Impact of fecal contamination on surface water quality in the São Francisco River hydrographic basin in Minas Gerais, Brazil

Marina Salim Dantas, Josiani Cordova de Oliveira, Carolina Cristiane Pinto and Sílvia Corrêa Oliveira

ABSTRACT

Proper water quality monitoring is a valuable tool for water resource management, helping to identify polluting sources and risks related to the use of water resources. One of the main types of contamination found in Brazilian water bodies is fecal contamination, which originates mainly from point source pollution through wastewater disposal. Thus, this study analyzed water quality monitoring data from the responsible environmental body (Minas Gerais Institute of Water Management, IGAM), related to the fecal contamination indicator (FCI), for the years 2000–2018. This was done for the Minas Gerais portion of the São Francisco River basin (SFRB-MG), one of the most important basins in the country. The 10 sub-basins in the area were compared using statistical tools. The work found significant differences between the sub-basins in terms of FCI concentration, highlighting the most impacted ones (SF2, SF3, and SF5) as also being the most densely populated. It is necessary to invest in sanitation measures in order to ensure that water resources are preserved, as well as to reduce the public health risks of downstream municipalities that are supplied with previously contaminated water.

Key words | fecal contamination, São Francisco River hydrographic basin, surface water quality, wastewater

Marina Salim Dantas (corresponding author)
Josiani Cordova de Oliveira
Sílvia Corrêa Oliveira
Department of Sanitary and Environmental Engineering,
Federal University of Minas Gerais,
Av. Presidente Antônio Carlos, 6627,
Belo Horizonte, CEP 31270-901, MG,
Brazil
E-mail: *marina-dantas@hotmail.com*

Carolina Cristiane Pinto
Department of Chemical Engineering,
Federal University of Minas Gerais,
Av. Presidente Antônio Carlos, 6627,
Belo Horizonte, CEP 31270-901, MG,
Brazil

INTRODUCTION

The lack of collection and treatment of wastewater directly affects water quality and has become a major problem in the environmental, social, and public health spheres. It is essential to note the ecological imbalance caused by the disposal of untreated effluents into water bodies, and the risk associated with the supply of water that was previously contaminated by the release of effluents (ANA 2017). The disposal of untreated or insufficiently treated domestic wastewater is the main source of pressure on Brazilian water bodies (ANA 2012).

According to the National System of Information on Sanitation (SNIS 2017), 59.7% of the Brazilian population was served by a wastewater collection service in 2016, meaning that approximately 100 million people utilized alternative measures such as septic tanks or even directly releasing effluents into the environment. A study disclosed by the National Water Agency and the Ministry of Cities of Brazil (ANA 2017) exposes the situation of the Brazilian urban population regarding wastewater services: 43% of the population is supplied by a collective system (collective network and wastewater treatment plant – WWTP), 12% is served by an individual solution (septic tanks), 18% has its wastewater collected but not treated, and 27% is not supplied, meaning there is no treatment or collection of wastewater.

doi: 10.2166/wh.2019.153

In 2015, 44.69% of the urban population in the state of Minas Gerais (MG) had their wastewater treated through regularized WWTPs (FEAM 2016). This was consistent with the evaluation made by the National Water Agency (ANA 2017), where there was a 44% index of the population served by wastewater treatment in the state. In developing countries, river water subject to wastewater contamination is often used for domestic supply (Rochelle-Newall *et al.* 2016). Most of the municipalities in Minas Gerais (60%) are supplied exclusively by surface water and 20% are supplied simultaneously by surface and underground water sources (ANA 2010). Poor sanitation contributes to public health risks. In 2016, the rate of hospitalizations for diseases associated with inadequate sanitation in Minas Gerais was 135.3 per 100,000 inhabitants (IBGE 2017). In the São Francisco River basin, 97% of the urban population is served by the water supply network (ANA 2012).

The National Water Agency (ANA 2017) warns that from all generated organic load (9.1 thousand tons of biochemical oxygen demand (BOD)·day^{-1}) only 39% is removed using the current wastewater treatment infrastructure in the Brazilian municipalities. As a result, approximately 5.5 thousand tons of BOD·day^{-1} can reach receiving water bodies, in terms of residual organic load.

Thus, water bodies continue to flow with a high load of pollutants, representing a risk to the environment and public health, which may affect current and future downstream uses of water resources. A water quality monitoring program evaluating physicochemical and biological parameters is able to identify different pollutants in waterways and quantify polluting agents (Zhang *et al.* 2011). The Minas Gerais Institute of Water Management (IGAM), through the program *Águas de Minas* (Minas Waters Project), has conducted water quality monitoring in the state since 1997 (IGAM 2016). Microbiological fecal contamination parameters are analyzed, which determine the concentration of indicators of the presence of pathogenic organisms in the water.

The monitoring generates an extensive database containing many sites and long sampling periods, and it is thus necessary to conduct analyses of data series to guarantee proper management of the water resources in the state (Minas Gerais). Statistical tools are useful for data interpretation and to discover more accessible results for public policies and actions focused on water resource management (Simeonov *et al.* 2003; Ouyang *et al.* 2006; Zhang *et al.* 2011).

The current work thus aims to evaluate surface water quality monitoring data from the São Francisco River basin in Minas Gerais state (SFRB-MG), as a function of fecal contamination indicators considering a large time series (2000–2018). The sub-basins from the region were compared to identify those that were the most impacted, in terms of FCI concentration. Trend tests were carried out to verify if FCI concentration increases or decreases in the study area. This deep and wide water quality analysis of the impact of the fecal contamination in one of the most important basins in Brazil may help basin managers with their decision-making.

METHODS

Study area

The São Francisco River basin is the largest watershed fully located in Brazil, with a drainage area of 638,466 km^2, occupying 7.5% of the Brazilian territory (CBHSF & ANA 2004). Due to its great socioeconomic importance to Brazil, connecting many regions and states (503 municipalities from the states of Minas Gerais, Bahia, Pernambuco, Alagoas, Sergipe, Goiás, and the Federal District), the São Francisco River is known as the 'River of the National Unity'. The hydrographic region is divided into four physiographic regions: Upper São Francisco, Middle São Francisco, Lower-Middle São Francisco, and Lower São Francisco (MMA 2006), as illustrated in Figure 1. Due to its large territory, the basin covers cities with very distinct population densities as well as prevailing economic activities. The basin is characterized by its agricultural activities and hydroelectric potential (CBHSF & ANA 2004). The region has a total population of approximately 14.3 million inhabitants, according to the Brazilian Institute of Geography and Statistics (IBGE 2010), with a population growth of 11.3% between 2000 and 2010 (ANA 2012). In terms of domestic effluent collection and treatment, 62% of the wastewater generated in the basin is collected, and 63% of this is treated (ANA 2015). Thus, only approximately 40% of the total generated wastewater is treated.

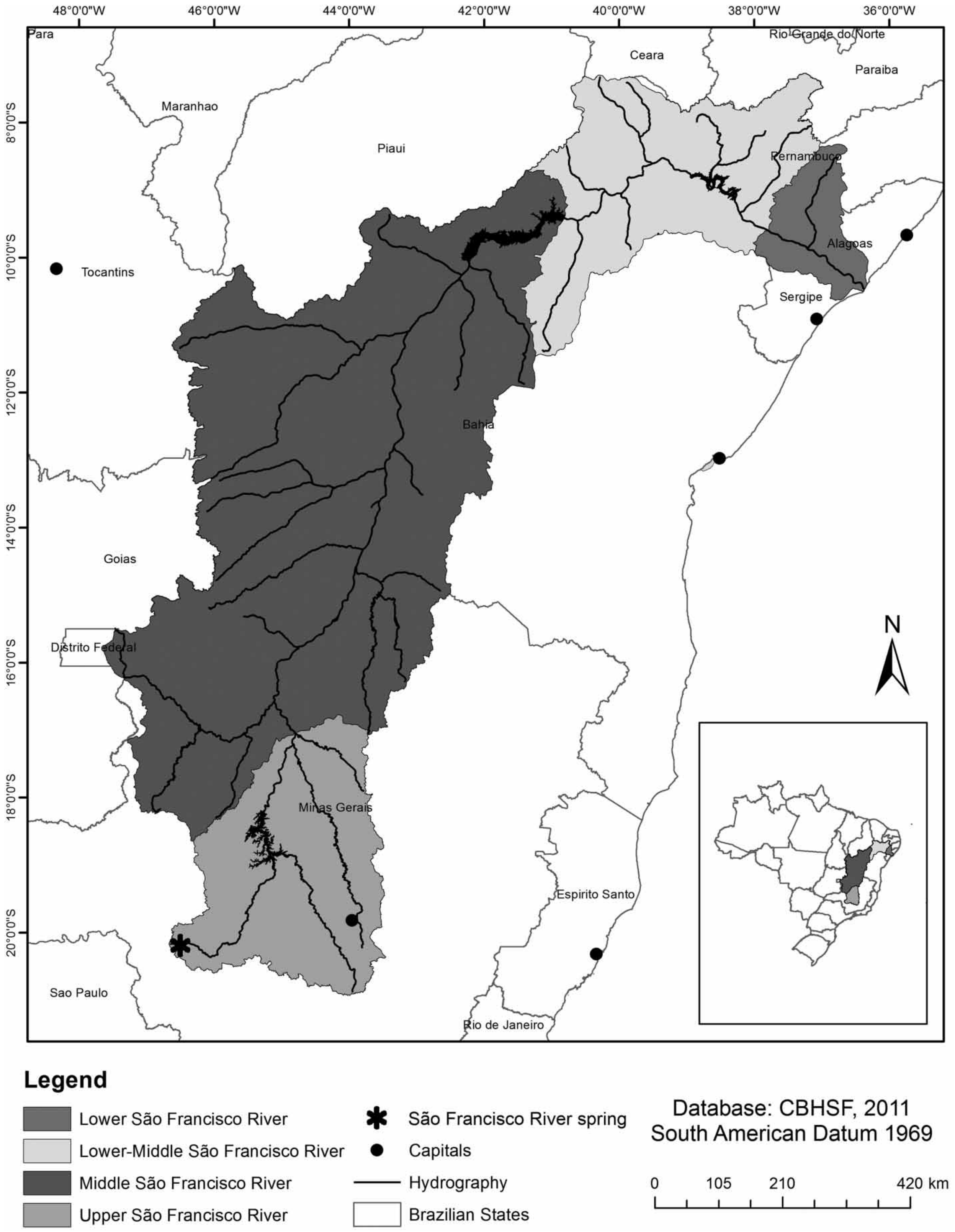


Figure 1 | Location of the São Francisco River basin and its four physiographic regions (Upper São Francisco, Middle São Francisco, Lower-Middle São Francisco, and Lower São Francisco).

The gross domestic product (GDP) of the basin was almost 250 billion reals in 2012, which corresponds to 5.7% of Brazil's total generated wealth that year (4,392 billion reals, approximately 8,600 billion dollars). The most important contribution is from the Upper São Francisco region (72%) (Nemus 2015), which is fully located in the state of Minas Gerais.

The São Francisco River spring is located in the municipality of São Roque de Minas/MG, and approximately 37% of the basin is within the state area, which is the object of the current study. In this state, the basin is divided into 10 Water Resource Management Units (WRMUs), which are physico-territorial units that comprise areas of basins, groups of basins or contiguous sub-basins with similar natural, socio-cultural and economic characteristics. The 10 WRMUs, also called sub-basins, are: High São Francisco River (SF1); Pará River (SF2); Paraopeba River (SF3); Três Marias Reservoir (SF4); Velhas River (SF5); Jequitaí and Pacuí Rivers (SF6); Paracatu River (SF7); Urucuia River (SF8); Pandeiros and Calindó Rivers (SF9); and Verde Grande River (SF10) (CERH 2010). Table 1 shows the population density in each WRMU.

Structuration and systematization of the database

Surface water quality monitoring data were obtained from the IGAM Minas Waters Project. The time period selected for the studied area (SFRB-MG) comprised the first trimester of 2000 until the second trimester of 2018.

It is important to emphasize that, from the first data retrieving of 2013, the parameter *Escherichia coli* (*E. coli*) started to be evaluated, replacing thermotolerant coliforms. According to the Joint Normative Deliberation COPAM/CERH n. 01/2008, *E. coli* is the only species of thermotolerant coliform whose habitat is the intestines of humans and homeothermic animals, where it appears in high densities. Hence, it is rarely found in water or soil that has not received fecal contamination (COPAM & CERH 2008). Thus, the parameters selected for the analyses in the selected time period were *E. coli* and thermotolerant coliforms, composing the fecal contamination indicator (FCI).

The detection method of FCI used in IGAM Minas Waters Project is the multiple-tube fermentation technique (Costa *et al.* 2017). Water quality analyses were performed in a laboratory accredited by the National Institute of Metrology, Quality and Technology (INMETRO), and followed *Standard Methods for Examination of Water and Wastewater* (APHA *et al.* 2012).

A total of 258 monitoring stations was analyzed in the study area, which had a sampling frequency of every three months (every month in a few cases of some stations located in the Velhas River channel).

Table 2 shows the number of monitoring sites analyzed in each WRMU from the SFRB-MG, while Figure 2 shows the location of the stations, different according to their

Table 1 | Population density in each WRMU of SFRB-MG

WRMU	Population density (residents per km^2)
SF1 – High São Francisco River	16.10
SF2 – Pará River	62.68
SF3 – Paraopeba River	93.24
SF4 – Três Marias Reservoir	9.21
SF5 – Velhas River	164.04
SF6 – Jequitaí and Pacuí Rivers	10.92
SF7 – Paracatu River	6.81
SF8 – Urucuia River	3.58
SF9 – Pandeiros and Calindó Rivers	8.75
SF10 – Verde Grande River	27.10

Source: Adapted from IGAM (2014).

Table 2 | Monitoring sites analyzed in each WRMU of SFRB-MG

WRMU	Number of water quality monitoring sites
SF1 – High São Francisco River	7
SF2 – Pará River	29
SF3 – Paraopeba River	33
SF4 – Três Marias Reservoir	18
SF5 – Velhas River	82
SF6 – Jequitaí and Pacuí Rivers	9
SF7 – Paracatu River	30
SF8 – Urucuia River	13
SF9 – Pandeiros and Calindó Rivers	16
SF10 – Verde Grande River	21
Total	258

rating class. In Brazil, inland water bodies are rated into five classes, each with target values for water quality parameters that must be achieved to maintain the quality of these water bodies, compatible with the locally predominant water uses. 'Special class' water bodies are intended for the most restrictive uses, such as human consumption after simplified treatment, and preservation of aquatic communities. The natural conditions of 'Special class' water bodies must be maintained. Hence, there are no target values specified in the legislation. 'Class 1' water bodies are intended for human consumption after simplified treatment and for recreation, while 'Class 2' water bodies require conventional treatment for human consumption. 'Class 3' water bodies require even more advanced treatment for human

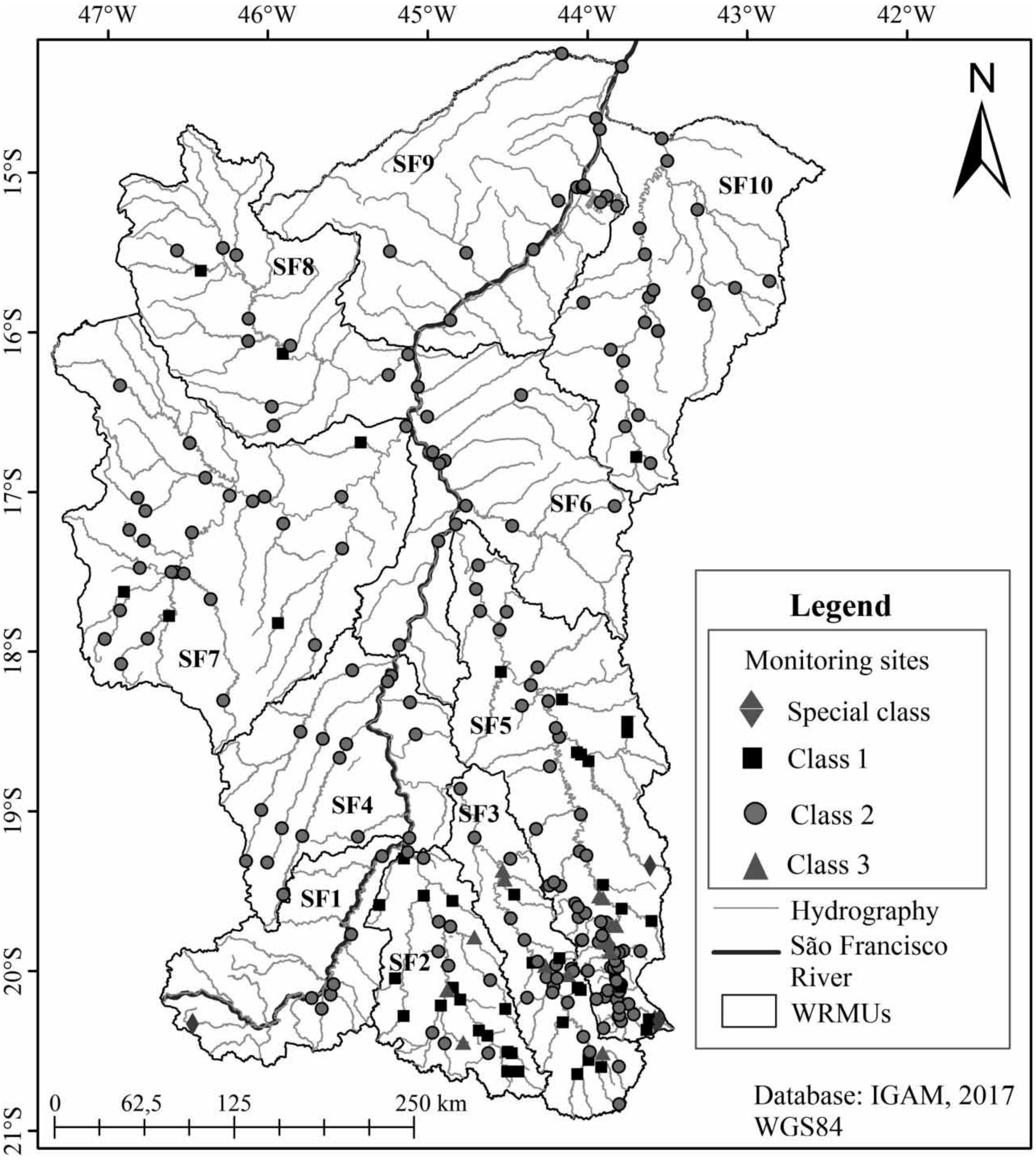


Figure 2 | Location of the evaluated monitoring sites, highlighted by WRMU and rating class.

consumption. Meanwhile, 'Class 4' water bodies are intended for less demanding uses, such as navigation.

In Minas Gerais, the Joint Normative Deliberation COPAM/CERH n. 01/2008 regards the water quality standards for each rating class, as well as the standards for disposal of effluents in recipient water bodies. The legislation establishes that *E. coli* can be determined in order to replace thermotolerant coliforms, respecting the same limits. The maximum permitted values for fresh water, according to each class, are 200 colony-forming units (CFU)$\cdot$100 mL^{-1} for class 1; 1,000 CFU$\cdot$100 mL^{-1} for class 2; and 4,000 CFU$\cdot$100 mL^{-1} for class 3. There are no target values for class 4.

Comparison between WRMUs

First, the descriptive statistics for the data from each WRMU of the study area were calculated. The Kruskal–Wallis nonparametric test was applied, followed by the multiple comparison test, when applicable, that is, when there is a significant difference between the concentrations of FCI in the sub-basins, at a 5% significance level (Conover 1999; Helsel & Hirsch 2002). In this stage, all data retrieved in the period for each WRMU were considered in all monitoring sites of each sub-basin. For the analyses, the software Statistica 13.0 was utilized.

The violation percentage was calculated for each WRMU, considering each monitoring site rating, according to the legally established limits. For the sites rated as 'Special class', the value for Class 1 was adopted, since according to the Joint Normative Deliberation COPAM/CERH n. 01/2008, 'In special class waters, the natural conditions of the water body must be maintained'.

Time series analysis

The Mann–Kendall nonparametric test was carried out in order to identify the change (increase or decrease) in FCI concentration over time for each monitoring site. Results were shown in terms of percentage of monitoring sites for each WRMU.

Most concentrations in surface waters show strong seasonal patterns (Hirsch *et al.* 1982; Helsel & Hirsch 2002). Hence, the Kruskal–Wallis nonparametric test was applied initially ($\alpha = 5\%$) to verify whether there are significant differences in FCI concentrations between the monitored semesters. If seasonality were found, then the seasonal Kendall test, which is insensitive to the existence of seasonality (Hirsch *et al.* 1982), was applied.

The existence of autocorrelation in the data increases the probability of detecting trends when no trends exist, and vice versa (Hamed & Rao 1998; Helsel & Hirsch 2002), so the existence of data autocorrelation was verified. The autocorrelation function measures the degree of correlation of a variable at a given time with itself at a later time (Christofaro & Leão 2009). In the case of data autocorrelation, the modified Mann–Kendall trend test was applied for autocorrelated data, as proposed by Hamed & Rao (1998).

The trend tests result in a p-value, in which at the significance level of 5%, for $p > 0.05$, there is no trend conclusion; and for $p < 0.05$, there is a tendency, which may be positive when there is an elevation trend ($S > 0$) or negative when there is a reduction trend ($S < 0$) (Hirsch *et al.* 1982; Yenilmez *et al.* 2011). Kruskal–Wallis and autocorrelation analysis were applied in the software Statistica 13.0 and trend analysis in XLSTAT 2019.1.3.

RESULTS AND DISCUSSION

Comparison of water quality between sub-basins

The descriptive statistics from the data of each WRMU are shown in Table 3.

After the application of Kruskal–Wallis and multiple comparison tests for FCI concentration data, it was possible to compare the WRMUs, as shown in Figures 3 and 4. It is apparent that the most impacted sub-basins, regarding FCI, are SF3 (Paraopeba River) and SF5 (Velhas River), which did not differ significantly and were higher than all other sub-basins. In addition, SF2 (Pará River) was also considered one of the most impacted sub-basins since its results were higher than all other sub-basins, with the exception of SF3 and SF5. These three WRMUs, which are the most impacted by fecal contamination, cover the Belo Horizonte Metropolitan Region (BHMR) municipalities. Thus, they are the most densely populated of the entire Minas Gerais portion of the São Francisco River basin (Table 1)

Table 3 | Descriptive statistics for the FCI concentrations (CFU·100 mL^{-1}) by WRMU

WRMU	No. of data	Arithmetic mean	Standard deviation	Geometric mean	Min.	10th perc.	25th perc.	50th perc. (median)	75th perc.	90th perc.	Max.
SF1	463	2,785	11,714	417	2	50	110	350	1,300	5,000	160,000
SF2	1,573	23,625	50,780	2,025	1	100	300	1,700	14,136	90,000	241,960
SF3	1,908	23,821	46,222	2,830	1	70	486	4,743	24,000	90,000	241,960
SF4	938	9,365	31,662	529	1	30	80	490	2,800	17,000	241,960
SF5	5,901	39,039	63,612	3,184	1	50	243	5,000	35,000	160,000	241,960
SF6	354	12,792	44,127	421	1	30	70	231	1,700	17,000	241,960
SF7	1,494	5,638	22,197	392	1	33	97	290	1,400	8,000	241,960
SF8	632	6,376	19,832	384	1	23	58	230	2,300	17,000	160,000
SF9	782	1,799	11,017	108	1	2	30	110	490	2,300	160,000
SF10	926	8,517	30,458	385	1	30	80	280	1,572	13,000	241,960

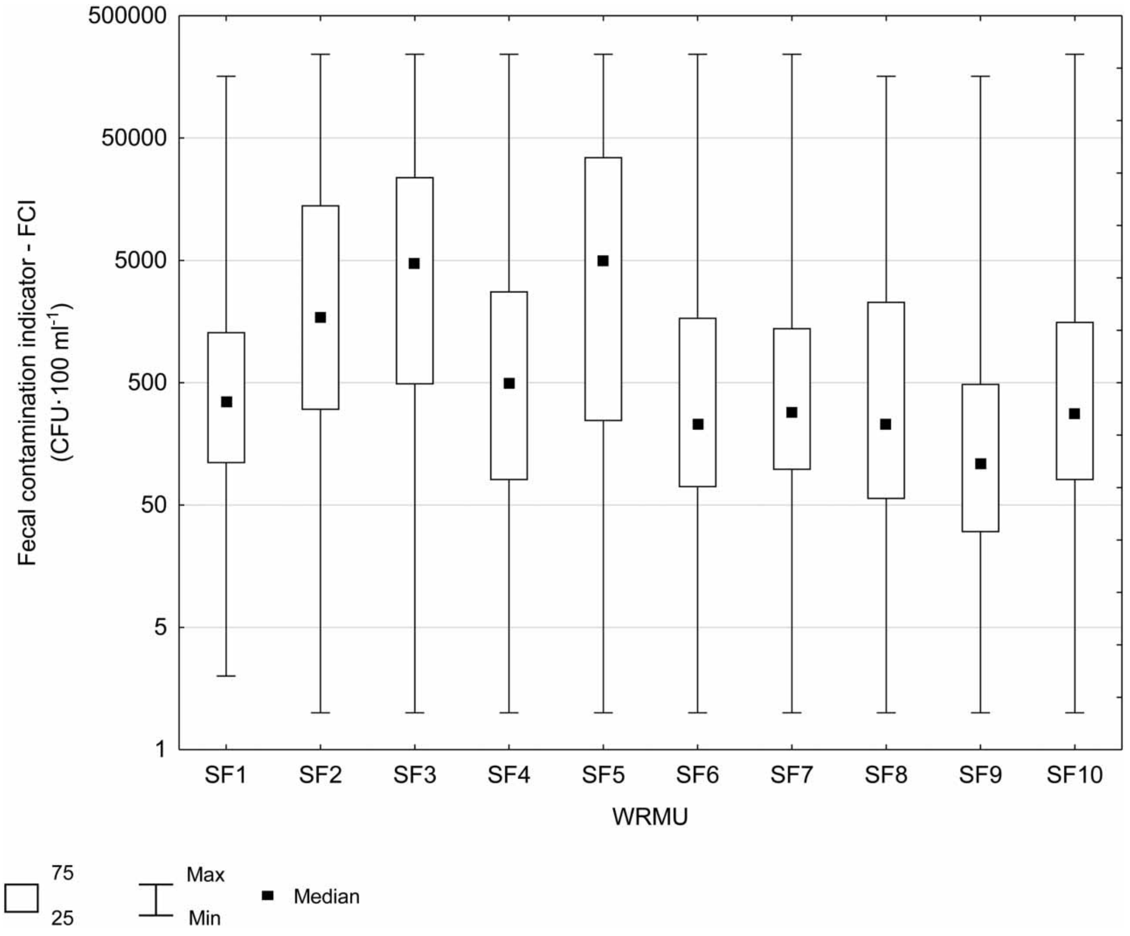
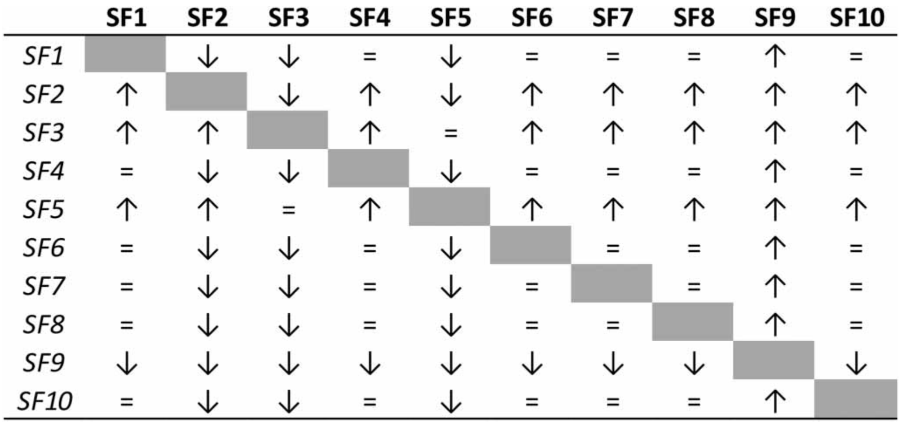


Figure 3 | Box-plot of the FCI concentrations of WRMUs.



	SF1	**SF2**	**SF3**	**SF4**	**SF5**	**SF6**	**SF7**	**SF8**	**SF9**	**SF10**
SF1		↓	↓	=	↓	=	=	=	↑	=
SF2	↑		↓	↑	↓	↑	↑	↑	↑	↑
SF3	↑	↑		↑	=	↑	↑	↑	↑	↑
SF4	=	↓	↓		↓	=	=	=	↑	=
SF5	↑	↑	=	↑		↑	↑	↑	↑	↑
SF6	=	↓	↓	=	↓		=	=	↑	=
SF7	=	↓	↓	=	↓	=		=	↑	=
SF8	=	↓	↓	=	↓	=	=		↑	=
SF9	↓	↓	↓	↓	↓	↓	↓	↓		↓
SF10	=	↓	↓	=	↓	=	=	=	↑	

Figure 4 | Results of the multiple comparison test following the significant difference detected by the Kruskal–Wallis test, considering the 10 WRMUs. *Note:* = Group in italic (left column) do not differ significantly ($\alpha = 5\%$) from the group in bold (top). ↑ Group in italic (left column) significantly ($\alpha = 5\%$) higher than the group in bold (up). ↓ Group in italic (left column) significantly ($\alpha = 5\%$) lower than the group in bold (top).

and have the largest urban areas. Consequently, the contamination by domestic effluents was the most influential factor in these results. Of the total volume of wastewater collected in Brazil, only 10% is treated at a tertiary level (ANA 2012). Therefore, even when treatment is carried out in a given municipality, FCI removal is insufficient.

This outcome is in agreement with the findings of Trindade (2013). The author evaluated the monitoring data of 72 water quality parameters (including thermotolerant coliforms) from SFRB-MG comprising the period spanning 2008–2011. The research showed that, among the 10 WRMUs, SF5 (Velhas River) had the highest water quality degradation by domestic and industrial effluents, and that SF5, SF3 (Paraopeba River), and SF2 (Pará River) showed higher concentrations of thermotolerant coliforms. The concentrations in the three sub-basins were significantly higher than the other sub-basins' concentrations found in the statistical tests, and did not show differences relating to this parameter, which also had the highest violation percentage according to the legislation in all units during the time period in question.

The least impacted sub-basin was SF9 (Pandeiros and Calindó Rivers), that showed a significant difference with a lower median value compared to all others. The results obtained in the tests also corroborated the descriptive statistics, which showed that SF9 had lower median and percentile values compared to the others. This is also shown in Figure 3. This sub-basin has a low population density (Table 1) and is largely composed of a rural population, i.e., 44.6% of rurals among the total inhabitants of the basin in 2010 (IGAM n.d.). Thus, it is possible to affirm that the impact caused by point domestic effluent disposal is considerably lower in the water bodies of the region. The presence of the Pandeiros River Environmental Protection Area (APA), known as the Pantanal of Minas Gerais, is also important. This is the largest sustainable use conservation area in Minas Gerais (IEF 2009). Hence, the expectation of the current study was for lower degradation in terms of fecal contamination.

The same study area (SFRB-MG) was analyzed by Costa *et al.* (2017) between 2000 and 2013, specifically looking at the violations of 26 water quality parameters when compared to the legislation. FCI represented the highest violation percentage for all WRMUs, except for SF9 (Pandeiros and Calindó Rivers), where it was the fourth most violated parameter. This result was related to the disposal of untreated or improperly treated domestic effluents, as well as to the diffuse pollution from livestock rural drainage.

The violation percentage for each WRMU (Figure 5), considering the limits for each class of their respective monitoring stations, was also calculated. The limits are established by the Joint Normative Deliberation COPAM/CERH n. 01/2008.

Notably, the violation percentage was indeed higher in the sub-basins identified as the most impacted by fecal contamination, SF2, SF3, and SF5, and lower in the least impacted, SF9. However, the violation percentage was higher in sub-basin SF2 when compared to SF3 and SF5, with these two showing significantly higher median concentration

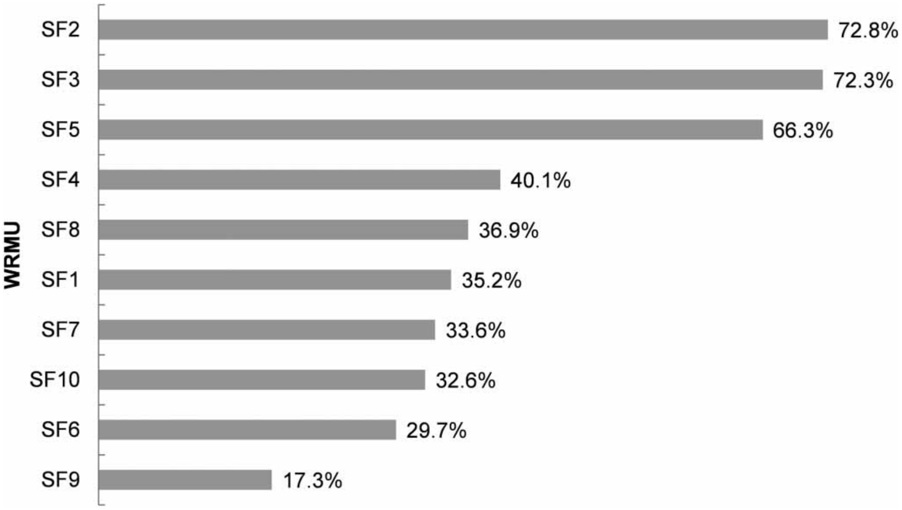


Figure 5 | Violation percentage of FCI for each WRMU, considering the water bodies' rating from their monitoring sites.

values than SF2 in the multiple comparison test, as shown in Figures 3 and 4. This may be due to the fact that the sites from Pará River basin violate limits more frequently, and the sites from Paraopeba River basin and Velhas River basin violate the limits by a greater magnitude over the target values.

SF3 and SF5 WRMUs had 30% of monitoring stations with median concentration above 20,000 CFU·100 mL^{-1}. This represents a five times higher concentration than target values for Class 3 water bodies, the least restrictive in the legislation. For SF2, the percentage was 21%. In the other sub-basins (SF1, SF4, SF6, SF7, SF8, SF9, and SF10) the percentage of sites with median FCI concentration above 20,000 CFU·100 mL^{-1} was below 12%.

Time series analysis

Table 4 shows the results of the Kruskal–Wallis test (comparison between trimesters), i.e., the percentage of sites with seasonality in the period. The percentage of sites that did not show any significant trends and the percentage of sites that showed trends of elevation or reduction in FCI concentration can also be seen.

Table 4 shows that SF2, SF3, and SF5 WRMUs, identified as the most impacted in terms of FCI concentration, have low percentage of sites with seasonality in the period. These WRMUs cover the BHMR municipalities, so they are densely populated and fecal contamination mainly arises from point source pollutions through wastewater disposal. In other sub-basins, there must be non-point source pollutions related to livestock activity, which results in higher FCI concentration during the rainy season (first and fourth semesters in the region) through rainfall runoff.

The influence of seasonality on FCI concentration was identified in several watersheds, in different countries in different climates (Schilling *et al.* 2009; Daly *et al.* 2013; Laurent & Mazumder 2014; Tornevi *et al.* 2014; Rochelle-Newall *et al.* 2016). Seasonal variability is more strongly associated with runoff in catchments where contamination is related to diffuse fecal sources (Laurent & Mazumder 2014). In more

Table 4 | Kruskal–Wallis and Mann–Kendall/seasonal Kendall test results in various WRMUs

WRMU	% Sites with seasonality	% Sites – no significant trend	% Sites – significant trend	
			Elevation	Reduction
SF1	71%	86%	0%	14%
SF2	44%	88%	13%	0%
SF3	48%	71%	14%	14%
SF4	100%	86%	14%	0%
SF5	37%	75%	8%	17%
SF6	100%	75%	25%	0%
SF7	88%	88%	13%	0%
SF8	75%	100%	0%	0%
SF9	71%	86%	0%	14%
SF10	50%	75%	0%	25%

urbanized regions, high variability in FCI concentration is mainly verified through point-source contamination, which is often unrelated to rainfall runoff (Schilling *et al.* 2009; Daly *et al.* 2013; Laurent & Mazumder 2014).

Regarding the results of the trend test for all WRMUs, as shown in Table 4, most monitoring stations showed no significant trend. Although Costa *et al.* (2017) identified the FCI parameter as the one related to more monitoring stations with significant elevation trends in violation percentages, they also found that most stations presented no trend for all WRMUs. According to the authors, the results are alarming, as they show the maintenance of a degradation state in water bodies from SFRB-MG.

CONCLUSIONS

Following the evaluations made for the FCI data retrieved from IGAM between 2000 and 2018, it is concluded that there is still a precarious situation of basic sanitation in the 10 sub-basins of the area. Despite the great socioeconomic importance of the area for Brazil and the use of water resources for many activities, water bodies find themselves degraded by fecal contamination in the region where the river starts and where there is a large part of the basin population, mainly due to domestic effluent disposal.

The most affected WRMUs regarding fecal contamination were SF5 (Velhas River) and SF3 (Paraopeba River), followed by SF2 (Pará River). These are the densest regions of the entire study area, comprising the BHMR sub-basins. Thus, the release of untreated or insufficiently treated sewage was the main factor influencing the results. The most impacted WRMUs were also those showing higher proportions of monitoring sites with median FCI concentration values above 20,000 $\mathrm{CFU{\cdot}100\,mL^{-1}}$.

On the other hand, the least impacted WRMU in terms of fecal contamination was SF9 (Pandeiros and Calindó Rivers). This sub-basin has a low population density and contains the important Pandeiros River Environmental Protection Area. Thus, a lower FCI concentration was already expected.

It can be concluded based on the findings that in urbanized areas, fecal contamination is mainly from point sources, while in less dense areas, diffuse pollution can also contribute to contamination, with a more seasonal influence. For most monitoring stations in all WRMUs there was no trend in concentrations over time, indicating the maintenance of a degradation state in water quality in SFRB-MG.

It is necessary to invest in actions, projects, and public policies involving sanitation in the municipalities of this important Brazilian region, in order to ensure proper collection and treatment of wastewater, reducing risks to public health and assuring higher environmental preservation.

ACKNOWLEDGEMENTS

The authors would like to thank the Instituto Mineiro de Gestão das Águas (IGAM) for providing the monitoring data, Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for their financial support during the course of the research. The funding sources had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

REFERENCES

Agência Nacional de Águas – ANA 2010 *Abastecimento urbano de água: Resultados por estado – Volume 2 (Urban water supply: Results by State – Volume 2)*. Available from: http://atlas.ana.gov.br/Atlas/downloads/atlas/Resumo%20Executivo/Atlas%20Brasil%20-%20Volume%202%20-%20Resultados%20por%20Estado.pdf (accessed 30 August 2019).

Agência Nacional de Águas – ANA 2012 *Panorama da Qualidade das Águas Superficiais do Brasil (Brazilian Surface Water Quality Overview)*. Available from: http://arquivos.ana.gov.br/imprensa/publicacoes/Panorama_Qualidade_Aguas_Superficiais_BR_2012.pdf (accessed 30 August 2019).

Agência Nacional de Águas – ANA 2015 *Conjuntura dos Recursos Hídricos no Brasil: regiões hidrográficas brasileiras (Water Resources in Brazil: Brazilian Hydrographic Regions)*. Available from: http://www.snirh.gov.br/portal/snirh/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/conjuntura_informe_2015.pdf (accessed 30 August 2019).

Agência Nacional de Águas – ANA 2017 *Atlas Esgotos: Despoluição de bacias hidrográficas (Sewage Atlas: Basin* *depollution)*. Available from: http://arquivos.ana.gov.br/imprensa/publicacoes/ATLASeESGOTOSDespoluicaodeBaciasHidrograficas-ResumoExecutivo_livro.pdf (accessed 30 August 2019).

APHA/AWWA/WEF 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Christofaro, C. & Leão, M. M. D. 2009 Caracterização temporal do arsênio nos cursos d'água da bacia hidrográfica do rio das Velhas, MG, Brasil, ao longo de uma década (1998–2007) (Temporal characterization of arsenic in the watercourses of the Velhas river basin, MG, Brazil, over a decade (1998–2007)). *Revista Ambiente & Água* **4** (3), 54–66.

Comitê da Bacia Hidrográfica do Rio São Francisco – CBHSF & Agência Nacional de Águas – ANA 2004 *Plano Decenal dos Recursos Hídricos da Bacia Hidrográfica (Ten-year Water Resources Basin Plan)*. Available from: http://www.saofrancisco.cbh.gov.br/_docs/planos/PlanoDecenaldeRecursosHidricos.pdf (accessed 30 August 2019).

Conover, W. J. 1999 *Practical Nonparametric Statistics*, 3rd edn. Wiley, New York, USA.

Conselho Estadual de Política Ambiental & Conselho Estadual de Recursos Hídricos de Minas Gerais 2008 *Deliberação Normativa Conjunta COPAM/CERH-MG n. 01, 2008 (Joint Normative Deliberation COPAM/CERH n. 01/2008)*. COPAM & CERH, Belo Horizonte, Brazil.

Conselho Estadual de Recursos Hídricos de Minas Gerais 2010 *Deliberação Normativa CERH-MG n. 36, 2010 (Normative Deliberation CERH n. 36/2010)*. CERH, Belo Horizonte, Brazil.

Costa, E. P., Pinto, C. C., Soares, A. L. C., Melo, L. D. V. & Oliveira, S. C. 2017 Evaluation of violations in water quality standards in the monitoring network of São Francisco River Basin, the third largest in Brazil. *Environmental Monitoring Assessment* **189** (11), 2–16.

Daly, E., Kolotelo, P., Schang, C., Osborne, C. A., Coleman, R., Deletic, A. & McCarthy, D. T. 2013 *Escherichia coli* concentrations and loads in an urbanised catchment: the Yarra River, Australia. *Journal of Hydrology* **497**, 51–61.

Fundação Estadual do Meio Ambiente – FEAM 2016 *Minas Trata Esgoto (Minas Treat Sewage Program)*. Available from: http://feam.br/images/stories/2017/Minas_trata_esgoto/Minas_trata_Esgoto_relat%C3%B3rio_2016_-_link.pdf (accessed 30 August 2019).

Hamed, K. H. & Rao, A. R. 1998 A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* **204** (1–4), 182–196.

Helsel, D. R. & Hirsch, R. M. 2002 *Statistical Methods in Water Resources*. Techniques of Water Resources Investigations Series, Book 4, Chapter A3. US Geological Survey, Reston, VA, USA.

Hirsch, R. M., Slack, J. R. & Smith, R. A. 1982 Techniques of trend analysis for monthly water quality data. *Water Resources Research* **18** (1), 107–121.

Instituto Brasileiro de Geografia e Estatística – IBGE 2010 *Pesquisa Nacional de Saneamento Básico – 2008 (Nacional Survey of Basic Sanitation – 2008)*. Available from: https://biblioteca.ibge.gov.br/visualizacao/livros/liv45351.pdf (accessed 30 August 2019).

Instituto Brasileiro de Geografia e Estatística – IBGE 2017 *Tabela 898 – Internações hospitalares por doenças relacionadas ao saneamento ambiental inadequado, total e segundo as categorias de doenças. SIDRA. Indicadores de Desenvolvimento Sustentável – Edição 2017 (Table 898 – Hospital Admissions for Diseases Associated with Inadequate Sanitation, Total and According to Disease Categories. SIDRA. Sustainable Development Indicators – 2017 Edition)*. Available from: https://sidra.ibge.gov.br/tabela/898 (accessed 27 August 2019).

Instituto Estadual de Florestas – IEF 2009 *Boletim Técnico Científico da Diretoria de Biodiversidade*. Pandeiros: O pantanal mineiro (Pandeiros: The Pantanal of Minas Gerais). Instituto Estadual de Florestas, Belo Horizonte, Brazil.

Instituto Mineiro de Gestão Das Águas – IGAM 2014 *2° Relatório de Gestão e Situação dos Recursos Hídricos em Minas Gerais (2nd Report on Water Resources Management and Situation in Minas Gerais)*. Available from: http://www.cbhdoce.org.br/documentos-sobre-recursos-hidricos/2-relatorio-de-gestao-e-situacao-dos-recursos-hidricos-de-minas-gerais-2013 (accessed 5 November 2019).

Instituto Mineiro de Gestão Das Águas – IGAM 2016 *Qualidade das águas superficiais de Minas Gerais em 2015: Resumo Executivo (Surface Water Quality of Minas Gerais State in 2015: Executive Summary)*. Available from: http://200.198.57.118:8080/handle/123456789/322 (accessed 30 August 2019).

Instituto Mineiro de Gestão Das Águas – IGAM n. d. *Comitês estaduais – MG – Bacia do rio São Francisco (State Committes – MG – São Francisco River Basin)*. Available from: http://comites.igam.mg.gov.br/comites-estaduais-mg (accessed 6 March 2017).

Laurent, J. S. & Mazumder, A. 2014 Influence of seasonal and inter-annual hydrometeorological variability on surface water fecal coliform concentration under varying land-use composition. *Water Research* **48**, 170–178.

Ministério do Meio Ambiente – MMA 2006 *Caderno da Região Hidrográfica do São Francisco (São Francisco Hydrographic Region)*. Available from: https://www.mma.gov.br/estruturas/161/_publicacao/161_publicacao03032011023538.pdf (accessed 30 August 2019).

Nemus 2015 *Gestão e Requalificação Ambiental. Plano de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco 2016–2025: RP3 Cenários de desenvolvimento e prognósticos da bacia hidrográfica do rio São Francisco. Volume 1 – Relatório (Water Resources Plan of the São Francisco River Basin 2016–2025: RP3 Development Scenarios and Forecasts of the São Francisco river Basin. Volume 1 – Report)*. Available from: http://2017.cbhsaofrancisco.org.br/wp-content/uploads/2015/10/12-e-13.10.2015-%E2%80%93-SSA-%E2%80%93-RP3_V1_Relatorio.pdf (accessed 30 August 2019).

Ouyang, Y., Nkedi-Kizza, P., Wu, Q. T., Shinde, D. & Huang, C. H. 2006 Assessment of seasonal variations in surface water quality. *Water Research* **40** (20), 3800–3810.

Rochelle-Newall, E. F., Ribolzi, O., Viguier, M., Thammahacksa, C., Silvera, N., Latsachack, K., Dinh, P., Naporn, P., Sy, H. T., Soulileuth, B., Hmaimum, N., Sisouvanh, P., Robain, H., Janeau, J., Valentin, C., Boithias, L. & Pierret, A. 2016 Effect of land use and hydrological processes on *Escherichia coli* concentrations in streams of tropical, humid headwaters catchments. *Scientific Reports* **6** (32974), 1–12.

Schilling, K. E., Zhang, Y., Hill, D. R., Jones, C. S. & Wolter, C. F. 2009 Temporal variations of *Escherichia coli* concentrations in a large Midwestern river. *Journal of Hydrology* **365**, 79–85.

Simeonov, V., Stratis, J. A., Samara, C., Zachariadis, G., Voutisa, D., Anthemidis, A., Sofoniou, M. & Koumitzis, T. 2003 Assessment of the surface water quality in Northern Greece. *Water Research* **37** (17), 4119–4124.

Sistema Nacional de Informações Sobre Saneamento – SNIS 2017 *Diagnóstico dos serviços de água e esgotos – 2015 (Diagnosis of Water and Wastewater Services – 2015)*. Available from: http://www.snis.gov.br/diagnostico-agua-e-esgotos/diagnostico-ae-2015 (accessed 30 August 2019).

Tornevi, A., Bergstedt, O. & Forsberg, B. 2014 Precipitation effects on microbial pollution in a river: Lag structures and seasonal effect modification. *Plos One* **9** (5), 1–10.

Trindade, A. L. C. 2013 *Aplicação de Técnicas Estatísticas para Avaliação de Dados de Monitoramento de Qualidade das Águas Superficiais da Porção Mineira da Bacia do Rio São Francisco (Application of Statistical Techniques for Analysis of Surface Water Quality Monitoring Data of the São Francisco River Basin in Minas Gerais)*. Master's dissertation, Department of Sanitary and Environmental Engineering, Federal University of Minas Gerais, Belo Horizonte, Brazil.

Yenilmez, F., Keskin, F. & Aksoy, A. 2011 Water quality trend analysis in Eymir Lake, Ankara. *Physics and Chemistry of the Earth* **36** (5–6), 135–140.

Zhang, X., Wang, Q., Liu, Y., Wu, J. & Yu, M. 2011 Application of multivariate statistical techniques in the assessment of water quality in the Southwest New Territories and Kowloon, Hong Kong. *Environmental Monitoring Assessment* **173** (1–4), 17–27.

First received 11 June 2019; accepted in revised form 14 November 2019. Available online 9 December 2019