Water quality index and spatio-temporal perspective of a large Brazilian water reservoir

Karla Lorrane de Oliveira, Ramatisa Ladeia Ramos, Sílvia Corrêa Oliveira and Cristiano Christofaro

ABSTRACT

The water spatio-temporal variability of the Irapé Hydroelectric Power Plant reservoir and its main tributaries was evaluated by analysing the temporal trend of the main parameters and applying the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), using data from 2008 to 2018. This reservoir is in Minas Gerais, Brazil, and covers an area of approximately 143 km^2 across seven municipalities. The dissolved iron (DFe) presented the highest percentage of standards violations (31.7% to 80.5%), most frequently in the reservoir tributaries. The Mann–Kendall tests indicated that the monitoring stations showed an increasing trend of 78.5% $N–NH_4^+$ and 64.1% DFe. During the evaluated period, the reservoir waters were classified as excellent (1.2%), good (61.3%), acceptable (29.5%), and poor (8.0%) according to the WQI for the proposed use. The poorest quality classes were more frequent in the tributaries, especially in the year 2009. The WQI seasonal assessment indicated a worsening during the rainy season in 57% of the stations, as a result of external material transport to the water bodies. The CCME WQI, in conjunction with temporal statistical analysis, contributed to the interpretation of the monitoring data, generating important information for reservoir water quality management.

Key words | environmental statistics, hydroelectric reservoir, spatio-temporal perspective, water quality index

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HIGHLIGHTS

- The large Brazilian reservoir and tributaries water was studied by statistical techniques in conjunction with a WQI.
- Mann-Kendall tests indicated the stations with an increasing trend in the parameters analyzed.
- The seasonal WQI indicated a worsening in the stations in the rainy seasons.
- CCME WQI and temporal statistical analysis generated information that can be used in reservoir management.

INTRODUCTION

Quality assessment is essential for the proper use of water in different human activities and is affected by natural and anthropogenic factors as well as by hydrological dynamics. Lentic ecosystems, such as reservoirs, have characteristics that affect the spatio-temporal scale, presenting a different dynamic to lotic ecosystems. Thus, programmes for monitoring physical, chemical, and biological parameters of water quality in these environments are indispensable for a

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better understanding and evaluation of water body conditions. However, these programmes generate a complex dataset, requiring specific tools for proper interpretation and evaluation of the temporal and spatial variability in the water quality parameters.

Several statistical techniques can be used to understand the temporal dynamics in water reservoirs, such as tests of seasonality and temporal trends of quality parameters (Penev *et al.* 2014). These analyses allow us to determine, statistically, if the values of a random variable are decreasing or increasing over a certain period. We can also determine the seasonality of these variables (Helsel & Hirsch 2002; Yenilmez *et al.* 2011).

The complexity of interpreting many quality parameters can be reduced by applying quality indices that enable simultaneous evaluation of several parameters as well as natural and anthropic influences on the aquatic ecosystem's environmental dynamics. The water quality index (WQI), developed by the Canadian Council of Ministers of the Environment (CCME), aims to assess the distance between the current water quality and the goal established by the water resource framework (CCME 2001). Some studies have demonstrated the applicability and contribution of WQI to water quality diagnosis (Rosemond *et al.* 2008; Tyagi *et al.* 2013). These benefits can be extended with their use in conjunction with other statistical analyses.

The Irapé Hydroelectric Power Plant (HPP), located in the state of Minas Gerais, Brazil, is in a semi-arid region at risk of desertification (Tomasella *et al.* 2018). It has a reservoir of approximately 143 km^2, whose waters are used by the population of seven municipalities. Population growth and climate change have increased concerns about the water quality in this reservoir. Thus, understanding the water quality spatio-temporal dynamics of the Irapé HPP Reservoir and its tributaries is highly relevant, and may support the actions of decision makers (Helsel & Hirsch 2002; Penev *et al.* 2014) while contributing to a more efficient use of its waters by the local population.

In this study, the spatio-temporal variability of surface water in the Irapé HPP Reservoir and its main tributaries was evaluated using statistical techniques, comparison with environmental standards, and application of the CCME WQI. The association between statistical analysis and quality indices allows the identification of the points under greatest anthropogenic pressure in the reservoir and its surroundings, evaluates natural influences, and helps understand the temporal dynamics of pollutants in the reservoir and its tributaries. Notably, the results of the study can be applied to other reservoirs and can aid in multiple water use analysis.

MATERIALS AND METHODS

Study area

The Irapé HPP (Presidente Juscelino Kubitscheck Hydroelectric Plant), located at 16°44′15″ S and 42°34′30″ W, was inaugurated in 2006 and has a 142.95 km^2 reservoir, covering seven municipalities. It has maximum total and useful volumes of 5,954.88 hm^3 and 3,689 hm^3, respectively, and an installed capacity of 399 MW. The operational water levels vary between 470.8 m and 510 m. The reservoir is in the Alto Jequitinhonha watershed (JQ1 Water Resource Management Units – WRMU), which has an area of 19,855 km^2, covering a total of 26 municipalities with a population of approximately 120,965 inhabitants. The Alto Jequitinhonha region predominantly produces forest products, specifically from *Eucalyptus* sp., agriculture, and livestock (Silva & Miranda 2015).

Water quality monitoring data

The secondary data used in the present study were obtained from the water quality monitoring carried out between 2008 and 2018 by the Companhia Energética de Minas Gerais (Cemig) at 14 sampling stations in the Irapé HPP Reservoir and its tributaries. The geographical location and description of the monitoring stations are shown in Figure 1 and Table 1, respectively.

The dataset includes 14 water quality parameters (Table 2) monitored quarterly. The samples were collected and analysed according to Cemig's Manual of Sampling Procedures and Water Analysis Methodologies (2009).

Water quality parameter limits recommended by legislation

The violation percentages for each database parameter that has a limit recommended in Brazilian legislation by CONAMA, Brazil's National Environmental Council (Brazil 2005), were

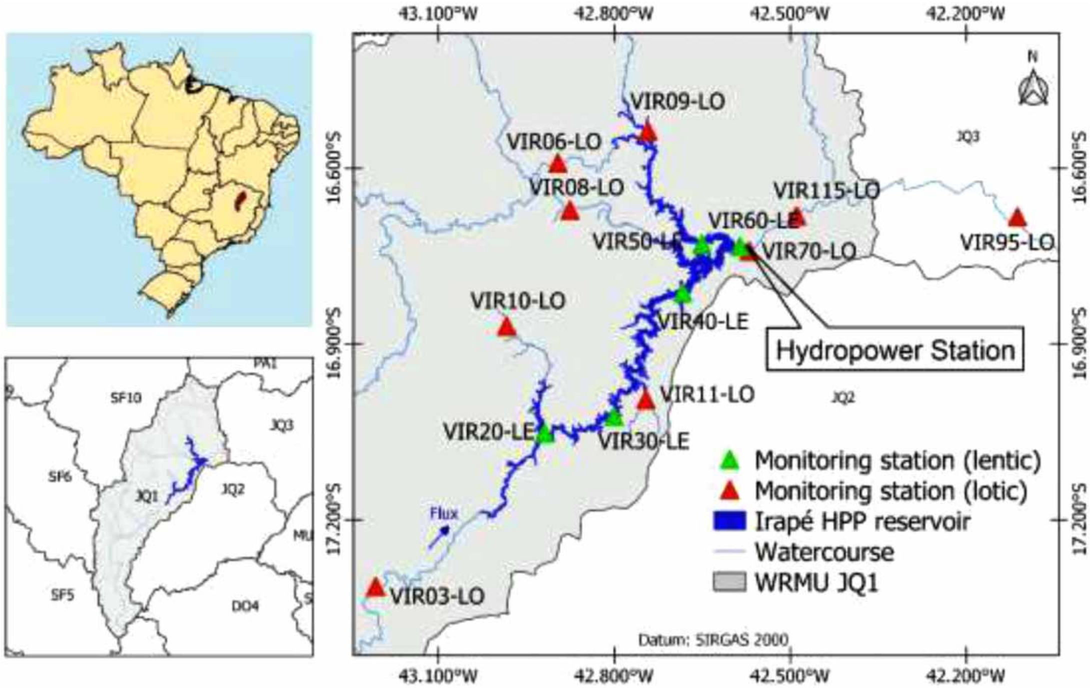


Figure 1 | Geographic location of the Irapé HPP Reservoir, its tributaries, and the water quality monitoring stations.

Table 1 | Description of the Irapé HPP Reservoir and its tributaries' monitoring stations

Station	Description	Watercourse	Município	Physical condition
VIR03-LO	Reservoir upstream – close to the Terra Branca ferry	Jequitinhonha River	Bocaiuva	Lotic
VIR06-LO	Reservoir upstream – below the bridge that connects Grão Mogol to Cristália	Itacambiruçu River	Grão Mogol	Lotic
VIR08-LO	Reservoir upstream – on the bridge that connects Grão Mogol to Cristália	Soberbo River	Cristália	Lotic
VIR09-LO	Reservoir upstream – on the bridge that connects Grão Mogol to Irapé HPP	Ventania River	Grão Mogol	Lotic
VIR10-LO	Reservoir upstream	Noruega River	Botumirim	Lotic
VIR11-LO	Reservoir upstream	Corrente River	Leme do Prado	Lotic
VIR70-LO	Downstream of the powerhouse – 500 m from the escape channel	Jequitinhonha River	Grão Mogol	Lotic
VIR95-LO	Downstream of the powerhouse – in front of Coronel Paulo Fernandes school	Jequitinhonha River	Coronel Murta	Lotic
VIR115-LO	Downstream of the powerhouse	Jequitinhonha River	Virgem da Lapa	Lotic
VIR20-LE	Reservoir	Jequitinhonha River	Turmalina	Lentic
VIR30-LE	Reservoir	Jequitinhonha River	Leme do Prado	Lentic
VIR40-LE	Reservoir	Jequitinhonha River	Grão Mogol	Lentic
VIR50-LE	Reservoir	Itacambiruçu River	Cristália	Lentic
VIR60-LE	Reservoir, 500 m from the dam	Jequitinhonha River	Grão Mogol	Lentic

Table 2 | Surface water quality and standards set by CONAMA

Parameter	Abbreviation	Unit	Standard
Total alkalinity	TAlc	$mg{\cdot}L^{-1}$ $CaCO_3$	*
Biochemical oxygen demand	BOD	$mg{\cdot}L^{-1}$ O_2	5
Dissolved oxygen	DO	$mg{\cdot}L^{-1}$ O_2	>5
Dissolved iron	DFe	$mg{\cdot}L^{-1}$ Fe	0.3
Electrical conductivity	EC	$\mu S.cm^{-1}$	*
Total ammoniacal nitrogen	$N\text{-}NH_4^+$ $pH \leq 7.5$	$mg{\cdot}L^{-1}$ N	3.7
	$N\text{-}NH_4^+$ $7.5 < pH < 8.0$	$mg{\cdot}L^{-1}$ N	2
	$N\text{-}NH_4^+$ $8.0 < pH < 8.5$	$mg{\cdot}L^{-1}$ N	1
	$N\text{-}NH_4^+$ $pH \geq 8.5$	$mg{\cdot}L^{-1}$ N	0.5
Nitrate	$N\text{-}NO_3^-$	$mg{\cdot}L^{-1}$ N	10.0
pH in loco	pH	–	6 to 9
Water temperature	Temperature	°C	*
Thermotolerant coliforms	Therm. coli.	$org.100\ Ml^{-1}$	1,000
Total dissolved solids	TDS	$mg{\cdot}L^{-1}$	500
Total phosphorus	TP (lotic)	$mg{\cdot}L^{-1}$ P	0.1
	TP (lentic)	$mg{\cdot}L^{-1}$ P	0.03
Sulfate	SO_4^{-2} T	$mg{\cdot}L^{-1}$ P	250
Turbidity	Turb.	NTU	100

*No limit recommended by CONAMA.

calculated according to the watercourse classification for each station (Class 2). The limits are listed in Table 2.

Trend analysis

The temporal trend analysis of the parameters was performed by station, using the Mann–Kendall test (MK) or Mann–Kendall Seasonal test (MKS), commonly used in temporal analysis of environmental data owing to its simplicity and robustness (Yenilmez *et al.* 2011). One assumption for the tests that produced reliable results was the lack of autocorrelation in the analysed data. In this study, the autocorrelation was verified through the autocorrelation function (ACF), which measures the degree of variable correlation at a given moment, with itself and at a later point in time.

The choice between MK and MKS was based on the presence or absence of seasonality within the data measured at different periods of the year, as this factor is a potential source of variation in the water quality data series (Helsel & Hirsch 2002). Seasonality was analysed using the Kruskal–Wallis (KW) non-parametric statistical test, applied to the quarterly data for all parameters in each season. When $p < 0.05$ in the KW test, the seasonality influence was considered to exist and the MKS test was applied. In cases where $p > 0.05$, the seasonality influence was considered to be non-existent and the parameter temporal trend was verified by the MK test.

The time trend was verified by Kendall's tau values (τ) calculated in MKS or MK. For $p < 0.05$, the trend was considered to exist, and the Kendall tau value (τ) determined whether this trend was upward (positive τ) or downward (negative τ). Statistical tests were performed using the programs XLSTAT® 2014.1.01 and/or Statistica® 8.0, at a significance level (α) of 5%.

CCME WQI

The Brazilian legal limits set by CONAMA (Brazil 2005) were used in the CCME WQI calculation. The index is a combination of three factors that represent non-compliance with the proposed quality criteria to produce a single value (between 0 and 100) that describes water quality (CCME 2001).

F1 (scope) represents the percentage of variables that did not meet the objectives at least once during the time period under consideration ('failed variables'), relative to the total number of variables measured (Equation (1)):

$$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\right) \times 100 \tag{1}$$

F2 (frequency) represents the percentage of individual tests that did not meet the objectives ('failed tests') (Equation (2)):

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) \times 100 \tag{2}$$

F3 (amplitude) represents the amount by which failed test values did not meet their objectives. It is calculated in three steps.

(1) The number of times by which an individual concentration is greater than (or less than, when the objective

is a minimum) that of the objective is termed an 'excursion' and is expressed as follows.

When the test value did not exceed the objective (Equation (3)):

$$\Delta v = \left(\frac{failed\ test\ value}{objective}\right) - 1 \quad (3)$$

For cases in which the test value did not fall below the objective (Equation (4)):

$$\Delta v = \left(\frac{objective}{failed\ test\ value}\right) - 1 \quad (4)$$

(2) The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their objectives and dividing it by the total number of tests (all those meeting objectives and not meeting objectives). This variable, referred to as the normalised sum of excursions (NSE) is calculated using Equation (5):

$$NSE = \frac{\sum_{i=1}^{n} excursion}{total\ number\ of\ tests} \quad (5)$$

(3) F3 is then calculated using an asymptotic function that scales the normalised sum of the excursions from objectives (nse) to yield a range between 0 and 100 (Equation (6)):

$$F_3 = \frac{NSE}{(0,01 \times NSE) + 0,01} \quad (6)$$

Finally, the WQI can be calculated using Equation (7):

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1,732}\right) \quad (7)$$

The index ranges from 0 to 100 were divided into five categories by the CCME: (i) excellent (95–100), (ii) good (80–94), (iii) reasonable (65–79), (iv) marginal (45–64), and (v) terrible (0–44). The WQI methodology proposed by CCME does not define the parameters but recommends a minimum of eight and a maximum of 20 parameters to be used in the calculation (CCME 2012). In this study, all monitored parameters that defined legal standards were considered (Table 2). The WQI was applied to each monitoring station and to each year. In the second step, the index was calculated by season, dry (April to September) and rainy (October to March), to analyse the influence of seasonality on the water quality.

RESULTS AND DISCUSSION

Legislation standards violations

Box-plot graphs with the standards violations of each parameter for all seasons are shown in Figure 2.

The legal limit violations registered for the pH occurred below the minimum allowed, highlighting the value of 2.99 recorded in 2017 for the station VIR10-LO. Acidic pH may be associated with the presence of red oxisols in the watershed, which in general are strongly acidic soils. In addition, the contact of aerated water from the reservoir with the dam, mainly a homogeneous pack of quartz-mica-shale containing sulphides disseminated in the rock matrix (Duarte *et al.* 2009), leads to the oxidation of sulphide minerals, resulting in low pH solutions that cause regional water acidification. Low pH values can affect growth or cause death in ichthyofauna. Wide pH variability can affect more sensitive organisms, even if the legal limits are not exceeded. In addition, low pH values can solubilise other metals, increasing environmental toxicity (Rodrigues 2002).

The high frequencies of dissolved Fe violations at all monitoring stations (31.7% to 80.5%) may be related to the local geochemical and pedological characteristics, such as the presence of red oxisols, which have a high Fe_2O_3 content. An association between high iron content and soil characteristics was observed in the Nisa River (Czech Republic and Germany) (Kändler *et al.* 2017). The reservoir waters' acidic pH can also contribute by reducing Fe^{+3} (insoluble) in Fe^{+2} (dissolved).

The high percentage of DO violation at the VIR70-LO station may be related to its location downstream from the powerhouse. The water intake of the HPP is 40 m deep,

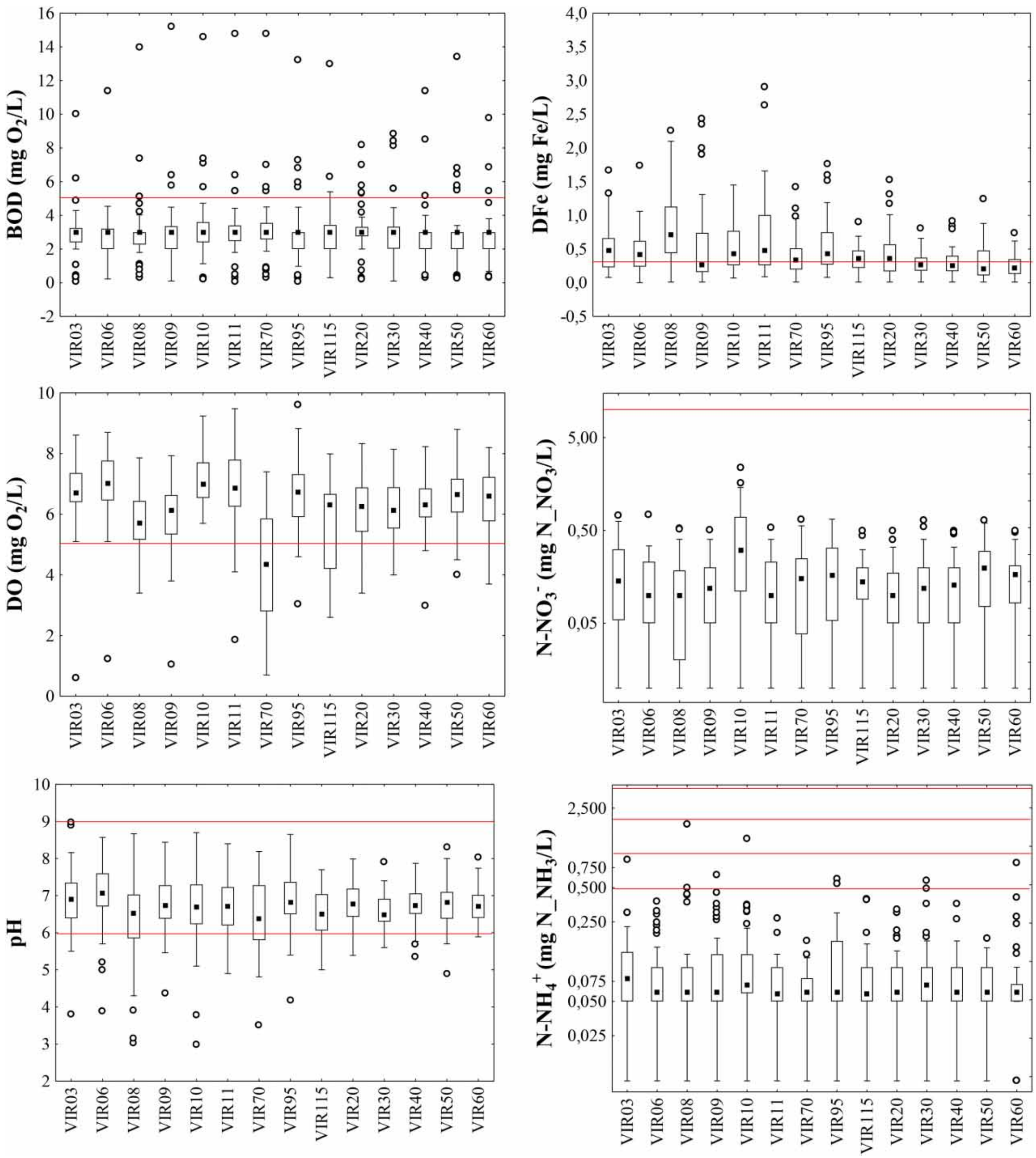


Figure 2 | Variability of water quality parameters and legal standards violations of the monitoring stations of Irapé HPP Reservoir and its main tributaries. *Note*: The gray horizontal line represents the legal standard or standard range of each parameter.

and thus the water returned from the machines can be characterised as bottom water, which in general has lower DO values than those of surface water. The low DO values should be monitored as this is an extremely important parameter for aerobic aquatic organism respiration and has been used in the calculation of various WQIs since the 1960s (Tyagi *et al.* 2013). In addition, the decrease in DO concentrations tends to influence chemical changes in the nutrient forms and metals, in addition to other water quality parameters, which may become available in the environment and/or have their values changed (Ashby 2009).

The parameters N–NO_3, N–NH_4^+, and SO_4^{-2} T did not exceed the legal limits, while the TDS showed a violation in a single sampling campaign at station VIR20-LE (2.4%).

However, the pH, BOD, and TP limits were violated at least once in every season and in all years of the historical series, with percentages varying between 4.8% and 34.9%; 2.4% and 14.3%; and 12.2% and 26.8%, respectively. BOD and TP are important indicators of organic pollution in water bodies. High BOD loads mainly originate from anthropogenic sources, including domestic and animal waste, industrial emissions, and sewage releases (Vigiak *et al.* 2019). These high values indicate a great demand for oxygen that is necessary to break down the organic matter present in the water body through bacterial respiratory activity, consequently decreasing the concentration of available DO. The bioavailable forms of phosphorus, together with inorganic nitrogen, play an important role in aquatic ecology. Excess phosphorus can lead to eutrophication of water resources, which can cause ecological and toxicological effects that are directly or indirectly related to primary producer proliferation (Wang *et al.* 2009; Moal *et al.* 2019).

For TP, 78% of the values above the limit occurred during the rainy season, indicating a greater transport of allochthonous material to the reservoir during this period by surface runoff. Yenilmez *et al.* (2011) and Li *et al.* (2019) found a statistically positive relationship between TP and precipitation when analysing the water quality of Lake Eymir in Turkey and the Three Gorges Reservoir in China, respectively, concluding that the parameter is introduced into the lake by runoff. In Irapé, the effects of agricultural or silvicultural practices in the tributary area, the main anthropic uses observed in the watershed (Silva & Miranda 2015), could be responsible for the TP contribution. The turbidity behaviour, with higher percentages of violation in the tributaries, although without the occurrence of values above the legal limits, reinforces this hypothesis. The reservoirs' low turbidity can be explained by the sedimentation effect, as also observed by Li *et al.* (2019) in the Three Gorges Reservoir region, China, and in the Nova Ponte Reservoir, Brazil by Christofaro *et al.* (2017).

Thermotolerant coliforms have a higher percentage of standards violations in the tributaries in relation to the reservoir. This parameter has a strong connection with point sources of untreated sanitary sewage, indicating that the tributaries are affected by this type of pollution. The highest percentage of violation of thermotolerant coliforms occurred at the VIR11-LO station (30%), located on the right arm of the main river, indicating that the flow rates and conditions for regeneration in the region reduce the impact of domestic sewage release (even if untreated).

Trend analysis of the reservoir water quality parameters and main tributaries

The autocorrelation coefficient did not reach a significant value for most parameters, except for isolated occurrences of autocorrelation for SO_4^{-2} T (Figures S1 to S14). Thus, the Mann–Kendall tests (MK or MKS) were used for all parameters at all stations.

The temperature showed a substantial seasonal variation, with values significantly higher ($p < 0.05$) in the rainy season in 11 stations. For the other parameters, seasonal differences, when detected, indicated higher levels during the rainy season (Table 3).

The $N{-}NH_4^+$ and DFe were the parameters that showed the highest time trend occurrences, detected in 78.6% and 64.3% of the monitoring stations, respectively. The tendency to increase $N{-}NH_4^+$ may be associated with a greater contribution from agricultural sources in the basin, which may result in greater toxicity to aquatic organisms as well as a reduction in DO concentration in the water. However, the concentrations of $N{-}NH_4^+$ did not exceed the legal standards. On the other hand, the DFe has a significant impact and a tendency to increase the reservoir water quality and its tributaries, which can be associated with an increase in soil exposure in the watershed over the study period.

Turbidity showed an upward trend at eight stations (57.1%), with five inside the reservoir. Although there are still no representative standards violations, the results indicate the need to adopt measures to control turbidity, especially in relation to tributaries and the reservoir surroundings.

Only TDS and thermotolerant coliforms showed significant reduction trends. All stations located in the reservoir presented a temporal tendency to reduce thermotolerant coliforms, two other stations are on the main river (Jequitinhonha River), immediately downstream of the water mirror (VIR70-LO and VIR115-LO). These results indicate that the point source effects of sanitary sewage on reservoir waters decreased over the study period.

Table 3 | Influence of seasonality and temporal trends of the analysed parameters in each monitoring station of the Irapé HPP Reservoir and its main tributaries

Parameters														
Stations	**TAlc***	**Therm. coli.**	**EC***	**BOD**	**DFe**	**TP**	**N-NO$_3^-$**	**N-NH$_4^+$**	**DO**	**pH**	**TDS**	**SO$_4^{-2}$ T**	**Temp***	**Turb.**
VIR03-LO		W (17.1%)		(4.9%)	(63.4%)	W (22.0%)	W (0.0%)	(0.0%)	D (2.4%)	(11.9%)	↓ (0.0%)	(0.0%)	W	↑ (17.5%)
VIR06-LO	D	W (22.5%)		↑ (2.4%)	W (68.3%)	W (20.0%)	W (0.0%)	↑ (0.0%)	(2.5%)	(9.8%)	(0.0%)	(0.0%)		W (18.0%)
VIR08-LO		(12.5%)		↑ (9.8%)	↑ (80.5%)	(15.4%)	↓ (0.0%)	(0.0%)	(22.5%)	(31.7%)	↓ (0.0%)	(0.0%)	W	W (7.9%)
VIR09-LO		(24.3%)		(9.8%)	↑ (43.9%)	(15.8%)	↑ (0.0%)	↑ (0.0%)	(22.5%)	(12.2%)	(0.0%)	(0.0%)	W	↑ (5.4%)
VIR10-LO		W (17.5%)	↑	(9.8%)	↑ (68.3%)	(22.5%)	D (0.0%)	(0.0%)	(0.0%)	↓ (19.5%)	(0.0%)	(0.0%)	↑	(5.6%)
VIR11-LO		W (30.0%)	↑	(9.5%)	↑ (72.5%)	(20.0%)	(0.0%)	↑ (0.0%)	(7.3%)	(16.7%)	(0.0%)	(0.0%)		W (5.3%)
VIR70-LO		W ↓ (13.2%)		(10.0%)	↑ (58.1%)	(14.3%)	(0.0%)	↑ (0.0%)	↑ (66.7%)	↑ (34.9%)	(0.0%)	(0.0%)	D	↑ (2.6%)
VIR95-LO		W (24.4%)		↑ (12.2%)	↑ (63.4%)	(24.4%)	W (0.0%)	↑ (0.0%)	(5.0%)	(12.2%)	(0.0%)	(0.0%)	W	W (26.3%)
VIR115-LO		↓ (15.8%)		(8.6%)	(60.5%)	(13.2%)	(0.0%)	↑ (0.0%)	↑ (27.0%)	(18.4%)	↓ (0.0%)	(0.0%)	W	(5.9%)
VIR20-LE		↓ (2.8%)		(12.5%)	↑ (56.4%)	(26.8%)	(0.0%)	↑ (0.0%)	(5.0%)	D (14.6%)	(2.4%)	(0.0%)	W	↑ (0.0%)
VIR30-LE	W	↓ (2.7%)		(10.0%)	↑ (46.3%)	(17.1%)	(0.0%)	↑ (0.0%)	(12.5%)	(10.0%)	↓ (0.0%)	(0.0%)	W	↑ (0.0%)
VIR40-LE	W	↓ (2.9%)		↑ (7.1%)	(39.0%)	↑ (12.2%)	(0.0%)	↑ (0.0%)	(4.9%)	(7.1%)	↓ (0.0%)	(0.0%)	W	↑ (0.0%)
VIR50-LE		↓ (5.7%)		(14.3%)	↑ (38.1%)	(23.1%)	(0.0%)	↑ (0.0%)	(4.9%)	(14.3%)	↓ (0.0%)	(0.0%)	W	↑ (0.0%)
VIR60-LE		↓ (0.0%)		(7.1%)	(31.7%)	(17.1%)	(0.0%)	↑ (0.0%)	(2.4%)	(4.8%)	(0.0%)	(0.0%)	W	↑ (0.0%)

(↑) = upward trend; (↓) = downward trend; ( ) = no trend; (W) = influence of seasonality with higher values observed in the rainy season; (D) = influence of seasonality with higher values observed in the dry season; (*) = no standard limit in the legislation.

CCME WQI application

Table 4 shows the CCME WQI values obtained in the seasons for the years in which there were quarterly samplings.

WQI values ranged between 54.68 and 100.00. Of the 88 indices calculated, one point, in 2014 (VIR06-LO), was classified as excellent, 61.3% were classified as good, indicating that they rarely differed from the legal limits, and 29.5% were acceptable, which sometimes went over the legislation limits. Only 8.0% fell into the bad range (they often violated legal limits), with no record of the very poor class. The monitoring points located inside the reservoir were generally classified as good, except for in 2009.

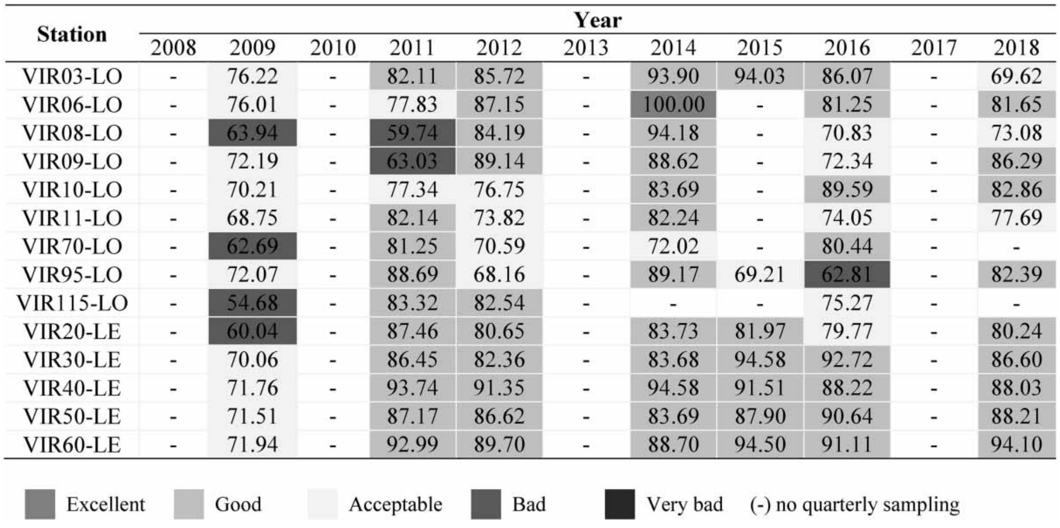
The better water quality at the reservoir's monitoring points indicated that the water body reduced the effects of pollution from tributaries, as observed by Xing *et al.* (2015), when comparing the water quality of the Danjiangkou Reservoir in China with the rivers that supply it. This reduction can be caused by changes in river dynamics, such as a decrease in water flow velocity and the consequent deposition of pollutants by sedimentation, a phenomenon common to lentic environments (Wang *et al.* 2009; Li *et al.* 2019).

Gao *et al.* (2016) also found similar results for the Three Gorges Reservoir, the largest hydroelectric project in the world, in which the decrease in concentrations of heavy metals from upstream to downstream was associated with reservoir self-purification, which was stable and acceptable from 2008 to 2013. Other studies have also shown that the CCME WQI is a valuable means of monitoring, communicating, and understanding surface water quality (Hurley *et al.* 2012; Ahmed *et al.* 2020).

Table 5 presents the WQI seasonality, considering the dry and rainy seasons. There is a deterioration of the index values in the rainy season (October to March), indicating a greater supply of nutrients with rain during this period, suggesting a predominance of diffuse pollution sources (Barbosa *et al.* 2019). In addition, the amplitude of reservoir seasonal variation was less than that observed for the tributaries.

The existing impacts on the water quality of the Irapé Reservoir have natural and anthropic origins and they can be intensified during rainy seasons. However, even though some problems have a natural origin, they can be aggravated by human actions, such as inadequate soil management in agricultural practices in the region. One strategy that can be adopted to minimise this problem is investment in reforestation and environmental restoration, where the vegetation acts as a filter and barrier for rainwater surface runoff,

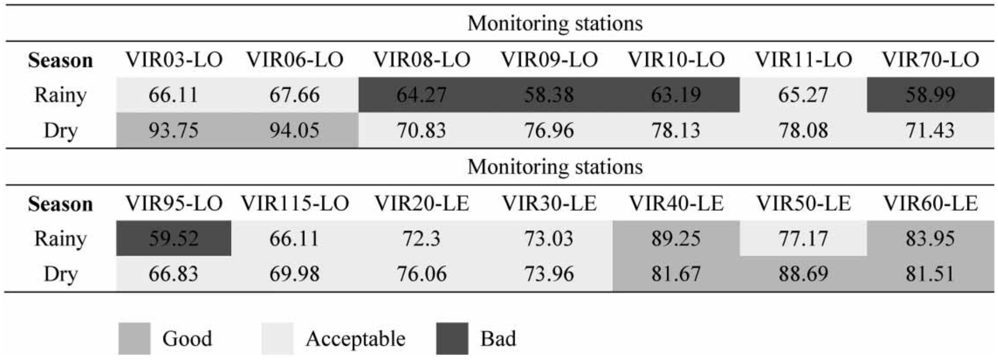
Table 4 | CCME WQI by season and year, applied to the Irapé HPP monitoring database and main tributaries



Station	Year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
VIR03-LO	-	76.22	-	82.11	85.72	-	93.90	94.03	86.07	-	69.62
VIR06-LO	-	76.01	-	77.83	87.15	-	100.00	-	81.25	-	81.65
VIR08-LO	-	63.94	-	59.74	84.19	-	94.18	-	70.83	-	73.08
VIR09-LO	-	72.19	-	63.03	89.14	-	88.62	-	72.34	-	86.29
VIR10-LO	-	70.21	-	77.34	76.75	-	83.69	-	89.59	-	82.86
VIR11-LO	-	68.75	-	82.14	73.82	-	82.24	-	74.05	-	77.69
VIR70-LO	-	62.69	-	81.25	70.59	-	72.02	-	80.44	-	-
VIR95-LO	-	72.07	-	88.69	68.16	-	89.17	69.21	62.81	-	82.39
VIR115-LO	-	54.68	-	83.32	82.54	-	-	-	75.27	-	-
VIR20-LE	-	60.04	-	87.46	80.65	-	83.73	81.97	79.77	-	80.24
VIR30-LE	-	70.06	-	86.45	82.36	-	83.68	94.58	92.72	-	86.60
VIR40-LE	-	71.76	-	93.74	91.35	-	94.58	91.51	88.22	-	88.03
VIR50-LE	-	71.51	-	87.17	86.62	-	83.69	87.90	90.64	-	88.21
VIR60-LE	-	71.94	-	92.99	89.70	-	88.70	94.50	91.11	-	94.10

■ Excellent ■ Good □ Acceptable ■ Bad ■ Very bad (-) no quarterly sampling

Table 5 | WQI by season, applied to the Irapé HPP monitoring database and main tributaries



	Monitoring stations						
Season	VIR03-LO	VIR06-LO	VIR08-LO	VIR09-LO	VIR10-LO	VIR11-LO	VIR70-LO
Rainy	□ 66.11	□ 67.66	■ 64.27	■ 58.38	■ 63.19	□ 65.27	■ 58.99
Dry	▨ 93.75	▨ 94.05	□ 70.83	□ 76.96	□ 78.13	□ 78.08	□ 71.43

	Monitoring stations						
Season	VIR95-LO	VIR115-LO	VIR20-LE	VIR30-LE	VIR40-LE	VIR50-LE	VIR60-LE
Rainy	■ 59.52	□ 66.11	□ 72.3	□ 73.03	▨ 89.25	□ 77.17	▨ 83.95
Dry	□ 66.83	□ 69.98	□ 76.06	□ 73.96	▨ 81.67	▨ 88.69	▨ 81.51

▨ Good □ Acceptable ■ Bad

preventing erosion caused by the direct impact of raindrops on the soil.

In this sense, Li *et al.* (2019) note that the Chinese government's investments in reforestation and environmental restoration has positive impacts on reservoir water quality. In addition, it is important to emphasise that actions for the management of this and other reservoirs include the awareness and environmental education of the region's population, including promoting the dissemination of and access to information related to water quality. It should also be noted that management must occur in an integrated manner, based on an understanding of the structure and functioning of the reservoir as an ecosystem, through the use of surveys and soil occupation in its surroundings, and with the help of the local communities.

CONCLUSION

High Fe concentrations and a large percentage of stations with an increasing trend indicate the increase of soil exposure in the watershed. Despite not exceeding legal standards, N–NH_4^+ showed an upward trend in 64% of the monitoring stations, which may be related to an increase in the contribution of agricultural runoff. The agricultural use of the soil can also be related to the TP contribution to the reservoir and tributaries and to the turbidity values that violated the limit in the tributaries. The occurrence of low pH values must be monitored, and they may be related to the presence of iron sulphides in the region. The thermotolerant coliforms showed a downward trend, mainly in the reservoir monitoring stations, indicating a reduction in the effect of point sources of sanitary sewage discharge.

The reservoir water quality and its tributaries were considered adequate during the study period, with approximately 61% of the 88 WQI qualifying as good, 29.5% as acceptable, and 8.0% as bad. The reservoir points are of better quality than the tributaries, and the WQI assessment showed a deterioration in the rainy season, reinforcing the influence of diffuse sources on water quality. The application of the CCME WQI together with temporal statistical analysis showed a potential contribution to the interpretation of environmental monitoring data, generating important information for reservoir water quality management. Therefore, the results can support control and management measures in specific stretches of watersheds, with a focus on the most relevant polluting sources.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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