

**INFLUENCE OF
SEASONALITY AND DEPTH
ON WATER QUALITY IN A
RESERVOIR IN THE
BRAZILIAN AMAZON**

**INFLUÊNCIA DA SAZONALIDADE E DA PROFUNDIDADE NA QUALIDADE
DA ÁGUA EM UM RESERVATÓRIO DA AMAZÔNIA BRASILEIRA**

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ABSTRACT

This study evaluated the influence of seasonality and depth on the physicochemical parameters of the Curuá-Una River, in the area of the Curuá-Una Hydroelectric Power Plant, between March 2015 and January 2016. Four sampling campaigns were conducted at eight stations, spanning four seasonal periods and three depths of the water column, with both univariate (two-way ANOVA) and multivariate (PCA) statistical analyses. The results indicated that seasonality was the main factor of variation, significantly influencing most parameters, especially those related to the input of particulate material, nutrients, and redox conditions, while depth exerted a limited effect. The multivariate analysis confirmed the separation among seasonal periods and revealed relative vertical homogeneity, demonstrating that regional hydrological dynamics predominantly control water quality in the studied system.

Keywords: Seasonality; Curuá-Una River; Water quality; Amazon; Vertical profile; Hydroelectric power plant.

RESUMO

Este estudo avaliou a influência da sazonalidade e da profundidade nos parâmetros físico-químicos do rio Curuá-Una, na área da Usina Hidrelétrica de Curuá-Una, entre março de 2015 e janeiro de 2016. Foram realizadas quatro campanhas de amostragem em oito estações, abrangendo quatro períodos sazonais e três profundidades da coluna d'água, com análises estatísticas univariadas (ANOVA de dois fatores) e multivariadas (PCA). Os resultados indicaram que a sazonalidade foi o principal fator de variação, influenciando significativamente a maioria dos parâmetros, especialmente aqueles relacionados à entrada de material particulado, nutrientes e condições redox, enquanto a profundidade exerceu um efeito limitado. A análise multivariada confirmou a separação entre os

períodos sazonais e revelou relativa homogeneidade vertical, demonstrando que a dinâmica hidrológica regional controla predominantemente a qualidade da água no sistema estudado.

Palavras-chave: Sazonalidade; Rio Curuá-Una; Qualidade da água; Amazônia; Perfil vertical; Hidroelétrica.

1. INTRODUCTION

The Amazon River basin, one of the most extensive and complex on the planet, harbors a wide diversity of interconnected aquatic systems. This heterogeneity largely results from variations in vegetation types around rivers and streams, as well as regional climatic conditions, which directly influence the processes of sediment and nutrient input to water bodies (SILVA et al., 2013). The historically established socio-environmental relationship between this vast aquatic system and local communities remains significant to this day. Activities such as fishing, water supply, bathing, and the use of the river as a transportation route reflect this strong relationship (LIMA et al., 2024; CANELA et al., 2024; ACIOLY et al., 2024).

According to CONAMA Resolution No. 357/2005, human health and well-being, as well as ecological and aquatic balance, should not be compromised by water quality deterioration (BRASIL, 2005). Thus, monitoring physicochemical parameters is essential to ensure the quality of Amazonian aquatic systems. Determining this quality must consider the different uses of the water resource—such as consumption, recreation, and supply—to identify the desirable characteristics for each purpose (RAMOS, OLIVEIRA & ARAÚJO, 2019). Furthermore, local seasonality exerts a significant influence on water conditions, making its consideration indispensable in detailed

analyses, since temporal variability directly impacts these parameters (CABRIA, BARQUÍN & PEÑAS, 2016; GOMES et al., 2020; AUBERT, GASCUEL-ODOUX & MEROT, 2013; GELSEY, CHANG & RAMÍREZ, 2022; RANGEL-PERAZA et al., 2009).

Studies have shown that seasonality exerts a significant influence on water quality parameters in different Brazilian river basins (RODRIGUES et al., 2018; ABOIM, GOMES & MAFALDA JUNIOR, 2020; BARBOSA, CARVALHO & AMORIM, 2022; GOMES et al., 2020; DIAS et al., 2018; BRITTO et al., 2018). Rodrigues et al. (2018) observed variations in pH and electrical conductivity as a function of the seasons in the Água Limpa Stream basin (SP), also highlighting the interference of soil management and riparian vegetation. Similarly, Aboim, Gomes & Mafalda Junior (2020) verified pH sensitivity to seasonality in the Jequitinhonha River (BA), in addition to increases in turbidity and COD during the rainy season, results compatible with those of Cruz et al. (2019) and El-Mazayen et al. (2018).

In the international context, research also shows the variability of physicochemical parameters between dry and rainy seasons, highlighting the role of precipitation as the main factor of variation in indicators such as pH and total dissolved solids (SODHI, DAHIPHALE & ARORA, 2024; PAK et al., 2021; GELSEY, CHANG & RAMÍREZ, 2022). These variations reinforce the idea that extreme climate changes—such as droughts, heat waves, and intense rainfall—can modify the hydrological cycle and compromise water quality by increasing the diffuse load of nutrients, reducing the dilution of pollutants, and causing thermal changes that affect ecological processes (REHANA & DHANYA, 2018; DAS, KAMRUZZAMAN & ISLAM, 2022; CHENG, CHEN & SUN, 2019; HUANG et al., 2022; PEÑA-GUERRERO et al., 2020).

Pioneering studies by Junk et al. (1981) characterized the reservoir's tributaries as nutrient-poor, with low electrical conductivity and acidic pH, particularly in the Mojuí and Moju branches. They also recorded weak thermal stratification and a severe reduction in dissolved oxygen levels ($< 0.5 \text{ mg L}^{-1}$) in deeper layers—conditions unfavorable to sensitive fish species. Subsequently, Vieira & Darwich (1999) and Gunkel et al. (2003) reported similar conditions, marked by deep-water hypoxia and persistent signs of eutrophication.

More recently, Santos et al. (2020) observed that seasonality drives physicochemical variations, with water quality worsening during the rainy season due to increased organic matter and reduced transparency, while also noting territorial expansion as a factor intensifying these impacts. Given this historical context, this work seeks to identify differences in water quality parameters across the seasonal periods and depths evaluated in the Curuá-Una River between 2015 and 2016, providing new data and interpretations on the combined influence of seasonality and depth on Amazonian water quality.

Therefore, the objective of this study was to analyze the influence of seasonality and water column depth on the physicochemical parameters of the Curuá-Una River, in the Brazilian Amazon. This river hosts the region's first hydroelectric power plant, the Curuá-Una HPP, whose installation generated environmental and social impacts that remain of significant scientific interest.

The next section of this paper presents the materials and methods used in the research to generate the results presented in section 3. This section presents and discusses the information obtained regarding descriptive statistics, seasonal and vertical variations of

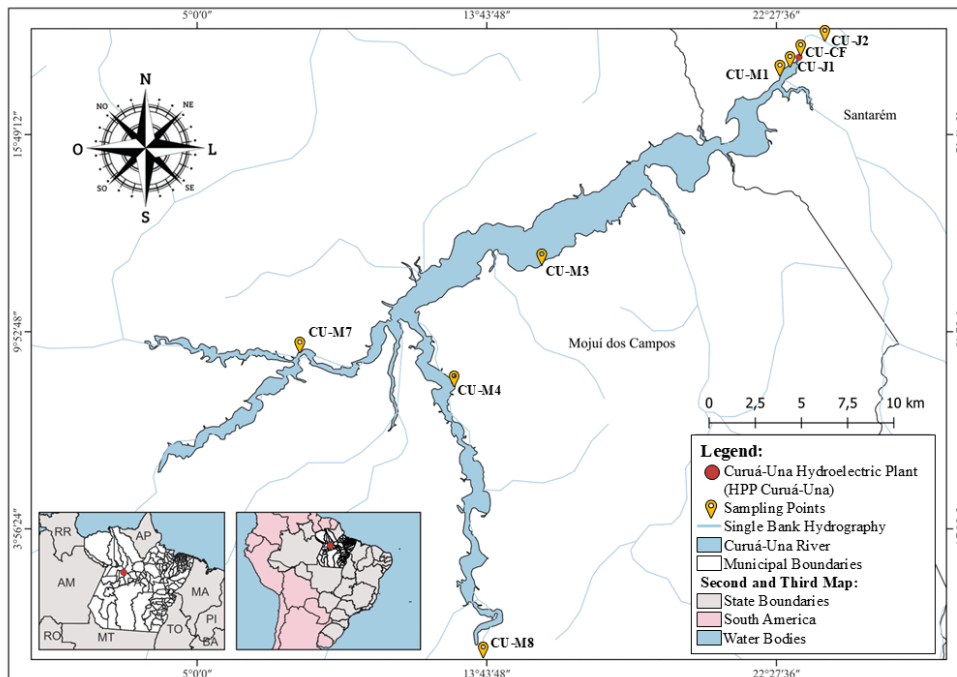
physicochemical parameters, and the results of the multivariate analysis. Finally, section 4 summarizes the main findings and presents the conclusions of the study.

2. MATERIALS AND METHODS

2.1. Study Area

The Curuá-Una River, a natural tributary of the Amazon River, is located in the western region of the state of Pará, approximately 70 km from the city of Santarém (Figure 1). Its waters, along with those of its tributaries—the Moju, Mojuí dos Campos, and Poraquê rivers—sustain the reservoir of the Curuá-Una Hydroelectric Power Plant (HPP). Managed by the energy company Eletronorte, the HPP currently operates with four generating turbines, providing an installed capacity of 42.8 MW.

Figure 1 - Location of the study area and sampling stations in the Curuá-Una Hydroelectric Power Plant reservoir, municipality of Santarém, Pará, Brazil.



Source: Instituto Brasileiro de Geografia e Estatística (IBGE), 2024; Agência Nacional de Águas e Saneamento Básico (ANA), 2024; field data.

2.2. Description Of The Methodology

The field research was conducted in partnership with the Environmental Protection Center (CPA) of Eletronorte, which provided full logistical support. Eight sampling stations were selected upstream and downstream of the Curuá-Una hydroelectric dam, accessed by speedboat-type vessels. Four sampling campaigns were carried out between March 2015 and January 2016 to cover the different seasonal periods of the region: March 2015 (rainy season), July 2015 (intermediate I), October 2015 (dry season), and January 2016 (intermediate II). Samples were collected at three distinct depths in the water column—surface, middle, and bottom—to evaluate potential vertical variations in physicochemical parameters.

Sample collection was carried out according to the recommendations of the Environmental Company of the State of São Paulo (CETESB, 1988), using 5 L Hale bottles. Samples intended for chloride, phosphate, and chlorophyll-a analyses were stored in 1 L polyethylene bottles, previously decontaminated with a 10% nitric

acid solution and rinsed with distilled water followed by water from the collection site.

After sampling, the material was packed in expanded polystyrene (EPS) thermal boxes with ice to maintain a temperature close to 4 °C until arrival at the laboratory. The samples were transported to the city of Belém (PA), where they were properly stored and subjected to laboratory analysis.

Physicochemical determinations followed, with specific adaptations, the protocols described in the *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA & WEF, 2017).

Several physicochemical parameters were measured *in situ* using a Hanna multiparameter probe, including temperature (°C), pH, redox potential (Eh, mV), dissolved oxygen (DO, mg L⁻¹), total dissolved solids (TDS, mg L⁻¹), and electrical conductivity (EC, μS cm⁻¹). Turbidity (NTU) was determined in the field using an AP2000 portable turbidimeter, and water transparency (m) was measured with a Secchi disk.

In the laboratory, the levels of chloride (mg L⁻¹), nitrate (mg L⁻¹), phosphate (mg L⁻¹), and ammonium ion (mg L⁻¹) were determined by electrometric methods. Apparent and true color (mg Pt L⁻¹) were analyzed by colorimetric methods using Hanna instruments. Chemical oxygen demand (COD) was determined by oxidative digestion in a digestion block, using potassium dichromate as the oxidizing agent, followed by back-titration. Chlorophyll-a concentration (mg L⁻¹) was quantified by spectrophotometry using an Even UV-VIS spectrophotometer.

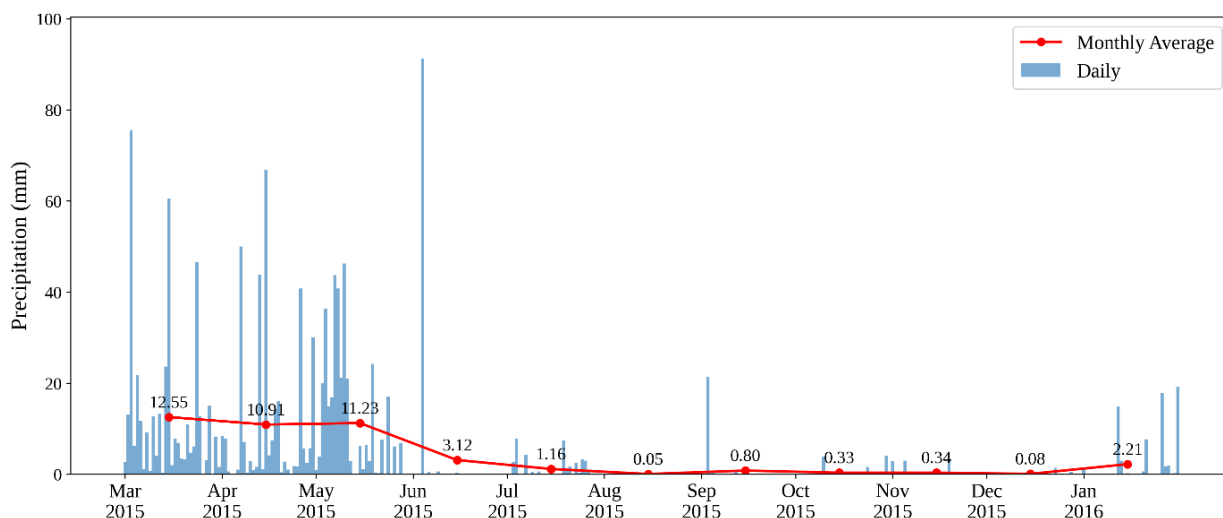
Statistical analyses were performed using Minitab® 19.2020.1 software and the Python programming language, utilizing the pandas, seaborn, scipy.stats, scikit-learn, and matplotlib libraries.

3. RESULTS AND DISCUSSION

3.1. Hydrological Context

The rainfall regime from March 2015 to January 2016 showed a typical seasonal pattern for the region, with higher average precipitation during the rainy season (12.55 mm), a reduction in the intermediate I season (1.16 mm), a minimum during the dry season (0.33 mm), and recovery in the intermediate II season (2.21 mm) (Figure 2). It is worth noting that the transition between the rainy season and the intermediate I season was marked by intense levels of precipitation, a factor that may have influenced the preservation of environmental conditions between both periods.

Figure 2 - Daily and average monthly rainfall recorded in the Curuá-Una Hydroelectric Power Plant area from March 2015 to January 2016.



Source: Merge/INPE e CENSIPAM, 2025.

3.2. Summary Descriptive Statistics

Among the evaluated parameters, pH and dissolved oxygen (DO) presented average values outside the limits established by CONAMA Resolution 357/2005 (Table 1). The pH was lower during the dry season (≈ 5.3 at all depths). However, this does not indicate an alarming condition, as pH levels ranging from acidic to neutral are a natural characteristic of this river (SIOLI, 1956; JUNK et al., 1981). Gunkel et al. (2000) highlight the river's buffering capacity based on its calcium content, which is derived from erosion processes in the surrounding carbonate rock areas. Thus, the acidic conditions observed during the dry season in this study may be associated with low precipitation and reduced river flow, leading to decreased transport of calcium-rich carbonate sediments and, consequently, reducing the water's buffering capacity.

Dissolved oxygen (DO) levels showed noncompliance with regulatory standards during the intermediate I period (only at the bottom) and intermediate II (at all depths), with direct implications for the biogeochemical processes of the local biota. Historically, the reduction in oxygen content within the reservoir was significant immediately after its construction, in contrast to the upstream rivers. Early studies indicate that low DO levels resulted from the leaching of newly flooded soils and the decomposition of submerged organic matter (JUNK et al., 1981; VIEIRA & DARWICH, 1999). DO concentrations in the reservoir vary according to factors such as seasonality, thermal stratification, and biological activity. A recent multivariate analysis suggests that the seasonal effect is the predominant driver, accounting for 56% of the variability in limnological parameters—a shift sufficient to alter biological processes (SANTOS et al., 2020). Oxygen stratification was also

observed by Gunkel et al. (2000) in this region, with concentrations decreasing in deeper layers and reaching anoxic conditions. In the present study, this behavior was also recorded, particularly during the intermediate I period.

Table 1 - Descriptive statistics (mean \pm standard deviation) of the physicochemical parameters in the Curuá-Una HPP reservoir, broken down by seasonal period and depth, compared to the limits established by CONAMA Resolution N°. 357/2005. Values in bold are non-compliant with CONAMA standards.

Season	Rainy Season			Intermed	
	Surface	Middle	Bottom	Surface	Midd
Transp. (m)	1.8 \pm 0.67	1.8 \pm 0.67	1.8 \pm 0.67	1.95 \pm 0.51	1.95 \pm (
Temp. (°C)	29.22 \pm 1.24	28.91 \pm 0.99	28.85 \pm 0.99	30.06 \pm 0.93	29.4 \pm (
pH	6.69 \pm 0.38	6.7 \pm 0.37	6.69 \pm 0.47	6.89 \pm 0.57	6.64 \pm (

⚠ Esta tabela possui muitas colunas e foi cortada para impressão. Para visualizá-la completa, acesse o artigo original em: <https://revistatopicos.com.br/artigos/influence-of-seasonality-and-depth-on-water-quality-in-a-reservoir-in-the-brazilian-amazon?noblockage>

3.3. Seasonal And Vertical Effects On Physicochemical Parameters

Analysis of the boxplots (Figure 3) revealed that depth exerted limited influence on most physicochemical parameters, with occasional exceptions for turbidity, dissolved oxygen (DO), color, and

redox potential (Eh). In contrast, seasonality proved to be a determining factor, reflecting the hydrological variations typical of the Amazon region.

During the rainy season and the intermediate I period, higher water transparency and lower temperatures were observed, which are associated with increased rainfall and reduced solar radiation. During the dry season, temperatures increased while the pH decreased, potentially due to the reduction in buffering capacity, as previously discussed.

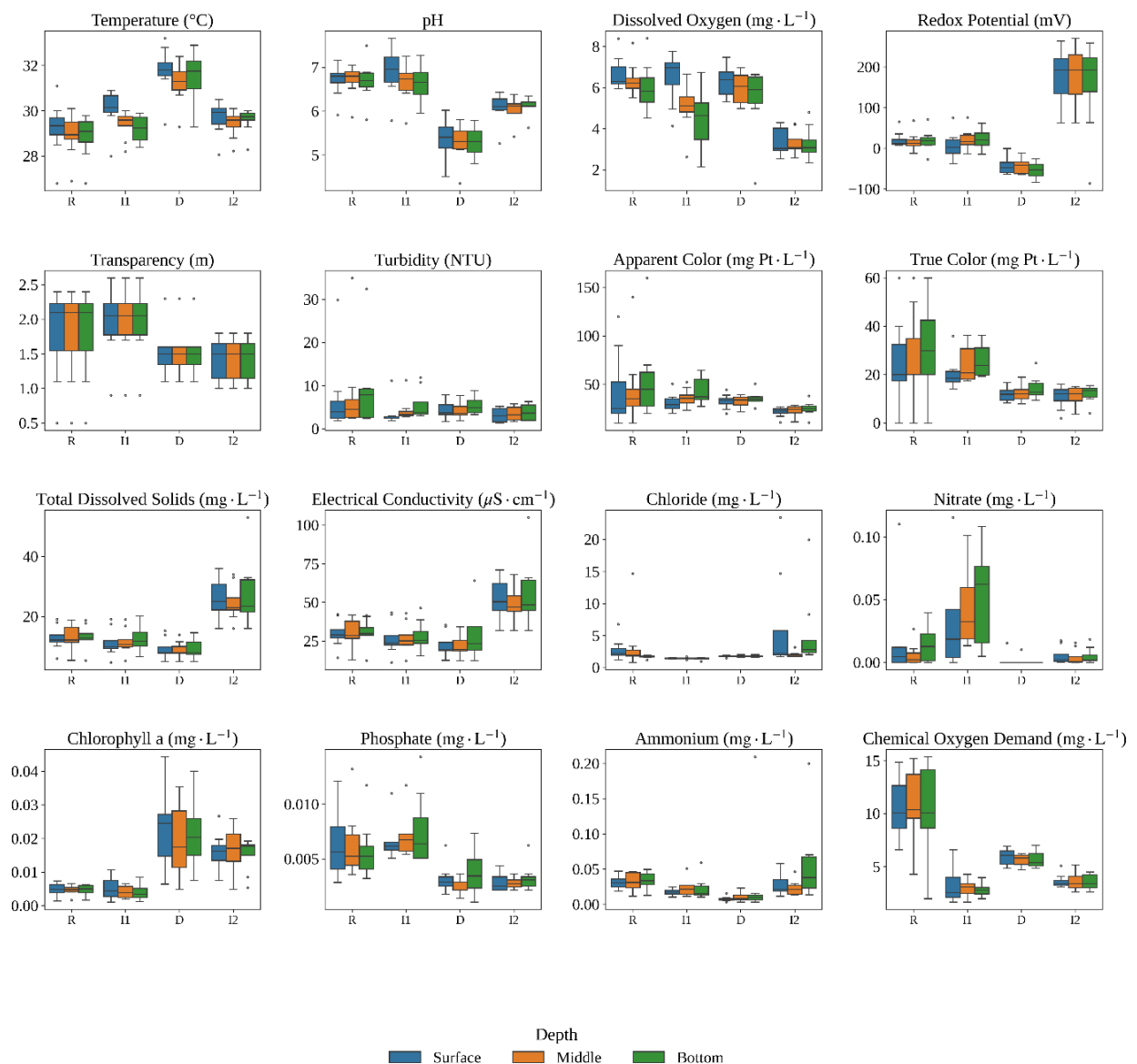
Eh and DO exhibited behavior consistent with redox dynamics and thermal stratification: more oxidizing environments during the rainy and intermediate I periods, and more reducing conditions during the dry season. The variation of DO as a function of depth was more evident during the rainy and intermediate I periods, reflecting greater water column stratification. Turbidity, apparent and true color, and COD were higher during periods of increased rainfall, reflecting the rise in particulate and organic matter carried into the reservoir by runoff.

Total dissolved solids (TDS) and electrical conductivity (EC) showed similar behavior, with a gradual reduction leading up to the dry season followed by an increase in Intermediate II, indicating a decrease in ionic concentration throughout the transitions toward the dry period. Among the nutrients, phosphate and nitrate concentrations were higher during the rainy and Intermediate I seasons, which is associated with leaching and allochthonous input. In contrast, ammonium levels increased during Intermediate II, potentially linked to organic matter decomposition and oxygen limitation. Finally, chlorophyll-a reached its maximum values during

the dry season, suggesting increased phytoplankton activity under more stable hydrological conditions and greater light availability.

Overall, the results demonstrate that while vertical stratification is not highly pronounced, seasonality plays a central role in modulating the physicochemical parameters of the Curuá-Una reservoir.

Figure 3 - Boxplots of physicochemical parameters in the Curuá-Una HPP reservoir, distributed by seasonal period and water column depth.



To assess significant differences between depths and seasonal periods, a two-way ANOVA with interaction was applied to the physicochemical parameters (Table 2). This method allowed for the comparison of means across three depths and four seasonal periods, using a significance level of $p < 0.05$. The results indicated a significant difference for dissolved oxygen (DO) between depths only during the intermediate I period. Regarding seasonality, most parameters exhibited statistically significant variations, with the exception of transparency, turbidity, chloride (surface and middle), nitrate (surface), apparent color, and ammonium (bottom).

Corroborating the findings of the boxplot analysis, the ANOVA results highlighted the significant influence of seasonality and demonstrated the minimal impact of depth on the evaluated parameters. Furthermore, the interaction effects were not significant, indicating that the influence of depth on the variables does not change across seasonal periods, and vice versa.

Table 2 - Two-way ANOVA results for the effects of seasonality, depth, and their interaction on water physicochemical parameters ($p < 0.05$)

Variable	Seasonality (F)	Seasonality (p-value)	Depth (F)	Depth (p-value)	Interaction (F)
Transp. (m)	5.95	0.0010	0.00	1.0000	0.00
Temp. (°C)	34.66	0.0000	2.35	0.1012	0.32
pH	61.89	0.0000	0.50	0.6057	0.22
Eh (mv)	82.70	0.0000	0.23	0.7925	0.23
DO (mg L ⁻¹)	37.38	0.0000	5.99	0.0037	1.28

⚠ Esta tabela possui muitas colunas e foi cortada para impressão. Para visualizá-la completa, acesse o artigo original em: <https://revistatopicos.com.br/artigos/influence-of-seasonality-and-depth-on-water-quality-in-a-reservoir-in-the-brazilian-amazon?noblockage>

3.4. Principal Component Analysis (PCA)

PCA was used to identify seasonal patterns and the most influential variables driving the variation between periods and depths. Following Kaiser's criterion (1960), components with eigenvalues greater than 1.0 were selected, resulting in the retention of the first five principal components (PCs). Together, these components explained approximately 78% of the total variance (Table 3).

Table 3 - Eigenvalues, explained variance percentage, and cumulative variance for the principal components (PCs) obtained from the PCA.

Principal Component	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
PC1	4.63	28.62	28.62
PC2	3.34	20.69	49.30
PC3	2.06	12.71	62.02
PC4	1.38	8.56	70.58
PC5	1.20	7.44	78.02
PC6	0.92	5.70	83.72
PC7	0.66	4.06	87.77
PC8	0.55	3.40	91.18
PC9	0.35	2.18	93.36

PC10	0.34	2.08	95.44
PC11	0.23	1.43	96.86
PC12	0.16	1.00	97.86
PC13	0.13	0.79	98.66
PC14	0.13	0.78	99.44
PC15	0.07	0.45	99.89
PC16	0.02	0.11	100.00

PC1 was dominated by turbidity, phosphorus, apparent color, and true color, with negative loadings for temperature and chlorophyll-a. This indicates the influence of particulate matter and chromophoric substances, which potentially limit phytoplankton production by reducing water transparency (Table 4). PC2 exhibited high loadings for total dissolved solids (TDS) and electrical conductivity, which were associated with the oxidation-reduction potential and inversely related to dissolved oxygen, thus characterizing a mineralization gradient and the redox conditions of the water. PC3 was strongly associated with transparency and showed a negative relationship with chlorophyll-a, reflecting an optical gradient linked to light availability in the water column. Components PC4 and PC5 were associated with chemical oxygen demand (COD) and ammoniacal nitrogen, respectively, indicating the influence of organic matter decomposition processes and the recent input of nitrogen compounds.

Table 4 - Factor loadings for the first five principal components of the PCA for the evaluated physicochemical parameters. Only loadings with an absolute value ≥ 0.60 are shown.

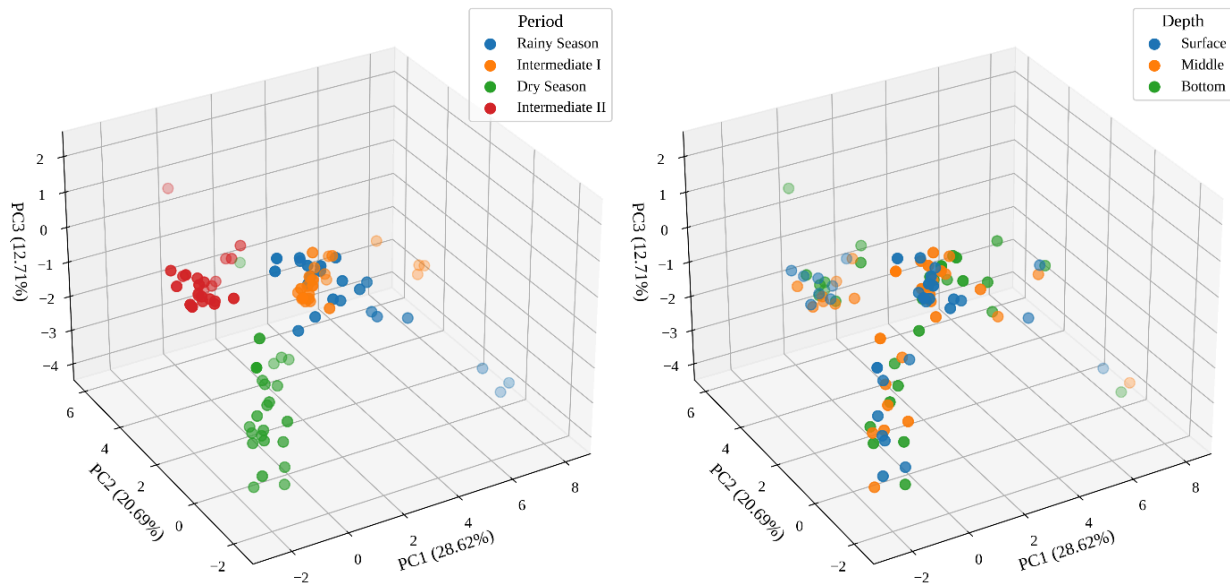
Variable	PC1	PC2	PC3	PC4	PC5
Transp. (m)			0.774		
Temp. (°C)	-0.735				
pH	0.633				
Eh (mv)		0.730			

⚠ Esta tabela possui muitas colunas e foi cortada para impressão. Para visualizá-la completa, acesse o artigo original em: <https://revistatopicos.com.br/artigos/influence-of-seasonality-and-depth-on-water-quality-in-a-reservoir-in-the-brazilian-amazon?noblockage>

To assess the patterns of the parameters in relation to seasonality and depth, three-dimensional (3D) plots were constructed using the first three principal components (Figure 4). Regarding seasonality, the periods exhibited distinct behaviors, grouping into specific regions of the plot. However, a similarity between the rainy and intermediate I periods was observed, as evidenced by the proximity of their respective groups. This suggests that the persistence of rainy-season characteristics throughout the transition period may have contributed to the preservation of similar environmental conditions. When evaluating the physicochemical behavior across depths, no clear distinction between the layers was found. This pattern suggests a relative homogeneity of physicochemical conditions throughout the water column during the sampling period.

Figure 4 - Three-dimensional (3D) PCA plot of the first three principal components, showing the sample distribution according to

seasonal periods and depths.



4. CONCLUSION

This study demonstrates that seasonality plays a predominant role in modulating the physicochemical parameters of the Curuá-Una River, whereas depth exerts only a secondary and localized influence on data variability. Both univariate and multivariate statistical analyses indicate that temporal variations associated with the Amazonian hydrological regime are the primary drivers for the differentiation of sampling periods. These variations reflect shifts in the input of particulate matter, nutrients, and organic matter—often linked to allochthonous processes—as well as changes in the redox conditions of the reservoir system.

The ANOVA results confirmed statistically significant differences for most parameters as a function of seasonality, while depth exhibited a limited effect, with the exception of dissolved oxygen under specific conditions. The absence of significant interaction between these factors reinforces that seasonal effects act independently of vertical variations in the water column. These findings corroborate

the low physicochemical stratification of the reservoir during the study period, likely associated with hydrological dynamics, wind action, and the system's morphometry.

Principal Component Analysis (PCA) underscores the dominance of seasonality, highlighting the clear separation of periods within the multivariate space. This separation was driven primarily by variables such as turbidity, color, phosphorus, electrical conductivity, total dissolved solids, and dissolved oxygen. The similarity observed between the rainy and intermediate I periods suggests that hydrological characteristics typical of the rainy season persist throughout the transition phase, maintaining similar environmental conditions. Conversely, the overlap between different depths indicates a relative homogeneity of physicochemical conditions across the water column.

In summary, the results demonstrate that water quality in the Curuá-Una River is strongly conditioned by climatic seasonality, with direct implications for the system's limnological and biogeochemical processes. These findings underscore the critical importance of integrating temporal variability into environmental monitoring programs and the hydrological management of Amazonian reservoirs, particularly in light of the intensifying frequency of extreme climatic events. Consequently, this study contributes to a comprehensive understanding of the seasonal and vertical dynamics of water quality in the Amazon, providing essential data for future environmental assessments and the sustainable management of the region's water resources.

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