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Uso de Mapeamento Espacial e Temporal como Ferramenta de Gestão da Qualidade da Água em um Reservatório Amazônico

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R E S U M O

Os reservatórios são estimadores para o equilíbrio ambiental. Os mapas de isotermas ajudam a visualizar mudanças na qualidade da água em reservatórios e são ferramentas úteis para monitorar parâmetros fisico-químicos. O objetivo deste trabalho foi avaliar a utilização de mapas geoestatísticos como ferramenta de gestão da qualidade da água utilizada na avaliação sazonal e temporal dos parâmetros: cloreto, condutividade elétrica, temperatura e sólidos totais dissolvidos na área da Usina Hidrelétrica de Tucuruí. Os dados foram avaliados em relação à estatística descritiva, ao teste e à garantia. Os mapas de isotermas foram desenvolvidos utilizando o software Surfer 13 para interpolar a distribuição espacial dos dados. A sazonalidade influenciou todos os parâmetros estudados, revelando-se um fator importante na alteração da qualidade da água. A pesquisa mostrou também que a qualidade da água do Rio Tocantins é influenciada pela agricultura, principal atividade humana na área de estudo. Os mapas geoestatísticos são importantes ferramentas de gestão da qualidade da água e podem ser utilizados em grandes áreas como reservatórios de hidrelétricas na Amazônia.
Palavras-chave: Usina Hidrelétrica; Monitoramento; Amazônia; Rio Tocantins.

Usage of Spatial and Temporal Mapping as a Water Quality Management Tool in an Amazon Reservoir

A B S T R A C T

Reservoirs are estimators for environmental balance. The isotherm maps help to visualize changes in water quality in reservoirs and are useful tools for monitoring physicochemical parameters. The objective of this work was to evaluate the use of geostatistical maps as a water quality management tool used in the seasonal and temporal evaluation of parameters: chloride, electrical conductivity, temperature, and total dissolved solids in the area of the Tucuruí hydroelectric power plant. The data were evaluated against descriptive statistics, the test, and the guarantee. The isotherm maps were developed using the Surfer 13 software to interpolate the spatial distribution of the data. Seasonality influenced all parameters studied, proving to be an important factor in changing water quality. The research also showed that the water quality of the Tocantins River is influenced by agriculture, the main human activity in the study area. The geostatistical maps are important water quality management tools and can be used in large areas such as hydroelectric reservoirs in the Amazon.
Keywords: Hydroelectric Power Plant; Monitoring; Amazon; Tocantins River.

Introduction

In order to evaluate the quality of water in rivers and reservoirs, quality standards are used, which define the concentration limits to which each substance present in the water must comply. Investigating their quality contributes to the prevention of pollution and, consequently, public health, in addition to the biological integrity of water bodies (Sun et al., 2022; Cao et al., 2023).

Water quality is a determining factor for human health and the environment, which depends on several natural factors that determine it, such as erosion processes and also anthropogenic interference (Kazi et al., 2009). Investigating its quality contributes to the prevention of pollution and consequently public health and also to the biological integrity of water bodies (Şener et al., 2017).

According to Madyouni et al. (2023), Zhang et al. (2024) and Chen et al. (2022), the complexity of determining water quality factors, and a large number of variables used to describe the status of water bodies in quantitative terms, lead to difficulties in obtaining a simple definition of water quality.

The chemical and physicochemical parameters of water bodies determine their usefulness and the status of aquatic ecosystems. Several studies have been carried out, which aimed to evaluate the influence of chemical and physicochemical parameters on the biotic community of rivers, lakes, and dams (Da Costa et al., 2020; Gobeze et al., 2023). Cudowski et al. (2015), in their work, investigated the effects of physical and chemical parameters of water on the abundance and diversity of aquatic fungi species in the Augustow Canal, located in northeastern Poland.

The balance of freshwater hydrological ecosystems is closely related to the natural Spatio-temporal flow regime, but most of them have undergone significant changes in recent years. For the monitoring and investigation of impacts on water bodies, Spatio-temporal variations in biological aspects and in natural chemical processes must be considered, as well as the hydrological cycle, mainly because it directly affects the drainage system of water bodies and causes surface runoff along river banks (Wang et al., 2024).

The importance of studying seasonality is an important step towards a better understanding of the physicochemical and biological characteristics of a water body, as it has direct effects on water quality variables, such as the concentration of dissolved organic matter in the surface water body of a river, influenced by climate change and seasonality reported in the research by Awad et al. (2017), in addition to other anthropogenic factors and peculiar natural processes. According to Álvarez-Cabria and Peñas (2016), some studies only consider information from one season (e.g., summer), losing the temporal variability of the various characteristics of water quality, which makes it difficult to understand the characteristics due to the lack of spatial and seasonal information.

The hydrological process is the driver of the ecological function and biodiversity in the plains of watercourses. Shallow lakes with medium and large rivers occupy large areas of tropical floodplains, where, in these environments, the hydrological cycle of the main river is the determining factor of the ecosystem function and also in the balance of biodiversity (Silva et al., 2013).

The water resources of the Amazon are recognized as an invaluable asset to the planet and their preservation represents a major challenge for Brazilian control agencies. Despite the great importance of water resources in the region, some are suffering deterioration in their quality, especially those located close to areas where activities such as agriculture, mining, industrial and urbanization expansion are developed. Added to this picture is the increase in population, deforestation, the opening of roads, and the construction of hydroelectric plants, which results in the increasing degradation of the region's water resources (El-Rawy et al., 2023; Asif et al., 2023).

The uses of water currently verified in the reservoirs of the Amazon are diversified, not only being used for irrigation and human consumption. The primary use concerns the generation of electricity which, despite not being a consumptive use, practically conditions the other uses, both upstream and downstream of the reservoirs (Castro-Diaz et al., 2024).

The option to generate energy through the construction of hydroelectric dams is a matter of concern, because, despite bringing benefits, they also generate many negative socio-economic and ecological impacts caused by dams in the Brazilian Amazon, which have already been observed in the plants, such as Balbina on the Uatumã River-AM, Tucuruí on the Tocantins River-PA and Samuel on the Jamari River-RO which cause enormous social and environmental impacts, causing changes to the water system despite being renewable (Arantes et al. 2023).

To assess the vulnerability of surface and groundwater resources to human actions and natural conditions, several methods have been used to identify the factors and mechanisms that are precursors to changes in water quality, such as multivariate statistical analysis, geostatistical techniques, etc. (Belkhiri & Narany, 2015). Currently, the use of geostatistical methods is found in several areas, such as soil science (Zawadzki et al., 2024), hydrology (Cigagna et al., 2015), and environmental sciences (Panagiotou et al., 2024; Oseke et al., 2021). It is understood as the set of methods that aim to estimate values of an attribute that are correlated in time and/or space (Koppe et al., 2006; Raman et al., 2023).

Geostatistical techniques can be used to describe and model spatial patterns (variography), predict values at unsampled locations (kriging), in order to obtain the uncertainty associated with an estimated value at unsampled locations (kriging variance), and improve sampling meshes (Rahman & Habiba, 2023).

The study of instruments that facilitate the management of water quality in Amazonian reservoirs is of great environmental importance for the region.

On the Tocantins River, in the State of Pará, the Tucuruí Hydroelectric Power Plant (HPP) was installed in the 1980s, with a generation capacity of 8,370 MW and a reservoir of 2,850 km² in area. In the area of the Tucuruí, navigation, fishing, use for recreation and domestic sewage dilution stand out (Godoy et al., 2022; Vieira Valadão et al., 2023).

This study aimed to characterize and evaluate the spatial and temporal patterns of water quality in the Tucuruí Hydroelectric Power Plant using isoteor maps in the seasonal assessment of water quality parameters.

Material and methods

The analytical procedures adopted in this work followed the criteria recommended by the Standard Methods (APHA, AWWA, WEF, 2017).

The sampling program was supported by the Environmental Protection Center (CPA) of Eletronorte Tucuruí HPP, based on the historical monitoring adopted. The collection was carried out with the help of speedboats along the study area, as shown in Figure 1.

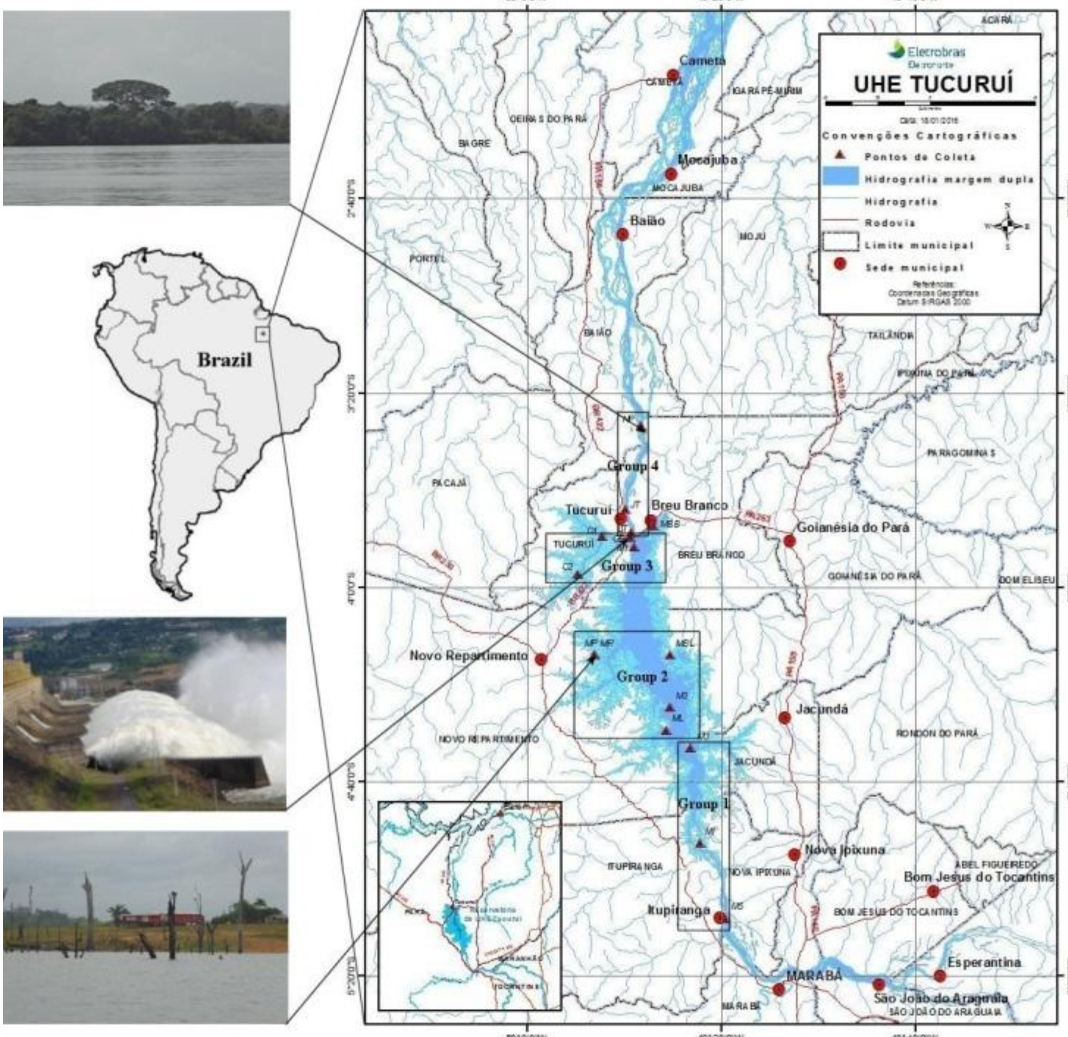

Figure 1. Map of location of the sampling stations in the Tucuruí HPP area.

Sixteen collection stations were selected and divided into four groups, group 1 - upstream Tucuruí HPP was formed by the stations at the entrance of the reservoir: M5 (Montante 5 - near the city of Itupiranga), MI (Montante Ipixuna - near the city of Ipixuna), MJ (Montante Jacundá - near the city of Jacundá); group 2 upstream Tucuruí HPP in central body of the reservoir: ML (Montante Lontra), M3 (Montante 3), MP (Montante Pucuruí), MBL (Montante Belauto), MR (Montante Repartimento - near the city of Novo Repartimento); group 3 upstream Tucuruí HPP, stations near Tucuruí HPP: C1 (Caraipé 1 - near the city of Tucuruí), C2 (Cararipé 2 - near the city of Tucuruí), M1 (Montante 1 - near the city of Tucuruí), MBB (Montante Breu Branco - near the city of Breu Branco); group 4 stations downstream of the Tucuruí HPP: CF (Canal de Fuga - near the city of Tucuruí), LT (Linha de Transmissão - near the city of Tucuruí), JT (Jusante Tucuruí - near the city of Tucuruí), NP (Nazaré dos Patos - near the city of Nazaré dos Patos). The collection stations were georeferenced through a global positioning system (GPS).

The collection and *in situ* measurements were carried out in four seasonal periods: a period of greater rainfall in the Amazon region (Wet Season - March), an intermediate period between the wet season and the dry season (Intermediate Season I - June), period of lower rainfall (Dry Season - August), the intermediate period between the dry season and the wet season (Intermediate Season II - October).

Surface water collections for Cl^- analysis were performed using a 5-liter vertical Hale bottle, and placed in 1-liter polyethylene bottles, previously decontaminated with a 10% nitric acid solution, washed with distilled water, dried, labeled, and washed with water from the collection station (ambient). For the packaging of the samples, an expanded polystyrene (EPS) box containing ice gel was used, to maintain a temperature of approximately 4 ºC for transport.

EC, Temperature, and Total Dissolved Solids

(TDS) analyzes were performed in situ, using a multiparameter probe (Hanna brand model HI98194), Cl^- was determined by electrometric method according to Standard Methods (APHA, 2017).

For the development of the geostatistical maps, an image converted to the RGB format (Red, Green, Blue) from the Landsat-8 satellite, OLI sensor with 0% cloud visibility of the area under study, were used, obtained from the image gallery available on the website. from INPE (National Institute for Space Research, 2024).

The results matrix of the evaluated parameters, together with the coordinates of each collection station, was used to perform the overlaps and interpolations using the georeferencing tool of the QGIS 16.2 software. Data were submitted to the kriging interpolation method in Surfer 13.0 software.

The geostatistical maps were generated using the grids generated from the results matrix and a color ramp that shows the intensities of the evaluated parameters. Each contour map was prepared through digitalization (cutting) concerning the area that comprises the entire study site, from the satellite image. The geostatistical maps clipped in the option (blank) were superimposed (Map Overlays) on the previously georeferenced satellite image. The last step consisted of characterizing the generated maps.

Results and Discussion

In natural waters, chloride (Cl^-) indices come from soils and rocks where it is widely distributed in nature in the form of sodium, potassium, and calcium salts due to weathering. Inland natural waters have low Cl^- with concentrations many times lower than those of carbonates and sulfates. Although it may be phytotoxic to some plants, agricultural uses of water with Cl^- concentrations lower than 100 $mg.L^{-1}$ do not, in principle, harm irrigated crops. However, high concentrations of Cl^- prevent the use of water for agriculture and require adequate treatment for industrial uses, as well as causing damage to metallic structures (Bhateria & Jain, 2016).

High concentrations of Cl^- in natural fresh waters may be associated with the input of industrial effluents, agricultural exploitation, and sewage pollution due to the excretion of Cl^- in the urine, especially in regions close to cities, contributing to the increase of the ion in the waters. surface and underground. The evaluation of the concentration of Cl^- present in the water is extremely important, due to the high concentrations of Cl^- being harmful to aquatic organisms, which can increase the mobility of metals and other bioactive compounds, and accelerate the corrosion processes in steel and aluminum pipes, in addition to changing the taste of the water (Edwards et al., 2023).

Cl^- concentrations in the studied dam were, in all stations evaluated, below the limit established by CONAMA (2005) Resolution 357/2005 (250 $mg.L^{-1}$), with a minimum of 0.80 $mg.L^{-1}$ in the MBB station (Montante Breu Branco) in the dry season, and a maximum of 2.02 $mg.L^{-1}$ in the MP station (Montante Pucuruí) in the Intermediate Season II (dry-wet seasons), with a general average of 1.17±0.26 $mg.L^{-1}$ (Table 1). The Cl^- concentration range in the region varied from 0.36 $mg.L^{-1}$ in Pará River to 2.82 $mg.L^{-1}$ in Tocantins River, values consistent with those found in this work (Bomfim et al., 2023).

Seasonality is an extremely important factor having direct effects on the results of the parameters studied. The effect of seasonality on the parameters was evaluated through the single-factor ANOVA calculation, where it was shown that the variation in Cl^- concentration was highly dependent on seasonality ($F_{calculated} = 12.8 > F_{critical} = 2.76$; p = 0.000).

The variability of the results for Cl^- and other parameters was studied through the Box Plot (Figure 2), where it was possible to observe that the greatest variability (larger box size) of the Cl^- parameter was obtained in the Intermediate Season II, with an anomalous result found in the Intermediate Season I for the MR collection station (1.79 $mg.L^{-1}$).

It can be assumed that the source of Cl^- in these waters is being influenced by the same source, however, it is difficult to say with certainty the source and the dimensions of the contributions of these sources, which can be the dissolution of minerals, contribution by non-point sources of pollution, etc.

In the geostatistical maps of Cl^- (Figure 3), the collection stations that most contributed to the concentration of the parameter in the waters of Tucuruí were MP, MR, C1, and C2. The MP and MR stations, which are part of group 2, in the central body of the reservoir, are located near the city of Novo Repartimento and may be receiving Cl^- contributions from the agricultural exploration and domestic sewage sites, mainly in the Intermediate Season I.

Table 1. Descriptive statistics of the parameters evaluated at Tucuruí HPP.
Legend: Cl^-: Chloride; EC: Electrical Conductivity; Temp.: Temperature; TDS: Total Dissolved Solids.

	Cl^- ($mg.L^{-1}$)	**EC ($\mu S.cm^{-1}$)**	**Temp. (ºC)**	**TDS ($mg.L^{-1}$)**
Wet Season				
Mean	1.12	45.6	29.3	20.1
Median	1.07	42.2	29.0	19.0
Standard deviation	0.15	11.0	0.97	4.46
Minimum	0.92	37.3	28.1	15.7
Maximum	1.42	80.6	31.3	34.1
Intermediate Season I				
Mean	1.13	40.3	30.7	16.8
Median	1.11	40.1	30.5	16.8
Standard deviation	0.22	2.47	0.73	0.89
Minimum	0.85	34.5	29.9	14.5
Maximum	1.79	45.3	32.5	18.6
Dry Season				
Mean	0.984	44.3	30.0	18.7
Median	0.940	43.3	29.9	18.4
Standard deviation	0.129	3.02	0.81	1.20
Minimum	0.800	41.3	28.8	17.2
Maximum	1.250	52.2	31.6	21.7
Intermediate Season II				
Mean	1.43	46.5	30.1	48.5
Median	1.35	45.0	30.0	47.0
Standard deviation	0.29	4.19	0.38	5.03
Minimum	1.01	42.2	29.4	44.0
Maximum	2.02	56.7	30.8	62.0

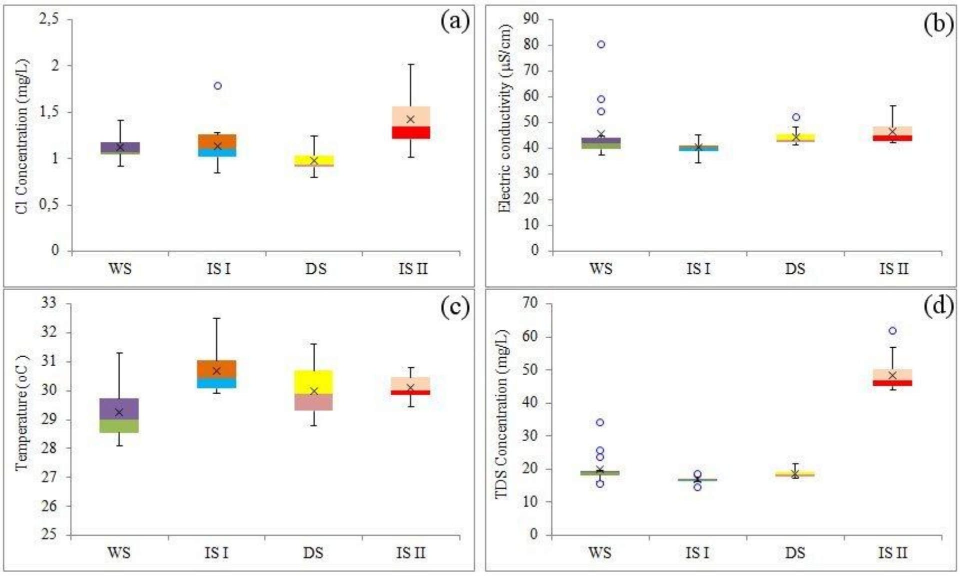

Figure 2. Variability of the results.
(a) Cl-; (b) Electric Conductivity; (c) Temperature; (d) TDS. WS: Wet Season; IS I: Intermediate Season I; DS: Dry Season; IS II: Intermediate Season II.

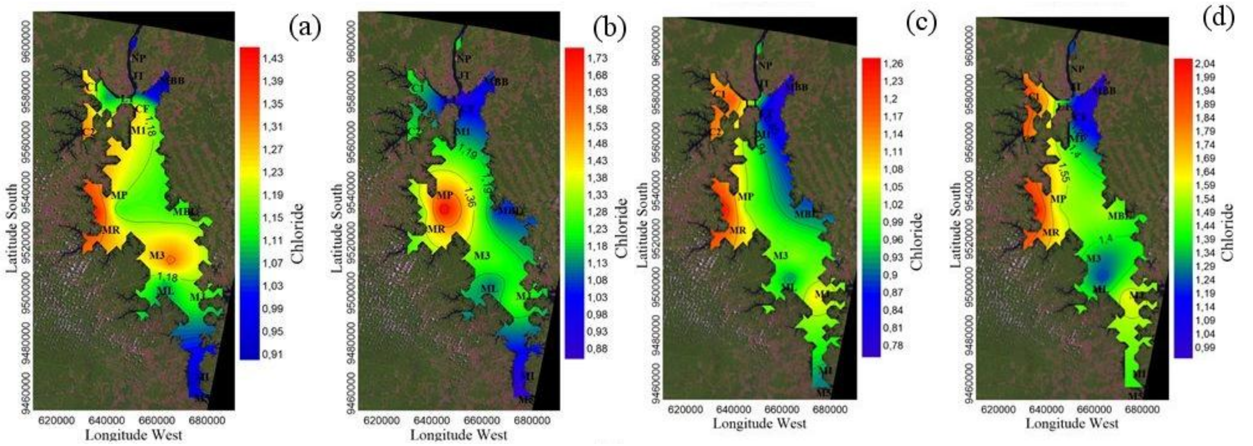

Figure 3. Chloride geostatistical map.
(a) Wet Season; (b) Intermediate Season I; (c) Dry Season; (d) Intermediate Season II.

At stations C1 and C2 (Caraipé) that are part of group 3 located near the city of Tucuruí and close to the Tucuruí HPP, due to the concentrations being far below the established limit, it may indicate the absence of contamination by anthropic sources throughout the dam, although it has greater influence in these areas.

The electric conductivity (EC) parameter is related to the presence of dissolved ions in the water, which are electrically charged particles, it does not specifically determine which ions are present in a given water sample, but it can contribute to the possible recognition of environmental changes that occur by releases industrial waste, mining, and sewage. The greater the number of dissolved ions, the greater the EC of the water. The ions directly responsible for the EC values are, among others, calcium, magnesium, potassium, sodium, carbonates, sulfates, and chlorides. For tropical regions, EC values in water bodies are closely linked with local geochemical characteristics, seasonality (dry and wet season), and less with the trophic state (Do Nascimento Monte et al., 2021; Vargas-Tierras et al., 2024).

The mean EC found in this work was 44.2±6.52 $\mu S.cm^{-1}$ with values ranging from 34.5

µS.cm^{-1} to 80.6 µS.cm^{-1} (highest value) found at the station of collection CF (escape channel) near the spillway of Tucuruí HPP in the wet season. Due to the increase in the flow of the Tocantins River at the time of greatest rainfall in the region, the spillway is open and violent turbulence occurs, which may be responsible for the increase in EC at this collection station.

The values found in this work are in agreement with those found by other authors, where the EC ranged from 17.0 µS.cm^{-1} in Negro River to 97.5 µS.cm^{-1} in Peixe-Boi River (Santos et al., 2020).

It was possible to verify the influence of seasonality on EC ($F_{calculated} = 3.17 > F_{critical} = 2.76$; $p = 0.031$) for the seasons evaluated. The greatest variability of the results occurred in the wet season, with three anomalous results in the sampling stations C2 (54.4 µS.cm^{-1}), MBB (59.2 µS.cm^{-1}) and CF (80.6 µS.cm^{-1}), and in the dry season with an anomalous result at the MP collection station (52.2 µS.cm^{-1}), as may be seen in the Figure 2.

In the evaluation of the geostatistical maps of the EC (Figure 4), for the wet season, higher values were observed in the eastern portion of the dam where the municipality of Breu Branco is located on the banks of the dam. Cintra et al. (2013) infer that greater rainfall contributes to the increase in EC in the region. A greater variation in this region may be related to agricultural activities, in addition to having a contributing factor, related to the local geochemical characteristics, framed in the central portion, between the municipalities of Tucuruí and Itupiranga, whose soils are characterized by red-yellow podzolic or red-yellow latosol, particularly on the right margin.

For the Intermediate Season I, this parameter is evenly distributed over a large part of the dam, with a higher EC in the central-west region along the lake shores. This higher concentration is also verified in this region for the dry season and the intermediate II shown in their geostatistical maps. The water bodies located on the shores of the lake receive an entire load of organic and inorganic nutrients from the soil that are swept away by rainwater and incorporated into the river, contributing greatly to the increase in TDS, turbidity, and consequently EC values.

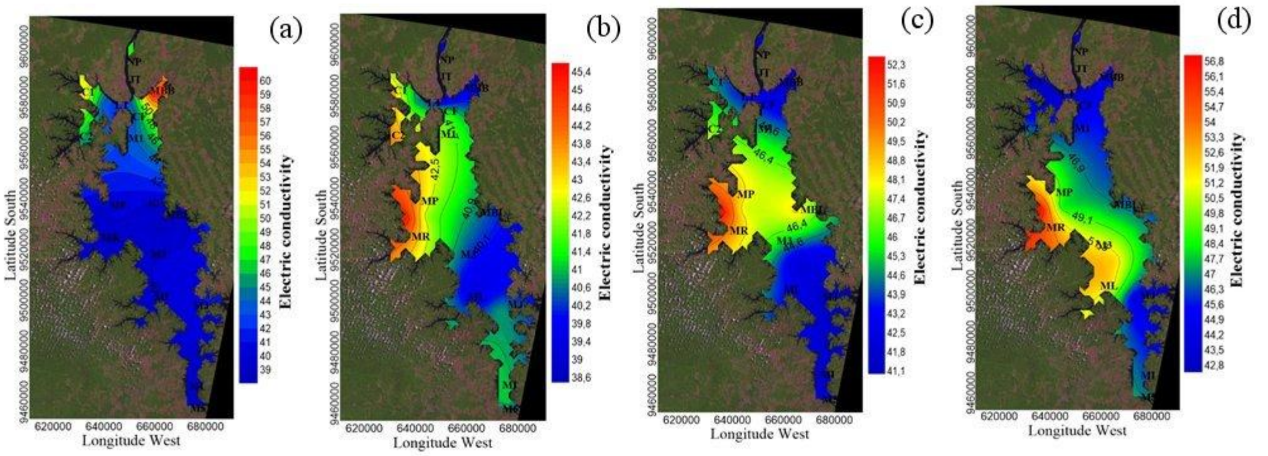

Figure 4. Geostatistical map of electrical conductivity.
(a): Wet Season; (b): Intermediate Season I; (c): Dry Season; (d): Intermediate Season II.

Temperature is an extremely important variable in water resources since it determines the dynamics in the hydrological cycle through the process of evaporation of water masses in the system, where an imbalance can affect other parameters such as dissolved oxygen. Temperature causes changes in the viscosity and density of the water, which consequently causes changes in the sedimentation rate. The rise in temperature causes an increase in the transfer of gases to the atmosphere and causes a decrease in the solubility of gases in water (Woolway et al., 2020; Zhang et al., 2023).

The metabolic processes of aquatic species depend on the temperature of the environment in which they live, as they enable good reproduction during the spawning season and perpetuation of the newly adapted species that inhabit there, in addition to guaranteeing the subsistence of communities that live near the lake (Cintra et al., 2013).

Temperature can influence almost all physical, chemical, and biological parameters. Microorganisms decompose organic matter faster at 30 °C than at 25 °C, the rate of most processes that affect water and soil quality doubles with every 10 °C increase in temperature (Li et al., 2020). The rise in temperature causes an increase in the concentration of free ammonia. For fish, ammonia releases volatile toxic substances and increases the reaction speed of aerobic and anaerobic chemical and biochemical processes, and increases the metabolic activity of aquatic organisms (Chamoli et al., 2024).

The average water temperature in the Tucuruí HPP area was 30.01±0.90 °C, ranging from 28.10 °C in the wet season to 32.50 °C in the Intermediate Season I at the MR collection station. These results are in agreement with other temperature assessment studies in the region, ranging from 26.8 °C in Peixe-Boi River (Santos et al., 2020) to 30.5 °C in Tocantins River (Santos et al., 2019).

Seasonality influenced the water temperature in the study region ($F_{calculated} = 9.55 > F_{critical} = 2.76$; $p = 0.000$) with greater variability in the results in the dry season and without anomalous results (Figure 2).

According to the geostatistical temperature maps (Figure 5) verified in the four evaluated seasons, coherent temperatures were recorded relative to the seasons, which were measured, recording variations along the entire dam. For the wet season, the highest temperatures were located in the center and south-central part of the dam. The values of lower thermal indexes were located in the northern portion where the dam is located, the municipalities of Tucuruí and Breu Branco in addition to the southwest region of the lake.

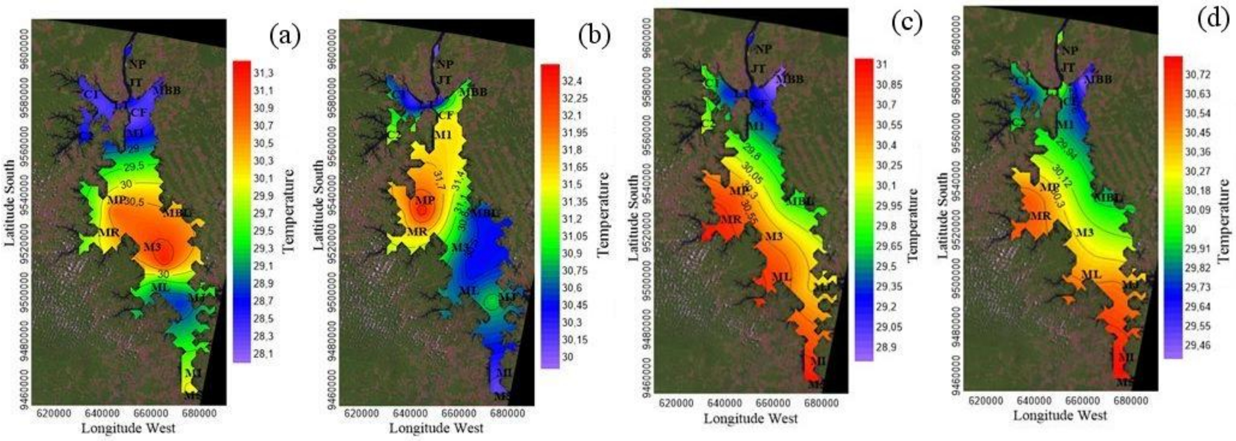

Figure 5. Geostatistical temperature map.
(a) Wet Season; (b) Intermediate Season I; (c) Dry Season; (d) Intermediate Season II.

In the Intermediate Season I, an increase in temperature values were observed to the north, in the eastern portion further north of the dam. In the south and center-west, there was a decrease in temperature, and higher values were verified in the central-west region.

For the thermal behavior verified in the geostatistical maps of the dry season and of the intermediate II, both showed similarities in the temperature dispersion in the upstream dam with the highest temperatures.

Temperature showed a positive (Pearson) correlation with Cl^- ($r = 0.659$, $p = 0.005$) and with EC ($r = 0.594$, $p = 0.015$) in the Intermediate Season I. This correlation can be observed in similar geostatistical maps and proves the influence of temperature on these parameters in this season.

The change in temperature observed in this work may have been influenced by the El Niño phenomenon, which occurred during the collection season (2015 to 2016), which according to NOAA (National Oceanic and Atmospheric Administration) is when there is abnormal heating of the surface waters of the oceans, causing a decrease in temperatures. rainfall and increase in temperature and consequently greater evaporation of surface water from rivers, thus affecting some parameters of water quality. According to Cintra et al. (2013), due to the proximity of the Amazon to the equator, the temperature shows a regularity in relation to the values found in rivers in the region.

According to the geostatistical maps for the TDS, shown in Figure 6, the largest TDS were located at different points in each season, where, in the wet season, the region of the MBB point was the place with the highest TDS found. In the Intermediate Season I, the central-west region and points C1 and C2, were the ones that obtained the highest TDS.

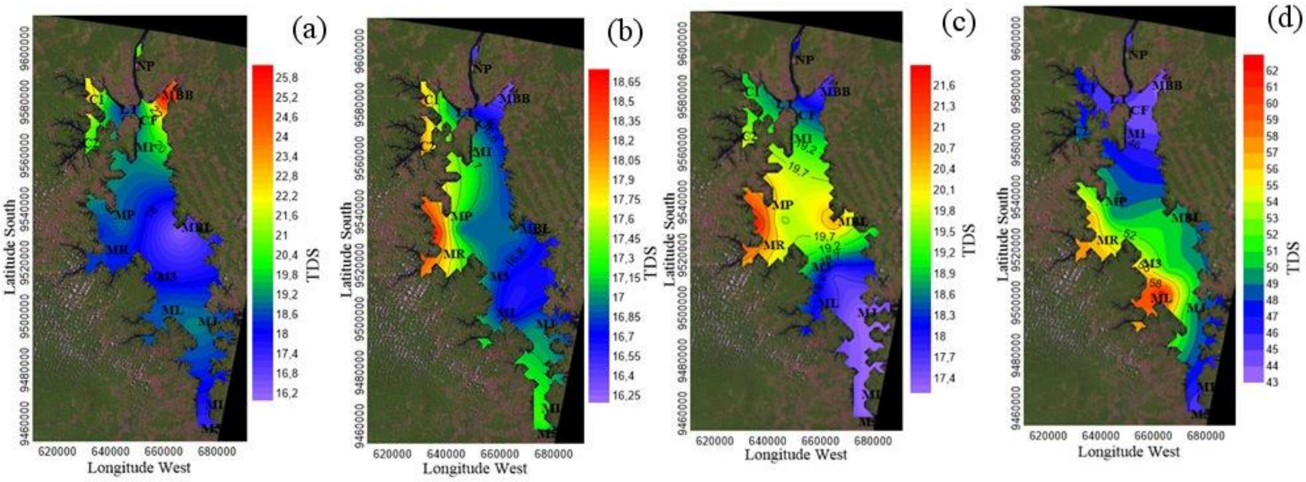

Figure 6. Geostatistical. TDS Geostatistical Map.
(a) Wet Season; (b) Intermediate Season I; (c) Dry Season; (d) Intermediate Season II.

The increase in TDS concentration for the wet season at the MBB collection station in front of the municipality of Breu Branco, to the right of the Tucuruí dam, may have been caused by the higher rainfall, favoring greater surface runoff, by the increase in organic and inorganic substances carried to this point of the dam, due to domestic discharges, agricultural activities, and the water retention time in these regions, which is usually longer, compared to other areas of the dam in addition to other point sources.

In the Intermediate Season I, the TDS was higher in the area close to the city of Novo Repartimento, this increase may be related to the influence of human activities such as agriculture and livestock and the phenomena caused by floods such as soil erosion and deposition of organic matter, mainly in the Midwest portion.

In the dry season, also in the central-west region, the TDS remained superior to the other regions, extending to the center of the dam. This behavior can be explained by the existence of strong water currents in the old river channel that would be responsible for dragging the debris to the other regions.

In the Intermediate Season II, the high TDS in the ML collection station (Montante Lontra), belonging to group 2 in the central body of the reservoir, the western portion south of the dam, can be explained by the same factors justified for other regions being affected by seasonality with the increase in rainfall and flooding of the banks.

There was a strong relationship between the TDS and the EC, in which the distribution of both parameters in the geostatistical maps was similar. The excellent positive correlation between TDS and EC was also confirmed in studies of Pearson's correlation for the following seasons: wet ($r = 0.990$; $p = 0.000$), Intermediate I ($r = 0.965$; $p = 0.000$), Dry ($r = 0.970$; $p = 0.000$) and Intermediate II ($r = 0.793$; $p = 0.000$).

Conclusions

The present study revealed that seasonal variations in the Tucuruí dam directly contribute to the water quality standards of the hydroelectric reservoir, and linked to this, the spatial heterogeneity left as a consequence of the construction of the hydroelectric plant, intensifies, even more, and the changes in the environment. All parameters evaluated presented values by Brazilian legislation.

The use of geostatistical maps as a management tool in the monitoring of large areas was presented as a valuable resource and a tool that provided practical assessments in highly complex environmental research, providing support for better interpretation of results, reduction of logistical costs for field analysis and supporting monitoring and planning in decision making and future research.

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References

Álvarez-Cabria, M.; Barquín, J.; Peñas, F. J., 2016. Modelling the spatial and seasonal variability of water quality for entire river networks: Relationships with natural and anthropogenic factors. Science of The Total Environment, 545-546, 152-162. https://doi.org/10.1016/j.scitotenv.2015.12.109

APHA - American Public Health Association; AWWA - American Water Works Association; WEF - Water Environment Federation. Standard Methods for the Examination of Water and Wastewater (23th edition). American Public Health Association: Washington DC, 4-77, 2017

Arantes, C. C., Laufer, J., Mayer, A., Moran, E. F., Sant' Anna, I. R. A., Dutka-Gianelli, J., Lopez, M. C., & Doria, C. R. C. , 2023. Large-scale hydropower impacts and adaptation strategies on rural communities in the Amazonian floodplain of the Madeira River. Journal of Environmental Management, 336, 117240. https://doi.org/10.1016/j.jenvman.2023.117240

Asif, Z., Chen, Z., Sadiq, R., & Zhu, Y., 2023. Climate Change Impacts on Water Resources and Sustainable Water Management Strategies in North America. Water Resources Management, 37(6-7), 2771-2786. https://doi.org/10.1007/s11269-023-03474-4

Awad, J.; Van Leeuwen, J.; Chow, C. W. K.; Smernik, R. J.; Anderson, S .J.; Cox, J. W., 2017. Seasonal variation in the nature of DOM in a river and drinking water reservoir of a closed catchment. Environmental Pollution, 220, 788-796. https://doi.org/10.1016/j.envpol.2016.10.054

Belkhiri, L.; Narany, T. S., 2015. Using multivariate statistical analysis, geostatistical techniques and structural equation modeling to identify spatial variability of groundwater quality. Water Resources Management, 29, 2073–2089. https://doi.org/10.1007/s11269-015-0929-7 29, 2073-2089

Bhateria, R., & Jain, D., 2016. Water quality assessment of lake water: a review. Sustainable Water Resources Management, 2(2), 161-173. https://doi.org/10.1007/s40899-015-0014-7

Bomfim, F. F., Deosti, S., Louback-Franco, N., Sousa, R. L. M., & Michelan, T. S., 2023. How are zooplankton's functional guilds influenced by land use in Amazon streams? PLOS ONE, 18(8), e0288385. https://doi.org/10.1371/journal.pone.0288385

Cao, Q., Yu, G., & Qiao, Z., 2023. Application and recent progress of inland water monitoring using remote sensing techniques. Environmental Monitoring and Assessment, 195(1), 125. https://doi.org/10.1007/s10661-022-10690-9

Castro-Diaz, L., Lopez, M. C., Moore, S., Radonic, L., Hodbod, J., & Moran, E., 2024. Multidimensional and multitemporal energy injustices: Exploring the downstream impacts of the Belo Monte hydropower dam in the Amazon. Energy Research & Social Science, 113, 103568. https://doi.org/10.1016/j.erss.2024.103568

Chamoli, A., Bhambri, A., Karn, S. K., & Raj, V., 2024. Ammonia, nitrite transformations and their fixation by different biological and chemical agents. Chemistry and Ecology, 40(2), 166-199. https://doi.org/10.1080/02757540.2023.2300780

Chen, X., Wang, Y., Sun, T., Chen, Y., Zhang, M., & Ye, C., 2022. Evaluation and prediction of water quality in the dammed estuaries and rivers of Taihu Lake. Environmental Science and Pollution Research, 29(9), 12832-12844. https://doi.org/10.1007/s11356-020-12063-6

Cigagna, C.; Bonotto, D. M.; Sturaro, J. R.; Camargo, A. F. M. 2015 Técnicas geoestatísticas aplicadas ao mapeamento de variáveis limnológicas e quantificação da incerteza associada às estimativas. Acta Limnologica Brasiliensia, 27(4), 421-430. https://doi.org/10.1590/S2179-975X3315

Cintra, I. H. A.; Flexa, C. E.; Silva, M. B.; Araújo,M. V. L. F.; Silva, K. C. A., 2013. Fishing in reservoir of the Tucuruí hydroelectric power station, Amazon region, Brazil: biological aspects, social, economic and environmental. Acta of Fisheries and Aquatic Resources, 1(1), 57-78.

CONAMA - National Environmental Council. Resolution CONAMA 357/2005. Available in http://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=450. Accessed in April 2024.

Cudowski, A.; Pietryczuk, A.; Hauschild, T., 2015. Aquatic fungi in relation to the physical and chemical parameters of water quality in the Augustow Canal. Fungal Ecology, 13, 193-204. https://doi.org/10.1016/j.funeco.2014.10.002

da Costa, H. C., Pereira, S. de F. P., Santos, L. P., de Oliveira, A. F. S., e Silva, T. de M., e Silva, C. S., Rocha, R. M., Freitas, K. H. G., Santos, D. C. dos, & Cruz, E. S., 2020. Chemometrics Applied in the Development of a Water Quality Indicator System for the Brazilian Amazon. ACS Omega, 5(51), 32899-32906. https://doi.org/10.1021/acsomega.0c03430

do Nascimento Monte, C., Correa Saldanha, E., Costa, I., Shinaigger Rocha do Nascimento, T., Santos Pereira, M., Farias Batista, L., & Costa Pinheiro, D., 2021. The physical-chemical characteristics of surface waters in the management of quality in clearwater rivers in the Brazilian Amazon. Water Policy, 23(5), 1303-1313. https://doi.org/10.2166/wp.2021.258

Edwards, M., Arnold, R., Rosenfeldt, B., Masters, S. v., Parks, J., & Tang, M., 2023. Utility considerations in developing a galvanized iron water pipe management plan. AWWA Water Science, 5(4). https://doi.org/10.1002/aws2.1350

El-Rawy, M., Batelaan, O., Al-Arifi, N., Alotaibi, A., Abdalla, F., & Gabr, M., 2023. Climate Change Impacts on Water Resources in Arid and Semi-Arid Regions: A Case Study in Saudi Arabia. Water, 15(3), 606. https://doi.org/10.3390/w15030606

Gobeze, A., Kaba, T., Tefera, M., Lijalem, T., Legesse, M., Engdaw, F., Mulu, M., Wubet, W., Adugna, A., & Guadie, A., 2023. Evaluation of water quality of Angereb reservoir: a chemometrics approach. Applied Water Science, 13(4), 103. https://doi.org/10.1007/s13201-023-01909-2

Godoy, B. S., Ishihara, J. H., Aguiar, R. L., & Teixeira, O. N., 2023. 50 years of the water-flow variance in Tucuruí reservoir related with Brazilian energy consumption. Heliyon, 9(2), e12640. https://doi.org/10.1016/j.heliyon.2022.e12640

INPE - National Institute for Space Research. Available in https://www.gov.br/inpe/pt-br. Accessed in February 2024.

Kazi, T. G.; Arain, M. B.; Jamali, M. K.; Jalbani, N.; Afridi, H. I.; Sarfraz, R. A.; Baig,J. A.; Shah, Abdul Q., 2009. Assessment of water quality of polluted lake using multivariate statistical techniques: A case study. Ecotoxicology and Environmental Safety, 72(2), 301-309. https://doi.org/10.1016/j.ecoenv.2008.02.024

Koppe, V. C.; Costa, J. F. C. L.; Koppe, J. C., 2006. Coordenadas cartesianas x coordenadas geológicas em geoestatística: Aplicação à variável vagarosidade obtida por perfilagem acústica. R. Esc. Minas, 59(1), 25-30. https://doi.org/10.1590/S0370-44672006000100004

Li, J., Nie, M., Pendall, E., Reich, P. B., Pei, J., Noh, N. J., Zhu, T., Li, B., & Fang, C., 2020. Biogeographic variation in temperature sensitivity of decomposition in forest soils. Global Change Biology, 26(3), 1873-1885. https://doi.org/10.1111/gcb.14838

Madyouni, H., Almanza, V., Benabdallah, S., Joaquim-Justo, C., Romdhane, M. S., Habaieb, H., & Deliege, J.-F., 2023. Assessment of Water Quality Variations and Trophic State of the Joumine Reservoir (Tunisia) by Multivariate Analysis. Water, 15(17), 3019. https://doi.org/10.3390/w15173019

Oseke, F. I.; Anornu, G. K.; Adjei, K. A.; Eduvie, M. O., 2021. Assessment of water quality using GIS techniques and water quality index in reservoirs affected by water diversion, Water-Energy Nexus, 4, 25-34. https://doi.org/10.1016/j.wen.2020.12.002

Panagiotou, C. F.; Chekirbane, A.; Eliades, M.; Papoutsa, C.; Akylas, E.; Stylianou, M.; Stathopoulos, N., 2024. Assessing the groundwater quality of El Fahs aquifer (NE Tunisia) using multivariate statistical techniques and geostatistical modeling. Appl Water Sci 14, 170. https://doi.org/10.1007/s13201-024-02233-z

Rahman, Md. A., & Habiba, U., 2023. Groundwater quality evaluation and pollution source apportionment using multivariate statistical analyses in Chuadanga municipality, Bangladesh. HydroResearch, 6, 166-176. https://doi.org/10.1016/j.hydres.2023.05.001

Raman, R. K., Bhor, M., Manna, R. K., Samanta, S., & Das, B. K., 2023. Statistical and geostatistical modelling approach for spatio-temporal assessment of river water quality: a case study from lower stretch of River Ganga. Environment, Development and Sustainability, 25(9), 9963-9989. https://doi.org/10.1007/s10668-022-02472-7

Santos, D. C.; Pereira, S. F. P.; Oliveira, A. F. S.; Silva, T. M. E.; Silva, C. S.; Rocha, R. M.; Freitas, K. H.; Santos, L. P., 2019. Distribution of chemical parameters in the water of the Tucuruí Reservoir, Amazon Region - Brazil: influence of seasonality and depth of water column. Exatas Online, 10(2), 71-82.

Santos, L. P.; Pereira, S. F. P.; Souza Junior, P. M.; Silva, C. S., 2020. Avaliação da qualidade da água na Amazônia brasileira: estudo de caso na bacia do rio Peixe-Boi-PA. Revista Sodebrás, 15(180), 69-75.

Şener, Ş.; Şener, E.; Davraz, A., 2017. Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Science of The Total Environment, 584–585, 131-144, https://doi.org/10.1016/j.scitotenv.2017.01.102

Silva, M. T.; Pereira, J. O.; Vieira, L. J. S.; Petry, A. C., 2013..Hydrological seasonality of the river affecting fish community structure of oxbow lakes: A limnological approach on the Amapá Lake, southwestern Amazon. Limnologica, 43(2), 79-90. https://doi.org/10.1016/j.limno.2012.05.002.

Sun, X., Zhang, Y., Shi, K., Zhang, Y., Li, N., Wang, W., Huang, X., & Qin, B., 2022. Monitoring water quality using proximal remote sensing technology. Science of The Total Environment, 803, 149805. https://doi.org/10.1016/j.scitotenv.2021.149805

Vargas-Tierras, T., Jiménez-Gutiérrez, M., Pastrano, S., Chávez, G., Morales-León, V., Morales-León, M., Paredes, F., & Vásquez-Castillo, W., 2024. Changes in Surface Water Quality of the El Salvador River in La Joya de los Sachas, Ecuadorian Amazon Region. Water, 16(9), 1259. https://doi.org/10.3390/w16091259

Vieira Valadão, L., Fonseca, I. R. da, Cicerelli, R. E., Almeida, T. de, Garnier, J., & Sano, E. E., 2023. Temporal Dynamics of the Hydropower Water Reservoirs of the Tocantins-Araguaia Basin, Brazil, Based on Remote Sensing and Hydrometeorological Station Datasets. Water, 15(9), 1684. https://doi.org/10.3390/w15091684

Wang, Y.-B., Junaid, M., Deng, J.-Y., Tang, Q.-P., Luo, L., Xie, Z.-Y., & Pei, D.-S., 2024. Effects of land-use patterns on seasonal water quality at multiple spatial scales in the Jialing River, Chongqing, China. CATENA, 234, 107646. https://doi.org/10.1016/j.catena.2023.107646

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O’Reilly, C. M., & Sharma, S., 2020. Global lake responses to climate change. Nature Reviews Earth & Environment, 1(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Zawadzki, J.; Fabijańczyk, P.; Magiera, T., 2024.Using geostatistical methods in soil magnetometry: a review. J Soils Sediments, 24, 2040-2057. https://doi.org/10.1007/s11368-024-03784-z

Zhang, L., Zheng, Z., Xu, F., Zou, Y., Zeng, T., Li, S., & Fang, S., 2024. Analysis of water quality and trophic status of reservoirs in Chuzhou City, China. Ecohydrology, 17(3). https://doi.org/10.1002/eco.2629

Zhang, Y., An, C., Zheng, L., Liu, L., Zhang, W., Lu, C., & Zhang, Y., 2023. Assessment of lake area in response to climate change at varying elevations: A case study of Mt. Tianshan, Central Asia. Science of The Total Environment, 869, 161665. https://doi.org/10.1016/j.scitotenv.2023.161665