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ARTIGO

Adjustment of the parameters of the Hargreaves and Samani model to estimate reference evapotranspiration on a daily scale for Rio Claro – RJ

Ajuste dos parâmetros do modelo de Hargreaves e Samani para estimativa de evapotranspiração de referência em escala diária para Rio Claro – RJ

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ABSTRACT: This study aimed to calibrate the Hargreaves-Samani (HS) model, a simplified alternative to the standard Penman-Monteith (PM) model, to estimate reference evapotranspiration (ETo) in Rio Claro, RJ, Brazil. Using daily meteorological data (maximum and minimum air temperature, wind speed, relative humidity, atmospheric pressure, and global solar radiation) from the INMET automatic weather station between 2016 and 2023, the HS model was calibrated with different parameter combinations (a, b, and c). Calibration performance was evaluated using statistical metrics (root mean square error - RMSE, coefficient of determination - R^2, mean square error - MSE, mean absolute error - MAE) and the "c" performance index proposed by Camargo and Sentelhas (1997). The three-parameter calibration (a=0.0019, b=10.30, c=0.6132) yielded the best results, with an RMSE of 0.27 mm/day and a "c" index of 0.85 ("very good"), outperforming calibrations with one or two parameters. Analysis of the residual distribution and spatial comparison with the PM model confirmed the good quality of fit of the calibrated HS model. The results demonstrate the importance of local calibration of the HS model to obtain accurate ETo estimates in Rio Claro, RJ, and its potential to assist in efficient irrigation management, water use optimization, and strategic decision-making in the agricultural sector, contributing to the sustainability of water resources in the region.
Keywords: reference evapotranspiration, model calibration, Hargreaves-Samani, Penman-Monteith, Rio Claro - RJ

RESUMO: Este estudo teve como objetivo calibrar o modelo de Hargreaves-Samani (HS), uma alternativa simplificada ao modelo padrão Penman-Monteith (PM), para estimar a evapotranspiração de referência (ETo) em Rio Claro, RJ. Utilizando dados meteorológicos diários (temperatura máxima e mínima do ar, velocidade do vento, umidade relativa do ar, pressão atmosférica e radiação solar global) da estação automática do INMET, entre 2016 e 2023, o modelo HS foi calibrado com diferentes combinações de parâmetros (a, b e c). O desempenho das calibrações foi avaliado por meio de métricas estatísticas (erro padrão de estimativa - EPE, coeficiente de determinação - R^2, erro quadrático médio - EQM, erro absoluto médio - EAM) e o índice de desempenho "c" proposto por Camargo e Sentelhas. A calibração com três parâmetros (a=0,0019, b=10,30, c=0,6132) apresentou os melhores resultados, com um EPE de 0,52 mm/dia e um índice "c" de 0,80 ("muito bom"), superando as calibrações com um ou dois parâmetros. A análise da distribuição dos resíduos e a comparação espacial com o modelo PM confirmaram a boa qualidade do ajuste do modelo HS calibrado. Os resultados demonstram a importância da calibração local do modelo HS para obter estimativas precisas da ETo em Rio Claro, RJ, e o seu potencial para auxiliar no manejo eficiente da irrigação, otimização do uso da água e tomada de decisões estratégicas no setor agrícola, contribuindo para a sustentabilidade dos recursos hídricos na região.
Palavras-chave: evapotranspiração de referência, calibração de modelo, Hargreaves-Samani, Penman-Monteith, Rio Claro - RJ

INTRODUCTION

Evapotranspiration (ET), the process encompassing evaporation of water from the soil and transpiration from plants, is a fundamental component of the hydrological cycle and plays a crucial role in various contexts. In agriculture, ET is the primary mechanism of water loss from crops, directly influencing productivity and the need for irrigation. On a global scale, ET contributes to climate regulation, affecting air temperature and humidity, in addition to playing a vital role in maintaining ecosystems by regulating the flow of water and nutrients.

The Penman-Monteith (PM) model, recognized as the standard by the Food and Agriculture Organization of the United Nations (FAO), is widely used to estimate reference evapotranspiration (ETo), a value representing the atmospheric evaporative demand under standardized conditions. However, the application of the PM model requires detailed meteorological data, such as solar radiation, relative humidity, and wind speed, which are often scarce or unavailable, especially in developing countries. Studies such as those by Allen et al. (1998), Ndulue & Ranjan (2021) and Talebmorad et al. (2020) highlight this limitation, demonstrating the need for alternative methods to estimate ETo in regions with limited meteorological data.

In this context, the Hargreaves-Samani (HS) model, proposed in 1985, emerges as a promising alternative, requiring only air temperature data, which are more easily accessible and widely available compared to other meteorological parameters. Several studies have demonstrated the potential of the HS model to estimate ETo in different regions and crops, especially when its parameters are calibrated to specific local conditions (Hargreaves & Samani, 1985; Kim et al., 2023; Niranjan & Nandagiri, 2021).

Calibration of the HS model is essential to ensure the accuracy of ETo estimates, particularly in humid regions, where air humidity exerts a significant influence on evapotranspiration. Studies such as those by Caya et al. (2020) and Dohler et al. (2020) highlight the need for HS model calibration to obtain more reliable results under different climatic conditions. The lack of calibration can lead to significant errors in ETo estimates, compromising irrigation management and water resource management.

Given this scenario, the present study aimed to calibrate the HS model to estimate ETo in the city of Rio Claro, RJ, Brazil. For this purpose, air temperature data collected by an automatic weather station located in the urban area of the city were used, covering the period from 2016 to 2024. Three different calibration approaches were explored, varying the number of adjusted parameters, with the aim of identifying the model that best represents ETo under local climatic conditions (Kukal et al., 2020).

The calibrated models were evaluated using statistical metrics such as standard error of estimation (SEE), Willmott's index (d), correlation coefficient (r), and "c" performance index. These metrics allow for comparing the performance of the adjusted models with the reference Penman-Monteith model and identifying the most accurate and reliable model for estimating ETo in Rio Claro (Lima Junior et al., 2016; Zanetti et al., 2019).

This study seeks to contribute to the improvement of ETo estimation in regions with limited meteorological data, as is the case in many areas in Brazil and other developing countries. By providing a calibrated and validated model for the city of Rio Claro, it is expected that the results of this research can be applied in other locations with similar climatic characteristics, assisting in irrigation management, water resource management, and agricultural planning.

MATERIALS AND METHODS

The study area encompasses the city of Rio Claro and its surroundings, located in the south-central region of the state of Rio de Janeiro, Brazil. The area is characterized by a Ws (Köppen) climate type, featuring a rainy season in the summer and a dry season in the winter, with average maximum temperatures of 24°C in January and February, and minimum temperatures of 16.7°C in July, with an average annual precipitation of around 1200 mm (Oliveira et al., 2011; Paiva & Coelho, 2015).

The region presents a varied topography, with altitudes ranging from 400 to 800 meters above sea level. The predominant vegetation consists of Atlantic Forest, with areas of pasture and agricultural crops such as coffee, corn, beans, and vegetables. The region also possesses important water resources, including rivers, lakes, and reservoirs, which are used for public supply, irrigation, and power generation (Oliveira et al., 2011).

For this study, daily data of maximum and minimum air temperature (°C), wind speed (m/s), relative humidity (%), atmospheric pressure (kPa), and global solar radiation (MJ/m²) were used. These data were obtained from the automatic weather station of the National Institute of Meteorology (INMET), station code 83961, located in Rio Claro - RJ, at geographic coordinates 22°43'26"S, 44°2'27.3"W, and an altitude of 516 meters, covering the period from 2016 to 2023.

Following FAO recommendations, empirical methods should be calibrated and validated based on the FAO-56 Penman-Monteith equation (Equation 1), given its robustness and performance under different climatic conditions. Therefore, this equation was adopted as the standard in this study.

$$ETo = \frac{0.408 \cdot \Delta \cdot \left(R_n - G\right) + \gamma \bullet \frac{900}{T+273} \bullet u_2 \bullet \left(e_s - e_a\right)}{\Delta + \gamma \bullet \left(1 + 0.34 \cdot u_2\right)} \quad (1)$$

where:

ETo – reference evapotranspiration (mm day^{-1});

Δ – slope of the saturation vapor pressure curve (kPa $°C^{-1}$);

Rn – net radiation (MJ m^{-2} day^{-1});

G – soil heat flux density (MJ m^{-2} day^{-1});

γ – psychrometric constant (kPa $°C^{-1}$);

T – air temperature measured at 2 meters height (ºC);

u_2 – wind speed measured at 2 meters (ms^{-1});
e_s – saturation vapor pressure (kPa); and
e_a – actual vapor pressure (kPa).

Considering the availability of global solar radiation (Rs) data, the use of sunshine duration data was not necessary, and net radiation values were directly inserted into the calculation routine of the Penman-Monteith model.

Hargreaves & Samani (1985) proposed the following equation for estimating ETo using only the maximum, minimum, and mean air temperatures and extraterrestrial solar radiation (Equation 2).

$$ETo = 0.408 \cdot a \cdot R_a \bullet \left(T_x - T_{mín}\right)^b \bullet \left(c + T_{máx}\right) \quad (2)$$

where:
a – adjustment parameter (original value 0.0023);
b – adjustment parameter (original value 0.5);
c – adjustment parameter (original value 17.8);
R_a – extraterrestrial solar radiation (MJ m^{-2} day^{-1});
Tx – mean daily air temperature (ºC);
Tmín – minimum daily air temperature (ºC); and
Tmáx – maximum daily air temperature (ºC).

The calibration of the Hargreaves-Samani (HS) model was performed using the FAO-56 Penman-Monteith (PM) model as a reference, aiming to minimize the differences between the ETo estimates of both models. For this purpose, the parameters a, b, and c of the HS equation were adjusted using the "Solver" optimization algorithm in Microsoft Excel, based on the generalized least squares method (Lasdon et al., 1978; Wraith & Or, 1998). The calibration process was divided into three stages, each exploring different parameter combinations:

One-parameter calibration: In this stage, only one of the parameters (a, b, or c) was adjusted at a time, keeping the others fixed at their original values (0.0023, 0.5, and 17.8, respectively). This approach allowed for evaluating the sensitivity of the HS model to each parameter individually.

Two-parameter calibration: In this stage, two parameters were adjusted at a time, keeping the third fixed at its original value. Three distinct calibrations were performed, adjusting the parameter pairs (a and b), (a and c), and (b and c). This approach allowed for evaluating the interaction between the parameters and identifying which pairs exert the greatest influence on the ETo estimation.

Three-parameter calibration: In this stage, all three parameters (a, b, and c) were adjusted simultaneously. This approach sought to find the optimal parameter combination that minimized the error between the HS model estimates and the FAO-56 PM model.

In each stage, the Excel "Solver" optimization algorithm was used to find the parameter values that minimized the sum of squared errors between the ETo estimates of the HS model and the FAO-56 PM model. The calibration process was repeated for different periods of the year to verify the stability of the adjusted parameters over time and identify possible seasonal variations.

The performance evaluation of the different HS model calibrations was conducted using statistical metrics such as the root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2). The RMSE and MAE quantify the magnitude of errors between the estimated and observed ETo values, while R^2 indicates the proportion of variance in the observed data explained by the model (Cobaner et al., 2017).

Additionally, the "c" performance index (Equation 3), proposed by Camargo & Sentelhas (1997), was used to classify the overall performance of the calibrated models. The "c" index combines Willmott's index (d) and the correlation coefficient (r) into a single metric, ranging from 0 to 1, with 1 indicating a perfect model. The classification of the "c" index (Table 1) allows for a qualitative assessment of model performance, ranging from "poor" ($c \leq 0.40$) to "excellent" ($c > 0.85$).

$$c = d \cdot r \qquad (3)$$

where:

c – Camargo and Sentelhas coefficient;
d – Willmott's index; and
r – correlation coefficient.

Table 1. Camargo and Sentelhas index classification.

Value of “c”	Performance evaluation
> 0.85	Excellent
0.76 – 0.85	Very good
0.66 – 0.75	Good
0.61 – 0.65	Average
0.51 – 0.60	Poor
0.41 – 0.50	Bad
≤ 0.40	Terrible

To complement the quantitative analysis, a graphical analysis of the residuals (difference between observed and estimated ETo values) was performed as a function of the estimated values. This graphical analysis allowed for identifying possible patterns in the model's errors, such as heteroscedasticity or systematic biases, which may indicate the need for further adjustments in the calibration. Additionally, the distribution of residuals was assessed through a histogram, aiming to verify the normality of errors and identify potential outliers that could influence performance metrics (De Lima et al., 2016; Gavilán et al., 2006).

Prior to calibration, the meteorological data underwent exploratory analysis, including descriptive statistics (mean, standard deviation, maximum, and minimum values) and assessment of the frequency distribution of variables. This step aimed to identify possible inconsistencies, such as outliers or missing data, and to verify the normality of variables, an important assumption for applying statistical tests and regression models (Niranjan & Nandagiri, 2021).

To validate the calibrated model, 20% of the data were randomly selected and set aside for this purpose. The HS model, with parameters adjusted during the calibration stage, was applied to the validation dataset, and its ETo estimates were compared with the reference values from the PM model (Paredes et al., 2020).

The same statistical metrics used in the calibration evaluation (RMSE, MAE, R^2, "c" index) were calculated for the validation dataset to verify the model's ability to generalize to new situations and ensure its applicability under real conditions.

The discussion of results will encompass the practical implications of the HS model calibration for the Rio Claro region and its surroundings. The potential benefits of using the calibrated model for irrigation management will be addressed, such as water use optimization, cost reduction, and increased agricultural productivity.

RESULTS AND DISCUSSION

The results obtained in this study highlighted the importance of calibrating the Hargreaves-Samani (HS) model for the accurate estimation of reference evapotranspiration (ETo) in Rio Claro, RJ. The different calibration approaches, varying the number of adjusted parameters, revealed that the inclusion of more parameters significantly improves the model's predictive capacity.

Adjustments with only one parameter (a, b, or c) showed unsatisfactory performance in estimating ETo, indicating that excessive simplification of the model compromises its accuracy. The inclusion of two parameters (a and b, a and c, or b and c) already resulted in improvements in predictive capacity, but it was still not enough to achieve optimal performance.

The calibration with three parameters (a, b, and c) stood out as the most effective, presenting the lowest standard error of estimation (MAE) and the highest "c" index among all tested approaches. The RMSE of 0.27 mm/day indicates a low average error in the estimates, while the "c" index of 0.85, classified as "very good," demonstrates a high agreement between the HS model estimates and the reference values of the Penman-Monteith (PM) model (Habeeb et al., 2021).

Table 2. Classification of statistical parameters for each of the calibrations performed.

Parameters			Classification				
a	b	c	RMSE	MAE	R2	d	c
0,0020	-	-	0,2864	0,4136	0,8236	0,8590	0,7852
-	12,3461	-	0,2849	0,4102	0,8243	0,8618	0,7878
-	-	0,4424	0,3098	0,4304	0,8119	0,8471	0,7743

0,0025	10,1368	-	0,2854	0,4099	0,8244	0,8625	0,7884
0,0015	-	0,6135	0,2723	0,4030	0,8331	0,8680	0,7934
-	6,2045	0,5782	0,2780	0,4026	0,8339	0,8690	0,7944
0,0019	10,2998	0,6132	0,2731	0,4003	0,8656	0,9160	0,8522

These results highlight the importance of considering the interaction between the HS model parameters and the need to adjust them jointly to obtain more accurate ETo estimates. The three-parameter calibration allowed the model to capture more effectively the complexity of evapotranspiration processes in the Rio Claro region, taking into account seasonal temperature variations, the influence of air humidity, and other factors that affect the atmospheric evaporative demand. Figure 1 presents the correlation analysis for the validation of the methodology with three adjustment parameters.

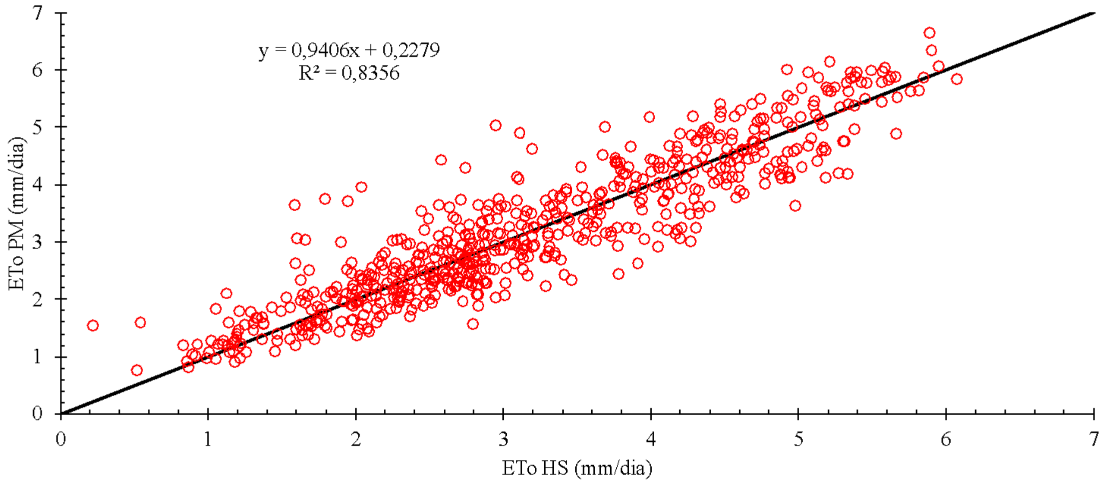

Figure 1. Scatter plot and correlation of data between the Penman-Monteith evapotranspiration estimate and the adjusted Hargreaves-Samani model.

Figure 2 illustrates the spatial distribution of ETo values estimated by the calibrated HS model compared to the reference values of the PM model. A good agreement is observed between the two models, with most points close to the 1:1 line, indicating that the calibrated HS model can adequately represent the spatial variability of ETo in the study region.

However, it is possible to notice that the HS model tends to overestimate ETo at some points, especially in areas with higher ETo values. This overestimation can be attributed to limitations of the HS model, which does not explicitly consider the influence of air humidity on evapotranspiration. In regions with high humidity, evapotranspiration tends to be lower than in regions with low humidity, even with similar temperatures (Almorox & Grieser, 2016; Rodrigues & Braga, 2021).

Despite this tendency for overestimation at some points, the spatial distribution of ETo values estimated by the calibrated HS model is consistent with the reference values of the PM model, demonstrating the model's ability to represent the spatial variability of ETo in the study region. The graphical analysis of Figure 2 complements the statistical performance metrics, providing a visualization of the model's fit quality and allowing for the identification of areas where the model may exhibit higher or lower accuracy (Pandey & Pandey, 2023).

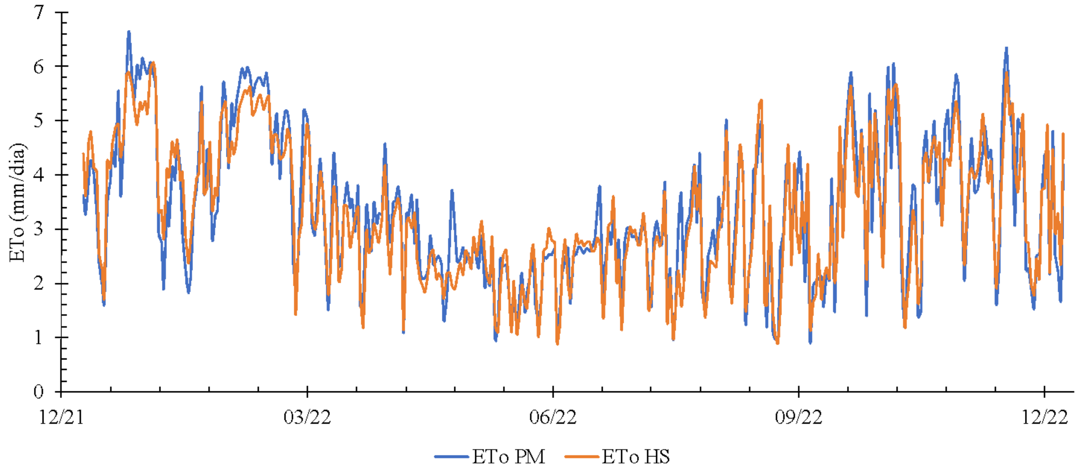

Figure 2. Spatial distribution and validation of data, of the evapotranspiration estimate by the adjusted model in comparison to the reference.

Figure 3, which presents the frequency distribution of residuals (difference between ETo values estimated by the calibrated HS model and reference values from the PM model), reinforces the quality of the model fit. The distribution of residuals is approximately normal, with most values concentrated around zero, indicating that the model does not exhibit systematic tendencies of overestimation or underestimation of ETo.

The symmetry of the residual distribution and the low frequency of extreme values (outliers) demonstrate that the calibrated HS model is capable of adequately representing the variability of ETo in the study region, even under extreme weather conditions. The analysis of the residual distribution complements the statistical performance metrics, providing an additional view of the model's fit quality and confirming its suitability for estimating ETo in Rio Claro and regions with similar climatic characteristics (Al-Asadi et al., 2023).

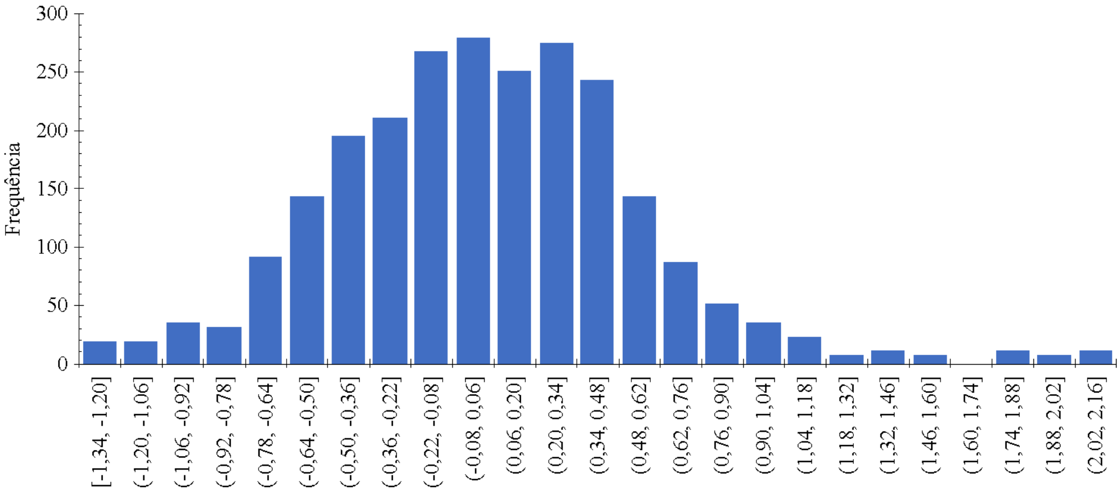

Figure 3. Frequency distribution of residuals from the Hargreaves-Samani evapotranspiration estimate.

These results corroborate other studies that have demonstrated the effectiveness of the calibrated HS model in estimating ETo in different regions and climatic conditions. Local calibration allows the model to adapt to the region's particularities, such as seasonal temperature variation and the influence of air humidity on evapotranspiration, resulting in more accurate and reliable estimates (Gentilucci et al., 2021; Moratiel et al., 2020).

The use of the calibrated HS model can bring significant benefits to irrigation management and water resource management in Rio Claro and regions with similar climatic characteristics. Accurate ETo estimates can aid in irrigation planning, water use optimization, and reduction of agricultural production costs. Furthermore, the calibrated HS model can be used in other applications, such as urban planning, environmental monitoring, and forecasting extreme weather events.

FINAL CONSIDERATIONS

In summary, this study demonstrated the importance of calibrating the Hargreaves-Samani (HS) model for the accurate estimation of reference evapotranspiration (ETo) in Rio Claro, RJ. The calibration with three parameters (a, b, and c) resulted in more accurate and reliable ETo estimates compared to the original model and calibrations using one or two parameters.

Additionally, the sensitivity analysis revealed that parameter "b" is the most sensitive, indicating that small variations in this parameter can have a significant impact on ETo estimates.

The results obtained in this study corroborate the importance of local calibration to improve the performance of the HS model, especially in regions with distinct climatic characteristics. The use of the calibrated HS model can significantly assist in irrigation management, optimizing water use, increasing agricultural productivity, and contributing to the sustainability of water resources in the region.

This study not only provides valuable information for agricultural and water management in Rio Claro but also demonstrates the importance of calibrating empirical models for local applications. The methodology employed, including exploratory data analysis, model calibration with different parameter combinations, performance evaluation using statistical metrics, and sensitivity analysis, can be replicated in other regions, contributing to the advancement of knowledge and water management practices in different climatic contexts.

In conclusion, the calibration of the HS model for the Rio Claro region demonstrated its potential to estimate ETo with good accuracy, providing a valuable tool for water resource planning and management. The model's simplicity and the ease of obtaining temperature data make it an attractive alternative for regions with limited resources, but the need for local calibrations and consideration of the model's limitations are crucial to ensure the accuracy and reliability of ETo estimates. Future studies can explore the combination of the HS model with other data sources, such as remote sensing and weather forecasting models, to further enhance its predictive capacity and expand its applicability in different contexts.

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