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Evapotranspiration in the Brazilian municipalities surrounding the Itaipu Binacional reservoir: characterization process and estimation methods

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Abstract
Seeking to contribute with the management of water resources in the Itaipu Binacional reservoir region, this research aimed to characterize the dynamics of evapotranspiration and evaluate the performance of different mathematical methods, which determine reference evapotranspiration (ETo) from air temperature values. Fifteen municipalities were analyzed. After obtaining the data series, ETo was estimated using six methods: Camargo (C), Hargreaves-Samani (HG-S), Jensen-Haise (JH), Penman-Monteith with missing data (PMm), Thornthwaite-Camargo (TW-C) and Penman-Monteith (PM) – the latter was the reference method. The performance of the methods was analyzed by several statistical indexes. Daily ETo values ranged from 2 to 10 mm d^{-1}, with an annual mean of 5.78 mm d^{-1}. We also observed that it is determined predominantly by radioactive parameters, which annually represent 76% of the evapotranspiration process, while aerodynamic parameters represent 24%. Among the ETo estimation methods, HG-S and PMm were the most suitable for estimating.

Keywords: hydrological cycle; temperature data; water resources.

Evapotranspiración en los municipios brasileños que rodea el reservatorio de Itaipu Binacional: proceso de caracterización y métodos de estimación

Resumen
Buscando contribuir con la gestión de los recursos hídricos en la región del reservorio de Itaipu Binacional, esta investigación tuvo como objetivo caracterizar la dinámica del proceso de evapotranspiración y evaluar el desempeño de diferentes métodos matemáticos, que determinan la evapotranspiración de referencia (ETo) a partir de los valores de temperatura del aire. Se analizaron quince ciudades. Después de obtener la serie de datos, la ETo se estimó utilizando seis métodos: Camargo (C), Hargreaves-Samani (HG-S), Jensen-Haise (JH), Penman-Monteith con datos faltantes (PMm), Thornthwaite-Camargo (TW- C) y Penman-Monteith (PM), siendo este último el método de referencia. El desempeño de los métodos ocurrió mediante varios índices estadísticos. Los valores diarios de ETo variaron de 2 a 10 mm d^{-1}, con una media anual de 5,78 mm d^{-1}. También observamos que ETo es determinada predominantemente por parámetros radiactivos, que anualmente representan el 76% del proceso de evapotranspiración, mientras que los parámetros aerodinámicos representan el 24%. Entre los métodos de estimación de ETo, los métodos HG-S y PMm fueron los más adecuados para estimar.

Palabras clave: ciclo hidrológico; datos de temperatura; recursos hídricos.

1. Introduction

The Itaipu Binacional hydroelectric plant was built on the banks of the Paraná river, on the border between the cities of Foz do Iguaçu, Brazil, and Ciudad del Este, Paraguay. The construction of the dam provided the formation of a water reservoir with an area of 1,350 km^2, at normal level, which can reach 1,561 km^2, at the maximum flood level. During the formation of the reservoir, part of the area was flooded in eight Brazilian municipalities. These counties were dismembered over time, resulting 15 of them, which surround the Itaipu Binacional reservoir [7].

Itaipu Binacional encourages several socio-environmental actions that seek to protect fauna and flora,

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care for water and create educational spaces. More information can be found at: https://www.itaipu.gov.br/. Considering that the success of regional development actions depends, fundamentally, on the quantity and quality of information available, research that seeks to gather information to support the management of water resources in the region becomes very relevant.

The management of water resources must be based on information on the main components of the hydrological cycle [23]. Among the components of the hydrological cycle, evapotranspiration stands out, as it corresponds to the rate of water loss from evaporating surfaces such as soils, lakes, rivers and vegetation. Evapotranspiration values are important for the design and management of irrigation; determining plant growth; carrying out water balance at different time and space scales; understanding the soil-plant-atmosphere relationship; analysis of microclimates and interactions with surfaces; and studies on soil drainage [2,4,27].

Measuring evapotranspiration in a direct way presents high financial costs for installation and requires periodic and specialized maintenance of equipment [15,22]. An alternative to obtain evapotranspiration values is the use of mathematical methods [4]. Empirical and semi-empirical methods result in evapotranspiration that occurs on a standardized grass surface, being named reference evapotranspiration (ETo) [2]. The Penman-Monteith method (PM) is currently recommended by the Food and Agriculture Organization (FAO) of the United Nations (UN) for ETo estimates. However, its application demands a large amount of meteorological data, such as average air temperature, wind speed at two meters high, solar net radiation, heat flow in the soil and average relative air humidity, bringing challenges for a better use of the method [14,29].

In the western region of the Paraná state, Brazil, where the surrounding municipalities of Itaipu Binacional reservoir are situated, there are seven weather stations, one maintained by Instituto de Desenvolvimento Rural do Paraná (IAPAR-EMATER), four by Sistema de Tecnologia e Monitoramento Ambiental do Paraná (SIMEPAR) and two by Instituto Nacional de Meteorologia (INMET). However, only two provide sufficient data to apply the PM method. Therefore, research is necessary to assess the performance of alternative methods for determining ETo for the region, since the available estimation methods were developed under specific spatial and atmospheric conditions [28]. There are several methods available to estimate ETo; the main ones are based on mass transfer, solar radiation, air temperature and pan evaporation [4]. Due to the greater availability of air temperature data, several studies have been carried out, in different parts of the world, to evaluate the performance of air temperature-based models in relation to the standard PM method [4,25,26,31].

Considering the average performance on a global scale, the Hargreaves-Samani method presented better performance in arid, semiarid, temperate, cold and polar climates. However, several methods based on air temperature showed high performance at local scale [4]. Nonetheless, for wide local use, the method needs to have its performance evaluated, considering the accuracy of estimates and availability of local meteorological data [26,28].

This research seeks to contribute with the management of water resources in the Itaipu Binacional reservoir region. Considering the limitation on the diversity of meteorological data and the climatic peculiarities that the reservoir can provide to atmospheric conditions [35], this research aimed to characterize the dynamics of evapotranspiration and evaluate the performance of different mathematical methods, which determine ETo from air temperature values, in the Brazilian region of municipalities surrounding Itaipu Binacional reservoir.

2. Material and methods

This research was carried out in the Brazilian region of the municipalities surrounding the Itaipu Binacional reservoir. Fifteen municipalities were analyzed, 14 in the state of Paraná and one in the state of Mato Grosso do Sul. All these counties have a humid subtropical climate, classified according to Köppen as Cfa [6]. The last climatological normal of the region indicates that the average annual rainfall for 12 of the 15 municipalities varies between 1,600 mm to 1,800 mm, except for the municipalities of Terra Roxa, Guaíra and Mundo Novo, with rainfall between 1,400 mm and 1,600 mm. The rainfall shows annual averages accumulated above 100 mm in the spring, summer and autumn, decreasing in the winter. The annual average temperatures range between 21 ºC and 24 ºC and the average annual relative air humidity remains above 70% (Table 1) [24].

To make the research, meteorological data from the network of automatic meteorological stations of INMET in Brazil were used. Data from six stations located in the state of Paraná and two in the state of Mato Grosso do Sul were used (Fig. 1).

Table 1.
Average annual accumulated rainfall (P, mm), mean air temperature (Tmean, ºC) and relative air humidity (RH, %) in the Brazilian region of the municipalities surrounding the Itaipu Binacional reservoir.

Municipalities surrounding the Itaipu Binacional reservoir	P (mm)	Tmean (ºC)	RH (%)
Diamante d'Oeste	1,600 – 1,800	21.1 – 22.0	70.1 – 75.0
Entre Rios do Oeste	1,600 – 1,800	22.1 – 23.0	75.1 – 80.0
Foz do Iguaçu	1,600 – 1,800	22.1 – 23.0	70.1 – 75.0
Guaíra	1,400 – 1,600	23.1 - 24.0	75.1 – 80.0
Itaipulândia	1,600 – 1,800	22.1 – 23.0	70.1 – 75.0
Marechal Cândido Rondon	1,600 – 1,800	22.1 – 23.0	75.1 – 80.0
Mercedes	1,600 – 1,800	22.1 – 23.0	75.1 – 80.0
Missal	1,600 – 1,800	21.1 – 22.0	70.1 – 75.0
Mundo Novo	1,400 – 1,600	23.1 - 24.0	75.1 – 80.0
Pato Bragado	1,600 – 1,800	22.1 – 23.0	75.1 – 80.0
Santa Helena	1,600 – 1,800	22.1 – 23.0	70.1 – 75.0
Santa Terezinha de Itaipu	1,600 – 1,800	21.1 – 22.0	70.1 – 75.0
São José das Palmeiras	1,600 – 1,800	21.1 – 22.0	70.1 – 75.0
São Miguel do Iguaçu	1,600 – 1,800	21.1 – 22.0	70.1 – 75.0
Terra Roxa	1,400 – 1,600	22.1 – 23.0	75.1 – 80.0
Mundo Novo	1,400 – 1,600	22.1 – 24.0	75.1 – 80.0

*P - average annual accumulated rainfall; Tmean - mean air temperature; RH - relative air humidity.
Source: The authors, based on information from [24]

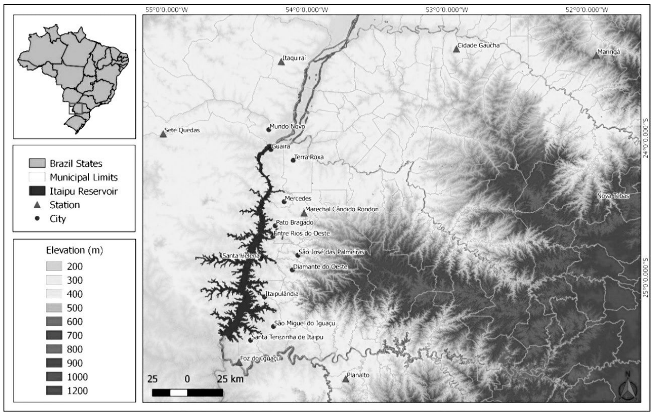


Figure 1. Location of the municipalities surrounding the Itaipu Binacional reservoir and meteorological stations used in the research with their representation of spatial elevation.
Source: The authors.

Hourly meteorological data of maximum and minimum air temperature (ºC), wind speed at 2 m high (m s^{-1}), solar radiation (MJ m^{-2} d^{-1}) and maximum and minimum air humidity (%) were obtained for a period of three years (January 1, 2016 to December 31, 2018). Hourly data was converted to daily data. In order to provide greater consistency and reliability of the results, the days had read faults in one or more variables were replaced by the simple arithmetic average of the previous years equivalent evaluated the same day with missing data [8].

After obtaining the data series, daily ETo of the study period was estimated for each meteorological station. Therefore, six estimation methods were used:

- Camargo (C) (eq. 1) [9]

$$ETo_C = 0.01 \cdot Ra \cdot T \tag{1}$$

- Hargreaves-Samani (HG-S) (eq. 2) [19]

$$ETo_{HG-S} = \frac{0.0023 \cdot Ra \cdot (T\max - T\min)^{0.5}}{(T + 17.8)^{-1}} \tag{2}$$

- Jensen-Haise (JH) (eq. 3) [20]

$$ETo_{JH} = Qg \cdot (0.025 \cdot T + 0.08) \tag{3}$$

- Penman-Monteith with missing data (PMm) (eq. 4) [2]

$$ETo_m = \frac{\dfrac{0.408 \cdot s}{(Rg - G)^{-1}} + \dfrac{\gamma \cdot \left(\dfrac{900}{T + 273}\right) \cdot 2}{\left(e_s - \left(0.611 \exp^{\left(\frac{17.67 \cdot T}{243 + T}\right)}\right)\right)^{-1}}}{s + \gamma \cdot (1 + 0.34 \cdot 2)} \tag{4}$$

- Thornthwaite-Camargo (TW-C) (eq. 5) [10]

$$ETo_{TW-M} = \cdot \frac{\left(10 \cdot \left(\dfrac{0.36 \cdot (3 \cdot T\max - T\min)}{I}\right)\right)^a}{\left(\dfrac{16}{30}\right)^{-1} \cdot \left(\dfrac{N}{30}\right)^{-1}} \tag{5}$$

- Penman-Monteith (PM) (eq. 6) [2]

$$ETo_{PM} = \frac{\dfrac{0.408 \cdot s}{(Rn - G)^{-1}} + \gamma \cdot \left(\dfrac{900}{T + 273}\right) \cdot U_2 \cdot (e_s - e_a)}{s + \gamma \cdot (1 + 0.34 \cdot U_2)} \tag{6}$$

Where, T - average air temperature (ºC); Tmax - maximum air temperature (ºC); Tmin - minimum air temperature (ºC); Ra - extraterrestrial radiation (mm d^{-1}); Rg - global solar radiation (MJ m^{-2} d^{-1}); Ra - global solar radiation (mm d^{-1}); N - Photoperiod (h d^{-1}); Rn - net radiation (MJ m^{-2} d^{-1}); s –slope of saturation vapor pressure curve at air temperature T (kPa $ºC^{-1}$); e_s –pressure of vapor saturation (kPa); e_a –pressure of actual vapor (kPa); U_2 - average wind speed at a height of 2 m (m s^{-1}); γ - psychrometric constant (kPa $ºC^{-1}$); G - heat flow in the soil (MJ m^{-2} d^{-1}); I - annual thermal index (dimensionless); and, a - location constant (dimensionless).

When necessary, global solar radiation was estimated using the Hargreaves-Samani method, based on the maximum minimum air temperature and extraterrestrial solar radiation (Qo) (MJ m^{-2} d^{-1}) (eq. 07) [2].

$$Rg = 0.19 \cdot Qo \cdot (T\max - T\min)^{0.5} \tag{7}$$

Subsequently, ETo estimation methods were evaluated in order to select those that presented the best performances. The Penman-Monteith method was used as a reference for comparison with the other methods [2]. In order to feature the evapotranspiration process in the surrounding municipalities, the Penman-Monteith method was subdivided into two equations, one representing aerodynamic parameters (ETo-aero, eq. 8) and the other representing radioactive parameters (ETo-rad, eq. 9) [12].

$$ETo - aero = \frac{\gamma \cdot \dfrac{900}{T + 273} \cdot U_2 \cdot (e_s - e_a)}{s + \gamma \cdot (1 + 0.34 \cdot U_2)} \tag{8}$$

$$ETo - rad = \frac{0.408 \cdot s \cdot (Rn - G)}{s + \gamma \cdot (1 + 0.34 \cdot U_2)} \tag{9}$$

Thus, the obtained values demonstrate the contribution of each parameter, aerodynamic or radioactive, to the reference evapotranspiration. After estimating ETo values for the locations where the weather stations were set, in order to determine the estimation method, based on air temperature values, which presents the best performance for the region, the daily data from these methods and the PM method were interpolated, using the inverse square distance method (eq. 10) [30], for the municipalities surrounding the Itaipu reservoir.

$$X_p = \frac{\sum_{i=1}^{n} \left(\dfrac{1}{d_i^2} X_i\right)}{\sum_{i=1}^{n} \left(\dfrac{1}{d_i^2}\right)} \tag{10}$$

Where, X_p –evapotranspiration value interpolated to the place of interest; X_i - evapotranspiration value of the i-th meteorological station; d_i - Euclidean distance between the i-th weather station and the place of interest. The places of interest corresponded to the 15 Brazilian municipalities surrounding the Itaipu reservoir (Table 1).

The performance of the methods was evaluated by the coefficient of determination, r^2, Willmott's agreement index, d (eq. 11), performance index, c (eq. 12) and the square root of the mean error, RMSE (Eq. 13).

$$d = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - X_i\right)^2}{\sum_{i=1}^{n}\left[\left(\left|Y_i - X_{ave}\right|\right) + \left(\left|X_i - X_{ave}\right|\right)\right]^2} \qquad (11)$$

$$c = r \cdot d \qquad (12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - X_i\right)^2}{n}} \qquad (13)$$

Where, Y_i - reference evapotranspiration estimated by the standard method (mm d^{-1}); X_i - reference evapotranspiration obtained by the evaluated method (mm d^{-1}); X_{ave} - average reference evapotranspiration obtained by the evaluated method (mm d^{-1}); r - Pearson's correlation coefficient; and, n - number of observations.

The performance of the methods was classified according to the performance index, which ranges from 0 to 1. The classification considers that: $c > 0.85$, great; $0.76 < c < 0.85$, very good; $0.66 < c < 0.75$, good; $0.61 < c < 0.65$, average, $0.51 < c < 0.60$, bad; $0.41 < c < 0.50$, not good; $c < 0.40$, terrible [11].

3. Results and discussion

According to the results obtained by the Penman-Monteith method (PM), considering a full weather data set, daily ETo values ranged from 2 to 10 mm d^{-1}, with an annual mean of 5.78 mm d^{-1}. The characterization of the evapotranspiration process in the region surrounding the Itaipu Binacional reservoir shows that the region is predominantly influenced by radioactive parameters and the influence of aerodynamic parameters is small (Fig. 2).

Thus, among the meteorological elements that interfere in ETo, solar radiation is largely responsible for the evapotranspiration process. In the month of January (summer), the radioactive portion was responsible for 83% of the evapotranspiration process, while in the month of June (winter), there was a reduction in the effect of solar radiation, representing 62% of the process. Annually, the radioactive parameter represents 76% of the evapotranspiration values and the aerodynamic represents 24%.

The municipalities surrounding the Itaipu Binacional reservoir are located in a relatively flat region with a large number of watercourses [7]. These physiographic conditions contribute to maintain the annual relative air humidity around 70% (Table 1) and reduce the influence of sensitive heat exchanges coming from the surroundings. Consequently, the

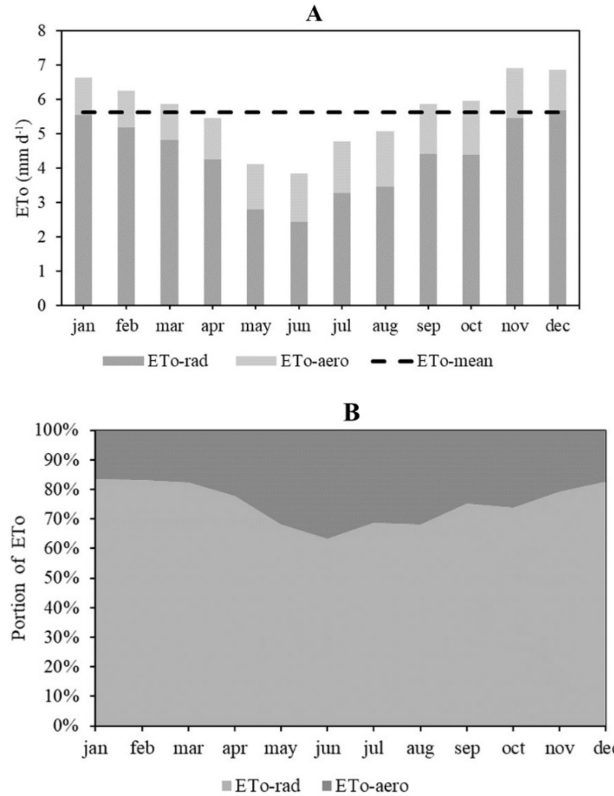


Figure 2. A - monthly average evapotranspiration, with partition of radioactive and aerodynamic parameters and annual mean ETo. B - representation of the ETo portion from radioactive and aerodynamic parameters. ETo was determined by the Penman-Monteith method (PM).
Source: The authors.

incident solar radiation becomes the main meteorological element that interferes in the reference evapotranspiration rate [21]. Therefore, ETo estimation methods based on solar radiation values tend to perform more satisfactorily. The observed results are in agreement with those found by several authors [17,18,32].

These results also evidence the effect of the Itaipu Binacional reservoir on the climate of the surrounding municipalities, presenting a maritime effect on the region [35], keeping the relative air humidity high, decreasing the local thermal amplitude and interfering in the evapotranspiration process [36]. However, in order to completely characterize the effect of maritime conditions on the climate of municipalities surrounding the Itaipu Binacional reservoir, studies that relate the variation in the level of the reservoir on the meteorological elements are still necessary.

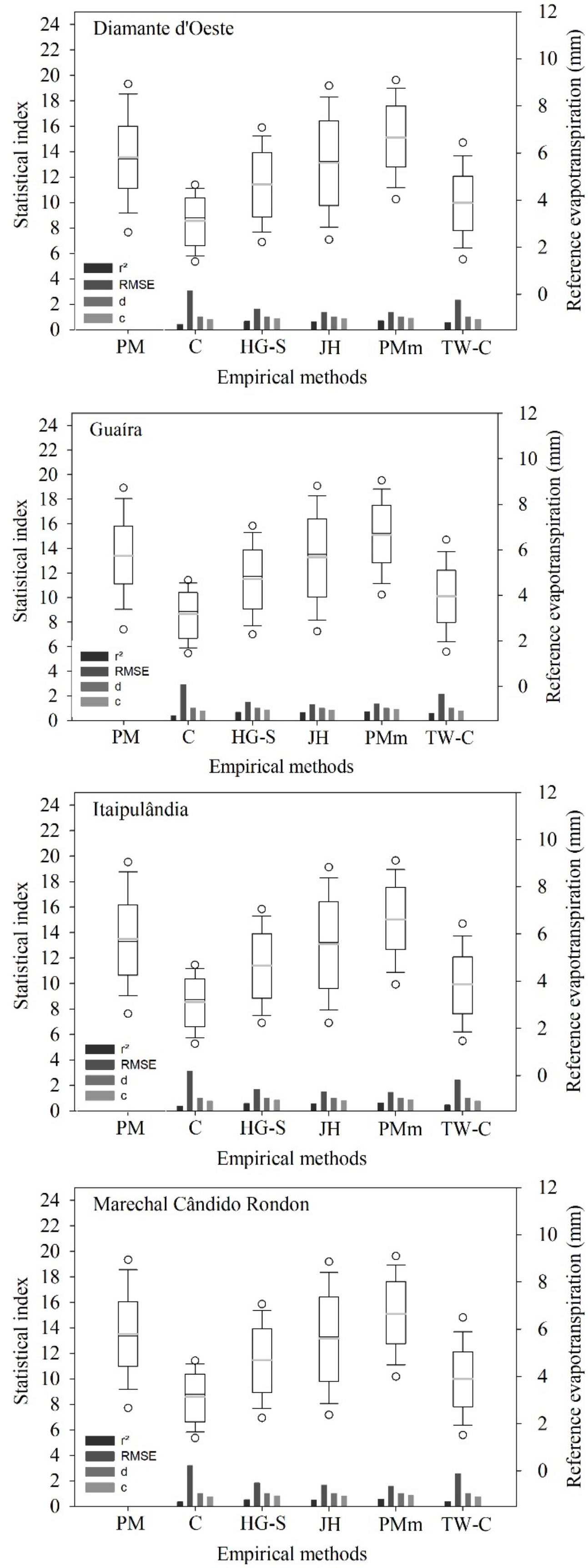
Analyzing ETo estimation methods graphically, it was observed that the HG-S, JH and PMm methods presented estimates similar to those of PM. The JH method showed a bigger distribution of values when compared with PMm and HG-S. Averages of ETo, represented in the graph by grey lines, showed that the values from the PM method were similar to those of the JH method, higher than the PMm method and lower than the HG-S method for all municipalities under study. Considering statistical indices, in general, we observed that the PMm and HG-

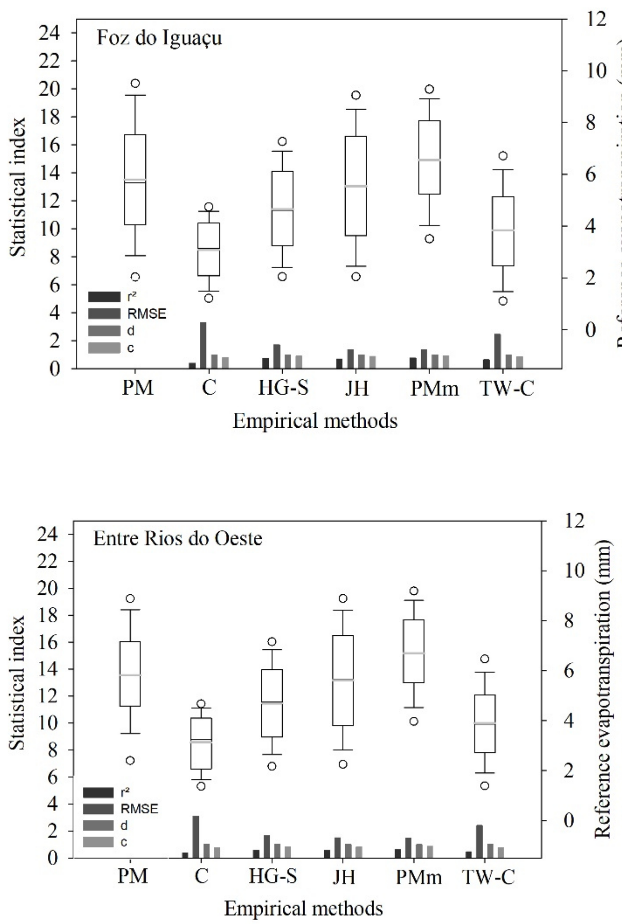
S methods provided better estimates of ETo, once they yielded higher values of "r²", "d" and "c", with lower values of RMSE (Fig. 3).

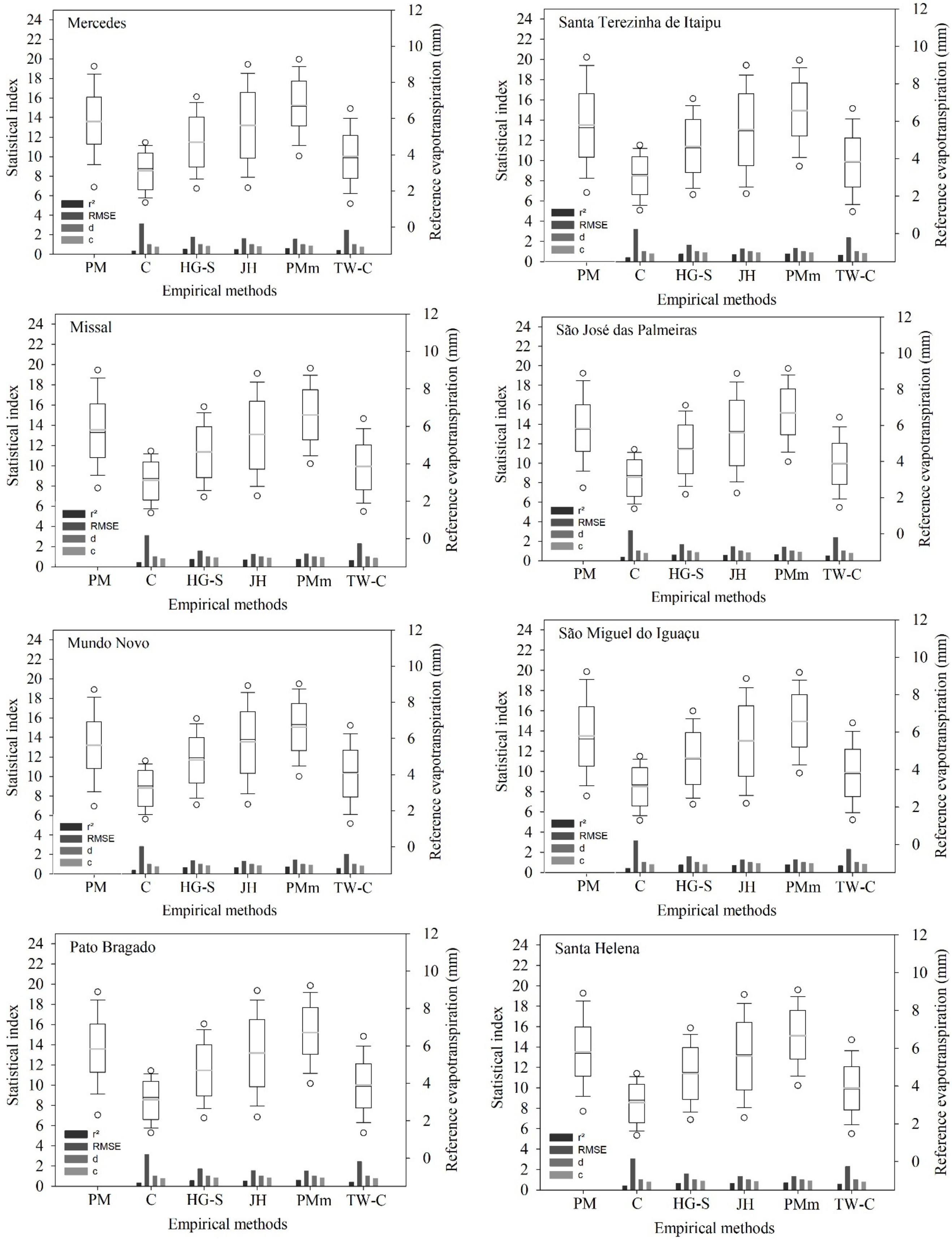
Considering the "r²" values, the HG-S and PMm methods showed greater precision in a linear regression model, indicating lower data variability [16], with $r^2 = 0.65$ and $r^2 = 0.69$, respectively. Regarding this indicator, the C method showed greater variability of the estimated ETo values, since it yielded a lower "r²" value ($r^2 = 0.38$). The estimation error indicator, represented in this research by the RMSE, varies from zero to $+\infty$. Methods that present values close to zero indicate smaller errors in their estimates. The lowest RMSE was observed using the JH and PMm methods (RMSE = 1.36 and 1.38 mm d^{-1}, respectively). The biggest estimate error was observed with the C method (RMSE = 3.08 mm d^{-1}).

The five evaluated methods showed agreement between the ETo values estimated by PM and the other methods evaluated, since the "d" values were close to the unit for all methods [33]. In relation to performance index "c", HG-S and PMm were classified as "great performance", whereas C, JH and PW-C were classified as "very good performance" [11].

The statistical indices observed in each ETo estimation method were similar among the evaluated locations. Thus, for better interpretation, the average among the statistical indexes was analyzed (Table 2).






Mercedes
Santa Terezinha de Itaipu
Missal
São José das Palmeiras
Mundo Novo
São Miguel do Iguaçu
Pato Bragado
Santa Helena
Statistical index
Reference evapotranspiration (mm)
Empirical methods
PM
C
HG-S
JH
PMm
TW-C
r²
RMSE
d
c

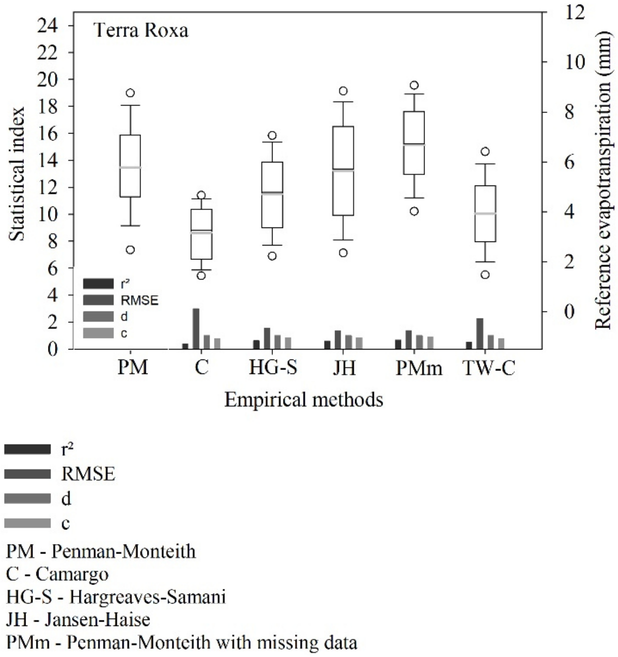


Figure 3. Statistical indexes represented by the bar graph and distribution of reference evapotranspiration (ETo) values represented by box plot graph obtained by different estimation methods for each municipality surrounding the Itaipu Binacional reservoir assessed.
Source: The authors.

Table 2.
Average annual accumulated rainfall (P, mm), mean air temperature (Tmean, ºC) and relative air humidity (RH, %) in the Brazilian region of the municipalities surrounding the Itaipu Binacional reservoir.

ETo estimation methods	r^2	RMSE (mm d^{-1})	d	c	Classification
C	0.38	3.08	0.99	0.77	very good
HG-S	0.65	1.63	0.99	0.85	great
JH	0.62	1.36	0.99	0.84	very good
PMm	0.69	1.38	0.99	0.88	great
TW-C	0.54	2.32	0.99	0.80	very good

*C - Camargo; HG - Hargreaves-Samani; JH - Jensen-Haise; PMm - Penman-Monteith with missing data; TW-C - Thornthwaite-Camargo.
Source: The authors.

Considering the "r²" values, the HG-S and PMm methods showed greater precision in a linear regression model, indicating lower data variability [16], with r2 = 0.65 and r2 = 0.69, respectively. Regarding this indicator, the C method showed greater variability of the estimated ETo values, since it yielded a lower "r²" value (r2 = 0.38). The estimation error indicator, represented in this research by the RMSE, varies from zero to +∞. Methods that present values close to zero indicate smaller errors in their estimates. The lowest RMSE was observed using the JH and PMm methods (RMSE = 1.36 and 1.38 mm d-1, respectively). The biggest estimate error was observed with the C method (RMSE = 3.08 mm d-1).

The five evaluated methods showed agreement between the ETo values estimated by PM and the other methods evaluated, since the "d" values were close to the unit for all methods [33]. In relation to performance index "c", HG-S and PMm were classified as "great performance", whereas C, JH and PW-C were classified as "very good performance" [11].

Overall, HG-S and PMm methods were the most suitable for estimating ETo in the surrounding municipalities of the Itaipu Binacional reservoir. Similar results were observed by [13,1,28]. These studies evaluated PMm as an alternative to PM for situations in which there is an absence of meteorological data. They reported satisfactory results for the use of PMm.

The use of PMm is indicated for regions where data on relative humidity, solar radiation and wind speed is not known [2]. The results observed suggest that: the average values of wind speed for the region show little temporal variability, since they were satisfactorily represented by 2 m s-1; the dew point humidity has a good correlation with the minimum air temperature and can be used to determine the relative air humidity; and, the Hargreaves-Samani method (Eq. 07) for estimating solar radiation may be a good alternative for the region. In relation to the HG-S method, it shows great potential to be applied in the region, since it is easy to apply, requires only maximum and minimum air temperature data and presents the possibility of local calibration of its coefficients, which can reduce the estimation errors [5,34].

4. Conclusions

Regarding the characterization of the evapotranspiration process, daily ETo values ranged from 2 to 10 mm d^{-1}, with an annual mean of 5.78 mm d^{-1}. It was also observed that it is determined predominantly by radioactive parameters, which annually represent 76% of the evapotranspiration process, while aerodynamic parameters represent 24%.

Among the reference evapotranspiration estimation methods evaluated, Hargreaves-Samani and Penman-Monteith with missing data methods were the most suitable for estimating, as they resulted in higher values of "r²", "d" and "c", with lower values of RMSE, being recommended for use in the surrounding municipalities of the Itaipu Binacional reservoir.

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