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Correlation and temporal dynamics of physical and chemical parameters of water in two Water Resources Management Units in the state of São Paulo (Brazil)

Rafaela Melissa Andrade Ferreira[1]*, Paulo Cesar Rocha[2], Renata Ribeiro de Araújo[3],

[1] *PhD candidate in Geography, Graduate Program in Geography, São Paulo State University (UNESP), School of Science and Technology, Presidente Prudente, Brazil. (**Corresponding author*:* rafaela.andrade-ferreira@unesp.br.).
[2]Professor, Department of Geography, São Paulo State University (UNESP), School of Science and Technology, Presidente Prudente, Brazil.
[3] Professor, Department of Environmental Engineering, São Paulo State University (UNESP), School of Science and Technology, Presidente Prudente, Brazil

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A B S T R A C T
This research analyzed the structure of water quality in the Water Resources Management Units of the Aguapeí and Peixe rivers, UGRHIs 20 and 21, located in western São Paulo State, Brazil. The study used data from physicochemical water parameters and applied non-parametric and multivariate statistical methods, including Spearman correlation, seasonal boxplots, and principal component analysis. The results indicated that, although the two units are located within the same regional context, they present distinct responses. In UGRHI 20, a greater separation was observed between parameters associated with material transport, such as turbidity, total dissolved solids, and total phosphorus, and those related to nitrogen-related dissolved load. In UGRHI 21, a more integrated structure was identified, marked by the association between electrical conductivity and total alkalinity, as well as positive correlations among total phosphorus, total nitrogen, turbidity, and total dissolved solids. The seasonal distribution reinforced the greater variability of UGRHI 21 during the rainy season, especially for turbidity, phosphorus, and dissolved solids. The PCA showed partial differentiation between the units, indicating greater dispersion in UGRHI 21. It is concluded that water quality in these basins is conditioned by the interaction among hydrological and hydrochemical processes, seasonality, land use, and landscape connectivity.

Keywords: Quality; Water; Fluvial systems; Statistics; Analysis.

Correlação e dinâmica temporal dos parâmetros físicos e químicos da água em duas Unidades de Gerenciamento de Recursos Hídricos do estado de São Paulo (Brasil)

R E S U M O (PT-BR)
Esta pesquisa analisou a estrutura da qualidade da água nas Unidades de Gerenciamento de Recursos Hídricos dos rios Aguapeí e Peixe, UGRHIs 20 e 21, localizadas no oeste do estado de São Paulo, Brasil. O estudo utilizou dados de parâmetros físico-químicos da água e aplicou métodos estatísticos não paramétricos e multivariados, incluindo correlação de Spearman, diagramas de caixa sazonais e análise de componentes principais. Os resultados indicaram que, embora as duas unidades estejam inseridas no mesmo contexto regional, apresentam respostas distintas. Na UGRHI 20, observou-se maior separação entre os parâmetros associados ao transporte de materiais, como turbidez, sólidos totais dissolvidos e fósforo total, e aqueles relacionados à carga dissolvida de nitrogênio. Na UGRHI 21, identificou-se uma estrutura mais integrada, marcada pela associação entre condutividade elétrica e alcalinidade total, bem como por correlações positivas entre fósforo total, nitrogênio total, turbidez e sólidos totais dissolvidos. A distribuição sazonal reforçou a maior variabilidade da UGRHI 21 durante o período chuvoso, especialmente para turbidez, fósforo e sólidos dissolvidos. A análise de componentes principais mostrou diferenciação parcial entre as unidades, indicando maior dispersão na UGRHI 21. Concluiu-se que a qualidade da água nessas bacias é condicionada pela interação entre processos hidrológicos e hidroquímicos, sazonalidade, uso da terra e conectividade da paisagem.

Palavras-chave: Qualidade da água. Sistemas fluviais. Parâmetros físico-químicos. Análise estatística. Conectividade da paisagem.

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Correlación y dinámica temporal de los parámetros físicos y químicos del agua en dos Unidades de Gestión de Recursos Hídricos del estado de São Paulo (Brasil)

R E S U M E N (SPANISH)
Esta investigación analizó la estructura de la calidad del agua en las Unidades de Gestión de Recursos Hídricos de los ríos Aguapeí y Peixe, UGRHIs 20 y 21, ubicadas en el oeste del estado de São Paulo, Brasil. El estudio utilizó datos de parámetros fisicoquímicos del agua y aplicó métodos estadísticos no paramétricos y multivariados, incluidos la correlación de Spearman, los diagramas de caja estacionales y el análisis de componentes principales. Los resultados indicaron que, aunque las dos unidades se encuentran dentro del mismo contexto regional, presentan respuestas distintas. En la UGRHI 20, se observó una mayor separación entre los parámetros asociados al transporte de materiales, como la turbidez, los sólidos disueltos totales y el fósforo total, y aquellos relacionados con la carga disuelta de nitrógeno. En la UGRHI 21, se identificó una estructura más integrada, marcada por la asociación entre la conductividad eléctrica y la alcalinidad total, así como por correlaciones positivas entre el fósforo total, el nitrógeno total, la turbidez y los sólidos disueltos totales. La distribución estacional reforzó la mayor variabilidad de la UGRHI 21 durante la estación lluviosa, especialmente en relación con la turbidez, el fósforo y los sólidos disueltos. El análisis de componentes principales mostró una diferenciación parcial entre las unidades, indicando una mayor dispersión en la UGRHI 21. Se concluyó que la calidad del agua en estas cuencas está condicionada por la interacción entre los procesos hidrológicos e hidroquímicos, la estacionalidad, el uso del suelo y la conectividad del paisaje.

Palabras clave: Calidad del agua. Sistemas fluviales. Parámetros fisicoquímicos. Análisis estadístico. Conectividad del paisaje

1. Introducción

Water quality in river systems is a key indicator of the environmental status of river basins, reflecting the interaction between natural processes and anthropogenic activities across the territory. In densely populated regions, especially those dominated by agricultural uses and urbanxpansion, changes in land use and cover, associated with hydrological and climatic dynamics, have promoted significant changes in the physicochemical parameters of water, with direct implications for aquatic ecosystems and the multiple uses of water resources (Pak, 2021; Zhang *et al*., 2021)

Several studies (Xiong *et al*., 2022; Qiu, 2023; Li *et al*., 2024; Pakoksung, 2025) have demonstrated that water quality in rivers and streams is strongly conditioned by the interaction between natural factors such as climate, geology, geomorphology, hydrological regime, and anthropogenic factors, especially those related to land use and cover.

From a landscape analysis perspective, river water quality can be understood as the result of the functional articulation between physical-natural components and anthropogenic transformations within the drainage basin. In this sense, geology, relief, soils, vegetation cover, land use, climatic seasonality, and hydrological connectivity do not act as isolated factors, but as interdependent elements that regulate runoff generation, sediment mobilization, nutrient transport, and dissolved-load dynamics (Downs, 1991; Fryris. 2012; Pedroza-Arceo, 2022; Yan *et al*., 2023).

Therefore, the hydrographic basin constitutes an integrated landscape unit in which changes occurring on hillslopes, floodplains, riparian zones, and drainage channels are reflected in the physicochemical composition of river waters. Thus, it is estimated that the conversion of natural areas into agricultural or urban landscapes tends to intensify surface runoff, reduce infiltration, and increase the input of sediments, nutrients, and contaminants to water bodies, altering fundamental physicochemical parameters such as turbidity, total solids, electrical conductivity, dissolved oxygen, and metal concentration (Reid, 1981; Silva, 2001; Hamid, 2020).

In tropical and subtropical regions, these impacts are frequently potentiated by high climatic variability and the occurrence of extreme precipitation events, which intensify erosive processes and the transport of particulate matter. Therefore, understanding the spatial and temporal patterns of water quality requires analytical approaches capable of integrating multiple variables and capturing both the structural associations between parameters and the long-term trends in river systems (Fong, 2020; Van Vliet *et al*., 2023)

In Brazil, a country with one of the largest freshwater reserves in the world, challenges related to water quality are particularly relevant due to the environmental and socioeconomic heterogeneity of the territory (Mendonça, 2006). Although water availability is high in absolute terms, the degradation of water quality in several river basins compromises the multiple uses of water resources, especially in regions subject to intense agricultural and urban expansion.

In this scenario, systematic water quality monitoring and the application of robust analytical methods become fundamental tools to support public policies and environmental management strategies (Machado, 2003). The Política Nacional de Recursos Hídricos (PNRH – National Water Resources Policy), by adopting the river basin as a planning unit, recognizes the need for integrated approaches that consider the different processes operating in the territory.

However, historical series of environmental monitoring often present characteristics that hinder the application of classical statistical methods, such as non-normal data distribution, the presence of extreme values, and temporal gaps resulting from the discontinuity of monitoring. In this context, non-parametric statistical methods have stood out as suitable alternatives for the analysis of environmental data, allowing the identification of associations and trends without imposing restrictive assumptions.

In addition to their statistical relevance, these methods can contribute to the interpretation of river basins as complex environmental systems. Correlation matrices, seasonal boxplots, and multivariate analyses allow the identification of how physicochemical parameters respond jointly to landscape controls, such as land use, soil exposure, vegetation fragmentation, hydrological seasonality, and the connectivity between source areas and the drainage network. Thus, statistical analysis becomes a means of translating the organization and functioning of the landscape into measurable hydrochemical patterns (Jain, 2022).

The state of São Paulo is part of this panorama as one of the most intensely occupied and economically dynamic regions in the country, presenting high pressure on its water resources. The Unidades de Gerenciamento de Recursos Hídricos (UGRHIs – Water Resources Management Units) constitute the main institutional scale for water planning and management in the state, allowing the integrated assessment of river systems and the implementation of conservation actions (Gomes, 2004; Leal, 2012). Among these units, the UGRHIs 20 and 21 (Aguapéi and Peixe), located in western São Paulo and associated with the Paraná River basin, stand out due to the predominance of agricultural activities, the fragmentation of vegetation cover, and the high connectivity between areas of anthropic use and the drainage network (Rocha, 2012; Rocha, 2018).

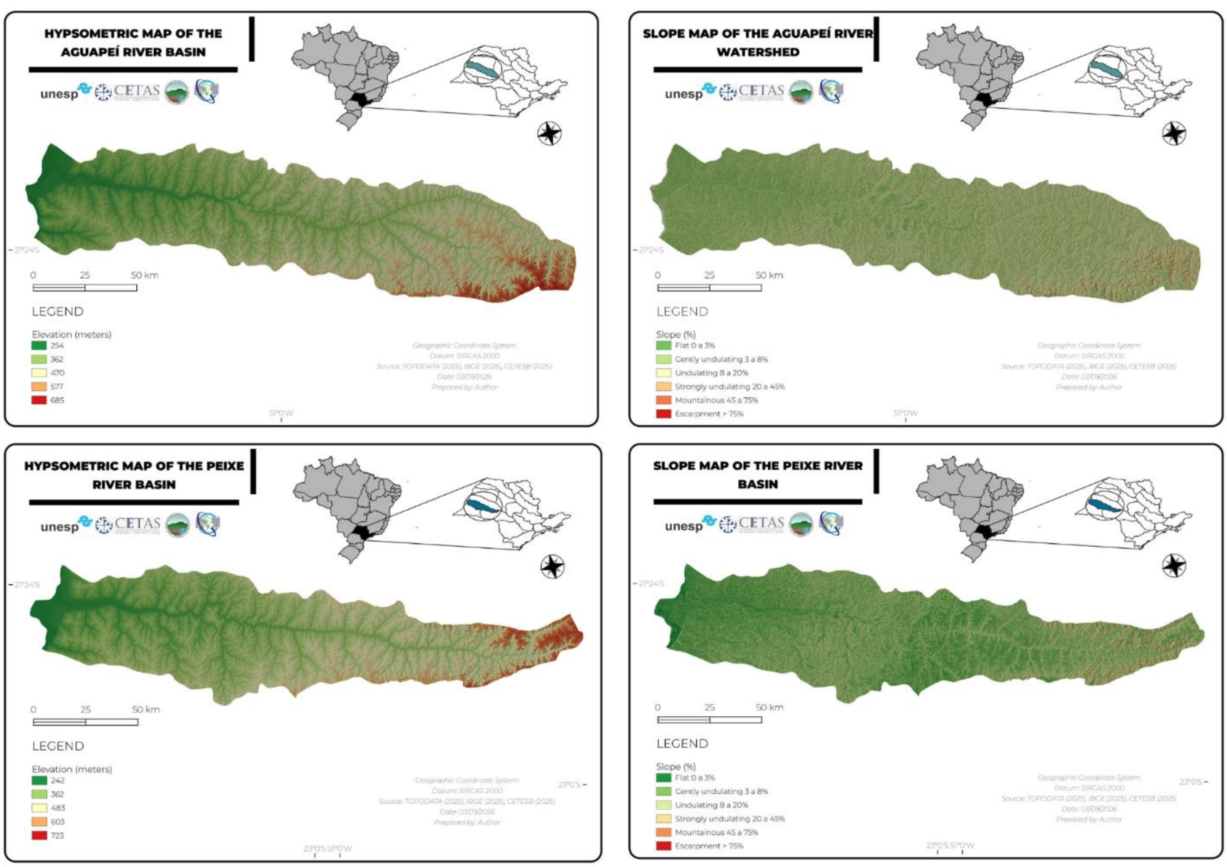
Studies carried out in this region have shown that changes in land use and cover have a direct influence on water quality, intensifying hydrosedimentological processes and affecting fundamental limnological parameters. However, analyses that systematically integrate the assessment of associations between water quality parameters and the identification of consistent temporal trends in different management units are still scarce (Rocha & Tommaselli, 2012; Santos, 2013; Andrade, 2014; Fernandes, 2019; Araújo *et al*., 2025)

Therefore, this study aims to analyze the dynamics of water quality in UGRHIs 20 and 21, through the application of non-parametric statistical methods to monthly time series of physicochemical parameters. The aim is to identify structural relationships between variables, assess trends over time, and compare the observed behaviors among management units, contributing to the understanding of the processes that control water quality in river basins in western São Paulo state and offering technical support for environmental planning and water resource management on a regional scale.

2. Characterization of the study area

The study area comprises the hydrographic basins of the Aguapeí and Peixe rivers, corresponding to UGRHIs 20 and 21, respectively, located in western São Paulo State, Brazil. These basins constitute important tributary systems of the Paraná River and play a fundamental role in the regional water balance (Figure 1). They also present ecological, economic, and social relevance, especially regarding water supply, agricultural irrigation, aquatic biodiversity maintenance, and regional water resources planning (Andrade, 2014; Rocha & Santos, 2018; Rocha & Tommaselli, 2012).

Figure 1. Hypsometric and slope maps of the Aguapeí and Peixe river basins, western São Paulo State, Brazil.



Source: Authors (2026)

From a geological perspective, the Aguapeí and Peixe river basins are located within the morphostructure of the Paraná Sedimentary Basin and the morphosculpture of the Western Plateau of São Paulo. Their lithological framework is predominantly composed of sandstones from the Bauru Group, as well as volcanic rocks and Cenozoic alluvial deposits associated with floodplains (IPT, 1981).

This lithological basis, marked by high porosity and low cohesion, conditions regional hydrogeomorphological dynamics, influencing infiltration, surface runoff, sediment production, and susceptibility to erosive processes (Santos, 2013). The predominance of the Adamantina Formation is noteworthy, as it is composed of fine to very fine and well-sorted sediments, with lithological subdivisions that reflect variations in grain size, cementation, and mineralogical composition (CBH-AP, 1997). This geological configuration exerts direct control over relief organization, drainage patterns, soil development, and sediment transport dynamics throughout the basins.

The regional climate is predominantly tropical, with marked seasonality. Rainfall is concentrated mainly during spring and summer, while autumn and winter are characterized by a more pronounced dry period. This climatic seasonality conditions the hydrological regime of the rivers, promoting variations in discharge, surface runoff, sediment transport, and the dilution or concentration of dissolved substances. Therefore, the alternation between rainy and dry seasons is essential for understanding the seasonal behavior of physicochemical water quality parameters, especially turbidity, total dissolved solids, nutrients, electrical conductivity, and water temperature.

The hypsometric maps show a clear altimetric gradient in both basins, with higher elevations concentrated in the eastern and upstream sectors and lower elevations toward the western portions and the Paraná River. In the Aguapeí River basin, elevations vary approximately from 254 to 685 m, while in the Peixe River basin they range from approximately 242 to 723 m. This configuration expresses the longitudinal organization of the drainage system and helps explain the general direction of water, sediment, and solute transport from headwater sectors toward lower fluvial reaches (Figures 1 and 3).

The slope maps complement (Figures 2 and 4) this interpretation by indicating the predominance of flat to gently undulating relief, especially in the middle and lower sectors of both basins. However, more dissected areas with undulating to strongly undulating slopes are observed mainly in the eastern and headwater portions, where the terrain may favor faster runoff responses and greater sediment mobilization during rainfall events. These sectors are particularly relevant for water quality interpretation because slope increases the potential connectivity between hillslopes, exposed soils, drainage channels, and floodplains. Regarding relief organization, the Aguapeí and Peixe river basins are predominantly located in the geomorphological context of the Western Plateau of São Paulo, a compartment whose configuration is associated with the geological structure of the Paraná Sedimentary Basin and with the predominance of gently dissected surfaces developed over sedimentary and volcanic lithologies (IPT, 1981; Ross & Moroz, 1997).

In this regional setting, the relief is generally characterized by broad hills, smoothed interfluves, and low to moderate slope gradients, although more dissected sectors occur in the eastern and headwater portions of the basins. The hypsometric pattern observed in the mapped area, with higher elevations in the eastern sectors and lower elevations toward the western portions and the Paraná River, reflects the general westward organization of the drainage system and contributes to the longitudinal transfer of water, sediments, and solutes along the fluvial network.

The hydrographic network is mainly composed of consequent rivers and tributaries developed within the Western Plateau, with drainage lines that follow the regional altimetric gradient toward the Paraná River system. In both basins, the main channels are associated with floodplains and alluvial deposits of different widths, which play an important role in sediment storage, lateral hydrological connectivity, and the regulation of fluvial processes (IPT, 1981; Santos, 2013). More dissected areas, especially near headwater sectors and locally steeper slopes, may favor faster runoff responses and greater sediment mobilization during rainfall events. Therefore, the geomorphological organization of the basins influences not only drainage patterns, but also the connectivity between hillslopes, exposed soils, floodplains, and river channels, which is essential for understanding the spatial variability of water quality parameters (Rocha & Santos, 2018)

The soils in the region are generally deep and well developed, reflecting the long-term evolution of the landscape under tropical climatic conditions. However, when associated with sandy lithologies, reduced vegetation cover, agricultural use, pasture areas, and inadequate soil management, these soils may become more susceptible to erosive processes (CBH-AP, 1997; Santos, 2013). The original vegetation cover of western São Paulo included formations associated with seasonal forest and savanna-like environments, especially Seasonal Semideciduous Forest and Cerrado physiognomies, which historically contributed to soil protection, infiltration regulation, sediment retention, and the maintenance of riparian ecological functions (Ross & Moroz, 1997).

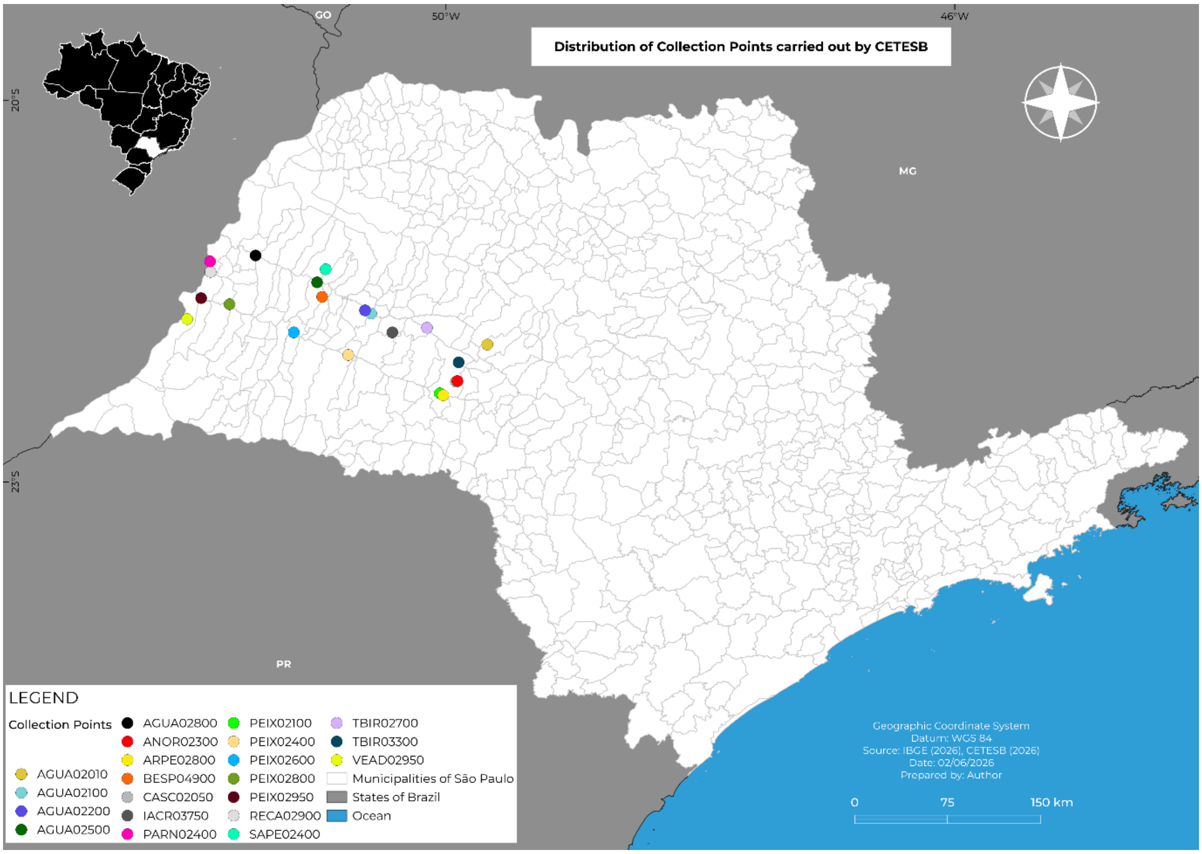
3. Materials and methods

3.1 Database

We built the database from water quality monitoring information from systematic campaigns carried out by the Companhia Ambiental do Estado de São Paulo (CETESB – Environmental Company of the State of São Paulo), made available through the InfoÁguas system. The monitoring campaigns were conducted at points located in the Unidades de Gerenciamento de Recursos Hídricos (UGRHIs – Water Resources Management Units) 20 and 21, in the west of the state of São Paulo, and are part of the institutional program for monitoring the quality of surface waters in the state.

The spatial distribution of the monitoring points used in this study is shown in Figure 2, which illustrates the location of CETESB's collection stations in the context of the regional hydrographic network and the administrative boundaries of the state. The map highlights the concentration of points along the main river courses of the Aguapeí and Peixe river basins, as well as the spatial heterogeneity of the monitoring, reflecting operational and historical criteria of the institutional network.

Figure 2. Spatial distribution of CETESB collection points

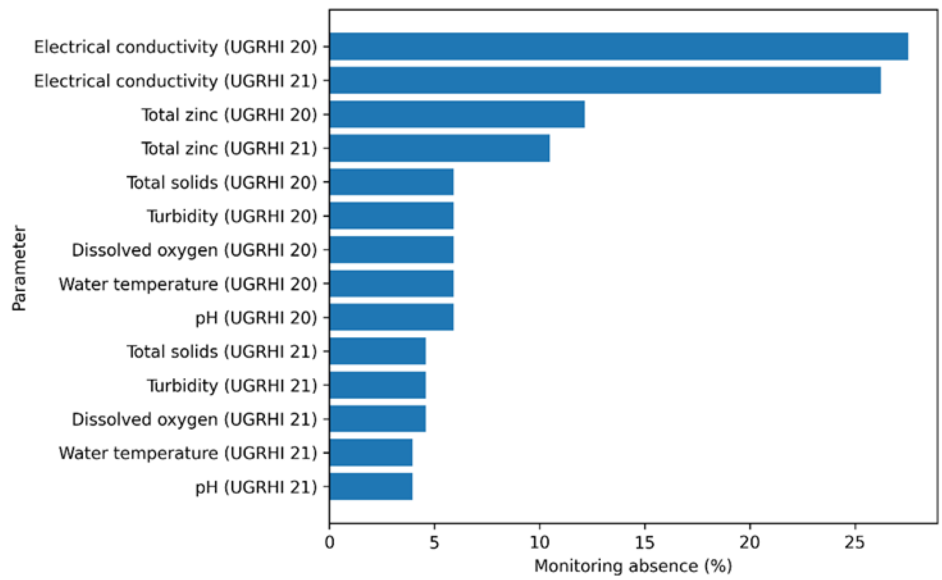


Source: Authors' own elaboration (2026).

We reorganized and structured the original data extracted from the InfoÁguas system to ensure temporal and spatial consistency and statistical feasibility for the proposed analyses. The records have a monthly temporal resolution, with a single observation per month, organized in month/year format, reflecting the periodicity of the collection campaigns and avoiding the occurrence of sample pseudorepetition. Each row of the database, therefore, corresponded to a monthly monitoring event, while we organized the variables analyzed into independent columns, representing the different physicochemical parameters of the water.

To allow spatial comparison between the management units, we identified the parameters by means of specific suffixes (_20 and _21), corresponding to UGRHIs 20 and 21, respectively. Not all parameters were monitored simultaneously in both UGRHIs or throughout the entire period analyzed, due to the operational guidelines of the CETESB monitoring program and methodological adjustments over time (Figura 3).

Figure 3. Percentage of absence of monitoring of physical-chemical parameters of water quality in the UGRHIs 20 (Aguapeí) and 21 (Peixe), state of São Paulo



Source: Authors' own elaboration (2026

No interpolation was performed for the data voids. The gaps identified in the monitoring series were interpreted as periods without sampling or monitoring, rather than as recording errors. Therefore, missing values were retained as such in the database, and no filling, imputation, or interpolation procedure was applied. The statistical analyses were conducted using only valid observed data for each parameter and period, in order to preserve the integrity of the original monitoring series and avoid introducing artificial values that could bias the correlation analysis, seasonal boxplots, or principal component analysis

3.2 Stastistical tests for correlation analysis

To evaluate the associations among the physicochemical parameters of water, Spearman's correlation coefficient (ρ) was used, a non-parametric method suitable for data that do not follow a normal distribution and for monotonic relationships between variables. Spearman's correlation was calculated based on the ranks of the observations, according to the following expression:

$$\rho = 1 - [\ 6\sum d_i^2 / n(n^2 - 1)\ ]$$

where ρ represents Spearman's correlation coefficient, d_i corresponds to the difference between the ranks of the two variables analyzed for each pair of observations, and nnn represents the total number of valid pairs. The values of p range from −1 to +1. Values close to +1 indicate a strong positive monotonic association, values close to −1 indicate a strong negative monotonic association, and values close to zero indicate a weak or nonexistent association. The correlation analyses were performed separately for each UGRHI, considering only the pairs of data observed in the same period, without gap filling.

The statistical significance of the correlations was evaluated at the 5% level ($p \leq 0.05$). Subsequently, the results were organized into correlation matrices, allowing the identification of association patterns among variables such as turbidity, total dissolved solids, electrical conductivity, pH, dissolved oxygen, and the other physicochemical parameters analyzed.

In addition to the descriptive and bivariate analyses, Principal Component Analysis (PCA) was applied in order to synthesize the multivariate structure of the data and identify the main gradients responsible for water quality variability in the UGRHIs of the Aguapeí and Peixe rivers. The use of PCA is justified because environmental water quality datasets are composed of several variables measured simultaneously at different points and periods, which makes the direct interpretation of the original tables more difficult.

As discussed by Zitko (1994), PCA allows a multidimensional space to be projected into a lower-dimensional space, preserving most of the original information and facilitating the identification of similarities, differences, and relationships among samples and variables. Felipe-Sotelo et al. (2007), when analyzing river waters in urban and semi-urban areas through physicochemical parameters and chemometric methods, also demonstrated the applicability of PCA in the differentiation of river basins, the identification of mineral gradients, and the interpretation of processes associated with organic matter.

The variables were standardized using the z-score, according to the following expression:

$$z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j}$$

where z_{ij} represents the standardized value of variable j in sample $_{i,}$ x_i corresponds to the observed value, $\bar{x}_j$, is the mean of variable *j*, and s_j corresponds to the standard deviation of variable $_j$. After this procedure, the variables had a mean equal to zero and a standard deviation equal to one, allowing all physicochemical parameters to contribute proportionally to the multivariate analysis.

PCA was applied to the standardized matrix *X,* composed of nnn observations and *p* variables. The matrix decomposition of PCA can be expressed as:

$$X = TP^T + E$$

where X corresponds to the standardized data matrix, *T* represents the scores matrix, P^T represents the transposed matrix of weights or loadings, and *E* corresponds to the residual matrix not explained by the model. The scores indicate the position of the samples in the new coordinate system defined by the principal components, while the loadings indicate the contribution of each original variable to the formation of these components. This distinction is central to the environmental interpretation of PCA, since the scores allow the analysis of groupings and differences among samples, whereas the loadings allow the identification of the variables responsible for such differences.

Each principal component was obtained as a linear combination of the standardized variables, according to the equation:

$$PC_j = a_{1j}z_1 + a_{2j}z_2 + a_{3j}z_3 + \ldots + a_{pj}z_p \quad (04)$$

where PC_j represents principal component *j*, a_{ij} corresponds to the loading or weight of variable iii in component *j*, z_i represents the standardized variable, and *p* corresponds to the total number of variables analyzed.

The boxplots were constructed based on the median, quartiles, and interquartile range of the data. For each parameter analyzed, the first quartile (*Q1*) represents the value below which 25% of the observations are found, while the third quartile (*Q3*) represents the value below which 75% of the observations are found. The central dispersion of the data was evaluated using the interquartile range (*IQR*), calculated as the difference between Q_3 and Q_1, according to the expression:

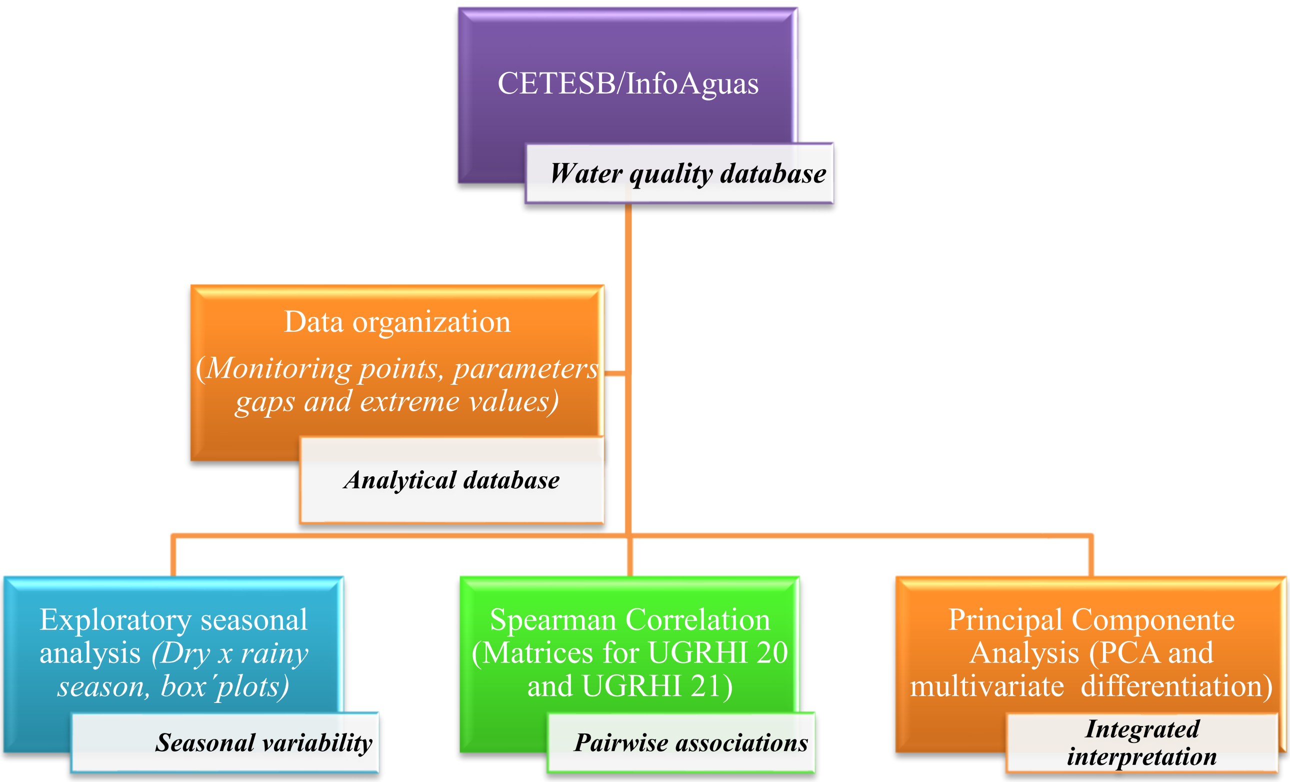
$$IQR = Q_3 - Q_1$$

All graphical material presented in this study was produced in a Python programming environment, using a previously organized and processed database prepared for the statistical analyses. Spearman correlation coefficients were calculated using the SciPy library, specifically the scipy. stats module, which enables the application of non-parametric statistical tests suitable for environmental time series with non-normal distribution, data gaps, and extreme values. Data organization, filtering, and structuring were performed with the support of the panda’s library, while the graphical outputs, including correlation heatmaps, seasonal boxplots, time series, and the principal component analysis biplot, were generated using the Matplotlib and Seaborn libraries.

It should be noted that the results obtained from the calculation of Spearman correlation coefficients in Python were checked in the SPSS environment, showing equivalence between the calculated values. The observed difference is restricted only to the number of decimal places displayed in the heatmaps, since the figures were configured with two decimal places to facilitate the visual reading of the correlation coefficients.

Figure 4 summarizes, in flowchart form, the methodological pathway adopted in this study, from the acquisition of water quality data from the CETESB/InfoÁguas database to the organization of the analytical dataset, the exploratory seasonal analysis, the application of Spearman correlation matrices, and Principal Component Analysis.

Figure 4. Methodological flowchart showing the procedures adopted for water quality analysis in UGRHIs 20 and 21, including data acquisition, database organization, exploratory seasonal analysis, Spearman correlation matrices, principal component analysis, and integrated interpretation.



Source: Authors' own elaboration (2026).

The flowchart also highlights the integration between the different statistical and interpretative stages, showing how the methodological procedures supported the analysis of seasonal variability, associations among physicochemical parameters, and the multivariate differentiation of water quality in UGRHIs 20 and 21.

4. Results and discussion

4.1 Correlations among physicochemical parameters in UGRHIs 20 and 21

Spearman's correlation analysis allowed the identification of the main monotonic associations among the physicochemical parameters of water in UGRHIs 20 and 21, considering the non-parametric nature of the environmental series and the presence of gaps and extreme values in the dataset.

Initially, the correlation matrix for UGRHI 20 (figure 5) revealed important associations among water temperature, total dissolved solids, turbidity, electrical conductivity, pH, total phosphorus, and total nitrogen. Overall, the results indicate that water quality in this unit is organized by two main sets of relationships: the first associated with the mobilization of materials and nutrients, mainly involving turbidity, total dissolved solids, and total phosphorus; and the second related to dissolved load and the presence of nitrogen compounds, expressed by the association between electrical conductivity and total nitrogen.

Figure 5. Spearman correlation heatmap among water physicochemical parameters in UGRHI 20.

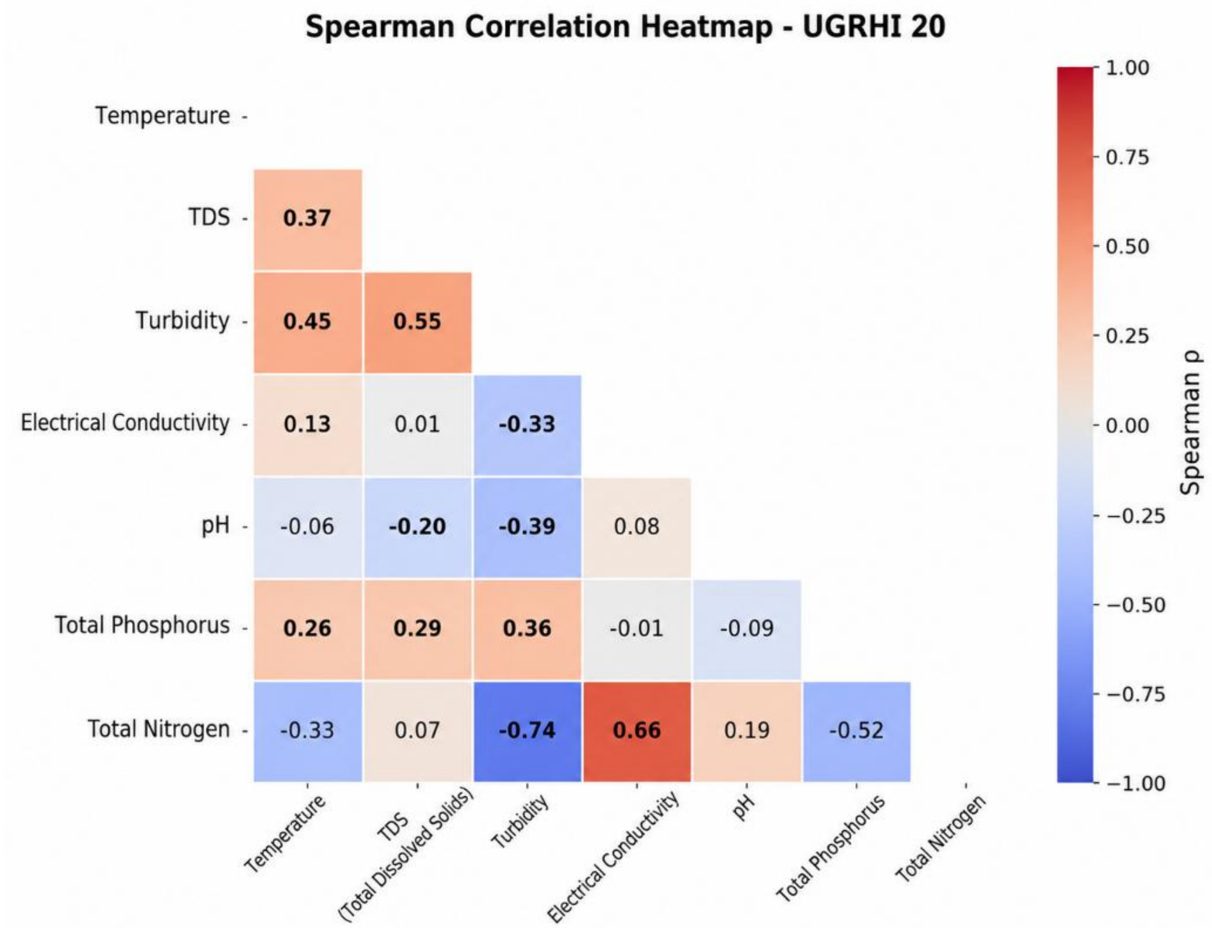


Figure 3. Spearman correlation heatmap among water physicochemical parameters in UGRHI 20.

Source: Authors' own elaboration (2026).

In UGRHI 20, a positive correlation was observed between turbidity and total dissolved solids, indicating that part of the increase in turbidity occurs alongside an increase in the dissolved load in the water.

Although turbidity is more directly related to the presence of suspended particles, its association with total dissolved solids suggests that higher-energy hydrological events, such as intense rainfall, increased discharge, and surface runoff, may simultaneously promote particle remobilization and the input of dissolved substances into the fluvial system. This interpretation is supported by Rocha and Santos (2018), who indicate that the runoff pattern in the Aguapeí and Peixe river basins is conditioned by the interaction among precipitation, physical-environmental characteristics, and land cover, and that changes in vegetation and land use can increase direct water flow to rivers.

The positive correlation between turbidity and total phosphorus also indicates that phosphorus, in this unit, may be related to surface transport processes and to the input of particulate material or associated organic matter. In fluviais systems, total phosphorus is often linked to the transport of fine particles, sediments, and organic matter, being mobilized mainly during periods of higher runoff (Silva, 2001; Koklu, 2010; Sharma, 2015).

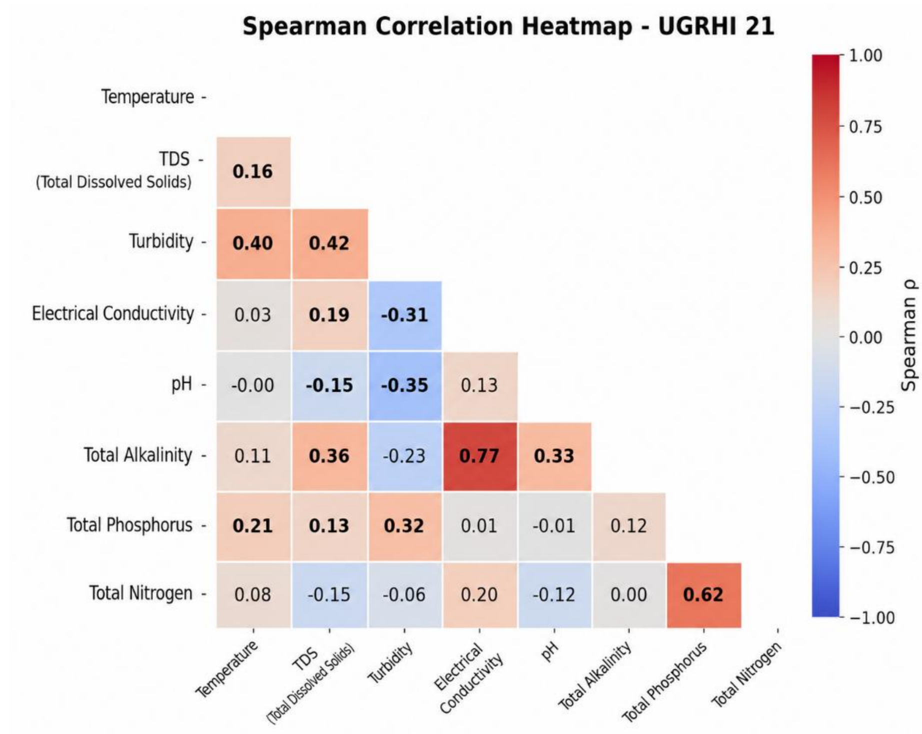
Thus, the association between turbidity and phosphorus suggests that events capable of increasing particle concentrations in the water may also favor nutrient enrichment, especially when there is connectivity among agricultural areas, exposed soils, and the drainage network (Xu et al., 2024; Dwivedi, 2025).

Another relevant result in UGRHI 20 was the expressive negative correlation between turbidity and total nitrogen. This behavior indicates that the highest nitrogen values do not necessarily coincide with periods of higher turbidity. Unlike phosphorus, which tends to be more closely related to the particulate fraction, nitrogen may occur in dissolved forms and respond to other control mechanisms, such as concentration during periods of lower discharge, dilution during higher-flow events, inputs from diffuse sources, or internal biogeochemical processes within the aquatic system. Thus, the negative correlation between turbidity and nitrogen suggests that these parameters are not controlled by exactly the same processes in UGRHI 20.

Studies such as that of Alam et al. (2007), although conducted in a different hydrographic context, help support this interpretation by demonstrating that indicators of particulate load and organic/nitrogen-related load may exhibit distinct seasonal responses. The authors observed higher turbidity during the monsoon season, whereas parameters associated with organic matter and contamination, such as BOD and fecal coliforms, showed higher concentrations during the dry season. In addition, they highlighted that conductivity tends to increase during periods of lower water volume due to the higher concentration of dissolved ions.
Complementarily, Li et al. (2008), when analyzing the relationship between water quality, land use, and land cover in the upper Han River basin, China, also demonstrated that physicochemical water parameters may respond differently to seasonal and territorial controls.

The authors observed that nitrogen, turbidity, and other indicators showed higher values during the rainy season, whereas electrical conductivity and total dissolved solids tended to show higher values during the dry season, mainly due to the dilution effect caused by precipitation. In addition, the study showed that areas with higher vegetation cover presented lower values of turbidity, suspended particulate matter, nutrients, and total dissolved solids, while different land use types exerted distinct controls on nitrogen, phosphorus, and particulate matter. In UGRHI 21 (figure 6), the correlation matrix showed a distinct structure, with emphasis on the strong association between electrical conductivity and total alkalinity.

Figure 6. Spearman correlation heatmap among water physicochemical parameters in UGRHI 21.



Source: Authors' own elaboration (2026).

In UGRHI 21, the strongest positive correlation was observed between electrical conductivity and total alkalinity (ρ = 0.77), indicating a close association between dissolved ionic load and the buffering capacity of the water. Another relevant positive association occurred between total phosphorus and total nitrogen (ρ = 0.62), suggesting that nutrient dynamics in this unit may be influenced by common sources or simultaneous mobilization processes. Turbidity also showed positive correlations with total dissolved solids (ρ = 0.42), temperature (ρ = 0.40), and total phosphorus (ρ = 0.32), reinforcing the role of hydrological events in the joint transport of suspended material, dissolved solids, and nutrients.

Moderate positive correlations were also observed between total dissolved solids and total alkalinity (ρ = 0.36), as well as between pH and total alkalinity (ρ = 0.33). In contrast, the main negative correlations involved turbidity and pH (ρ = -0.35), turbidity and electrical conductivity (ρ = -0.31), and turbidity and total alkalinity (ρ = -0.23), indicating that increases in particulate material do not always occur simultaneously with increases in alkalinity or ionic concentration.

These results indicate that the variation in conductivity in this unit is strongly related to the dissolved ionic load and to the buffering capacity of the water. Alkalinity represents the capacity of water to neutralize acids and is frequently associated with the presence of bicarbonates, carbonates, and other dissolved ions. Therefore, its correlation with conductivity suggests stronger hydrogeochemical control over water composition in UGRHI 21, possibly related to water–rock interaction, soil leaching, and the input of solutes from the drainage basin (Wetzel, 2001; Kney & Brandes, 2007).

In addition to the relationship between conductivity and alkalinity, UGRHI 21 showed a significant positive correlation between total phosphorus and total nitrogen. This result suggests that, in this unit, nutrients tend to respond in a more integrated manner, possibly associated with common input sources into the fluvial system. Such behavior may be related to surface runoff in agricultural areas, the transport of organic matter, fertilizer inputs, and the mobilization of materials during rainy periods. Unlike UGRHI 20, where phosphorus and nitrogen showed a more contrasting behavior, in UGRHI 21 these nutrients appear to share similar mobilization mechanisms or sources.

Turbidity in UGRHI 21 showed a positive correlation with total dissolved solids and total phosphorus. This result reinforces the importance of hydrosedimentological processes in the organization of water quality, indicating that the input of particles and dissolved materials may occur in an articulated way under certain hydrological contexts. The association between turbidity and total phosphorus indicates that events of greater particle remobilization may also favor an increase in nutrient concentration, especially when phosphorus is associated with fine sediments, organic matter, or particles transported by surface runoff (Wang et al., 2023).

The comparison between the two matrices shows that UGRHIs 20 and 21, although located within the same regional context of western São Paulo, present distinct correlation structures. In UGRHI 20, the results indicate a greater separation between the turbidity/phosphorus dynamics and the nitrogen/conductivity dynamics. In contrast, UGRHI 21 shows greater integration among nutrients and a stronger relationship between conductivity and alkalinity, revealing a system with greater articulation between dissolved load and the joint input of nutrients.

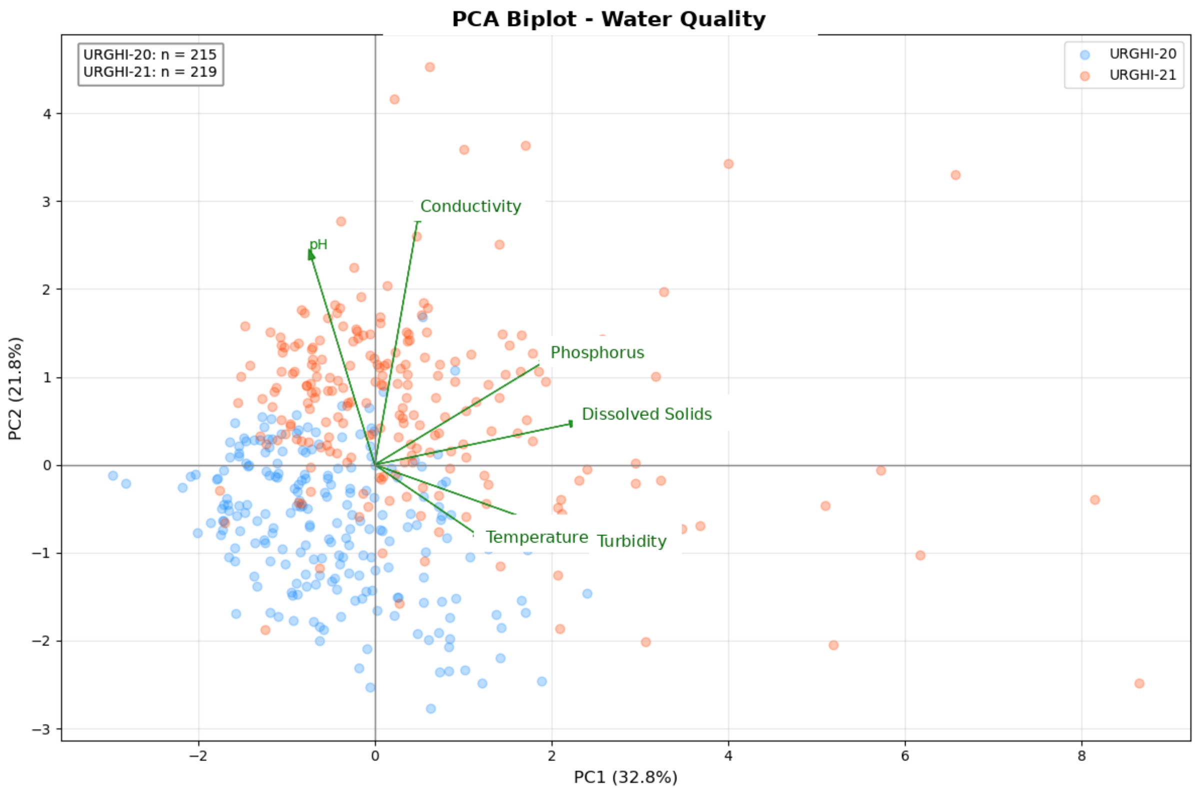
In summary, the Spearman heatmaps indicate that water quality in UGRHIs 20 and 21 is conditioned by different combinations of physical and chemical processes. UGRHI 20 shows a clearer differentiation between parameters linked to material transport and those associated with nitrogen-related dissolved load. UGRHI 21, on the other hand, reveals a stronger association among nutrients and greater control of conductivity by alkalinity, indicating a more pronounced expression of dissolved ionic load. These results demonstrate that the two basins should not be interpreted solely as regionally similar units, but rather as fluvial systems with their own hydrochemical responses, conditioned by the interaction among natural characteristics, land use, seasonality, and hydrological connectivity.

4.2 Multivariate structure of water quality between the UGRHIs

Principal Component Analysis was applied with the aim of synthesizing the joint variability of the physicochemical water parameters and evaluating the multivariate differentiation between UGRHIs 20 and 21. While the Spearman correlation matrices allowed the identification of pairwise associations among variables, PCA enabled an integrated reading of the dataset, showing how the parameters are simultaneously organized in the multivariate space and how the samples from each management unit are distributed in relation to the main axes of variation.

The first two principal components explained 54.6% of the total variance in the data, with 32.8% attributed to the first principal component and 21.8% to the second. This result indicates that a significant portion of water quality variability can be interpreted through two main axes of organization. The first component appears to represent a gradient associated with increased dissolved load, nutrient input, and material transport, as indicated by the projection of the vectors of total dissolved solids, total phosphorus, turbidity, and electrical conductivity toward the positive sector of this axis (Figure 7).

Figure 7. Principal component analysis (PCA) biplot showing the multivariate distribution of physicochemical water quality parameters and the partial differentiation between UGRHIs 20 and 21



Source: Authors' own elaboration (2026).

Furthermore, the distribution of samples in the biplot reveals a partial differentiation between the two UGRHIs. Samples from UGRHI 20 are more concentrated, especially in the negative sector of the first component, suggesting comparatively more homogeneous behavior. In contrast, samples from UGRHI 21 show greater dispersion in the multivariate space and tend to be more closely associated with the vectors of electrical conductivity, total phosphorus, total dissolved solids, and turbidity. Thais pattern indicates greater environmental heterogeneity in UGRHI 21, possibly reflecting higher variability in dissolved load, nutrient input, and hydrosedimentological processes.

The interpretation is consistent with Araújo et al. (2025), who analyzed hydrological dynamics, land use, and trophic state in the lower course of the Peixe River, located within UGRHI 21. The authors identified total phosphorus concentrations above the limit established by CONAMA Resolution No. 357/2005* in all samples, in addition to the eutrophic classification of the water body.

They also observed that the watershed is predominantly agricultural, with approximately 86% of its area associated with pastures, temporary crops, land-use mosaics, and perennial crops. This condition, when associated with surface runoff, may favor nutrient inputs and intensify eutrophication processes. Thus, the greater dispersion of UGRHI 21 in the PCA can be interpreted as an expression of a more heterogeneous hydrochemical response, sensitive to the input of materials, nutrients, and dissolved loads into the fluvial system.

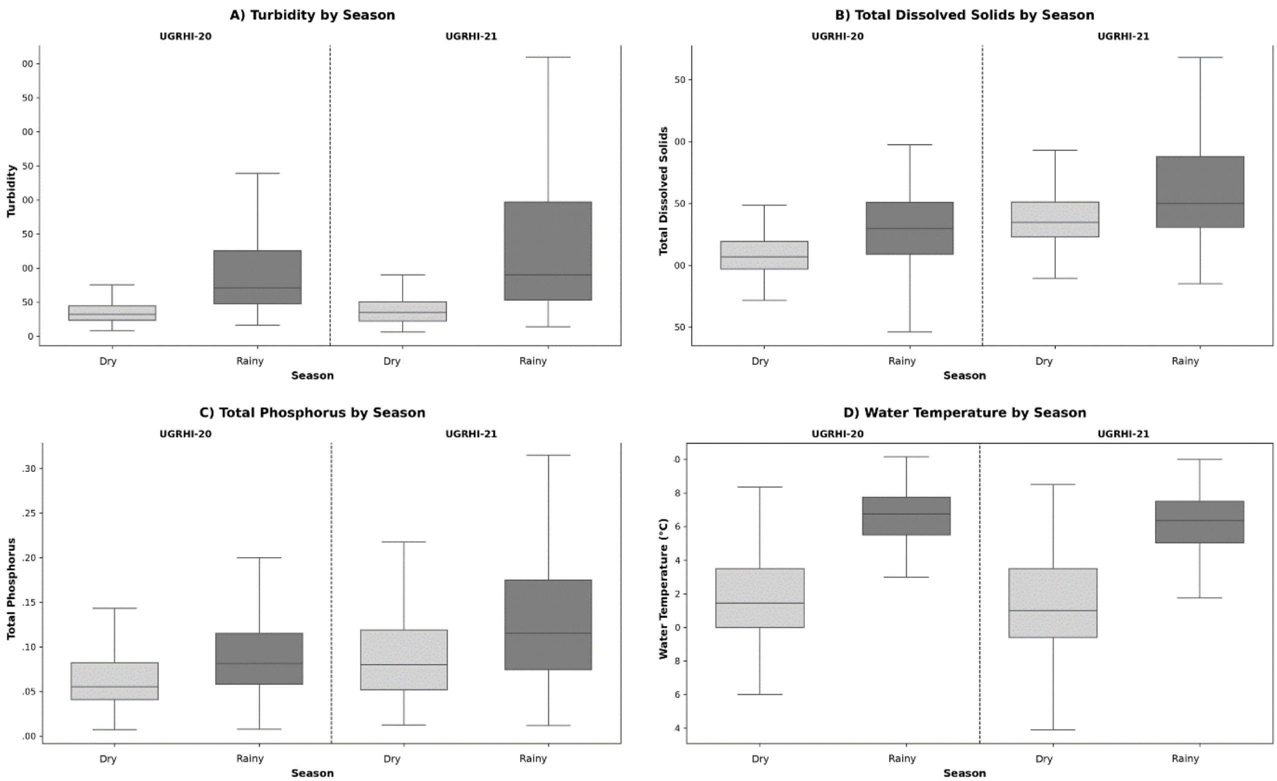
The orientation of the vectors reinforces the existence of different controls on water quality. Thus, turbidity, total phosphorus, total dissolved solids, and temperature are positioned in relatively similar directions, suggesting that these parameters may respond jointly to hydrological events capable of promoting surface runoff, sediment remobilization, and the transport of materials from the drainage basin to the river channels. This dynamic is also consistent with the previously observed positive correlations among turbidity, total dissolved solids, and total phosphorus in UGRHI 21.

The position of electrical conductivity in the PCA space reiterates its role as an indicator of the presence of dissolved ions in water, while pH expresses conditions related to acid–base neutralization capacity and the chemical equilibrium of the system. This perspective is consistent with the strong correlation observed between electrical conductivity and total alkalinity in UGRHI 21.

The seasonal distribution of the selected parameters (Figure 8 also helps explain the multivariate organization observed in the PCA. In this context, the boxplots showed a greater range of variation for turbidity, total dissolved solids, and total phosphorus, especially in UGRHI 21 and during the rainy season, indicating greater sensitivity of this unit to pulses of material mobilization, nutrient input, and variation in dissolved load under conditions of higher hydrological activity.

* CONAMA Resolution No. 357/2005 is a regulation issued by the National Environment Council that provides for the classification of water bodies and establishes guidelines, conditions, and quality standards for surface waters in Brazil, according to their predominant uses.

Figure 8. Seasonal distribution of selected physicochemical water quality parameters in UGRHIs 20 and 21, comparing dry and rainy seasons for: (A) turbidity; (B) total dissolved solids; (C) total phosphorus; and (D) water temperature.



Source: Authors' own elaboration (2026).

The seasonal boxplots indicate that turbidity, total dissolved solids, total phosphorus, and water temperature presented higher median values and greater dispersion during the rainy season, especially in UGRHI 21. For turbidity, the median increased from approximately 20–30 NTU in the dry season to around 90–100 NTU in the rainy season in UGRHI 21, with maximum values exceeding 300 NTU. In UGRHI 20, turbidity also increased during the rainy season, although with lower amplitude than that observed in UGRHI 21.

This behavior is consistent with the intensification of surface runoff, sediment remobilization, and particulate matter transport during periods of greater rainfall (Koklu et al., 2010; Wang et al., 2023; Xu et al., 2024). Total dissolved solids also showed higher values during the rainy season, with UGRHI 21 reaching the highest upper values, close to 230–240 mg L^{-1}, while UGRHI 20 presented a more moderate distribution. Total phosphorus followed the same seasonal pattern, with higher medians during the rainy season and maximum values above 0.30 mg L^{-1} in UGRHI 21, indicating greater nutrient mobilization under conditions of increased hydrological connectivity between hillslopes, agricultural areas, exposed soils, and drainage channels (Li *et al*., 2008; Araújo *et al*., 2025; Xu *et al*., 2024).

Water temperature showed clear seasonal differentiation in both units, with medians around 21–23 °C during the dry season and approximately 26–28 °C during the rainy season, reinforcing the role of climatic seasonality in the organization of physicochemical water parameters (Xu *et al.,* 2022; Tibebe *et al*., 2022; Pant *et al.*, 2025).

These results reinforce that the rainy season intensifies hydrosedimentological and hydrochemical responses, particularly in UGRHI 21, where wider interquartile ranges and higher maximum values indicate greater relative hydrochemical variability. Therefore, the PCA statistically synthesizes a dynamic already indicated by the seasonal distribution: UGRHI 21 presents greater dispersion and sensitivity to seasonal pulses of material and nutrient transport, whereas UGRHI 20 shows a more concentrated and less dispersed behavior for the selected parameters.

5. Conclusions

This study analyzed the structure of water quality in UGRHIs 20 and 21 through Spearman correlation, seasonal boxplots, and principal component analysis. The results showed that, although both units are located within the same regional context of western São Paulo, they present distinct hydrochemical and seasonal responses. Therefore, the Aguapeí and Peixe river basins should not be interpreted only as environmentally similar management units, but as fluvial systems whose water quality is conditioned by different combinations of hydrological, hydrochemical, seasonal, and land-use-related processes.

In UGRHI 20, the correlation matrix indicated a clearer separation between parameters associated with material transport and those related to nitrogen-related dissolved load. Turbidity showed positive correlations with total dissolved solids ($\rho = 0.55$) and total phosphorus ($\rho = 0.36$), suggesting that part of the increase in turbidity is associated with the simultaneous mobilization of particles, dissolved solids, and phosphorus. However, turbidity was strongly and negatively correlated with total nitrogen ($\rho = -0.74$), while electrical conductivity showed a positive correlation with total nitrogen ($\rho = 0.66$). These results indicate that nitrogen does not necessarily respond to the same hydrosedimentological processes that control turbidity and phosphorus, reinforcing the importance of dissolved forms, dilution and concentration dynamics, diffuse inputs, and internal biogeochemical transformations within the aquatic system.

In UGRHI 21, the results revealed a more integrated hydrochemical structure. The strongest correlation was observed between electrical conductivity and total alkalinity ($\rho = 0.77$), indicating the importance of dissolved ionic load and buffering capacity in the organization of water composition. Total phosphorus and total nitrogen also showed a positive correlation ($\rho = 0.62$), suggesting more integrated nutrient dynamics in this unit. Turbidity was positively associated with total dissolved solids ($\rho = 0.42$), water temperature ($\rho = 0.40$), and total phosphorus ($\rho = 0.32$), indicating that particulate transport, dissolved load, and nutrient input may respond jointly to hydrological conditions, especially under greater connectivity among agricultural areas, exposed soils, hillslopes, floodplains, and the drainage network.

The seasonal distribution reinforced these differences between the two management units. The boxplots showed higher medians and greater dispersion during the rainy season, especially in UGRHI 21. In this unit, turbidity increased from approximately 20–30 NTU in the dry season to around 90–100 NTU in the rainy season, with maximum values exceeding 300 NTU. Total dissolved solids reached upper values close to 230–240 mg L^{-1} during the rainy season, while total phosphorus presented maximum values above 0.30 mg L^{-1}. Water temperature also showed a clear seasonal pattern in both UGRHIs, with medians around 21–23 °C in the dry season and approximately 26–28 °C in the rainy season. These results indicate that the rainy season intensifies hydrosedimentological and hydrochemical responses, particularly in UGRHI 21, where the wider interquartile ranges and higher maximum values suggest greater relative instability.

The PCA synthesized the patterns identified in the correlation matrices and seasonal boxplots. The first two principal components explained 54.6% of the total variance, with 32.8% attributed to PC1 and 21.8% to PC2. This result indicates that more than half of the multivariate variability of water quality can be interpreted through two main axes of organization. UGRHI 20 presented more concentrated samples in the multivariate space, suggesting comparatively more homogeneous behavior. In contrast, UGRHI 21 showed greater dispersion and stronger association with the vectors of electrical conductivity, total phosphorus, total dissolved solids, and turbidity, indicating greater environmental heterogeneity and stronger sensitivity to dissolved-load, nutrient-input, and material-transport processes.

Overall, the combined use of Spearman correlation, seasonal boxplots, and PCA proved suitable for interpreting environmental datasets marked by non-normality, temporal gaps, and extreme values. The numerical results show that UGRHI 20 is characterized by a stronger contrast between turbidity/phosphorus dynamics and nitrogen/conductivity dynamics, while UGRHI 21 presents greater integration among nutrients, dissolved ionic load, and hydrosedimentological processes. From a water resources management perspective, these findings highlight the need to strengthen continuous monitoring, especially in UGRHI 21, and to prioritize soil conservation practices, riparian vegetation protection, and drainage management to reduce the input of sediments, nutrients, and dissolved loads into fluvial systems.

1. Finally, future studies should deepen the integration between physicochemical water quality parameters, hydrological events, precipitation data, river discharge, and land-use dynamics. The incorporation of higher-frequency monitoring and event-based sampling may improve the identification of short-term responses during intense rainfall events. In this sense, the continuity of this research may contribute to a more integrated interpretation of the landscape, linking processes occurring on hillslopes, soils, anthropic land-use areas, floodplains, and fluvial channels.

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