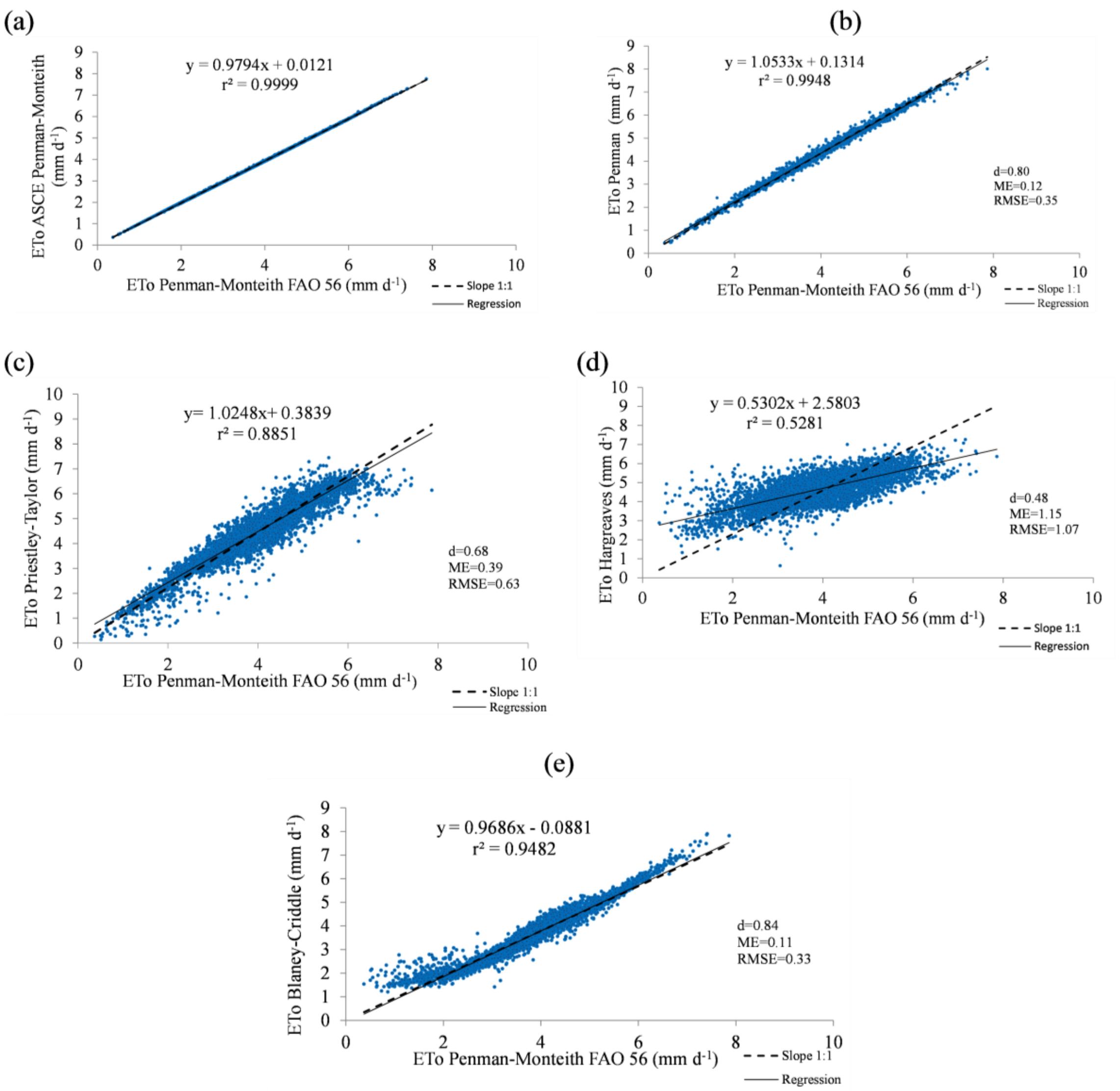


FIGURE 5. Linear regression for the different methods of daily reference evapotranspiration compared to the standard PM-FAO56, for the rainy period, within decennials 1 to 12 and 31 to 36

Regarding accuracy of estimates as for Willmott's agreement index (d), we found values above 0.84 for ASCE- PM (Figure 5a), Penman (Figure 5b) and BC (Figure 5e); in contrast, PT (Figure 5c) and HS (Figure 5d) achieved lower accuracy (> 0.48).

CONCLUSIONS

PENMAN (1948/1963) and ASCE-PM-Monteith methods performed better in estimating reference evapotranspiration for the study area, followed by Priestley-Taylor, being all of them indicated for both dry and rainy seasons.

Blaney-Criddle method showed the best fit to the standard (FAO-56) if compared to Hargreaves, thus being recommended in cases of climatological data limitation. Through overall statistics, HARGREAVES & SAMANI method can be used in cerrado areas for dry and rainy seasons, as a method with higher errors and intermediate accuracy.

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