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Article

Evapotranspiration Estimates in Different Semi-Arid Municipalities of Northeastern Brazil Under Drought Scenarios

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RESUMO

A estimativa da evapotranspiração é uma excelente ferramenta para o desenvolvimento de estudos e atividades voltados para projetos de uso e gestão de recursos hídricos, especialmente em regiões com escassez hídrica. Este trabalho teve como objetivo avaliar o desempenho de métodos mais simplificados e práticos para estimar a evapotranspiração em diferentes regiões do estado do Rio Grande do Norte sob diferentes condições climáticas, utilizando o método Penman-Monteith-FAO56 como modelo padrão. Os métodos testados foram: Linacre (1993), Priestley-Taylor (1972), Souza-Silva (2022) e Radiação Solar. Foram utilizados dados climatológicos das microrregiões de Macau, Mossoró e Seridó Ocidental, referentes ao período de 2007 a 2019. O modelo de Linacre (1993) apresentou o melhor desempenho nas regiões avaliadas e pode ser recomendado em diferentes condições climáticas do ano.

Palavras-chave: evaporação; condições climáticas; modelos de estimativa; Gestão de recursos hídricos.

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ABSTRACT
Estimating evapotranspiration is an excellent tool for developing studies and activities aimed at water use and water resource management projects, especially in regions of water scarcity. This work aimed to evaluate the performance of more simplified and practical methods for estimating evapotranspiration in different regions of the state of Rio Grande do Norte under different climatic conditions, using the Penman-Monteith-FAO56 method as a standard model. The methods tested were: Linacre (1993), Priestley-Taylor (1972), Souza-Silva (2022) and Solar Radiation. Climatological data from the microregions of Macau, Mossoró and Western Seridó were used from 2007 to 2019. The Linacre model (1993) presented the best performance in the regions evaluated and can be recommended in different climatic conditions of the year.
Keywords: evaporation; climatic conditions; estimation models; water management.

Introduction

The prognosis of evapotranspiration is an excellent tool in the development of studies and activities aimed at irrigation projects, shrimp farming, animal husbandry, reservoir management or urban hydrology, aimed at the proper use of water resources. In addition, observing the behavior of a region's climatic variables contributes to a more accurate and efficient estimate. In semi-arid regions, for example, there is less variation in meteorological parameters, as there are no great differences in temperature throughout the year, which favors the intensification of water loss through evapotranspiration, which can reach more than 2000 mm per year.

Evapotranspiration was a term introduced by climatologist C. W. Thornthwaite in the mid-1930s to express the simultaneous processes of evaporation by the soil and transpiration by plants. This term was used to replace the previous concept of consultative use, which also considered the water retained by the plant. Thus, evapotranspiration can be described as the total loss of water, in the form of vapor, from the surface of a vegetated area (Pereira; Sediyama; Villa Nova, 2013).

The state of Rio Grande do Norte, located in the northeast of Brazil, has around 93% of its area in the semi-arid region (Vale *et al.*, 2020). According to Silva et al. (2022), water availability in a region is highly influenced by its climate and hydrological characteristics, with economic activities and popular supply being directly dependent on these parameters. Hydro-climatological studies are therefore important tools for managing water resources efficiently.

In semi-arid regions, where high evaporation rates are observed with increasing supply demands, such as the state of Rio Grande do Norte, knowledge of evaporation rates becomes very important, especially when applied directly to reservoirs, be they dams, weirs, storage tanks or lakes (Oliveira *et al.*, 2012). In addition, according to Santiago et al. (2016), knowledge of crop water requirements is a key factor in managing the use of water in production processes in the agricultural sector, especially in irrigation.

Water loss due to evapotranspiration can be estimated using mathematical models that use climatological parameters and/or empirical values (Santos, 2019), and may present different results depending on the climatic conditions of the region in which they are being used. It is therefore essential to carry out research aimed at evaluating the results of applying each model and indicating which is the most suitable for a given location.

Considering this, this work evaluated the estimation of evapotranspiration in the municipalities of Caicó, Macau and Mossoró, located in the state of Rio Grande do Norte, using the Penman-Monteith-FAO56, Linacre (1993), Priestley-Taylor (1972), Souza (2022) and FAO Solar Radiation methods; in addition to observing the impact of climate change on water loss over the years 2007 to 2019. The behavior of the empirical equations tested will be evaluated when compared to the standard Penman-Monteith-FAO56 equation and through analysis of the coefficient of determination, in order to determine the relevance of using simpler and more practical theoretical methods as well as present their limitations, and verify the degree of influence of the different meteorological variables within the equations studied, relating them to the climatic conditions found in the different regions.

Material and Methods

Methods for estimating evapotranspiration

The Penman-Monteith-FAO56 method was recommended in May 1990 by the FAO as the standard method for estimating reference evapotranspiration. Previously, Penman (1948) proposed an estimation method that combined the effects of the energy balance with the evaporative power of air and, for this reason, was defined as a combined method (Fontes, 2005). The main objective of the Penman (1948) method was to disregard the parameter of the surface temperature of the water, thus considering the surface temperature of the water to be equal to the temperature of the adjacent air layer. The Penman (1948) method considered net radiation, the psychrometric constant, the evaporative power of the air and the tangent from the vapor saturation pressure curve to estimate evaporation. In addition, he disregarded the portion corresponding to the heat flow in the medium, which resulted in a greater balance of energy available for the evaporation process.

The equation proposed by Linacre (1993) is a simplification of the Penman model for estimating evaporation in lakes. Previously, Linacre (1977) had proposed a simplification of the Penman method which required only average temperature data and geographical coordinates of the study site. However, this method did not provide satisfactory results, since it disregarded aerodynamic parameters and the radiation balance and, consequently, underestimated evaporation in reservoirs. With this in mind, Linacre (1993) proposed a new simplification that estimated evaporation using precipitation data, wind speed and radiation parameters. This method was tested on three lakes in the United States and obtained satisfactory results.

According to Pereira et al. (2013), the method developed by Priestley-Taylor can also be described as a simplification of the Penman (1948) method. Priestley-Taylor (1972) concluded, based on lysimetric measurements taken in different regions, that the aerodynamic term could be eliminated, but that there should be a correction coefficient, which, due to its good performance in various regions, became known as the Priestley-Taylor parameter. The method therefore makes use of the Priestley-Taylor coefficient (α), which purpose is to represent the evaporative control carried out by the vegetation (Priestley; Taylor, 1972).

The removal of the aerodynamic term proposed by Priestley-Taylor (1972) resulted in vapor pressure values not being used, requiring only radiation and surface temperature parameters to estimate evaporation.

The Souza (2022) model was developed to propose a simpler method for estimating evapotranspiration in arid regions. This method was tested in the Brazilian semi-arid region in a fruit-growing region and the evapotranspiration estimate was compared with the estimate obtained by the Penman-Monteith and Priestley-Taylor model (α), which aims to represent the evaporative control carried out by vegetation (Priestley; Taylor, 1972).

To estimate evapotranspiration, Souza (2022) model used variables based on the water vapor pressure deficit and solar radiation. The method showed excellent results in estimating evapotranspiration, with very little error, presenting a huge advantage for use in places where climatological data is not readily available.

The FAO Solar Radiation method is an adaptation of the Makkink method carried out by Doorenbos-Pruitt (1997) and Doorenbos-Kassam (1979) which consisted of replacing the coefficients a and b with a single coefficient c, which depends on relative humidity and wind speed. The increase in this coefficient can be called the angular coefficient of the regression (Pereira; Villa Nova; Sediyama, 1997).

Characterization of the study areas Caicó, Macau and Mossoró

The municipality of Caicó is located in the Central Potiguar Mesoregion and the Western Seridó Microregion, at 6°27'28.8" S, 37°5'52.8" O, with an area of 1.228.584 km², 221 km from the capital Natal-RN and 144 km from Mossoró-RN.

The climate classification of the municipality of Caicó falls into the BSh category, based on the Koppen methodology, with a very hot and semi-arid climate, with a rainy season delayed until the fall; with a rainy season between February and May, an average annual rainfall of 716.6 mm, average annual maximum temperatures of 33.0 °C, average temperatures of 27.5 °C and minimum temperatures of 18 °C and average annual relative humidity of 59% (Beltrão *et al.*, 2005a).

The municipality of Macau is located in the Central Potiguar Mesoregion and Macau Microregion, at coordinates 05°06'54.0" S, 36°38'02.4" O, with an area of 775.302 km², 175 km from the capital Natal-RN and 79 km from Mossoró-RN.

Macau is located at an altitude of less than 100 m and has a climate classified as BSh, based on the Koppen methodology, characterized by being very hot and semi-arid, with a rainy season delayed until autumn; annual rainfall of 515.1 mm; with a rainy season from March to April; maximum temperature of 32 ºC, minimum temperature of 23 ºC and average annual temperature of 27.2 °C and average annual relative humidity of 68% (Beltrão *et al.*, 2005b).

Mossoró is located at the coordinates: 05°11'16.8" S, 37°20'38.4" O, and is situated in the Mesoregion West Potiguar and in the Microregion Mossoró. The area of the municipality is 2.099.334 km², 246 km from the capital Natal-RN.

The municipality has a very hot, semi-arid climate, with the rainy season delayed until the fall, falling into the BSh category according to the Koppen classification. The rainy season is characterized by an average annual rainfall of 695.8 mm, with a rainy period from February to April; a maximum temperature of 36 °C, a minimum temperature of 21 °C, an average annual temperature of 27.4 °C and an average annual relative humidity of 70% (Beltrão *et al.*, 2005c).

Obtaining climate data

Meteorological data was obtained from the National Institute of Meteorology - INMET and the NASA/POWER platform, from the weather stations in Caicó (A316) latitude -6.47°, longitude -37.08°, and altitude 171.26 m; Macau (A317) latitude -5.15°, longitude -36.57°, and altitude 17.37 m; and Mossoró (A318) latitude -5.12°, longitude -37.18°, and altitude 36 m.

For each station, the monthly averages of maximum and minimum air temperature and dew point; relative humidity; wind speed; rainfall; radiation and maximum and minimum atmospheric pressure were obtained from INMET, while the rainfall data was obtained from the NASA/POWER platform using the geographical coordinates of the weather stations.

The base data period for calculating evapotranspiration was determined from the date of operation of the weather stations until 2019. Data from later years was not used due to numerous failures at the desired stations, probably due to the Covid-19 pandemic. The methodology used to correct the gaps in the meteorological data was the same as that used by Santos (2019).

Models used in the estimation of evapotraspiration

The calculated data was obtained from daily values applied to the equations in Table 1 and then the monthly average evapotranspiration was calculated. Table 2 shows the meteorological variables used for each equation.

Table 1. Models used to estimate evapotranspiration (ET).

Method	Equation	N°
Penman-Monteith-FAO56	$\frac{0{,}408\,\Delta\,(\mathrm{Rn}-\mathrm{G})+\gamma\frac{900}{T+273}\,u_2\,(e_s-e_a)}{\Delta+\ \gamma\,(1+0{,}34\,u_2)}$	(1)
Linacre (1993)[1]	$(0{,}015+0{,}00042\,T+10^{-6}\,z)\,[0{,}8\,R_s-40+2{,}5\,F\,u_2\,(T-T_o)]$	(2)
Priestley-Taylor (1972)	$1{,}26\left(\frac{\Delta}{\gamma+\Delta}(R_n-G)\right)$	(3)
Souza-Silva[2] (2015)	$-0{,}00728+1{,}356325\,DPV+0{,}174658\,Rs$	(4)
FAO Solar Radiation[3]	$c\,W\,Rs$	(5)

Where "γ" is the psychrometric coefficient (KPa ºC^{-1}) ; "Δ" is the slope of the water vapor saturation pressure curve (KPa ºC^{-1}) ; "Rn" is the daily solar radiation measured over the liquid surface (W m^{-2}); "G" is the change in heat storage in the reservoir (W m^{-2}) ; "λ " is the latent heat of evaporation (MJ kg^{-1}) ; "ρ " is the specific weight of water (kg m^{-3}) ; "u_2" is the average wind speed measured at a height of 2 meters (m s^{-1}) ; "e_s" is the saturation pressure of water vapor at air temperature (mb); "e_a" is the partial pressure of water vapor at air temperature (mb); "T" is the daily average air temperature (°C) obtained by averaging the daily extreme values; "z" is the site altitude (m); "Rs[1]"is the solar irradiance at the lake surface (W m^{-2}) ; "F" is the correction factor due to the site altitude; "T_o" is the dew point temperature (°C); "DPV" is the water vapor pressure deficit (KPa); "Rs[2]" is the incidence of global solar radiation (MJ m^{-2} d^{-1}); "c" is the angular coefficient; "W" is the weighting factor depending on the air temperature and the psychometric coefficient; "Rs[3]" is the solar radiation at ground surface level (mm day^{-1}). Source: prepared by the authors

Table 2. - Meteorological variables used and auxiliaries.

Group	Methods	Meteorological variables used	Auxiliary input variables	Original and/or cited reference
Standard	Penman-Monteith-FAO56	T_{max}, T_{min}, T, RH_{max}, RH_{min}, u_2, P, $R_{s,\,Rn}$, G	D_j, ϕ	Allen *et al.*, (1998)
Tested	Linacre (1993)	T, T_o, R_s, u_2	-	Linacre *et al.*, (1993)
	Priestley-Taylor (1972)	T, P, R_n, G	D_j, ϕ	Pereira *et al.*, (1997)
	Souza (2022)	T, UR, Rs	-	Souza *et al.*, (2022)
	Solar Radiation FAO	UR, u_2, T, Rs	-	Doorembos; Pruitt (1977)

Where "T" is the average daily air temperature; "T_{max}" is the maximum daily air temperature; "T_{min}" is the minimum daily air temperature; "T_o" is the dew point temperature; "RH_{max}" is the maximum relative humidity; "RH_{min}" is the minimum relative humidity; "RH" is the average relative humidity; "u_2" is the wind speed at a height of 2 m; "P" is the atmospheric pressure (KPa); "R_s" is the solar or short-wave radiation; "R_n" is the radiation balance; "G" is the heat stored in the watercourse; "D_j" is the Julian day; "ϕ " is the latitude of the location (rad). Source: prepared by the authors

Results and Discussion

The comparison between the evapotranspiration calculation models used by Linacre (1993), Priestley-Taylor (1972), Souza (2022) and Solar Radiation was analyzed considering a historical series of thirteen years, from 2007 to 2019, in three different regions of the state of Rio Grande do Norte, in the municipalities of

Caicó, Macau and Mossoró. To assess the sensitivity of these models, graphs were developed for evapotranspiration, temperature, solar radiation, relative humidity and wind speed. Graphs of the averages of the years considered very dry and graphs of the models' adjustments in relation to the standard are presented.

As shown in Fig. 1, when analyzing the behavior of evapotranspiration in the years classified as very dry in the Western Seridó Microregion - Caicó, a period with an average annual rainfall of 226.8 mm, it was observed that, for the first six months of the year, all the models studied showed a tendency for evapotranspiration to decrease, with a slight increase between February and March, caused by the increase in solar radiation on the surface. For the rest of the year, there was an increase in evapotranspiration, with a reduction after October, which accompanied the reduction in wind speed and solar radiation on the surface, as well as a slight increase in relative humidity, as shown in Fig. 2.

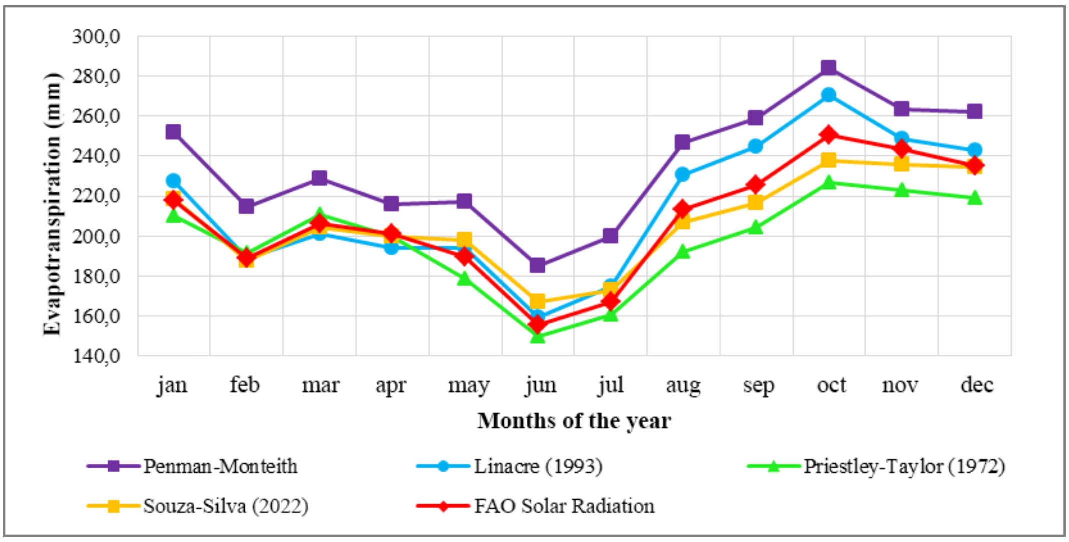

Fig. 1. Evapotranspiration estimates obtained from the different methods during a year in Caicó-RN. Source: prepared by the authors

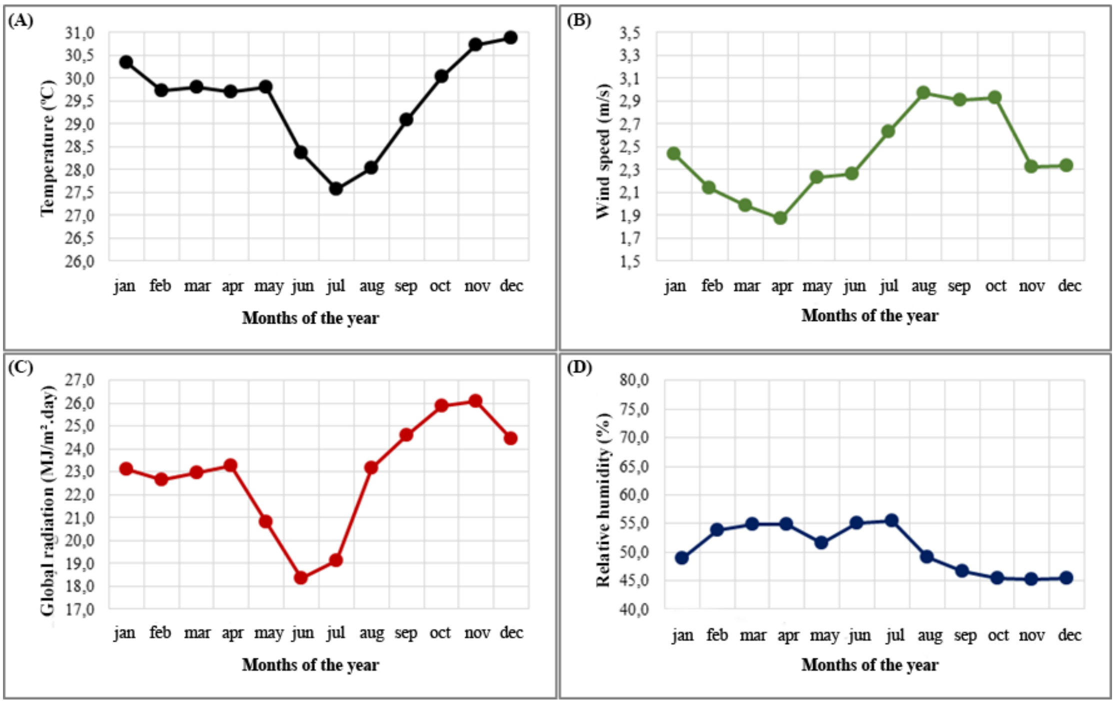

Fig. 2. Average air temperature (A), wind speed (B), global radiation (C) and relative humidity (D) for very dry years in Caicó-RN. Source: prepared by the authors

It can be seen that all the models analyzed in Fig. 1 underestimated the standard model throughout the year and that the one that came closest to the Penman-Monteith model was Linacre (1993) with minimum error values during the months of August to November of 6.9; 5.9; 4.9 and 5.9% respectively, where there was an increase in global solar radiation and higher wind speed averages, with a decrease in November, and maximum error values during the months of June and July with values of 16.1 and 14.4% respectively, when the lowest solar radiation averages were observed on the surface. Fig. 1 shows that, for very dry years, the FAO Solar Radiation and Souza (2022) methods obtained similar results when compared to the standard model, with the FAO Solar Radiation method being the closest. For both models, the minimum error was observed in April, with 7.4% for Solar Radiation and 8.2% for Souza (2022), this being the period in which the lowest average wind speed was obtained and which had the highest average relative humidity. Souza (2022) obtained maximum error values between August and October of 19.3; 19.7 and 19.3%, respectively, a period which saw high averages for solar radiation and low averages for relative humidity, while the FAO Solar Radiation method obtained maximum error values between June and July of 18.8 and 19.7%, respectively, which saw growth in wind speed, lower averages for solar radiation at the surface with an upward trend, and higher averages for relative humidity for very dry years with a downward trend.

The Priestley-Taylor (1972) method showed the greatest divergence from Penman-Monteith in very dry years, with the greatest differences in evapotranspiration estimates during the months of August to October of 28.5; 26.8 and 25.1%, respectively, and the minimum errors between the months of February to April of 11.9; 8.6; 2.3 and 7.9%, respectively.

When analyzing Fig. 3, for the very dry years in the Macau micro-region, with average annual rainfall of 256.3 mm, it was observed that all the models underestimated the standard model throughout the year. In the first seven months, evapotranspiration varied in a similar way for all the models, showing successive decreases and increases until July, with the exception of Priestley-Taylor (1972), which showed a decreasing behavior from March to June. Between July and October, all the methods showed an increasing behavior, with a reduction from October onwards, caused by the decrease in solar radiation on the surface and wind speed and the increase in relative humidity, as shown in Fig. 4.

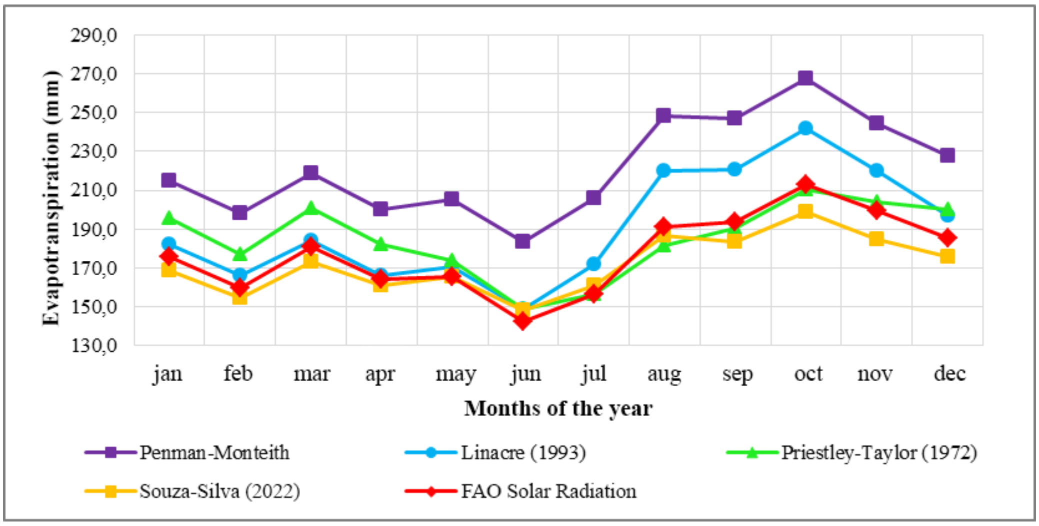

Fig. 3. Evapotranspiration estimates obtained from the different methods during a year in Macau-RN. Source: prepared by the authors

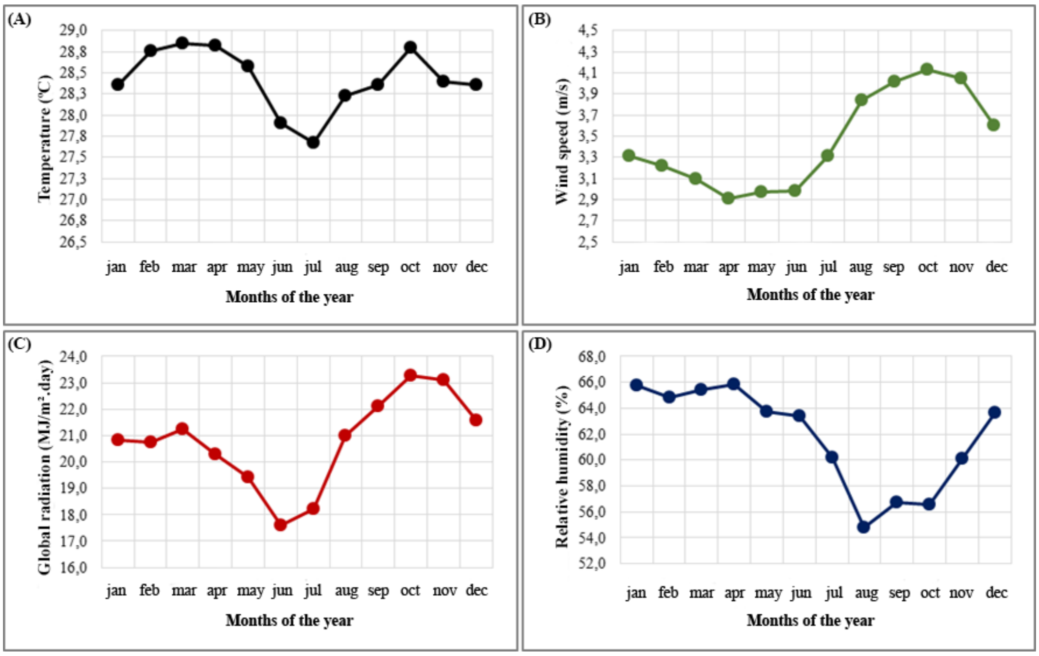

Fig. 4. Average air temperature (A), wind speed (B), global radiation (C) and relative humidity (D) for very dry years in Macau-RN. Source: prepared by the authors

For estimating evapotranspiration in very dry years, the method that was closest to the standard model was Linacre (1993) with the smallest errors observed between August and November of 12.9; 12.2; 10.4 and 10.8%, respectively, a period in which there was an increase in surface solar radiation and higher average wind speeds. According to Collischonn and Tucci (2014), on the northeastern coast and in the semi-arid region, the most intense wind occurs more frequently in dry weather. However, when the equation was estimated using the Linacre (1993) model, the month of June showed the greatest error of 23.3%, this being the month with the lowest average solar radiation and lowest average wind speed.

The Priestley-Taylor (1972) model was the second closest to the standard model, with the smallest errors observed between January and April of 9.7; 11.9; 9.0 and 9.8%, respectively, and the largest errors observed between July and October of 31.3; 37.0; 29.7 and 26.9%, respectively.

The methods with the worst results were FAO Solar Radiation and Souza (2022), with Souza method showing the greatest discrepancy in relation to the Penman-Monteith-FAO56 model. The minimum values observed for FAO Solar Radiation were between the months of March and April at 20.8 and 21.7%, these being the months that showed a decrease in solar radiation, low wind speed averages and higher relative humidity averages, while the maximum values were observed between the months of June and September at 28.9; 31.4; 29.8 and 27.6%, respectively, where there was an increase in surface solar radiation and wind speed and a decrease in relative humidity, with a tendency to increase from August onwards, where the errors of the FAO Solar Radiation method in relation to the standard model begin to decrease.

Regarding to the Souza (2022) model, the months with the smallest errors were between March and June at 26.2; 24.1; 24.0 and 23.9% respectively, a period in which there was a drop in solar radiation and higher relative humidity averages, while the largest errors were obtained between August and November at 32.9; 34.5; 34.5 and 32.4% respectively, a period in which there was an increase in solar radiation between August and October and a tendency for radiation to decrease from October onwards, as well as lower relative humidity averages.

When analyzing Fig. 5, for the years classified as very dry in the Mossoró microregion, with average annual rainfall of 291.4 mm, it can be seen that, with the exception of Priestley-Taylor (1972) all the models underestimated the standard model. For the first four months of the year, all the models showed similar behavior in estimating evapotranspiration, with an increasing behavior between February and March, which followed the behavior of solar radiation on the surface. Between April and June, there is a downward trend in evapotranspiration. For the remaining six months, evapotranspiration shows an upward trend until October, when it decreases in line with the behavior of surface solar radiation and wind speed, as shown in Fig. 6.

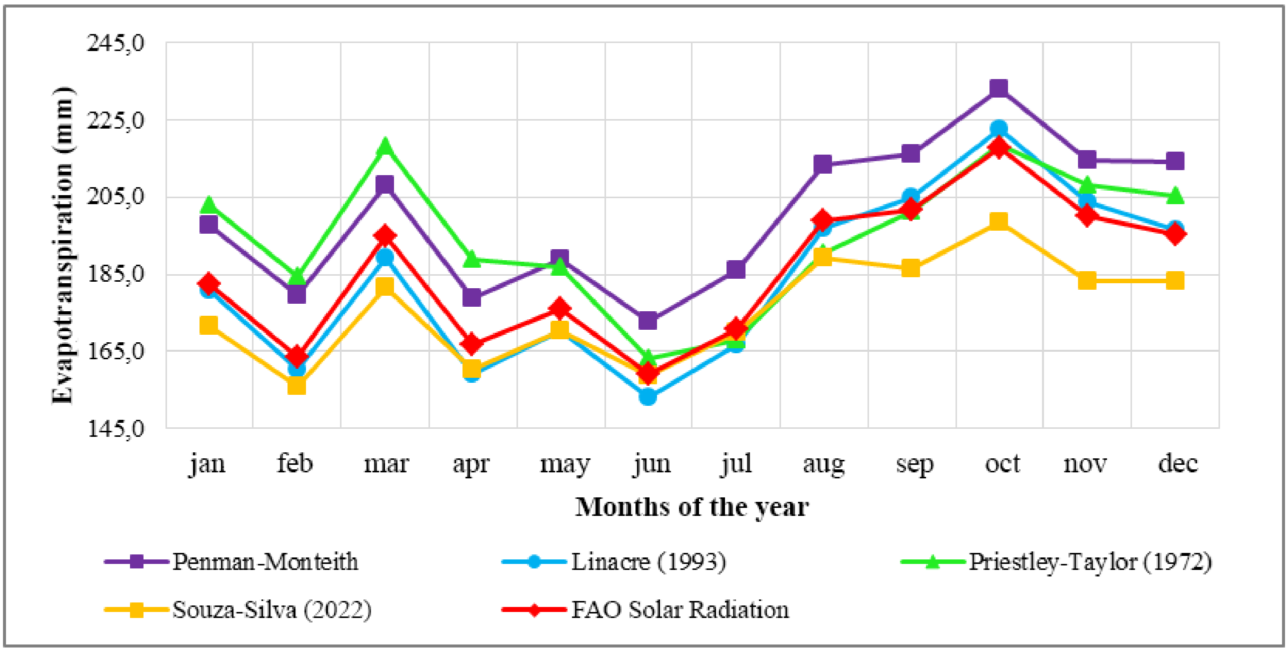

Fig. 5. Evapotranspiration estimates obtained from the different methods during a year in Mossoró-RN. Source: prepared by the authors

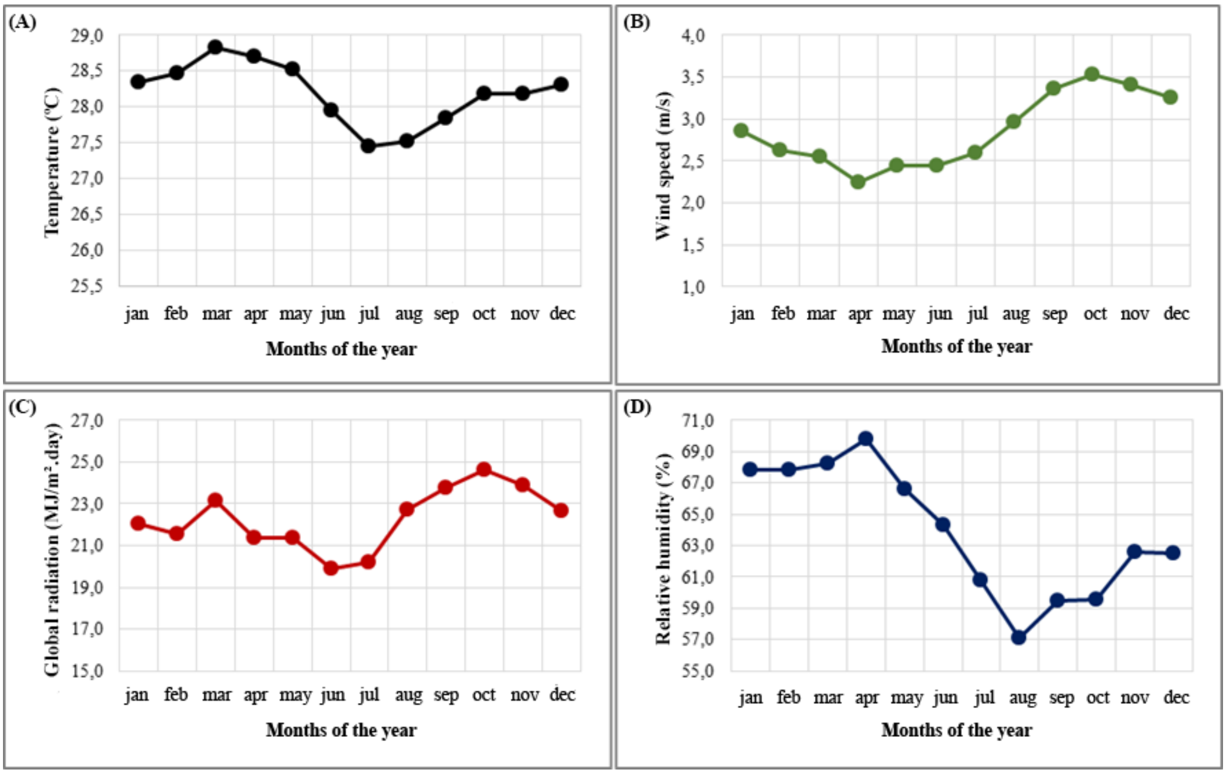

Fig. 6. Average air temperature (A), wind speed (B), global radiation (C) and relative humidity (D) for very dry years in Macau-RN. Source: prepared by the authors

The model that came closest to Penman-Monteith-FAO56 in the years classified as very dry was Priestley-Taylor (1972), which showed the smallest error of 1.1% in the month of May, while the months of July and August showed the largest errors in relation to the standard model, of 10.8 and 11.9%, respectively. The Priestley-Taylor (1972) model overestimated Penman-Monteith between January and April. The methods that were closest were the FAO Solar Radiation method and Linacre (1993), with the FAO Solar Radiation method being the second closest to the estimate made by the standard model with the smallest error observed in the month of March equal to 6.9%, a period with decreasing average wind speed and very high relative humidity, while the largest errors were between the months of December and February of 9.6; 8.3 and 9.9% respectively; and between June and July of 8.4 and 9.0% respectively.

Looking at Fig. 5, it can also be seen that Linacre (1993) showed the lowest errors between September and November, when there was no precipitation, with errors of 5.6, 4.7 and 5.2%, respectively, where there were high averages of solar radiation and wind speed. It should be noted that the month of October, which estimated evapotranspiration with the lowest error, had the highest average solar radiation on the surface, as well as wind speed. According to Collischonn and Tucci (2014), wind increases evapotranspiration as it removes moisture from the surface, bringing in less saturated air. According to these authors, in semi-arid regions, wind frequency is higher during dry periods.

The greatest errors obtained by Linacre (1993) occurred between the months of February, April, June and July, at 12.0, 12.3, 12.6 and 11.8%, respectively, and it was also found that the greatest errors occurred in the first half of the year, when there are lower averages of solar radiation and wind speed, a period when rain occurs.

However, Souza (2022) was the method that distanced itself the most from the standard model, showing the greatest errors between October and December of 17.4; 16.9 and 16.8%, respectively, a period when there were higher averages of solar radiation and lower averages of relative humidity. The period in which Souza (2022) came closest to the standard model was between April and July, at 11.5; 10.8; 8.7 and 9.6%, respectively, when there was a reduction in solar radiation at the surface and a downward trend in relative humidity. It can be seen that the month of June was the closest to the standard model and had the lowest annual average solar radiation.

Cavalcante Júnior (2011), when analyzing different methods of estimating reference evapotranspiration for the conditions of the northeastern semi-arid region, in the municipality of Mossoró, found that, in dry periods, the FAO Radiation method performed very well, while Priestley-Taylor performed poorly. This corroborates the result obtained in this study by the FAO Solar Radiation model for the municipality of Mossoró. However, when analyzing the Priestley-Taylor (1972) model for Mossoró, it showed excellent performance in relation to the standard model, while for the municipalities of Caicó and Macau, the Priestley-Taylor (1972) model did not show satisfactory results.

Taking Fig. 1, 3 and 5, when evaluating the behavior of evapotranspiration using the Souza (2022) model, it was found that the municipalities of Caicó and Mossoró obtained the best results, while the municipality of Macau did not show satisfactory results, probably due to the greater influence of wind speed in the coastal region. The largest errors were observed for the periods with the highest wind speeds, with the maximum value recorded between September and October, the period in which this parameter grew. It can be seen that the Souza (2022) model does not consider the influence of wind, unlike the Linacre (1993), FAO Solar Radiation and standard models.

When analyzing Table 3, which compare the estimate of evapotranspiration for the three regions studied in the state of Rio Grande do Norte, in years classified as very dry, it can be seen that for the municipalities of Macau and Caicó, the method that came closest to the standard model when analyzing only the error in relation to Penman-Monteith throughout the year was Linacre (1993), with an error equal to 16.2% in Macau and 9.7% in Caicó.

It was observed that the greatest errors in relation to the standard model in the municipality of Macau were obtained by the Souza (2022) method, with an error of 29.1%, showing greater divergence in the second half of the year, a drier period. However, when analyzing the coefficient of determination, Souza (2022) showed a satisfactory result, with an R^2 value of 0.9778. The Priestley-Taylor (1972) model had the lowest coefficient with an R^2 of 0.5367 and an error of 19.8%, proving the model's poor performance in Macau.

When evaluating the error in relation to the standard model for the municipality of Mossoró, the Priestley and Taylor (1972) method showed the best performance, with an error of 5.4%. However, when evaluating the coefficient of determination, R^2, this same model had the lowest performance among the methods evaluated, with R^2 equal to 0.8585, compared to Linacre (1993) with R^2 equal to 0.9936 and an error of 9.0%; Souza (2022) with R^2 equal to 0.9883 and an error of 13.9%; and FAO Solar Radiation with R^2 equal to 0.9968 and an error of 7.9%. It was therefore observed that for the very dry years in Mossoró, all the models evaluated showed satisfactory results when analyzing the coefficient of determination.

Oliveira et al. (2020), however, when estimating reference evapotranspiration in the dry season in Mossoró, obtained coefficients of determination (R^2) for Priestley-Taylor (1972) equal to 0.538, while for Linacre (1993) it was 0.458. In this study, the rainfall data used was obtained from a NASA satellite, considering the average of four years classified as very dry, namely 2012, 2014, 2015 and 2016, with rainfall of 291.4 mm. However, Oliveira et al. (2020) used data from 2012, with average annual rainfall of 199.41 mm.

A study carried out by Alencar et al. (2011), when evaluating the performance of reference evapotranspiration estimation methods in periods of high evaporative demand in the municipalities of Espinosa, Montes Claros and Salinas, located in the state of Minas Gerais, observed that in the periods with high evaporative demand, comprising the months of October to March, the Priestley-Taylor method performed slightly better than the FAO Solar Radiation method for the municipalities of Espinosa and Montes Claros. However, these results differ from the estimates found in the three regions evaluated in the state of Rio Grande do Norte, where the FAO Solar Radiation method performed better when compared to Priestley-Taylor, with higher coefficients of determination for the three municipalities, equal to 0.9968; 0.9573 and 0.9442 against 0.8585; 0.7941 and 0.5367, respectively for the municipalities of Mossoró, Caicó and Macau. The study by Alencar (2011) shows that the highest evaporative demands occur in the months with the highest rainfall and temperature. In the region evaluated by the authors, the solar declination towards the southern hemisphere contributes to an increase in solar radiation and, consequently, to an increase in evapotranspiration during the rainy season.

Table 3. Penman-Monteith errors in years classified as very dry

Region	Method	Smallest error		Largest error		Total error in relation to Penman-Monteith-FAO56
		Month	Error	Month	Error	
Macao micro-region	Linacre (1993)	Oct	10,4%	Jun	23,3%	16,2%
	Priestley-Taylor (1972)	Mar	9,0%	Aug	37,7%	19,8%
	Souza (2022)	Mar	26,2%	Sep/Oct	34,5%	29,1%
	Solar Radiation FAO	Mar	20,8%	jul	31,4%	25,0%
Mossoró micro-region	Linacre (1993)	Oct	4,7%	Jun	12,6%	9,0%
	Priestley-Taylor (1972)	May	1,1%	Aug	11,9%	5,4%
	Souza (2022)	Jun	8,7%	Oct	17,4%	13,9%
	Solar Radiation FAO	Mar	6,9%	Feb	9,9%	7,9%
Western Seridó micro-region	Linacre (1993)	Oct	4,9%	Jun	16,1%	9,7%
	Priestley-Taylor (1972)	Apr	7,9%	Aug	28,5%	19,4%
	Souza (2022)	Apr	8,2%	Sep	19,7%	14,0%
	Solar Radiation FAO	Apr	7,4%	Jul	19,7%	13,3%

Source: prepared by the authors

When analyzing the coefficient of determination, R^2, shown in Table 4, Linacre (1993) also showed the best performance for these municipalities, with the highest coefficients for Macau and Caicó, equal to 0.9957 and 0.9908 respectively. For Caicó, however, it showed the greatest discrepancy in relation to the standard model, with an error of 19.4%. This fact was confirmed when the coefficient of determination was evaluated, with R^2 equal to 0.7941.

Table 4. Coefficient of determination values for very dry years in the micro-regions of Macau, Mossoró and Western Seridó in the state of Rio Grande do Norte, from 2009 to 2019.

Region	Method	R^2	Equation
Macau micro-region	Linacre (1993)	0,9957	$y = 1{,}1335\,x - 60{,}439$
	Priestley-Taylor (1972)	0,5367	$y = 0{,}5487\,x + 63{,}475$
	Souza (2022)	0,9778	$y = 0{,}5794\,x + 43{,}307$
	FAO Solar Radiation	0,9442	$y = 0{,}7851\,x + 3{,}2854$
Mossoró micro-region	Linacre (1993)	0,9936	$y = 1{,}1572\,x - 46{,}336$
	Priestley-Taylor (1972)	0,8585	$y = 0{,}746\,x + 49{,}854$
	Souza (2022)	0,9883	$y = 0{,}7154\,x + 32{,}852$
	FAO Solar Radiation	0,9968	$y = 0{,}9766\,x - 7{,}3599$

Western Seridó micro-region	Linacre (1993)	0,9908	$y = 1{,}136\,x - 52{,}878$
	Priestley-Taylor (1972)	0,7941	$y = 0{,}7203\,x + 27{,}557$
	Souza (2022)	0,9259	$y = 0{,}7521\,x + 29{,}473$
	FAO Solar Radiation	0,9573	$y = 0{,}959\,x - 18{,}065$

Where "R^2" is the coefficient of determination. Source: prepared by the authors

Conclusions

The Linacre (1993) model can be recommended for the regions analyzed and can be used in different climatic conditions throughout the year.

The Priestley-Taylor (1972) model performed worst in the coastal region of Macau, where the vegetation is classified as Caatinga Hiperxerófila.

Among the equations tested, Linacre (1993) showed the best fit compared to Penman-Monteith-FAO56 for the different regions of the state of Rio Grande do Norte.

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