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Temporal and spatial trend analysis of surface water quality in the Doce River basin, Minas Gerais, Brazil

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Abstract
In Brazil, specifically in the Doce River basin, there is still a great lack of studies on temporal and spatial trends in water quality, since the water quality in the monitoring campaigns is basically evaluated when it comes down to the concentrations of monitored variables. In this sense, the objective of this work was to perform a temporal and spatial trend analysis of water quality data in the Minas Gerais portion of the Doce River basin, Brazil. For this, the Mann–Kendall, seasonal Mann–Kendall and Spearman correlation tests were used in the temporal analysis and the cluster analysis in the spatial analysis. In the analysis of temporal trends, the analyses were performed using the values of the National Sanitation Foundation Water Quality Index (NSFWQI) and the variables that compose it. In the analysis of spatial trends, the stations were evaluated only based on the WQI. With the results of the analysis of temporal trend, it was identified that most stations did not present a statistically significant trend for the WQI. In the stations that presented trends of quality reduction, most of them are in densely populated areas, demonstrating the strong influence of the poor sanitary conditions of the municipalities to the water quality of the basin. When analyzing the variables that compose the WQI, the results found for nitrate demonstrated that water quality deterioration is also affected by the diffuse pollution originating from farming areas. The results for *Escherichia coli* reinforced the impact of the discharge of domestic effluents and demonstrated the absence of a significative trend is still of concern because it can represent the maintenance of a degradation state in the water bodies. In the spatial trend analysis, the CA grouped the monitoring stations into six clusters based on their similarity among the WQI values, and, together with the results of the other analyses, it was verified that the Caratinga River basin (UGRH5 Caratinga) presented the highest degree of pollution. It was also possible to identify five stations that can be reallocated or deactivated since they have similarities with other stations located in the same watercourse.

Keywords Cluster analysis · Doce River · Monitoring network · Trend analysis · Water pollution

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1 Introduction

In the water basins, water quality can be influenced by a number of natural factors, such as weathering of rocks and soil erosion, as well as by anthropic factors, through agricultural expansion and accelerated population and industrial growth (Bu et al. 2014; Barakat et al. 2016; Zeinalzadeh and Rezaei 2017). However, the deterioration of water bodies has been aggravated and is becoming a threat to water security around the world (Zhai et al. 2014).

Considering that water quality behavior is a result of the river basin conditions, periodic monitoring campaigns are the first step toward developing a reliable and adequate database that can be useful for water resource planning and management (Pesce and Wunderlin 2000; Simeonov et al. 2003; Shrestha and Kazama 2007). These campaigns allow the evaluation of the behavior of water quality variables, detecting spatial and temporal variations and support the planning of water resources in the implementation of management instruments, such as water use permits, collection and framing of water bodies in classes of use (ANA 2013a).

In the state of Minas Gerais, Brazil, the monitoring of surface water began to be carried out in 1997 through the "Waters of Minas Project", under the responsibility of the Minas Gerais Water Management Institute (IGAM). In the Minas Gerais portion of the Doce River basin, the network currently has 65 stations in operation and four annual campaigns with quarterly frequency, two complete and two intermediates. In the complete campaigns, carried out every six months, 51 water quality variables are analyzed in common to the set of stations. For the partial campaigns, carried out between the complete campaigns, 19 variables are analyzed in common to the set of stations and to the four monitoring campaigns.

The water quality monitoring campaigns in the Doce River basin are essential, since they allow the identification of diffuse and punctual contaminations, such as the discharge of domestic effluent without treatment, causing contamination by thermotolerant coliforms; inadequate disposal of solid waste, causing them to be carried to the water bodies; generation of industrial effluents, causing the release of toxic contaminants of different kinds; and inadequate soil use, which, thanks to climatic conditions, provides erosion and sediment transport to the water bodies (ECOPLAN-LUME 2010a).

Although the monitoring program has demonstrated its importance in providing basic information for the definition of strategies and the evaluation of the effectiveness of the environmental control system itself, the monitoring campaigns, when carried out for long periods, end up generating an extensive and complex database, which may hinder its analysis and interpretation, often leading to underutilization (Trindade et al. 2017). On the other hand, the existence of historical data series allows a better understanding of the temporal and spatial evolution of water quality and its correlation with natural and anthropic factors.

Among the available methodologies to interpret qualitative data sets, trend analysis studies have demonstrated their potential use as a tool to help water quality management, showing positive, negative or zero trends for the analyzed water quality variables (Yenilmez et al. 2011; Tabari et al. 2011; Elçi and Selçuk 2013; Sun et al. 2013; Kisi and Ay 2014; Chowdhury and Al-Zahrani 2014; Kurdi et al. 2015; Dou et al. 2016; Trindade et al. 2017; Oliveira et al. 2017b; Costa et al. 2017; Anand et al. 2019; Ebadati and Hooshmandzadeh 2019). Trend analysis allows the evaluation of long data series, being useful for monitoring the evolution of water quality, as well as to understand the influence that factors such as changed land use and sources of pollution in the basin exert on water quality, identifying basins with similar characteristics.

Trend analysis in water quality from monitoring networks is rarely published in scientific journals. This may be partly due to the difficulties associated with maintaining long term, stable (consistent over time) and un-interrupted water quality monitoring (Ballantine and Davies-Colley 2014). In Brazil, specifically in the Doce River basin, there is still a great lack of studies on temporal and spatial trends in water quality, since the water quality in the monitoring campaigns carried out by IGAM is basically evaluated when it comes down to the concentrations of monitored variables.

The choice of the Doce River basin as a study area is also justified by its economic and environmental context since the basin was the target of a major environmental disaster in Brazil. On November 05, 2015, the Fundão tailings dam, operated by Samarco Mineração SA. collapsed. It was in the district of Bento Rodrigues, municipality of Mariana. The dam, classified as Class III, with high environmental damage potential, was destined to receive and store the waste generated by the iron ore beneficiation activity (IGAM 2017a). The dam contained 56.4 million m^3 of tailings, of which 43 million m^3 (80% of the total volume) were released into the environment. This amount reached 668 km of rivers and streams of the Doce River basin, in the states of Minas Gerais and Espírito Santo (Carmo et al. 2017), resulting in several impacts on water resources and their uses, such as public supply, irrigation, industrial use, power generation electrical, leisure and fishing, destruction of permanent preservation areas, silting and morphological alterations of water bodies (ANA 2016).

Based on the above, the objective of this work was to analyze the temporal and spatial trend of water quality data in the Minas Gerais portion of the Doce River basin, allowing the identification of the water quality variation, the most impacted areas over the years of monitoring and the main monitoring stations to be maintained in the network, which may subsidize management and planning actions aiming the improvement of the monitoring of water quality in the basin.

2 Materials and methods

2.1 Study area

The study was developed in the Minas Gerais portion of the Doce River basin, Brazil, corresponding to 86% of the total area of approximately 82,427 km^2 (ANA 2013b). The Doce River begins in the state of Minas Gerais, in the Mantiqueira and Espinhaço mountains and flows about 879 km until reaching the Atlantic Ocean in the state of Espírito Santo.

In the state of Minas Gerais (Fig. 1), the Doce River basin is subdivided into six water resources management units (UGRH) (CBH-Doce 2016a). The UGRH has regional identities characterized by physical, sociocultural, economic and political aspects (IGAM 2016).

The basin has 98% of its area inserted in the Atlantic Forest biome, one of the most important and threatened in the world. The remaining 2% are Savanna Formation (CBH-Doce 2016b). According to Köppen's climatological classification, the predominant climates in the basin are Aw—tropical monsoon zone and Cwa—humid subtropical zone, which is characterized by a dry winter and hot summer, and Cwb – humid subtropical zone, which is characterized by a dry winter and temperate summer (Alvares et al. 2013), with average annual precipitation around 1200 mm (Lima et al. 2019).

The economic activity in the Doce River basin is quite diversified, with emphasis on: farming (traditional crops, coffee, sugar cane, animal husbandry); reforestation; the

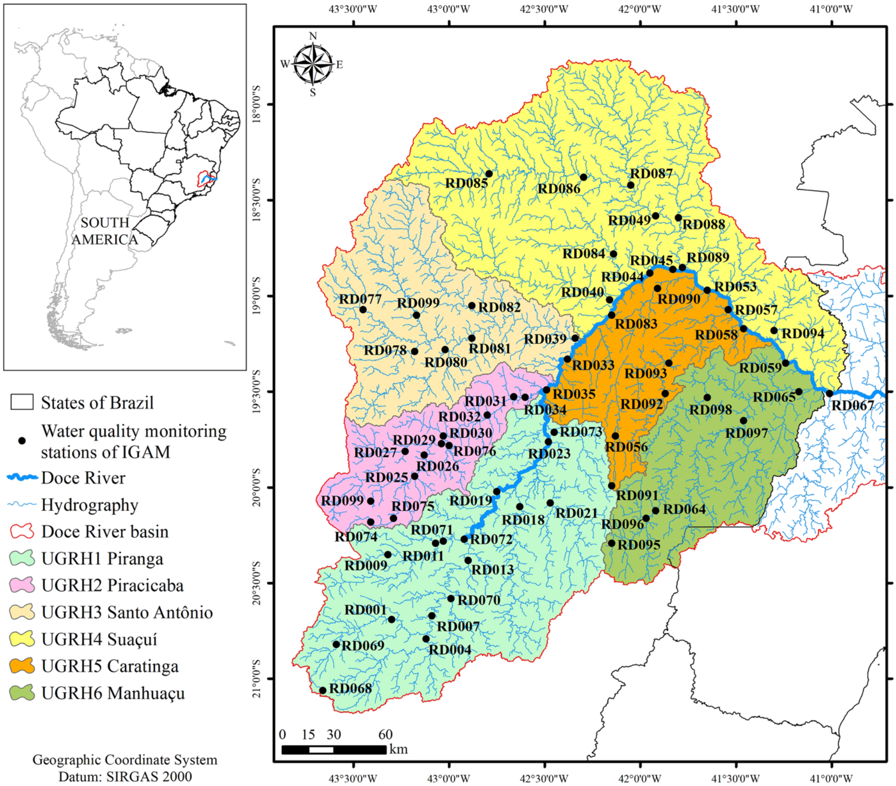

Fig. 1 Division of the Minas Gerais portion of the Doce River basin per UGRH and spatial distribution of IGAM water quality monitoring stations

agribusiness (sugar and ethanol); mining (iron, gold, bauxite, precious stones, etc.); industry (pulp, steel and dairy); trade and support services of industrial complexes; and electricity generation (ECOPLAN-LUME 2010a). The region has the largest steel mill complex in Latin America, which is associated with mining and reforestation companies (CBH-Doce 2016b).

2.2 Database and analysis methods used

The water quality data used in the study came from the water quality monitoring campaigns of the "Waters of Minas Project", where the water quality analyses are carried out by a laboratory accredited by the National Institute of Metrology, Quality and Technology (INMETRO), which regularly participates in analytical quality control (AQC) evaluations and follows standardized methods for water and sewage analysis (APHA et al. 2012). Data analysis was performed in each water quality monitoring station and divided into two stages: (a) temporal trend analysis; and (b) spatial trend analysis.

In general, the water quality can reflect changes in basins, making rivers good indicators of land use and land cover (Oliveira et al. 2017a; Marmontel et al. 2018; Shukla et al. 2020; Zhang et al. 2020). To support the discussion of the results obtained, the land use and land cover change in the UGRH1 Piranga was also analyzed.

2.3 Temporal trend analysis

In the analysis of temporal trend, it was decided to analyze monitoring stations with at least 10 years of operation, as was also done in other studies (Ballantine and Davies-Colley 2014; Dou et al. 2016; Trindade et al. 2017; Diamantini et al. 2018). Trend analysis over shorter periods tends to provide results influenced by local hydrological variability and therefore provides misleading results on long-term trends (Howden et al. 2011). Therefore, 32 of the 65 water quality monitoring stations located in the Doce River basin (Table 1) were selected and a base period from 2000 to 2017 was adopted.

Due to the period of the database used, the results found were affected by the tailings dam collapse in the municipality of Mariana, since the IGAM historical series include variables sensitive to the impacts resulting from the accident. It is also worth noting that, of the 65 monitoring stations of the IGAM, 14 were affected by the collapse.

For the stations presented in Table 1, the analyses were performed using National Sanitation Foundation Water Quality Index (NSFWQI), as well as the variables that comprise it: dissolved oxygen, thermotolerant coliforms, hydrogenionic potential, biochemical oxygen demand, nitrate, total phosphorus, water temperature, turbidity, and total solids. The WQI was chosen because it is a globally used index that reflects water contamination due to the nine variables considered most representative for the characterization of water quality. The index value varies from 0 to 100, and it is interpreted as follows: excellent ($90 < WQI \leq 100$), good ($70 < WQI \leq 90$), medium ($50 < WQI \leq 70$), bad ($25 < WQI \leq 50$) and very bad ($WQI \leq 25$). For the present study, the thermotolerant coliforms were replaced by the *Escherichia coli* from 2013. This fact is due to studies that have shown the species *E. coli* as the only indicator of contamination by thermotolerant coliforms species in IGAM water quality analyzes (IGAM 2016). Studies suggest that *E.coli* is a more reliable indicator of fecal pollution and the occurrence of pathogens in water than total and thermotolerant coliforms (Edberg et al. 2000; Leclerc et al. 2001).

To evaluate the existence of trends in the historical series, each of the 32 stations was analyzed individually. For this purpose, we used the nonparametric Mann–Kendall tests (MK) (Mann 1945; Kendall 1975), seasonal Mann–Kendall test (SMK) (Hirsch et al. 1982) and Spearman (Gauthier 2001). The main reason for the use of nonparametric statistical tests is that they are considered more adequate for data that do not present normal distribution, as it frequently happens in time series (Yue et al. 2002; Trindade et al. 2017; Costa et al. 2017).

Since the variables evaluated have a quarterly frequency, it was first verified the existence of seasonality among the data using the Kruskal–Wallis (KW) nonparametric test (Kruskal and Wallis 1952) at a significance level of 5%. For the series that presented significant difference among the quarters (p value < 0.05), the influence of seasonality on the data was taken into account. In these situations, the Seasonal Mann–Kendall test (SMK) was applied, which consists of a variation of the MK test in which seasonality is considered in the data series (Anghileri et al. 2014). For the series in which no seasonality was identified, the MK test was used for temporal trend analysis.

The MK and SMK tests were applied at a significance level of 5%, and the non-trend null hypothesis (H_0) in the series was rejected when S was significantly different from zero (p value < 0.05), in favor of the alternative hypothesis (H_1) of data trend. Positive values of the S statistics and Kendall's τ indicate an elevation trend, negative values indicate a reduction trend, and zero indicates no trend in the series.

Table 1 Water quality monitoring stations located in the Minas Gerais portion of the Doce River basin used in the temporal trend analysis

Station[a]	Coordinates		UGRH	Water course
	Latitude	Longitude		
RD001	−20°41′18.66″	−43°18′08.42″	1 Piranga	Piranga River
RD004	−20°47′06.99″	−43°06′56.99″	1 Piranga	Xopotó River
RD007	−20°40′18.99″	−43°05′30.99″	1 Piranga	Piranga River
RD009	−20°21′00.00″	−43°19′05.00″	1 Piranga	Carmo River
RD013	−20°22′59.80″	−42°54′08.50″	1 Piranga	Piranga River
RD018	−20°05′53.00″	−42°37′46.99″	1 Piranga	Casca River
RD019	−20°01′18.99″	−42°45′07.99″	1 Piranga	Doce River
RD021	−20°04′35.77″	−42°27′58.61″	1 Piranga	Matipó River
RD023	−19°45′34.99″	−42°29′06.00″	1 Piranga	Doce River
RD025	−19°56′21.69″	−43°10′48.99″	2 Piracicaba	Piracicaba River
RD026	−19°50′04.34″	−43°7′38.431″	2 Piracicaba	Piracicaba River
RD027	−19°48′36.00″	−43°14′00.00″	2 Piracicaba	Santa Bárbara River
RD029	−19°46′00.99″	−43°02′38.99″	2 Piracicaba	Piracicaba River
RD030	−19°44′03.75″	−43°01′41.24″	2 Piracicaba	Peixe River
RD031	−19°31′33.86″	−42°39′28.78″	2 Piracicaba	Piracicaba River
RD032	−19°37′11.80″	−42°48′02.71″	2 Piracicaba	Piracicaba River
RD033	−19°19′38.93″	−42°22′32.98″	2 Piracicaba	Doce River
RD034	−19°31′48.27″	−42°36′09.17″	2 Piracicaba	Piracicaba River
RD035	−19°29′18.99″	−42°29′38.99″	2 Piracicaba	Doce River
RD039	−19°13′25.03″	−42°20′34.68″	3 Santo Antônio	Santo Antônio River
RD040	−19°01′14.95″	−42°9′45.529″	4 Suaçuí	Corrente Grande River
RD044	−18°53′00.00″	−41°57′10.00″	4 Suaçuí	Doce River
RD045	−18°51′36.19″	−41°50′01.35″	4 Suaçuí	Doce River
RD049	−18°34′35.99″	−41°55′14.00″	4 Suaçuí	Suaçuí Grande River
RD053	−18°58′10.19″	−41°38′49.39″	4 Suaçuí	Doce River
RD056	−19°43′36.00″	−42°07′58.99″	5 Caratinga	Caratinga River
RD057	−19°04′15.78″	−41°32′39.83″	5 Caratinga	Caratinga River
RD058	−19°09′58.84″	−41°27′35.69″	5 Caratinga	Doce River
RD059	−19°20′45.72″	−41°14′19.49″	6 Manhuaçu	Doce River
RD064	−20°06′59.11″	−41°55′09.80″	6 Manhuaçu	Manhuaçu River
RD065	−19°29′51.00″	−41°10′09.99″	6 Manhuaçu	Manhuaçu River
RD067	−19°30′20.00″	−41°00′47.00″	6 Manhuaçu	Doce River

[a]Stations highlighted in bold refer to those affected by the tailings dam collapse

Then, to corroborate with the results found in the MK and SMK tests, the autocorrelation of the time series was verified using the Spearman nonparametric test. This test is based on the correlation coefficient (Spearman's R), and the trend of data elevation or reduction over time is evaluated. The use of this test was based on the fact that the outliers have little influence on their results, the collection of samples at regular intervals is not necessary, and the test is simple to apply even in a large dataset (Gauthier 2001).

Similarly, to the MK and SMK tests, correlations with *p* value less than 0.05 (5% significance level) were considered significant, there was a trend over time for the analyzed variable. In this case, the positive or negative sign of the *R* coefficient indicated the rising or decreasing trend, respectively, since it corresponds to the correlation of the values of the variable with time (Trindade et al. 2017).

For monitoring stations, whose results were not significant for the MK or SMK test, but significant for the Spearman correlation test, or vice versa, the results were considered as inconclusive with the possibility of elevation, when the values were positive, or reduction when values were negative.

2.4 Spatial trend analysis

The cluster analysis (CA) was used to verify the spatial trend of monitoring station data in the Minas Gerais portion of the Doce River basin. The CA aimed to group the monitoring stations into clusters, so that the stations within a group are similar to each other, but different from other groups (Shrestha and Kazama 2007; Jung et al. 2016). The CA was used to reliably classify the surface water quality and to allow the guidance of future spatial sampling decisions, reducing the number of stations and the costs (Shrestha and Kazama 2007; Zhang et al. 2011; Ajorlo et al. 2013; Muangthong and Shrestha 2015; Jung et al. 2016; Barakat et al. 2016; Calazans et al. 2018a).

In order to obtain a more recent characterization of the water quality and to evaluate most of the monitoring stations, the CA was applied considering the data from 2010 to 2017. The time series of the WQI per monitoring station were used as input data and evaluated 64 of the 65 existing monitoring stations, justified by the fact that the RD011 station has data only from the year 2016 on, which made it impossible to use them in the analysis. In the CA, the hierarchical grouping was applied through the Ward method in the normalized data set, using Euclidean distance as a measure of dissimilarity (linkage distance), as also used in several other studies (Zhang et al. 2011; Ajorlo et al. 2013; Muangthong and Shrestha 2015).

In order to confirm the results obtained in the CA, the percentage of violation of the water quality variables was calculated according to the limits established by CONAMA Resolution No. 357/2005 (Brasil 2005) and by COPAM/CERH-MG DN No. 01/2008 (Minas Gerais 2008). To do this, a preliminary analysis was carried out to filter out the 51 water quality variables common to the stations, which had their limits established in the legislation, which resulted in the selection of 32 variables (Table 2).

Since only the Piracicaba River and its tributaries have a framing approved in the scope of the State Water Resources Council (CERH-MG), in the Doce River basin, the class 2 of framing was adopted for the other water bodies, according to CNRH Resolution No. 91/2008 (Brasil 2008). Waters with class 2 framing can be used for the following purposes: supply to human consumption, after conventional treatment; protection of aquatic communities; recreation of primary contact, such as swimming, water skiing and diving, according to CONAMA Resolution No. 274/2000 (Brasil 2000); irrigation of vegetables, fruit plants and parks, gardens, sports and leisure fields, with which the public may come into direct contact; and aquaculture and fishing. The results of the analysis highlighted the monitoring stations that presented the highest and lowest violation rates according to the limits established by the legislation, which were compared to the CA results.

Table 2 Variables of water quality with limits established in the legislation according to the classification class

Variables	
Dissolved aluminium (mg L^{-1})	Total manganese (mg L^{-1})
Total arsenic (mg L^{-1})	Total mercury (μg L^{-1})
Total boron (mg L^{-1})	Total nickel (mg L^{-1})
Total cadmium (mg L^{-1})	Nitrate (mg L^{-1})
Total lead (mg L^{-1})	Nitrite (mg L^{-1})
Free cyanide (mg L^{-1})	Total ammoniacal nitrogen (mg L^{-1})
Total chloride (mg L^{-1})	Dissolved oxygen (mg L^{-1})
Chlorophyll a (μg L^{-1})	Hydrogenionic potential
Dissolved copper (mg L^{-1})	Total selenium (mg L^{-1})
True color (mg L^{-1})	Total dissolved solids (mg L^{-1})
Total chromium (mg L^{-1})	Total suspended solids (mg L^{-1})
Biochemical oxygen demand (mg L^{-1})	Surfactants (mg L^{-1})
Escherichia coli (MPN 100 mL^{-1})	Total sulfate (mg L^{-1})
Total phenols (mg L^{-1})	Sulfide (mg L^{-1})
Dissolved iron (mg L^{-1})	Turbidity (NTU)
Total phosphorus (mg L^{-1})	Total zinc (mg L^{-1})

2.5 Land use and land cover change

The land use and land cover (LULC) maps for the years 2000 and 2017 were compared. The LULC classes were obtained based on the mapping carried out by the MapBiomas Project, collection 4.1 (MapBiomas 2019). MapBiomas Project is an initiative that involves a collaborative network of biomes, land use, remote sensing, geographic information system and computer science experts that rely on Google Earth Engine platform and its cloud processing and automated classifiers capabilities to generate Brazil's annual land use and land cover time series.

In total, 13 classes of LULC were obtained in both years evaluated. To facilitate the analysis, it was decided to merge some of the LULC classes obtained, totaling nine classes (Table 3).

3 Results and discussion

The results of the statistical tests proposed in the methodology were organized in individual worksheets for the WQI and for each water quality variable analyzed. In the KW test, the statistically significant results ($p < 0.05$) indicated the presence of seasonality among the data. Statistically significant results ($p < 0.05$) from the MK, SMK and Spearman correlation tests suggested that there is a trend to change the variable over time. The Kendall's Tau and Spearman's R values indicated the direction of the trend of the variable over time, with positive values indicating elevation and negative values indicating reduction. The results of the temporal trend analyses for the WQI are presented in Table 4 and defined as:

Table 3 LULC classes obtained by the MapBiomas Project

Class nomenclature used in the MapBiomas Project	Class nomenclature adopted
Forest formation	Forest formation
Savanna formation	Savanna formation
Forest plantation	Forest plantation
Grassland	Non-forest natural formation
Other non-forest natural formation	Non-forest natural formation
Pasture	Farming
Annual and perennial crop	Farming
Mosaic of agriculture and pasture	Farming
Urban infrastructure	Urban infrastructure
Other non-vegetated area	Urban infrastructure
Rocky outcrop	Rocky outcrop
Mining	Mining
River, lake and ocean	Water bodies

(↑) elevation trend; (↓) reduction trend; (?↑) inconclusive with possibility of elevation; (?↓) inconclusive with possibility of reduction; and (–) no trend.

As can be seen in Table 4, the Spearman correlation test and MK or SMK were coincident regarding the indication of whether there was a trend in most of the analyzed cases. However, situations were found, as for the WQI, in stations RD007, RD031, RD044 and RD065, in which the tests did not show the same result regarding the significance of the temporal trend. For these stations, the WQI trend was considered as inconclusive, with the possibility of elevation or reduction. Among the analyzed stations, it was also observed that only stations RD021 and RD056 do not present seasonality between the values, both of which presented a reduction trend. In other words, water quality may be decreasing in every period of the year analyzed. For a better visualization, the spatial distribution of the WQI temporal trend analysis results for the 32 monitoring stations analyzed in the Minas Gerais portion of the Doce River basin is presented in Fig. 2.

As can be seen in Table 4, 20 of the 32 monitoring stations (62.5%) evaluated did not present a trend in relation to the WQI. However, this scenario should not be understood as good, since the stations that did not present a significant trend of elevation and have low values of WQI is an indication that the water quality is presenting a constant degradation.

As a result of the analysis of temporal trend, it was also possible to verify that five stations presented statistically significant temporal trends of WQI elevation: RD009 (UGRH1), RD018 (UGRH1), RD027 (UGRH2), RD040 (UGRH4), RD053 (UGRH4). Among them, only the RD040 station is in a rural area, while the others are downstream from the city of Tumitiringa (RD053) and districts of Monsenhor Horta (RD009), Águas Férreas (RD018) and Santa Rita de Pacas (RD027). For the reduction trend, four stations presented statistically significant results: RD021 (UGRH1), RD032 (UGRH2), RD056 (UGRH5), RD064 (UGRH6). Except for the RD032, these stations are in the urban area, downstream of the cities of Raul Soares (RD021), Caratinga (RD056) and Santana do Manhuaçu (RD064).

Based on the results, it is possible to state that the trend to reduce water quality is typical of metropolitan regions and large cities in the countryside, where water bodies present high degradation of water quality resulted from the discharge of domestic

Table 4 Results of the WQI temporal trend analyses in the Minas Gerais portion of the Doce River basin for the 32 monitoring stations analyzed

Station[a]	KW test	MK test	Kendall's Tau[b]	S[b]	SMK test	Kendall's Tau[c]	S[c]	Spearman's R	WQI
RD001	0.017				0.289	0.093	57	0.186	–
RD004	0.010				0.272	0.097	59	0.189	–
RD007	0.019				0.225	0.106	65	0.196	?↑
RD009	0.003				0.011	0.221	135	0.314	↑
RD013	0.004				0.622	0.044	27	0.162	–
RD018	0.000				0.035	0.183	112	0.256	↑
RD019	0.000				0.865	−0.016	−10	0.011	–
RD021	0.219	0.001	−0.264	−672				−0.384	↓
RD023	0.000				0.325	−0.087	−53	−0.057	–
RD025	0.000				0.185	−0.116	−71	−0.118	–
RD026	0.013				1	0.002	1	0.056	–
RD027	0.032				0.008	0.229	140	0.299	↑
RD029	0.007				0.596	−0.047	−29	−0.068	–
RD030	0.009				0.051	−0.170	−104	−0.157	–
RD031	0.000				0.051	−0.170	−104	−0.204	?↓
RD032	0.001				0.043	−0.177	−108	−0.239	↓
RD033	0.000				0.677	−0.038	−23	0.005	–
RD034	0.013				0.353	0.082	50	0.135	–
RD035	0.000				0.970	−0.005	−3	−0.011	–
RD039	0.000				0.733	−0.031	−19	−0.004	–
RD040	0.001				0.010	0.224	137	0.322	↑
RD044	0.000				0.021	−0.201	−123	−0.150	?↓
RD045	0.000				0.677	0.038	23	0.062	–
RD049	0.000				0.596	−0.048	−29	0.009	–
RD053	0.000				0.010	0.224	137	0.296	↑
RD056	0.349	0.000	−0.291	−743				−0.406	↓
RD057	0.000				0.609	0.046	28	0.068	–
RD058	0.000				0.405	−0.074	−45	−0.065	–
RD059	0.001				0.211	0.110	67	0.151	–
RD064	0.020				0.007	−0.234	−143	−0.316	↓
RD065	0.000				0.078	0.154	94	0.188	–
RD067	0.000				0.649	−0.041	−25	−0.035	–

[a]Stations highlighted in bold refer to those affected by the Fundão tailings dam collapse;

[b]Values for the MK test

[c]Values for the SMK test

effluents and industrial effluents. Most municipalities in the basin do not have effluent treatment plants, and when they do, treatment is insufficient. According to a study carried out on sanitary sewage in Brazil, the municipalities of Caratinga and Raul Soares release a total daily load of 3988.0 and 857.4 kg of biochemical oxygen demand, respectively, while smaller municipalities like Piranga and Tumiritinga release much lower values: 328.9 and 234.7 kg of biochemical oxygen demand per day, respectively (ANA

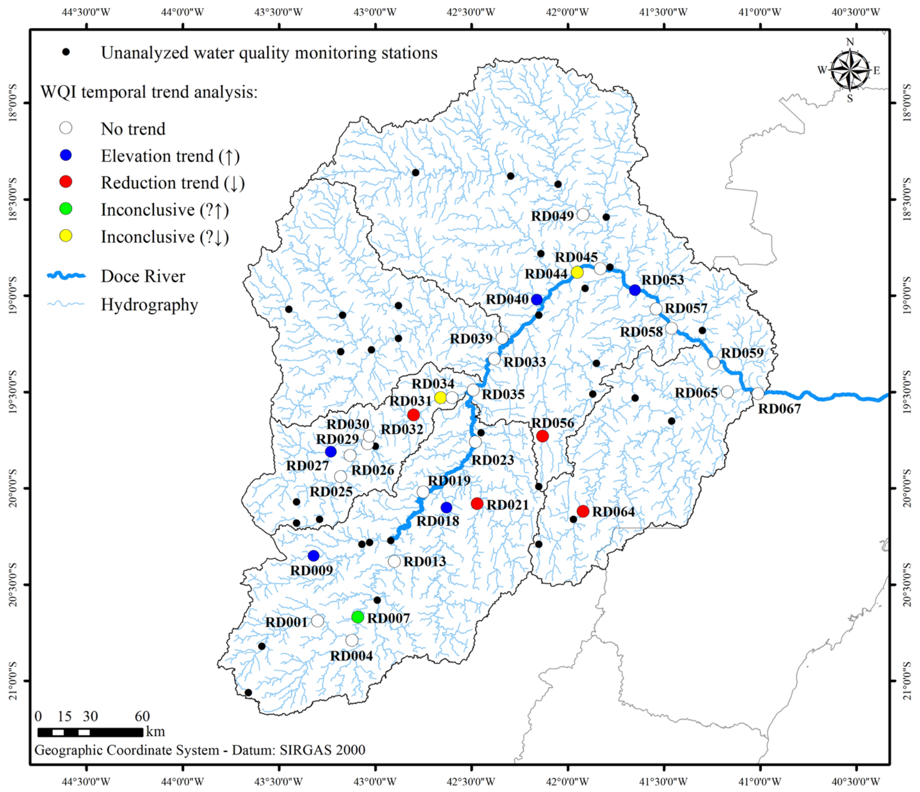

Fig. 2 Spatial distribution of the WQI temporal trend analysis in the Doce River basin for the 32 monitoring stations analyzed

2017). This result also corroborates with what was found in other studies carried out in Brazil, which point out the release of non-treated or partially treated domestic effluents as the main cause of water quality reduction (Oliveira et al. 2017b; Trindade et al. 2017; Costa et al. 2017; Calazans et al. 2018a, b). According to Kamal et al. (2020), the status of river water quality, especially in urban areas needs to be monitored closely and frequently due to the steady increase in population and vast development activities in these areas.

For the nine variables of water quality analyzed, the conclusion of the results of the analysis of temporal trend for each station is presented in Table 5.

As can be observed in Table 5, nitrate presented the worst results, showing an elevation trend in all monitoring stations evaluated. As reported in the literature, nitrate is mainly related to the use of fertilizers in agriculture (Chen et al. 2019; Sorando et al. 2019; Shukla et al. 2020; Kamal et al. 2020) and irrigation with untreated wastewater (Dhanasekarapandian et al. 2016). In a water quality study in the Tahtali basin, Turkey, Elçi and Selçuk (2013) found a reduction trend for nitrate. The authors attributed the improvements in nitrate concentrations to the new fertilizer use regulations. In the Verde River basin, Brazil, Pinto et al. (2017) also found an elevation trend for nitrate in all evaluated water quality monitoring stations, with the results attributed to the carrying of pollutants from the farming and urban areas.

Table 5 Temporal trends of water quality variables in the Doce River basin

Station[a]	Variables[b]								
	BOD	*E. coli*	P_T	NO_{3-}	DO	pH	TS	T	TU
RD001	↓	–	↓	↑	↑	–	–	–	–
RD004	?↓	?↓	–	↑	–	–	–	–	–
RD007	–	–	–	↑	↑	–	–	–	?↓
RD009	–	↓	–	↑	–	–	–	↑	↓
RD013	–	–	–	↑	–	–	–	–	?↓
RD018	↓	–	↓	↑	?↑	–	–	–	↓
RD019	↓	–	–	↑	–	–	–	–	–
RD021	–	↑	–	↑	–	–	↑	–	–
RD023	↓	–	–	↑	–	–	–	–	–
RD025	–	–	–	↑	–	–	↑	–	–
RD026	?↓	–	↑	↑	–	–	↑	–	–
RD027	?↓	↓	–	↑	–	–	–	–	↓
RD029	↓	–	–	↑	–	–	↑	–	–
RD030	–	–	↑	↑	–	–	↑	–	–
RD031	↓	–	–	↑	–	–	↑	–	↓
RD032	↓	–	–	↑	–	–	↑	–	?↓
RD033	?↓	–	–	↑	↑	–	?↑	–	–
RD034	↓	↓	↓	↑	–	–	↑	–	↓
RD035	↓	–	↓	↑	–	–	–	?↓	–
RD039	?↓	–	–	↑	?↑	–	–	–	–
RD040	–	↓	↓	↑	–	–	–	↑	↓
RD044	–	↑	–	↑	–	–	–	–	↓
RD045	–	–	–	↑	?↑	–	–	↑	↓
RD049	?↓	↑	↓	↑	–	–	–	–	↓
RD053	?↑	↓	↓	↑	↑	–	–	–	↓
RD056	?↑	?↑	↑	↑	↓	–	↑	?↑	–
RD057	–	–	?↓	↑	↑	–	–	–	?↓
RD058	–	?↑	?↓	↑	?↑	–	–	–	↓
RD059	?↑	–	–	↑	↑	–	–	?↑	↓
RD064	–	↑	?↓	↑	–	?↓	↑	–	↓
RD065	↓	–	–	↑	?↓	–	–	↑	↓
RD067	–	–	↓	↑	–	–	–	–	↓

[a]Stations highlighted in bold refer to those affected by the tailings dam collapse

[b]BOD: biochemical oxygen demand; *E. coli*: *Escherichia coli*; P_T: total phosphorus; NO_{3-}: nitrate; OD: dissolved oxygen; pH: hydrogen-ionic potential; TS: total solids; T: water temperature; TU: turbidity

When comparing the maps of LULC between the years 2000 and 2017 (Fig. 3), it can be seen that the farming areas represent the highest percentage of LULC with little variation between the years evaluated (Table 6). It is also possible to observe that the urban infrastructure obtained one of the highest percentage values of growth between the years evaluated. In Brazil, many studies have noted the significant contribution of increases in urban areas to the water quality deterioration and the alteration of flow regimes (Calijuri et al.

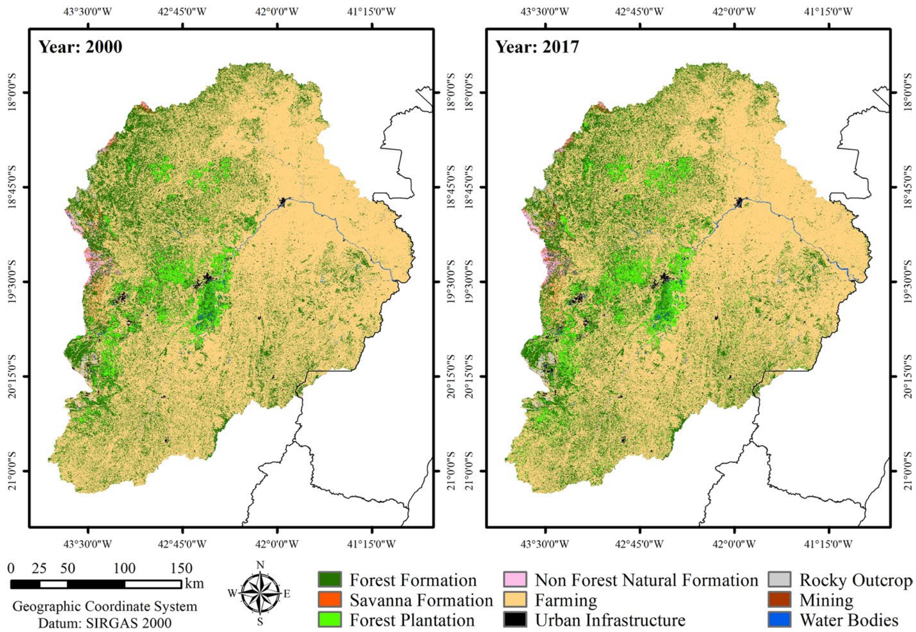

Fig. 3 LULC maps for the years 2000 and 2017

Table 6 Changes in land cover and use between 2000 and 2017

Casses of land cover and use	2000		2017		Increase and decrease (km^2)
	Area (km^2)	Cover (%)	Area (km^2)	Cover (%)	
Forest formation	17,065.85	23.90	17,298.65	24.22	232.80
Savanna formation	412.16	0.58	383.72	0.54	−28.44
Forest plantation	2454.92	3.44	3430.11	4.80	975.19
Non-forest natural formation	430.40	0.60	402.12	0.56	−28.28
Farming	49,969.24	69.97	48,587.38	68.04	−1381.86
Urban infrastructure	366.96	0.51	521.63	0.73	154.67
Rocky outcrop	443.40	0.62	489.77	0.69	46.37
Mining	4.41	0.01	6.30	0.01	1.89
Water bodies	264.44	0.37	292.10	0.41	27.66

2015; Rodrigues et al. 2019). These facts reaffirm the poor sanitary conditions of the basin, demonstrating that, in addition to the contamination from the point pollution (domestic and industrial effluents), the water quality deterioration is also affected by the diffuse pollution originating from farming areas (Yidana et al. 2010; Dhanasekarapandian et al. 2016; Şener et al. 2017; Wu et al. 2018).

While some contaminants have shown significant reduction trends, they may still have concentration levels that exceed the standards set by legislation. This fact can be exemplified by the *E. coli* variable that, although it was pointed out as one of the most critical variables in the Doce River basin (IGAM 2017b), it presented a larger number of stations with a significant reduction trend than with elevation trend. However, when evaluating the *E. coli* data at stations RD021 and RD027, they are above the limit established by local legislation most of the time (Fig. 4), regardless of the outcome of the trend analysis.

According to Fraga et al. (2019), this result corroborates most of the studies found in the literature on water quality in Brazilian basins, which highlights the release of domestic effluents without proper treatment as the main source of pollution, with high values of violation mainly for *E. Coli*. Unlike other coliform bacteria, *E. Coli*. are almost exclusively of fecal origin and can be detected in elevated densities in human and animal feces, sewage and water subjected to recent fecal pollution (Hachich et al. 2012). Violations found at *E. Coli* levels for stations RD021 and RD027 classify water quality as unsuitable for recreation of primary contact, according to CONAMA Resolution No. 274/2000.

Despite the indicative of poor sanitary conditions, the trends found for BOD, total phosphorus, DO and turbidity are considered good results, since most of them positively favor water quality. It can be seen that the few sewage treatment plants present in the basin manage to reduce a great part of the organic matter and nutrients, such as BOD and total phosphorus, as evidenced by the reduction trend for both variables in the RD035 station, located downstream of the municipality of Ipatinga, in which collects and treats 100% of its domestic effluents (ANA 2017). It is also observed that the

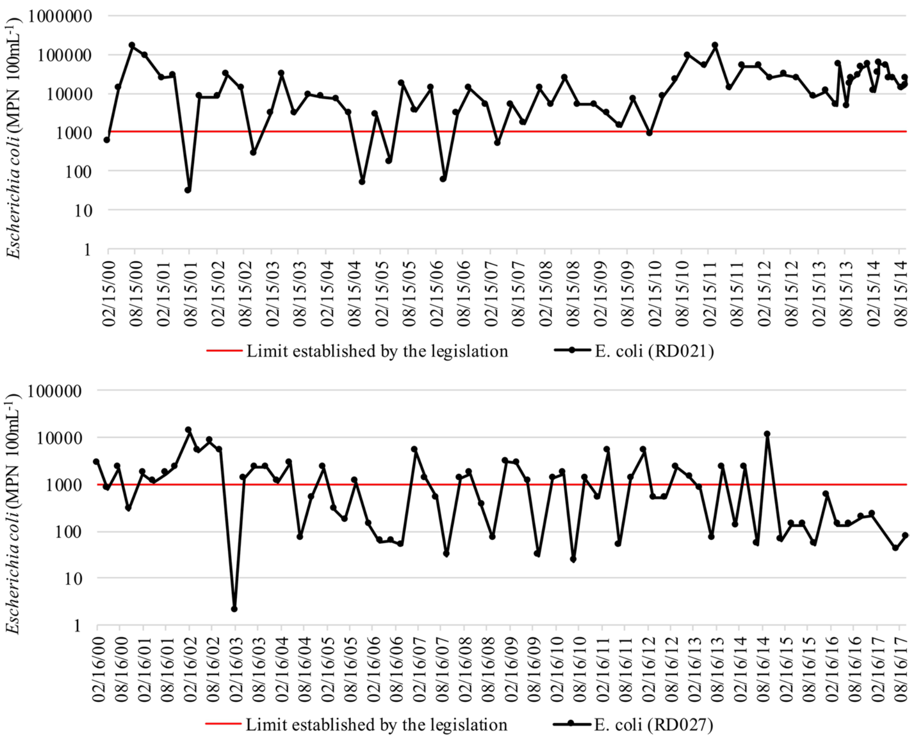

Fig. 4 Historical *E. coli* data series for RD021 and RD027 stations

turbidity exhibited a trend behavior opposite to TS. Since TS is composed of total suspended solids (TSS) and total dissolved solids (TDS), while turbidity represents basically TSS (Effendi et al. 2015), it can be concluded that TS is increasing as a function of TDS.

When comparing the data in Tables 4 and 5, it can be seen that most of the stations with a significant reduction trend (RD021, RD032, RD056, RD064), presented a significant trend of elevation for *E. coli*, nitrate and TS, which leads to the conclusion that these variables are primarily responsible for the reduction trends of the WQI.

By associating the variables analyzed with the collapsed dam in Mariana, ANA (2016) reports that turbidity and TS peaks were recorded as the tailings wave moved along the course of the Doce River, with higher values upstream and reduction trend downstream. Tailing particles caused severe changes in the water quality of the Doce River and estuarine region, increasing the turbidity levels in Minas Gerais up to 6000 times (600,000 NTU) higher than the upper limit established by legislation for this parameter (IGAM 2015). Despite the increase in the concentrations of such variables (Fig. 5), the dam collapse was not enough to cause significant elevation trends in the historical series of the affected stations.

It is important to note that the values shown in Fig. 5 refer to the water quality campaigns of the "Waters of Minas Project", which did not include measurements right after

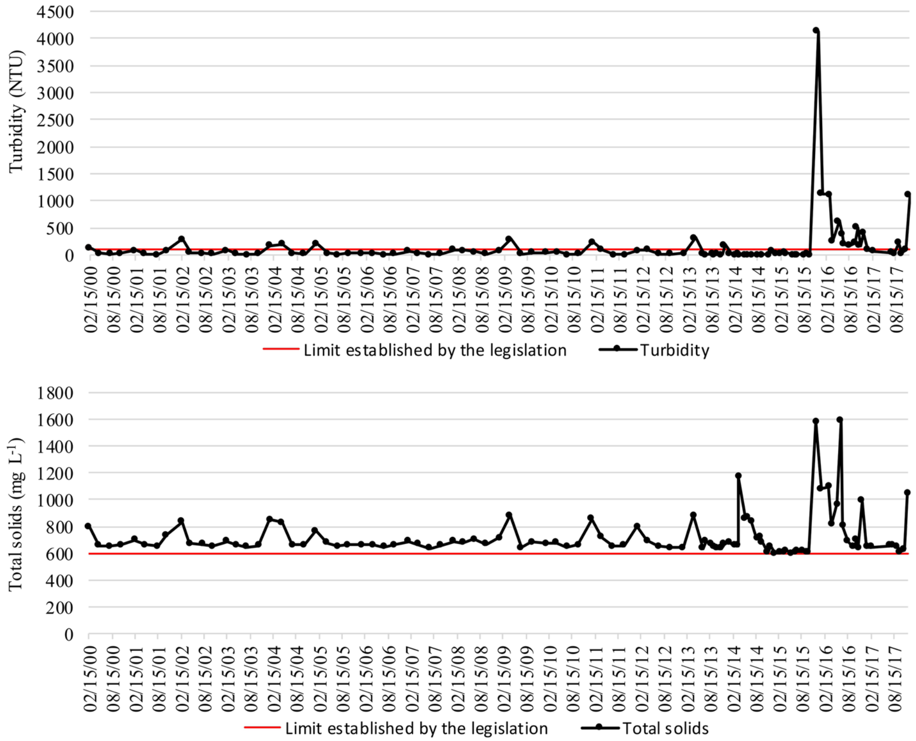

Fig. 5 Historical series of turbidity and total solids data for the RD019 station, located in the Doce River downstream of the Fundão tailings dam, in Mariana, Minas Gerais state

the collapse of the dam and consequently has lower levels of turbidity and total solids than the one registered by IGAM (2015).

For stations that showed an elevation trend for TS, it is possible to state that the result was caused by the deficient soil management in farming and mining, which causes the transport of solids to water (Hatje et al. 2017; Costa et al. 2017). As shown in Table 6, farming areas correspond to the highest percentage of LULC in the basin. The characteristics of soils and relief lead the basin to a condition of fragility regarded to the susceptibility to erosion, being aggravated by the high percentage of anthropized areas and human activities (ECOPLAN-LUME 2010a; Oliveira and Quaresma 2017). In Table 6, it is possible to observe that, together with the urban infrastructure, mining obtained one of the highest growth percentages between the years evaluated (2000–2017). According to Hatje et al. (2017), small-scale clandestine mining is still present in the basin and contributes to the contamination of the environmental compartments to levels that may have adverse effects on ecosystem services.

Although the dam collapse has no connection with the trends of the water quality variables evaluated, the economic and environmental impacts were disastrous. In addition to turbidity and TS, high levels of arsenic, cadmium, copper, chromium, nickel and mercury in water samples from the Doce River following the dam collapse (IGAM 2015). Based on a survey of 308 cases of mining dam collapses in the world (1915–2016), the Fundão dam disaster can be regarded as the largest technological disaster, considering the volume of tailings released and the geographical extension of environmental damage (Carmo et al. 2017), leaving 19 dead, 3 missing and over 600 homeless (Neves et al. 2016). The tailings directly hit 135 identified semideciduous seasonal forest fragments, in a 298 ha of vegetation suppression, located on the banks of Gualaxo do Norte and Carmo Rivers and its tributaries. The tailings also directly hit 863.7 ha of permanent preservation areas associated to watercourses, which were in protected areas, as defined by the federal forest code. Santarém Stream (11.9 km impacted), Gualaxo do Norte River (68.4 km) and Carmo River (24.7 km) were the main rivers and streams completely silted by the tailings. In addition, 294 small creeks were affected by the tailings (Carmo et al. 2017). Forty-one municipalities in the states of Minas Gerais and Espírito Santo were affected, and hundreds of thousands of people were left without access to clean water (Neves et al. 2016) and activities such as fishing and irrigation (Fernandes et al. 2016). As a consequence of this, thousands of individual lawsuits and dozens of class actions seeking compensation for material and moral damages were filed at courts in the states of Espirito Santo and Minas Gerais (Losekann et al. 2020).

In the analysis of spatial trend, the CA grouped the 64 monitoring stations of the Minas Gerais portion of the Doce River basin into six clusters, as can be observed in Table 7. Figure 6 shows the profile of the clusters based on the analyzed observations.

In order to improve the visualization of the spatial distribution of the stations among the six clusters obtained in the CA, the result of the analysis can also be observed in Fig. 7.

Although the CA has grouped the monitoring stations with similar characteristics in relation to the WQI, the clusters have stations grouped in different stretches of river and in different UGRHs that, in turn, have extensive areas and quite diversified economic activities. Thus, in the case of the Doce River basin, the choice of the representative stations of each cluster should consider the connectivity between them, their distribution among the UGRHs and the factors that most influence the variation of water quality. In other words, it is recommended that rivers that have a single monitoring station grouped by the CA should have it prioritized in the network, since timely and more detailed

Table 7 Monitoring stations that makeup the clusters obtained by the CA in the Minas Gerais portion of the Doce River basin

Clusters					
C1	C2	C3	C4	C5	C6
RD001	RD009	RD027	RD031	RD039	RD056
RD004	RD013	RD040	RD032	RD049	
RD007	RD021	RD065	RD058	RD053	
RD018	RD025	RD069	RD064	RD057	
RD019	RD026	RD077	RD073	RD059	
RD023	RD029	RD078	RD074	RD067	
RD070	RD030	RD079	RD076	RD082	
	RD033	RD080	RD085	RD083	
	RD034	RD081	RD092	RD084	
	RD035	RD086	RD093	RD088	
	RD044	RD087	RD095	RD089	
	RD045	RD090	RD096	RD094	
	RD068	RD097			
	RD071	RD098			
	RD072	RD099			
	RD075				
	RD091				

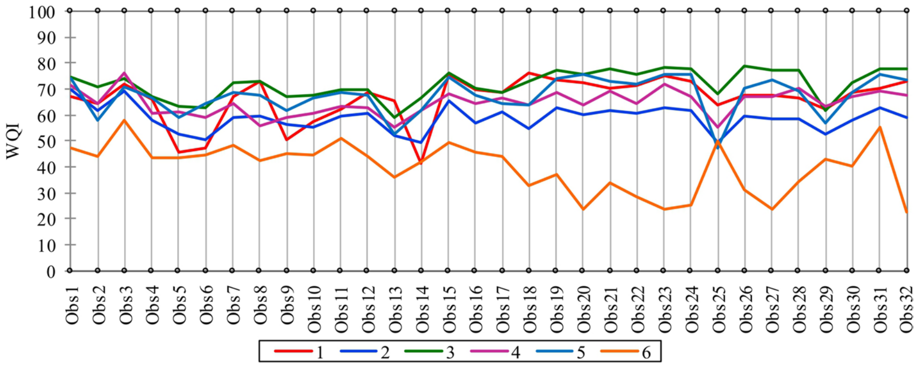

Fig. 6 Profile of the six clusters obtained in the Minas region of the Doce River basin

information may be needed. For those who have more than one station in the same cluster it is possible to consider abdicating one of them.

In Table 8, it is possible to observe the grouping of the stations among the clusters, as well as the identification of the UGRH and the watercourse in which they are inserted.

As can be observed in Table 8, all the stations grouped in cluster 1 are inserted in the UGRH1. It is verified that only the Piranga and Doce rivers presented more than one station in the same cluster, a fact that, as already mentioned, allows the abdication of some of them.

In the Piranga River, stations RD001 and RD007 are located in the cities of Piranga and Porto Firme, respectively, which, according to ANA (2017), have an index of 0.0%

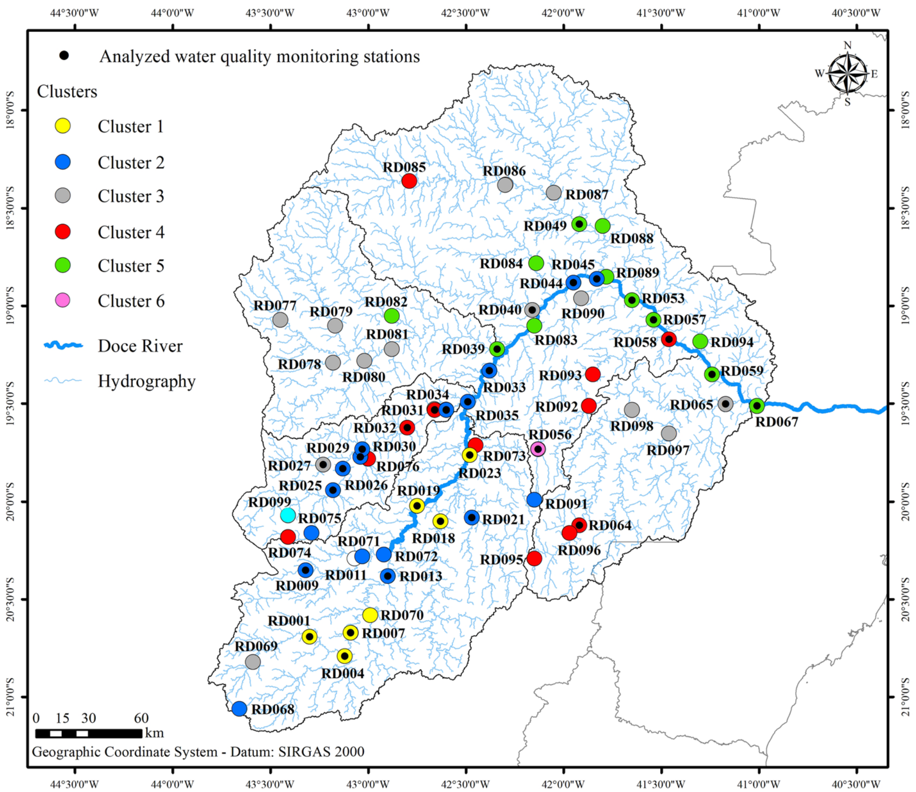

Fig. 7 Map resulting from the CA for the grouping of the 64 monitoring stations in the Minas Gerais portion of the Doce River basin

of collection and treatment of effluents. Despite the precariousness of basic sanitation, the stations did not present a significant trend for the WQI (RD001) and an inconclusive trend with possibility of elevation (RD007). Thus, when analyzing all the information, it is not recommended to exclude one of them, since both are susceptible to variations in water quality due to the release of untreated domestic effluent. In the Doce River (RD019 and RD023), the stations did not present a significant trend and are in the rural area, which implies minor importance to maintain both stations. However, due to the collapse of the tailings dam in the municipality of Mariana, the maintenance of both stations is extremely important since they are part of the water quality monitoring points that are used by IGAM to assess the impacts caused by the disaster (IGAM 2017a).

In cluster 2, there is more than one station in the Piranga, Carmo, Piracicaba and Doce rivers. For grouped stations in Piranga River, RD013 showed no trend for the WQI, while the RD068 station did not possess enough series of data for analysis. Despite the similarity between the water quality data, both stations can be considered as priorities in the monitoring network, since they are very distant from each other, also having stations that were grouped in clusters 1 and 3. In the Piracicaba River, only in the RD075 no trend analysis was performed, and all the others did not present a trend in the WQI data. Despite the nontrend of the data, stations RD025, RD026, RD029, RD034 are in or downstream of the cities of Rio Piracicaba, João Monlevade, Nova Era and Coronel Fabriciano, respectively.

Table 8 Grouping of the stations among the clusters and the identification of the UGRH and the watercourse in which they are inserted

Cluster	UGRH	Station	Water course
1	1 Piranga	RD001, RD007	Piranga River
		RD004	Xopotó River
		RD018	Casca River
		RD019, RD023	Doce River
		RD070	Turvo River
2	1 Piranga	RD009, RD071	Carmo River
		RD013, RD068	Piranga River
		RD021	Matipó River
		RD072	Doce River
	2 Piracicaba	RD025, RD026, RD029, RD034, RD075	Piracicaba River
		RD030	Peixe River
		RD035	Doce River
	4 Suaçuí	RD044, RD045	Doce River
	5 Caratinga	RD033	Doce River
		RD091	Pião Creek
3	1 Piranga	RD069	Piranga River
	2 Piracicaba	RD027	Santa Bárbara River
		RD099	Maquiné River
	3 Santo Antônio	RD077, RD081	Santo Antônio River
		RD078	Preto River
		RD079	Peixe River
		RD080	Tanque River
	4 Suaçuí	RD040	Corrente Grande River
		RD086	Suaçuí Grande River
		RD087	Urupuca River
	5 Caratinga	RD090	Traíras Stream
	6 Manhuaçu	RD065, RD098	Manhuaçu River
		RD097	José Preto River
4	1 Piranga	RD073	Sacramento River
	2 Piracicaba	RD031, RD032, RD074	Piracicaba River
		RD076	Prata River
	4 Suaçuí	RD085	Suaçuí Grande River
	5 Caratinga	RD058	Doce River
		RD092	Preto River
		RD093	Caratinga River
	6 Manhuaçu	RD064, RD095	Manhuaçu River
		RD096	São Mateus River

Table 8 (continued)

Cluster	UGRH	Station	Water course
5	3 Santo Antônio	RD039	Santo Antônio River
		RD082	Guanhães River
	4 Suaçuí	RD053, RD083	Doce River
		RD084	Suaçuí Pequeno River
		RD088	Itambacuri River
		RD049, RD089	Suaçuí Grande River
		RD094	Eme River
	5 Caratinga	RD057	Caratinga River
	6 Manhuaçu	RD059, RD067	Doce River
6	5 Caratinga	RD056	Caratinga River

Among the cities, only the Rio Piracicaba has 17.2% of its effluents collected and treated, while Coronel Fabriciano, which has the largest number of inhabitants and generates a load of 5775.0 kg BOD day^{-1}, this value is 0.0% (ANA 2017). Thus, although they are all allocated in the same watercourse, the stations must be maintained in the monitoring network.

In the Doce River, two of the stations are located upstream (RD044) and downstream (RD045) of the city of Governador Valadares, presenting an inconclusive trend for the WQI with possibility of reduction and non-trend, respectively. Although the city of Governador Valadares has an effluent collection rate of 95.4%, the treatment percentage corresponds to 0.0% (ANA 2017). Thus, it is noticed that the two stations were established in order to verify the influence of the discharge of the Governador Valadares effluent on the water quality of the Doce River. However, because the two stations are grouped in the same cluster, it can be concluded that the objective is not being met or that the impact of the discharge of the municipal effluent in the Doce River is not significant. For both hypotheses, the RD045 station has a priority over RD044, since, because it is located downstream, it allows to continue evaluating the impact of the discharge of the effluents from the municipality of Governador Valadares in the Doce River.

Cluster 3 grouped stations of all UGRHs, presenting the best WQI results among the six clusters obtained and more than one station grouped only in the Manhuaçu and Santo Antônio rivers. In the Manhuaçu River, both stations are in the rural area, with trend analysis only for RD065, which did not present a trend of elevation for the WQI. In the Santo Antônio River, the stations are also located in the rural area, however, none of them had enough data to perform the trend analysis. Therefore, due to the result of no trend of the RD065 station and the lack of information about the other stations makes it difficult to infer about them.

Cluster 4 has stations from the UGRHs 1, 2, 4, 5 and 6. Of the stations located in the Piracicaba River, only RD074 has no trend analysis, while RD031 and RD032 presented an inconclusive trend with the possibility of reduction and reduction trend, respectively. Among the two stations, RD031 is closer to the city of Timóteo, in the metropolitan region of Vale do Aço, considered an important pole of the steel industry in the state of Minas Gerais (ECOPLAN-LUME 2010b). Therefore, the maintenance of RD031 in the monitoring network is more relevant than RD032, since together with RD034, it is possible to evaluate the influence of the metropolitan region of Vale do Aço on the water quality of the Piracicaba River. The RD074, besides being far from the others, should be kept in the network as a monitoring measure in bedside areas.

In the Manhuaçu River, the RD064 station is in the city of Santana do Manhuaçu. It presented a reduction trend for the WQI and an elevation trend for the variables *E. coli,* nitrate and total solids, which demonstrates the importance of monitoring water quality on site. The RD095 station is located upstream of RD064 and the effluents from most of the municipalities in the region, including the municipality of Manhuaçu, which has the largest population of UGRH6, with 79,574 inhabitants (IBGE 2010). Although the municipality has a 95.0% domestic effluent collection index, the percentage of treatment corresponds to 0.0% (ANA 2017). Therefore, the RD064 station has priority over RD095 since it can better evaluate the impact of the discharge of the effluent from the region on the Manhuaçu River.

In cluster 5, there is more than one station allocated in the Suaçuí Grande e Doce rivers. Among the two stations allocated in the Suaçuí Grande River, only RD049 had enough data for the trend analysis, presenting a nonsignificant result for the WQI. RD049 is located after the cities of Frei Inocêncio and Mathias Lobato, both with an effluent collection and treatment index of 0.0% (ANA 2017). The RD089 station is located at the mouth of the Suaçuí Grande River and no longer receives the contribution of domestic effluents after the monitoring in RD049, receiving only the contribution of small tributaries and the Itambacuri River, which in turn already has the water quality monitoring being performed in the RD088 station. Therefore, station RD049 has priority over RD089.

For the Doce River, only in the RD083 station was not possible to carry out the trend analysis. The RD053 presented a significant elevation trend, while stations RD059 and RD067 presented nonsignificant results for the WQI. In addition to the elevation trend in WQI, RD053 showed a trend to reduce *E. coli* and total phosphorus, which are considered critical in UGRH4 (ECOPLAN-LUME 2010a; IGAM 2017b). As can be seen in Fig. 6, station RD053 is allocated between RD045 (cluster 2) and RD058 (cluster 4), which, as discussed above, was recommended to maintain them in the monitoring network. Thus, when analyzing all the information, it can be concluded that stations RD059 and RD067 should have a higher priority in the monitoring network compared to RD053.

Cluster 6 grouped only the RD056 station, which presented the worst WQI values (Fig. 5). The station presented a significant reduction trend for WQI and dissolved oxygen, in addition to an elevation trend for total phosphorus and nitrate. The station is in the Caratinga River, downstream of Santa Bárbara do Leste, Santa Rita de Minas and Caratinga municipalities, all of which have an effluent collection and treatment index equal to 0.0%. The municipality of Caratinga is still characterized as the most populous in UGRH6, with approximately 85,239 inhabitants (IBGE 2010) and a release of 3999.3 kg BOD day^{-1} (ANA 2017).

The results found for the RD056 station deserve attention of the water resource management agencies, so that management actions can be carried out to improve the water quality. The establishment of new monitoring stations in UGRH5 can also be performed since other areas of the basin may also be showing signs of deterioration of surface water quality. Figure 8 shows the violation percentage of the framing class according to the limits established by the legislation for the 64 monitoring stations evaluated in the Minas Gerais portion of the Doce River basin.

As shown in Fig. 8, the RD056 station was the one with the highest violation index of the framing class for the set of water quality variables analyzed, a result that corroborates with the CA, where the station was grouped in the cluster with the worst WQI values.

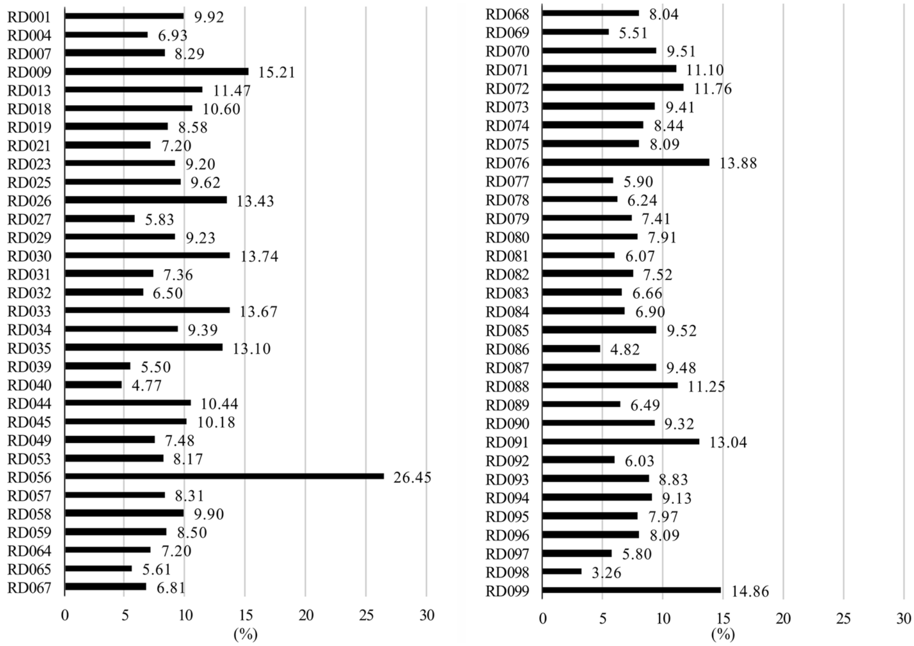

Fig. 8 Violation percentage of the framing class for the 64 monitoring stations according to the limits established by CONAMA Resolution No. 357/2005 and by COPAM/CERH-MG DN No. 01/2008

Stations with high index of violation of variables can be considered as the most relevant in the network since they indicate areas of degradation and require more monitoring. As for the stations with the lowest violation rates, most of them are grouped in cluster 3, which presented the best results for the WQI (Fig. 6), thus corroborating with the CA results.

4 Conclusions

The significative trend to reduce water quality is typical of metropolitan regions and large cities in the countryside, where water bodies present high degradation of water quality resulted from the discharge of domestic effluents and industrial effluents (point pollution). In addition to the contamination from the point pollution, the water quality deterioration is also affected by the diffuse pollution originating from farming areas.

The absence of a significative trend is still of concern because can represent a stagnation in violation percentage values and therefore the maintenance of a degradation state in the water bodies.

The increases in the concentrations of turbidity and total solids after the collapse of the dam it was not enough to cause significant elevation trends in the historical series of the affected stations.

The CA results allowed the identification of the main monitoring stations to be maintained in the network, thus subsidizing management and planning actions to monitor the water quality in the Minas Gerais portion of the Doce River basin. Stations RD044, RD032, RD095, RD89 and RD053 can be relocated or deactivated. RD056 has the highest degree of pollution, with priority being given to its maintenance in the monitoring area.

The results of the study demonstrate the potential of using methodologies in the temporal and spatial characterization of the stations monitoring data, which may support planning and management actions in the water quality monitoring network of the Doce River basin.

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