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Relação entre o regime hidrológico e uso e cobertura do solo da Bacia Hidrográfica do Rio das Mortes

Relationship between the hydrological regime and the land use and cover of the Rio das Mortes Basin

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ABSTRACT: Interactions between land use and cover and a basin hydrological regime are complex and dynamics. The identification of trends and changes in rainfall and flow regimes in a region is relevant in water resources planning and management so that environmental, economic and social adversities are avoided. Thus, this study aims to identify possible trends in the historical series of rainfall and fluviometric stations in Rio das Mortes basin, Minas Gerais, Brazil, as well as to relate the modifications in the flow rate behaviour due to changes in land use and cover in the basin between the years of 1985 and 2017. For that, hydrological data were used from the Ibituruna-MG river station and 12 rainfall stations and orbital images from Landsat-5 and Sentinel satellites. Flow rate and precipitation behavior were performed using the nonparametric Mann-Kendall test and the Pettitt's test, while the land use and cover classification was performed in an eCognition Developer® 64 environment. Significant trends were observed in the average of total annual rainfall series and decreasing trends in the average of monthly flow rate series of lowest runoff over the years 1925 to 2014. There were changes in land use and cover in the studied region, however, these were not significant enough to modify the hydrological regime of Rio das Mortes basin during the analysed period.

KEYWORDS: Mann-Kendall test; Streamflow characterization; Rainfall characterization; Classification of satellite images.

RESUMO: As interações entre uso e cobertura do solo e o regime hidrológico de uma bacia hidrográfica são complexas e dinâmicas. A identificação de tendências e mudanças nos regimes de chuva e vazão de uma região é de suma relevância no planejamento e gestão dos recursos hídricos para que adversidades ambientais, econômicas e sociais sejam evitadas. Sendo assim, o objetivo desse trabalho foi identificar possíveis tendências nas séries históricas de estações pluviométricas e fluviométricas da bacia hidrográfica do Rio das Mortes, Minas Gerais, bem como relacionar as eventuais alterações no comportamento da vazão devido às mudanças no uso e cobertura do solo na bacia entre os anos de 1985 e 2017. Para isso, foram utilizados os dados da estação fluvial de Ibituruna-MG e de 12 estações pluviométricas, além de imagens orbitais dos satélites Landsat-5 e Sentinel. As análises do comportamento da vazão e precipitação foram realizadas por meio do teste não paramétrico de Mann-Kendall e de Pettitt, já a classificação de uso e cobertura do solo foi realizada no software eCognition Developer® 64. Observou-se tendências significativas na média das séries totais anuais de precipitação e tendências decrescentes na média das séries mensais de menor vazão ao longo dos anos de 1925 a 2014. Houve alterações no uso e ocupação do solo na região estudada, no entanto, estas não foram significativas a ponto de modificar o regime hidrológico da bacia do Rio das Mortes durante o período analisado.

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PALAVRAS-CHAVE: Teste de Mann-Kendall; Caracterização da vazão; Caracterização da precipitação; Classificação de imagens de satélite.

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INTRODUCTION

The complex interaction between region climate, vegetation cover, soil type and basin relief reflects directly in the basin hydrological regime (Oliveira *et al.*, 2018). Therefore, studying the hydrological components influence on rainfall and streamflow regime, especially under extreme conditions, is important to estimate possible future changes in the hydrological regime, in order to assist in water resources planning and proper management (DI Baldassarre *et al*., 2017; Kibria *et al.*, 2016; Unisdr, 2017; Winsemius *et al*., 2016).

Changes in land use and cover have been considered to be the main causes of changes in the basin flow rate regime, as well as in climate and rainfall variations (Kliment *et al.*, 2011). The types of land use and soil surface cover impact surface runoff, underground recharge, soil moisture, soil loss by erosion, sediment transport, and the basin peak flow rate (PERAZZOLI; Pinheiro; Kaufmann, 2013). In addition, the removal of the original vegetation cover from the soil in a basin reduces surface roughness, increases surface runoff and consequently soil erosion, and decreases water infiltration on the surface, which results in lower aquifer recharge (Cawson *et al*., 2012; Baker; Miller, 2013).

Thus, the detection of changes on soil surface through remote sensing images can help to relate these changes to the basin hydrological regime. The monitoring of changes in land use and cover is widely recognized by the international scientific community as a key element in global changes studies (Smith *et al.,* 2014).

The Rio das Mortes basin has great importance in terms of water availability and environmental preservation in the area where it is located, because the region is prone to gully erosion. According to Ferreira and Ferreira (2009), the central portion of this basin has undergone changes due to anthropogenic activities, which affects areas with soils and relief that favour erosion processes. These activities impact the hydrosedimentological dynamics, affecting the hydrological cycle and aquatic biodiversity. This region erosive processes are mainly resulted by inadequate agricultural practices, the back roads opening, and the mineral resources exploitation, among others, which contribute to the water resources degradation by transporting sediments to the water sources (IGAM, 2014). Notably, in the cities, the watercourses margins, such as Barbacena, Dores de Campo, and Carandaí, suffered an accelerated springs degradation, mainly by the riparian protection total removal and the waste and garbage disposal, which changed the regional water body (IGAM, 2014).

Given the above, this study aimed to characterize the streamflow and rainfall regime of the Rio das Mortes Basin, Minas Gerais, Brazil, by identifying possible trends in the hydrological series through nonparametric tests. In addition, we sought to quantify the areas that underwent land use and cover changes in the basin from 1985 to 2017 and to associate them with the basin runoff flow rate behaviour.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The Rio das Mortes basin, located in Campos das Vertentes region in Minas Gerais, Brazil, has a drainage area of 6,050 km² and encompasses (totally or partially) 23 municipalities with an estimated population of 522,135 inhabitants (ANA, 2017). The basin climate is classified as Cwb according to the Köppen classification, i.e., subtropical highland with dry winter and mild summer. The rainiest months coincide with the spring/summer seasons between September and March, while the drought months coincide with the fall/winter seasons between April and September. The rainfall indices vary from 1,000 mm to 1,500 mm per year, and the highest indices occur in the highest basin regions and the lowest indices occur in the river valleys regions (IGAM, 2014).

This watershed is part of Grande River Water Resources Planning and Management Unit (UPGRH-GD2, for its acronym in Portuguese), which includes the Rio das Mortes, Jacaré River, and Cervo River Basins (IGAM, 2014). Moreover, the Rio das Mortes is one of the main Grande River tributaries; its source is located between the boundaries of Barbacena and Senhora dos Remédios cities, on Serra da Mantiqueira slopes at 1,200 m altitude and it travels 250 km until flowing into Funil hydroelectric plant reservoir (UHE FUNIL, for its acronym in Portuguese), located on the Grande River within the Ibituruna- MG city limits (Minas Gerais, 2010).

The basin relief is classified as wavy to smooth-wavy, with a predominance of Cambisols in the headwater region and Latosols in the regions where the relief is smoother. As the Rio das Mortes is moving towards its mouth in the Grande River, dystrophic red-yellow latosol soils appear more frequently (Amâncio *et al.*, 2018). The main basin land uses are related to agriculture, for example, irrigated crops and livestock, and are associated with inadequate management, and gullies and localized erosion processes occur (IGAM, 2014). Significant mineral extraction activities are also found within the basin (Minas Gerais, 2010). Figure 1 shows a map of the Rio das Mortes basin, the soil (IBGE, 2001), and vegetation (IBGE, 1992) and highlights the municipalities within its drainage area (ANA, 2017).

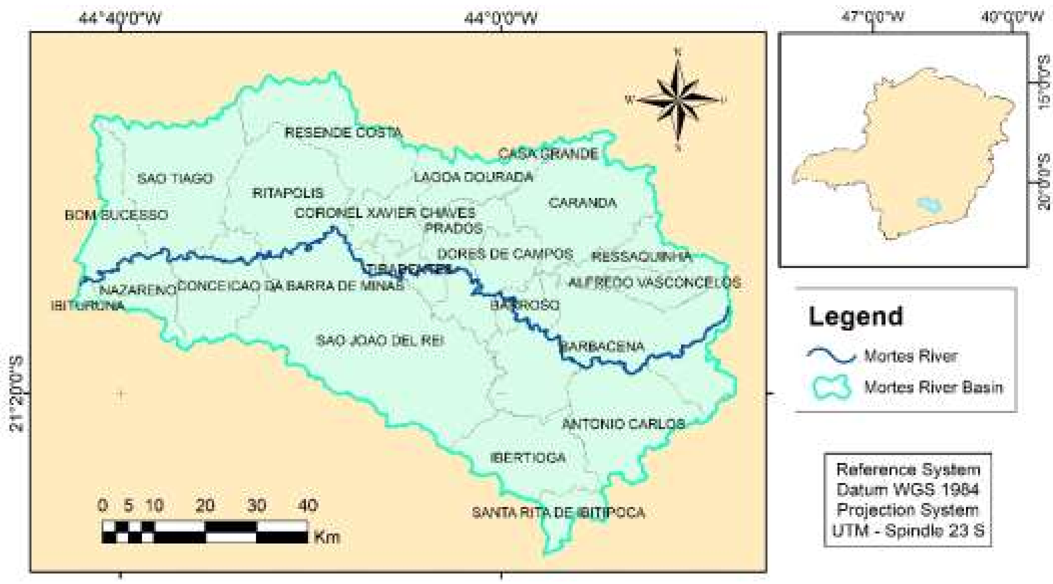

Figure 1. Mortes River basin.

2.2 RAINFALL CHARACTERIZATION

The rainfall data used in this study were extracted from the HidroWeb hydrological information system of the National Water Agency (ANA, for its acronym in Portuguese). The analysed stations were selected based on the spatial distribution criterion of the stations located inside and around the basin, which had historical series with at least 49 years of observation. In total, were used 12 rainfall stations being them: Madre de Deus de Minas, code 2144007; Conceição do Ibitipoca, code 2143011; Oliveira, code 2044001; Itumirim, code 2144005; Vargem do Engenho, code 2143007; Fazenda Campo Grande, code 2044009; Carandaí, code 2043018; Barroso, code 2143006; Usina Barbacena, code 2143009; Campolide, code 2143005; Porto do Elvas, code 2144009 and Porto Tiradentes, code 2144002 (Figure 2).

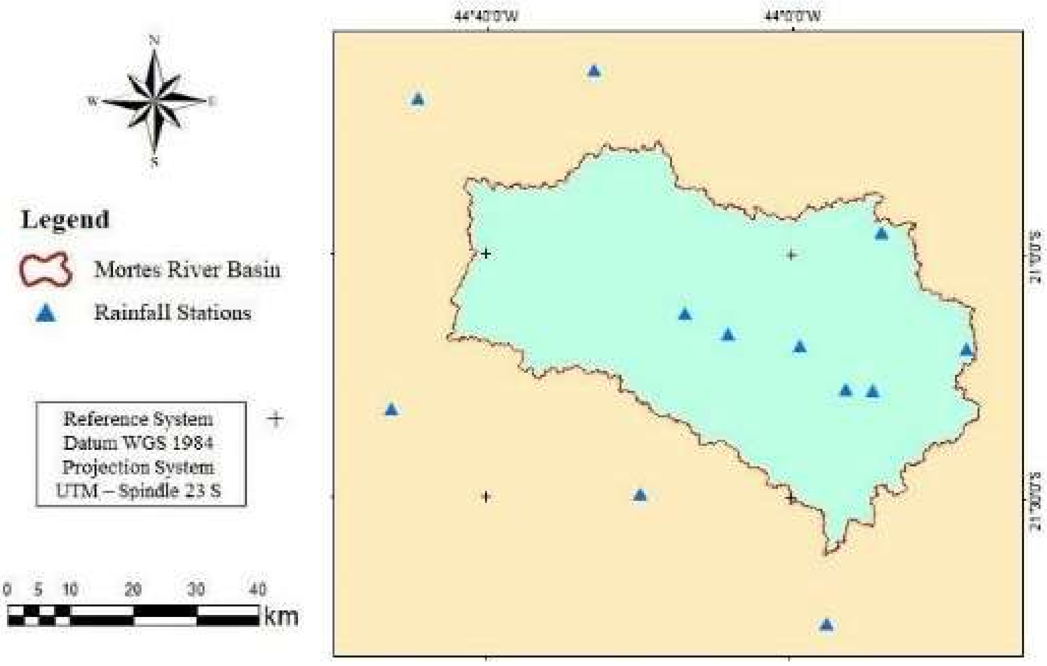

Figure 2. Location of the 12 rainfall stations.

The average monthly rainfall series gaps were filled using the inverse square distance (ISD) method based on the information collected in the neighbouring rainfall stations from 1941 to 2016, totalling a 76 years series.

A spatial distribution map of Rio das Mortes basin average annual rainfall was produced using rainfall data interpolated by the ISD by assuming that each value decreases with the distance from its location and using a weighted linear combination of the sampled points.

2.3 STREAMFLOW CHARACTERIZATION

For the flowrate analysis, the streamflow series from the river station located at the Rio das Mortes mouth in Ibituruna, MG, (code 61135000) were obtained from the HidroWeb system. The flow rate data processing was performed in the Computational System for Hydrological Analysis - SisCAH version 1.0, a software developed by the Water Resources Research Engineering Group of the Viçosa Federal University Agricultural Department (Souza *et al.,* 2009).

Were analysed the maximum and minimum annual flows associated with the return periods of 5, 10, 25, 50 and 100 years, the monthly and long-term average flows, the lowest average flow rates over a period of seven consecutive days with an average recurrence interval of 10 years (Q7,10), the series of average flow rates of the flood and drought periods, and the average flow rates of the highest and lowest monthly volume. To estimate the flows for different return periods, it was necessary to adjust the parameters of the probability distributions. In this sense, the probability distributions of Gumbel, LogNormal type 2 and 3, Pearson type 3, LogPearson type 3 and Weibull were implemented in SisCAH (Souza *et al.,* 2009).

2.4 RAINFALL AND FLOW RATE TREND ANALYSIS

The flow rate and rainfall behaviour trend analysis was performed using the nonparametric Mann-Kendall sequential test, a methodology that has been widely used in hydrological studies to evaluate the significance of temporal trends of variables such as rainfall, flow rate, temperature and water quality (Andrade *et al.,* 2019). On this purpose, the historical flow rate and rainfall series were analyzed by applying the Mann-Kendall test with a significance level of 5% using the Nonparametric Trend Tests and Change-Point Detection package in R software (R Core Team, 2018).

In addition, for the flow rate series, the Pettitt test was applied (Pettitt, 1979; Moraes *et al.,* 1995), which identifies the point where there is a significant sudden change in a time series average. The Pettitt test was analysed at a 95% reliability level using R (R Core Team, 2018) and GRETL (Mixon Junior, 2009) software.

2.5 TEMPORAL ANALYSIS OF LAND USE AND COVER

Changes in land use and cover were identify through the analysis of satellite imagens from de years 1985 and 2017, that were acquired, respectively, by Landsat 5 and Sentinel satellites. The images were segmented using the multiresolution segmentation algorithm available in the eCognition Developer® 64 software (Trimble Geospatial, 2009) The ideal segmentation parameters vary according to the region based on the scale, shape, and compactness parameters. If the study area is heterogeneous and highly fragmented, the scale values should be lower so that each object formed contains only the same class pixels (Silva, 2012). The images were segmented with different scale parameters (ranging from 100 to 1000). Some segmentation parameters, such as the objects compactness and shape, were tested and analyzed at various scales, and the bands were equally represented by a weight of 1.0.

Subsequently, the subset procedure was performed. From the image mosaic, the land use and cover and the spatial distribution within the study area were identified. For the classification, objects were collected in the images to obtain representative samples of the land use and cover main types. This procedure allowed the definition of the interest following classes: water, native vegetation, cultivation area, pasture, planted forest, exposed soil, and other uses. The water class included rivers, lakes, and dams; the cultivation area class included areas modified for planting by crops different types; the exposed soil class encompassed vegetation cover areas devoid, as they deal with annual crops areas or those in degradation or erosion process, degraded pastures, and plowed land; and the other uses class included urban agglomerates and ore extraction areas.

From the previously defined training samples, the soil cover classification was performed using the support vector machine (SVM) machine learning algorithm. The classifications then went through a visual interpretation stage. The different types areas of land use were exported to the ArcGIS environment, and the differences between the areas between 1985 and 2017 were recorded.

3 RESULTS AND DISCUSSION

3.1 CHANGES IN LAND USE AND COVER IN RIO DAS MORTES BASIN

The Figure 3 shows the land use and cover mapping allowed the temporal dynamics identification and analysis of anthropic actions and natural landscape modifications in the Rio das Mortes basin through the 7 classes definition of water land use, native vegetation, cultivation area, pasture, planted forest, exposed soil, and other uses.

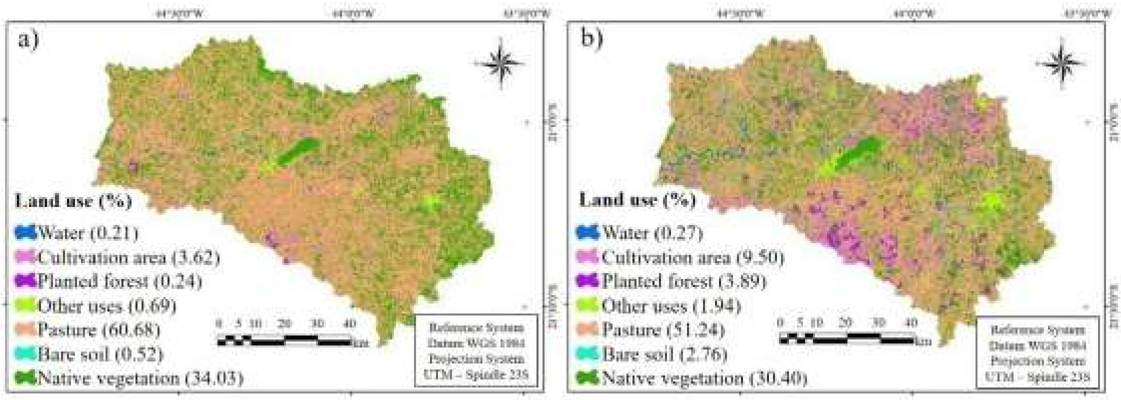

Figure 3. Rio das Mortes basin map of land use and cover in 1985 (a) and 2017 (b).

As can be seen in Figure 3, there was an increase in cultivation areas, planted forest, bare soil, other uses, and water and a decrease in the areas of native vegetation and pasture. In 1985, areas of anthropic use represented 66% of the basin use and coverage and occupied an area of 4,211.11 km² in 2017, which corresponded to 70% of the total area. Planted forest areas grew significantly between 1985 and 2017, with an increase of 220 km² from 1985 (14 km²) to 2017 (235 km²). According to data from IGAM (2014), the planted forest areas increased 53% between 2008 and 2011 and occupied a territory from 114.17 km² to 245.81 km² throughout the GD2 basin.

The total cultivation area grew the most within the Rio das Mortes basin, increasing from 218 km² in 1985 to 574 km² in 2017. There was also an increase in Rio das Mortes basin bare soil area –the bare soil area was 31 km² in 1985 and increased to 166 km² by 2017. In a study by Amâncio *et al*. (2018), in which water quality and sediment discharge in the Rio das Mortes basin (GD2) were analysed, the water quality index was classified as poor due to the high organic and inorganic matter levels associated with inadequate soil management, such as degraded pastures and contact of cattle with the effluent margins, which caused what the author classified as clear silting, related to the type of soil in the basin.

More than half of the Rio das Mortes basin territory was occupied by pastures in 1985 (60.68%) which gave way to the growth of other uses, such as the cultivation areas expansion, planted forests, ore extraction, and city growth, dropping to 51% of the total area in 2017. The native vegetation basin area also decreased from 1985 to 2017, especially in the Rio das Mortes basin headwater, as observed in Figure 3. An initial area of 34% of the basin total area was recorded in 1985, which decreased to 30% in 2017 – a total of almost 600 km² of native vegetation area was removed.

3.2 ANALYSIS OF RAINFALL TRENDS

The nonparametric Mann-Kendall test result for the Rio das Mortes basin average total annual rainfall was equal to Z = 0.6413 and the Figure 4 shows its average total annual rainfall from the years 1941 to 2016.

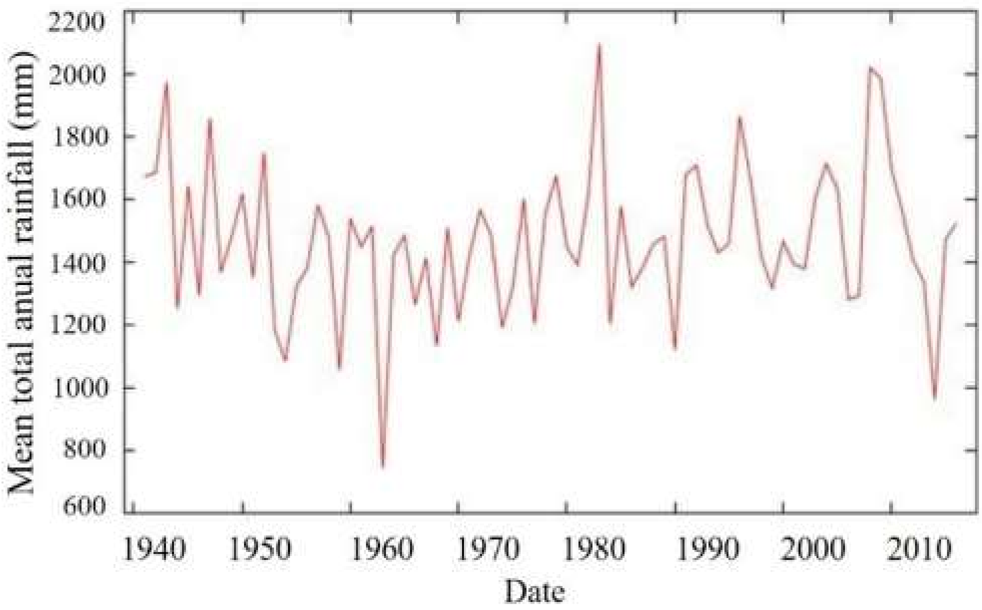

Figure 4. Rio das Mortes basin average total annual rainfall from the year 1941 to 2016.

The Mann-Kendall result showed that the basin average rainfall series has no trends within the reliability limits at 95% level (Figure 4). The accepted hypothesis is that the rainfall series are independent and identically distributed, i.e., the sequence values fluctuate randomly around an average value that remains constant over time, and the dispersion of the data around the average also remains constant, which characterizes the historical series stationarity (Clarke, 2003). The average total annual rainfall series for the Rio das Mortes Basin is considered a stationary series, in which the statistical parameters remain constant over time.

In the exploratory analysis of the data from 1941 to 2016 and as showed in Figure 4, the average total annual rainfall for the Rio das Mortes basin was 1469.81 mm, with a 1464.80 mm median and 238.60 mm standard deviation. In addition, the average rainfall varied from 1391.00 to 1605.00 mm and the highest average observed was in 1983, reaching 2095.21 mm, and the lowest average rainfall was 745.60 mm and occurred in 1963. Castro *et al.* (2008) comments that the average total annual rainfall in the region comprised by the municipalities of Bom Sucesso, São Bento Abade and São João del Rei is 1411.00 mm. Amâncio *et al.* (2018) found that the average annual rainfall for the subbasins of the Capivari and Rio das Mortes is 1470.00 mm. As can be seen in Figure 5, the higher concentration was in the higher basin areas, while the areas closer to the riverbed exhibited lower values. This is the case of Vargem do Engenho station, which recorded the highest altitude (1120 m) and average rainfall (1605.10 mm) and is located in the northeastern region of the municipality of Barbacena; it also occurs in Conceição do Ibitipoca rainfall station – 970 m altitude and average rainfall of 1581.90 mm – in the municipality of Lima Duarte.

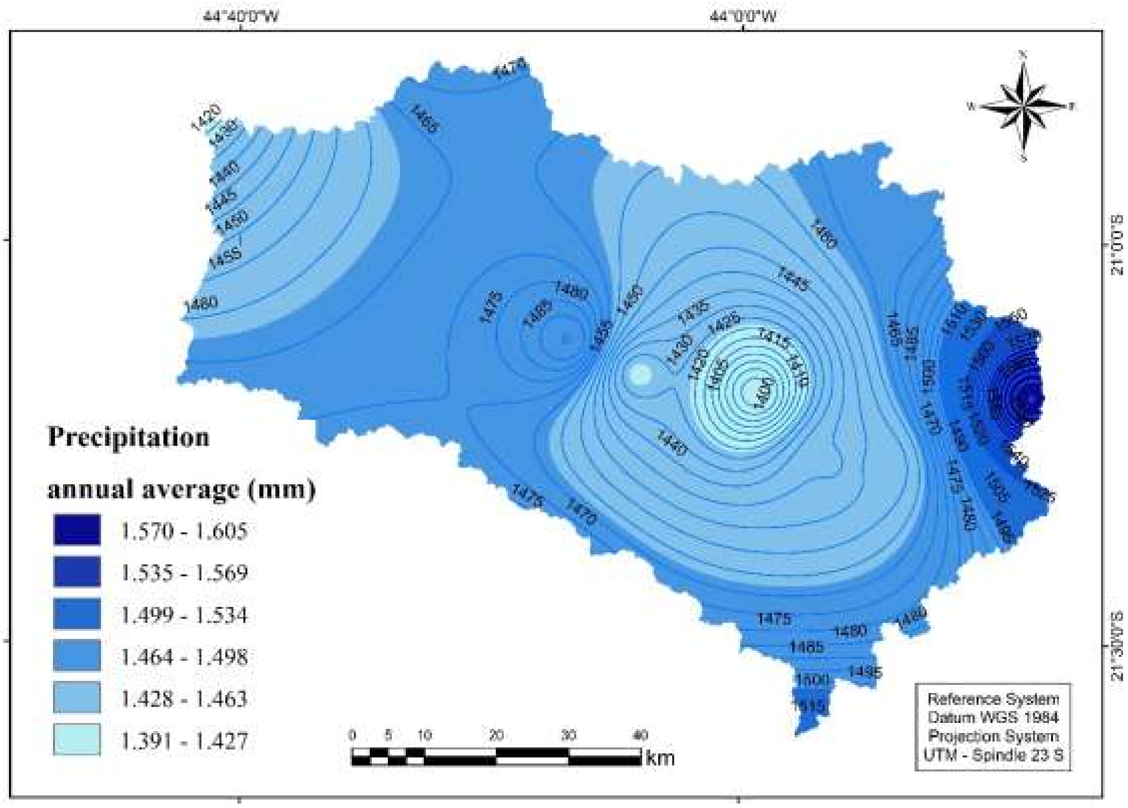

Figure 5. Rio das Mortes basin spatial distribution map of average annual rainfall.

As introduced in Table 1, the significance level α describes the probability of finding a value more extreme than that observed in the sample. Increasing rainfall trends were observed over the years for the Conceição do Ibitipoca and Carandaí rainfall stations, while decreasing rainfall trends were detected for the Oliveira and Vargem do Engenho rainfall stations in the analysed period. The other eight stations analysed showed no trends in their data, as they exhibited rainfall events around their average annual rainfall.

Table 1. Mann-Kendall trend test for the analyzed rainfall stations

Station	n	Trend	| Z |	p-value
Madre de Deus de Minas	76	NT	0.148	0.882
Conceição do Ibitipoca	69	PT	2.429	0.015
Oliveira	49	NG	4.370	0.000
Itumirim	76	NT	0.283	0.778
Vargem do Engenho	76	NG	2.077	0.038
Fazenda Campo Grande	76	NT	0.875	0.382
Carandaí	76	PT	3.054	0.002
Barroso	59	NT	0.902	0.367

Usina Barbacena	76	NT	0.875	0.382
Campolide	69	NT	1.777	0.076
Porto do Elvas	59	NT	0.105	0.917
Porto Tiradentes	63	NT	0.113	0.910

n = number of events in the historical series; NT = no trend in the data; NG = negative trend in the data; PT = positive trend in the data.

3.3 ANALYSIS OF FLOW RATE TRENDS

From 1925 to 2014, a seasonality could be observed in the time series average monthly flows of the fluviometric station of Ibituruna, with values fluctuating between 18.55 and 603.43 m^3s^{-1}. The 7-day 10-year low flow rate ($Q_{7,10}$) estimated by the probability distribution models used, presented values ranging between 25.53 and 26.02 m^3s^{-1}. It was found that the Weibull, LogPearson 3 and Pearson 3 distributions were the ones that presented the lowest standard errors, 0.87, 0.90 and 0.94 $m^3.s^{-1}$ respectively, therefore the best fit, while the distributions that presented the highest standard errors were the LogNormal 3 and 2 parameter distributions, 1.02 and 1.12 $m^3.s^{-1}$ respectively.

In a research carried out by Zoneamento Ecológico-Econômico de Minas Gerais (Minas Gerais, 2008), it was found a value of 29.28 $m^3.s^{-1}$ for low flow rate $Q_{7,10}$, with a relative error of 27.01% for the same fluviometric station of this study. In addiction, Melo et al. (2019) found values close to $Q_{7,10}$ for fluviometric station of Jequitibá River (MG), 23.60 $m^3.s^{-1}$, which has a drainage area similar to that of Rio das Mortes basin.

By analyzing the flow permanence curve obtained by SisCAH application (Souza *et al.,* 2009), it was found that the reference flows $Q_{90\%}$ and $Q_{95\%}$ showed values of 41.40 and 35.78 $m^3.s^{-1}$, respectively. So, it is observed that the lowest flow rate $Q_{7,10}$ (25.53 m^3s^1) is more restrictive than the reference flows $Q_{90\%}$ and $Q_{95\%}$, even when compared to $Q_{99\%}$, which value is 25.62 m^3s^{-1}. Therefore, the low flow $Q_{7,10}$ is commonly used as a reference flow, offering greater guarantees that there will be no failures to meet the demands (Pereira; Lanna, 1996).

The long-term average flow observed in the period of data collection was 114.59 $m^3.s^{-1}$, a value above the median extracted from the permanence curve of 78.5 m^3s^{-1}, characterizing a positive asymmetry in the series history of flows in Rio das Mortes basin. Throughout the historical series, the lowest flow rate value occurred in the months of August and September, coinciding with the period os lowest rainfall in the south of Minas Gerais state. The highest flow corresponds to the month of January (232.97 m^3s^{-1}) and the lowest to the month of August (48.75 m^3s^{-1}).

The lowest minimum flow found was obtained for the longest analyzed return time (100 years), using the LogNormal 3 distribution. Also with the longest return time, the highest maximum flow was found, using the Person 3 distribution.

The results of the Mann-Kendall trend test for the flow rates series from the years of 1925 to 2014 and from the years of 1985 to 2014, can be seen in Table 2.

Table 2. Results of the Mann-Kendall trend test for the historical series of maximum, average, minimum annual flow rates, average monthly flow rate, average flow rate of the rainy season, average flow rate of the drought season and average of the month of highest and lowest flow rates per year between 1925 and 2014 and for the years between 1985 to 2014.

Flow rate - time series	year 1925 to 2014				year 1985 to 2014			
	n	Trend	| Z |	p-value	n	Trend	| Z |	p-value
Minimum annual	90	NT	0.962	0.336	30	NT	0.999	0.317
Average annual	90	NT	0.977	0.329	30	NT	0.606	0.544
Average monthly	1061	NT	1.539	0.124	353	NT	0.008	0.994
Average during the flood season	89	NT	1.244	0.214	30	NT	0.606	0.544
Average during the drought season	90	NT	1.599	0.109	30	NT	0.250	0.803
Average of the month with the highest value	89	NT	1.067	0.286	30	NT	0.464	0.643
Average of the month with the lowest value	90	NEG	1.969	0.049	30	NT	0.464	0.643
Maximum annual	90	NT	1.662	0.097	30	NT	0.000	1.000

n = number of events in the historical series; NT = no trend in the data; NG = negative trend in the data.

According to Table 2, the changes in land use and cover, quantified from 1985 to 2014, were not significant to the point of causing changes in Rio das Mortes hydrological regime during the period analysed. But when the Mann-Kendall test was applied to the entire historical flow series, which goes from 1925 to 2014, a decreasing trend was found for the average month flow rate with the lowest volume; i.e., the test found a statistically significant decreasing trend in the month average with the lowest Rio das Mortes basin volume over the years. This indicates a decrease in the drought flow rate over the 90-year period.

The Pettitt test identified significant abrupt change point in the monthly series of lowest flow rate in 1952. This abrupt change point may have been caused in several ways by several different phenomena, which may occur naturally or due to anthropic actions. However, no references were found in the literature that justified this sudden drop in the average in 1952 or in years close to that date in the Rio das Mortes basin or in its surroundings.

4 FINAL CONSIDERATIONS

The average annual rainfall series of the Conceição do Ibitipoca and Carandaí stations showed increasing trends, while the Oliveira and Vargem do Engenho stations showed decreasing trends. The other eight analysed rainfall series did not show significant trends.

A decreasing trend was also observed in the average monthly flow rate series with the lowest streamflow over the years. This reduction in the average streamflow in the month with the lowest annual value is worrisome, especially as water resources are becoming increasingly scarce. However, no trends were observed in the streamflow series from 1985 to 2014, so the Rio das Mortes basin changes in land use and cover were not significant to causing changes point in the basin hydrological regime. When the Pettitt test was applied, a significant abrupt change point was identified in the historical flow series of the month with the lowest runoff for 1952. However, no causes were found to justify this change.

The Rio das Mortes basin use and cover land analysis showed that there were increases in the cultivation (+5.88%), planted forest (+3.65%), bare soil (+2.24%), other use (+1.25%), and water (+0.06%) areas and decreases in the native vegetation (-3.63%) and pasture (-9.44%) areas. The presence of a decreasing trend in the month with the lowest flow rate may have occurred due to rainfall or anthropogenic factors such as increased water consumption for irrigation, an increase in cultivation areas within the basin, an increase in planted forest areas, and an increase in the population and areas with anthropic uses.

5 DATA AVAILABILITY

All necessary data are included in this article.

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