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Morphometric analysis and water quality assessment in the Retiro Baixo Reservoir, Paraopeba River (Brazil)

Análise morfométrica e avaliação da qualidade da água no reservatório de Retiro Baixo, Rio Paraopeba (Brasil)

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Abstract: Aim: This study aims morphometric analysis and water quality assessment in the Retiro Baixo Reservoir, located in the mouth of Paraopeba River. **Methods:** Morphometric parameters were investigated based on the governmental agencies, field works and geoprocessing software. Ninety water samples were collected in three points at three different depths between 02/2019 and 08/2022. **Results:** The involvement factor (If) showed that the reservoir dilution capacity may be small compared to the large basin drainage area. During higher inflow periods, there was an increase in the total suspended sediment (TSS), copper (Cu), iron (Fe), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations. The results also showed vertical variation in temperature and dissolved oxygen values, with the highest copper (Cu) concentrations measured at the deeper depths. In fact, 60% of the Cu values samples exceeded the limit established by Brazilian legislation, while most of the Fe and Mn samples analysed had low concentrations (91.1% Mn and 66.6% Fe), with a few exceptions. **Conclusions:** This concentration is also strongly influenced by hydrodynamic seasonality and geochemical background.

Keywords: land use; hydric balance; degraded area; iron; manganese; Brumadinho.

Resumo: Objetivo: Este estudo tem como objetivo a análise morfométrica e avaliação da qualidade da água no Reservatório Retiro Baixo, localizado na foz do Rio Paraopeba. **Métodos:** Os parâmetros morfométricos foram investigados com base nas agências governamentais, trabalhos de campo e software de geoprocessamento. Foram coletadas 90 amostras de água em três pontos, em três profundidades diferentes, entre 02/2019 e 08/2022. **Resultados:** O índice do fator de envolvimento (If) demonstrou que a capacidade de diluição do reservatório pode ser pequena em comparação com a grande área de drenagem da bacia. Em períodos de maior afluência, houve um aumento nas concentrações de sedimentos totais em suspensão (SST), cobre (Cu), ferro (Fe), nitrato (NO_3^-) e fosfato (PO_4^{3-}). Os resultados também demonstraram variação vertical nos valores de temperatura e oxigênio dissolvido, com as maiores concentrações de cobre (Cu) medidas nas maiores profundidades. De fato, 60% das amostras apresentaram valores de Cu que excederam o limite estabelecido pela legislação brasileira, enquanto a maioria das amostras analisadas apresentou baixas concentrações de Fe e Mn (91,1% de Mn e 66,6% de Fe), com poucas exceções. **Conclusões:** A concentração dos íons mensurados, provavelmente, é influenciada pela sazonalidade da região, hidrodinâmica e uso do solo no entorno do reservatório.

Palavras-chave: uso da terra; balanço hídrico; área degradada; ferro; manganês; Brumadinho.

1. Introduction

The artificial reservoirs were created with the primary objective of ensuring the water supply for the population and promoting the most diverse human needs such as energy generation, irrigation, animal watering, fish farming, navigation and leisure. Water stored in lakes, dams and reservoirs differs in quality, which may be closely linked to the environment morphology (Sperling, 1999). According to Barroso et al. (2014) the morphology of a lake can be quantified based on morphometric parameters that are descriptors of the features and flooded areas dimensions. Morphometric characteristics directly influence water quality, as they condition heat and gas exchanges, water column and sediments mixtures, hydrochemical dynamics, and nutrient distribution (Håkanson, 2005; Loverde-Oliveira et al., 2007; Moses et al., 2011; Cigagna et al., 2014; Gonçalves et al., 2016; Anda et al., 2019).

Reservoirs are created by man's direct action, by damming a natural valley or the artificial formation of lakes. Another peculiar characteristic of reservoirs is the presence of effluent flows subject to control, which is related to human exploitation (Wetzel & Likens, 1991). However, variations in outflows generate fluctuations in the water level and can lead to changes in the water physical, chemical, and biological conditions (Esteves, 2011; Leira & Cantonati, 2008).

The waters of the reservoirs come from drainage networks surface runoff, that results from rainfall over a river basin, which, due to land use, can result in the transport of nutrients, metals, organic matter, among others. Artificial reservoirs have a wide spectrum of interactions with river basins, interactions of ecological, economic and social nature (Tundisi & Matsumura-Tundisi 2008). Therefore, the water quality also reflects the water quality of the rivers that form the reservoirs (Pires et al., 2015; Hou et al., 2016; Atique & Kwang-Guk, 2019; Winton et al., 2019; Dębska et al., 2021; Kong et al., 2022).

Mining is a human activity capable of generating wealth and social development, but it is also a source of environmental impacts and risks that can compromise environmental quality (Armstrong et al., 2019; Cardoso et al., 2022; López-Ramírez & Cuevas-Cardona, 2022; Matveeva et al., 2022). The environmental consequences derived from tailings dam's collapses head the list of negative impacts related with this activity (Pacheco et al., 2022). In addition, according to Sánchez et al. (2018) and Silva et al. (2024) dam failures increase the concentration of pollutants in the river system by releasing large volumes of tailings that are remobilized and stored in the ecosystem over time.

The rupture of a tailing dam in Brumadinho (Córrego do Feijão dam) on 2019 January 25th released around 10 million cubic meters of tailing, which spilled into the Ferro Carvão creek valley, reaching the Paraopeba River. According to Pacheco et al. (2022) in the Paraopeba River basin, natural processes and human activities have a long-term impact on water quality, characterized by a large percentage of non-compliance with Brazilian standards legislation. The reservoir of the Retiro Baixo HPP was built in the lower course of the Paraopeba River, where a few kilometers downstream, it flows into the lake of the Três Marias HPP, on the São Francisco River. Therefore, the present work aims to evaluate the morphometric analysis and water quality assessment in the Retiro Baixo Reservoir.

2. Study Area

The Paraopeba River Basin, with a 12,054 km^2 drainage area, is located in the southeast region of the Minas Gerais State (Figure 1). The Paraopeba River source is located in the extreme south of Serra do Espinhaço, municipality of Cristiano Otoni, covering an approximate distance of 510 km to its mouth at the Três Marias Dam on the São Francisco River, being divided in Upper Paraopeba, Middle Paraopeba and Lower Paraopeba (CBHSF, 2019).

According to Schvartzman et al. (2002) the basin's occupation began in the last decades of the 17th century with the search for mineral wealth, through the "bandeirantes" routes (colonial explorers' path). Agriculture and livestock activities are widespread throughout the basin and in the Upper and Middle Paraopeba regions, the most important activities are iron ore and manganese open mining. Furthermore, the basin is responsible for supplying approximately 53% of the Belo Horizonte (Capital of the state of Minas Gerais) metropolitan region (FEAM, 2016).

This region is mainly characterized by agricultural exploration, pastures, urban occupation, Cerrado and native forest areas, eucalyptus planting and an extensive area of exposed soil predominate (Soares 2021) (Figure 1). According to IDE-Sisema (2024) most of the cities don't have information or adequate solid waste disposal and/or wastewater treatment systems. The limited information shows a low percentage of adequate waste disposal and wastewater collection and treatment (Figure 2a). Nowadays, the main economic activities are mining (Figure 2b), steelmaking, industry and agriculture, with mining activities being developed throughout the basin (FEAM, 2011).

The east border of the watershed partially follows the highlands and ranges of an important Brazilian mineral province, named Quadrilátero Ferrífero (Iron Quadrangle) (Alkmim & Marshak, 1998). According to Vicq et al. (2015) the Iron Quadrangle is one of the World's richest mineral regions, covering approximately a 7000 km^2 area with important mining activities focused on iron ores and vast reserves of gold, limestone, dolomite, bauxite, steatite, manganese, topaz, clay, and others.

The basin geological substrate is made up of diversified lithotypes and Precambian geotectonic arrangements (CPRM, 2001). According to Sardinha et al. (2025), in the Upper and Middle

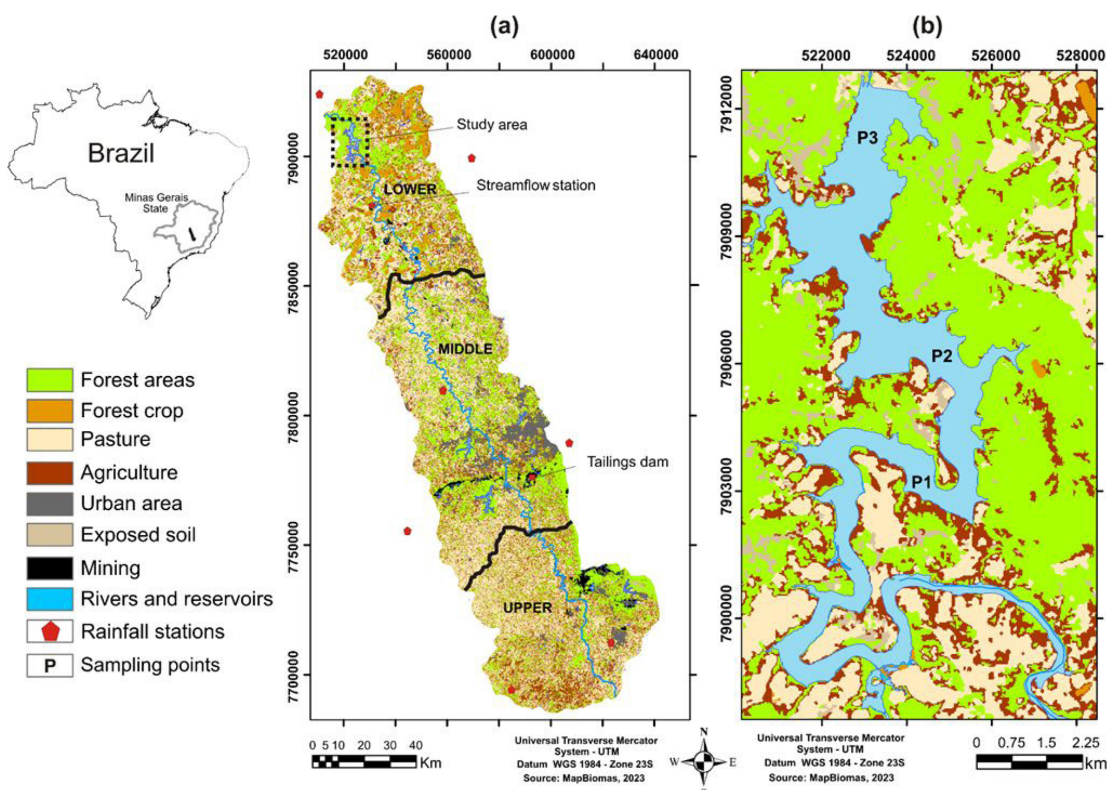

Figure 1. (a) Location and land use in the Upper, Middle and Lower Paraopeba River basin with emphasis on the tailings dam, streamflow and rainfall stations, modified Sardinha et al. (2025). (b) Retiro Baixo Reservoir with water sampling points location, modified Sardinha et al. (2024).

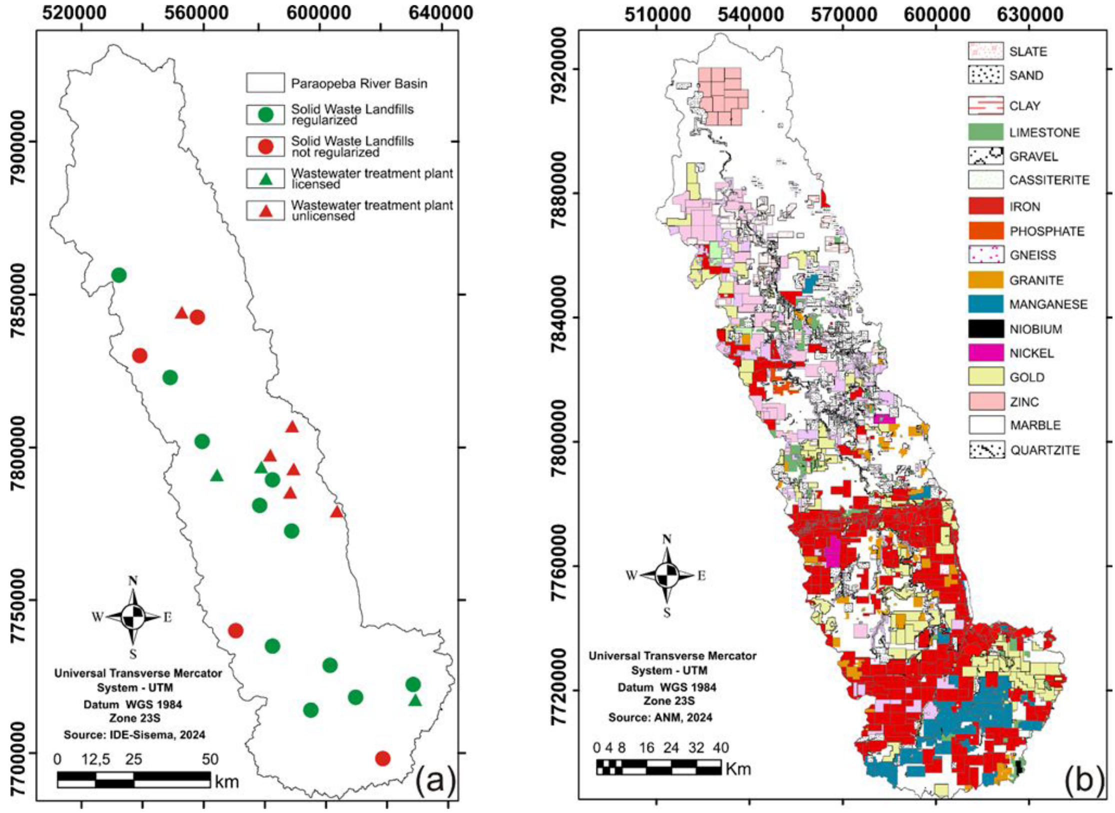

Figure 2. (a) Wastewater plants and waste disposal areas in the Paraopeba River basin based on the Minas Gerais Spatial Data Infrastructure (IDE-Sisema, 2024). (b) Mining areas registered for National Mining Agency in the Paraopeba River basin (ANM, 2024).

Paraopeba River, the granite-gneissic rocks from the Belo Horizonte and Bonfim Complexes (Archean), the Archean green rock belt from the Rio das Velhas Supergroup and the Proterozoic metasedimentary units from the Minas Supergroup, stand out. In the Lower Paraopeba, the Neoproterozoic sedimentary units of the Paraopeba (Serra da Saudade) and Três Marias formations, from the Bambuí Group, are highlighted (Figure 3a).

The basin is characterized by plateaus, depressions and dissected areas predominantly resulting from the alternation of morphoclimatic processes associated with geological conditioning. The existing geomorphological units are: Dissected Plateau of the central-south and east of Minas, São Franciscana Depression, São Francisco Plateau and Iron Quadrangle (Durães, 2010). The relief is characterized by the presence of rounded mountains with two main sets of rugged and elevated topography, and flat or slightly undulating topography (FEAM, 2011).

The region has a mean annual temperature varying between 19 and 23°C, with the lowest temperatures found in the southern portion due to the orography and higher latitudes, with a temperature increase as lower latitudes are reached (CPRM, 2001). According to FEAM (2011), the characteristic climate is tropical high altitude, with mild summers and milder temperatures, below 20°C. Which is hottest month, mean temperatures vary from 20°C to 25°C and which is coldest month, cold temperatures vary between 15°C and 20°C. The area is located in a transition region between the Atlantic Forest and the Cerrado biomes, which are responsible for the wide variety of species (FEAM, 2016). Argisols, Cambisols, Ferrasols and Litholic Neosols emerge in the basin region, with Ferrasols and Cambisols being the most common in the region (Figure 3b).

3. Materials and Methods

3.1. Morphometric analysis

In this study, the primary morphometric parameters such as maximum length (L_{max}), reservoir area (A_r), hydrographic basin area (A_b), reservoir volume (V_r), maximum depth (D_{max}) were investigated based on the technical sheets and bathymetries provided by Eletrobrás Furnas (2023)

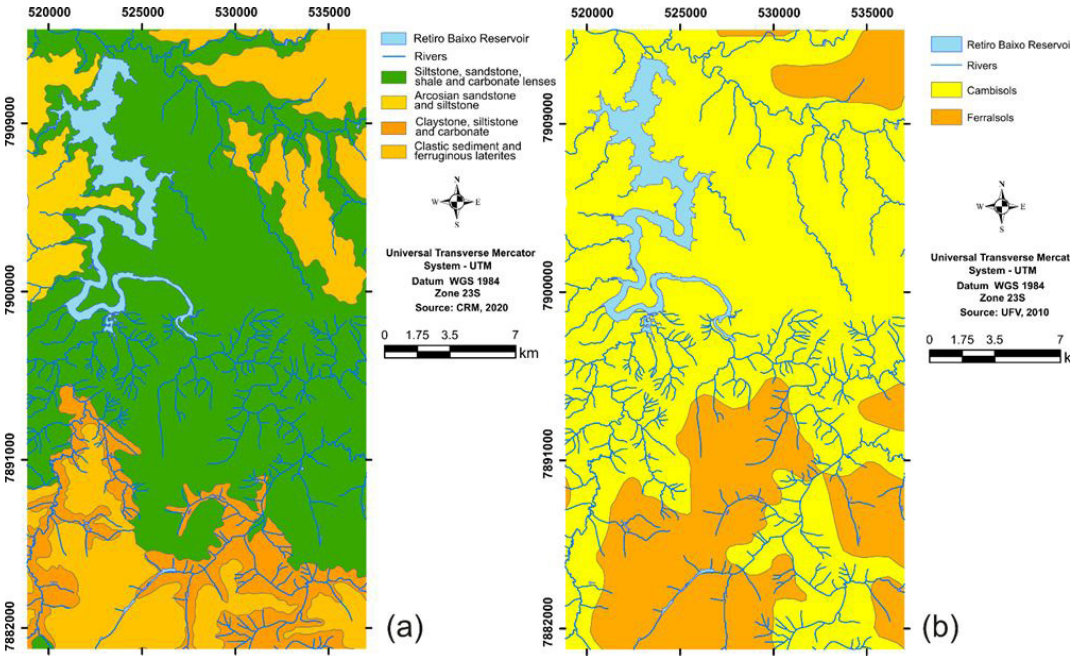

Figure 3. (a) Lithological map near the Retiro Baixo Reservoir based on (CPRM, 2020). (b) Soil map near the Retiro Baixo Reservoir based on (UFV, 2010).

and SNIRH (2023a). Using geoprocessing software, the shoreline length (l_0) and maximum width (B_{max}) were estimated. Through data collection and he secondary morphometric parameters mean width (B_m = Equation 1 - Wetzel, 1983), mean depth (D_m = Equation 2 - Håkanson, 1981), relative depth (D_r = Equation 3 - Håkanson, 1981), shore development index (F = Equation 4 - Wetzel, 1983), volume development index (V_D = Equation 5 - Håkanson, 2004) and involvement factor (I_f = Equation 6 - Sperling, 1999) were calculated.

$$B_m = \frac{A_r}{L_{\max}} \tag{1}$$

Where: B_m = mean width (m); A_r = reservoir area (m^2); L_{max} = maximum length (m).

$$D_m = \frac{V_r}{A_r} \tag{2}$$

Where: D_m = mean depth (m); V_r = reservoir volume (m^3); A_r = reservoir area (m^2).

$$D_r = \frac{\left(D_{\max} \times \sqrt{\pi}\right)}{\left(20 \times \sqrt{A_r}\right)} \tag{3}$$

Where: D_r = relative depth (%); D_{max} = maximum depth (m); A_r = reservoir area (km^2).

$$F = \left[\frac{(l_0)}{\left(2 \times \left(\sqrt{\pi \times A_r}\right)\right)}\right] \tag{4}$$

Where: F = shore development index (dimensionless); l_0 = shoreline lenght (km); A_r = reservoir area (km^2).

$$V_D = 3 \times \left(\frac{D_m}{D_{\max}}\right) \tag{5}$$

Where: V_D = volume development index (dimensionless); D_m = mean depth (m); D_{max} = maximum depth (m).

$$I_f = \left(\frac{A_b}{A_r}\right) \tag{6}$$

Where: I_f = involvement factor (dimensionless); A_b = hydrographic basin area (m^2); A_r = reservoir area (m^2).

3.2. Hydric balance

Due to the large extension and aiming the comparison of average rainfall values during the study period, the Thiessen method (1911) was used. The calculation was carried out using the weighted mean between the rainfall at each station and the weight assigned to it, which is the rainfall influence area at each station, according to Equation 7.

$$P_m = \frac{\sum_{i-1}^{n} A_i \times P_i}{A_b} \quad (7)$$

Where: P_m = mean rainfall in the basin (mm); Ai = influence area on the i-th rainfall station (km^2); Pi = rainfall in the i-th rainfall station (mm); A_b = basin total area (km^2).

Rainfall data from the historical series were obtained from pluviometric stations in operation on the Hidroweb Portal (SNIRH, 2023b). The mean rainfall was calculated from seven rainfall stations (Conselheiro Lafaiete - 2043005, Lagoa Dourada - 2044079, Ibirité - A555, Divinópolis - A564, Florestal - A535, Sete Lagoas - A569 and Três Marias - A528) that belong to the historical series of the National Water Agency (ANA) hydrometeorological network, covering the sampling periods (2019, 2021 and 2022). The flow data were obtained at the station (40865001) on the Paraopeba River, located on the last bridge before the Retiro Baixo Reservoir, between the municipalities of Pompéu and the Anguereta district.

According to Tundisi & Matsumura-Tundisi (2008), the ratio between the reservoir volume (Vr) and its tributary flows (Q) determines the theoretical retention time. In this work, the theoretical retention time was calculated using Equation 8.

$$R_e = \left(\frac{V_r}{Q}\right) \quad (8)$$

Where: R_e = theoretical retention time (days); V_r = reservoir volume (m^3); Q = tributary flows to the reservoir (m^3.s^{-1}).

3.3. Water quality analysis

To assess water quality, sampling was taken on 02/2019, 04/2019, 08/2019, 11/2019, 05/2021, 08/2021, 11/2021, 02/2022, 05/2022 and 08/2022 at three representative points located within the reservoir: close to the beginning or river zone (P1), in the central region or intermediate zone (P2) and close to the spillway or lake area (P3) (Figure 1). The samples were collected with a Van Dorn bottle at three different depths, according to Oliveira (2012), bottom or bed or deep aphotic zone, medium depth and superficial depth of air-water interface or euphotic zone, totaling 90 samples. The mean sampling depths were: P1 (P1.1 = 0.49 m, P1.2 = 4.45 m and P1.3 = 9.07 m); P2 (P2.1 = 0.45 m, P2.2 = 6.00 m and P2.3 = 12.17 m); P3 (P3.1 = 0.51 m, P3.2 = 10.87 m and P3.3 = 21.77 m. A Secchi disk (Zds) was used to estimate the extent of light penetration and/or euphotic zone (Z_{eu}) from the 2.7 factor (Esteves, 2011).

The reservoir waters were monitored in situ by using direct reading equipment with electrodes at the sampling site, a portable meter U-50 Multiparameter Water Quality Checkers from Horiba previously calibrated. At each point, we measured the pH values, electrical conductivity, redox potential, turbidity, depth and dissolved oxygen concentrations. Water samples were stored in clean one-liter polypropylene bottles, and at the time of sampling, the flasks were rinsed with local water, and placed in a thermal box containing ice.

The samples were taken to the Hydrogeochemical laboratory (Unifal-MG; Poços de Caldas campus), and subsamples of total suspended solids were taken in triplicate, according to gravimetric methodology (APHA, 2012). Na^+ and K^+ contents were determined using a MOD Flame Photometer Analyser 910 MS (Na^+ and K^+ standards of 20 ppm and 100 ppm) resolution of 1.0 ppm ± 0.1 ppm. The contents of manganese Mn (PAN method, from 0 to 0.700 mg.L^{-1} ± 0.013 mg.L^{-1}), copper Cu (Bicinchoninate method, from 0.0 to 5.0 mg.L^{-1} ± 0.02 mg.L^{-1}), iron Fe (FerVer method, from 0 to 3.0 mg.L^{-1} ± 0.017 mg.L^{-1}), phosphate PO_4^{3-} (ascorbic acid method, from 0.02 to 2.5 ± 0.01 mg.L^{-1}), sulfate SO_4^{2-} (sulfaver 4 method, from 0 to 70 mg.L^{-1} ± 0.9 mg.L^{-1}) and nitrate NO_3^- (cadmium reduction method, from 0 to 30.0 ± 0.3 mg.L^{-1}) were quantified by DR 890 spectrophotometer model from Hach Company.

The hydrochemical data analysis from the Retiro Baixo Reservoir was carried out using descriptive statistics with the help of electronic calculation and processing spreadsheet of the PAST software - Palaeontological Statistics, version 4.09 (Hammer et al., 2023). Pearson's linear correlation analyses (r) were carried out to identify the relationships between the independent (x) and dependent (y) variables.

The results provided by this study were compared with reference values of the Brazilian legislation CONAMA Resolution nº. 357 of 2005 Class II (Brasil, 2005) and Minas Gerais legislation COPAM/CERH Normative Deliberation nº. 8 of 2022 (Minas Gerais, 2022), which classified Paraopeba River as a Class II lentic environment, according to COPAM Normative Deliberation nº 14 of 1995 (Minas Gerais, 1995). According to these regulations, class II freshwater aquatic ecosystems serve the following purposes: a) providing water for human consumption after conventional treatment; b) preserving aquatic communities; c) enabling recreational activities involving direct contact; d) watering crops; and e) supporting aquaculture and fishing activities.

4. Results and Discussion

4.1. Morphometry of the Retiro Baixo Reservoir

The Retiro Baixo Reservoir is located 619 m above sea level, has a flooded area (A_r) of 22.58 km^2 and a 0.24 km^3 (2.41×10^8 m^3) volume (V_r), which insert it as a medium reservoir category (10^2 to 10^4 km^2 and 10^8 to 10^{11} m^3; see Table 1) according to flooded area (Tundisi & Matsumura-Tundisi, 2008). The reservoir, whose maximum length (L_{max}) is 37.60 km, maximum (B_{max}) and mean (B_m) width of 2930.15 and 600.53 meters, respectively, is irregularly elongated and N-S oriented, with inflections towards NE-SW (Figure 1). The shape, together with B_{max} and B_m, are important parameters that, according to Håkanson (1981), influence the morphological contexts of the shore and establish predominant dynamic situations at the reservoir bottom (erosion-transport-accumulation).

According to Itaipu Binacional (2023), the largest artificial lake in Brazil is Sobradinho with a 4,214 km^2 flooded area, whereas Itaipu Reservoir, with 1,350 km^2, is the seventh largest with a 170 km extension and maximum and mean widths of 12 and 7 km, respectively. On the other hand, the Serra da Mesa Reservoir with 54.4 km^3 followed by Tucuruí with 45.5 km^3 are the largest in terms of volume, according to Sperling (1999). In Lake Palmas, Barroso et al. (2014) found a maximum depth of 50.7 m, a mean of 21.4 m and a relative depth of 1.4%. Gonçalves et al. (2016) in Lake Nova identified a maximum, mean and relative depth of 33.9 m, 14.7 m and 0.7%, respectively.

Artificial reservoirs may have considerable maximum depths, according to data from Sperling (1999) for Itaipu with 170 m and Serra da Mesa with 150 m. The Retiro Baixo Reservoir has 45 meters maximum (D_{max}), 10.70 m mean (D_m), and 0.84% relative (D_r) depths respectively (Table 1). In the Três Marias Reservoir, Tundisi & Matsumura-Tundisi (2008) found a maximum depth of 30 m and a 6.8 m mean. According to Wetzel & Likens (1991) most lakes have a relative depth of less than 2%, this indicates that there are no morphological limitations for the water mass complete mixing as it is exposed to the wind action. Therefore, the Retiro Baixo Reservoir does not present limitations for water column complete vertical circulation, which probably can contribute to changes some parameters values, such as temperature, dissolved oxygen, redox potential, electrical conductivity, turbidity, and total dissolved and suspended solids at surface.

The shore development index (7.89) illustrates the relationship between the shoreline length and the circle circumference length with an area equal to the reservoir's total area (Håkanson, 2004). A perfectly circular lake has a value equal to 1, while irregular values equal to or greater than 10 are rare and are probably obtained by the most irregular lakes in the world. On the other hand, Morais et al. (2005) discuss that narrow and elongated morphologies increase the development rate due to the area/shoreline length ratio, that is, the area of the lakes is small compared to the extent of the shoreline length, this does not mean that the lakes have irregular shores, but rather shores with an elongated and well-defined tendency. Morais et al.

Table 1. Morphometric parameters from Retiro Baixo Reservoir.

Morphometric parameters	Symbol	Unit	Value
Paraopeba River Basin Area	A_b	km^2	12054.25
Retiro Baixo Reservoir Area	A_r	km^2	22.58
Maximum length	L_{max}	km	37.60
Shoreline length	l_0	km	132.84
Reservoir volume	V_r	m^3	2.41×10^8
Maximum depth	D_{max}	m	45.00
Maximum width	B_{max}	m	2930.15
Mean width	B_m	m	600.53
Mean depth	D_m	m	10.70
Relative depth	D_r	%	0.84
Shore development index	F	dimensionless	7.89
Volume development index	V_D	dimensionless	0.71
Involvement Factor	I_f	dimensionless	533.85

(2005) found 13.65 values for Lake Piedade (São Paulo State) and Gonçalves et al. (2016) found a 5.0 value for Lake Nova, classifying it as slightly dendritic. In the Hedberg dam (São Paulo State), Silva et al. (2016) found a 2.28 index, which indicates a medium degree of irregularity on its shores.

The 132.84 km shoreline length (l_0) and the 22.58 km^2 area (A_r) indicate a 7.89 shore development (F) for the Retiro Baixo Reservoir, suggesting irregularly shaped contour-line that promotes complex shores with greater habitat heterogeneity (Singh et al., 2023). For Tundisi & Matsumura-Tundisi (2008) extremely irregular dendritic lakes have values between 3 and 5 and, artificial dams with a pronounced dendritic pattern and complex morphometry present a high rate of shore development. Lakes and reservoirs with irregular contours of the shore are more resistant to the impacts arising from effluent reception and other polluting pulses, since the vegetation on the shore presents a high capacity to assimilate pollutants (Cigagna et al., 2014).

The volume development index is a morphometric parameter that indicates the water body vertical shape characteristics (Cigagna et al., 2014). Lakes or dams that present volume development (V_D) equal to 1, have their basins in the shape of an approximate cone; as V_D moves away from 1 value, lakes and dams assume convex ($V_D < 1$) or concave ($V_D > 1$) shapes (Silva et al. 2016). In the Retiro Baixo Reservoir, V_D is 0.71, therefore a convex shape that presents a certain relationship with the relative depth (Dr), as the parameters express aspects of the lake's shape. According to Tundisi & Matsumura-Tundisi (2008), the shape of the basin can be evaluated by the mean depth over maximum depth (D_m/D_{max}), with 0.333 being the ratio for an ideal cone. The relationship ($D_m/D_{max} = 0.24$) and ($V_D = 0.71$) indicate that the Retiro Baixo Reservoir is close to a V-shape. According to Sperling (1999), this is characteristic of reservoirs whose shore are more exposed to wind action, which can contribute to the water column mixing cooling down the superficial layer.

Involvement factor, according to Sperling (1999), indicates the probability of sediments and nutrients transport that can contribute to the reservoir silting and eutrophication, and in natural lakes the most common values are in the order of a few tens, while in dams, the value can reach hundreds, and may eventually be greater than 1000. The involvement factor ($I_f = 533.85$) indicates that the Retiro Baixo Reservoir is a small environment (A_r = 22.58 km^2) with a large contribution area (A_b = 12054.25 km^2), demonstrating that the dilution capacity may be small compared to the large drainage basin area, being prone to siltation and eutrophication.

4.2. Hydric balance

A total of seven rainfall stations were used (Table 2). The annual rainfall had an average of 1281.50 mm for 2019, 1557.47 mm for 2021, and 1643.11 mm for 2022. Using the Thiessen method, annual rainfall had an of 1289.10 mm, 1541.48 mm, and 1656.27 mm for 2019, 2021, and 2022, respectively. Comparing the means (average and Thiessen method) annual rainfall, the differences were small (≤ 1%) and the values were close to those found by Aires et al. (2016) of 1,370 to 1,450 mm and COBRAPE (2020) of 1,100 to 1,700 mm.

During the study period, low rainfall periods between May and September was observed, with variations of 0.37 mm (July 2021) to 19.54 mm (September 2021) (Table 3). High rainfall occurred between October and April, with emphasis on the variation from 503.21 mm (January 2022) to 331.14 mm (December 2021).

The minimum monthly flow corresponded to September 2019 (13.61 m^3.s^{-1}), while the maximum was in February 2022 (570.92 m^3.s^{-1}), with

Table 2. Location, influence area, % of the related to total area and weight factor of the stations used for rainfall means calculation.

Station	Locality	Area (km^2)	(%) related to total area	Weight factor
2043005	Conselheiro Lafaiete	1460	12.11	0.121
2044079	Lagoa Dourada	2600	21.57	0.216
A555	Ibirité	726	6.02	0.060
A564	Divinopolis	2449	20.32	0.203
A535	Florestal	1443	11.97	0.120
A569	Sete Lagoas	2549	21.15	0.211
A528	Três Marias	827	6.86	0.069
Total	--	12054	100	1

Table 3. Weighted mean rainfall (Thiessen method), mean inflow and theoretical retention time in the Retiro Baixo Reservoir.

Thiessen	Jan	Feb	Mar	Apr	May	JUN	Jul	Aug	Sep	Oct	Nov	Dez
	(mm)											
2019	86.90	294.98	146.16	104.44	42.43	9.72	0.97	4.29	35.76	59.96	223.18	280.31
2021	210.52	351.51	105.48	15.18	12.61	9.87	0.37	7.43	19.54	265.72	212.11	331.14
2022	503.21	336.09	28.22	57.35	31.31	2.95	1.41	3.04	54.34	81.12	231.33	325.91
Inflow	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dez
	($m^3.s^{-1}$)											
2019	78.07	82.69	136.39	82.47	51.47	34.18	22.11	18.91	13.61	27.94	53.82	133.82
2021	212.91	257.05	132.90	69.16	50.06	46.60	35.72	28.89	22.06	99.26	118.82	209.45
2022	503.76	570.92	206.38	138.67	106.81	78.02	62.38	49.92	41.15	58.60	94.19	203.55
Retention time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dez
	(days)											
2019	35.82	33.82	20.50	33.91	54.33	81.82	126.47	147.84	205.49	100.08	51.96	20.90
2021	13.13	10.88	21.04	40.43	55.85	60.01	78.29	96.78	126.75	28.17	23.53	13.35
2022	5.55	4.90	13.55	20.16	26.18	35.84	44.82	56.01	67.95	47.72	29.69	13.74

annual means of 61.29 $m^3.s^{-1}$, 106, 91 $m^3.s^{-1}$ and 176.19 $m^3.s^{-1}$ for 2019, 2021 and 2020 respectively (Table 3). The lowest and highest flow values were recorded in dry and rainy months, reducing the enormous seasonal influence of this parameter, with a variation of approximately 123 $m^3.s^{-1}$ in 2019, 235 $m^3.s^{-1}$ in 2021, and 530 $m^3.s^{-1}$ in 2022.

The hyrodynamics of the tributary river weighted over the lake volume produces the retention time, which in turn control the mass balance of substances, such as contaminants (Gonçalves et al., 2016). According to Håkanson (2004 and 2005), retention time, also known as residence time, hydraulic retention time, or retention rate, is associated with the main differences in water quality between reservoirs, a fundamental component that regulates the dissolved and suspended material that is carried by the rivers tributary flows. The theoretical mean retention time of the Retiro Baixo Reservoir was 51.31 days, considering 2019 (76.08 days), 2021 (47.35 days) and 2022 (30.51 days). According to Barroso et al. (2014) the theoretical retention time is longer in deeper reservoirs, and is generally less than one year, with a limit below 200 days. The values are close to those found for the Tucuruí (51 days), Itaipu (40 days) and Três Marias (29 days) reservoirs, according to data from Tundisi and Matsumura-Tundisi (2008). The reduced flow (13.61 $m^3.s^{-1}$) during the dry period caused a longer retention time, as observed for September 2019 (205 days), with exactly the opposite occurring during the rainy period in February 2022 (4.90 days), when the flow was higher (570.92 $m^3.s^{-1}$).

4.3. Water quality assessment

The mean values of Secchi disk depth (Zds) and extent of light penetration and/or euphotic zone (Z_{eu}) varied between the sampling points: Zds = 1.40 m and Z_{eu} = 3.77 m at point P1; Zds = 1.56 m and Z_{eu} = 4.20 m at point P2; and Zds = 1.98 m and Z_{eu} = 5.33 m at point P3. The values were lower during the rainy period of February 2022, varying from Zds = 0.10 m and Z_{eu} = 0.27 m to Zds = 5.0 m and Z_{eu} = 13.50 m in May 2021 at point P3. The highest water transparency value recorded at point P3 is in accordance with the reservoir compartmentalization theory by Kimmel et al. (1990), where there is greater water transparency in dammed rivers due to lower concentrations of suspended particulate matter and a decrease in primary productivity.

We observed that the lowest water temperature value was recorded at point P1.3 (bottom) on 05/2022 sampling (18.57°C) and the maximum at P3.1 (surface) on 02/2019 (29.75°C), with a mean of 23.08°C, allowing us to observe a water temperature variation of approximately 11.18°C between the different sampling periods (Table 4). The pH values varied between 5.32 and 9.02, with 94% of the samples within the range of 6.0 to 9.0, in accordance with the Brazilian and Minas Gerais legislation CONAMA Resolutions nº 357 and COPAM/CERH nº 8 guidelines. The Redox potential values (ORP) varied between -155.0 and 331.0 mV, indicating an environmental predominance of oxidizing conditions, according to variations in dissolved oxygen (DO) concentrations, at the sampled points within the extent of light penetration and/or euphotic zone (Z_{eu}), reducing in some points of the aphotic zone (P2.3 and P3.3).

Electrical conductivity (Cond.) varied between 46 $\mu S.cm^{-1}$ and 259 $\mu S.cm^{-1}$, with the median and mean equal 176.00 $\mu S.cm^{-1}$ and 151.33 $\mu S.cm^{-1}$, respectively (Table 4). Approximately 62% of water turbidity samples (Turb) presented values below 100

Table 4. Descriptive statistics with the results from the ninety water samples collected in three points at three different depths between 02/2019 and 08/2022. CONAMA Resolution 357 (Brasil, 2005) related to Class 2 waters.

Parameter	Unit.	Mean	Median	Minimum detected	Maximum	Variance (%)	Standard Deviation	Conama 357
T	°C	23.08	22.72	18.57	29.75	6.63	2.56	--
pH		7.18	7.16	5.32	9.02	0.70	0.83	6 a 9
ORP	mV	137.20	149.50	-155.00	331.00	10678.77	102.76	--
Cond	$\mu S.cm^{-1}$	151.333	176.00	46.00	259.00	4339.53	65.51	--
Turb	NTU	55.66	15.80	2.10	800.00	14807.24	121.01	100.00
TDS	$mg.L^{-1}$	96.32	114.00	30.00	169.00	1728.18	41.34	500.00
TSS	$mg.L^{-1}$	32.53	6.56	0.22	295.11	3669.95	60.24	--
DO	$mg.L^{-1}$	5.54	6.03	0.14	12.32	6.38	2.51	5.00
Na^{+}	$mg.L^{-1}$	12.15	11.00	1.20	51.00	59.33	7.66	--
K^{+}	$mg.L^{-1}$	3.12	3.00	1.40	6.20	1.62	1.27	--
Mn	$mg.L^{-1}$	0.13	0.02	0.01	2.95	0.19	0.43	0.10
Cu	$mg.L^{-1}$	0.06	0.02	0.01	0.30	0.01	0.08	0.009
Fe	$mg.L^{-1}$	0.30	0.17	0.01	1.33	0.11	0.33	0.30
SO_4^{2-}	$mg.L^{-1}$	2.61	2.00	0.01	10.00	4.98	2.22	250.00
NO_3^{-}	$mg.L^{-1}$	1.99	1.60	0.10	6.20	2.04	1.42	10.00
PO_4^{3-}	$mg.L^{-1}$	0.28	0.26	0.01	1.11	0.03	0.17	--

NTU, values that are in accordance with the Brazilian and Minas Gerais legislation CONAMA Resolutions nº 357 and COPAM/CERH nº 8 guidelines. Total suspended solids concentrations (TSS) varied between 0,22 $mg.L^{-1}$ and 295,11 $mg.L^{-1}$ (mean concentration of 32.53 $mg.L^{-1}$). All samples showed sulfate concentrations within the limits of Class 2 CONAMA Resolutions nº 357 (250.0 $mg.L^{-1}$), as also observed for nitrate concentrations (10.0 $mg.L^{-1}$), which had maximum concentrations of 10.0 $mg.L^{-1}$ for sulfate and 6.20 $mg.L^{-1}$ for nitrate (Table 4). The dissolved phosphate concentrations (PO_4^{3-}) varied between a minimum of < 0.01 $mg.L^{-1}$ and a maximum of 1.11 $mg.L^{-1}$ (mean concentration of 0.28 $mg.L^{-1}$; Table 4).

The mean concentrations for Mn (0.13 $mg.L^{-1}$), Cu (0.06 $mg.L^{-1}$), and Fe (0.30 $mg.L^{-1}$) exceeded or were equal to the limits of CONAMA Resolutions nº 357 and COPAM/CERH nº 8 guidelines. Our results showed that 60% of the samples presented Cu values that exceeded the established limit, mainly in the deeper layers. On the other hand, most of the analyzed samples presented low concentrations of Fe and Mn (91.1% of Mn and 66.6% of Fe), with few exceptions, for example, for manganese (Mn) there were only 8 samples with values above 0.10 $mg.L^{-1}$. Indeed, the median concentration for Mn (0.02 $mg.L^{-1}$) and Fe (0.17 $mg.L^{-1}$) stayed below these limits. These results suggest that the mean values of these variables (Mn and Fe) were affected by specific events or outliers.

During the study period, we observed a decrease in temperature, pH and dissolved oxygen mean values when comparing the surface and bottom of the sampling points, such as the temperature values difference (3.8°C) between P3.1 and P3.3 and dissolved oxygen concentrations (difference of 4.70 $mg.L^{-1}$) between P3.1 and P3.3 (Figure 4). Oxygen consumption by bacterial respiration is intensive at all depths but in the hypolimnion is rarely offset by the oxygen renewal mechanisms of circulation and photosynthesis that occur in the epilimnion and metalimnion (Wetzel, 1983). These factors may contribute to the environmental predominance of oxidizing conditions, with higher temperatures and pH values close to neutrality, mainly in the most superficial euphotic zone (P1.1, P2.1, and P3.1). However, in the aphotic zone at greater depths (P1.3 and P2.3) and close to the spillway or lake zone (P3.3), we observed lower temperatures, turbidity, and higher conductivity values. Furthermore, there is a significant increase in total suspended solids, manganese and iron concentrations in deeper layers. While the mean concentrations of Mn are higher near the spillway or lake zone (P3.3 = 0.53 $mg.L^{-1}$), those of iron are higher near the beginning or river zone (P1.3 = 0.39 $mg.L^{-1}$), as shown in Figure 4. For the other parameters (potassium, copper, sulphate, nitrate and phosphate), there were no major variations.

The shore development index (F = 7.89) for the Retiro Baixo Reservoir, indicates that the shorelines contours are irregular, which can mitigate the impacts of effluent receipt and other polluting pulses according to Cigagna et al. (2014). On the other hand, the involvement factor (I_f = 533.85)

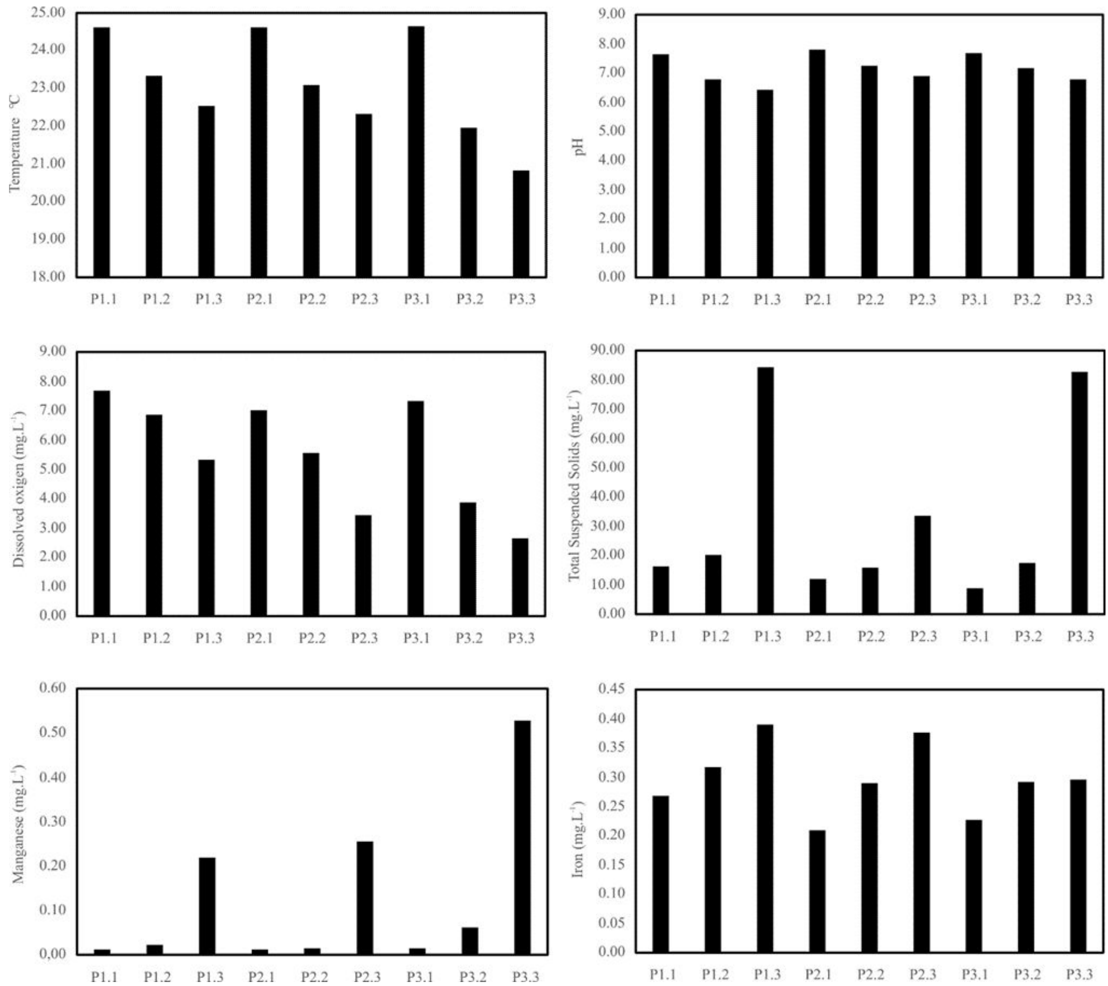

Figure 4. Mean values of temperature, pH, dissolved oxygen, total suspended solids, manganese and iron in the waters of the Retiro Baixo Reservoir. This figure shows the sampling points P1, P2, and P3, followed by the numbers representing the sampling depths (1 = surface, 2 = middle, and 3 = bottom).

indicates that sediment, metals and nutrients may be transported into the system. Morphometric and land use factors, together with river dynamics variation, caused by the mean inflow and retention time, can also influence the transport dynamics and retention of nutrients, metals, and sediments (Table 5).

The variation of 649,00 $m^3.s^{-1}$ (02/2022) and 19,70 $m^3.s^{-1}$ (08/2019) in the inflow to the Retiro Baixo Reservoir influences the solids concentration. In the highest flow months (649.00 $m^3.s^{-1}$), there is a greater input of sediments into the reservoir waters, probably due to the morphometric involvement factor, which leads to an increase in total suspended solids (TSS = 136.19 $mg.L^{-1}$) (Table 5). On the other hand, considering the total dissolved solids concentrations (TDS), the dilution process occurred in surface waters, with lower concentrations (32.78 $mg.L^{-1}$) during periods of higher flow (649.00 $m^3.s^{-1}$). During periods of low flow, with an increase in the theoretical retention time, there is an increase in the total dissolved solids concentration (Table 5).

The Retiro Baixo Reservoir has no morphological limitations for the complete mixing of the water mass, according to maximum, mean and relative depths morphometric data, which together with the location, hydrological factors and winds can lead to the development of vertical and horizontal patterns. However, our results demonstrated a vertical variation in temperature and dissolved oxygen values. According to Esteves (2011), chemical stratification, resulting from the variation in dissolved oxygen concentrations, is typically triggered by thermal stratification. Furthermore, in lakes from tropical regions, such as the study area, stratification is more commonly observed in summer, destratification in winter, or even daily

Table 5. Mean concentrations of sodium (Na^+), potassium (K^+), sulfate (SO_4^{2-}), nitrate (NO_3^-), phosphate (PO_4^{3-}), manganese (Mn), copper (Cu), iron (Fe), total dissolved solids (TDS), and total suspended solids (TSS) from the water samples, mean inflow and retention time to the Retiro Baixo Reservoir by sampling date.

Date	Na^+	K^+	SO_4^{2-}	NO_3^-	PO_4^{3-}	Mn	Cu	Fe	TDS	TSS	Inflow	Retention time
	(mg.L^{-1})										($m^3.s^{-1}$)	(days)
02/2019	11.00	3.00	1.89	4.01	0.28	0.28	0.13	0.38	120.56	22.25	46.00	60.79
04/2019	12.33	4.00	2.89	2.74	0.51	0.37	0.11	0.33	113.44	47.17	57.80	48.38
08/2019	22.56	4.22	3.11	1.76	0.29	0.08	0.02	0.13	125.11	37.16	19.70	141.94
11/2019	23.61	3.09	7.00	1.01	0.13	0.13	0.03	0.24	149.56	38.52	57.57	48.57
05/2021	10.41	2.08	1.56	0.62	0.40	0.34	0.01	0.03	125.00	14.44	46.10	60.65
08/2021	15.21	2.26	3.00	0.96	0.12	0.01	0.00	0.06	134.22	1.97	27.19	102.84
11/2021	8.77	3.04	4.33	1.53	0.38	0.04	0.19	0.97	55.56	17.94	96.46	28.99
02/2022	5.23	1.89	2.00	3.79	0.26	0.02	0.13	0.59	32.78	136.19	649.00	4.31
05/2022	1.23	5.90	0.33	1.80	0.20	0.01	0.02	0.20	51.56	2.56	93.24	29.99
08/2022	11.17	1.70	0.00	1.68	0.22	0.00	0.01	0.05	55.44	7.11	46.87	59.66

stratification. These processes can also be influenced by the inflow of water from the Paraopeba River and the reservoir operation (inflow and retention time).

The involvement factor index (I_f) demonstrated that the dilution capacity of the reservoir might be small in comparison to the large drainage area of the basin, being more prone to siltation and eutrophication. These characteristics, together with hydrodynamics, indicated that, in periods of higher inflow, there was an increase in the total suspended sediments (TSS), copper (Cu), iron (Fe), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations. On the other hand, at the low inflow periods, there was an increase in the theoretical retention time (R_e) and total dissolved solids (TDS), sodium (Na^+), sulfate (SO_4^{2-}), manganese (Mn) and potassium (K^+) concentrations.

Our results demonstrated that manganese (Mn), copper (Cu) and iron (Fe) concentrations exceeded or were equal to the current legislation limits. In the euphotic zone, with higher dissolved oxygen concentrations, iron and manganese could be present in insoluble form (Fe^{3+} and Mn^{4+}), while in the absence of dissolved oxygen, which was the case of aphotic zones at greater depths, they could turn into the soluble form (Fe^{2+} and Mn^{2+}) and becoming available to biota causing toxic effects (Borch et al. 2010). High concentrations of Mn, Cu and Fe in tropical reservoirs were also found by Flauzino (2008), Breda (2011), Pedrazzi et al. (2014), Voigt et al. (2016), Assunção et al. (2016), Bento et al. (2019) and Coura (2020). These authors attribute such results to local geochemical characteristics, mining activities, leaching from agricultural soils (fertilizers), domestic and industrial effluents.

Land use in the Paraopeba River basin is marked by urban agglomerations, agricultural exploration, steelmaking, metallurgical, automobile, petrochemical industries, and large mining enterprises (Sardinha et al. 2024, 2025). The physiographic influences of the Paraopeba River basin (lithology, relief, climate, hydrography, soil, and vegetation cover), morphometric characteristics of the Retiro Baixo Reservoir and historical land use and occupation may be affecting the reservoir water quality. Furthermore, influent flow, the water retention time, stratification and destratification may also contribute to sediments, metals and nutrients transport and mobilization into the system.

5. Conclusion

Paraopeba River basin is located in the Minas Gerais state central region and drains diverse physiographic (geology, relief, pedology iron quadrangle) and land uses (steel industry, metallurgical, automotive industries, agriculture, livestock farming and mining). The rupture of iron ore tailings dam in Brumadinho, together with land use and land cover with urban agglomerations (domestic sewage and dumping of untreated solid waste), agricultural exploitation (application of fertilizers and pesticides), geochemical background (relief, lithology and soil), iron ore and manganese mining, as well as metallurgical, automobile and petrochemical industries can contribute to the concentration of these elements in the reservoir, strongly influenced by hydrodynamic seasonality.

To mitigate the adverse effects on biological communities and ecosystem service loss caused by the metal levels, it is imperative to implement and enhance public policies for monitoring and regulating land use and occupation. Additionally, financial incentives should be provided to promote sustainable mining, industrial, urban and agricultural practices. Engaging with local communities, governments and stakeholders to raise awareness about the environmental risks associated with urban waste and wastewater, mining and agricultural activities and the importance of sustainable practices can foster greater cooperation and support for mitigation efforts.

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Data availability

The data that support the findings of this study are available from the authors upon reasonable request.

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