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Definition of water quality variability parameters and dynamics to improve management in a deep canyon type subtropical hydroelectric reservoir

Definição de parâmetros de dinâmica e qualidade da água para o gerenciamento em reservatório profundo de hidrelétrica subtropical tipo cânion

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ABSTRACT

Spatial and temporal variability patterns of water quality were evaluated through monthly collection of water samples (surface, subsurface and bottom) from 2005 to 2012. Principal Component Analysis was used to define the relative importance of each variable and Anova (two way) to analyze the significance of differences in water quality in the longitudinal axis of the reservoir. The variables: turbidity, Secchi transparency, residence time and temperature have greater importance on water quality. It was observed spatial and temporal gradients, related to the circulation, sedimentation and resuspension processes, and the influence of low flow, high residence time and winter mixing of water column on the cycling of solids and nutrients may explain the variation in these processes. The use of multivariate statistical analysis methods provided important information to understand these processes, it helps the interpretation of complex data to improve monitoring, and use of information to decision makers.

Keywords: Water quality; Spatial and seasonal gradient; Canyon reservoir; Monitoring program; Reservoir management.

RESUMO

Os padrões de variabilidade espacial e temporal da qualidade da água foram avaliados através de coletas mensais de amostras de água (superfície, subsuperfície e fundo) de 2005 a 2012. A Análise de Componentes Principais foi utilizada para definir a importância relativa de cada variável e Anova (bidirecional) para analisar a significância das diferenças na qualidade da água no eixo longitudinal do reservatório. As variáveis: turbidez, transparência de Secchi, tempo de residência e temperatura têm maior importância na qualidade da água. Foram observados gradientes espaciais e temporais, relacionados aos processos de circulação, sedimentação e ressuspensão, e a influência da baixa vazão, alto tempo de residência e mistura invernal da coluna d'água na ciclagem de sólidos e nutrientes pode explicar a variação desses processos. A utilização de métodos de análise estatística multivariada forneceu informações importantes para a compreensão desses processos, auxilia na interpretação de dados complexos para melhorar o monitoramento e uso das informações para os tomadores de decisão.

Palavras-chave: Qualidade da água; Gradiente espacial e sazonal; Reservatórios em canyon; Programa de monitoramento; Gestão de reservatórios.

INTRODUCTION

Artificial reservoirs are hydraulic systems for accumulating water for various uses and are key components of water infrastructure that serve many functions, such as water supply, hydroelectric power generation, flood control, recreation, ecosystem services, etc. (Azadi et al., 2019). The expansion of electricity supply in Brazil until the mid-2000s was predominantly based on hydropower and, in 2014, Brazil ranked third among countries with the highest level of hydropower production and installed capacity of UHEs (Sgarbia et al., 2019). Problems related to population growth, pollution, increased demand for food and water, and market fluctuations remain challenging in the management of water resources. Furthermore, the effects of climate change can make these problems more complex (Allawi et al., 2019; Morais & Maia, 2021).

The dynamics of the reservoirs are controlled according to their uses and purposes and, in the case of the operation of hydroelectric plants, there are impacts on the hydrodynamics of the reservoir, which force deep stratification, promote vertical mixing, reduce horizontal dispersion and change the flow defluent (Ibarra et al., 2015; Rossel & De La Fuente, 2015; Mirza et al., 2013). Reservoirs are generally considered as intermediary bodies of water between rivers and lakes, sharing some characteristics with both. A deeper and larger reservoir behaves more like a lake or a river, depending mainly on residence time (Casamitjana et al., 2003). Several factors determine the quality of water in reservoirs, among them the seasonality of climatic variables, the action of the wind, the geological origin of the catchment basin, the transport of nutrients by tributary rivers and deforestation and land use in the area of influence (Dar & Romshoo, 2008). In the current scenario, climate change affects the hydrology of rivers and promotes changes in the tributary areas of the reservoirs, which can profoundly impact their operation and, possibly, the quality of the water in the reservoirs (Azadi et al., 2019).

These fluctuations can lead to spatial and temporal heterogeneity in the chemical characteristics of water (Magbanua et al., 2015; Mirza et al., 2013). Thus, it is important to investigate the impacts due to the construction and operation of reservoirs on the dynamics of water quality (Olden & Naiman, 2010; Mirza et al., 2013; Beghelli et al., 2014; Rossel & De La Fuente, 2015).

The knowledge of hydrodynamic conditions in canyon reservoirs play a key role in understanding the spatiotemporal distribution of physical and chemical properties of stored water, irregular topography and energy of the water flow result in spatial heterogeneity in sediment deposition (Qin et al., 2020). The almost lentic nature of the reservoirs leads to a greater accumulation of phosphorus, which can trigger the production of phytoplankton, abundance and frequency of algal blooms (Lobo et al., 2021). In a canyon reservoir when water velocity decreases, depth increases, oxygen and pH decrease and water temperature tends to decrease with a larger water mass, indicating the existence of a transition zone from the river to the reservoir (Zhang et al., 2017). In addition, autochthonous organic carbon has a greater accumulation flux than surface carbon emitted to the atmosphere as CO_2, indicating that the reservoir is a major carbon sink (Qin et al., 2020). The eutrophic upper half has a more fluvial behavior and receives the main nutrients. The lower half of the reservoir can be considered a non-eutrophic deep stratified lake (Lindim et al., 2011). This gradient from the headwaters to the dam is primarily influenced by hydrodynamic characteristics, such as river flow, vertical circulation and the effluent flow regulated by the dam operation (Rodrigues et al, 2018). Parameters such as dissolved oxygen, nutrients (phosphorus and total nitrogen), turbidity, total solids and temperature are identified as relevant for determining temporal and spatial variation (Hajigholizadeh & Melesse, 2017; Ling et al., 2017; Barakat et al., 2016; Xiang et al., 2016; Xu et al., 2019; Calijuri et al., 2015)

Effective management of reservoir water resources requires a good knowledge of ecological processes in the water body (Lindim et al., 2011), so it is common practice for government regulatory agencies to define a series of parameters representative of physical. chemical, biological, hydrometeorological and hydromorphological conditions, through monitoring stations along a river at regular intervals (Pinto et al., 2013).

Assessing environmental water quality controls requires the compilation of many datasets across wide regions and over time into an integrated database (Soranno et al., 2017). Therefore, it is important to use methods that analyze spatiotemporal trends in water quality and identify the factors that affect this quality (Gu et al., 2016; Zhang et al., 2009; Su et al., 2011; Behmel, et al., 2016; Shoda, 2019; Li et al., 2016). The application of multivariate statistical techniques is very useful for the interpretation of complex data matrices from studies of water quality and ecological status of ecosystems. It also allows the interpretation of possible factors that influence aquatic systems and provides a valid tool for management and management of water resources, both in quality and quantity (Muangthong & Shrestha, 2015; Ruzdjak & Ruzdjak, 2015; Phung et al., 2015; Calazans et al., 2018; Barra Rocha & Pereira, 2016; Diamantini et al., 2018; Zeinalzadeha & Rezaeib, 2017, Xu et al., 2019; Zheng & Wang; 2016; Ling et al., 2017). Principal component analysis is a multivariate analysis technique that allows gathering a large number of variables and establishing possible patterns (Silva, 2016).

This study performed an analysis of temporal and spatial gradients of water quality and reservoir dynamics, with a wide range of water level variation. The Principal Component Analysis (Multivariate Analysis Technique) was the method used to identify the most relevant parameters for monitoring and understanding ecosystem dynamics.

MATERIAL AND METHODS

Description of the study area

The watershed of the Pelotas River, up to the Barra Grande HPP implantation site, drains a territorial extension of approximately 13,000 km^2. The main tributaries that directly contribute to the reservoir are, on the right bank, the Pelotinhas and Vacas Gordas Rivers and, on the left bank, the Santana and Socorro Rivers. The Pelotas River and its tributaries, in the site of the project, generally present a great slope and very deep, narrow and deep valleys, draining areas of thin soil and low permeability.

Such characteristics define a fluvial regime strictly linked to the pluvial regime, resulting in daily flushes, with great variability (Engevix, 1998).

The Barra Grande HPP reservoir has 92 km^2 of flooded area and approximately 5,000x106 m^3 of accumulated volume at the maximum normal level. The dam has a maximum depth of 185m and an average of 100m. The altitude of the maximum operational level is 647.00m; the maximum elevation: 650.14m; and the minimum operating quota: 617.00m. The maximum depletion foreseen by the operation at the water level is 30m (Engevix, 1998). The location is presented in Figure 1.

The region where the Barra Grande HPP is located has a predominance of rural occupation, with no significant polluting loads of industrial origin. Agriculture without proper soil management allows erosion to start, increasing water turbidity (Engevix, 1998). At the time of the project's implementation, there were no significant sources of pollution in the Pelotas River basin (Socioambiental, 2002). It was identified that the few and small polluting sources are located almost entirely near the headquarters of the municipalities, having a long journey until the pollutants reach the reservoir (Engevix, 1998).

Experimental and sampling design

In this work, data from the period from November 2005 to December 2012 were used, period when the reservoir was operational. The periodicity of the collections is monthly, making a total of 285 samples analyzed in this period.

Sampling was carried out at three points in the reservoir, one more upstream (P3), which includes contributions from the tributaries forming the head of the reservoir, one point in the central region (P2), which covers contributions from the tributaries forming the central part of the reservoir and another close to the dam (P1), which covers all contributions received by the Pelotas River. At each sampling point, water samples were collected on the sub-surface and bottom. On the sub-surface the samples were collected up to 70 cm deep and at the bottom up to 100 meters deep (P1 point). The identification, description and coordinates of the points are shown in Table 1 and in Figure 1. The methodology analysis is shown in Table 2.

To assess the existence of possible temporal and spatial gradients in the water quality dynamics of the Barra Grande HPP reservoir, from the monitoring carried out by the company, the main variables were defined to characterize the water quality, in this way, was analyzed eleven water quality variables in the sub-surface samples, namely: chlorophyll-a, electrical conductivity, total phosphorus, total nitrogen, pH, total solids, turbidity, Secchi transparency, water temperature and dissolved oxygen. The residence time was obtained by the ratio between the total volume of the reservoir (m^3) and the affluent flow (m^3/s). The samples were collected at the sub-surface, middle and bottom, and the depth measurements at each point varied or according to the depth of the point (the bottom at the P1 point was 100 meters, at the P2 point it was 50 meters and at the P1 10 meters). For background samples, a total of nine variables were analyzed,

Table 1. Description and coordinates of the sampling points for the analysis of the water quality of the Barra Grande HPP reservoir, SC.

Local	**Coordenates**	
	Lat	**Long**
P1	50° 47' 19" O	28° 11' 20" S
P2	50° 57' 06" O	27° 57' 47" S
P3	51° 10' 31" O	27° 47' 05" S

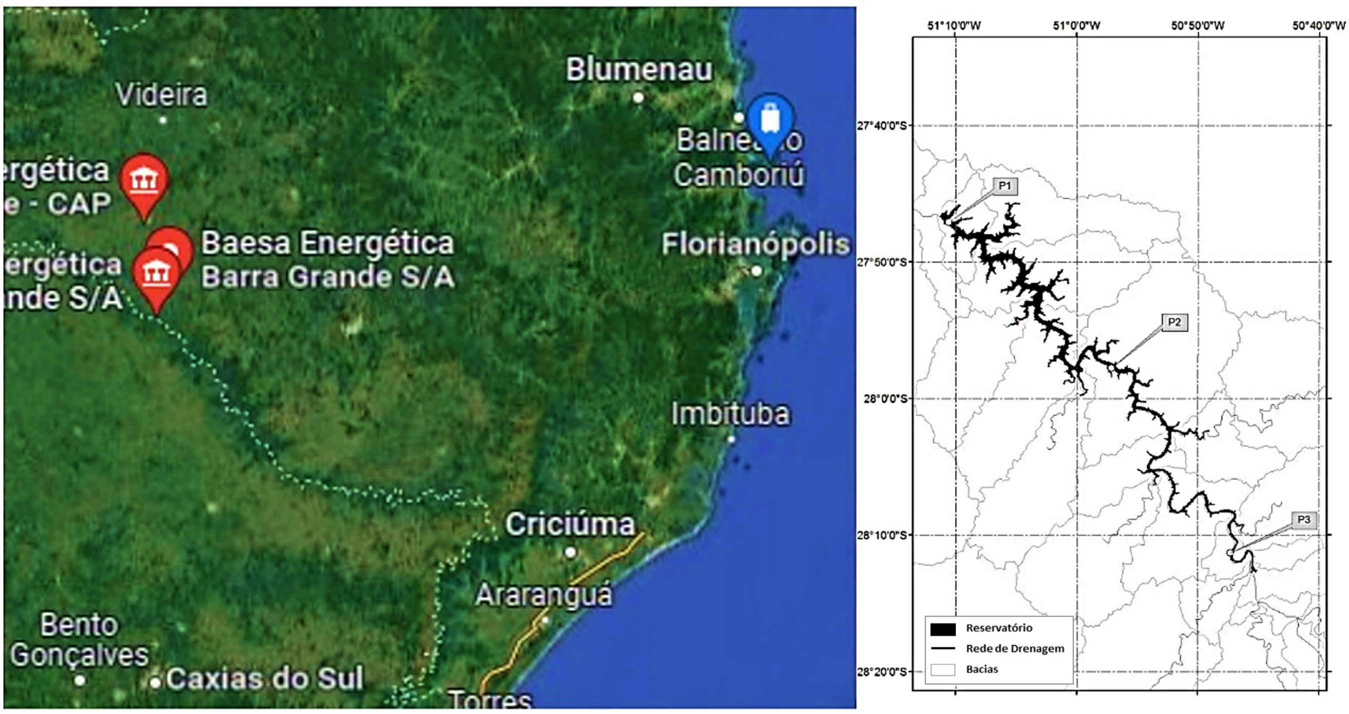


Figure 1. Location of the Barra Grande HPP reservoir and sampling points.

Table 2. Variables analyzed and respective units, quality standards defined in the legislation and methods of analysis.

Variable	Unit	Class 2 quality standard Res. CONAMA 357/2005	Method
Chlorophyll a	$\mu g.L^{-1}$	30	CETESB L5.306
Eletric Condutivity	$\mu S.cm^{-1}$	No comparative	SMEWW 21st 2510 B
Total Phosphorus	$mg.L^{-1}$	Intermediate environment: 50μg/L; lentic: 30μg/L; lotic: 10μg/L	NBR 12772 / 1992
Total Nitrogen	$mg.L^{-1}$	≤1.27(lentic); ≤2.18 (lotic)	NBR 10560
pH	-	6.0 - 9.0	SMEWW 21st 4500-H+ B
Total Solids	$mg.L^{-1}$	No comparative	SMEWW 2540 B
Turbidity	NTU	100	SMEWW 21st 2130 B
Dissolved Oxigen	$mg.L^{-1}$	5.00	Standard Methods O C
Secchi Transparency	m	No comparative	-
Water temperature	°C	No comparative	-

excluding only chlorophyll-a and Secchi transparency from the variables mentioned above. Table 2 presents the variables analyzed, with the respective units, quality standards defined in the legislation and the methods of analysis.

The variables water temperature, dissolved oxygen, pH and electrical conductivity were measured on site, at the time of sample collection using a multiparameter probe YSI Model 6600. Secchi transparency was measured using the Secchi disk. Water samples were collected at the sampling points using Acrylic / Vertical / 5L Van Dorn Bottle, both for the sub-surface and bottom samples. The collection of samples was punctual, that is, it was carried out in a single sample taking, at a certain moment, to carry out all determinations and tests (Agência Nacional de Águas, 2011). In order to evaluate possible stratification in the system, the temperature was measured at the intermediate depth of the reservoir (50% of the total depth), in addition to surface and bottom measurements, at the three sample points.

Measurements of affluent flow and reservoir level

The water level in the reservoir is measured every hour at a station located near the dam. From the level data it is possible to obtain the volume stored in the reservoir through the hypsometric curve. The affluent flow rates are estimated by a reverse water balance, since the difference in volume, the flow rates, the precipitated and evaporated volumes are known every hour. The level data and affluent flow are transmitted to the web service of the National Water Agency.

Spatio-temporal analysis of water quality

To identify and compare possible spatial and temporal gradients of abiotic variables, univariate and multivariate statistical analyzes were used. To analyze spatial and temporal trends, analysis of variance (ANOVA two way) was used, the factors used in the analysis were the collection site in the reservoir and the season, both fixed, representing the space and time factors, respectively.

Principal Component Analysis (PCA) was used to order the variables and describe potential spatial and temporal gradients, with data logarithmization ($\log x + 1$) and use of the PC-ORD software, version 5.0 (McCune & Mefford, 2006). For the temporal analysis, the data were classified into two periods: (a) from December to March, covering summer and autumn; and (b) from April to November, covering winter and spring.

RESULTS AND DISCUSSION

Reservoir hydraulics

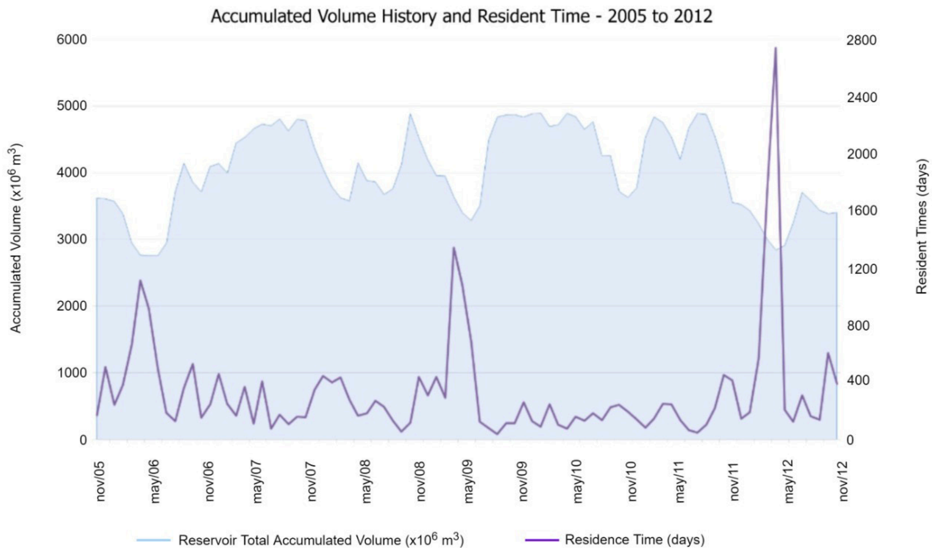
The level variation of the reservoir started with a value of 631.05 meters in November 2005, ranging from 617.7 meters in June 2006 to 646.8 meters in May 2010. The average monthly affluent flow of the reservoir varied between 12.0 m^3/s in May 2012 to 1447.1 m^3/s in September 2009, while residence time ranged from 38.7 days in September 2009 to 2739.6 days in May 2012 (Figure 2a, b and c).

Analyzing the variation in the dynamics of influent flow and residence time over the years determined by analysis of variance, there seems to be no defined annual pattern. In a seven-year period, 3 peaks of residence time in the reservoir were observed, all in late autumn (May 2006, 2009 and 2012), when the reservoir volume was very low. Actually, if the volume was low the residence time should be high. Therefore, a reason for the high peak of residence time was the low inflow. The four wettest years had peaks of inflow (August 2007, 2008 and 2009 and May 2010 and August 2011).

Environmental quality parameters dynamics

Although there is no well-marked seasonal or annual pattern, in extremes flow, such happen in autumn some years, we observe that the turbidity, transparency, conductivity and total solids vary significantly. The increase of residence time reduces these variables and increase chlorophyll and total phosphorus (Tables 3 and 4). There seems to be an influence on the cycling of solids and nutrients caused both by the flow and residence time, as well as by the mixing of the water column that occurs in winter. The great variation in the flow, allied to the operation of the reservoir, influences the water dynamics in a more complex way, where we can have a high outflow even with a low level and

A



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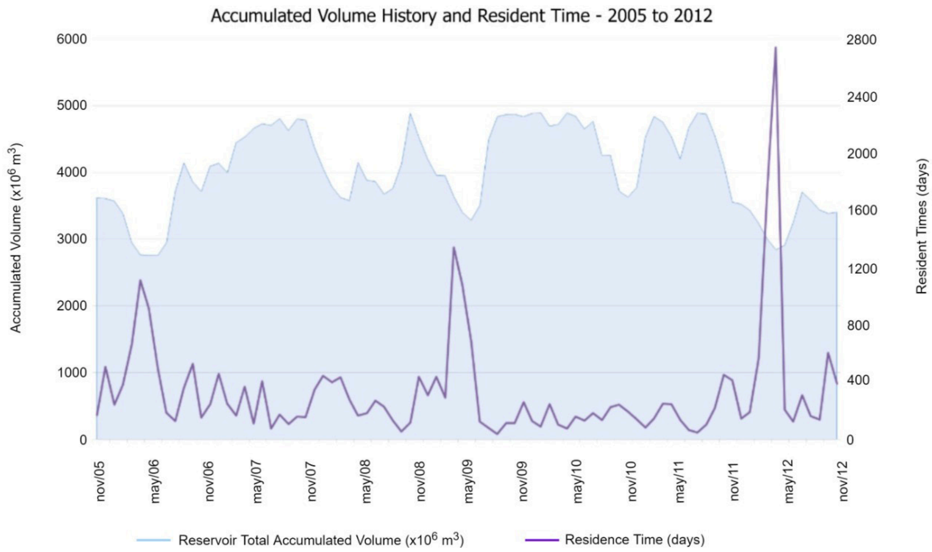

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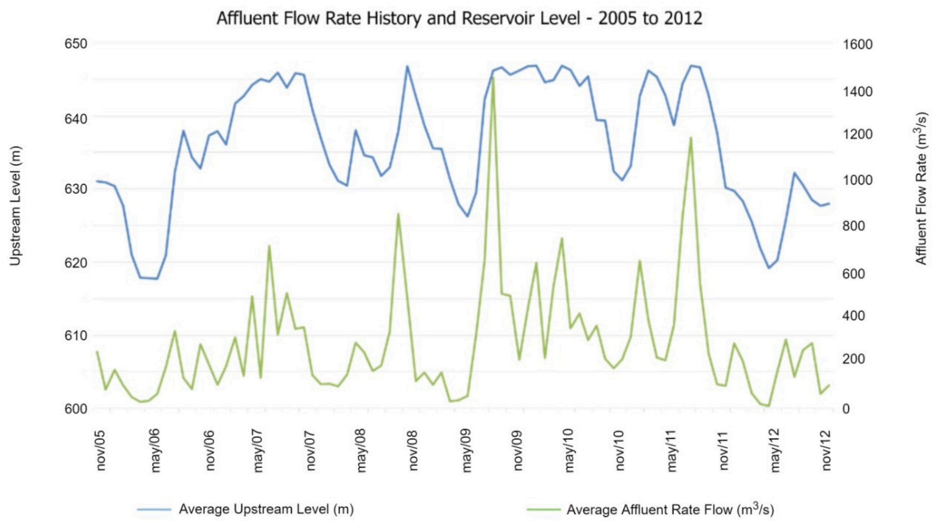

Figure 2. Average monthly values of accumulated volume and residence time (a), affluent flow and level of reservoir amount in meters (b), affluent flow (m^3 / s) and residence time in days (c) in the Barra Grande HPP reservoir, SC in the period between November 2005 and December 2012.

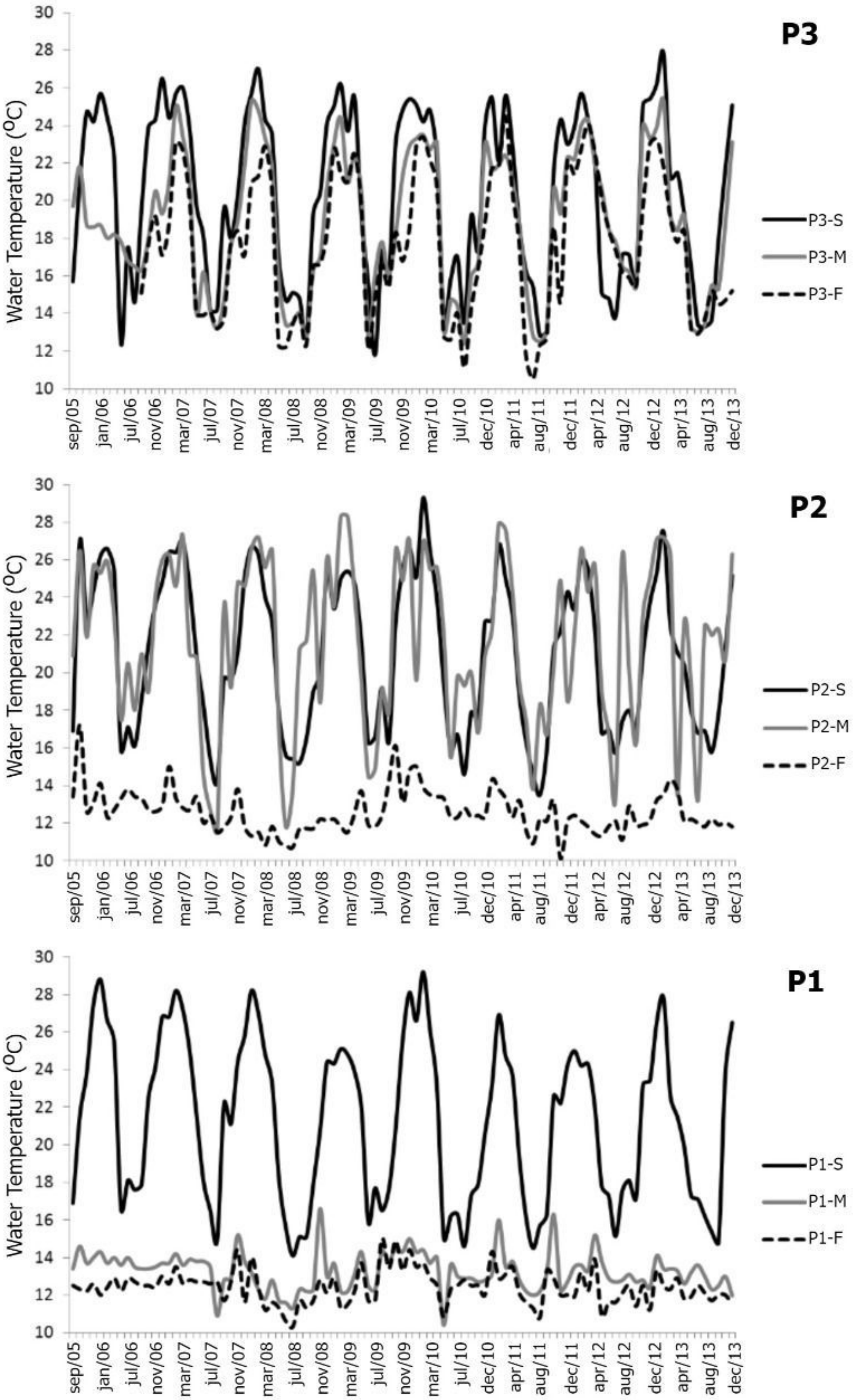

Figura 3. Temperature variation at the P3, P2 and P1 points in the Barra Grande hydroelectric plant reservoir, considering the period from September 2005 to December 2013, at the surface, middle and bottom depths.

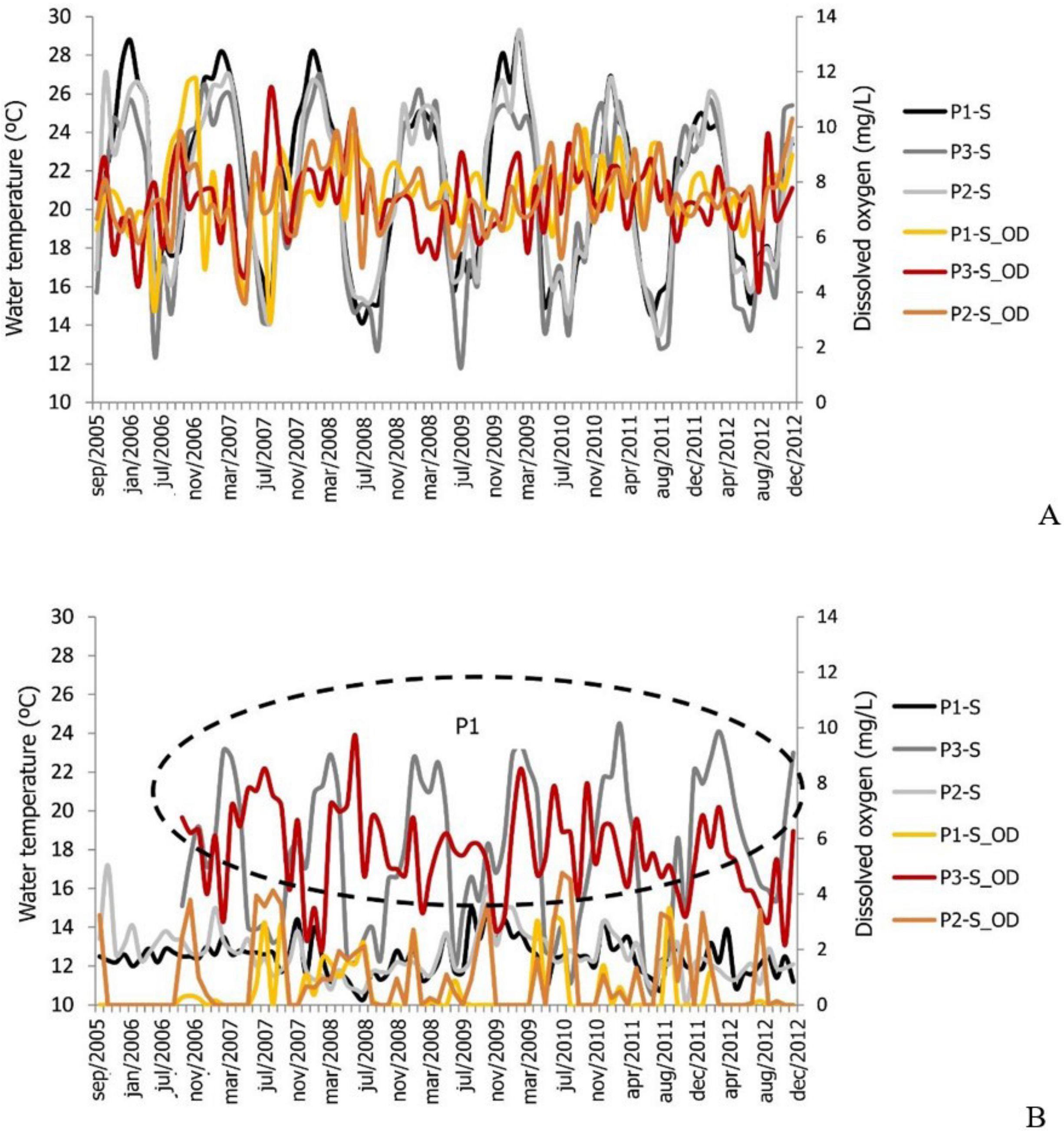

Figure 4. Variation of temperature and dissolved oxygen at the P3, P2 and P1 points in the Barra Grande hydroelectric plant reservoir, considering the period from September 2005 to December 2013 in the surface and bottom depths.

influent flow. The variation is constant and the environmental factors show this dynamic. Allied to this, the great depth, the recessed valleys, shallow soils and non-intensive use of the soil leave an oligotrophic situation.

According to Geraldes & George (2012), in deep canyon-type reservoirs, concentrations of total phosphorus are expected to be high during periods of greater precipitation and conductivity reduces during these periods, but many variations in environmental conditions are induced by other factors that vary subtly seasonally or inter-annually and regardless of rainfall intensity (Armengol et al., 1999; Alvarez-Cobelas et al., 2006; Marcé et al., 2006; Naselli-Flores, 2011; Geraldes & George, 2012).

On the other hand, according to Zanata & Espíndola (2002), in canyon-type reservoirs, there is a degree of decay of the concentrations in the river-dam direction, where is observed a significant correlation in the dry period for phosphorus and suspended material. And in the rainy season, nitrite and conductivity are correlated with the distance from the dam, which demonstrates the effect of precipitation and the operating mechanism of the dam, as well as the distinction between physical (sedimentation), chemical (oxidation) and biological (decomposition) processes) in the spatial heterogeneity of the system. Nutrients and solids entering the reservoir tend to settle close to the dam, but these mechanisms change this pattern, which can suspend the material or increase its decomposition or oxidation.

The residence time, chlorophyll a, pH and dissolved oxygen variables showed increased values in the autumn/ winter period, the transparency Secchi showed an increase in summer and turbidity in autumn, as expected, given the inflows obtained. The transparency increased at the upstream and downstream sampling points in the reservoir as it approached the dam, promoting the decantation of solids (see Tables 3 and 4).

On the surface, the analysis showed greater similarity of data between the P2 and P1 points, that is, the effectively lentic portions of the system, being discriminated from the P3 point, which corresponds to the Pelotas River, in the stretch that covers the contributions of the tributaries that form the headwater of the reservoir, representing the lotic fraction of the system. In all analyses, both by point and together, it was possible to observe the importance of variables: turbidity, Secchi transparency, residence time and temperature, showing two trends. First, a temporal gradient in the system, grouping the sampling units according to temperature (cold months and hot months) and second, a spatial gradient, distinguishing the upstream and downstream sections of the system, through greater similarity between the points that cover the central part of the reservoir (P2) and the region close to the dam (P1), possibly related to the circulation, sedimentation and resuspension processes (variables turbidity, Secchi transparency, residence time).

Time and space gradients in water quality

It was identified that the temporal gradient prevails for sub-surface and bottom samplings and spatial variation was especially significant for bottom samplings. Tables 5 and 6, respectively, show the results of the analysis of variance (two-way Anova) for sub-surface and bottom sampling.

The differences observed in the variance between sampling points and seasons, show spatial and seasonal differences in the dynamics of the reservoir's surface water, which, in the autumn, showed less water flow and more transparent waters. In the months of greater fluency and temperature was observed greater turbidity and pH. Therefore, in the gradient along the reservoir towards the dam, there is an increase in nutrients in the aquatic environment.

The water course in the reservoir guides the annual cycle of the longitudinal pattern of circulation in deep canyon reservoirs. Temperature, dissolved oxygen and influx conductivity are the main factors that describe these processes, but the efficiency of this system depends on the loads and concentration of nutrients in the reservoir, sedimentation rates, biological activity and water flow. The flow of water in the reservoir, flowing at the bottom (underflow), middle (interflow) or upper layers (overflow) greatly influences the degree of mixing between the waters of the river and the reservoir. (Armengol et al., 1999). We observed that the reservoir system can allow underflow to occur in winter when there

Table 3. Averages of the physicochemical variables of water quality sampled in the sub-surface of the Barra Grande reservoir, with the general average in the reservoir, average by season and by collection point, at the P3, P2and P1 points.

Variable	Reservoir				Season (average)				Colect point		
	Min	Max	Average	SD	spring	summer	autumn	winter	P3	P2	P1
Secchi Transparency (m)	0.21	4.17	1.62	0.46	1.17	1.78	2.08	1.52	1.15	1.79	1.92
Temperature (°C)	11.80	29.30	20.95	0.21	20.15	25.54	19.06	15.73	20.47	21.05	21.35
Dissolved Oxigen (mg.L^{-1})	2.92	11.73	7.45	0.18	7.42	7.39	7.25	7.66	7.33	7.42	7.60
Condutivity (µS.cm^{-1})	2.70	96.50	31.66	0.39	27.50	36.07	36.83	27.94	30.60	32.95	31.44
pH	4.61	9.87	7.32	0.09	7.37	7.18	7.08	7.52	7.36	7.24	7.34
Chlorophyll *a* (µg.L^{-1})	0.50	46.48	2.38	2.01	1.69	2.30	1.93	3.53	1.43	2.85	2.74
Total Nitrogen (mg.L^{-1})	0.01	3.12	0.40	0.74	0.44	0.38	0.42	0.37	0.38	0.41	0.41
Total Phosphorus (mg.L^{-1})	9.00	81.00	29.46	0.56	30.24	28.06	30.87	31.11	30.63	27.59	29.23
Turbidity (NTU)	0.96	54.70	7.24	1.16	4.51	12.91	10.00	4.24	11.13	5.58	4.27
Total Solids (mg.L^{-1})	10.00	90.00	45.81	0.38	49.43	47.41	47.48	39.65	49.08	44.62	44.14
Residence time (days)	38.00	2739.00	309.62	1.27	257.43	210.76	290.17	573.56	315.39	315.39	315.39

Table 4. Averages of the physical-chemical variables of water quality sampled at the bottom of the Barra Grande reservoir, with the general average in the reservoir, average by season and by collection point, at the P3, P2 and P1.

Variable	Reservoir				Season (average)				Points (average)		
	Min	Max	Average	SD	spring	summer	autumn	winter	P3	P2	P1
Temperature (°C)	7.48	24.50	14.19	0.24	13.7	15.6	14.8	12.3	12.39	17.71	12.47
Dissolved Oxigen (mg/L^{-1})	0.00	9.69	2.39	1.1	2.17	2.05	2.38	2.91	0.53	5.56	1.09
Condutivity (µS.cm^{-1})	6.10	163.80	49.05	0.58	38.73	42.19	56.33	54.78	62.59	32.89	48.68
pH	5.02	8.91	7.048	0.1	7.06	7.00	6.98	6.89	6.93	7.25	6.97
Total Nitrogen (mg/L^{-1})	0.03	3.32	0.53	0.68	0.47	0.6	0.49	0.56	0.58	0.44	0.57
Total Phosphorus (mg/L^{-1})	9.00	99.00	54.70	0.52	46.91	56.93	57.04	57.31	74.65	40.01	49.44
Turbidity (NTU)	2.40	101.00	18.09	0.71	17.45	16.69	18.12	19.5	17.64	17.76	18.85
Total Solids (mg/L^{-1})	19.00	198.00	62.49	0.43	62.48	61.74	62.46	60.96	65.96	61.76	59.72
Residence time (days)	38	2739	312	1.26	201	289	574	195	312.07	312.07	312.07

Table 5. Analysis of variance (Anova two way) for sub-surface sampling in the Barra Grande reservoir.

Variable	Spatial variation	Temporal variation
Water temperature	0.281	< 0.001
Dissolved Oxigen	0.647	0.246
Condutivity	0.586	< 0,001
pH	0.613	0.001
Total Nitrogen	0.902	0.490
Total Phosphorus	0.631	0.542
Turbidity	< 0.001	< 0.001
Total solids	0.244	0.146
Residence time	-	0.001
Secchi Transparency	0.457	< 0.001
Chlorophyll α	0.138	0.512

Table 6. Analysis of variance (Anova two way) for bottom of the Barra Grande reservoir.

Variable	Spatial variation	Temporal variation
Water temperature	< 0.001	< 0.001
Dissolved oxygen	< 0.001	0.039
Condutivity	< 0.001	0.016
pH	0.063	0.628
Total Nitrogen	0.054	0.282
Total Phosphorus	< 0.001	0.190
Turbidity	0.780	0.356
Total Solids	0.174	0.978
Residence time	-	0.001

is a mixture of the water layer and then alters the mechanisms of decantation, resuspension of nutrients and materials. Furthermore, the horizontal extension of a zone varies from reservoir to reservoir and depends mainly on morphometry, water retention time, thermal stratification, season of the year and geographic location. In temperate regions, during the summer, the reservoir can be considered as a river zone if it has a retention time of less than 10 days (Santos, 2003).

The observed gradient seems to be related to the distribution of the values of the main variables (turbidity, Secchi transparency and residence time). Similar values for these variables observed in this study were found by other studies (Smith et al., 2014: Bezerra et al., 2014). Longitudinal heterogeneity was also observed to be influenced by flow and precipitation (Deng et al., 2018). Dai et al. (2013) also observed the influence of an additional current close to the dam due to the effluent flow. Reservoir operation can influence water quality at times of lower flow and longer residence time (Rossel & De La Fuente, 2015). In this study, a large variation in level, flow and residence time during the study period was observed. As the operation can affect the quality of the water in the reservoir, especially at the time of lower flow and longer residence time, the management of this reservoir operation should be based on knowledge of the system dynamics and reservoir gradients, whenever there are threats to water quality. Adjustments in the effluent flow intensity, in order to reduce the reservoir level and the residence time in these critical events can be efficient ways to avoid undesirable plankton proliferation events (Rossel & De La Fuente, 2015; Salusso & Moraña, 2018).

With this information in hand, the analysis of historical series generated in monitoring programs can reveal trends in the rise or fall of quality parameters and similarities between different locations in the reservoir. These results can often point to an optimization of the proposed monitoring network and, consequently, a reduction in costs associated with monitoring programs (Barbosa, 2015).

Different patterns associated with spatial and temporal variations are observed, depending on the variables and the period considered (Hajigholizadeh & Melesse, 2017). The results of the water quality variables observed in this study show the existence of a seasonal gradient, as observed by Rodrigues et al. (2018). Also is observed a zoning along its longitudinal axis (Dai et al., 2013; Lindim et al., 2011; Muangthong & Shrestha, 2015. Ibarra & De La Fuente; Contreras, 2015; Barakat et al., 2016). On the shallow reservoirs surface, the gradient is especially related to processes of circulation, sedimentation and resuspension (Muangthong & Shrestha, 2015; Rossel & De La Fuente, 2015). In the depth reservoirs, a big deep prevents resuspension mechanisms influence over surface, but the operation, where water is captured at 30m depth, may have influence in water dynamic, because it seems that plant operation difficult the mixing in the deepest zone. The flow of water in the reservoir in the lower (underflow), intermediate (interflow) or upper (overflow) layers greatly influences the degree of mixing in reservoir (Zhu et al., 2020; Ramaswamy & Saleh 2020; Yoshioka & Yoshioka, 2019).

A spatial effect observed in this work highlights the initial portion of the reservoir, where surface water carries more non-biogenic solids in suspension and at the bottom the warmer and more oxygenated water has less nutrients (N and P) and lower conductivity. We observed much higher turbidity and total solids values in the portion closest to the dam, which is in agreement with what was observed by Bezerra et al. (2014). Likewise, Lindim et al. (2011) identified the gradient in the reservoir, where the lotic initial portion behaves like a river and receives greater input of nutrients and the lentic portion can be considered a deep and stratified non-eutrophic lake. This gradient was also observed by Muangthong & Shrestha (2015), in three stretches in the reservoirs, high, medium and low.

The differences observed in the variance between the sampling points and seasons of the year show spatial and seasonal variations in the dynamics of the reservoir surface water, which, in autumn, had lower water flow and more transparent waters, with higher turbidity and pH in the months of greater fluency and temperature. Therefore, in the gradient along the reservoir towards the dam, we have an increase in nutrients and light in the aquatic environment at the surface.

Thermal and oxygen stratification and dynamics in the reservoir

At the upstream point of the reservoir, the occurrence of thermal stratification was not identified (Figure 3), the mixing condition remaining at all times. At the P2 point, the central portion of the reservoir, similarity of temperature values was identified between the surface and the intermediate depth of the reservoir, with mixing being observed in a few events, such as in July 2007 and April 2013. At point P1, near the dam, the occurrence of thermocline in the transition from the intermediate depth towards the bottom of the reservoir was shown (Figure 3). Finally, at the P1 point, the closest point to the dam, a similarity of temperature values was identified between the intermediate depth and the bottom of the reservoir. However, as in the P2 point, the occurrence of thermocline was observed, but in the transition from the superficial and intermediate depths and the bottom of the reservoir, associated with the greater depth of the system (Figure 4).

In the joint analysis of temperature and dissolved oxygen on the surface of the P3, P2 and P1 points, the differences in temperature or oxygen gradient was identified (Figure 4). In the combined analysis of temperature and dissolved oxygen at the bottom depth of the P3, P2 and P1 points, the separation of the P3 point (initial portion of the reservoir) from the other fractions of the system was identified, and effective stratification of both temperature and oxygen at both the P2 and P1 point. (Figure 4).

As a result, it is observed that in sub-surface samplings only turbidity had a significant spatial and temporal effect ($p<0.001$). The temporal effect was significant for the variables temperature ($p<0.001$), Secchi transparency ($p<0.001$), conductivity ($p<0.001$), pH ($p<0.001$), turbidity ($p<0.001$) and residence time ($p <0.001$).

For the background samples, the variables that showed a significant spatial effect were temperature ($\varrho<0.001$), dissolved oxygen ($\varrho<0.001$) and conductivity ($\varrho<0.001$); together with a significant temporal effect: temperature ($\varrho<0.001$), dissolved oxygen ($\varrho<0.001$) and conductivity ($\varrho<0.001$). Total phosphorus had only a spatially significant effect ($\varrho<0.001$) while residence time had only a temporally significant effect ($\varrho<0.001$).

In terms of system functioning, the analysis of variance indicated that the turbidity values in the sub-surface demonstrate a statistically significant spatial difference. The temporal effect was more prominent in the variables temperature, Secchi transparency and turbidity. In the background samples, this gradient between the headwater and the point in the reservoir dam was evidenced for the variables dissolved oxygen, total phosphorus, total nitrogen, electrical conductivity and temperature. Oxygen and temperature have a significant effect both spatially and temporally, given the greater depth near the dam.

In the shallower region of the reservoir (P3), the mixture of the entire water column was observed in the absence of significant temperature variation, unlike in the median regions of the reservoir, where there is medium depth, and the regions close to the dam (P2 and P1) where there is a stratification pattern of temperature and oxygen. This thermal structure and the location of the thermocline can be influenced by the height of the water intake at the plant and the water level in relation to this intake (Ibarra et al., 2015). Our results also corroborate what was observed by Lindim et al. (2011), with stratification for most of the year, where heat exchange and vertical circulation are difficult. In the driest season there is a break in stratification due to water flow (Lindim et al., 2011). Deep reservoirs in the Midwest of China do not present stable thermal stratification during the year, only in late spring and summer a weak stratification can appear due to temperature change (Dai et al., 2012), because the absence or the low temperature variation in the water body facilitates mixing of the entire water column (Olden & Naiman, 2010; Papadimitrakis, 2011; Dai et al., 2012). We observed that, at the extremes of low flow, the values of turbidity, transparency, conductivity and total solids vary significantly, as there seems to be an effect both from the low flow and high residence time, as well as from the mixing of the water column that occurs in winter, on the cycling of solids and nutrients, which may explain this variation observed by Dai et al. (2012) and our results.

Trends in sub-surface water quality

In Figure 5, Principal Component Analysis by point in sub-surface sampling, showed that at the P3 point, the first two components explained 38.5% of the data variability (axis 1 = 26.7% and axis 2 = 11.8%) ($p <0.001$). The most important variables in the ordering of axis 1 were turbidity (-0.90), Secchi transparency (0.79), residence time (0.72) and temperature (0.65). In ordering axis 2, the most representative variables were pH (0.78) and total phosphorus (0.61). At the P2 point, the PCAexplained 40.1% of the data variability in axes 1 and 2 (axis 1 = 24.3% and axis 2 = 15.8%) ($p <0.001$). The most important variables in the ordering of axis 1 were turbidity (-0.87), Secchi transparency (0.79), temperature (0.69) and residence time (0.60). In ordering axis 2, the most representative variables were pH (0.75), chlorophyll (0.72) and dissolved oxygen (0.54). In the P1 point, the PCA explained 38.0% of the data variability in axes 1 and 2 (axis 1 = 21.6% and axis 2 = 16.4%) ($p = 0.001$). The most important variables in the ordering of axis 1 were Secchi transparency (0.83), turbidity (-0.83) and dissolved oxygen (-0.52). In ordering axis 2, the most representative variables were pH (-0.73), temperature (-0.67) and residence time (-0.50).

In the joint analysis of the three sampling points, P3 explained 37.0% of the variability of the data in axes 1 and 2 (axis 1 = 23.3% and axis 2 = 13.7%) ($p < 0.001$). The most important variables in the ordering of axis 1 were turbidity (-0.89), Secchi transparency (0.83), temperature (0.63) and residence time (0.58). In the order of axis 2, the most representative variables were pH (0.79), chlorophyll (0.56) and dissolved oxygen (0.53) (Figure 5).

Trends in bottom water quality

In Figure 6, for the background samples, the principal component analyzes per point showed that at the P3 point, the P3 explained 42.9% of the data variability in axes 1 and 2 (axis 1 = 24.4% and axis 2 = 18.5%) ($p = 0.01$). The most important variables in the ordering of axis 1 were turbidity (0.83), total solids (0.66) and total phosphorus (0.63). In the order of axis 2, the most representative variables were temperature (0.76) and conductivity (0.68). At the P2 point, P3 explained 37.6% of the variability of the data in axes 1 and 2 (axis 1 = 22.0% and axis 2 = 15.6%) ($p < 0.01$). The most important variables in the ordering of axis 1 were total solids (0.68), turbidity (0.65) and conductivity (0.64). In the order of axis 2, the most representative

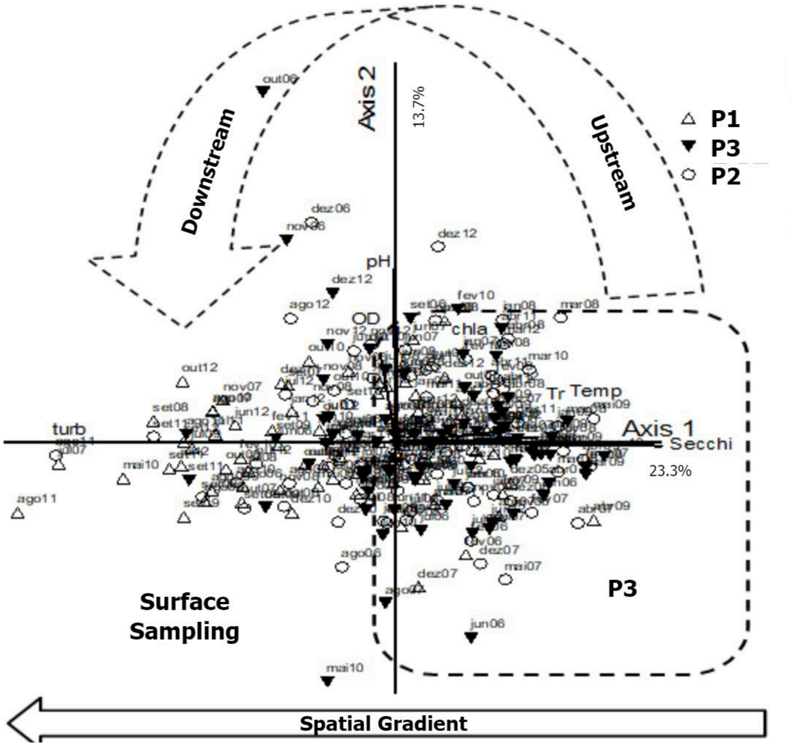

Figure 5. Results of the principal component analysis (P3) applied to the environmental variables together at the P3, P2 and P1 points, on the surface of the Barra Grande reservoir, SC, which correspond, respectively, to the region of the tributaries forming the head of the Barra reservoir; the section of contributions from the tributaries forming the central part of Reservoir and the section near the dam. Turbidity = turb, Transparency Secchi = Secchi, Residence time = Tr, temperature = temp.

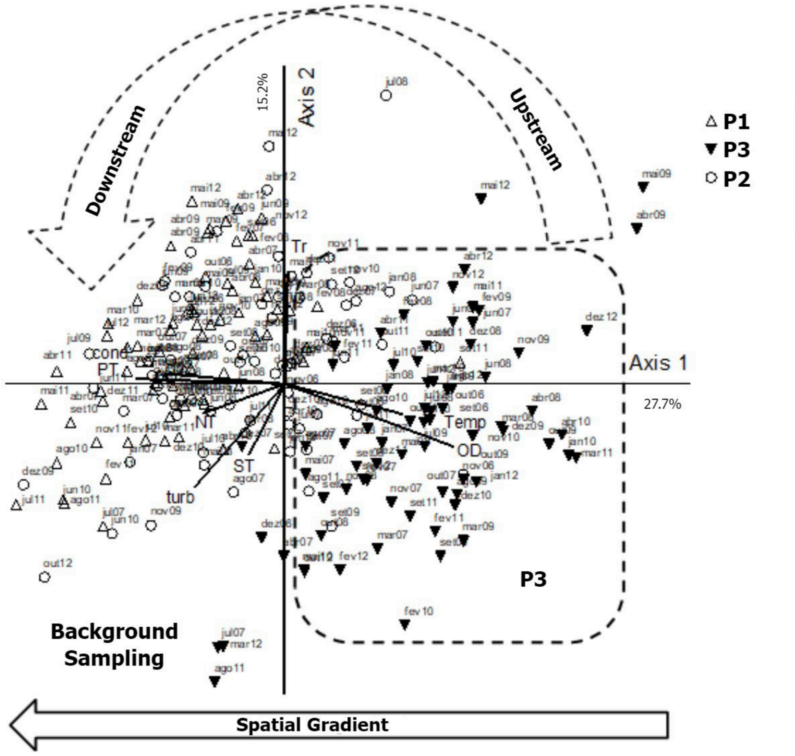

Figure 6. Results of the principal component analysis (PCA) applied to the environmental variables at the points P3_botton, P2_ botton and P1 botton _fundo, which correspond, respectively, to the region of the tributaries forming the head of the Reservoir; the section of contributions from the tributaries forming the central part of the Reservoir and the section near the dam. Turbidity = turb, Total Solids = ST, Dissolved Oxygen = OD, temperature = temp.

variables were pH (-0.61) and residence time (-0.59). At the P1 point, P3 explained 39.7% of the variability of the data in axes 1 and 2 (axis 1 = 23.0% and axis 2 = 16.7%) ($p < 0.01$). The most important variables in the ordering of axis 1 were turbidity (0.72), conductivity (0.72) and total nitrogen (0.61). In the order of axis 2, the most representative variables were pH (0.70) and dissolved oxygen (-0.69).

In the joint analysis of the three sampling points, the P3 explained 42.9% of the variability of the data in axes 1 and 2 (axis 1 = 27.7% and axis 2 = 15.2%) ($p = 0.001$). The most important variables in the ordering of axis 1 were dissolved oxygen (-0.72), temperature (-0.63), total phosphorus (0.66) and conductivity (0.62). In the order of axis 2, the most representative variables were turbidity (0.70) and total solids (0.70) (Figure 5). The joint analysis of the background points also showed greater similarity of the variables between the P2 and P1 points, differently from the P3 point.

The results of this study indicate that the use of multivariate statistical analysis methods allows the information to be used to optimize management programs. Thus, from a monitoring program using more than 60 parameters that had been carried out in the reservoir, the definition of 11 monitoring parameters in this study was sufficient to characterize the dynamics of water quality in the reservoir. Similar conclusions were observed in monitoring after multivariate statistical analysis, it was concluded that it was necessary to optimize the number of collection stations and use only four stations and nine water quality parameters, with tests in three specific months of the year (Chounlamany et al., 2017). With the multivariate analysis, parameters that did not show variance were eliminated (Barra Rocha & Pereira, 2016). Likewise, through cluster analysis, it was defined that the number of three stations and nine monitoring parameters would be sufficient to determine water quality (Xiao et al., 2016)

Muangthong & Shrestha, (2015), through discriminant analysis, concluded by reducing from sixteen to eight parameters and using the Cluster analysis technique. However, reducing the number of sampling stations and the associated costs depends on the objectives of the monitoring program (Zhang et al., 2011; Muangthong & Shrestha, 2015). Tripathi & Singal (2019), through Principal Component Analysis (PCA) indicated the reduction of parameters number from 28 to 9, to make monitoring more viable and economical, as it allows to drastically reduce the time, effort and cost necessary for monitoring a large number of parameters. Using PCA takes variation across the entire dataset and projects it into new dimensions, reducing the number of parameters but maintaining maximum variation.

The optimization of water quality monitoring in reservoirs, through reducing the number of parameters, allows for reduction of resources, costs and risks of monitoring efforts, through better targeting of actions, which makes all the data generated to be used effectively as information for the management of water resources. However, these actions can only be adopted efficiently from a broad knowledge of the environmental factors involved in the system. This way, management actions become more focused on really relevant issues, factors and events, without wasting time, human and financial resources.

CONCLUSION

The variables turbidity, total solids, total phosphorus, conductivity and temperature have great importance in water quality of the reservoir and showed trends, both in sub-surface and bottom sampling, as drives of temporal gradient in the system, of according to temperature (cold months and hot months), and a spatial gradient, distinguishing the upstream and downstream sections of the system.

The use of multivariate statistical analysis methods allows the information to be used to optimize monitoring and management programs, as it helps in the interpretation of complex data matrices for a better understanding of water quality and the optimization of monitoring, in order to reduce efforts and costs and optimize the execution of programs and the use of the information generated.

In This deep canyon reservoir, there are different patterns due to the lack of regularity in water flow and reservoir dynamics and is so difficult to predict conditions of water quality. For this reason, it is very important to adopt methodologies that optimize monitoring efforts and efficiently prioritize actions. however it must be done from a base of information and knowledge about the environment.

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