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Geo-Sciences

Comparison between evapotranspiration estimate methods in the state of Rio Grande do Sul

Comparação entre métodos de estimativa de evapotranspiração no estado do Rio Grande do Sul

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ABSTRACT

The characterization of evapotranspiration requires time and financial investment, but from meteorological data, it is possible to estimate the values of this phenomenon by means of indirect methods. The Penman-Monteith FAO (PM) method is considered the most accurate by the Food and Agriculture Organization of the United Nations (FAO), which recommends its use because it takes into account solar radiation, temperature, relative humidity, and wind speed, data that are not always available in some locations in Brazil, making it necessary to use more simplified methods. Therefore, the objective of this work is to compare the evapotranspiration estimated by the Penman-Monteith FAO method with the evapotranspiration estimated by the methods of Penman-Monteith Simplified (PMS), Priestley-Taylor (PT), and Hargraves-Samani (HS) for the 10 weather stations of the National Institute of Meteorology (INMET) distributed in the Pampa biome in the state of Rio Grande do Sul. The results obtained indicated some divergences between the compared methods. However, the PT method showed more accurate results, with the best performance among the proposed methods. This indicates that this method can be used in future studies in the region, especially in cases of a lack of meteorological data.

Keywords: Evapotranspiration; Pampa biome; Estimation methods

RESUMO

A caracterização da evapotranspiração requer tempo e investimento financeiro, porém a partir de dados meteorológicos é possível estimar os valores deste fenômeno por meio de métodos indiretos. O método de Penman-Monteith (PM) é considerado como o mais preciso pela Organização das Nações

Unidas para Agricultura e Alimentação (FAO), que recomenda seu uso, pois leva em conta a radiação solar, temperatura, umidade relativa e velocidade do vento, dados que nem sempre estão disponíveis em alguns locais do Brasil, sendo necessário utilizar métodos mais simplificados. Portanto, o objetivo deste trabalho é comparar a evapotranspiração estimada pelo método de Penman-Monteith (PM) com a evapotranspiração estimada pelos métodos de Penman-Monteith Simplificado (PMS), Priestley-Taylor (PT) e Hargraves-Samani (HS) para as 10 estações meteorológicas do Instituto Nacional de Meteorologia (INMET) distribuídas no bioma Pampa no estado do Rio Grande do Sul. Os resultados obtidos indicaram algumas divergências entre os métodos comparados. Contudo, o método de PT demonstrou resultados mais precisos apresentando o melhor desempenho entre os métodos propostos. Esse método pode ser utilizado em estudos futuros na região, principalmente em caso de falta de alguns dados meteorológicos.

Palavras-chave: Evapotranspiração; Bioma Pampa; Métodos de Estimativa

1 INTRODUCTION

Water planning and management in several regions uses water balance, with evapotranspiration being one of its main components. This, water balance is important to understanding the hydrological cycle and the soil-plant-atmosphere system, because it represents the loss of water from the surface to the atmosphere (Djaman et al., 2018; Sena, 2021). Water balance is key for water management. Thus, several hydrological models and tools that support irrigation management require evapotranspiration values in order to understand water dynamics and to estimate optimal irrigation rates, taking into account the type of soil and crop in a given area. (Thaines, 2022; Zappa, 2022)

Evapotranspiration is the combination of two processes: evaporation, which occurs on water surfaces; and transpiration, which occurs on plant leaves (Collischonn & Tassi, 2008; Maidment, 1992; Tucci, 2012). Both processes depend on climatic factors that control the availability of energy and water. Among these factors, the most important are solar radiation, air temperature, relative humidity, and wind speed, in addition to soil and plant characteristics (Allen, 1998; Jensen & Allen, 1990).

From meteorological data available in databases, it is possible to estimate evapotranspiration through methods developed over the years (Allen, 1998). Some methods are based on different parameters, such as the combined method of Penman Monteith (PM), whose use is recommended by the Food and Agriculture Organization of the United Nations (FAO) (Allen, 1998; Jacobs & Satti, 2001), which considers solar radiation, temperature, wind speed, and relative humidity, while the Hargreaves-Samani method (Hargreaves & Samani, 1985; Jacob & Satti, 2001) considers only air temperature (Allen, 1998). Among the existing methods, Penman-Monteith FAO is considered the standard by the FAO because it unites both biological and climatic factors, important in evapotranspiration (Garcia, 2004; Hess, 1998). Several studies show that this method is the most accurate under different climatic conditions, presenting satisfactory results when compared with lysimeter data in humid tropical climates. Despite being the most suitable, input variables are required that are often unavailable at the study site (Djaman, 2016; Stöckle, 2004).

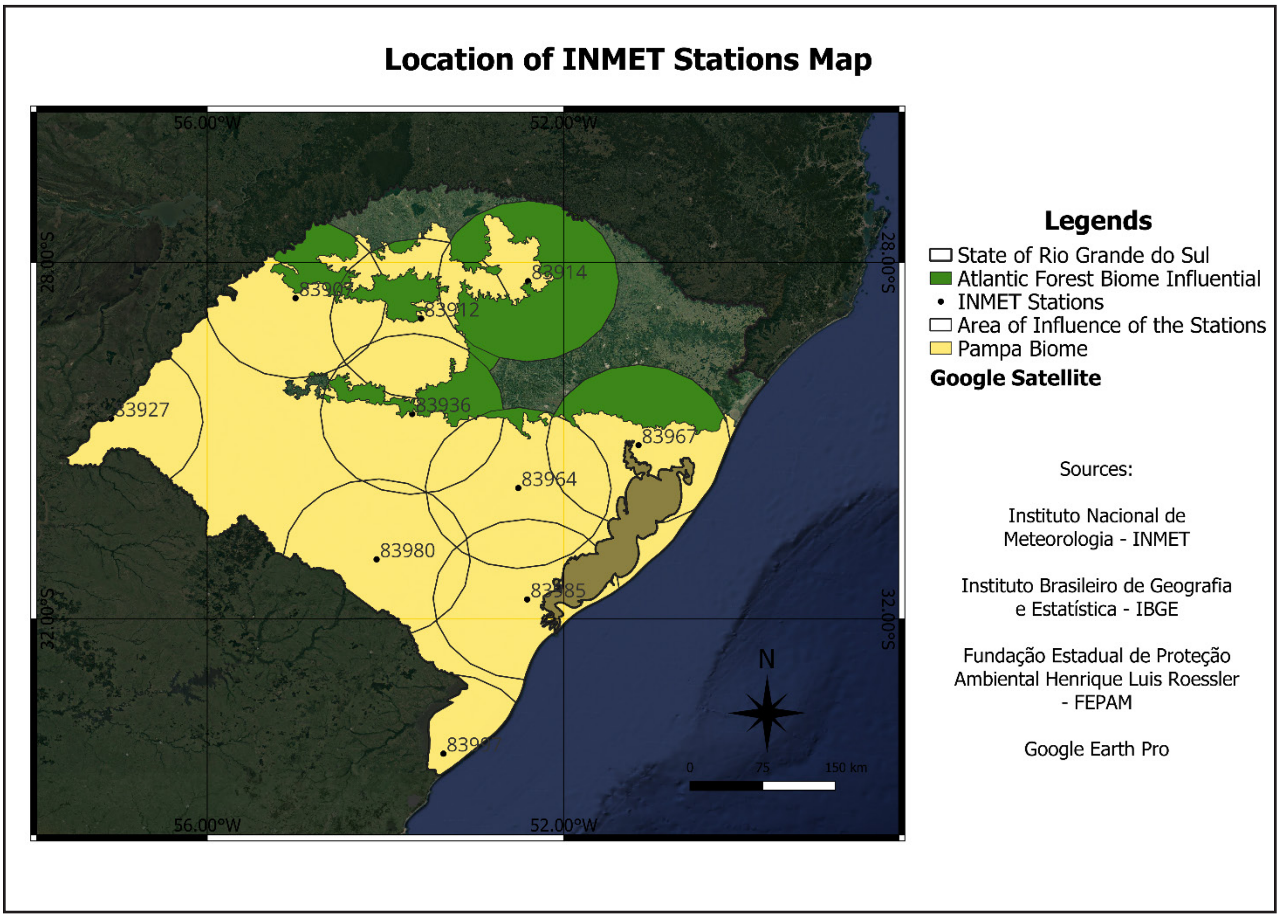
Aware of the importance of evapotranspiration estimation and the lack of studies using de methods mentioned for the entire biome area, this work proposes a comparative analysis between three existing methods of indirect evapotranspiration estimation (Penman-Monteith Simplified, Priestley-Taylor, Hargreaves-Samani) with the standard method of Penman-Monteith FAO, using data from weather stations made available by the Meteorological Database for Teaching and Research (BDMEP) for the Pampa biome in the state of Rio Grande do Sul, with the objective of identifying which method can be replaced by Penman-Monteith FAO in case of meteorological data failure.

2 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Pampa biome, an area in the state of Rio Grande do Sul, which is located in Southern Brazil. With a subtropical climate, it has a total territory of 750 thousand km². The area analyzed in the study is approximately 193 thousand km². The National Institute of Meteorology (INMET) manages ten weather stations in the area. Figure 1 represents the spatial distribution of the stations in the biome (IBGE, 2019; INMET, 2019). According to the World Meteorological Organization (WMO), the representative area of a weather station is 100 km, Figure 1 shows the radius of each station.

Figure 1 – INMET stations distribution map



Source: Authors (2023)

The data used in this work were obtained from the INMET Meteorological Database (BDMEP) from the period 01/01/2009 to 12/31/2018. For each of the stations, ten years of daily data of maximum temperature, minimum temperature, insolation, relative humidity, and wind speed were collected. The location map below represents the spatial distribution of the INMET stations.

Stations located further north in the state, according to Brazilian Institute of Geography and Statistics (IBGE) data, some stations end up covering both biomes (Pampa and Atlantic Forest).

2.2 Estimation methods

2.2.1 Penman-Monteith FAO

Penman-Monteith is the method that best approximates actual values (measurements), (Allen, 1998). It is based on the original combination equation that Penman developed in 1948. Because it is a combined method, it requires more input variables than others, including maximum and minimum temperature, relative humidity, wind speed, and solar radiation. In addition, some parameters are fixed that must be taken into account based on a reference surface, such as a hypothetical grass crop with a height of 0.12m, surface resistance of 70 s.m^{-1}, and albedo of 0.23.

$$ETo = \frac{0.408 * \Delta * (Rn - G) + \gamma * \frac{900}{T + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma(1 + 0.34 * u_2)} \quad (1)$$

Where:
ETo is the reference evapotranspiration (mm.day^{-1});
Rn is the net solar radiation at the crop surface (MJ m^{-2} day^{-1});
G is the soil heat flux density (MJ.m^{-2}. day^{-1});
T is the daily average temperature (ºC);
u_2 is the wind speed;
e_s is the saturation vapor pressure (kPa);
e_a is the current vapor pressure (kPa);
γ is the piezometric constant (kPa ºC^{-1});
Δ is the slope of the vapor pressure curve (kPa ºC^{-1}).

2.2.2 Simplified Penman-Monteith

This study was developed to estimate evapotranspiration, considering that at the site there are no insolation, relative humidity and wind speed values. Thus, the equation used is Equation (1), the same that Penmam-Monteith FAO cited above, but assumes values and other means of calculating the missing variables, as shown below:

$$Rs = Krs(Tmax - Tmin)^{0,5} * Ra \qquad (2)$$

Where Krs is:

$$Krs = 0.17\left(\frac{P}{P_o}\right)^{0,5} \qquad (3)$$

For the absence of relative humidity data, the current vapor pressure (ea) can be estimated by the equation proposed by Allen (1998), which assumes that the dew point temperature is close to the daily minimum temperature.

$$ea = e^0(Tmin) = 0,611Exp\left(\frac{17,27Tmin}{Tmin + 237,3}\right) \qquad (4)$$

Where:
Rs is the short-wave solar radiation ($MJ.m^{-2}.day^{-1}$);
Ra is the extraterrestrial solar radiation ($MJ.m^{-2}.day^{-1}$);
Tmax is the maximum temperature (°C);
Tmin is the minimum temperature (°C);
P is the average atmospheric pressure at the station site and Po the atmospheric pressure at sea level (101.3 kPa).

For wind speed, when unavailable, the value of 2 (m/s) is adopted, which is considered the global average speed, as demonstrated in 2000 meteorological stations around the world (Allen, 1998; Jabloun & Sahli, 2008; Martinez-Cob & Tejero-Juste, 2004).

2.2.3 Priestley Taylor

The Priestley-Taylor equation is an abbreviation of the original Penman-Monteith equation. It was developed based on the idea that the effect of atmospheric movements is small compared to the effects of solar radiation and this condition occurs when the air is saturated, leading to an equilibrium in evapotranspiration. The equation used is shown below:

$$ETo = \alpha + \frac{\Delta}{(\Delta + \gamma)} * \frac{(R_n - G)}{\lambda} \qquad (5)$$

Where:
ETo is the reference evapotranspiration ($mm\ day^{-1}$);
Rn is the net solar radiation at the crop surface ($MJ.m^{-2}.day^{-1}$);
G is the soil heat flux density ($MJ.m^{-2}.day^{-1}$);

λ is the latent heat of vaporization (2.45);
γ is the piezometric constant (kPa.ºC^{-1});
Δ is the slope of the vapor pressure curve (kPa.ºC^{-1});
α is the compensation constant (1.26).

2.2.4 Hargreaves and Samani

The Hargreaves and Samani (1985) equation were developed based on other methods for estimating evapotranspiration, which is a simplification of the original Hargreaves formula (Hargraves, 1975, 1982), and estimates reference evapotranspiration only as a function of maximum and minimum temperatures.

$$ETp = 0{,}0023 * \frac{Ra}{\lambda} * (Tmax - Tmin)^{\frac{1}{2}} * (T + 17{,}8) \tag{6}$$

Where:
ETp is the potential evapotranspiration (mm.day^{-1});
Ra is the extraterrestrial solar radiation;
λ is the latent heat of vaporization (2.45);
Tmin is the minimum temperature (ºC);
Tmax is the maximum temperature (ºC).

Thus, it is one of those recommended by WMO when there are data limitations for estimation by Penman-Monteith.

Table 1 – variables used by each methodology

Method	Approach	Variables (*)
Penman-Monteith, FAO	Combination	Rn, G, T, U_2, e_s, e_a,γ, Δ
Penman-Monteith Simplificado	Combination	Ra, G, T, U_2, e_s, e_a, γ, Δ
Priestley-Taylor	Radiation	Rn, G, α, γ, λ, Δ
Hargreaves-Samani	Temperature	Ra, Tmax, Tmin, T, λ

Source: the authors (2023)
(*) Rn: net solar radiation at crop surface; Ra: extraterrestrial radiation; Tmax: maximum daily temperature; Tmin: minimum daily temperature; T: average daily temperature; G: soil heat flux density; U_2: wind speed at two meters from ground level; es: saturation vapor pressure; ea: actual vapor pressure; α: Priestley-Taylor coefficient (1.26); γ: piezometric constant; Δ: slope of the vapor pressure curve; λ: latent heat of saturation (2.45)

2.3 Statistical Analysis

2.3.1 Correlation Coefficient

The methods were compared by correlation analysis run in R software. The linear correlation coefficient measures the degree of correlation between two variables. The correlation coefficient (R^2) is expressed by a numerical value; the closer the value is to 1, the greater the correlation between the variables.

2.3.2 Standard Deviation

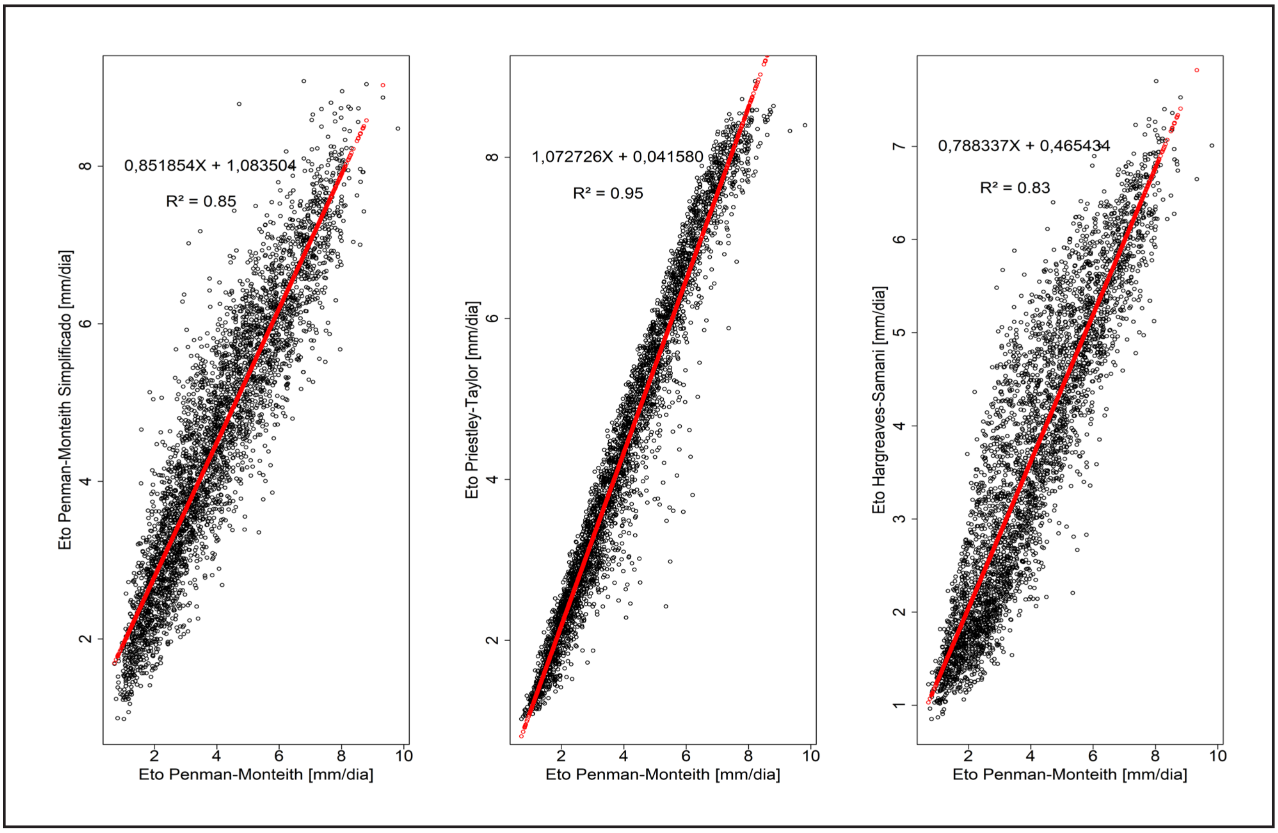
The results were presented using standard deviation maps for each method. The stations were distributed throughout the biome according to their coordinates. With the standard deviation values already performed, data interpolation was performed using the IDW method (inverse distance weighted), which uses values from the stations' surroundings to predict values from places where there are no measurements. The values of closer stations have a greater weight than more distant places. Thus, the influence of each point is proportional to the inversed distance from the mesh node (Gomes, 2018; Jakob & Young, 2006).

3 RESULTS

3.1 Correlation Coefficient

Figure 2 presents the correlation of the methods of Penman-Simplified, Priestley-Taylor, and Hargreaves-Samani (from left to right) with the Penman-Monteith FAO method for the Pampa biome in Rio Grande do Sul, using averages from INMET stations. The Priestley-Taylor method was the one that showed the best correlation when compared to the other two methods, being the correlation coefficient (R^2) of 0.95, while the other methods were 0.85 for Penman-Monteith Simplified and 0.83 for Hargreaves-Samani.

Figure 2 – Linear correlation plots of the Penman-Monteith Simplifield, Priestley-Taylor, and Hargreaves-Samani methods against Penman-Monteith FAO for the Pampa biome



Source: Authors (2023)

Considering the variables used in each method, Penman-Monteith Simplified differs from the Penman-Monteith FAO method in that is assumes a constant value for wind speed (2 m/s) and considers the absence of insolation data, which is replaced by equations (2) and (3), the Pampa biome presents low vegetation, the wind presents a variability at the site, assuming a constant speed for an area can lead to inaccuracy of the estimate. Among the Hargreaves-Samani and Priestley-Taylor methods, the one that comes closest to the standard method in terms of variables is the Priestley-Taylor method, since it considers insolation, minimum temperature, and relative humidity, as opposed to the Hargreaves method, which only uses temperature. For this reason, it may be the best fit for the standard method.

3.2 Standard Deviation Maps

According to what is observed in Figure 3, the Penman-Monteith Simplified method presents the highest value of standard deviation for station 83914 (located in the northeast of the biome) in the value of 674.14 mm.

Looking at Figure 1, Passo Fundo station 83914 is heavily influenced by the Atlantic Forest biome, according to Table 2 76% of the area of influence belongs to this biome.

Table 2 – influence of other biome

Station	Influence Area	Atlantic Forest Area	Atlantic Forest Area (%)
83907	30807,01	5958,07	19,34
83912	30875,35	11006,7	35,65
83914	30910,21	23711,5	76,71
83927	30661,84	0	0
83936	30872,6	6854,33	22,20
83964	30908,61	965,53	3,12
83967	30924,44	9757,87	31,55
83980	30858,32	0	0
83985	30911,03	0	0
83997	30888,31	0	0

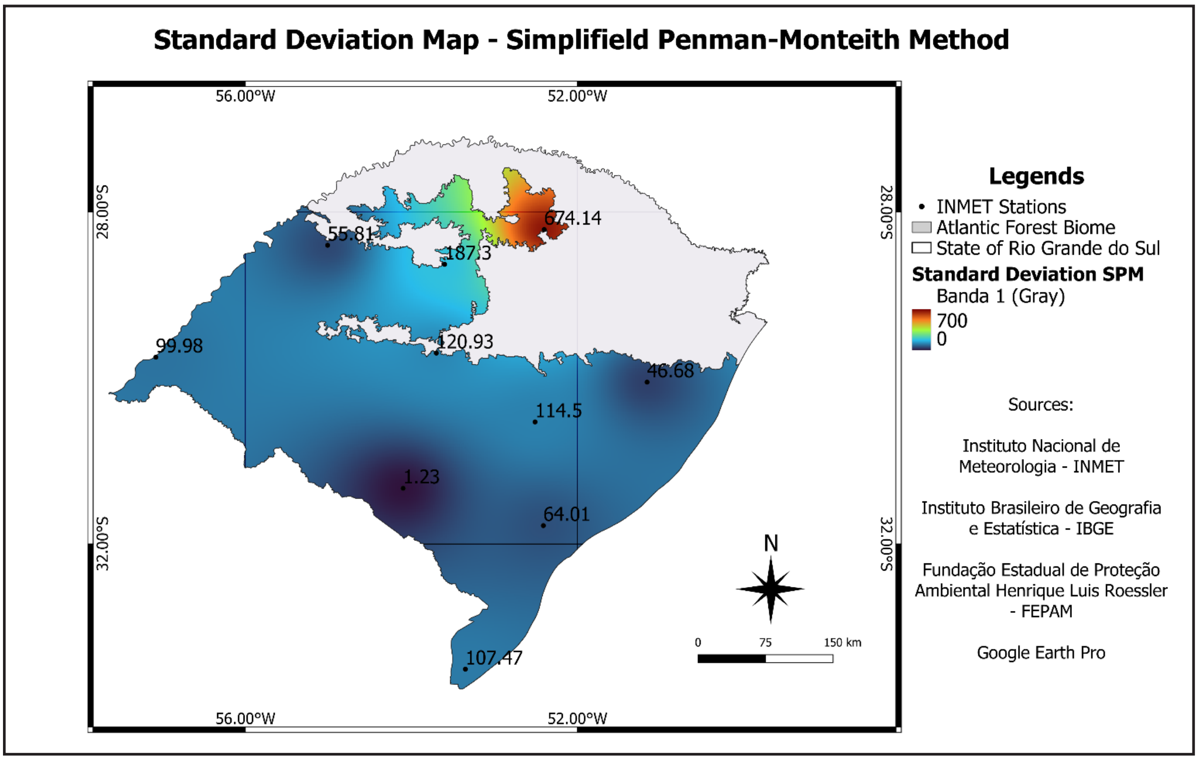
Source: Authors (2024)

According to Câmpara (2018), the use of cartographic products, such as IBGE data, ends up separating the biomes with a line, but defining a transition strip between the biomes is a complex task, as the change in vegetation occurs gradually. In this case, it can be a station (83914) heavily influenced by the transition zone, resulting in the standard deviation value found.

On average, the Priestley-Taylor method is the one that presents the lowest values of standard deviation. Figure 3, Figure 4, and Figure 5 below represent the interpolation map of the standard deviation data for each of the methods.

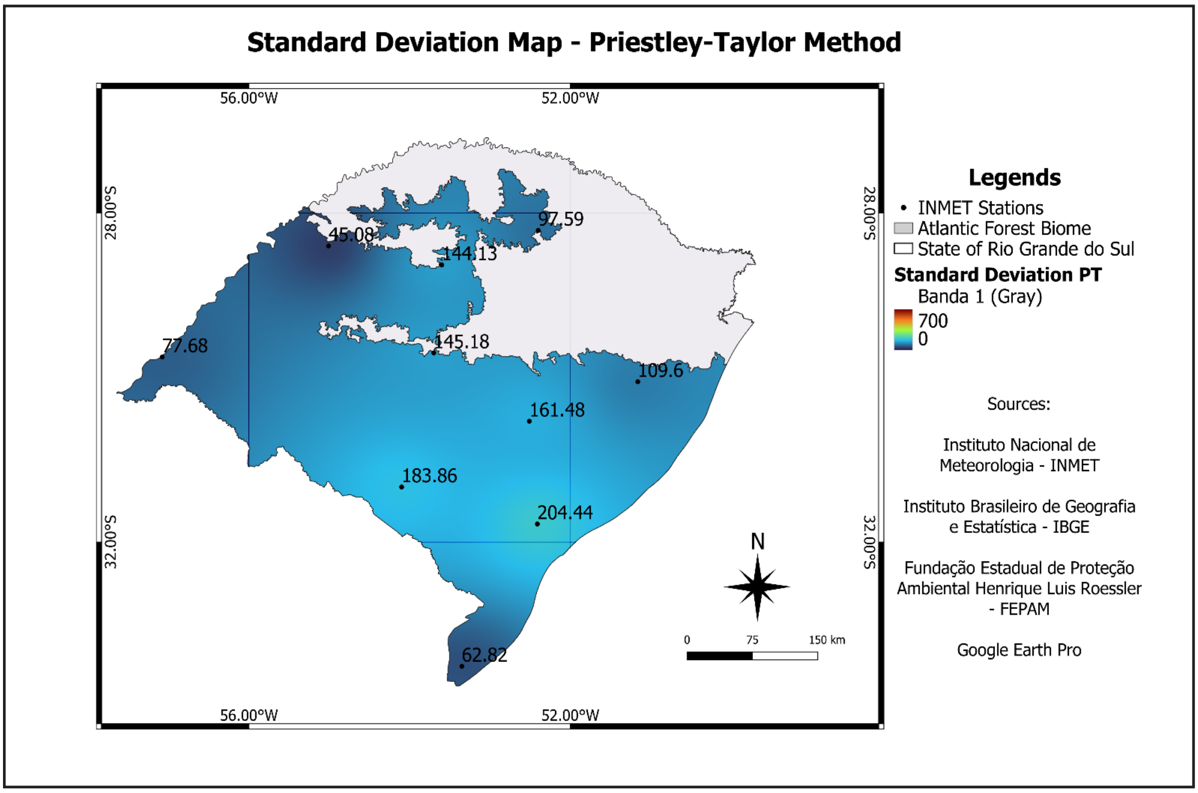
Analyzing the maps above, the method that best resembles the Penman-Monteith FAO method is the Priestley-Taylor method, which presented a better homogeneity in the distribution of standard deviation values for the stations, while in the other methods, there were high standard deviation values, creating altered colors for different stations. Again, the fact of fixing values for some parameters, as in the case of the wind variable, may have caused these differences to appear at the time of analysis. Another important point is the influence that insolation data has on evapotranspiration. In both methods (Penman-Montei FAO [PM] and Priestley-Taylor [PT]) used this variable; thus, the homogeneity of the methods can be attributed to this factor as well.

Figure 3 – Standard Deviation Map (PM-PMS)



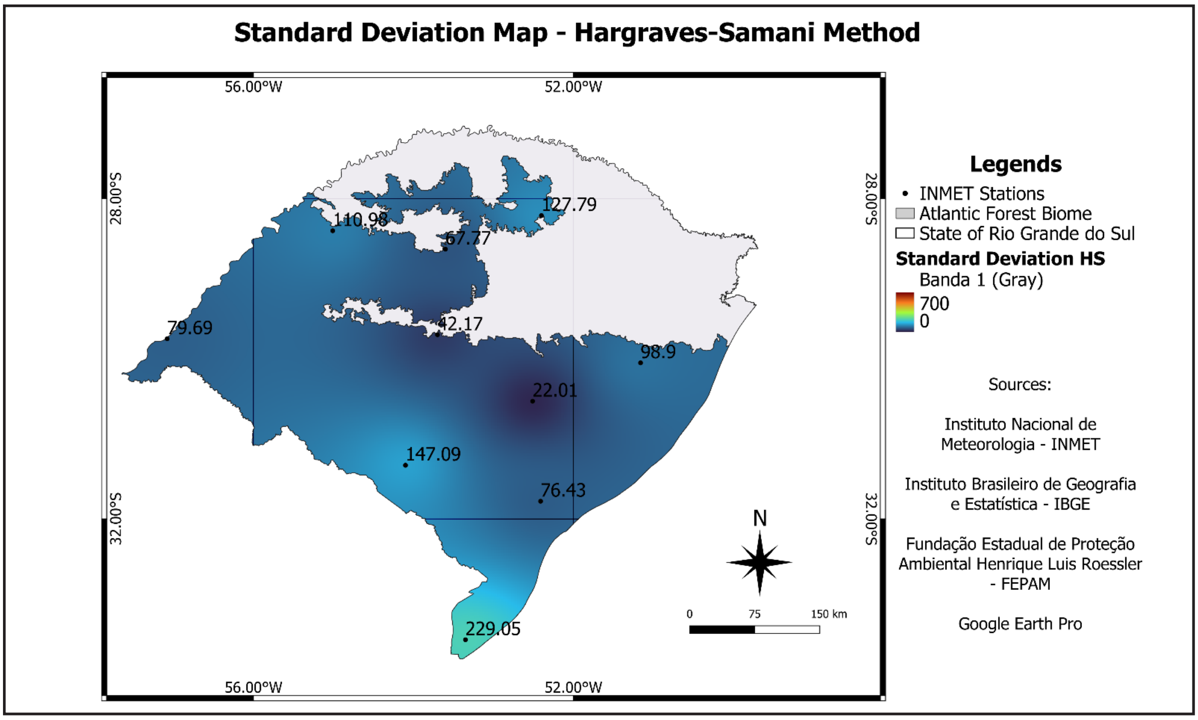
Source: Authors (2023)

Figure 4 – Standard Deviation Map (PM – PT)



Source: Authors (2023)

Figure 5 – Standard Deviation Map (PM – HS)



Source: Authors (2023)

4 CONCLUSIONS

A problem to be highlighted during the development of this work is the inconsistency in the conventional BDMEP data, which present some flaws. As observed in the results, the methods chosen were well suited when compared to the standard method, with emphasis on the Priestley-Taylor method, which presented a better performance than the other methods, indicating that for the study region, when there are no measurement data available, this method is most suitably replaced by Penman-Monteith FAO.

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