

Options for Reference Evapotranspiration Estimation in Northern Espírito Santo and Eastern Minas Gerais States, Brazil

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Authors' contributions

This work was carried out in collaboration between all authors. Authors ADBG and GHSV designed the study and managed the writing of the manuscript. Author ADBG performed the statistical analysis and author GHSV translated the manuscript. Authors GP, PAB and JLFJ helped with data acquisition. Authors RMG and PAVLO contributed to discussion of the paper. Authors IRH and ACN assisted with statistical analysis. All authors read and approved the final manuscript.

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ABSTRACT

Due to the misuse and management of drinking water sources, in the last few decades there has been increasing waste of this resource and, as a consequence, the state of Espírito Santo, Brazil, has experienced a period of water crisis that has resulted in a fall in production in several agricultural sectors. In view of this, it is proposed that measurements related to water management should be carried out, such as the estimation of reference evapotranspiration (ET₀), with the objective of optimising water use in agriculture by more efficient management, based on the collection and calculation of daily climatic data. Thus, this study aimed to estimate reference evapotranspiration (ET₀) using six different methods and to compare the results with the values estimated by the Penman-Monteith-FAO 56 (PM) method in the municipalities of Aimorés, MG and

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Linhares, ES, Brazil. The methods of Hargreaves-Samani (HS), Solar Radiation FAO (RS-FAO), Makkink (MKK), Jense-Haise (JH), Linacre (LIN) and simplified Penman (PS) were investigated. For both cities, the results were similar in terms of method performance, especially PS and RS-FAO, with the highest indexes and efficiency, as well as smaller errors, followed by HS and MKK, both with indexes smaller than the most efficient methods. However, it was necessary to apply linear adjustment, using the coefficients "a" and "b". The LIN method is not recommended for either city, since the results using this method were unsatisfactory for most analyses.

Keywords: Agrometeorology; evapotranspiration; irrigation; penman-monteith.

1. INTRODUCTION

The sustainable use of water resources and the lack of water are increasingly recurrent themes in social media and television, as well as in most of the academic studies related to the management and conservation of water resources. In view of this, there should be efficient use of water which aims at sustainability and responsible use of this resource.

As a consequence of the misuse and lack of management of drinking water sources, in recent decades there has been increased waste of this resource and, as a consequence, the Espírito Santo state has gone through a period of the water crisis that has resulted in the fall in production from various agricultural sectors in the state. The lack of water has occurred mainly due to low rainfall levels, but also it is related to anthropic activities, such as deforestation, drilling of clandestine underground wells and poorly designed and managed irrigation systems and facilities.

In view of this, it is proposed that measurements related to water management should be carried out, such as the estimation of reference evapotranspiration (ET₀), with the objective of optimising water use in agriculture by more efficient management, based on the collection and calculation of daily climatic data.

Improving the management of water resources is an initial step in conserve water. For this reason, evapotranspiration, as one of the components of the water balance, is of great importance and usefulness in climatology and in quantifying water availability in the regions [1]. The estimation of evapotranspiration losses is essential for the elaboration of irrigation projects, management of reservoirs and for granting and planning the use of water resources.

Currently, water demand is a crucial factor for agriculture. According to Silva et al. [2], agriculture is responsible for the largest portion of water consumption on the planet, representing

approximately 70% of good quality water [3], because the production of one ton of food requires one million liters of water. Inevitably, the intensive use of water for farming adversely affects water reserves. Knowledge of water availability and proper management of irrigation allows better management of water resources and better economic returns on investments [4].

In view of the above, this study involved an estimation of reference evapotranspiration using 'meteorological data based on daily measurements over a nine-year period', calculated using six different methods, and comparison of the results with the values determined using the Penman-Monteith-FAO 56 method 'in the municipalities of Aimorés in the east of Minas Gerais (MG) and Linhares in the north of Espírito Santo (ES), Brazil.

2. MATERIALS AND METHODS

This study was conducted using meteorological data from the automatic stations A614 and A534, belonging to INMET, located at the geographical coordinates 19°21'25" S, 40°04'07" W (Linhares-ES) and 19°31'58" S, 41°05'26" W (Aimorés-MG), with altitudes of 38 m and 288 m, respectively.

The climate of Linhares, according to the classification of Koppen-Geiger is "Af", is a warm tropical humid climate with rain in the summer and a dry winter. The rainfall is 1193 mm per year and the average temperature is 23.4°C, with a maximum of 32°C and a minimum of 19.6°C [5]. The climate of Aimorés is characterised as tropical semi-humid tropical, or tropical with dry season (type "Aw", according to Köppen [6]), with dry and mild winters and rainy summers with high temperatures. The average annual temperature is 25.2°C (maximum of 33.9°C and minimum of 16.9°C) and the average annual precipitation is 1169 mm.

Due to the availability of viable data, it was decided to use daily data collected between January 2008 and June 2017. According to

Mendonça et al. [7], meteorological stations may present reading errors due to several factors, such as equipment or human failures. Due to these errors, data that had inconsistent reading or incomplete records were eliminated.

Based on the climatic data, reference evapotranspiration (ET_0) was calculated using Penman-Monteith-FAO56 (PM = Equation 1), Hargreaves-Samani (HS = Equation 2), FAO Solar Radiation (RS FAO = Equations 3 to 5), Makkink (MKK = Equations 6 to 8), Jensen-Haise (JH = Equation 9), Linacre (LIN = Equation 10) and simplified Penman (PS = Equation 11) methods. Among the methods used, the first one (PM) was used as the calibration standard for the others.

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)} \quad (1)$$

Where:

ET_0 = reference evapotranspiration (mm day^{-1});
 R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$);
 G = soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$);
 T = mean daily air temperature at 2 m height ($^{\circ}\text{C}$);
 U_2 = wind speed at 2 m height (m s^{-1});
 e_s = saturation vapour pressure (kPa);
 e_a = actual vapour pressure (kPa);
 Δ = slope vapour pressure curve ($\text{kPa}^{\circ}\text{C}^{-1}$);
 γ = psychrometric constant ($\text{Pa}^{\circ}\text{C}^{-1}$).

$$ET_0 = 0.0023 R_a \sqrt{T_{\max} - T_{\min}} (T + 17.8) \quad (2)$$

Where:

R_a = extraterrestrial radiation (mm day^{-1});
 T_{\max} = maximum air temperature ($^{\circ}\text{C}$);
 T_{\min} = minimum air temperature ($^{\circ}\text{C}$);
 T = average air temperature ($^{\circ}\text{C}$).

$$ET_0 = c W R_s \quad (3)$$

Where:

C = angular coefficient, calculated using Equation 4;
 W = weighting factor dependent on air temperature and the psychrometric coefficient;
 R_s = solar radiation at the soil surface, expressed as evaporation equivalent (mm day^{-1}).

$$c = c_0 + cL \quad (4)$$

Where:

cL = coefficient, calculated using Equation 5;
 $c_0 = -0.3$.

$$cL = a_0 + a_1 UR + a_2 Vd + a_3 UR Vd + a_4 UR^2 + a_5 Vd^2 \quad (5)$$

Where:

$a_0 = 1.0656$; $a_1 = -0.0012795$; $a_2 = 0.044953$; $a_3 = 0.00020033$; $a_4 = -0.000031508$; $a_5 = -0.0011026$;
 UR = average relative humidity (%);
 Vd = wind speed at 2 m height (m s^{-1}); we considered $Vd = 70\%$ wind speed on a 24-h basis.

$$ET_0 = 0.61 WR_s - 0.12 \quad (6)$$

Where:

R_s = global solar radiation (mm dia^{-1});

According to Tanaka et al. [8], the factor "W" can be calculated according to the daily conditions based on the temperature and using Equations 6 or 7.

$$W = 0.407 + 0.0145T; \quad 0 < T < 16 \text{ }^{\circ}\text{C} \quad (7)$$

$$W = 0.483 + 0.01T; \quad 16.1 < T < 32 \text{ }^{\circ}\text{C} \quad (8)$$

$$ET_0 = (0.0252 T + 0.078) R_s \quad (9)$$

Where:

R_s = global solar radiation (mm day^{-1}).

$$ET_0 = \frac{500(T + 0.006H) + 15(T - T_d)}{(100 - \varphi) (80 - T)} \quad (10)$$

Where:

H = altitude (m);
 φ = latitude (degrees);
 T_d = dew point temperature ($^{\circ}\text{C}$).

$$ET_0 = 0.408 \frac{(R_n - G)}{(2 - W)} \quad (11)$$

Where:

G = soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$);
 R_n = diurnal net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$);

For this study, the values of G were considered null because they were calculated on a daily basis. Fausto et al. [9] obtained small values for this variable, indicating a mean of 0.18 W m⁻², the largest partition of radiation in the form of sensible heat, which corroborates the use of an insignificant value of "G" under these conditions.

For initial analysis of data, linear regressions were performed, comparing the methods studied with the standard Penman-Monteith method. With the regression analysis we obtained the linear equations, and the linear and angular coefficients, 'a' and 'b', respectively. From the adjustment equations the corrected ET₀ values were calculated and compared to the values before the corrections.

In addition to the coefficients, the Standard Error of Estimate (SEE) was also calculated for the evapotranspiration values before and after the corrections. The standard error of a sample estimate is an estimate of the standard deviation of the means distribution of samples with the same size obtained from the same population, and thus a measure of the uncertainty associated with the mean population estimate [10]. The SEE can be calculated using the methodology proposed by Jensen et al. [11] (Equation 12). The SEE adopts the same unit of its sample group, so for ET₀ the results were reported in mm day⁻¹.

$$SEE = \sqrt{\frac{\sum_{i=1}^n (Y_{p_i} - Y_{met_i})^2}{n - 1}} \quad (12)$$

Where:

SEE = standard error of estimate (mm day⁻¹);
 n = number of sample terms;
 Y_p = ET₀ estimated by the standard (PM) method (mm day⁻¹);
 Y_{met} = ET₀ estimated by the method to be evaluated (mm day⁻¹).

In order to evaluate the performance of the methods tested in relation to the PM method, we calculated the agreement index (D) according to Willmott et al. [12], the absolute mean error (AME), the maximum error (EMAX), the method efficiency (EF) and the performance index (c) proposed by Camargo and Sevens [13], with equations 13,14,15, 16 and 17, respectively.

$$D = 1 - \frac{\sum_i^n (P_i - O_i)^2}{\sum_i^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (13)$$

$$AME = \frac{1}{n} \sum_{i=1}^n |O_i - P_i| \quad (14)$$

$$EMAX = \text{MAX}(|O_i - P_i|) \quad (15)$$

$$EF = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (16)$$

$$c = r D \quad (17)$$

Where:

P_i = values estimated by the method under test;
 O_i = values estimated by the standard method, ET₀PM;
 \bar{O} = mean of the values estimated by the standard method, ET₀PM;
 MAX = absolute maximum value;
 r = Pearson correlation coefficient;
 D = Willmott's concordance index.

According to Peixoto et al. [14], for the 'D', 'EF' and 'c' indexes, the closer the value is to 1, the better the method performance. However, the difference between these three indexes is that 'D' and 'c' can assume only values between 0 and 1, i.e., positive. The values obtained in 'EF' can vary from -∞ to 1 [15,16] which means that the mean of the data from the standard method better predicts the results than those estimated by the method under study [14].

As a method of classifying the indices, different categorisation tables were used to relate the value obtained to a specific category, transforming the numerical or quantitative data into qualitative data.

The classification of the method efficiency (EF), also known as Nash-Sutcliffe coefficient (C_{NS}), was arranged according to the indication of different authors. Beskow et al. [17] suggest that when EF index = 1, the fit is considered perfect; with EF>0.75, the method is considered good, and with 0.36<EF<0.75, the method is considered adequate. However, for Zappa and Gurtz [18], EF values greater than 0.5 the method can be used for simulation. Classification of the performance index (c) following the criteria of Camargo and Sevens [13] is shown in Table 1.

Table 1. Criteria for classifying the performance index "c"

Performance index "c"	Classification
> 0.85	Excellent
0.76 – 0.85	Very good
0.66 – 0.75	Good
0.61 – 0.65	Median
0.51 – 0.60	Affordable
0.41 – 0.50	Bad
≤ 0.4	Terrible

3. RESULTS AND DISCUSSION

The relationships between the tested methods and the standard method, observing the historical series as a whole for Aimorés and Linhares, are presented in Figs. 1 and 2, respectively.

When observing the graphs, it can be seen that, for both municipalities, the MKK, LIN and PS methods tend to underestimate the reference evapotranspiration, while the RS and JH methods tend to overestimate the values, especially on days when the mean ET_0 is very high, that is, the greater the evapotranspiration, the greater the error of overestimation.

According to the study of Tanaka et al. [8] in the region of Mato Grosso, a southern state that has a similar climate to the regions studied here (Aw, according to the Koppen classification), the MKK, LIN, RS-FAO and JH methods tend to overestimate the ET_0 values, which corroborates in parts the results obtained in this study.

On the other hand, the HS method tends to overestimate the lower ET_0 and subtly underestimate the higher ET_0 . Reis et al. [19] when evaluating ET_0 estimated during the dry period using different methods for three different locations in Espírito Santo state, obtained results that corroborate with those obtained in this study, since the HS method tended to overestimate by up to 0.71 mm day^{-1} during the evaluated period.

Graphical analysis shows a good fit of all methods, except Linacre which had a very low R^2 for the two regions (0.2435 and 0.2745), which indicates the precarious quality of the adjustment of this method to the standard for the regions studied. Therefore, it can be stated that the Linacre method has a low percentage of adjustment, with 24% and 27% for the localities. This means that the values obtained cannot

express the results determined with the standard method.

This result is mainly related to the Linacre equation being developed for places with a temperate and dry climate, conditions that are quite different from the evaluated regions. The results obtained by Martí [20] for the region of Valencia, Spain, corroborate those obtained in this study, due to the locality studied having a climate that is mainly Mediterranean (Csa), according to the classification of Koppen, and a secondary climate of Cold Estepe (BSk) thus presenting good adaptation to the Linacre method.

Not only does the Linacre method have a low coefficient of determination, it also has a large dispersion of points in both graphs, which reinforces a low adaptation of this method to the regions of Aimorés and Linhares.

The results obtained by Gurski et al. [21] are distinguished from this study because, when evaluating the performance of the LIN method in the Curitiba-PR region, the authors concluded that this method presented the best results for the hottest seasons, from November to March, but it overestimated the values in the colder seasons, probably due to the climatic characteristics.

In addition to the balance of the results obtained graphically, Table 2 allows an analysis of the efficiency of the methods, from the analysis of the average and maximum errors, as well as the correlation and Willmott's coefficients.

As can be observed, in relation to the D coefficient, all the methods presented values above 0.6. The values for RS-FAO, PS and HS methods stood out for both locations with values above 0.9; values were very close to 1, thus showing optimal performance.

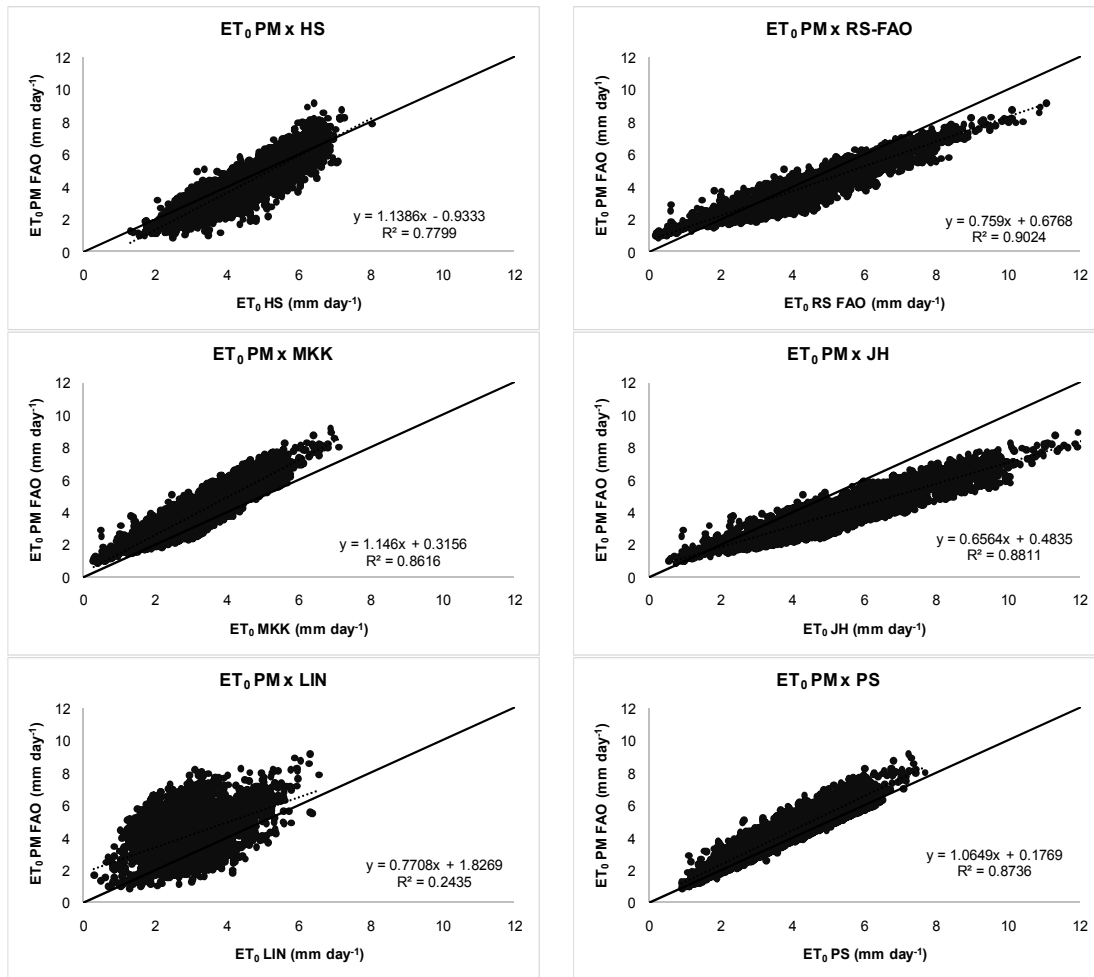


Fig. 1. Relationship between the evaluated methods and the Penman-Monteith method in the Aimorés region

Table 2. Indexes and comparative errors of the test methods with respect to the standard method for Aimorés and Linhares regions

Aimorés						
Method	D	MAE	EMAX	EF	c	Classification
RS-FAO	0.947	0.631	2.568	0.732	0.900	Excellent
PS	0.942	0.526	2.411	0.795	0.882	Excellent
HS	0.911	0.636	2.983	0.727	0.805	Very good
MKK	0.878	0.845	2.646	0.570	0.815	Very good
JH	0.817	1.485	4.280	-0.251	0.767	Very good
LIN	0.613	1.336	5.077	-0.324	0.303	Terrible
Linhares						
RS-FAO	0.969	0.435	2.076	0.843	0.943	Excellent
PS	0.964	0.373	2.789	0.863	0.934	Excellent
HS	0.933	0.480	2.892	0.771	0.832	Very good
MKK	0.875	0.820	2.846	0.518	0.837	Very good
JH	0.816	1.369	4.156	-0.377	0.789	Very good
LIN	0.583	1.419	4.916	-0.840	0.306	Terrible

Note: D – Willmott's concordance index; AME - absolute mean error; EMAX – maximum error; EF – method efficiency; c – performance index

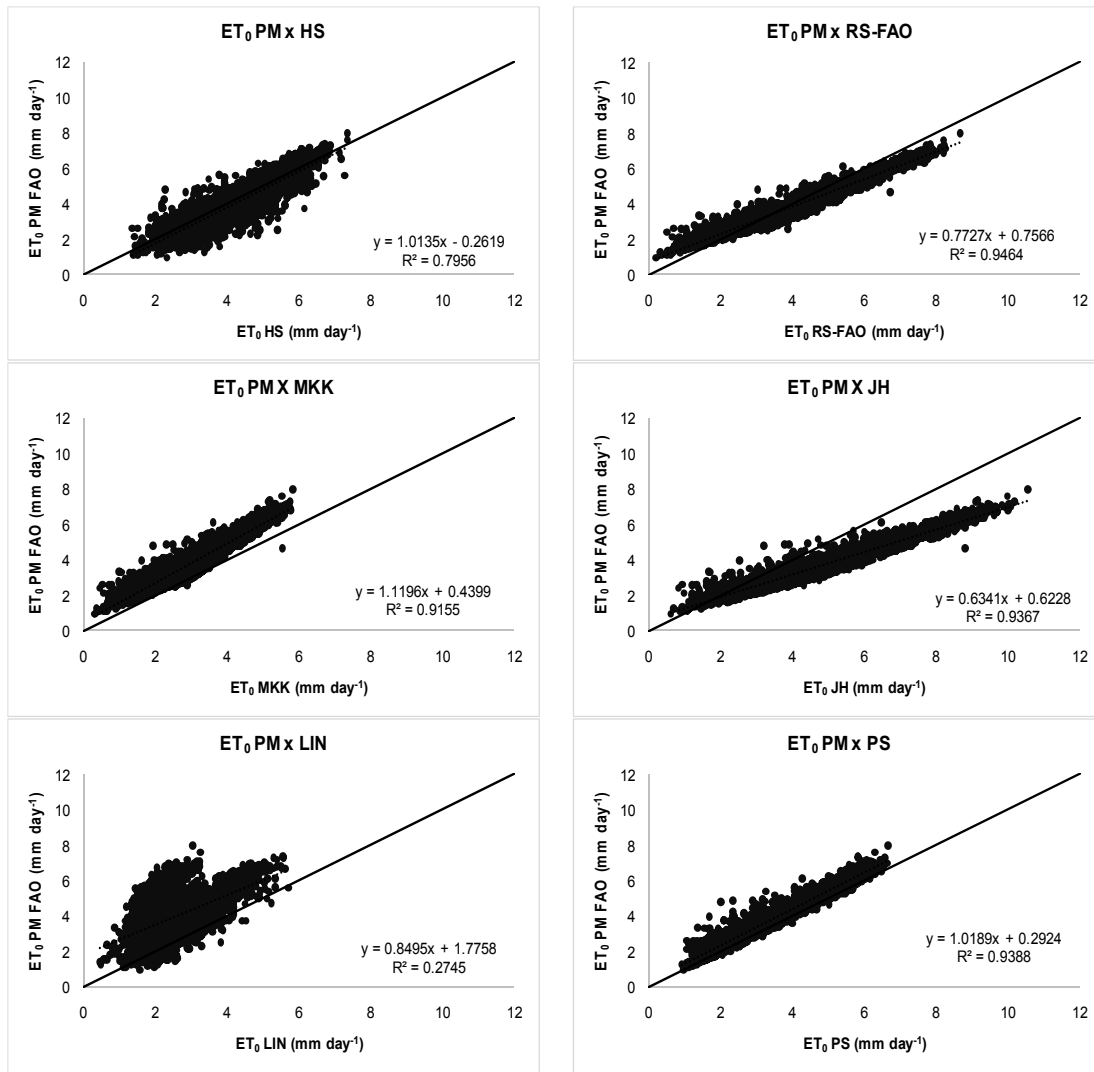


Fig. 2. Relationship between the evaluated methods and the Penman-Monteith method in the Linhares region

According to Araujo et al. [22], the agreement index is based on a mathematical approximation that evaluates the accuracy, the dispersion and the distance of the simulated values in relation to the standard ones. In this sense, the closer to 1, the more perfect is the method. In view of this, the methods with the lowest data dispersion and better accuracy are RS-FAO, PS and HS, all with indexes above 0.9.

With regard to efficiency and following the Beskow classification, the HS and RS-FAO methods presented an "acceptable" result for the Aimorés region, while for Linhares they were considered "good". The PS method was rated "good" for both regions and MKK as

"acceptable", also for both locations. The JH and LIN methods were considered unacceptable in both cases.

According to Zappa's classification, all methods were considered adequate for the two locations, except for JH and LIN, since they presented values below 0.5.

The maximum errors (above 4 mm day⁻¹) and absolute mean errors (above 1 mm day⁻¹) in both regions are presented for the LIN and JH methods, which caused them to have a negative efficiency (EF). The low efficiency of the LIN method is related to the high results dispersion and the low concordance index, whereas for JH,

the main factor that caused the ET_0 overestimation is that there were very high daily evapotranspiration averages, greater than 5 mm day^{-1} .

In Linhares, located in the northeast region of Espírito Santo, irrigated coffee cultivation predominates, with 90% of the crops being dependent on irrigation systems. Therefore, a good efficiency is necessary to estimate the need to replenish water in coffee plantations [23].

The ranking of the methods for the performance index was the same for both regions, with RS-FAO and PS classified as "great", followed by HS, MKK and JH which were rated "very good" and LIN which was classified as "terrible".

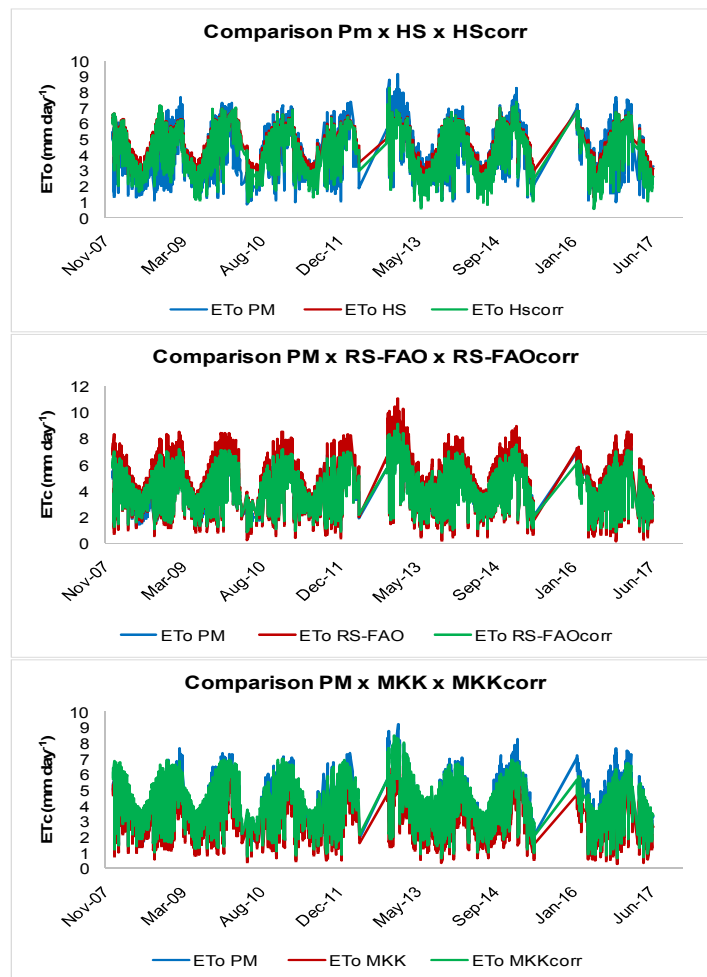
Results of studies performed by Santos [24] in Feira de Santana, Bahia state, a region with a climate classified as Aw according to the Koppen system, corroborate the results obtained here,

since LIN presented a "terrible" performance and HS was "optimal", similar to this study.

Figs. 3 and 4 show the correlation behaviour of ET_0 estimates on the same days between the methods tested and the standard method, before and after correction by means of the linear equation generated by linear regression.

It is observed that the JH method overestimates the ET_0 in relation to the standard. However, it is verified that, after applying the linear correction equation, these values are practically equivalent to those obtained by the PM method for both regions.

Another important finding is that, although the corrections are applied, the HS method does not present significant corrections, indicating that there is no need to perform these corrections, since these are insignificant.



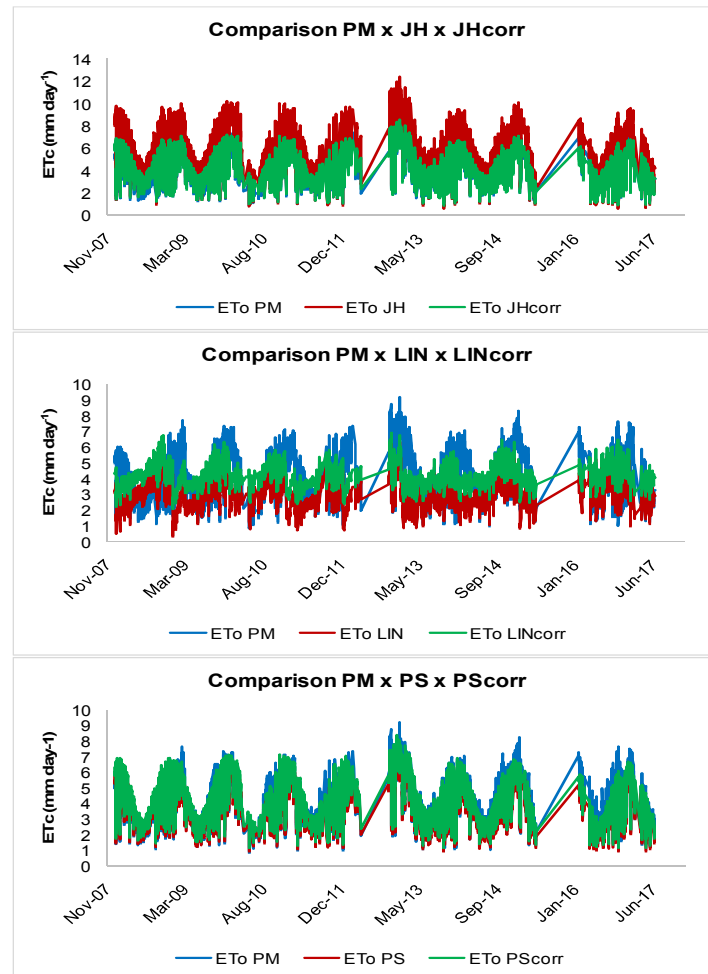


Fig. 3. Comparison between the ET_0 estimates of the standard methods and the evaluated methods for the same periods in Aimorés

In addition, the LIN method, as already demonstrated in the other evaluations, presented very different results from the other methods, that is, even after corrections there is a high error in ET_0 estimation. Even with the application of the linear equation, [25] emphasise that not all situations are well adjusted or approximate with the regression application. In view of this, it is necessary to conduct preliminary studies to determine if a linear model is more appropriate.

Tables 3 and 4 present the linear and angular coefficients of the adjustment equations, as well as the standard errors of the estimations, before and after the corrections. The results further corroborate those presented in Figs. 3 and 4.

When evaluating the difference between the SEE for both regions, it is verified that, for the HS method and despite the good fit with the original

equation, there are very few differences between the values when the correction is applied. The RS-FAO, MKK and PS methods, originally, have good adjustments to the standard for the regions under study. However, when applying the correction equation, it is noticed that there is an adjustment very similar to the values generated by PM, which indicates the need to adjust these methods according to their coefficients "a" and "b".

The linear coefficient "a" represents the ET_0 estimated by the PM method, in which the evapotranspiration observed by the test method is equal to zero. That is, the more "a" tends to zero, the better the adjustment. The angular coefficient "b" indicates the sensitivity. This means that the higher the value, the more sensitive is the method adjustment. Moreover, the more the trend line is parallel to the linear

straight line and, therefore, closer to 1, the smaller the variation between two near estimates [26].

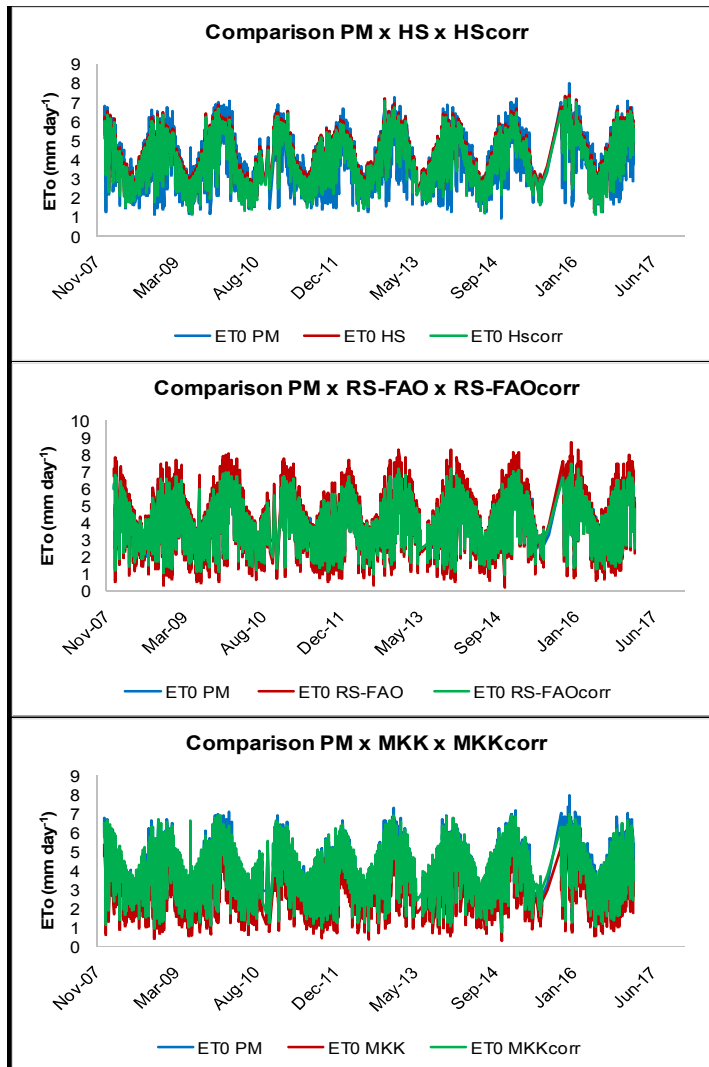
From the analysis shown in Tables 3 and 4, it was verified that the LIN method, although it

greatly reduced the estimate error, with a wide difference before and after the adjustment, presented the highest values for these evaluations. Therefore, this method is the least suitable of those studied for these regions.

Table 3. Comparison of the standard error of estimation between the evaluated methods and the standard method in Aimorés

Method	a	b	SEE	SEEA	Difference
HS	-0.9333	1.1386	0.800	0.718	0.082
RS-FAO	0.6768	0.759	0.792	0.478	0.314
MKK	0.3156	1.146	1.003	0.569	0.434
JH	0.4835	0.6564	1.712	0.528	1.184
LIN	1.8269	0.7708	1.762	1.332	0.430
PS	0.1769	1.0649	0.693	0.544	0.149

a = linear coefficient; b = angular coefficient; SEE = standard error of estimation; SEEA = adjusted standard error of estimation



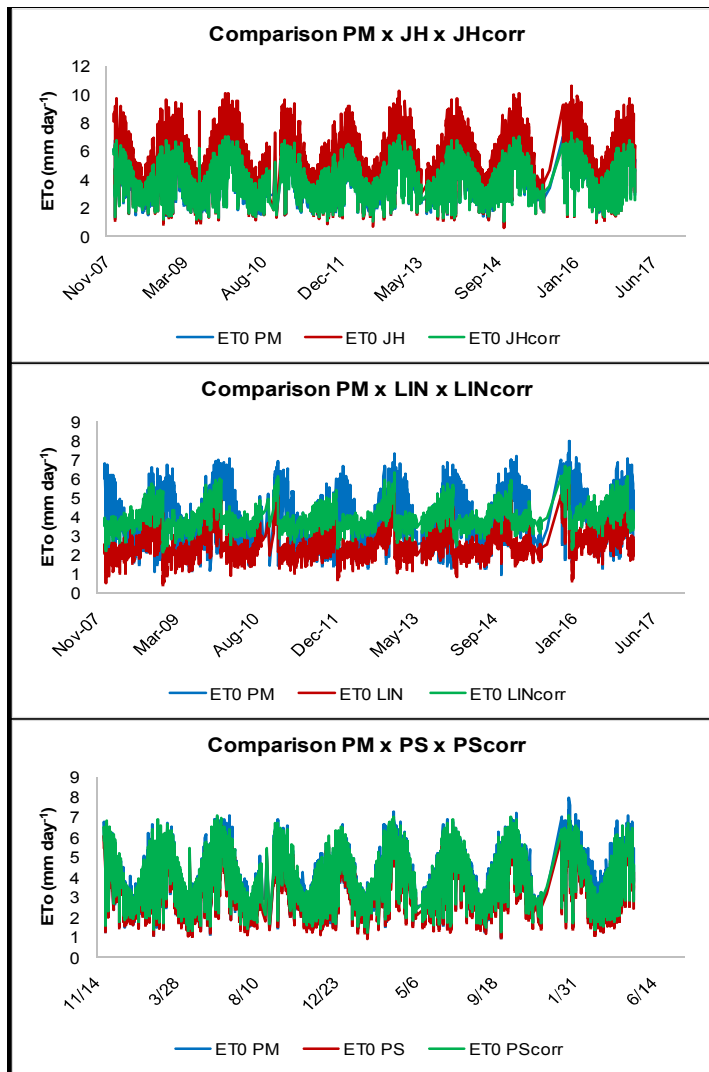


Fig. 4. Comparisons between the ET₀ estimates of the evaluated methods and the standard for the same periods in Linhares

Table 4. Comparison of the standard error of estimation between the evaluated methods and the standard method in Linhares

Method	a	b	SEE	SEEA	Difference
HS	-0.2619	1.0135	0.630	0.595	0.035
RS-FAO	0.7566	0.7727	0.522	0.305	0.217
MKK	0.4399	1.1196	0.914	0.383	0.531
JH	0.6228	0.6341	1.545	0.331	1.214
LIN	1.7758	0.8495	1.786	1.121	0.665
PS	0.2924	1.0189	0.487	0.326	0.161

a = linear coefficient; *b* = angular coefficient; *SEE* = standard error of estimation; *SEEA* = adjusted standard error of estimation

In contrast to the results obtained in this study, [27] evaluating the performance of different methods in the municipality of Chapadão do Sul, Mato Grosso do Sul state, with a tropical humid climate, reported that Makkink, Jensen-Haise and Linacre methods overestimated ET₀ due to

the high values of the linear and angular coefficients, which in the present study occurred only in the JH method.

The JH method, in both locations, presented a high standard error of the estimate, mainly due to the overestimation of ET_0 . However, when correcting these values, the standard error of the adjustment is much lower than the original estimate, implying the need to correct the ET_0 values originated by this method.

The results obtained by Palaretti et al. [28], which estimated ET_0 in different citrus-producing regions in the state of São Paulo, corroborate findings of this study since the HS method, although there was a decrease in SEE after adjustment, these values were very low, close to 0.04 mm day^{-1} , and no adjustment is necessary for its use.

On the other hand, [29] studying the region of Campos Sales, Ceará state, observed that the methods of RS-FAO and JH, followed by HS had the lowest SEE, attributing this result to the fact that the first two are based on solar radiation. The HS method is not based on solar radiation, but it was developed for regions of hot climates.

Although the method of HS is not the best among the tested, it is very advantageous in relation to the others, since it has little requirement in data entry, only temperature and extraterrestrial radiation that are easily obtained, so it is very useful to use both in research and in the farms routine activities.

4. CONCLUSION

In view of the presented results, it is concluded that the Solar Radiation (RS_FAO) and Simplified Penman (PS) methods are the most suitable of the methods evaluated for the two regions, Aimorés and Linhares. The Hargreaves-Samani (HS) and Makkink (MKK) methods presented very good results and also have the advantage of simplicity.

The Jensen-Haise method did not present satisfactory results when used in its original form, so correction is necessary when this model is used. Rated as poor in terms of performance, the LIN method is not indicated for either city.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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