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DISTRIBUIÇÃO ESPAÇO-TEMPORAL DA EVAPOTRANSPIRAÇÃO NO NOROESTE PAULISTA[1]

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1 RESUMO

O sensoriamento remoto tornou-se uma importante ferramenta na agricultura, principalmente na obtenção de dados sobre variáveis climáticas, como o alcance de medidas de evapotranspiração. Dessa forma, o presente trabalho objetivou estimar a evapotranspiração em escala regional no Noroeste Paulista e sua distribuição temporal e espacial por meio da aplicação do algoritmo SAFER (*Simple Algorithm for Evapotranspiration Retrieving*) em imagens dos satélites Landsat 5 e Landsat 8 dos anos 2010, 2017 e 2018. O algoritmo SAFER mostrou-se eficaz para a estimativa de evapotranspiração em larga escala e esta metodologia pode ser aplicada em estudos futuros para monitoramento dos indicadores agrícolas e climatológicos da região. Os valores médios de evapotranspiração variaram entre 0,5 e 2,5 mm dia^{-1}, sendo os maiores valores registrados nas áreas irrigadas. Regionalmente, as maiores médias foram obtidas no período de chuvas da região, com valores próximos a 2 mm dia^{-1}.

Palavras-chave: sensoriamento remoto, SAFER, larga escala.

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2 ABSTRACT

The remote sensing became an important tool in agriculture, mainly in obtaining data on weather variables, like the range of evapotranspiration averages. This way, this work aimed to estimate the evapotranspiration in a regional scale in the Paulista Northwest and it’s temporal and spatial distribution by using SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm and images from the satellites Landsat 5 and Landsat 8 in 2010, 2017, and 2018. The SAFER algorithm showed effective for estimating evapotranspiration in large

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scale and this methodology can be applied in further studies to monitor agricultural and climatological indicators of the region. The medium values of evapotranspiration ranged from 0.5 and 2.5 mm day^{-1}, being the highest values were recorded in the irrigated areas. Regionally, the highest averages were obtained in the rainy season of the region, with values close to 2 mm day^{-1}.

Keywords: remote sensing, SAFER, large scale.

3 INTRODUCTION

Evapotranspiration (ET) consists of the process of transferring water from the Earth's surface to the atmosphere by two different means: the evaporation of free water on the evaporating surface and plant transpiration (ALLEN et al., 1998). It is therefore one of the most important variables of the hydrological cycle, and its understanding becomes essential for the management of water resources (BASTIAANSSEN et al., 2005).

The northwest of the state of São Paulo is located in the Great Lakes region, which has great potential for the development of irrigated agriculture. Despite the large supply of water resources, it is the region that records the highest reference evapotranspiration (ET_0) rates in the state and high variability of rainfall, causing a period of water deficit throughout the year of up to 8 months (SANTOS; HERNANDEZ; ROSSETTI, 2010; HERNANDEZ et al., 2003).

The accurate quantification of ET contributes to a better understanding of the water cycle and a better ability to quantify future changes in water resource management in a given region. However, ET cannot be directly observed on a large scale; thus, remote sensing techniques offer increasing possibilities for obtaining agrometeorological information on a regional scale (GHILAIN; ARBOLEDA; GELLENS-MEULENBERGHS, 2011). Evapotranspiration can be estimated through models that use images from orbital sensors and agrometeorological data (ALLEN et al., 2007; BASTIAANSSEN et al., 2005; SENAY; BUDDE; VERDIN, 2011).

The use of remote sensing stands out for being a low-cost technique with broad spatial and temporal coverage, in which there is no need for soil or crop data (BASTIAANSSEN et al., 2005). In this context, the application of algorithms in satellite images to estimate evapotranspiration has been used in several regions of Brazil, including Northwest São Paulo (TEIXEIRA et al., 2014; FRANCO; HERNANDEZ; TEIXEIRA, 2015; AVILEZ, 2018; OLIVEIRA et al., 2019).

The simple algorithm for retrieving evapotranspiration (TEIXEIRA, 2010) stands out. SAFER is based on modeling the ratio between actual evapotranspiration and reference evapotranspiration, relating the following parameters obtained via remote sensing: surface temperature, albedo, and the normalized difference vegetation index (NDVI) (TEIXEIRA, 2010; TEIXEIRA et al., 2013). Unlike models that propose a complete solution to the energy balance equation, which limits the applicability of this technology to large areas or areas with a lack of data, SAFER's main advantage is its operational practicality, as it can be applied with meteorological data from conventional and automatic agrometeorological stations, allowing the evaluation of water productivity indicators over the years, since automatic sensors are relatively recent advances in instrumental technology (TEIXEIRA et al., 2013).

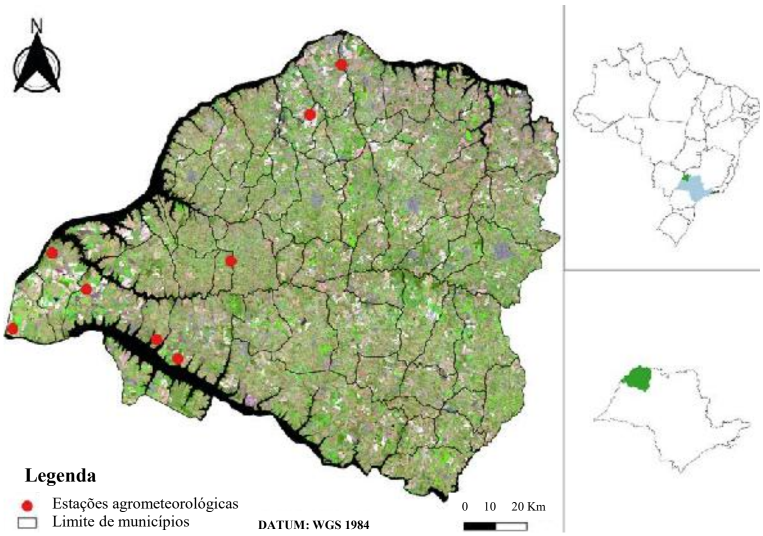
Thus, this work aimed to introduce studies of the temporal and spatial distributions of evapotranspiration at a regional scale in northwestern São Paulo, combining remote sensing and data from agrometeorological stations, to determine evapotranspiration and possible incremental evapotranspiration in the years 2010, 2017 and 2018, applying the SAFER algorithm.

4 MATERIALS AND METHODS

4.1 Location of the study area

The study area is located in the northwest of the state of São Paulo, between coordinates 19°47' and 21°8' South Latitude and 49°47' and 51°34' West Longitude, covering 60 municipalities in an area of 1,613,000 hectares. This area was delimited on the basis of the work of Silva Junior (2017) on the operational representability of the variables obtained by the Agrometeorological Network of Northwest São Paulo, which is composed of 8 automatic stations located in 7 different municipalities in the region, namely, Ilha Solteira, Itapura, Marinópolis, Paranapuã, Pereira Barreto, Populina and Sud Mennucci (Figure 1).

Figure 1. Location of the study area and the Northwest São Paulo Agrometeorological Network.



4.2 SAFER Algorithm

To model the energy components obtained via remote sensing, the methodology described by Teixeira et al. (2013) was applied, allowing the following parameters to be obtained: reflectance of each band; planetary albedo; surface albedo (α_0); net radiation; latent heat flux; sensible heat flux; ground heat flux; brightness temperatures of bands 10 and 11; incident global solar radiation; longwave radiation emitted by the Earth's surface; longwave radiation emitted by the atmosphere; surface temperature (T_0); and the normalized difference vegetation index (NDVI).

The parameters obtained via remote sensing were applied via Equation (1), where the SAFER algorithm calculates the relationship between the actual or current evapotranspiration and the reference evapotranspiration (ET/ET_0):

$$ETa/ET_0 = \exp [a + b (T_0/ (\alpha_0 \times NDVI))] \quad (1)$$

In which,
T_0 = Surface temperature (K);
α_0 = Albedo;
NDVI = normalized difference vegetation index;
Coefficient "a" = Adjusted as 1.0 for Northwest São Paulo (HERNANDEZ et al., 2014); and
Coefficient "b" = Adjusted to -0.008 (TEIXEIRA, 2010).

The current evapotranspiration (ETa) (mm day $^{-1}$) was obtained via Equation 2:

$$ETa = ET_0 \times (ETa/ET_0) \quad (2)$$

In which,
ET_0 = Reference evapotranspiration (mm day $^{-1}$).

4.3 Database acquisition

The agrometeorological variables required for the application of SAFER were obtained from the stations of the Northwest São Paulo Agrometeorological Network, which already provides the reference evapotranspiration (ET0) on a daily basis estimated by the Penman–Monteith equation (ALLEN et al., 1998), as well as precipitation data in the region in each year studied (UNESP, 2019).

To apply the SAFER algorithm, images from 2010, 2017 and 2018 were used. For the years 2017 and 2018, images from the American satellite Landsat 8, which entered orbit in 2013, were used, and for the year 2010, images from the satellite Landsat 5 were used. Both have scenes offered with coverage of 185 by 185 km, revisiting the same area every 16 days.

Images from orbits 222 and 74 were collected and made available free of charge by the *United States Geological Survey* through the *Earth Explorer platform*. Partially or completely cloud-free images were considered. To estimate ETa via remote sensing, the images were processed with geometric corrections, radiometric calibrations, and biophysical information.

Thus, the images used were as follows: 02/02/2010, 22/03/2010, 07/04/2010, 23/04/2010, 10/06/2010, 26/06/2010, 12/07/2010, 29/08/2010, 17/11/2010, 21/02/2017, 09/03/2017, 28/05/2017, 13/06/2017, 15/07/2017, 31/07/2017, 01/09/2017, 17/09/2017, 19/10/2017, 23/01/2018, 08/02/2018, 28/03/2018, 13/04/2018, 29/04/2018, 15/05/2018, 02/07/2018, 18/07/2018, 19/08/2018, 22/10/2018 and 09/12/2018.

4.4 Processing

The images were processed in the ILWIS 3.3 Academic software, and after applying the SAFER algorithm, they were exported to the ArcGIS software - Version 10.1 (ESRI) licensed to the Hydraulics and Irrigation Area of UNESP Ilha Solteira, where the ETa and ET/ET_0 data were extracted to an electronic spreadsheet and graphs were created, with the monthly average of these variables and, for the months that did not have satellite images without major cloud interference, averages were made between the previous and subsequent images.

The monthly precipitation and evapotranspiration reference data for 2017 and 2018 were interpolated via the kriging method, following the methodology recommended by Silva et al. (2013). However, in 2010, there were only two agrometeorological stations in the region; thus, in that year, the data were interpolated via IDW (inverse distance weighting). All the maps were created via ArcGIS software.

5 RESULTS AND DISCUSSION

Figures 2, 3, and 4 present the current evapotranspiration maps of the study area, referring to the dates of the satellite images, for the years 2010, 2017, and 2018, respectively. The ETa values varied between 0.5 and 2.5 mm day $^{-1}$ in the region during the years studied, similar to that reported by Feitosa et al. (2015), who evaluated the ETa in a microbasin in northwestern São Paulo, with an area corresponding to 0.3% of the study area of interest.

Figure 2. Spatial and temporal distributions of evapotranspiration (mm day $^{-1}$) in 2010.

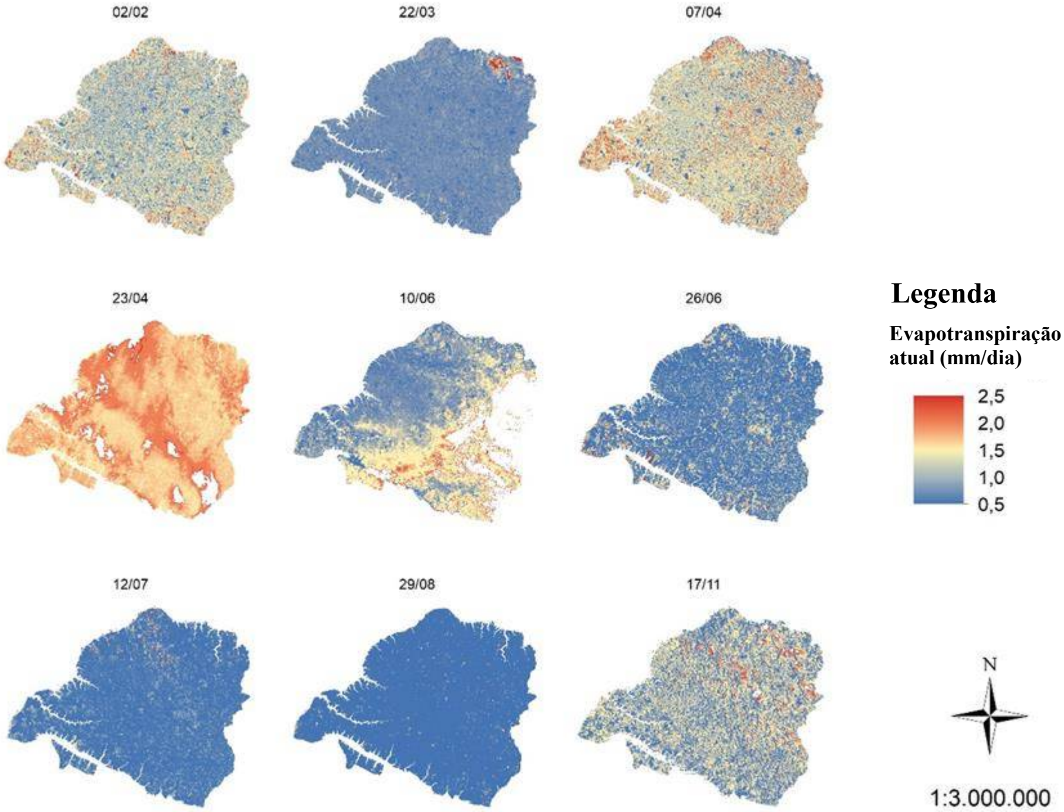


Figure 3. Spatial and temporal distributions of evapotranspiration (mm day $^{-1}$) in 2017.

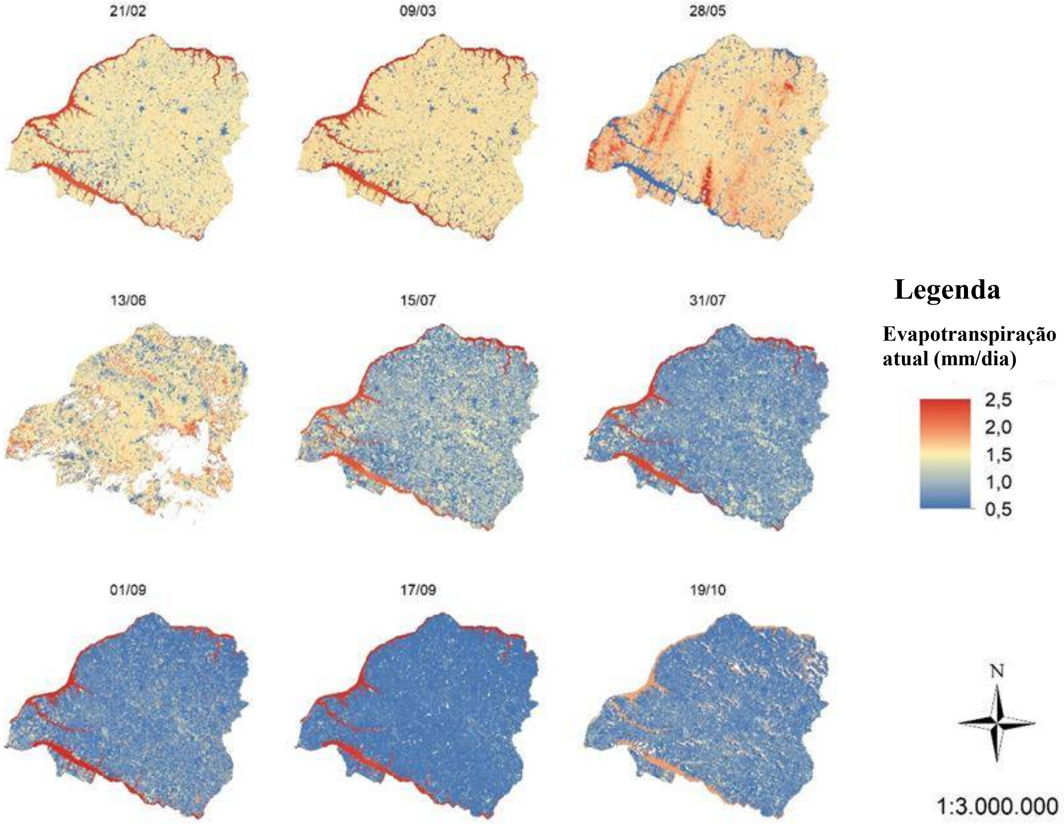
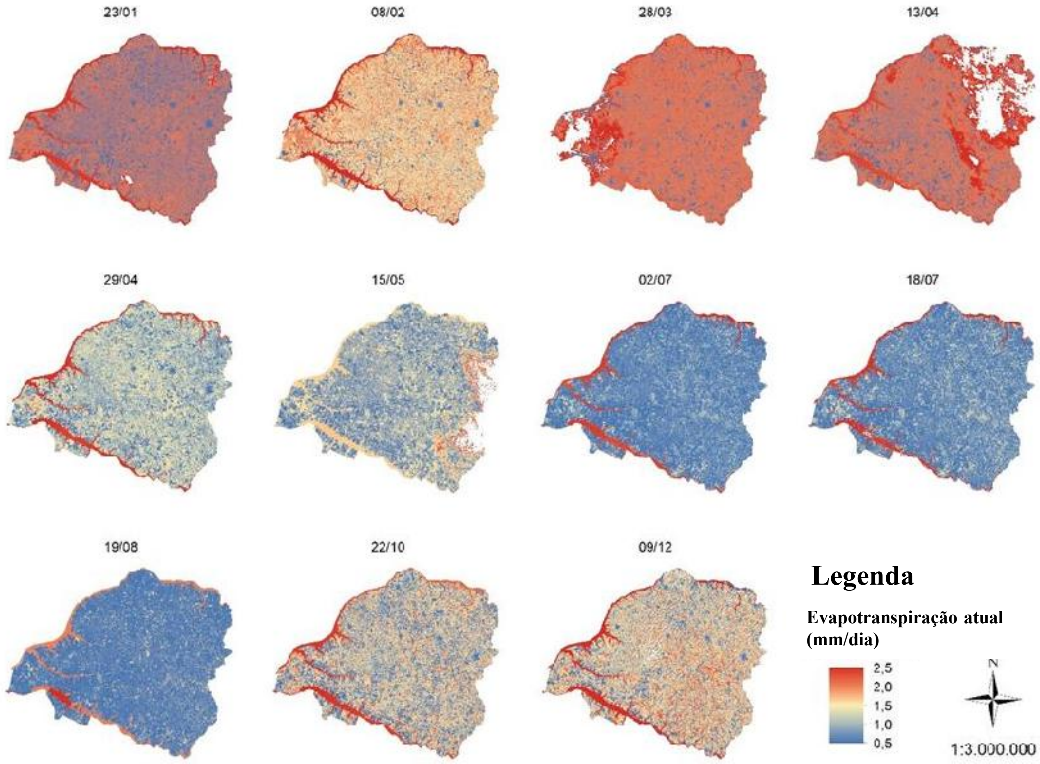


Figure 4. Spatial and temporal distributions of evapotranspiration (mm day $^{-1}$) in 2018.



The annual average values in 2010, 2017, and 2018 were 1.0, 1.2, and 1.2 mm day$^{-1,}$ respectively. Variations in evapotranspiration under regional conditions can vary due to changes in rainfall patterns throughout the year, both in terms of time and volume, changes in climate variables, changes in land use, and the adoption of irrigation systems as a factor in the sustainability of food production.

A better distribution of rainfall throughout the year in adequate volumes maintains soil water storage at levels suitable for increased crop evapotranspiration. Conversely, increases in climate variables, especially global radiation, temperature, and wind speed, increase reference evapotranspiration. This may or may not increase the actual evapotranspiration of an area of interest, depending on soil water storage, which can be guaranteed at adequate levels through the use of irrigation systems. Therefore, it is necessary to understand the reasons behind increased evapotranspiration in a region or area of interest, as this may compromise multiple uses or certain economic activities dependent on surface water resources.

Taking into account studies with specific crops in the region, Teixeira et al. (2014) reported that ETa values were higher than those reported in this work and were between 1.1 and 4.4 mm day $^{-1}$ during the production cycle of irrigated corn. For sugarcane, Oliveira et al. (2019) obtained ETa values of up to 3.5 mm day $^{-1}$ under irrigated conditions and a maximum of 2 mm day $^{-1}$ for rainfed crops, as these locations may experience a soil water deficit on the day of satellite passage, thus reflecting low evapotranspiration values.

Nevertheless, Franco et al. (2015) reported the spatial variability of ETa values in the same region with different land uses, where on the same day, the forest fragment (natural conditions) presented an ETa of 0.64 to 1.28 mm day $^{-1}$, crops under central pivots reached 3.83 mm day $^{-1}$, and on a day with precipitation that occurred a few days before, uniformity in ETa values was observed in the different types of soil cover analyzed.

Notably, in all the years analyzed, the lowest values were obtained between the months of July and October, the months that correspond to the greatest water deficit in the region (SILVA JUNIOR et al., 2018; OLIVEIRA; HERNANDEZ; TEIXEIRA, 2019). Araujo et al. (2017) presented minimum evapotranspiration values below 20 mm month-1 in the Cerrado for the dry period because its trees lose their leaves during this period to avoid excessive water loss.

The highest ETa averages in the region were observed during the rainy months, corroborating the findings of Coaguila et al. (2017), who reported that the temporal variability in ETa adjusts to the region's climatic seasonality, especially rainfall, reinforcing the strong relationship between soil water and evapotranspiration. In this study, the highest value was 2.2 mm day $^{-1}$ on April 23, 2010 (Figure 2), reflecting rainfall of approximately 50 mm days before the satellite's passage, followed by values of 1.8 mm day $^{-1}$ on February 21, 2017, March 9, 2017, and March 28, 2018. In this sense, the occurrence of incremental evapotranspiration due to large-scale land use change will depend on the relationship between crop changes and the total area of interest and how irrigated these new uses are.

According to Allen et al. (1998), current evapotranspiration can equal crop evapotranspiration, which by definition is the maximum ET potential for a crop, when there are good conditions in the field, that is, without excess or shortage of water and without the presence of pests and diseases. Therefore, the estimation of ETa through remote sensing techniques can be a good indicator of the quality of irrigation and phytosanitary management of a cultivated area.

Maps of the relationships between current evapotranspiration and reference evapotranspiration (ET/ET_0) are presented in Figures 5, 6 and 7. Spatially, the values varied between 0.2 and 1.0, with the highest average in the region being 0.7 on 05/28/2017, a month of adequate rainfall on a day when reference evapotranspiration was only 2.3 mm (Figure 6), a value below the common value for the month in Northwest São Paulo, which has an average of 3.9 mm day^{-1} (SILVA JUNIOR, 2017). Identifying crop evapotranspiration and relating it to reference evapotranspiration results in crop coefficient (Kc) values, which vary from 0.2 to 1.2 (ALLEN et al., 1998). However, under limiting field conditions, current evapotranspiration is lower than crop potential, reducing the values of current crop coefficients, that is, those that are actually recorded.

In the three years analyzed, the temporal variations in the ET/ET_0 ratio are similar, with the highest averages occurring in the first half of the year, when soil water storage occurs until March/April; thus, evapotranspiration is high. From April onward, when water deficits begin, reference evapotranspiration is lower, mainly because of the decrease in temperature between May and July, maintaining the regional average between 0.3 and 0.7 in these months. On the other hand, the lowest averages were observed in the last six months, which was the period with the greatest water deficit, and when ET_0 increased in the region. The ET_a estimated by SAFER did not increase in the same proportion, leaving ET/ET_0 values between 0.2 and 0.3.

The greatest difficulty when working with a model such as SAFER on a large scale is that the region has different crops and cultivations, such as irrigated and dryland, as well as areas with bare soil and virgin forest. Therefore, when extracting regional ET/ET_0 data, it is difficult to compare them to the standard values in the literature, described by Allen et al. (1998), since a value is determined for each crop and its different phenological phases.

Figure 5. Spatial and temporal distributions of the $ET/ET_{0\ ratio}$ in 2010.

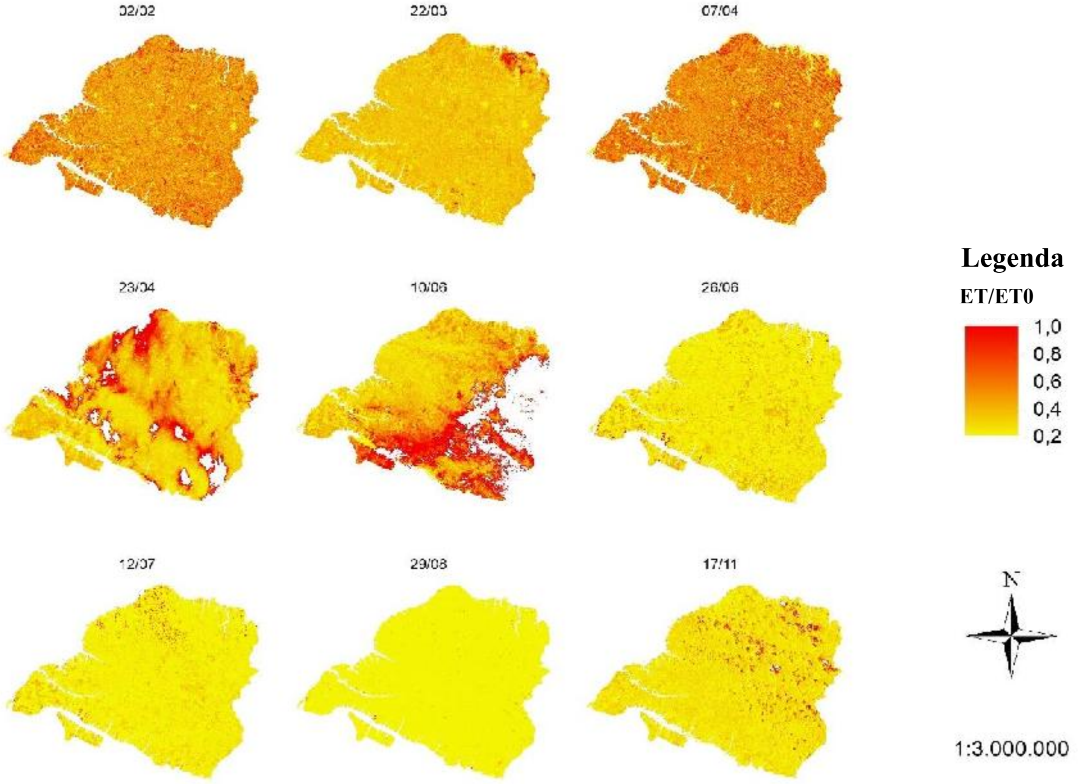


Figure 6. Spatial and temporal distributions of the $ET/ET_{0\ ratio}$ in 2017.

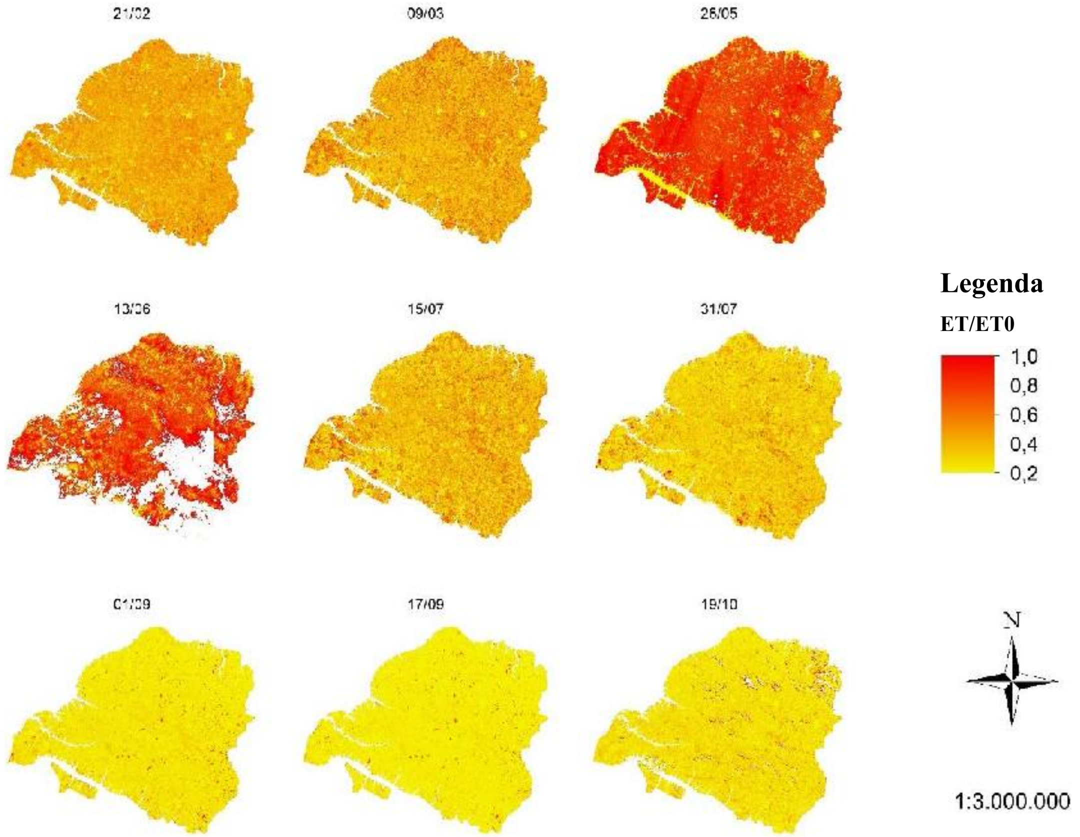
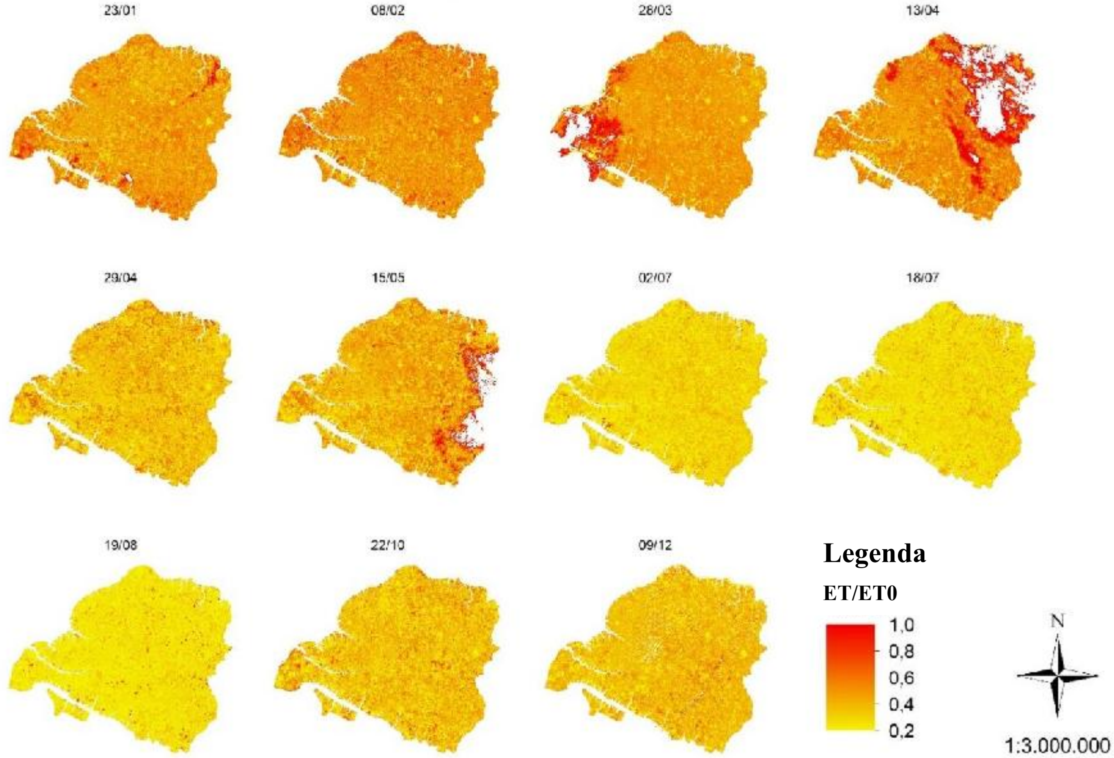


Figure 7. Spatial and temporal distributions of the $ET/ET_{0\ ratio}$ in 2018.



The $_{0}$ ratio values found in this study, in which most averages were 0.3, are considered low compared with those reported in the literature. The same was observed by Avilez (2018) and Oliveira et al. (2019) when determining the crop coefficient through SAFER in sugarcane and by Bispo, Hernandez, and Trinca (2019), where SAFER underestimates evapotranspiration values in corn. However, Sales et al. (2017) reported $ET/ET_{0\ values}$ close to those reported by Allen et al. (1998) for creeping tomatoes grown without water restriction in the state of Goiás.

The monthly rainfall distributions in the northwestern São Paulo region during the years studied are presented in Figures 8, 9, and 10. The total annual precipitation was 1,078 mm in 2010, 1,548 mm in 2017, and 1,120 mm in 2018. Considering that the eight-year average for the region was 1,243 mm, in 2010, only 86% of the expected rainfall fell, reaching 90% in 2018, which was 25% higher than the historical series in 2017. Despite the volume, the temporal variability of rainfall is significant in the region, with some months experiencing less than 40 mm of rainfall and others exceeding 300 mm. This volume accumulates in few but heavy rainfall events, making dryland agriculture a major challenge in Northwest São Paulo state since soil water storage from these heavy rainfall events is limited. The period of lowest rainfall, which begins in April/May and ends in October/November, results in eight months of water deficiency, a characteristic of the region reported in the works of Santos, Hernandez and Rossetti (2010) and Silva Junior et al. (2018).

Figure 8. Rainfall distribution in Northwest São Paulo in 2010.

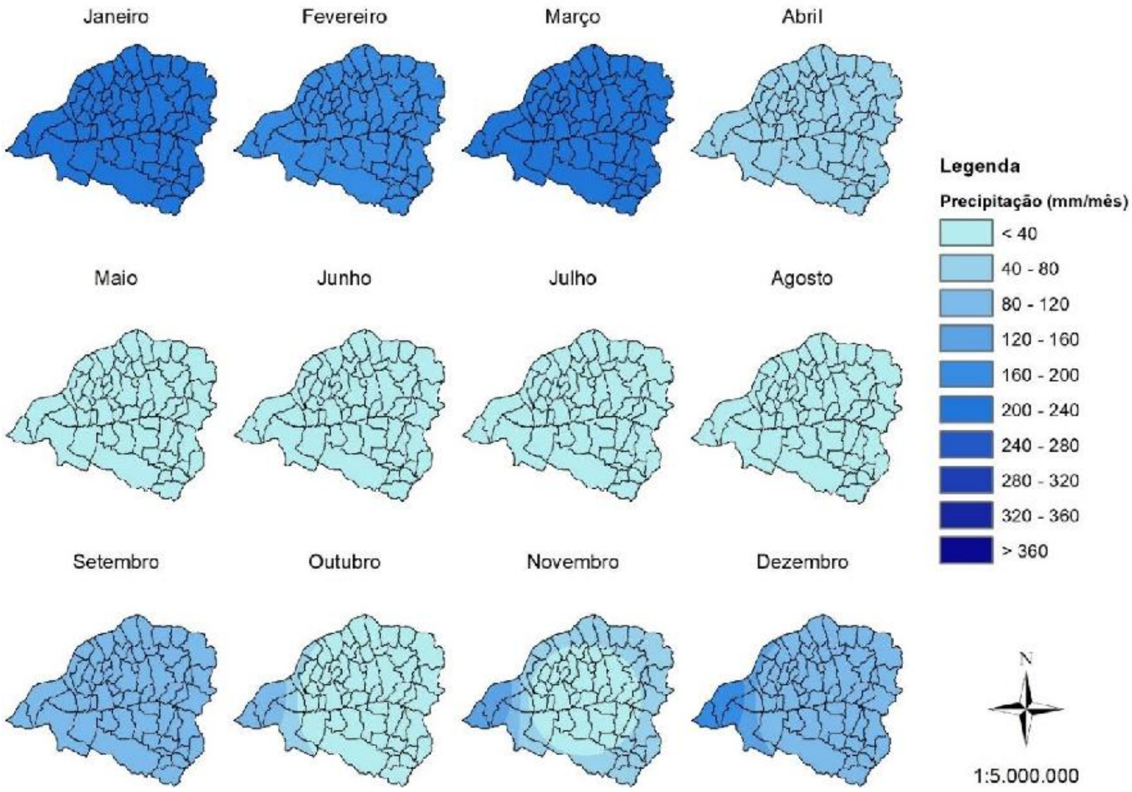


Figure 9. Rainfall distribution in Northwest São Paulo in 2017.

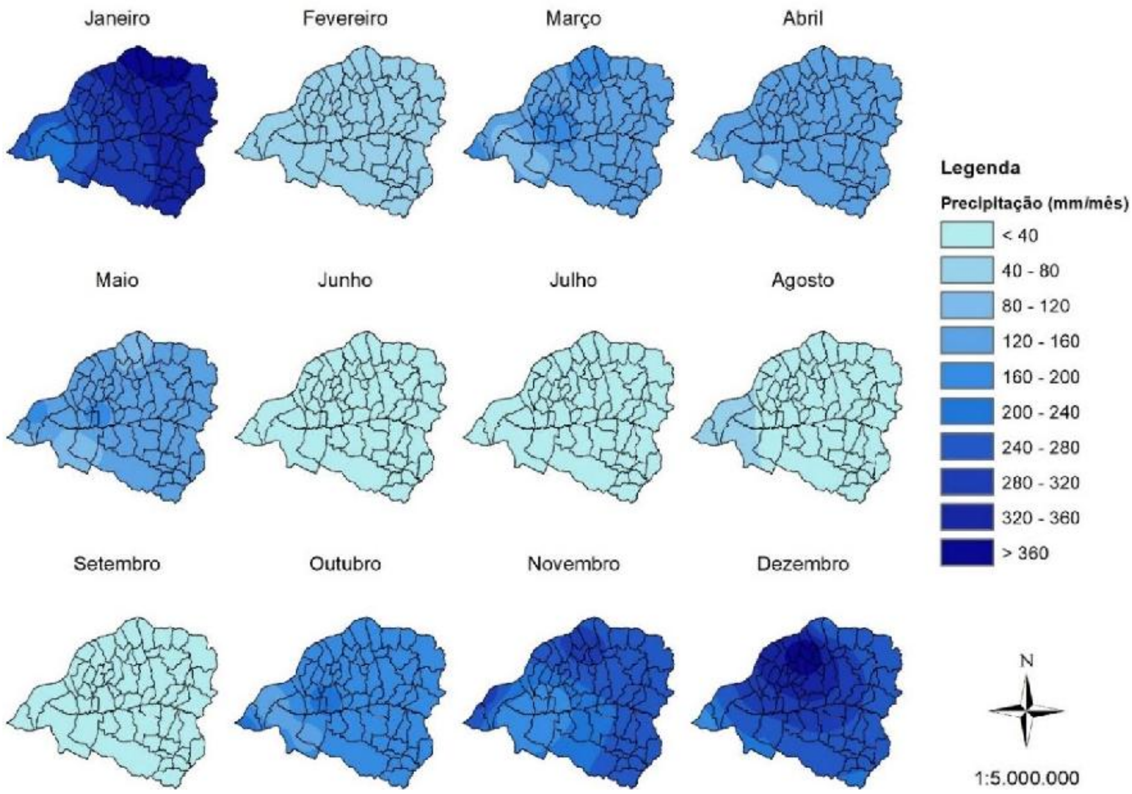
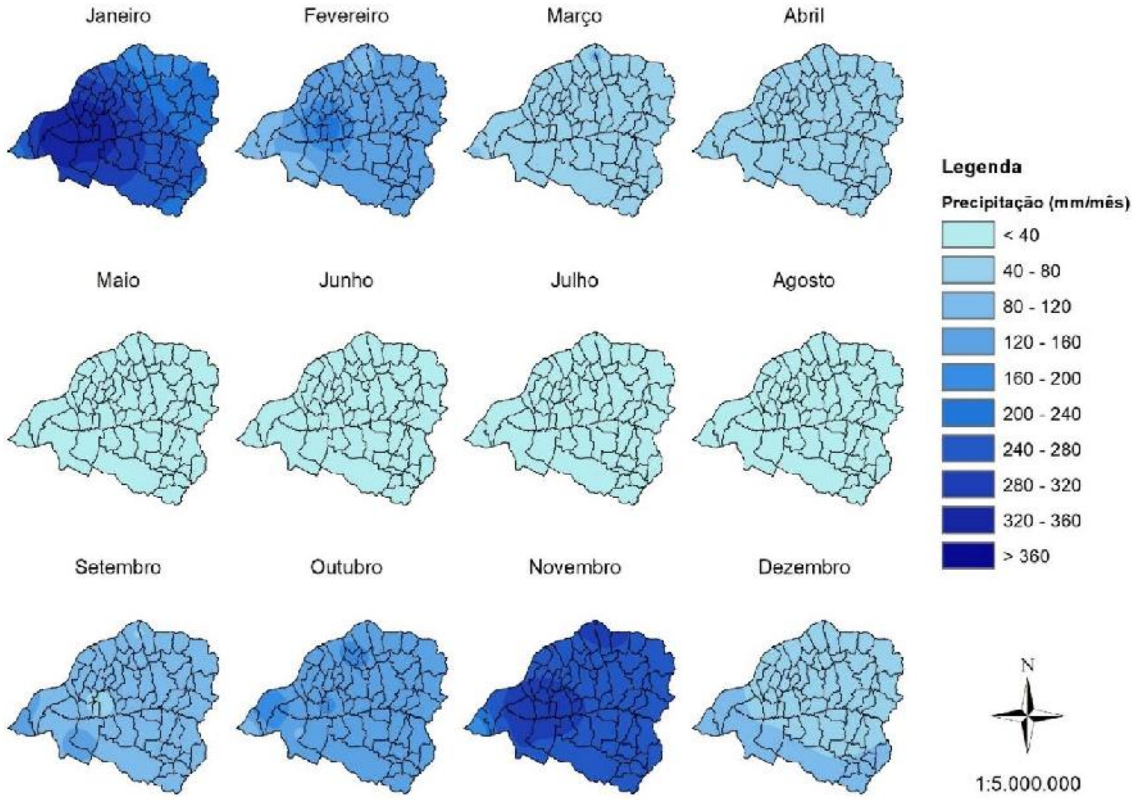


Figure 10. Rainfall distribution in Northwest São Paulo in 2018.



In January 2018, spatial variability in precipitation of up to 130 mm was also observed between locations. According to Oliveira, Hernandez, and Teixeira (2019), 2018 was a difficult year for agriculture in the region, as some locations went up to 166 days without rainfall greater than 10 mm, compromising dryland crops and increasing production costs for irrigated agriculture. However, investments in irrigation systems for water security are still relevant to guarantee crop productivity in northwestern São Paulo, as stated by Bispo, Hernandez, and Teixeira (2017) and Hernandez et al. (2003).

Cunha and Martins (2009) reported only four months of water deficit per year in two municipalities in the state of São Paulo (Botucatu and São Manuel) that have annual precipitation close to the values recorded in northwestern São Paulo, probably due to lower evapotranspiration rates and better rainfall distributions. The same was observed by Horikoshi and Fisch (2007), who reported an annual precipitation of 1,336 mm in the municipality of Taubaté, which was only 93 mm greater than the historical average for Northwest China, which presented four months of annual water deficit.

The reference evapotranspiration rates, which are dependent on meteorological variables, for the years studied are presented in Figures 11, 12 and 13. Notably, the highest ET_{0} values are between September and December, with locations recording monthly averages of up to 5.5 mm day^{-1}. The annual averages for 2010 (11), 2017 (12) and 2018 (13) were 4.2, 3.7 and 3.6 mm day^{-1}, respectively.

Figure 11. Distribution of reference evapotranspiration in northwestern São Paulo in 2010.

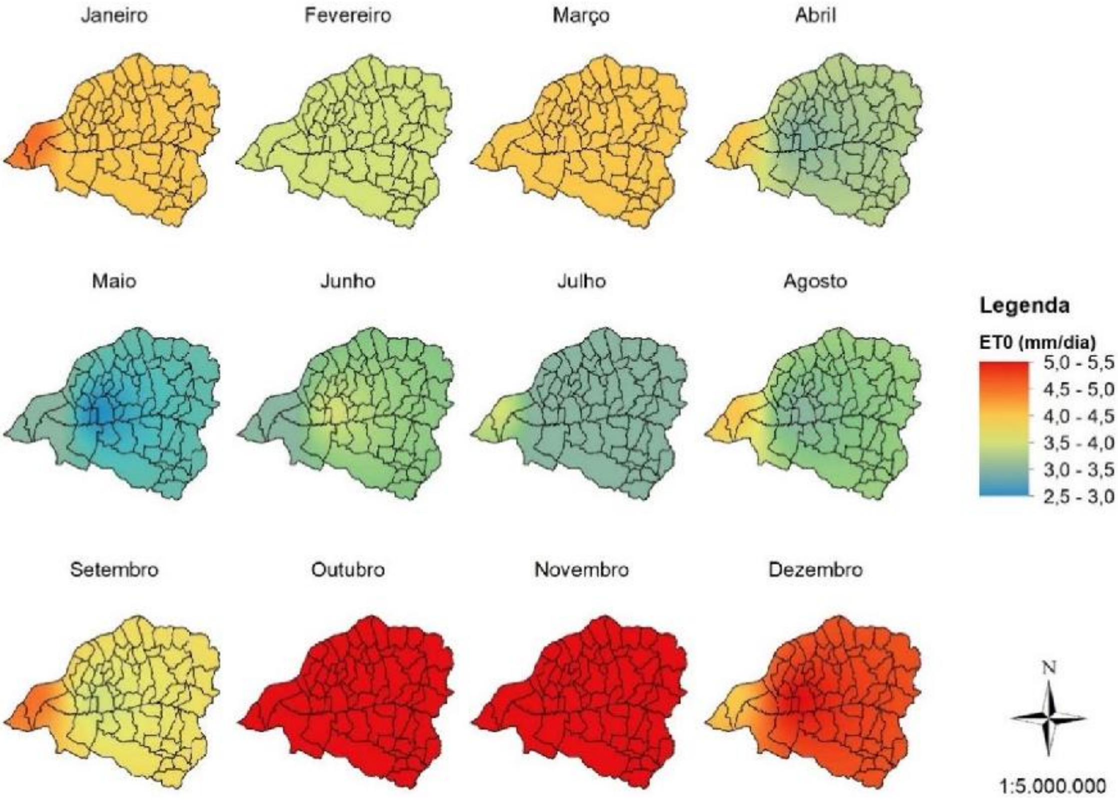


Figure 12. Distribution of reference evapotranspiration in northwestern São Paulo in 2017.

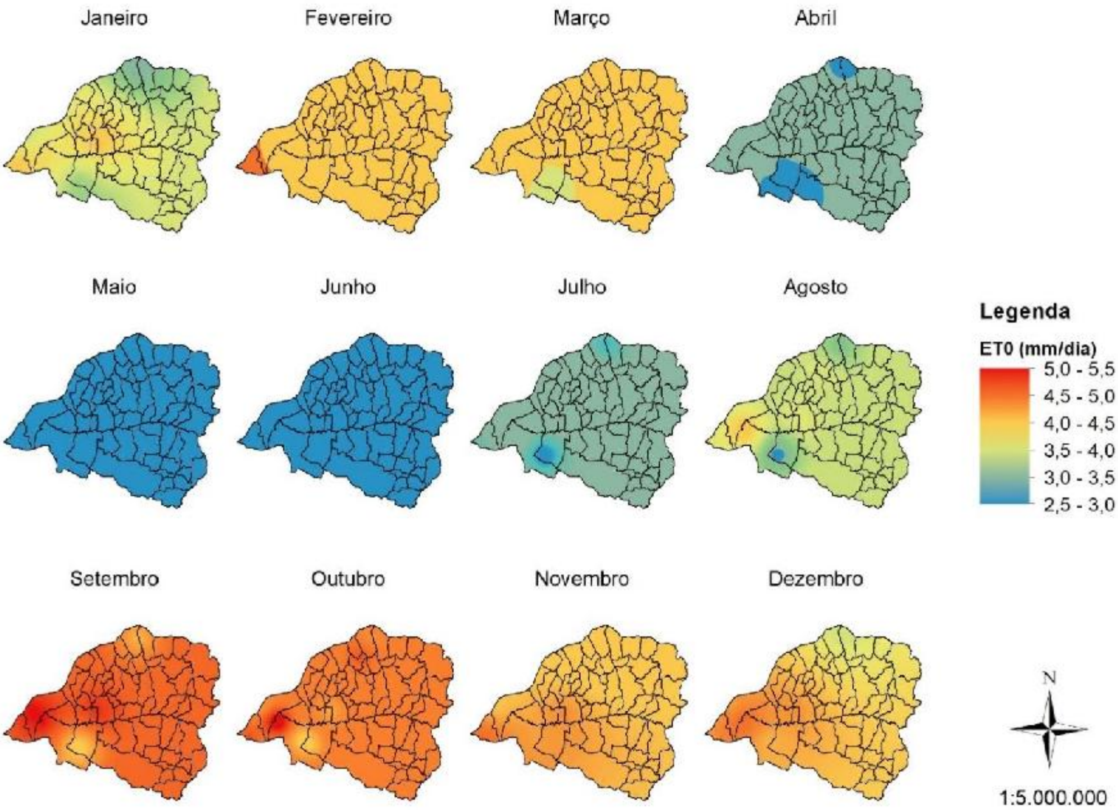
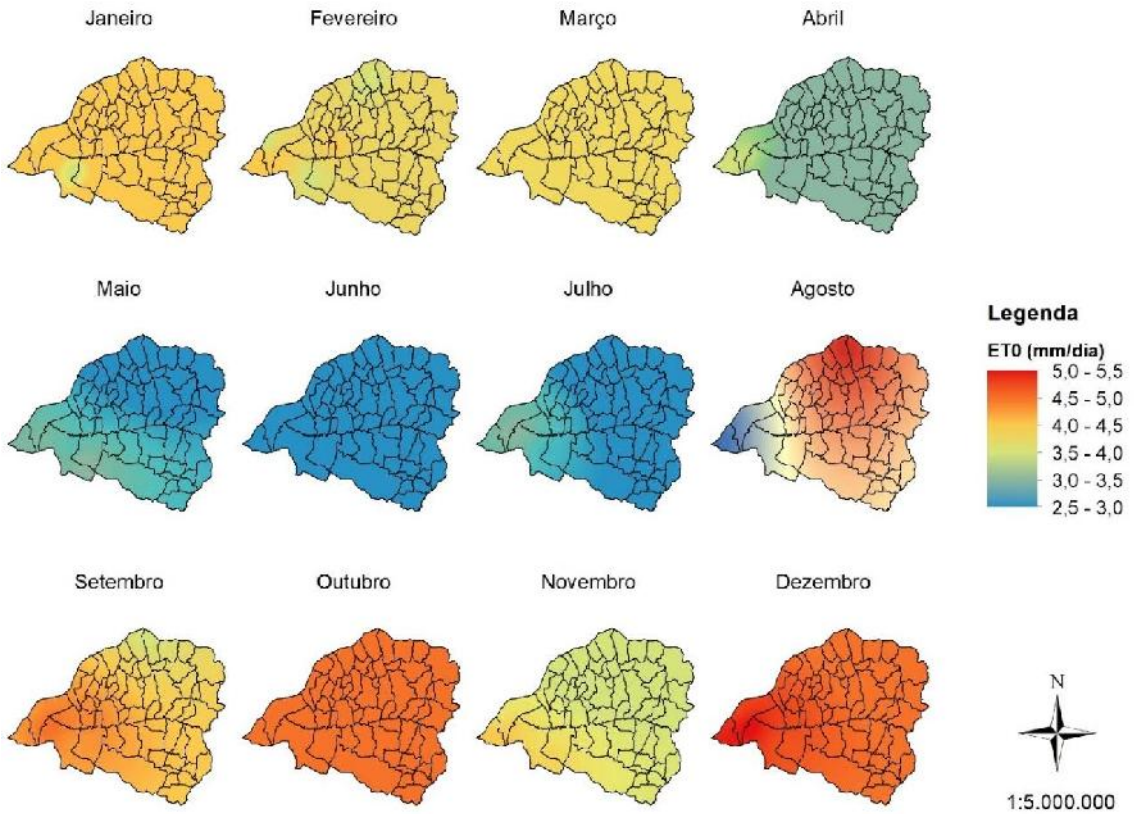


Figure 13. Distribution of reference evapotranspiration in northwestern São Paulo in 2018.



Although April to July have the lowest ET0 rates, they are also the driest months in the region. Considering that the lowest recorded value, 2.5 mm day $^{-1}$, results in 75 mm month $^{-1}$, this water loss is not replaced by rainfall, as precipitation does not exceed 40 mm in the region during this period. In terms of crop evapotranspiration, the amount of water lost to the atmosphere can be even greater, depending on the crop's phenological phase, as this ET0 value is still multiplied by a crop coefficient.

Although the stations of the Northwest São Paulo Agrometeorological Network are located only a few kilometers apart, the spatial variation in evapotranspiration rates is also high. In August 2018, a difference of up to 33 mm was observed between stations, which, in terms of irrigation management, represents the application of up to 330,000 liters of water more or less per hectare per month. This justifies the implementation and availability of data from agrometeorological stations to assist irrigators in promoting better use of water resources and ensuring crop productivity.

Data on current evapotranspiration, the ET/ET_0 ratio, rainfall, and reference evapotranspiration were compiled, and the results are shown in Figures 14, 15, and 16. Note that during the region's dry months, ETa and, consequently, ET/ET_0 values decrease and increase again with the arrival of rains. For the ET_0 rates, the variations in 2010 and 2018 were closer to historical values, although the values differed by up to 0.7 mm day $^{-1}$ from August onward. In 2017, the ET_0 values were lower than the historical values for only three months of the year. Although a dry season can be defined for a region, the volume of rainfall when it occurs is very unstable, changing its distribution each year and thus interfering with the estimate of current evapotranspiration.

The study region does not have a significant irrigated area, and the consequences of the period of up to 166 days without rain in 2018 included a decrease in the ET/ET_{0} ratio during this period. On the other hand, during the rainy season, the ratio presented higher values than those in the two other study years did, demonstrating the importance of rainfall distribution or the use of irrigation systems in ensuring water security for economic activity. The fact that the average ETa value does not exceed 2 mm day $^{-1}$ can be explained by the dynamics of land use and cover in Northwest São Paulo. The images analyzed revealed ETa values in central pivots that exceeded 2 mm day $^{-1}$, even in images from the region's dry season months. However, according to Oliveira (2020), the area irrigated by central pivots was only 17,135 hectares in the region, and considering the harvest and/or fallow periods in these areas, high ETa values were not sufficient to increase the regional average.

Andrade et al. (2016) obtained similar results when applying SAFER to estimate evapotranspiration in a river basin. While the average values of current evapotranspiration ranged from 0.6 to 2.4 mm day $^{-1}$, values above 3.5 mm day $^{-1}$ were found in irrigated areas, which was more than double the average value for the entire basin. Therefore, when working with a larger area, the ETa tends to be lower when most of the region does not have irrigated areas.

Figure 14. Agroclimatological indicators - Rain × ET/ET_{0}.

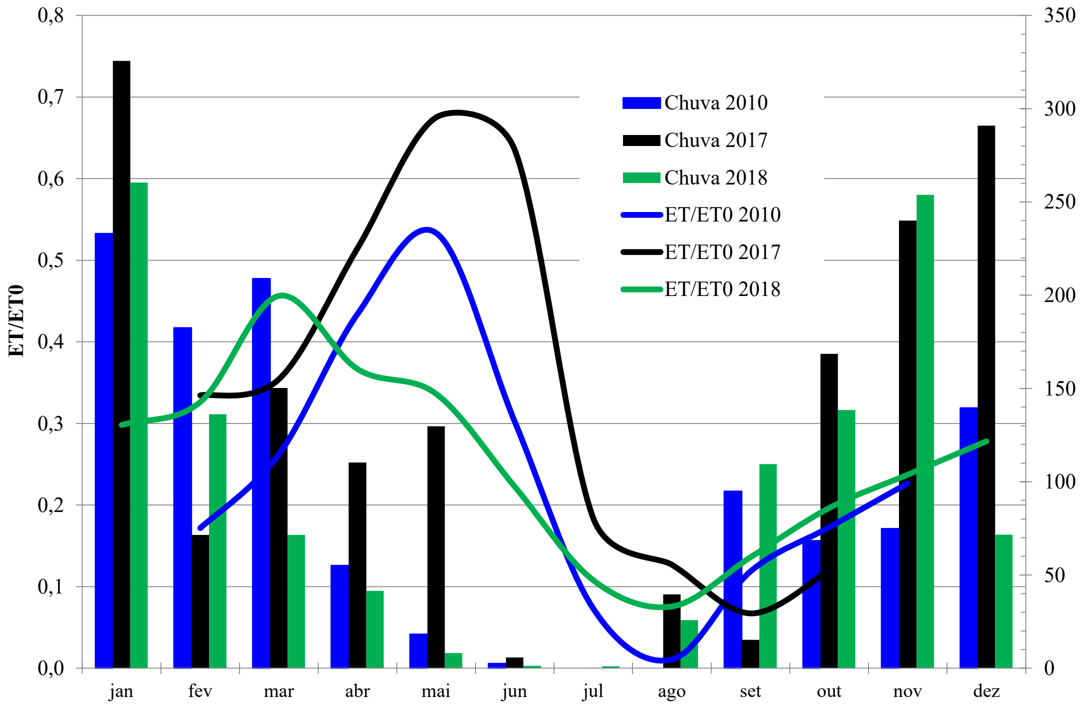


Figure 15. Agroclimatological indicators - Rain x ETa.

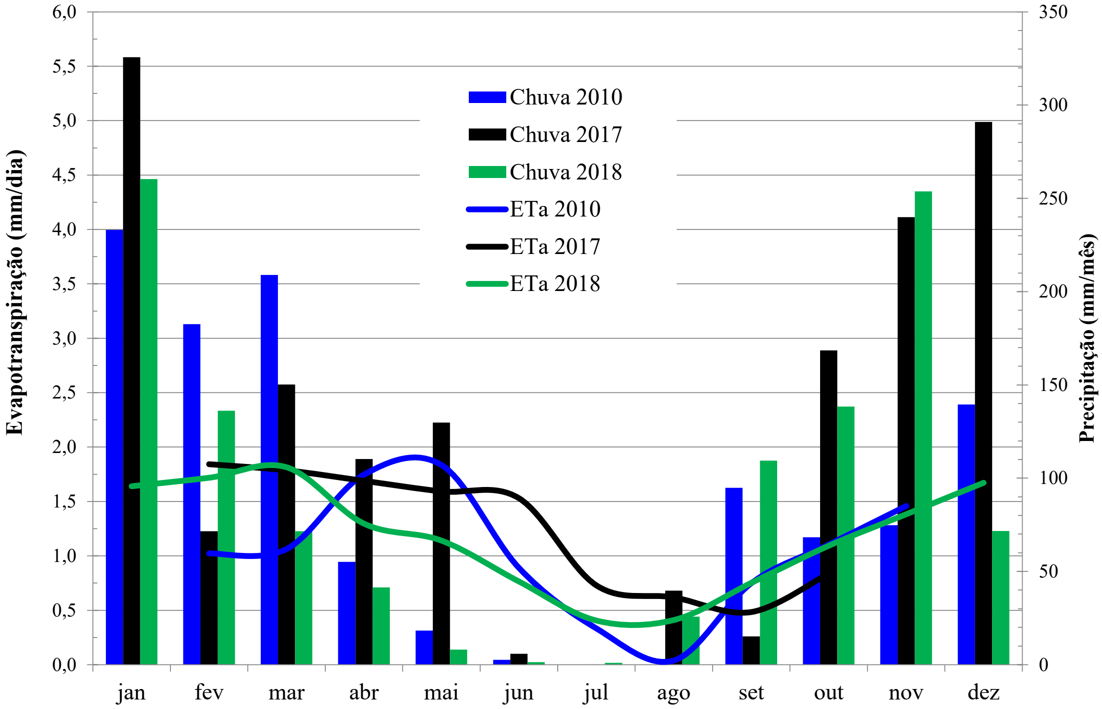
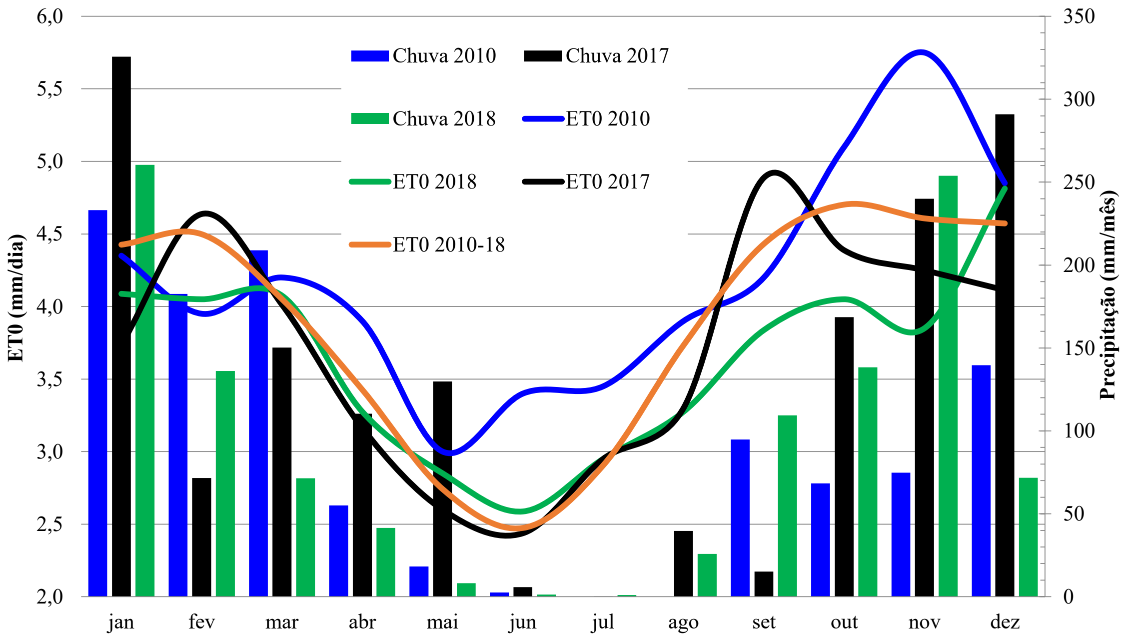


Figure 16. Agroclimatological indicators - Rain × ET $_0$.



Recently, the National Water Agency (ANA) published a study on evapotranspiration estimation by remote sensing in Brazil, in which the SSEBop model was used to estimate ETa in 1,275 central pivots, and demonstrated the ability to portray the spatiotemporal variability of evapotranspiration through estimation models applied to satellite images and thus identify trends in water consumption for irrigation and management variability in water use by irrigators (AGÊNCIA NACIONAL DE ÁGUAS, 2020).

Between 2010 and 2017, an increase in ETa of 0.4 to 0.8 mm day -1 was observed in the months of February, March, June, July, and August. In comparison, between 2010 and 2018, ETa also increased in February, March, July, and August to a lesser extent, but in April and May, the values obtained in 2010 were higher than those in more recent years. The average ETa of the years studied increased from 1.0 mm day $^{-1}$ in 2010 to 1.2 mm day $^{-1}$ in 2017 and 2018. This increase of 0.2 mm day $^{-1}$ characterizes possible incremental evapotranspiration in the region.

The years chosen for this study were very different from each other and atypical for the region in terms of precipitation, a phenomenon that directly impacts evapotranspiration. Therefore, more studies of this nature are needed in Northwest São Paulo to monitor agroclimatic indicators, although the difficulty of obtaining cloud-free images at the same time each year hinders studies on this topic.

The ratio remained at 0.3. The low ET/ET_0 ratios estimated by the SAFER algorithm can be explained by the need for further work to adjust and calibrate the a=1.0 coefficient used in the algorithm for different land uses. However, compared with the SEBAL model in the northwestern São Paulo region, SAFER shows better agreement with the reference crop coefficients (WARREN et al., 2014) and is sensitive to the variations observed between land use and land cover classes, making it a useful tool for analyzing agrometeorological indicators over time in the region.

6 CONCLUSIONS

The current evapotranspiration values differed spatially and temporally in northwestern São Paulo, with the highest values occurring in irrigated areas and during the rainy season. The average current evapotranspiration increased from 1.0 mm day $^{-1}$ in 2010 to 1.2 mm day $^{-1}$ in 2017 and remained at 1.2 mm day $^{-1}$ in 2018. This was due to the insignificant one-year land use change in the region and the fact that the irrigated areas were not very representative. This resulted in an incremental evapotranspiration of 0.2 mm day $^{-1}$ over the eight years considered in this study.

The SAFER algorithm has proven effective for estimating evapotranspiration at a regional scale and identifying changes in water transfer to the atmosphere over several months, and the methodology can be adopted for future work of the same nature, including work at the river basin level.

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