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A COMPARATIVE RELATION OF DISTINCT REFERENCE CROP EVAPOTRANSPIRATION MODELS FOR SOUTHERN BRAZIL

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Abstract

Water is one of the main limiting factors for achieving high productivity in agriculture. The hydric requirement of plants is fundamental for the dimensioning of the irrigation system and contributes to the better use of hydric resources. Moreover, the accurate computation of this element is essential for water management in agricultural systems. Nonetheless, due to the heterogeneity of different evapotranspiration estimation methods, the performance of its calculation can be considerably compromised. Accordingly, the aim of this study was to compare the methods for estimating reference evapotranspiration (ETo) by Benevides & Lopes, Camargo, Hargreaves & Samani, Jensen & Haise, Linacre, Makkink, Penman, Priestley & Taylor, Tanner & Pelton, and Turc, with the FAO-56 Penman-Monteith standard method, to evaluate the performance and accuracy of equational models. Furthermore, data from an automatic weather station belonging to the Brazilian National Institute of Meteorology (INMET), located in Palmeira das Missões, Rio Grande do Sul, Brazil, from January 1, 2020, to January 1, 2021, were used. Comparative statistical methods were utilized to express the accuracy of the models and indicate the most appropriate equations for the conditions of the selected location. Cluster analysis and Principal Component Analysis (PCA) were applied. For Palmeira das Missões, the model proposed by Hargreaves & Samani indicated the best results and was characterized as the most appropriate alternative to estimate the ETo more accurately. The method indicated the most favorable results for R^2 (0.9890), d (0.9253), and r (0.9944). Furthermore, cluster and PCA analyses expressed the behavior of relationships between different mathematical models and meteorological parameters in relation to the ETo determination.

Keywords: conservation and efficient use of water in agriculture; FAO-56; empirical models; water requirement of plants.

UMA RELAÇÃO COMPARATIVA DE DISTINTOS MODELOS DE EVAPOTRANSPIRAÇÃO DE REFERÊNCIA DE CULTURAS PARA O SUL DO BRASIL

Resumo

A água é um dos principais fatores limitantes para se atingir altas produtividades na agricultura. A necessidade hídrica da cultura é fundamental para o dimensionamento do sistema de irrigação e contribui para o melhor aproveitamento dos recursos hídricos. Desta forma, a computação acurada de tal elemento é essencial para o manejo da água em sistemas agrícolas. Entretanto, devido à heterogeneidade de diferentes métodos de estimativa da evapotranspiração, o desempenho de sua apuração pode ser consideravelmente comprometido. Adequadamente, o objetivo deste estudo foi comparar os métodos de estimativa da evapotranspiração de referência (ETo) de Benevides & Lopes, Camargo, Hargreaves & Samani, Jensen & Haise, Linacre, Makkink, Penman, Priestley & Taylor, Tanner & Pelton e Turc, com o método padrão FAO-56 Penman-Monteith, com o propósito de avaliar a performance e precisão dos modelos equacionais. Com isso, foram utilizados dados de uma estação meteorológica automática pertencente ao Instituto Nacional de Meteorologia (INMET), localizada em Palmeira das Missões, Rio Grande do Sul, Brazil, de 1 de janeiro de 2020 a 1 de janeiro de 2021. Métodos estatísticos comparativos foram utilizados para expressar a precisão dos modelos e indicar as equações mais apropriadas para as condições do local selecionado. A análise de agrupamento e Análise de Componentes Principais (PCA) foi aplicada. Para Palmeira das Missões, o modelo proposto por Hargreaves & Samani indicou os melhores resultados e se caracterizou como a alternativa mais apropriada para estimar a ETo da forma mais precisa. O método indicou os resultados mais favoráveis para R^2 (0,9890), d (0,9253) e r (0,9944). Ainda, as análises de agrupamento e PCA expressaram o comportamento de relações entre os diferentes modelos matemáticos e parâmetros meteorológicos em relação à determinação da ETo.

Palavras-chave: conservação e uso eficiente de água na agricultura; FAO-56; modelos empíricos; requerimento hídrico das plantas.

Introduction

Evapotranspiration is characterized as a primordial and vital mechanism for plants, referring to the association of two distinct process components: plant transpiration, pertinent to the suppression of water from the plant towards the atmosphere; and soil evaporation, related to the removal of the same resource, from the soil surface to the atmospheric layer (JERSZURKI *et al*., 2017). Evapotranspiration is a fundamental component for the characterization of the plant water balance since it considers different parameters, such as water and processes acting on plants (DAROUICH *et al*., 2022). The relevance of such an approach is supported by the ability to measure flows in plant species and the dynamics of water in the soil-plant-atmosphere continuum, which is directly related to the global hydrological cycle (BOTTAZZI *et al*., 2021). According to

Allen *et al*. (1998), the determination of the reference evapotranspiration (ETo) of crops is inferred as a crucial factor to determine their water requirements. Nonetheless, physical methods, such as the application of lysimeters and the Eddy Covariance method, cause a range of errors in the absolute values of crop evapotranspiration, mainly due to the compromised accuracy in the field measurement processes.

Accordingly, the availability of specific strategies that provide precision and speed in the processes of obtaining data is valuable, mainly due to the reliability required in the information obtained (AFZAAL *et al*., 2020). Currently, the development of models referring to ETo determination is inferred as a major factor, mainly due to the accuracy and applicability of the data in irrigation programming and management strategies. Nevertheless, due to a range of existing methods for developing ETo estimates, the choice of the most appropriate resource depends on the number of meteorological parameters required and the availability of these parameters (SANTOS *et al*., 2021).

The Penman-Monteith method (ALLEN *et al*., 1998), recommended by the Food and Agriculture Organization (FAO), for estimating evapotranspiration, is globally accepted as a standard and widely used method for large-scale approaches (DLOUHÁ *et al*., 2021). Furthermore, the Penman-Monteith method has been widely used to calibrate other methods. Nonetheless, this method requires several meteorological variables that are not measured in many locations, limiting its use (DEBNATH *et al*., 2015). Moreover, the necessity for a range of meteorological components and poor arrangement of locations for obtaining the data compromise the computation of evapotranspiration, as well as resulting in gaps, considering the complexity of its estimation (CELESTIN *et al*., 2020).

Besides, accuracy and precision in evapotranspiration estimates are key components for proper water management in agricultural systems and subsequent assessment of soil water balance (GHIAT *et al*., 2021). Nonetheless, the difficulty of an accurate determination of evapotranspiration becomes an important factor to be considered. Therefore, over the years, many approaches have been developed to estimate ETo (JO *et al*., 2021). Each approach differs in relation to the meteorological variables required to calculate the evapotranspiration estimate. Consequently, numerous studies have been conducted with the purpose of comparing the accuracy of different methods, in different scenarios and climatic conditions, based on the standard Penman-Monteith method (ČADRO *et al*., 2017; SALAM *et al*., 2020).

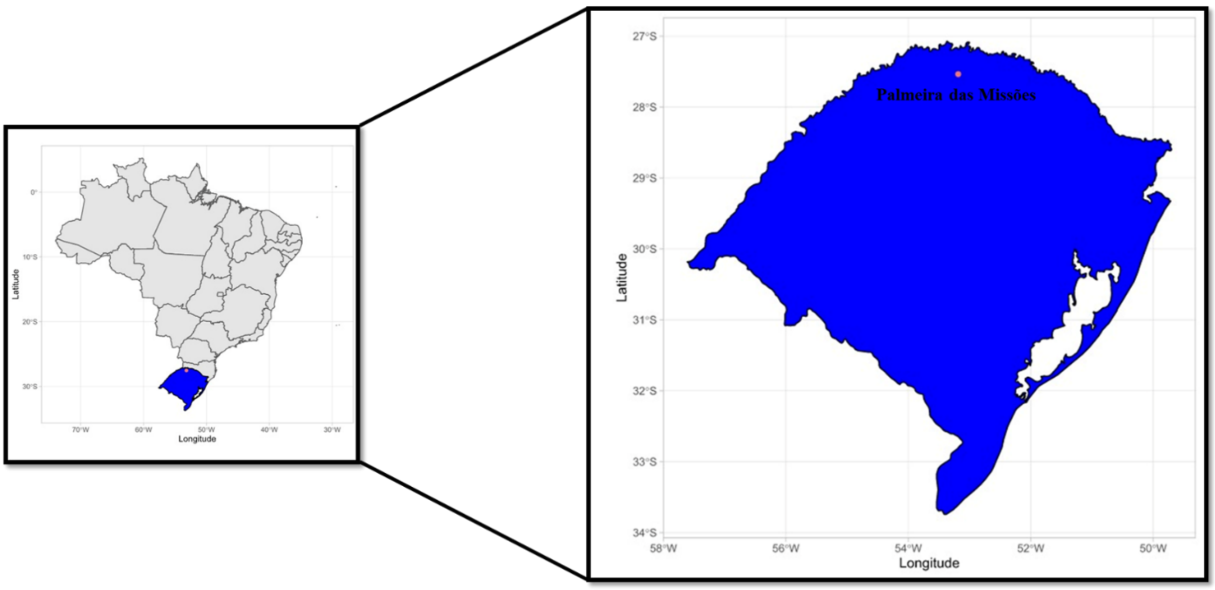
Due to the heterogeneity of the models, depending on the range of different parameters, the performance in estimating the reference evapotranspiration is also variable. Moreover, the importance of comparing different ETo estimation methods is emphasized, considering different behaviors of the meteorological variables of a specific location. Appropriately, this study aimed to estimate evapotranspiration using the methods of Penman, Priestley & Taylor, Tanner & Pelton, Makkink, Jensen & Haise, Hargreaves & Samani, Camargo, Benevides & Lopes, Turc, and Linacre; and compare the results with the standard Penman-Monteith method, to evaluate the performance and precision of these different strategies in Palmeira das Missões, Rio Grande do Sul, Brazil.

Material and Methods

Location characterization

Daily weather data were obtained from an automatic weather station from the Brazilian National Institute of Meteorology (INMET), located in Palmeira das Missões, Northern Rio Grande do Sul, Brazil (Figure 1). It is noteworthy that the data comprise the period between January 1st, 2020, and January 1st, 2021, totaling 12 months. According to the Köppen-Geiger climate characterization, the climate of Palmeira das Missões is classified as Cfa, subtropical with rainfall significantly distributed throughout the year (PEEL *et al*., 2007). Accordingly, the geographical characteristics of Palmeira das Missões were: latitude (°): -27.5319, longitude (°): -53.1819, altitude (m): 639. The automatic station provided the parameters T_{max} (daily maximum temperature, °C), T_{min} (daily minimum temperature, °C), Ws (wind speed at 2 meters high, m s^{-1}), atmospheric pressure (hPa), RH_{max} (daily maximum relative humidity, %), RH_{min} (daily minimum relative humidity, %), and K↓ (incident global radiation, MJ m^{-2} day^{-1}).

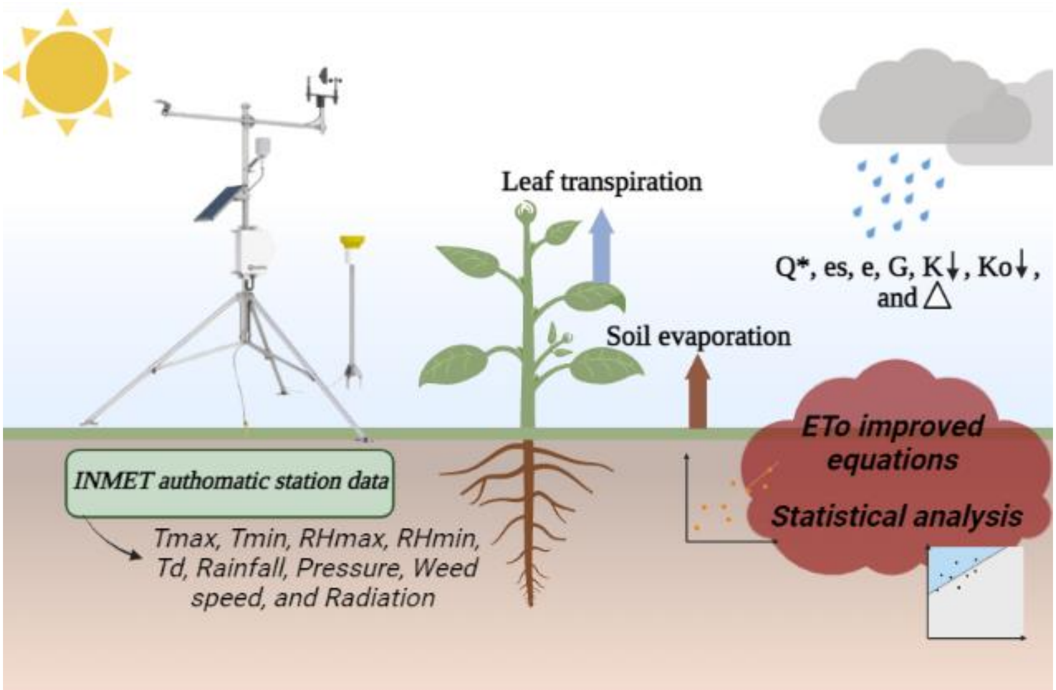
Figure 1. Geographical location of Palmeira das Missões, Rio Grande do Sul, Brazil.



Meteorological data

Figure 2 represents the steps established for obtaining parameter values for reference evapotranspiration (ETo) determination based on distinct empirical models. Initially, for the determination of ETo and subsequent comparison between the different estimation methods, the following meteorological data on a daily scale were obtained from the INMET meteorological station belonging to Santo Augusto, Rio Grande do Sul, approximately 60 km away from Palmeira das Missões: T_{max} (daily maximum temperature, °C), T_{min} (daily minimum temperature, °C), Ws (wind speed at 2 meters high, m s^{-1}), atmospheric pressure (hPa), RH_{max} (daily maximum relative humidity, %), RH_{min} (daily minimum relative humidity, %), and K↓ (incident global radiation, MJ m^{-2} day^{-1}). Subsequently, these parameters were applied to calculate Q* (radiation balance, MJ m^{-2} day^{-1}), es (saturation vapor pressure, hPa), e (partial pressure water vapor, hPa), G (daily soil heat flux, MJ m^{-2} day^{-1}), K↓ (incident solar radiation, MJ m^{-2} day^{-1}), K0↓ (solar radiation in the absence of the atmosphere, MJ m^{-2} day^{-1}), and Δ (slope of the saturation curve at the daily temperature, kPa $°C^{-1}$). Finally, with the application of empirical models of ETc and the comparison under a statistical approach, the best models for the determination of ETc are verified, based on leaf transpiration and soil evaporation.

Figure 2. A summary structure on the steps adopted to ETo determination by the Penman-Monteith and the empirical models tested in this study.



Penman-Monteith standard model

The Penman-Monteith standard model, expressed by the FAO-56, was characterized as the standard method for comparison in this study. Accordingly, Eq. 1 expresses the Penman-Monteith mathematical detail (ALLEN *et al*., 1998):

$$0{,}408\Delta(Q^{*} - G) + \frac{\left[(\gamma \times 900 \times Ws)\frac{(e_s - e)}{(T_{med} + 273)}\right]}{\Delta + \gamma(1 + (0.34 \times Ws))} \qquad (1)$$

Which: ET_o: reference evapotranspiration (mm day^{-1}), Δ: slope of the saturation curve at the daily temperature (kPa ºC^{-1}); γ: psychrometric constant (0.066 kPa ºC^{-1}); Q^*: radiation balance (MJ m^{-2} dia^{-1}); G: daily soil heat flux (MJ m^{-2} dia^{-1}) (0, as stipulated by Allen *et al*. (1998)); T_{med}: average daily air temperature at 2 m height (°C); Ws: wind speed at 2 m height (m s^{-1}); and (e_s-e): d: saturation deficit (kPa).

The Penman-Monteith parameters are specifically described by Santos *et al*. (2021).

ETo empirical models

As a strategy of better characterizing and comprehending the distinct methodologies to be applied in the study, as well as the possibility of a succinct assessment of the parameters necessary for the development of the respective calculations, the equations used to estimate evapotranspiration by the different previously mentioned methods. Therefore, Table 1 presents the Penman, Priestley & Taylor, Tanner & Pelton, Makkink, Jensen & Haise, Hargreaves & Samani, Camargo, Benevides & Lopes, Turc, and Linacre mathematical equations.

Table 1. Detailed characterization of the empirical models applied for the ETo determination.

No.	ETo model	Empirical equation	Required inputs	Basic reference
1	Benevides & Lopes	$\left[\left(1.21 \times 10^{\left[\frac{7.5 \times T_{med}}{237.5 + T_{med}}\right]}\right)\left(1 - (0.01 \times RH_{med})\right) + 0.21(T_{med} - 2.3)\right]$ (2)	T_{med}[1], RH_{med}[2]	Benevides; Lopes (1970)
2	Camargo	$0.01\left(\frac{K0\downarrow}{2.45}\right)T_{med}$ (3)	$K0\downarrow$[3], T_{med}	Camargo (1971)
3	Hargreaves & Samani	$\left(\frac{0.023 \times K0\downarrow}{2.45}\right)\left[(T_{max} - T_{min})^{0.5}\,(T_{med} + 17.8)\right]$ (4)	$K0\downarrow$, T_{max}[4], T_{min}[5], T_{med}	Hargreaves; Samani (1985)
4	Jensen & Haise	$\left(\frac{K\downarrow}{2.45}\right)\left((0.0252 \times T_{med}) + 0.078\right)$ (5)	$K\downarrow$[6]	Jensen; Haise (1963)
5	Linacre	$\frac{\left[\left(\frac{500 \times T_H}{100 - \theta}\right) + \left(15 \times (T_{med} - Td)\right)\right]}{(80 - T_{med})}$ (6)	T_H[7], θ[8], T_{med}, Td[9]	Linacre (1977)
6	Makkink	$0.61\left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{K\downarrow}{2.45}\right) - 0.12$ (7)	Δ[10], γ[11], $K\downarrow$	Makkink (1957)

7	Penman	$\frac{\left[\left(\frac{s}{\gamma}\right)\left(\frac{Q^*}{2.45}\right)+E_a\right]}{\frac{s}{\gamma}+1}$ (8)	s, γ, e[12], es[13], Q*[14], E_a[15]	Penman (1948)
8	Priestley & Taylor	$1.26\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{Q^*-G}{2.45}\right)$ (9)	Δ, γ, Q*, G[16]	Pristley; Taylor (1972)
9	Tanner & Pelton	$\frac{(1.12\times Q^*)}{(2.45-0.11)}$ (10)	Q*	Tanner; Pelton (1960)
10	Turc	$0.013\left[\frac{T_{max}}{(T_{max}+15)(50+(23.88\times K\downarrow))}\right]$ (11)	T_{max}, K↓	Turc (1961)

[1]average daily air temperature at 2 m height (°C), [2]average daily relative humidity (%); [3]solar radiation in the absence of the atmosphere (MJ m^{-2} day^{-1}); [4]daily maximum air temperature at 2 m height (°C); [5]daily minimum air temperature at 2 m height (°C); [6]incident solar radiation (MJ m^{-2} day^{-1}); [7]air temperature at sea level (°C); [8]local latitude (°); [9]daily dew point temperature (°C); [10]s: Δ: slope of the saturation curve at the daily temperature (kPa $°C^{-1}$); [11]psychrometric constant (0.066 kPa $°C^{-1}$); [12]partial pressure water vapor (hPa); [13]saturation vapor pressure (hPa); [14]radiation balance (MJ m^{-2} day^{-1}); [15]evapotranspiration aerodynamic factor (mm); and [16]daily soil heat flux (MJ m^{-2} day^{-1}).

Performance of ETo empirical models

In order to compare the different methods used to estimate evapotranspiration, statistical analysis is characterized as a fundamental tool to be applied. Accordingly, the parameters utilized in the statistical analyzes performed are then presented, as a form of an accurate assessment of the parameters necessary for its determination. Properly, a simple linear regression, the determination coefficient (R^2), mean square error (nRMSE), mean bias error (MBE), Willmott index (d) (WILLMOTT *et al*., 2012), and Pearson's correlation coefficient (r) were performed (SANTOS *et al*., 2021). The equations of these parameters, respectively, are presented by Eqs. (12–16):

$$R^2 = \frac{\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2}{\sum_{i=1}^{n}(ETo_{obs} - \overline{ETo_{sim}})^2} \quad (12)$$

$$nRMSE = \sqrt{\frac{1}{2}\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2} \quad (13)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n} ETo_{sim} - ETo_{obs} \quad (14)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2}{\sum_{i=1}^{n}([ETo_{obs} - \overline{ETo_{sim}}] + [ETo_{sim} - \overline{ETo_{sim}}])^2}\right] \quad (15)$$

$$r = \frac{cov(ETo_{sim}, ETo_{obs})}{\sigma_{ETo_{sim}}\sigma_{ETo_{obs}}} \quad (16)$$

Which: ETo_{obs}: ETo estimated by FAO56 Penman-Monteith model (mm day^{-1}), ETo_{sim}: ETo estimated the empirical models (mm day^{-1}), and n: total number of daily ETo values.

Multivariate statistical analysis

The multivariate statistical analyses were performed by clustering and Principal Component Analysis (PCA) analyses. The statistical software RStudio® 4.0.5 (RSTUDIO, 2015) integrated for R language (R CORE TEAM®, 2019) was adopted. The specific packages applied, considering the CRAN repository (The Comprehensive R Archive Network), were detailed by Santos *et al*. (2021). For Principal Component Analysis (PCA), the correlation and its p-value were described by Santos *et al*. (2021). Accordingly, for better visualization of the Cluster Analysis, 5 homogeneous groups were generated based on the R language.

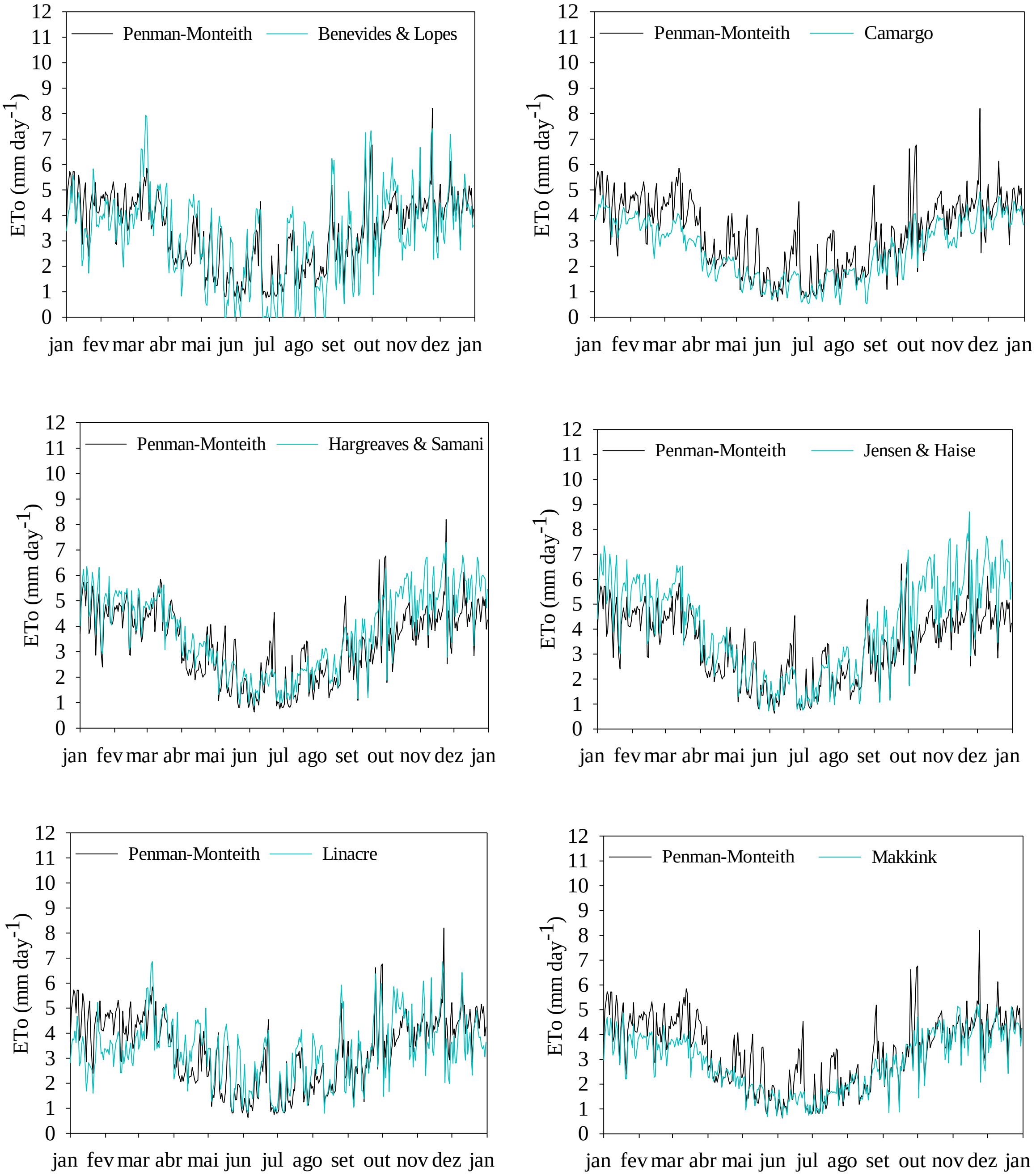
Results and Discussion

ETo empirical models estimates

Figure 3 presents the daily performance of the empirical mathematical equations for each ETo estimate in contrast to the FAO-56 method. Appropriately, the difference between the model estimates against a standard model is clearly observable. This panorama can also be observed in the total value of $ETo_{accumulated}$. Considering Palmeira das Missões and its particularities, the $ETo_{accumulated}$ in the studied period was 1215.22 mm. The results that most underestimate $ETo_{accumulated}$ were established by the Camargo (972.48 mm), Makkink (1052.87 mm), and Benevides & Lopes (1179.70 mm) empirical models. The Hargreaves & Samani indicated a total $ETo_{accumulated}$ de 1387.08 mm. The Tanner; Pelton (1555.49 mm) and Jensen & Haise (1492.22 mm) models expressed the most overestimated ETo estimations. The Camargo (972.48 mm) and Makkink (1052.87 mm) equations underestimated the ETo. Accordingly, the linear coefficient (a) varied from 0.6517 to 1.5799 for Tanner; Pelton and Jensen; Haise, respectively (Figure 3). Furthermore, the slope coefficient (b) varied from 0.0256 to 1.0936 for Turc and Benevides & Lopes, respectively. Ultimately, the determination coefficient (R^2) varied from 0.5864 to 0.9890 for Linacre and Hargreaves & Samani, respectively (Figure 4).

The time scale increase to determine the ETo guarantees higher accuracy and reliability, mainly to provide an irrigation management schedule that contributes to the total water required by the plant (VENANCIO *et al*., 2019). The results indicated by this study agree with those proposed by Raziei and Pereira (2013), that reported the methods of Hargreaves & Samani and Penman-Monteith as highly accurate prediction models and contribute to the determination of ETo appropriately in Iran's climatic conditions. The Hargreaves & Samani model is able to estimate the ETo highly accurately even requiring only the temperature and solar radiation parameters to equate (HABEEB *et al*., 2021). Moreover, in predominantly dry or arid conditions, the daily ETo stipulated by the model tends to show significantly higher ETo values when compared to other regions. A study conducted in Tunisia presented considerable overestimation in drier locations and underestimation in wetter locations. (ALTHOFF *et al*., 2019). The location stipulated in this study does not present extreme conditions of temperature and humidity, which promotes the high precision of the method compared to the FAO-56 model. Furthermore, the Hargreaves & Samani model is widely suggestible for locations with a scarcity of data, since it requires less complexity of meteorological variables for its computation, and its calibration is necessary to accurately determine the ETo (ALTHOFF *et al*., 2019). A study developed in Chinese territory reported that the accuracy of the model tends to reduce in places with extreme conditions since the method does not consider variables such as relative humidity and wind speed (ZHU *et al*., 2019).

Figure 3. ETo performance by the FAO-56 Penman-Monteith model compared to empirical models, from January 1st, 2020, to January 1st, 2021, in Palmeira das Missões, Rio Grande do Sul, Brazil.



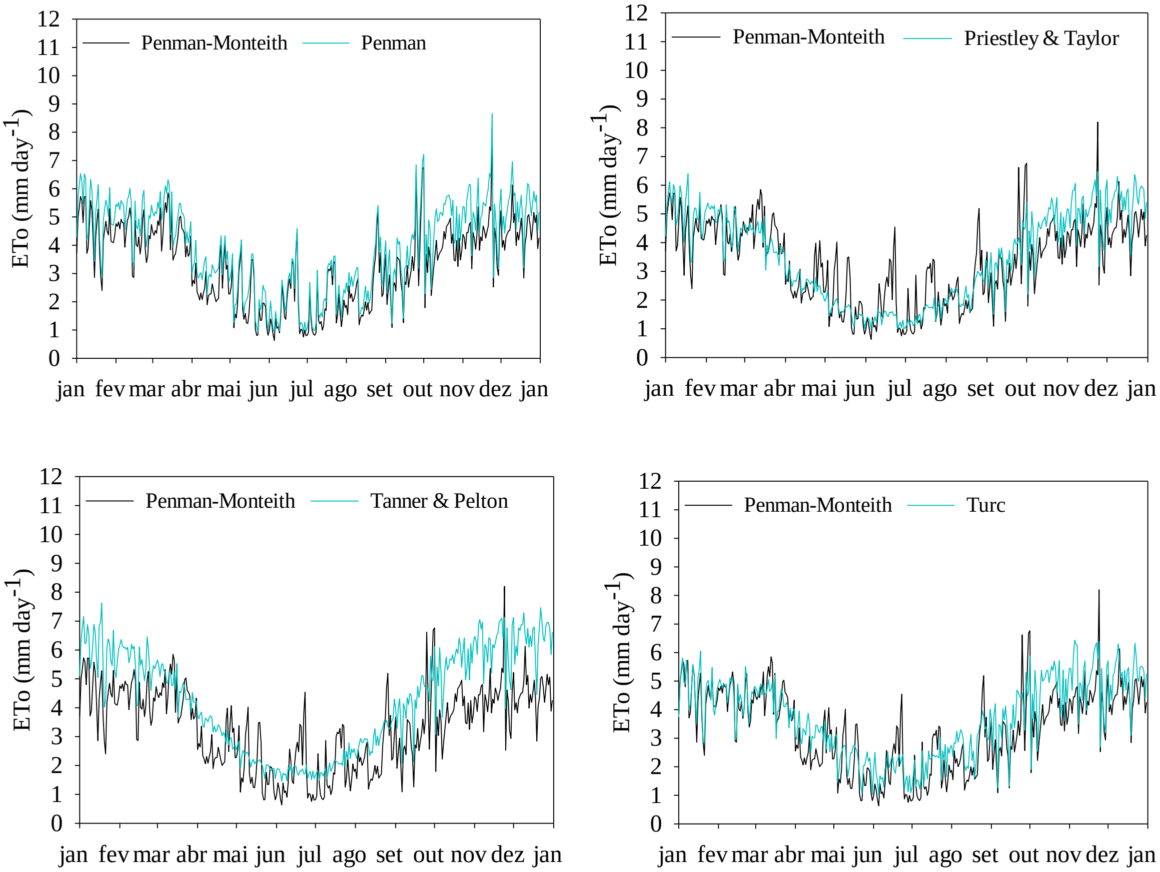
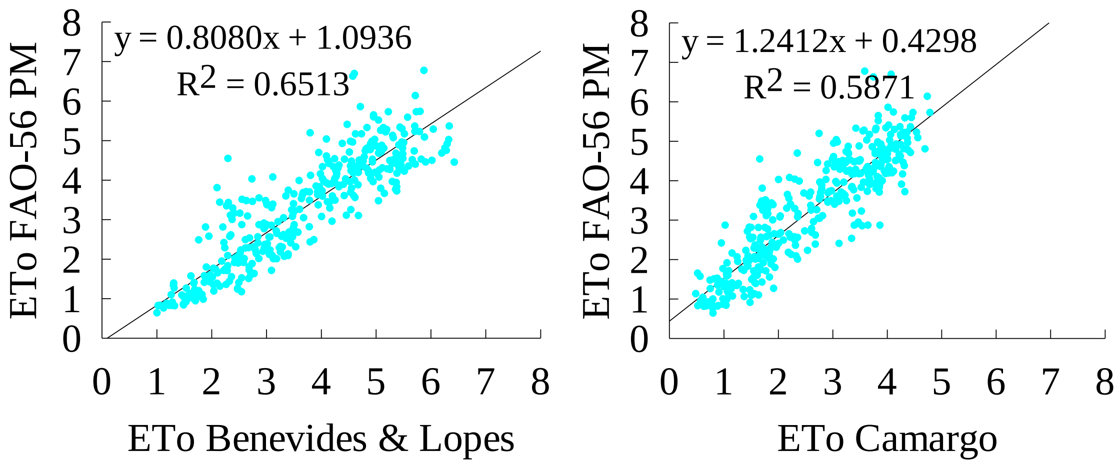
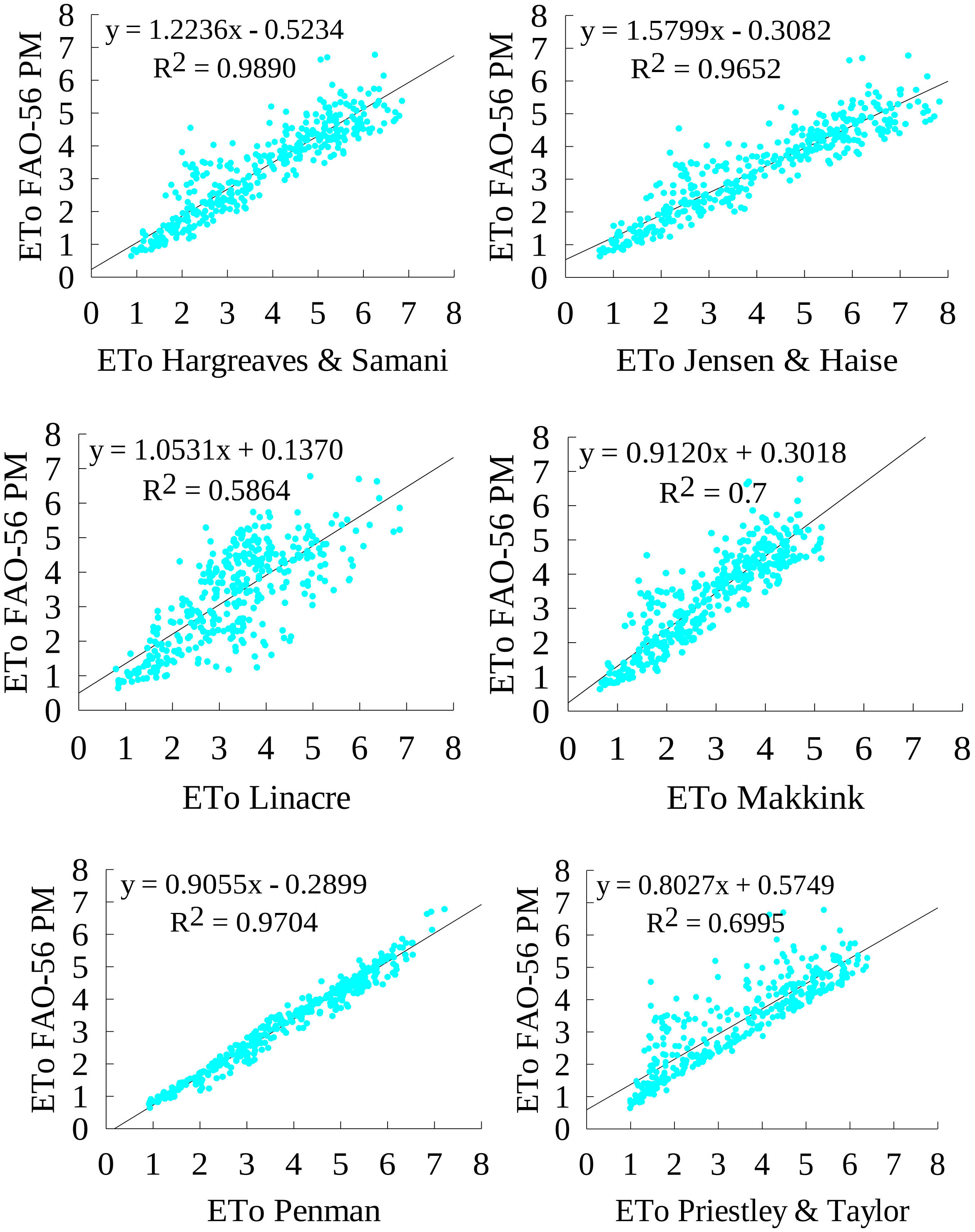
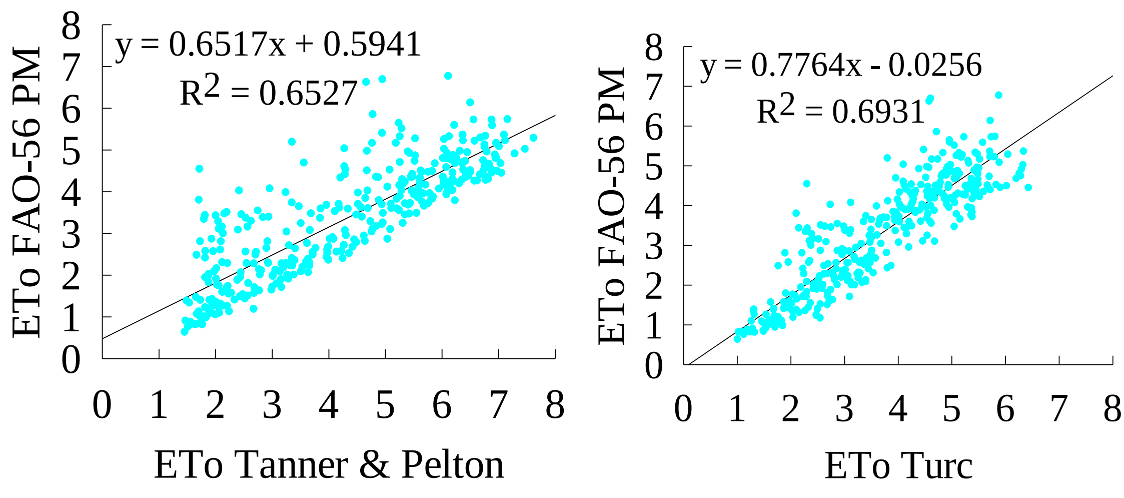


Figure 4. Linear regression performance by the FAO-56 Penman-Monteith model compared to empirical models, from January 1st, 2020, to January 1st, 2021, in Palmeira das Missões, Rio Grande do Sul, Brazil.




y = 1.2236x - 0.5234
R2 = 0.9890
ETo FAO-56 PM
ETo Hargreaves & Samani
y = 1.5799x - 0.3082
R2 = 0.9652
ETo FAO-56 PM
ETo Jensen & Haise
y = 1.0531x + 0.1370
R2 = 0.5864
ETo FAO-56 PM
ETo Linacre
y = 0.9120x + 0.3018
R2 = 0.7
ETo FAO-56 PM
ETo Makkink
y = 0.9055x - 0.2899
R2 = 0.9704
ETo FAO-56 PM
ETo Penman
y = 0.8027x + 0.5749
R2 = 0.6995
ETo FAO-56 PM
ETo Priestley & Taylor



Performance of ETo empirical models

A detailed statistical investigation of the differentiation between the empirical models is necessary. Accordingly, Table 2 shows the selected criteria for this study to indicate the performance of the empirical statistical models in comparison to the FAO-56 model. According to the coefficient of determination (R^2), the highest values were obtained for the Hargreaves & Samani (0.9890), Penman (0.9704), and Jensen & Haise (0.9652).

Table 2. Statistical criteria performance by the equation models, from January 1, 2020, to January 1, 2021, in Palmeira das Missões, Rio Grande do Sul, Brazil.

Equation model	Statistical criteria				
	R^2 [1]	***n*RMSE[2]**	**MBE[3]**	**d[4]**	**r[5]**
Benevides & Lopes	0.6513	0.9360	0.0970	0.9072	0.8070
Camargo	0.5871	0.9930	0.6632	0.8674	0.7662
Hargreaves & Samani	0.9890	0.5780	0.4695	0.9253	0.9944
Jensen & Haise	0.9652	0.9010	0.7568	0.8897	0.9824
Linacre	0.5864	1.1120	0.0117	0.8619	0.7657
Makkink	0.7	0.8640	0.4435	0.9035	0.8366
Penman	0.9704	0.6350	0.6090	0.9498	0.9850
Priestley & Taylor	0.6995	0.1660	0.1737	0.9285	0.8363
Tanner & Pelton	0.6527	1.1000	0.9297	0.8256	0.8078
Turc	0.6931	0.5620	0.3862	0.9210	0.8325

[1]determination coefficient, [2]mean square error, [3]mean bias error, [4]Willmott index, and [5]Pearson's correlation coefficient.

The best results according to *n*RMSE (<1) were observed for the Priestley & Taylor (0.1660 mm), Turc (0.5620 mm), and Penman (0.6350 mm) mathematical equations. According to the MBE parameter, the highest results were verified for Tanner & Pelton (0.9297 mm), Jensen & Haise (0.7568 mm), and Camargo (0.6632 mm). Considering the Willmott index (d), the models indicated high values. The highest values were observed for the Penman (0.9498), Priestley & Taylor (0.9285 mm), and Hargreaves & Samani (0.9256) models. The lowest values were observed for the Tanner & Pelton (0.8256), Linacre (0.8619), and Camargo (0.8674) models. Finally, Pearson's linear correlation performance is expressed in Table 3. T_{max}, T_{med}, T_{min}, Td, K0↓, K↓, Q*, es, e, and es-e indicated a positive linear correlation for all the models considered in this study. This scenario is the result of the high proportion of empirical models for estimating ETo that use these parameters in the application of mathematical equations. The highest correlations were obtained for the Tanner & Pelton (Q*, 1), Priestley & Taylor (Q*, 0.9939), and Makkink (K↓, 0.9899) models.

Table 3. Pearson's linear correlation performance for the main meteorological parameters necessary to determine ETo by the equation models, from January 1, 2020, to January 1, 2021, in Palmeira das Missões, Rio Grande do Sul, Brazil.

Equation models	Meteorological parameters													
	T_{max}	**T_{min}**	**T_{med}**	**RH_{max}**	**RH_{min}**	**RH_{med}**	**Td**	**Ws**	**K0↓**	**K↓**	**Q^***	**es**	**e**	**es-e**
Penman-Monteith	0.8841	0.6754	0.8317	-0.3137	-0.5502	-0.5174	0.4398	0.1810	0.7751	0.8415	0.8444	0.8698	0.4242	0.5174
Penman	0.8927	0.6339	0.8167	-0.3336	-0.6190	-0.5745	0.3726	0.0622	0.8148	0.9065	0.8935	0.8590	0.3592	0.5745
Priestley & Taylor	0.7836	0.5709	0.7238	-0.0861	-0.4385	-0.3473	0.4381	-0.1833	0.9457	0.9603	0.9939	0.7559	0.4384	0.3473
Tanner & Pelton	0.7225	0.4960	0.6528	-0.0479	-0.4251	-0.3226	0.3841	-0.2240	0.9563	0.9683	1.0000	0.6843	0.3881	0.3226
Makkink	0.8183	0.4934	0.7064	-0.2023	-0.5902	-0.5018	0.2981	-0.2100	0.8789	0.9899	0.9696	0.7531	0.2915	0.5018
Jensen & Haise	0.8872	0.6346	0.8138	-0.2318	-0.5521	-0.4863	0.4226	-0.1294	0.8682	0.9446	0.9468	0.8567	0.4116	0.4863
Hargreaves & Samani	0.8514	0.5611	0.7579	-0.2150	-0.5727	-0.4943	0.3580	-0.1743	0.8811	0.9738	0.9651	0.8037	0.3502	0.4943
Camargo	0.8517	0.7947	0.8707	-0.1416	-0.3613	-0.3142	0.6248	-0.0532	0.9188	0.8329	0.9081	0.8789	0.6229	0.3142
Benevides & Lopes	0.9576	0.8207	0.9438	-0.5524	-0.6253	-0.6658	0.4416	0.1027	0.5636	0.6436	0.6240	0.9626	0.4048	0.6658
Turc	0.8302	0.4921	0.7126	-0.2151	-0.6070	-0.5188	0.2919	-0.2051	0.8637	0.9883	0.9609	0.7571	0.2827	0.5188
Linacre	0.8456	0.5546	0.7515	-0.7034	-0.8507	-0.8866	0.0612	-0.0372	0.4569	0.6539	0.5540	0.8022	0.0300	0.8866

T_{max} (daily maximum temperature, °), T_{min} (daily minimum temperature, °C), T_{med} (daily average temperature, °C), RH_{max} (daily maximum relative humidity, %), RH_{min} (daily minimum relative humidity, %), RH_{max} (daily average relative humidity, %), Td (daily dew point temperature, °C), Ws (wind speed at 2 meters high, m s^{-1}), K↓ (incident global radiation, MJ m^{-2} day^{-1}), K0↓ (solar radiation in the absence of the atmosphere, MJ m^{-2} day^{-1}), Q^* (R_n) (radiation balance, MJ m^{-2} day^{-1}), es (saturation vapor pressure, hPa), e (partial pressure water vapor, hPa), and es-e (partial pressure saturation deficit, hPa).

RH_{max}, RH_{min}, RH_{med}, and Ws parameters expressed a negative linear correlation for the distinct models, showing the minimal influence for ETo determination. The least results were observed for the Linacre (RH_{med}, -0.8866, RH_{min}, -0.8507, and RH_{max}, -0.7034) models.

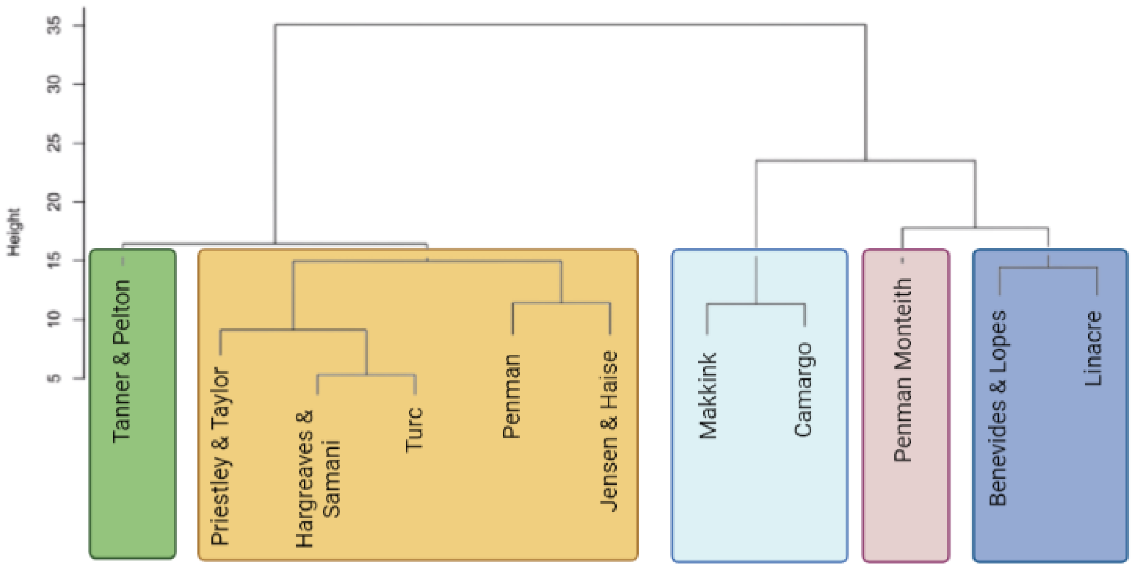
Research conducted in Paraná, which has similar conditions to the application site of this study, established that the Hargreaves & Samani model presented the most satisfactory performance in estimating ETo for the different physiographic regions of the state (GURSKI *et al*., 2018). Moreover, the Hargreaves & Samani and Camargo methods were the most accurate for Cfa and Cfb climatic conditions. Furthermore, the model provides more accurate readings in warmer regions, where average temperatures have significant values (FERNANDES *et al*., 2018). Correspondingly, as stipulated in this study, the Camargo model was found to underestimate evapotranspiration, specifically by the MBE criterion, since it only needs T_{med} and solar radiation.

Finally, K0↓, K↓, Q*, indicated high positive linear correlations considering all the distinct empirical models. For K0↓, the Tanner & Pelton model (0.9563) indicated the highest correlation. According to K↓, the Makkink empirical model expressed a positive correlation (0.9899). Ultimately, considering Q*, the Tanner & Pelton (1) model indicated the highest result.

Clustering and PCA analyses

Initially, clustering according to the Ward agglomerative hierarchical method was performed using the daily ETo values (mm day^{-1}) by the FAO-56 Penman-Monteith standard and the other equational models. The results of clustering directed to Palmeira das Missões in the stipulated period originated five main clusters: Tanner & Pelton; Priestley & Taylor, Hargreaves & Samani, Turc, Penman, and Jensen & Haise; Makkink and Camargo; Penman-Monteith; and Benevides & Lopes (Figure 5).

Figure 5. Dendrogram from clustering by the Ward agglomerative hierarchical method based on ETo by the FAO-56 Penman-Monteith standard and empirical models for Palmeira das Missões, Rio Grande do Sul, Brazil.

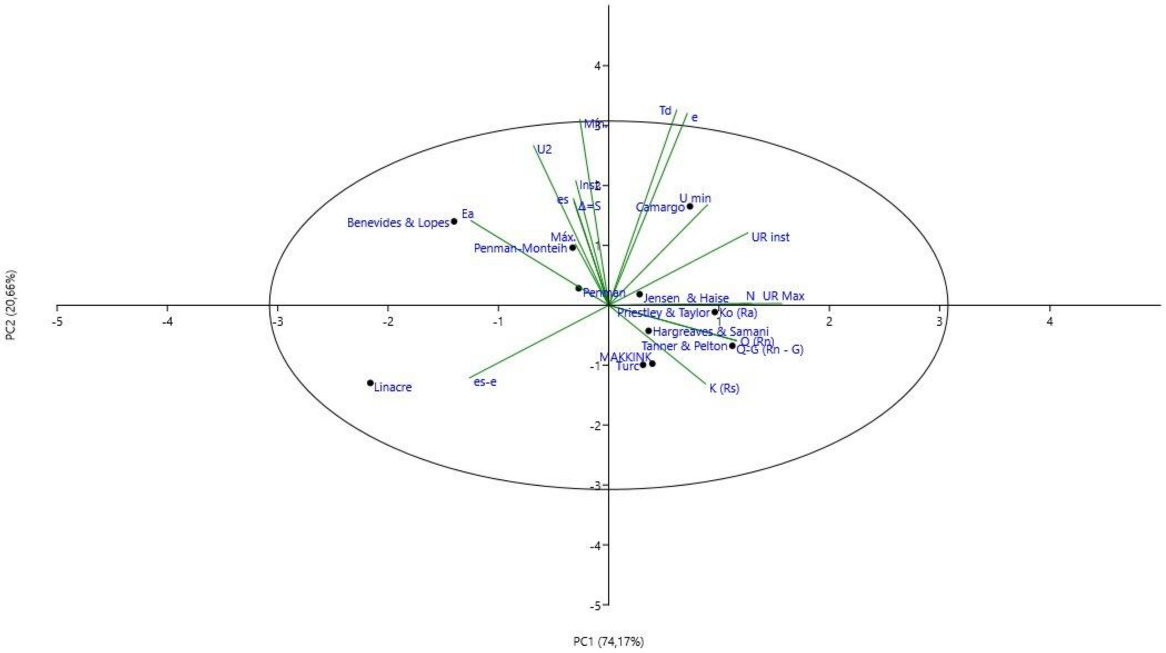


In this study, the hierarchical structure allows as the main objective the association of models that serve as complementary tools in the absence of meteorological data that make the application of other models infeasible. Particularly, it serves as a parameter for the adequacy of other models in the study area.

For the clustering analysis by the Ward agglomerative hierarchical method, the ETo_{med} and the $ETo_{accumulated}$ were considered. Considering the FAO-56 model, the $ETo_{accumulated}$ and ETo_{med} were 1215.22 mm and 3.32 mm day^{-1}, respectively. The related mathematical models generated specific clusters. The first cluster comprised the methods proposed by Tanner & Pelton (1555.49 mm and 4.25 mm day^{-1}). Additionally, Priestley & Taylor (1278.80 mm and 3.49 mm day^{-1}), Hargreaves & Samani (1387.08 mm and 3.79 mm day^{-1}), Turc (1356.59 mm and 3.71 mm day^{-1}), Penman (1438.12 mm and 3.93 mm day^{-1}), and Jensen & Haise (1492.22 mm and 4.08 mm day^{-1}) ordered a new cluster. Moreover, clusters were ordered to Makkink (1052.87 mm and 2.88 mm day^{-1}) and Camargo (972.48 mm and 2.66 mm day^{-1}), Penman-Monteith (1215.22 mm and 3.32 mm day^{-1}), and Benevides & Lopes (1179.70 mm and 3.22 mm day^{-1}) and Linacre (1210.92 mm and 3.31 mm day^{-1}). The clusters are formed based on the distance from the FAO-56 standard method and on the relationship between the results found based on the ETo_{med} and the $ETo_{accumulated}$.

Moreover, the PCA presented the strong effects of meteorological parameters on the ETo estimates and the relationships with the FAO-56 Penman-Monteith standard model. According to Palmeira das Missões, the first and second components are represented by a variability of 74.17% and 20.66%, respectively (Figure 6). The ETo was largely impacted by the direct action of the variables, essentially, K0↓, K↓, and Q*. Variables such as Td and e were not dominant for the determination of ETo estimates. These results are expressed in Table 3, where these variables expressed the best results in Pearson's correlation.

Figure 6. Principal Component Analysis (PCA) of the ETo expressed by the empirical models and the meteorological parameters for Palmeira das Missões, Rio Grande do Sul, Brazil.



Conclusions

A comprehensive comparison of distinct mathematical equations for ETo estimation and the FAO-56 Penman-Monteith standard model was attributed and the main conclusions are described below:

- The calculated solar radiation balance indicated a positive linear relationship with ETo;
- The Hargreaves & Samani mathematical model presented the highest R^2 (0.9890) when compared with the different models for Palmeira das Missões;
- The study promotes valid and highly practical assertions for the accurate determination of ETo in Southern Brazil and in locations with similar edaphoclimatic conditions;
- Evapotranspiration is one of the variables related to the amount of water that must be applied to meet the plant requirements, significantly considering the optimization of resources in irrigation programs and plant management.

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