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ZONAS HOMOGÊNEAS DE EVAPOTRANSPIRAÇÃO DE REFERÊNCIA PARA O ESTADO DE MINAS GERAIS

FRANCIELE ALVES BARBOSA[1], PATRÍCIA DE OLIVEIRA E LUCAS[2], MARCELO ROSSI VICENTE[2], RONALDO MEDEIROS DOS SANTOS[2]

[1] *Departamento de Ciência da Computação, Universidade Federal de Minas Gerais. Av. Antônio Carlos 6627, 31270-901, Belo Horizonte, MG, Brasil. https://orcid.org/0009-0005-3964-7391, francieleab@ufmg.br*
[2] *Instituto Federal do Norte de Minas Gerais – Campus Salinas. Fazenda Varginha, Rodovia Salinas / Taiobeiras, Km 2, CEP 39560-000. Salinas, Minas Gerais, Brasil. https://orcid.org/0000-0002-7334-8863, patrícia.lucas@ifnmg.edu.br; https://orcid.org/0000-0003-2516-5656, marcelo.vicente@ifnmg.edu.br; https://orcid.org/0000-0003-1717-5467, ronaldo.medeiros@ifnmg.edu.br*

RESUMO: A determinação da quantidade de água necessária para as culturas é um dos principais fatores para o correto planejamento, dimensionamento e manejo de qualquer sistema de irrigação. Uma forma de estimar a quantidade de água requerida por uma cultura é através da evapotranspiração de referência ETo. Porém, quando dados climáticos em um local são insuficientes para estimar o valor da ETo, uma estimativa regional pode ser realizada a partir de valores médios de zonas homogêneas, sendo a análise de agrupamento uma forma de obter esses valores médios. Portanto, esse trabalho teve como objetivo a criação de zonas homogêneas de ETo através do agrupamento de séries temporais de ETo para o estado de Minas Gerais. Para isso, foram realizados experimentos para a escolha do algoritmo e do número de clusters que melhor se ajustasse ao problema. Para a avaliação do número de clusters, utilizou-se uma segunda base de dados normais climatológicas com 62 estações. A partir dos experimentos, foi possível concluir que o algoritmo K-means e o modelo com 10 clusters, mostraram ser uma melhor opção para o agrupamento de zonas homogêneas para todo o estado de Minas Gerais.

Palavras-chaves: K-means, Ward, clusters, irrigação.

REFERENCE EVAPOTRANSPIRATION ZONES FOR THE STATE OF MINAS GERAIS

ABSTRACT: Determining the amount of water needed for crops is among the main factors for the correct planning, sizing and management of any irrigation system. One way to estimate the amount of water required by a crop is through the ETo reference evapotranspiration. However, when climatic data in a location are insufficient to estimate the ETo value, a regional estimate can be made from the average values of homogeneous zones, with cluster analysis being a way to obtain these average values. Therefore, this work aimed to create homogeneous ETo zones by grouping ETo time series for the state of Minas Gerais. For this purpose, experiments were carried out to choose the algorithm and the number of clusters that best fit the problem. To assess the number of clusters, a second normal climatological database with 62 stations was used. From the experiments, it was possible to conclude that the K-means algorithm and the model with 10 clusters proved to be better options for grouping homogeneous zones for the entire state of Minas Gerais.

Keywords: K-means, Ward, clusters, irrigation.

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1 INTRODUCTION

Owing to low rainfall, high temperatures throughout the year, and low soil water storage capacity, some regions of Brazil suffer from water scarcity and consequently cannot meet the water needs of their crops; thus, they resort to irrigation.

Determining the amount of water needed for crops is among the main factors for the correct planning, sizing, and management of any irrigation system. One way to estimate the amount of water required by a crop is through reference evapotranspiration (ETo) and the crop coefficient (Kc) (Carvalho *et al.,* 2011).

Although ETo can be estimated from climate data, when data at a given location are insufficient for a reliable estimate, a regional estimate should be performed to obtain ETo at an unmeasured location. In this regional estimation process, locations should be assigned to homogeneous regions (Chen; Chang; Wu, 2013).

As presented by Bork (2018), one way to divide a study area into homogeneous regions is through cluster analysis of ETo time series. This analysis can be divided into hierarchical and nonhierarchical clustering, whose main purpose is to group objects according to their characteristics and on the basis of a similarity measure. Ward's hierarchical method and the nonhierarchical K-means method are simple and widely used for cluster analysis in climatological studies and yield satisfactory results (Araújo; Maia; Neves, 2015).

Ward's method is a hierarchical agglomerative procedure in which each data vector is a cluster in itself, and then these clusters are merged one by one until all the data vectors belong to a single cluster. The merging criterion in Ward's method is to minimize the sum of the squared deviations in a group of newly formed clusters (Pelczer *et al.,* 2007). K-means, on the other hand, is an iterative clustering algorithm that seeks to minimize the sum of intragroup distances, allocating observations to the nearest centroid and updating these centroids until the objective function converges (Jain, 2010).

The K-means method was used by Dourado, Oliveira, and Ávila (2013) to identify pluviometrically homogeneous zones in the state of Bahia and to analyze the climatic conditions of each zone between 1981 and 2010. The clustering coherently identified and delimited the five pluviometrically homogeneous regions of the state. Gomes, Blanco, and Pessoa (2018) used the fuzzy C-means method to identify homogeneous precipitation regions in the Tocantins-Araguaia Hydrographic Region. Three homogeneous precipitation regions were identified, and the results of the performance indices of the regional probability distribution models were satisfactory for estimating the average monthly and annual precipitation.

Santos and Souza (2012) used Ward's method to identify pluviometrically homogeneous precipitation regions in Northeast Brazil, enabling the identification of four homogeneous subregions (groups) in Northeast Brazil.

Araújo, Maia, and Neves (2015) compared the results obtained by the K-means and Ward methods in determining homogeneous areas in terms of the precipitation regime in the state of Rio Grande do Norte. They concluded that the state of Rio Grande do Norte can be characterized by four homogeneous regions. The results of the two methods were similar, with differences at only 5 stations, and both results can be used as clustering results. Pelczer *et al.* (2007) compared the results obtained from the K-means and Ward methods, with K-means proving to be the most appropriate option for obtaining homogeneous zones in the Sonora River Basin. According to Araújo, Maia, and Neves (2015), in the studies developed to define homogeneous regions, the use of various clustering analysis methods is indicated, opting for those whose results are most consistent with the phenomenon under study.

In this context, the main objective of this work is the creation of homogeneous ETo zones through the clustering of ETo time series for the state of Minas Gerais.

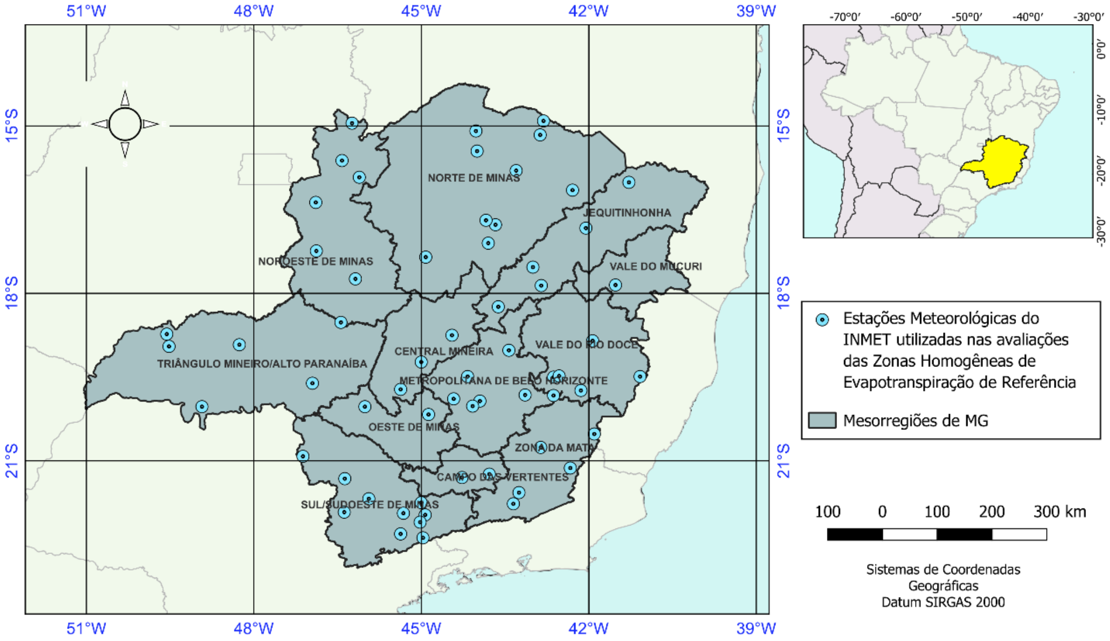
2 MATERIALS AND METHODS

For the execution of the work, two climate databases were used. The first was used to generate the clustering models, and the second was used to evaluate the best clustering model.

To generate the clustering models, a reference evapotranspiration (ETo) database provided by Xavier, King and Scanlon (2015) for the state of Minas Gerais was used, which was obtained by the inverse weighted distance interpolation method for 5285 points in a grid (0.5° × 0.5°). The period analyzed was 1980–2016, where the decision was made to work with the monthly averages of ETo for the period, i.e., with 12 values for each of the 5285 time series.

The second climate database was used to validate the number of clusters of homogeneous evapotranspiration zones. The Brazilian Climatological Normals database (INMET, 2018) from 62 stations covering the period from 1981 to 2010 was used (Figure 1). Using the meteorological variables (maximum and minimum temperatures, relative humidity, wind speed, and insolation), the monthly ETo was calculated using the FAO Penman–Monteith method (Allen *et al.,* 2006).

Figure 1. Map showing the locations of the 62 stations for evaluation.



To determine the number of clusters and the algorithm that best fits the problem, two experiments were conducted. In Experiment 1, the silhouette metric, proposed by Rousseeuw (1987), was used to choose the algorithm and define the number of clusters, as suggested by Faceli *et al.* (2011). The range of 3 to 15 clusters was tested for the K-means algorithm and for Ward's algorithm, choosing the one with the highest silhouette value. Because this is an unsupervised problem, there is no external element to guide the learning process; that is, the data are not labeled. Furthermore, according to Araújo, Maia, and Neves (2015), the use of several cluster analysis methods is recommended for those whose results are most consistent with the phenomenon under study.

Therefore, Experiment 2 was conducted to verify whether the best number of clusters was correctly chosen in Experiment 1. To do this, the 5 best models from the algorithm that obtained the best silhouette in Experiment 1 were selected, and the validation database was used to verify which of these groupings (number of clusters) presented the best ETo estimate using the cluster centroid as a label. The root mean square (RMSE) was used as the metric (Equation 1).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(yi - \widehat{yi})^2} \qquad (1)$$

where RMSE is the root mean square *within the cluster;* yi is the ETo of the stations used for validation, in mm day $^{-1;}$ and $\widehat{yi}$ is the ETo estimated by the clustering algorithm, in mm day $^{-1}$.

After the number of homogeneous zones was defined, different statistical indicators were used to correlate the monthly ETo values (mm day $^{-1}$) observed by the 62 conventional meteorological stations located within the area of interest with the average monthly ETo values (mm day $^{-1}$).

The indicators used to validate the homogeneous ETo zones were Pearson's correlation coefficient (r), the coefficient of determination (R^2), Willmott's (1981) concordance index (d) and the confidence index (c) proposed by Camargo and Sentelhas (1997), in addition to the RMSE.

The coefficient of determination (R^2) is used to assess the association between two factors through the proportion of variability in one variable and is expressed by Equation 2.

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \qquad (2)$$

where $\bar{Y}$ is the average ETo of the stations used for validation, in mm day $^{-1}$.

Pearson's correlation coefficient (r) ($r=\sqrt{R^2}$) was classified according to the methodology of Hopkins *et al.* (2009) (Table 1).

Table 1. Pearson correlation coefficient (r) and its respective classification.

Correlation coefficient Pearson's (r)	**Classification**
0.0 – 0.1	Very High
0.1 – 0.3	Low
0.3 – 0.5	Moderate
0.5 – 0.7	High
0.7 – 0.9	Very High
0.9 – 1.0	Almost Perfect

Source: Hopkins *et al.* (2009).

The agreement index (d) ranges from zero to one, where d = 1 for perfect agreement and d = 0 for no agreement. The value of d is determined by Equation 3:

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(|y_i-\bar{y}|+|\hat{y}_i-\bar{y}|)^2} \qquad (3)$$

The confidence index (c) was proposed by Camargo and Sentelhas (1997) because it allows for the joint analysis of the precision and accuracy of the results obtained through the product of the correlation coefficient (r) and the agreement index (d) (Castro *et al.,* 2010). The criteria for evaluating the performance of the models with respect to the confidence index are presented in Table 2.

Table 2. Analysis of model performance based on the confidence index.

Value of c	Performance
> 0.85	Excellent
0.76 to 0.85	Very good
0.66 to 0.75	Good
0.61 to 0.65	Median
0.51 to 0.60	Terrible
0.41 to 0.50	Bad
≤ 0.4	Terrible

Source: Camargo and Sentelhas (1997).

3 RESULTS AND DISCUSSION

In Experiment 1, the K-means algorithm presented, in most runs (3 to 15 clusters), silhouette values closer to 1 compared to the Ward algorithm, indicating that the samples are better grouped.

After the K-means algorithm was selected, Experiment 2 was conducted. The models with 10 and 11 clusters presented better results, with an average RMSE value of 0.26 mm d^{-1}. These results are similar to those of Silva Júnior, Hernandez and Silva (2017) and Santos *et al.* (2020). Although the 10- and 11-cluster models had the same average RMSE, the 10-cluster model was chosen, for simplicity, as the best grouping. From the choice of the 10-zone model, the average monthly and annual time series of each homogeneous zone were generated, as presented in Table 3.

Table 3. Average monthly and annual reference evapotranspiration (mmd $^{-1}$) of the homogeneous zones.

Zone	1	2	3	4	5	6	7	8	9	10
					ETo (mm d^{-1})					
Jan.	4.23	4.16	4.74	4.67	4.55	4.15	3.93	4.25	4.60	4.16
Feb.	4.50	4.38	5.05	4.86	4.84	4.38	4.09	4.35	4.78	4.4
Sea.	4.01	3.74	4.52	4.25	4.3	3.78	3.49	3.96	4.14	3.89
Apr.	3.77	3.2	4.23	3.61	3.95	3.38	2.98	3.68	3.43	3.58
May.	3.25	2.54	3.74	2.96	3.40	2.75	2.28	3.03	2.75	3.00
June.	3.01	2.25	3.5	2.63	3.14	2.47	2.00	2.82	2.41	2.75
July.	3.34	2.48	3.8	2.84	3.43	2.73	2.23	3.19	2.58	3.07
Aug.	4.13	3.14	4.64	3.51	4.24	3.45	2.87	4.07	3.19	3.87
Set.	4.74	3.65	5.35	4.22	4.95	3.99	3.32	4.56	3.72	4.43
Out.	4.82	4.04	5.49	4.63	5.13	4.33	3.76	4.80	4.15	4.64
Nov.	4.23	3.96	4.66	4.3	4.45	4.11	3.84	4.64	4.11	4.26
Ten.	4.03	3.96	4.47	4.39	4.28	3.98	3.82	4.36	4.27	4.05
Average	4.01	3.46	4.52	3.91	4.22	3.62	3.22	3.98	3.68	3.84

The data in Table 3 indicate that the highest ETo values occur between August and October, a period characterized by high solar radiation, low cloud cover, and low relative humidity. In several zones, such as zones 1, 3, and 5, the maximum values in this quarter exceed 4.5 mm d^{-1}, with Zone 3 standing out and reaching the highest observed value (5.49 mm d^{-1} in October). In contrast, the lowest ETo values are concentrated in autumn and winter, especially in higher altitude zones with milder climates, such as Zone 7, where the minimum indices vary between approximately 2.0 and 2.3 mm d^{-1}.

Zones 1, 3, and 5 have the highest annual averages (4.01 to 4.52 mm d^{-1}), indicating warmer environments with high radiation incidence. On the other hand, Zones

2, 6, and 7 present the lowest averages (3.22 to 3.62 mm d^{-1}), characteristic of regions with lower temperatures and higher altitudes. These results show that ETo in Minas Gerais is simultaneously influenced by climatic seasonality and regional geographic conditions, as observed by Martins *et al.* (2018).

Table 4 shows the validation indices for the homogeneous zones.

When the precision and accuracy of the results obtained through the confidence index (c) were analyzed together, the performance was considered very good and excellent, according to the criteria of Camargo and Sentelhas (1997). The results of the ETo estimates obtained by the K-means algorithm, on the basis of the indicators shown in Table 4, can be considered satisfactory.

Table 4. Indicators used for validation of homogeneous ETo zones.

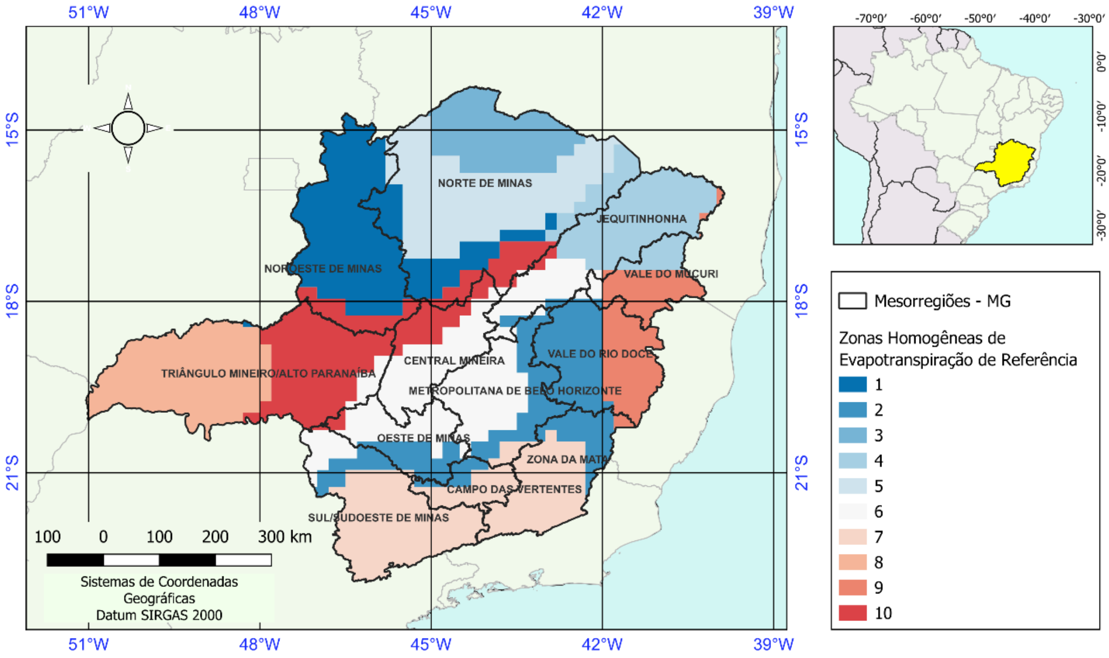
Zone	**Normal ETo (mm d^{-1})**	**ETo Z ona (mm d^{-1})**	**RMSE (mm d^{-1})**	**R²**	**d**	**r**	**w**	**Classification**
1	4.21	4.01	0.31	0.84	0.93	0.916	0.85	M. good
2	3.49	3.46	0.22	0.90	0.97	0.951	0.93	Excellent
3	4.58	4.52	0.31	0.77	0.93	0.875	0.81	M. good
4	3.89	3.91	0.21	0.93	0.98	0.965	0.94	Excellent
5	4.19	4.22	0.23	0.86	0.96	0.926	0.89	Excellent
6	3.76	3.63	0.36	0.77	0.92	0.878	0.81	M. good
7	3.48	3.22	0.37	0.88	0.94	0.936	0.88	Excellent
8	4.14	3.98	0.23	0.94	0.97	0.968	0.94	Excellent
9	3.69	3.68	0.18	0.95	0.99	0.975	0.96	Excellent
10	3.69	3.84	0.19	0.96	0.97	0.981	0.95	Excellent

Legend: M. good – Very good

The division of the state of Minas Gerais into 10 homogeneous reference evapotranspiration (ETo) zones is shown in Figure 2. Zone 1 included the northwestern mesoregion of Minas Gerais and the southern portion of northern Minas Gerais. These regions exhibit high evapotranspiration demands, especially from September to October (4.74 to 4.82 mm d^{-1}). This is related to the fact that they are areas of high temperatures and high solar radiation.

The north of the Minas mesoregion predominantly has Zones 3 and 5, with average ETo values of 4.52 and 4.22 mm d^{-1}, respectively. Similar results for ETo and spatial distribution were reported by Santos *et al.* (2020).

Figure 2. Homogeneous ETo Zones for the state of Minas Gerais.



The Jequitinhonha mesoregion predominantly comprises Zones 4 and 6, with average ETo values of 3.91 and 3.63mm d^{-1}, respectively. Notably, Zone 6 prevails in the higher altitude portion of the region, where temperatures are milder, consequently resulting in lower evapotranspiration demands. Zone 6 is also observed in a large area of the state, beginning in a small portion of the South/Southwest Minas Gerais mesoregion, passing through western Minas Gerais and covering the Central and Metropolitan mesoregions of Belo Horizonte, which are predominantly regions with altitudes above 800 m and mild temperatures. It is important to highlight that altitude is a significant element of climate control, since, in association with the characteristics of the relief, it directly influences air temperature and, consequently, evapotranspiration, as highlighted by Martins *et al.* (2018).

The Mucuri Valley mesoregion is mostly composed of Zone 9, with an average ETo of 3.68 mm d^{-1}, and Zone 4 on the border with the Jequitinhonha Valley. The maximum values of 4.60 and 4.78mm d^{-1}, which were found in Zone 9, were observed in January and February, respectively. These high demands, combined with dry spells, can lead to losses in agricultural production.

The Rio Doce Valley mesoregion is located in Zones 2 and 9, with the western portion of the mesoregion situated within Zone 2, with an average ETo value of 3.46 mm d $^{-1}$. Notably, this portion of the mesoregion is where the highest altitudes are found.

The Triângulo Mineiro/Alto Paranaíba mesoregion, which encompasses regions with strong agribusiness development, largely comprises Zones 8 and 10, with averages of 3.98 and 3.84mm d $^{-1}$, respectively. Both homogeneous zones have the highest rainfall demands in October, with 4.80 and 4.64mm d $^{-1}$ for Zones 8 and 10, respectively.

The mesoregions Zona da Mata, Sul/Sudoeste de Minas and Campo das Vertentes predominantly have Zone 7, which has the lowest average ETo observed (3.22 mm d $^{-1}$), as also observed by Lemos Filho *et al.* (2010), who correlated the lower ETo values with a lower incidence of solar radiation.

4 CONCLUSIONS

It was concluded that, for the grouping of reference evapotranspiration time series, the K-means method performed better than the other methods did, resulting in the definition of 10 homogeneous zones for the state of Minas Gerais.

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