**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), considering data from 2008 to 2018. This reservoir is in Minas Gerais, Brazil, covering an area of approximately 142 km², across seven municipalities. The dissolved iron (DFe) presented the highest percentage of standard violations (31.7% to 80.5%), with most frequencies being verified in the reservoir tributaries. The Mann–Kendall test indicated that the monitoring stations showed an increasing trend of 78.5% N–NH₄ 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 period 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 monitoring data interpretation, generating important information for reservoir water quality management.

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

**HIGHLIGHTS**

- The large Brazilian reservoir and tributaries water was studied by statistical techniques in conjunction with water quality index (WQI).
- Mann-Kendall test indicated the stations with an increasing trend in the parameters analyzed.
- The seasonal WQI indicated a worsening in the stations at rainy period.
- CCME WQI and temporal statistical analysis generated information that can be use in the 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 in relation to lotic ecosystems. Thus, programs for monitoring physical, chemical, and biological parameters of water quality in these environments are indispensable for a better understanding and evaluation of water body conditions. However, these programs generate

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a complex interpretation data set, requiring specific tools for proper interpretation and evaluation of the water quality parameters temporal and spatial variability.

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 as well as 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 142 km², 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 Kubitschek Hydropower Plant), located at 16°44’15” S and 42°34’30” W, was inaugurated in 2006 and has a 142.95 km² reservoir, covering seven municipalities. It has maximum total and useful volumes of 5,954.88 hm³ and 3,689 hm³, respectively, and an installed capacity of 399 MW. The operational water levels vary between 470.8 m and 510 m. The reservoir is inserted in the Alto Jequitinhonha watershed (JQ1 Water Resource Management Units – WRMU), which has an area of 19,855 km² covering a total of 26 municipalities and a population of approximately 120,965 inhabitants. The Alto Jequitinhonha region predominantly produces forest products, specifically with 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 by the Companhia Energética de Minas Gerais (Cemig) at 14 sampling stations in the Irapé HPP reservoir and its tributaries, between 2008 and 2018. 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 parameters limits recommended by legislation

The violation percentages for each database parameter that has a limit recommended in Brazilian legislation by CONAMA Resolution No. 357, of March 17, 2005 (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 | Bocaíva            | 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 the 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             |
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 parameter in each season. For a \( p < 0.05 \), in the KW test, the seasonality influence was considered to exist and the MKS test was the applied. In cases where \( p > 0.05 \), the seasonality influence was considered non-existent and the parameter temporal trend was verified by the MK test.

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

### CCME water quality index

The Brazilian legal limits in the Resolution CONAMA N° 357, of March 17, 2005 (Brazil 2005) were considered for 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)).

\[
F_1 = \left( \frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \quad (1)
\]

F2 (Frequency) represents the percentage of individual tests that did not meet the objectives (‘failed tests’) (Equation (2)).

\[
F_2 = \left( \frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \quad (2)
\]

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

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

### Table 2 | Surface water quality and standards sets in CONAMA resolution 357/2005

| Parameter | Abbreviation | Unit            | Standard |
|-----------|--------------|-----------------|----------|
| Total Alkalinity | TAlc | mg·L\(^{-1}\) CaCO\(_3\) | 500 |
| Biochemical Oxygen Demand | BOD | mg·L\(^{-1}\) O\(_2\) | 5 |
| Dissolved Oxygen | DO | mg·L\(^{-1}\) O\(_2\) | >5 |
| Dissolved Iron | DFe | mg·L\(^{-1}\) Fe | 0.3 |
| Electrical conductivity | EC | μS·cm\(^{-1}\) | 5 |
| Total Ammoniacal Nitrogen | N-NH\(_\text{3}\) | mg·L\(^{-1}\) N | 3.7 |
| Ph | 7.5 | mg·L\(^{-1}\) N | 2 |
| Ph | <8.0 | mg·L\(^{-1}\) N | 1 |
| Ph | >8.0 | mg·L\(^{-1}\) N | 0.5 |
| Nitrate | N-NO\(_3\) | mg·L\(^{-1}\) N | 10 |
| pH in loco | pH | – | 6 to 9 |
| Water Temperature | Temperature | °C | 9 |
| Thermotolerant Coliforms | Therm. Coll. | org.100 MI\(^{-1}\) | 1,000 |
| Total Dissolved Solids | TDS | mg·L\(^{-1}\) | |
| Total Phosphorus | TP (lotic) | mg·L\(^{-1}\) P | 0.1 |
| TP (lentic) | mg·L\(^{-1}\) P | 0.03 |
| Sulfate | SO\(_4^2\)-T | mg·L\(^{-1}\) P | 250 |
| Turbidity | Turb. | NTU | 100 |

*No limit recommended by CONAMA Resolution 357/2005.
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)).

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

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

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

where A corresponds to the concentration of the compound in the sample after fortification, B is the concentration of the compound in the non-fortified sample, C is the concentration in the fortified sample, and MEF is the matrix effect correction factor.

(b) 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, or nse, is calculated using Equation (5).

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}}{\text{numero total de coletas}}$$  \hspace{1cm} (5)

(c) $F_3$ 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)).

$$F_3 = \frac{nse}{(0,01 \times nse) + 0,01}$$  \hspace{1cm} (6)

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

$$\text{WQI} = 100 - \left( \frac{F_1^2 + F_2^2 + F_3^2}{1,752} \right)$$  \hspace{1cm} (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 twenty 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 violation

Box-plot graphs with the standard 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, constituted predominantly by 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 lethality 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, with a high Fe$_2$O$_3$ 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 dissolved oxygen (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, 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-NO₃, N-NH₄, and SO₄²⁻ 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 presented the limits 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 stabilise 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 of 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 Pᵣ, 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 Pᵣ and precipitation when analysing the water quality of Lake Eymir in Turkey and 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 Pᵣ 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 these introductions. 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 SO₄²⁻ T (Figure 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 period in eleven stations. For the other parameters, seasonal differences, when detected, indicated higher levels during the rainy period (Table 3).

The N-NH₄ 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-NH₄ 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-NH₄ 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 total solids dissolved (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
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 | TAIC* | Therm. Coli. | EC* | BOD | DFe | TP | N-NO 3 | N-NH 4 | DO | pH | TDS | SO 4 | Temp* | Turb. |
|------------|----------|-------|--------------|-----|-----|-----|----|--------|--------|----|-----|-----|-----|-------|-------|
| VIR03-LO   | W (17.1%) | (4.9%) | (63.4%)     | W (22.0%) | W (0.0%) | D (2.4%) | (11.9%) | ↓ (0.0%) | (0.0%) | W    | ↑ (17.5%) |
| VIR05-LO   | D (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    | 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%) | ↓ (19.5%) | (0.0%) | (0.0%) | W    | ↑ (5.6%) |
| VIR11-LO   | W (30.0%) | ↑ (9.5%) | ↑ (72.5%)   | (20.0%) | ↑ (0.0%) | ↑ (7.3%) | (16.7%) | (0.0%) | (0.0%) | W    | 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%) |
| VIR85-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    | 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; ( ) = without trend; (W) = influence of seasonality with higher values observed in the rainy period; (D) = influence of seasonality with higher values observed in the dry period; (*) = it does not have a standard limit in the legislation.
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.

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 distanced themselves from 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 generally showed a predominance of the good class, 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 periods.

There is a deterioration of the index values in the rainy season (October to March), indicating a greater supply of nutrients by 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.

In general, it is perceived that the existing impacts on the water quality of the Irapé Reservoir have natural and

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

| Station   | 2008  | 2009  | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| VIR03-LO  | 76.22 | -     | 82.14 | 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 | -     | -     |
| VIR05-LO  | 72.07 | -     | 88.69 | 68.16 | -     | 89.17 | 69.21 | 62.81 | -     | 82.39 |
| VIR15-LO  | 54.68 | -     | 83.32 | 82.54 | -     | -     | -     | 75.27 | -     | -     |
| VIR20-LF  | 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-LF  | 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-LF  | 71.94 | -     | 92.99 | 89.70 | -     | 88.70 | 94.50 | 91.11 | -     | 94.10 |

- Excellent
- Good
- Acceptable
- Bad
- Very bad

(-) There were no quarterly sampling
anthropic origins and that they can be intensified during rainy seasons. However, even though some problems have a natural origin, it is noted that 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 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 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 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 soil exposure growth 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 runoffs. The agricultural use of the soil can also be related to the $P_T$ 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 it 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 sanitary sewage discharge point sources.

The reservoir water quality and its tributaries were considered adequate during the study period, with approximately 61% of the 88 WQI qualified as good, 29.5% as acceptable, and 8.0% as bad. The reservoir points are of better quality than those of 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 the watershed, 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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