

**Aplicação de diferentes métodos de calibração do modelo de Hargreaves-Samani no Sudeste do Brasil**

**Application of different calibration methods for the Hargreaves-Samani model in Southeast Brazil**

**Aplicación de diferentes métodos de calibración para el modelo Hargreaves-Samani en el Sureste de Brasil**

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**Resumo**

A evapotranspiração é uma variável importante no ciclo hidrológico e um dos principais componentes do balanço hídrico no solo. O uso de equações simplificadas é uma alternativa potencial para estimar a evapotranspiração de referência ( $ET_0$ ) quando os dados

meteorológicos são limitados. O objetivo deste estudo foi testar diferentes métodos para estimar a ET<sub>0</sub> usando a equação de Hargreaves-Samani (HS) sob diferentes condições meteorológicas. A ET<sub>0</sub> foi calibrada com HS, ajustando o coeficiente de HS (HC), utilizando diferentes métodos. O ajuste por regressão linear também foi realizado. A ET<sub>0</sub> também foi estimada usando os métodos originais de HS e Penman-Monteith FAO-56 com dados climáticos limitados (PML). O desempenho dos métodos (erro absoluto médio, mm dia<sup>-1</sup>) para estimar a evapotranspiração, baseado em Penman-Monteith, foram: PML (1,46); HS (0,68); Vanderlinden et al. (2004) (0,81); Martí et al. (2015) (0,77); e regressão linear (0,53). O método PML apresentou o pior desempenho. O ajuste por regressão linear apresentou um desempenho melhor que os ajustes usando do HC, melhorando as estimativas de ET<sub>0</sub> em até 30%, sendo considerado o mais recomendável dos métodos testados.

**Palavras-chave:** Balanço hídrico; Evapotranspiração potencial; Penman-Monteith; Agrometeorologia.

## Abstract

The evapotranspiration is an important variable in the hydrological cycle and one of the main components of water balance in the soil. The use of simplified equations is a potential alternative to estimate reference evapotranspiration (ET<sub>0</sub>) when there is limited meteorological data. The objective of this study was to test different methods to estimate ET<sub>0</sub> using the Hargreaves-Samani equation (HS) under different meteorological conditions. ET<sub>0</sub> was calibrated with HS, adjusting the HS coefficient (HC), using different methods. Adjustment by linear regression was also performed. ET<sub>0</sub> was also estimated using the original HS and Penman-Monteith FAO-56 methods with limited climatic data (PML). The performance of the methods (mean absolute error, mm day<sup>-1</sup>) to estimate evapotranspiration, based on Penman-Monteith, were: PML (1.46); HS (0.68); Vanderlinden et al. (2004) (0.81); Martí et al. (2015) (0.77); and linear regression (0.53). The PML method presented the worst performance. Adjustment by linear regression presented a better performance than the adjustments of HC, improving the ET<sub>0</sub> estimates by up to 30%, and it is considered the most recommendable of the methods tested.

**Keywords:** Water balance; Potential evapotranspiration; Penman-Monteith; Agrometeorology.

## Resumen

La evapotranspiración es una variable importante en el ciclo hidrológico y uno de los principales componentes del equilibrio hídrico en el suelo. El uso de ecuaciones simplificadas es una alternativa potencial para estimar la evapotranspiración de referencia ( $ET_0$ ) cuando hay datos meteorológicos limitados. El objetivo de este estudio fue probar diferentes métodos para estimar  $ET_0$  utilizando la ecuación Hargreaves-Samani (HS) en diferentes condiciones meteorológicas.  $ET_0$  se calibró con HS, ajustando el coeficiente HS (HC), utilizando diferentes métodos. El ajuste por regresión lineal también se realizó.  $ET_0$  también se estimó utilizando los métodos originales HS y Penman-Monteith FAO-56 con datos climáticos limitados (PML). El desempeño de los métodos (error absoluto medio, mm día<sup>-1</sup>) para estimar la evapotranspiración, basados en Penman-Monteith, fueron: PML (1.46); HS (0,68); Vanderlinden y col. (2004) (0,81); Martí y col. (2015) (0,77); y regresión lineal (0.53). El método PML presentó el peor desempeño. El ajuste por regresión lineal presentó un mejor desempeño que los ajustes de HC, mejorando las estimaciones de  $ET_0$  hasta en un 30%, y se considera el más recomendable de los métodos probados.

**Palabras clave:** Balance hídrico; Evapotranspiración potencial; Penman-Monteith; Agrometeorología.

## 1. Introduction

Freshwater availability on the Earth has diminished in recent years due to a combination of more frequent droughts and intensification of demands on hydrological resources from agricultural, industrial and urban applications (WWAP-UNESCO, 2015). Evapotranspiration (ET) is an important variable of the hydrological cycle and one of the main components of the hydrological balance in soil (Carvalho, Rocha, Bonomo, & Souza, 2015). However, its direct determination is difficult and costly, requiring specialized personnel and equipment. Therefore, indirect ET estimates are fundamental to improve the use of hydrological resources in forestry and agricultural areas.

There are several models to calculate reference evapotranspiration. The Penman-Monteith method (PM), standardized by the Food and Agriculture Organization (FAO), has been used as a standard (Allen et al., 1998; Pereira et al., 2015). However, the use of this model requires numerous meteorological data that are frequently unavailable or unreliable, as is often the case with wind speed or net radiation (Gocic & Trajkovic, 2010; Martí et al., 2015). Therefore, the use of simplified equations is a potential alternative for  $ET_0$  estimation

(Alencar, Sediyama, & Mantovani, 2015; Carvalho et al., 2015; Hargreaves & Samani, 1985; Pereira et al., 2015; Sentelhas, Gillespie, & Santos, 2010; Thornthwaite, 1948).

Some authors have evaluated the performance of the Penman-Monteith method applied with limited climatological data to estimate  $ET_0$  and obtained satisfactory results (Alencar et al., 2015; Carvalho et al., 2015; Jabloun & Sahli, 2008; Raziei & Pereira, 2013; Sentelhas et al., 2010). Other authors have suggested using alternative methods for  $ET_0$  estimation with limited meteorological data, such as artificial neural networks (Falamarzi, Palizdan, Huang, & Lee, 2014; Martí, Manzano, & Royuela, 2011; Shiri et al., 2014; Zanetti, Sousa, Oliveira, Almeida, & Bernardo, 2007). However, given that these methods are empirical, they should not be extrapolated to other locations where there is limited meteorological data (Martí et al., 2015).

The use of the method proposed by Hargreaves and Samani (1985) (HS) is indicated as an alternative to estimate reference evapotranspiration with limited meteorological data (Allen et al., 1998; Sentelhas et al., 2010). The HS model is an empirical method initially developed in California (USA) that only requires extraterrestrial solar radiation and maximum and minimum air temperature data. However, various studies have shown that the HS method overestimates  $ET_0$  in humid regions and underestimates it in dry regions (Bezerra, Moura, Silva, Lopes, & Silva, 2014; Carvalho et al., 2015; Fanaya Júnior, Lopes, Oliveira, & Jung, 2012; Kisi, 2014; Tagliaferre, Silva, Rocha, Santos, & Silva, 2010; Trajkovic, 2007).

Therefore, the HS equation should be calibrated for each location seeking to improve the  $ET_0$  estimates for different climatic conditions (Allen et al., 1998; Xu and Singh, 2002; Martínez-Cob and Tejero-Juste, 2004; Jabloun and Sahli, 2008; Fernandes et al., 2012; Alencar et al., 2015; Shiri et al., 2015). Studies have proposed the calibration of the Hargreaves-Samani equation, taking as a reference the standard PM method to determine local  $ET_0$  (Berti, Tardivo, Chiaudani, Rech, & Borin, 2014; Gavilán, Lorite, Tornero, & Berengena, 2006; Maestre-Valero, Martínez-Álvarez, & González-Real, 2013; Mendicino & Senatore, 2013; Ravazzani, Corbari, Morella, Gianoli, & Mancini, 2012; Shahidian, Serralheiro, Serrano, & Teixeira, 2013; Vanderlinden et al., 2004). However, adjusted HS equations are specific to the location where there is data for calibration of  $ET_0$ , not being capable of extrapolation to other locations where meteorological data is limited (Martí et al., 2015). Therefore, in addition to local calibration, numerous authors have proposed calibration using the Hargreaves-Samani method, inserting geographic parameters to improve the  $ET_0$  estimates and allow the use of calibration in locations different to those where the method was adjusted (regional calibration) (Berti et al., 2014; Droogers & Allen, 2002; Lee, 2010;

Maestre-Valero et al., 2013; Martínez-Cob & Tejero-Juste, 2004; Mendicino & Senatore, 2013; Ravazzani et al., 2012; Thepadia & Martinez, 2012; Vanderlinden et al., 2004).

In Brazil, except for Zanetti, Dohler, Cecílio, Pezzopane, & Xavier (2019), existing studies are related to the HS method's local calibrations, with the development of regional calibrations being more necessary, as has been performed in a promising fashion in some other countries (Lee, 2010; Martí et al., 2015; Ravazzani et al., 2012; Thepadia & Martinez, 2012; Vanderlinden et al., 2004).

The objective of the present study is to apply and evaluate calibration methods for the Hargreaves-Samani equation under different meteorological conditions in the state of Espírito Santo, with limited meteorological data.

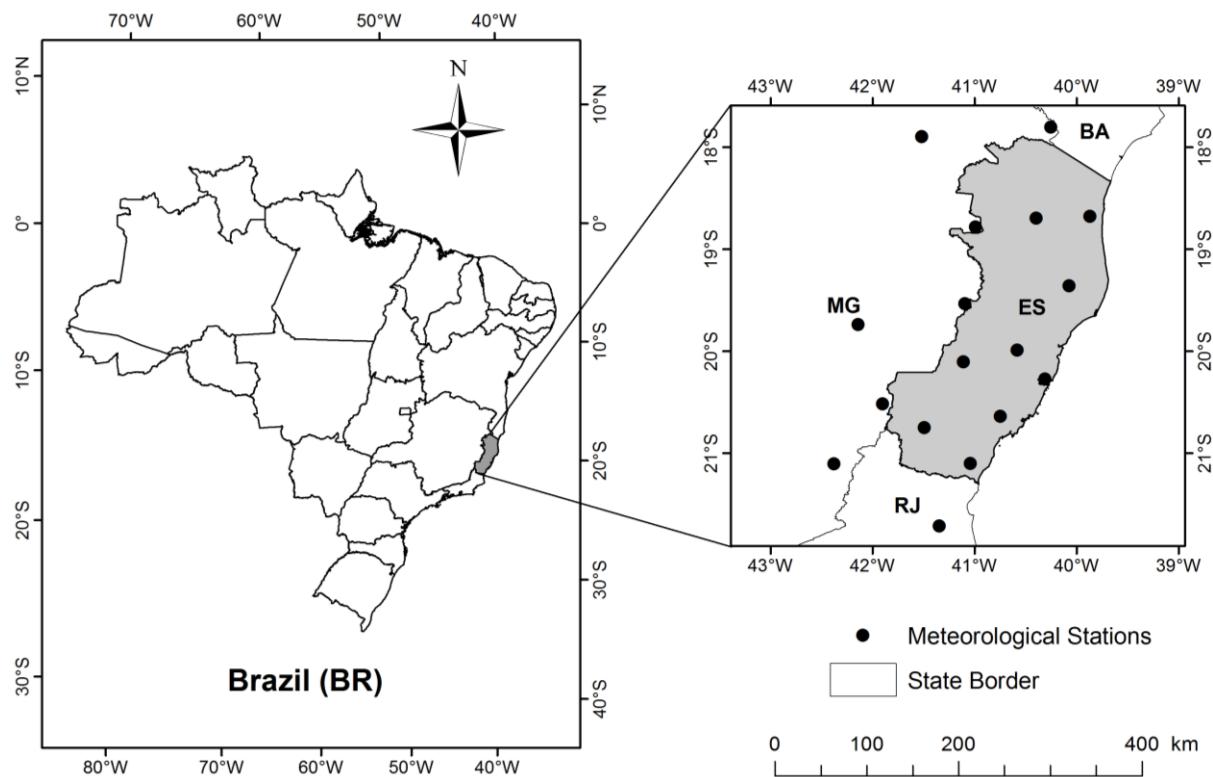
## 2. Methods

The present research is a case study of a quantitative nature. The research was developed in a natural environment, where the researcher made the analysis of the collected descriptive data. Another characteristic of this study is that it is laboratory research, since the analysis employed, which involved the obtaining and organizing data and execution of statistical adjustments, was all carried out in a computational environment, that is, the research was controlled (Pereira, Shitsuka, Parreira, & Shitsuka, 2018).

### 2.1. Area and data used in the study

The study was developed for the state of Espírito Santo (Figure 1), with a total area of 46,184.1 km<sup>2</sup>, geographically situated between the latitudes 39°38' and 41°50' W and between the longitudes 17°52' and 21°19' S.

**Figure 1.** Location of the study area (state of Espírito Santo – ES), with spatial distribution of the weather stations used.



Source: Zanetti, Dohler, Cecílio, Pezzopane, & Xavier (2019).

Weather data provided by Xavier et al. (2015) was used, with which the authors performed consistency tests. The data used in this study was derived from the network of weather stations of the National Meteorology Institute (INMET) for the period from 2009 to 2013 (five complete years) with daily information for maximum and minimum air temperature, global solar radiation, relative air humidity and wind speed.

For the state of Espírito Santo, data from nine automatic weather stations were obtained. Eight neighboring weather stations outside the state were also included, to minimize the frontier effect, with seven automatic weather stations and one conventional one. In total, 17 weather stations were used with their spatial distribution (Fig. 1).

The data records were analyzed, with the days with failures being discarded to perform this study. The description of the weather stations, with the Köppen climate classification (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013), is presented in Table 1.

**Table 1.** Weather stations, from the National Meteorology Institute, used in the study.

Code	County	State	Latitude	Longitude	Alt.*	Climate
A617	Alegre	ES	-20°45'01"	-41°29'19"	129	Cfa
A615	Alfredo Chaves	ES	-20°38'11"	-40°44'30"	14	Cfa
A614	Linhares	ES	-19°21'24"	-40°04'07"	38	Aw
A623	Nova Venécia	ES	-18°41'42"	-40°23'25"	156	Aw
A622	Presidente Kennedy	ES	-21°06'02"	-41°02'21"	69	Aw
A613	Santa Teresa	ES	-19°59'17"	-40°34'46"	976	Cfb
A616	São Mateus	ES	-18°40'33"	-39°51'50"	29	Aw
A612	Vitória	ES	-20°16'01"	-40°18'21"	9	Am
A534	Aimorés	MG	-19°31'57"	-41°05'26"	288	Aw
A607	Campos dos Goytacazes	RJ	-21°42'52"	-41°20'38"	17	Aw
83639	Caparaó	MG	-20°30'59"	-41°54'00"	843	Cwb
A554	Caratinga	MG	-19°44'08"	-42°08'13"	609	Cwa
A540	Mantena	MG	-18°46'50"	-40°59'11"	255	Aw
A517	Muriaé	MG	-21°06'17"	-42°22'33"	283	Cwa
A522	Serra dos Aimorés	MG	-17°47'55"	-40°14'59"	212	Aw
A527	Teófilo Otoni	MG	-17°53'34"	-41°30'55"	467	Aw

\*Altitude (meters above sea level). Source: Elaborated by the authors.

In most of the state, the total mean annual rainfall ranges from 1,000 to 1,600 mm, and the annual mean air temperature ranges from 18 to 24 °C, varying according to the climate of each region (Alvares et al., 2013).

## 2.2. Penman-Monteith FAO-56 Method (PM)

The standard Penman-Monteith FAO-56 equation (Allen et al., 1998) was applied to estimate evapotranspiration, the values ( $ET_0^{PM}$ ) of which were used in this study as a reference for all the adjustments and comparisons undertaken. The calculation to obtain the  $ET_0^{PM}$  was performed in a standardized manner according to Allen et al. (1998). Heat flow in soil (G) was equal to zero and the albedo of the reference culture was equal to 0.23.

### 2.3. Penman-Monteith Method with limitation of meteorological data (PML)

For reasons of comparison, the realization of the Penman-Monteith method was evaluated, only using air temperature data to determine ET<sub>0</sub>. Allen et al. (1998), in the FAO bulletin N°56, presented the methodology that should be used in the absence of wind speed, global solar radiation and relative humidity data.

Wind speed estimates depend on local climate and the season of the year. Where wind speed data is unavailable, the value 2 m s<sup>-1</sup> can be used as a provisional estimate. This value is a mean from more than 2,000 weather stations studied around the world (Allen et al., 1998).

In the absence of relative humidity data or when data quality is unreliable, the estimate of actual vapour pressure (e<sub>a</sub>) can be obtained assuming that the dew point temperature (T<sub>po</sub>) value is close to minimum temperature (T<sub>min</sub>) (Allen et al., 1998). This implicitly presupposes that at sunrise, when the temperature is close to T<sub>min</sub> the air is practically saturated, that is, the relative air humidity is nearly 100%. Therefore, e<sub>a</sub> was estimated using T<sub>min</sub> to represent T<sub>po</sub> in Tetens' equation.

For the calculation of the solar radiation (R<sub>s</sub>, MJ m<sup>-2</sup> day<sup>-1</sup>), Eq. 1 is used, proposed by Hargreaves and Samani (1985), that estimates global solar radiation as a function of the maximum (T<sub>max</sub>) and minimum daily air temperature (thermal amplitude).

$$R_s = k_{R_s} R_a \sqrt{(T_{\max} - T_{\min})} \quad (1)$$

Where R<sub>a</sub> is the extraterrestrial radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), and k<sub>R<sub>s</sub></sub> is the adjustment coefficient (°C<sup>-0.5</sup>).

The k<sub>R<sub>s</sub></sub> value varies from 0.16 to 0.19, with the value 0.16 used for interior regions (further than 20 km from the ocean) and 0.19 for coastal regions (up to 20 km from the ocean) (Hargreaves & Samani, 1985). R<sub>a</sub> values were also calculated according to the recommendations of Allen et al. (1998).

## 2.4. Hargreaves-Samani Method (1985) (HS)

The method proposed by Hargreaves and Samani (1985) was used to estimate  $ET_0$  (Eq. 2), which only requires the determination of air temperature data. Replacing Eq. 1 in Eq. 2, the original HS equation used in this study is obtained (Eq. 3).

$$ET_0 = 0.0135 \frac{R_s}{\lambda} (T_{mean} + 17.8) \quad (2)$$

$$ET_0^{HS} = 0.0023 \frac{R_a}{\lambda} \sqrt{(T_{max} - T_{min})} (T_{mean} + 17.8) \quad (3)$$

Where  $\lambda$  is the latent heat of water vaporization ( $2.45 \text{ MJ kg}^{-1}$ ), and  $T_{mean}$  is the mean daily air temperature ( $^{\circ}\text{C}$ ) at 2 m height (mean between  $T_{max}$  and  $T_{min}$ ).

The HS equation was adjusted for the study area using different methods: Hargreaves-Samani coefficient (HC) adjustment, using the Vanderlinden et al. (2004) and Martí et al. (2015) methods; and the  $ET_0^{HS}$  adjustment using simple linear regression. These methodologies are described in the following items.

## 2.5. Vanderlinden et al. (2004) method for the adjustment of HS equation

The method proposed by Vanderlinden et al. (2004) (Eq. 4) to adjust HC in Espírito Santo, was tested. Firstly, the daily HC values observed were determined for each weather station using Eq. 5. Based on the daily HC values, their mean was calculated for each station. With the mean air temperature, thermal amplitude and mean HC data for each station, a regression equation was adjusted ( $k_1$  and  $k_2$ ) to obtain the regional HC for the state.

$$HC = k_1 \frac{T_{mean}}{\Delta T} + k_2 \quad (4)$$

$$HC = 0.0023 \frac{ET_0^{PM}}{ET_0^{HS}} \quad (5)$$

## 2.6. Martí et al. (2015) method for adjustment of the HS equation

The methodology proposed by Martí et al. (2015), which takes new input variables and mean air temperature and thermal amplitude into account, was used to adjust HC. The input variables were: latitude ( $\tau$ ), longitude ( $\varphi$ ), altitude (z), mean air temperature ( $T_{mean}$ ) and thermal amplitude ( $\Delta T$ ). All the information for these variables was obtained from the stations studied. With the input variables and the mean HC for each station, the multiple linear regression equations were used to adjust the regional HC. Different combinations of the input variables were adopted to adjust the models. Firstly, models were proposed using only  $T_{mean}$  and  $\Delta T$ . Following this, the temperature inputs were combined with the latitude, longitude and altitude.

## 2.7. Evapotranspiration adjustment of the HS equation using linear regression

In the FAO bulletin n°56, Allen et al. (1998), recommend that the  $ET_0$  adjustment estimated by the HS equation be performed using a simple linear regression equation. In this case, the PM method was used as an independent variable to perform the  $ET_0$  adjustment on a daily timeframe (Eq. 6).

$$ET_0 = a + b ET_0^{HS} \quad (6)$$

The adjustment of the empirical parameters (a and b) was performed using the data from all the weather stations simultaneously (Table 1).

## 2.8. Evaluation of the performance of models

For the evaluation of the results, five statistical indices were used: the absolute mean error (MAE), mean error (MBE), root square mean error (RMSE) (Willmott, 1982), relative RMSE (RRMSE) (Martí et al., 2015) and the coefficient of determination of linear regression between observed and estimated  $ET_0$  ( $r^2$ ).

$$MAE = \frac{\sum_{i=1}^n |\hat{y}_i - y_i|}{n} \quad (7)$$

$$MBE = \frac{\sum_{i=1}^n (\hat{y}_i - y_i)}{n} \quad (8)$$

$$RMSE = \left( \frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n} \right)^{0.5} \quad (9)$$

$$RRMSE = \frac{RMSE}{\bar{y}} \quad (10)$$

Where  $\hat{y}$  is the  $ET_0$  estimated by the several methods evaluated,  $y$  is the  $ET_0$  obtained by PM (reference), and  $n$  is the number of data.

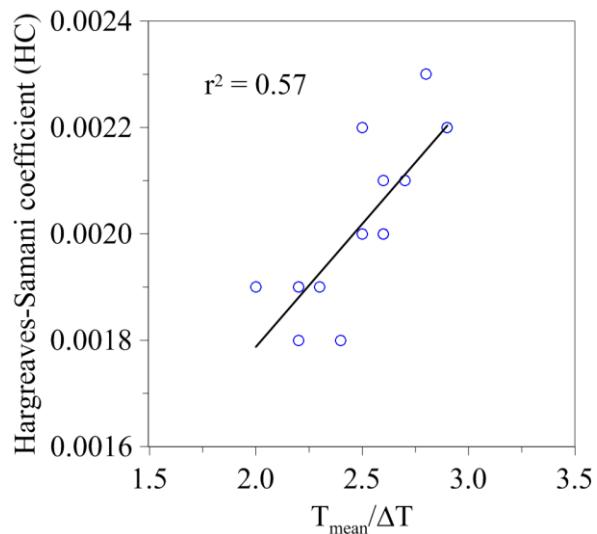
The evaluation of the performance of the models was performed individually for each of the 16 weather stations used in the study. In the evaluation of the performance of the model adjusted by linear regression (Eq. 6), the leave-one-out cross-validation was used: for each station evaluated, the model was adjusted using the data from the other 15 stations, that is, the model was evaluated with data not used in its adjustment, seeking to obtain a non-tendentious evaluation.

As the Vanderlinden et al. (2004) and Martí et al. (2015) models were adjusted using the data from all the stations simultaneously, as was done by the authors themselves. The evaluation of the performance of these models was consequently performed with the same data used in their adjustment. This procedure was carried out like this to allow comparison of the results from the present study with those obtained by the aforementioned authors.

### 3. Results and Discussion

Figure 2 presents the data and the adjustment of the method proposed by Vanderlinden et al. (2004), in Espírito Santo (Eq. 11).

**Figure 2.** Dispersion of the Hargreaves-Samani coefficient (HC) in relation to the ratio between mean air temperature and thermal amplitude ( $T_{\text{mean}}/\Delta T$ ), of the weather stations used, in the period from 2009 to 2013.



Source: Elaborated by the authors.

$$HC = 0.0004 \frac{T_{\text{mean}}}{\Delta T} + 0.0011 \quad (11)$$

The  $k_1$  and  $k_2$  values found in this study were close to the values found by Vanderlinden et al. (2004) in southern Spain. However, these authors observed an  $r^2$  of 0.90, significantly higher to that obtained in this study. The superior adjustment of the HC by the authors can be explained, probably, due to southern Spain having a homogeneous climate, different to Espírito Santo, which contains different climates (Table 1), and due to the similarity of the climate of eastern Spain with that of California (USA), the place where the original Hargreaves and Samani (1985) equation was developed.

The  $T_{\text{mean}}/\Delta T$  ratio varied from 2.0 in Caratinga-MG up to 2.9 in Linhares-ES and São Mateus-ES. For the HC, the values varied between 0.0018 in Matena-MG and Muriaé-MG, and 0.0023 in Presidente Kennedy-ES (Table 2).

**Table 2.** Adjustment of the models proposed by Martí et al. (2015) to estimate the coefficient of Hargreaves-Samani (HC) in the state of Espírito Santo, Brazil.

Model	Inputs	Model	RRMSE	r <sup>2</sup>	MAE
1	Temperature	$HC = 1.90 \times 10^{-3} + 4.49 \times 10^{-5} T_{mean} - 1.01 \times 10^{-4} \Delta T$	0.048	0.53	0.00008
2	Temperature, altitude	$HC = 2.12 \times 10^{-3} + 3.57 \times 10^{-5} T_{mean} - 9.80 \times 10^{-5} \Delta T - 5.89 \times 10^{-8} z$	0.047	0.54	0.00007
3	Temperature, latitude	$HC = 1.65 \times 10^{-3} + 4.54 \times 10^{-5} T_{mean} - 1.01 \times 10^{-4} \Delta T - 1.25 \times 10^{-5} \tau$	0.047	0.54	0.00008
4	Temperature, longitude	$HC = 9.91 \times 10^{-4} + 4.88 \times 10^{-5} T_{mean} - 1.10 \times 10^{-4} \Delta T - 2.22 \times 10^{-5} \phi$	0.047	0.54	0.00008
5	Temperature, latitude, altitude	$HC = 1.85 \times 10^{-3} + 3.78 \times 10^{-5} T_{mean} - 9.90 \times 10^{-5} \Delta T - 1.11 \times 10^{-5} \tau - 4.85 \times 10^{-8} z$	0.047	0.54	0.00008
6	Temperature, latitude, longitude	$HC = 1.18 \times 10^{-3} + 4.76 \times 10^{-5} T_{mean} - 1.07 \times 10^{-4} \Delta T - 9.06 \times 10^{-6} \tau - 1.33 \times 10^{-5} \phi$	0.047	0.54	0.00008
7	Temperature, longitude, altitude	$HC = 7.00 \times 10^{-4} + 3.46 \times 10^{-5} T_{mean} - 1.13 \times 10^{-4} \Delta T - 3.91 \times 10^{-5} \phi - 1.10 \times 10^{-7} z$	0.046	0.56	0.00007
8	Temperature, latitude, longitude, altitude	$HC = 6.61 \times 10^{-4} + 3.43 \times 10^{-5} T_{mean} - 1.13 \times 10^{-4} \Delta T + 1.40 \times 10^{-6} \tau - 4.11 \times 10^{-5} \phi - 1.14 \times 10^{-7} z$	0.046	0.56	0.00007

HC: adjusted Hargreaves-Samani coefficient,  $T_{mean}$ : mean air temperature,  $\Delta T$ : thermal amplitude,  $z$ : altitude,  $\tau$ : latitude,  $\phi$ : longitude, RRMSE: relative root mean square error (dimensionless),  $r^2$ : adjusted coefficient of determination, MAE: mean absolute error (dimensionless).  
Source: Elaborated by the authors.

Table 2 presents the models adjusted for HC, using the Martí et al. (2015) method, using multiple linear regression. Several combinations were performed, with model 1 depending only on temperature data, whereas models 2 to 8 are combinations of the temperature data with geographic information.

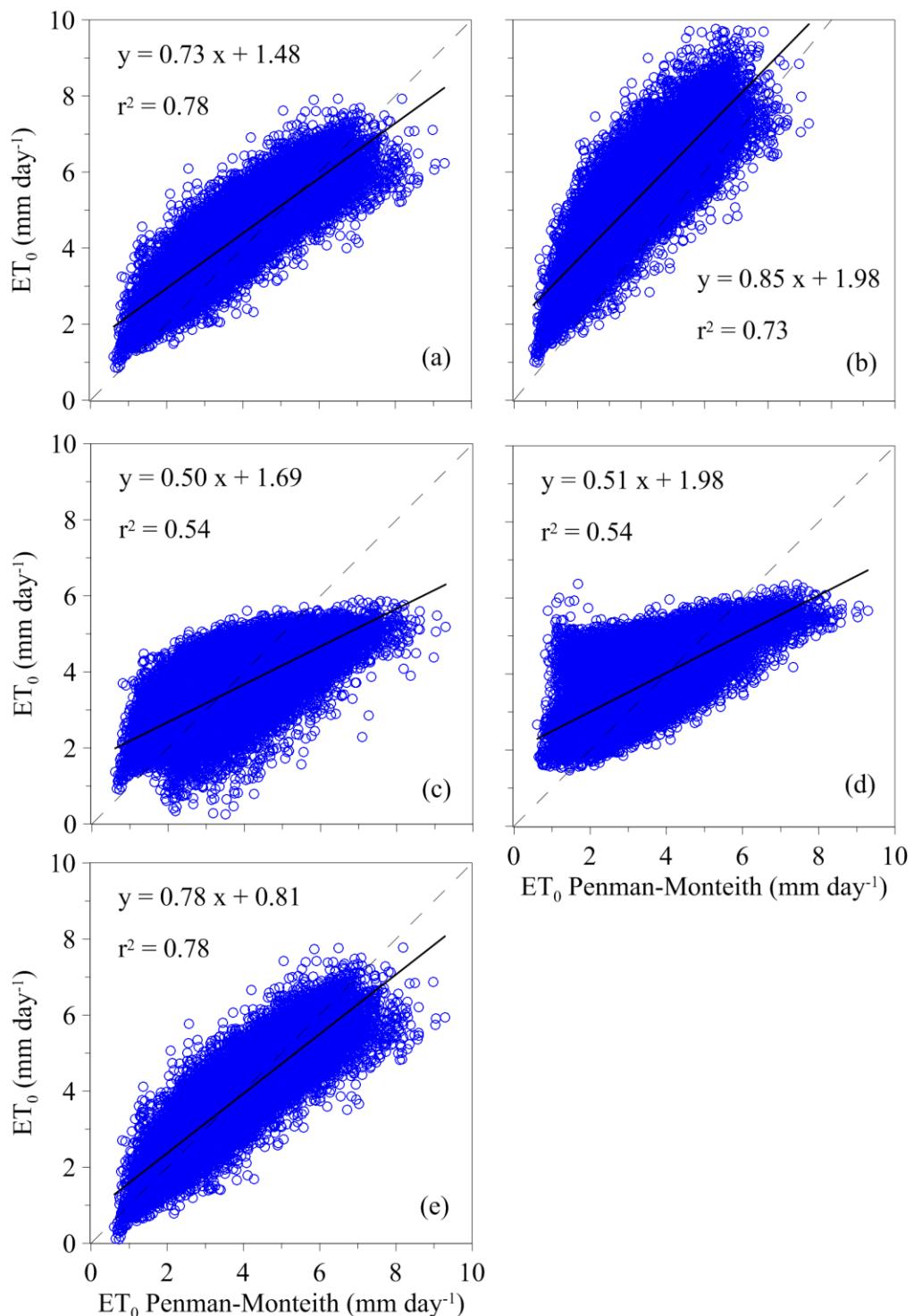
The use of the geographic coordinates that are easily accessible for any station or location, did not present a significant difference in relation to the model only temperature-based. In eastern Spain, an improvement of the models to estimate HC with geographic coordinates was observed by Martí et al. (2015). These authors also observed a better adjustment of the models, in relation to this study, with RRMSE of up to 0.037, which could also be explained by the homogeneity of the climate in eastern Spain. To evaluate the adjustment of Martí et al. (2015) in the present study, model 7 was adopted, due to its ease of application and better performance. These results are presented and compared with the other models later on.

When adjusting the  $ET_0$  of the HS equation using linear regression (Eq. 6), the Eq. (12) was obtained, with  $r^2 = 0.78$  significant at 1% probability by F test ( $p<0.01$ ).

$$ET_0 = 1.08 ET_0^{HS} - 0.81 \quad (12)$$

Figure 3 shows the dispersion graphs demonstrating the quality of the adjustment of the methods evaluated in this study, in relation to the Penman-Monteith method with complete data, applied simultaneously with all stations.

**Figure 3.** Dispersion of daily ET<sub>0</sub> (mm) estimated by the Hargreaves-Samani (a), PML (b), Martí et al. (2015) (c), Vanderlinden et al. (2004) (d) and linear regression adjustment (e), in the period between 2009 and 2013, in relation to the Penman-Monteith method.



Source: Elaborated by the authors.

The general performance of the models evaluated in this study, by the statistical indices, is presented in Table 3. Generally, in Espírito Santo, the HS method overestimated ET<sub>0</sub> by

0.47 mm day<sup>-1</sup> (MBE). Similar results were observed by Reis et al. (2007) and Carvalho et al. (2015), in the same state. Even though this value seems low, it is a daily mean error, that is, a daily hydrological sequence was performed showing an accumulative error in the ET<sub>0</sub> of 172 mm year<sup>-1</sup>.

**Table 3.** General performance of the models evaluated for the locations studied, in the period between 2009 and 2013.

Method	MAE (mm day <sup>-1</sup> )	MBE (mm day <sup>-1</sup> )	RMSE (mm day <sup>-1</sup> )	RRMSE	r <sup>2</sup>
Hargreaves-Samani (1985)	0.68	0.47	0.83	0.22	0.78
PML*	1.46	1.43	1.63	0.44	0.73
Martí et al. (2015)	0.81	-0.18	1.01	0.27	0.54
Vanderlinden et al. (2004)	0.77	0.17	1.00	0.27	0.54
Linear regression adjustment	0.53	0.00	0.68	0.18	0.78

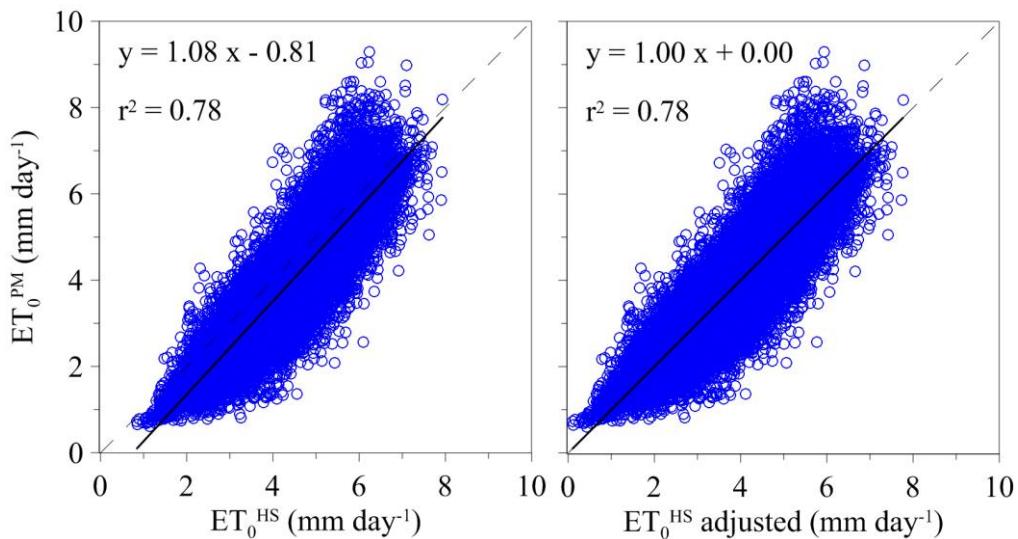
\*Penman-Monteith method applied with limited climatological data. Source: elaborated by the authors.

The Martí et al. (2015) and Vanderlinden et al. (2004) methods presented coefficients of determination ( $r^2$ ) of 0.54, with the lower value found between the methods tested. In their better model to estimate HC in Spain, Martí et al. (2015) encountered RRMSE of 0.19 and  $r^2$  of 0.87, significantly higher than that found in this study using the same method.

The PML method presented the worst performance of the methods, differing on average by 1.46 mm day<sup>-1</sup> from the PM method. Using 72 weather stations in Florida, Martinez and Thepadia (2010), obtained similar performance for the PML and HS methods, in which the HS method provided better ET<sub>0</sub> estimates than the PML method.

The adjustment of the HS equation, using linear regression, corrects the ET<sub>0</sub> without altering the  $r^2$  values, as illustrated in Figure 4. This adjustment alters the inclination and the vertical position of the line of tendency, without altering the data dispersion around it, resulting in null MBE values (this detail only can be seen putting ET<sub>0</sub><sup>HS</sup> on the x-axis.).

**Figure 4.** Daily  $ET_0$  dispersion (mm) estimated using the original (a) and adjusted (b) Hargreaves-Samani method in relation to the Penman and Monteith method, in the period between 2009 and 2013.



Source: Elaborated by the authors.

In general, adjustment by linear regression presented better performance than the HC adjustments, which improved the  $ET_0$  estimation by up to 30%, in relation to the original HS method. It is also worth noting that in the present study, independent stations were used to test the adjustment by linear regression, different to the adjustment methods for the HC.

Table 4 present the performance of the adjustments in the locations where their best and worst results were observed. The Hargreaves and Samani (1985) method presented better  $ET_0$  estimates in locations with a drier climate, such as Linhares-ES (climate Aw) for example, and worse estimates in locations with a humid climate, such as Caparaó-MG (climate Cwb) (Table 1). This demonstrates the need for local calibration of the HS equation to improve  $ET_0$  estimates depending on climatic condition (Allen et al., 1998; Fernandes et al., 2012; Alencar et al., 2015; Shiri et al., 2015).

**Table 4.** Locations with better and worse performance of evaluated methods, in the period between 2009 and 2013.

Method	MAE (mm day <sup>-1</sup> )	MBE (mm day <sup>-1</sup> )	RMSE (mm day <sup>-1</sup> )	RRMSE	r <sup>2</sup>	Place
Better performance						
Hargreaves-Samani (1985)	0.48	0.13	0.61	0.15	0.80	Linhares
PML	0.96	0.95	1.07	0.37	0.85	Santa Teresa
Martí et al. (2015)	0.66	-0.13	0.81	0.21	0.65	São Mateus
Vanderlinden et al. (2004)	0.61	0.19	0.79	0.25	0.59	Caparaó
Linear regression adjustment	0.42	0.03	0.54	0.14	0.88	Serra dos Aimorés
Worse performance						
Hargreaves-Samani (1985)	0.91	0.87	1.03	0.32	0.79	Caparaó
PML	1.91	1.90	2.08	0.65	0.61	Caparaó
Martí et al. (2015)	1.00	-0.13	1.24	0.31	0.49	Presidente Kennedy
Vanderlinden et al. (2004)	1.04	-0.53	1.29	0.30	0.50	Aimorés
Linear regression adjustment	0.78	-0.60	1.01	0.25	0.80	Presidente Kennedy

Source: Elaborated by the authors.

The RMSE values referent to the PML method, in Espírito Santo, varied between 1.07 and 2.08 mm day<sup>-1</sup>. These values were higher than those found for daily estimates in Bulgaria, Tunisia and in the Mediterranean, by Popova, Kercheva and Pereira (2006) (0.52–0.58 mm day<sup>-1</sup>), Jabloun and Sahli (2008) (0.41–0.80 mm day<sup>-1</sup>) and Todorovic, Karic and Pereira (2013) (0.60–0.65 mm day<sup>-1</sup>), respectively. In southeastern Brazil, (Carvalho et al., 2015) found values between 0.05 and 0.85 mm day<sup>-1</sup>.

The adjustment methods by linear regression presented better performance in Serra dos Aimorés-MG, and worse performance in Presidente Kennedy-ES. In the location of its worst performance, the adjustment methods by regression underestimated ET<sub>0</sub>, presenting MAE of up to 0.78 mm day<sup>-1</sup>.

Even with a 5-year meteorological data series, adjustments by linear regression provided satisfactory ET<sub>0</sub> estimates. However, new studies to calibrate the Hargreaves and Samani (1985) equation by linear regression should be performed in other regions of Brazil, with a longer meteorological data series, to provide better ET<sub>0</sub> estimates.

#### 4. Final Considerations and Suggestions

Adjustments by linear regression obtained better performance than the HC adjustments with the Vanderlinden et al. (2004) and Martí et al. (2015) methods.

The general adjustment method by linear regression is considered the most recommendable of the methods tested due to its ease of application.

In order of increasing efficiency for the evapotranspiration estimation methods with limited meteorological data, we have: PML, Martí et al. (2015), Vanderlinden et al. (2004), Hargreaves and Samani (1985), and general adjustment by linear regression.

Future research may be more promising using the method proposed by Zanetti et al. (2019) to calibrate empirical temperature-based models to estimate ET<sub>0</sub>. Using this method, on hotter and drier days (with greater thermal amplitude), when ET<sub>0</sub> is higher, it can be estimated more accurately using a specific calibration for each day's condition. It is a simple method that can improve results. This method can be applied to calibrate any empirical methods to estimate ET<sub>0</sub>. Also, future research may improve the quality of results if, in addition to temperature, other variables are added to the empirical models, such as relative humidity. Currently, the relative humidity can also be obtained in a practical and inexpensive way, using automatic psychrometers built with sensors such as thermistors and thermocouples, using low-cost platforms such as Arduino®.

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