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Spatio-temporal variability of water quality and trophic state in a semi-arid basin of northeastern Brazil

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Abstract

Urban semi-arid rivers in developing regions remain understudied regarding water quality, a gap that is critical in the Brazilian semi-arid region, the most densely populated of its kind worldwide. This study evaluated the water quality of the Salgado River, northeastern Brazil, through five sampling campaigns conducted between 2023 and 2024 across rainy and dry hydrological periods. Eleven sites were monitored along the fluvial gradient, and the following parameters were analyzed: pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), turbidity, dissolved oxygen (DO), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), and thermotolerant coliforms (TC). pH remained near neutral (7.1 ± 0.3). Temperature was higher in the dry season (29.4 ± 3.1°C) than in the rainy season (27.6 ± 1.5°C). EC increased markedly during the dry period (722 ± 250 µS cm^{-1}), while turbidity was higher in the rainy season (108 ± 150 NTU). DO remained low in both periods (3.3–3.7 mg L^{-1}). BOD was elevated in the dry season (8.7 ± 9.2 mg L^{-1}). TN was higher in the dry period (5.27 ± 6.3 mg L^{-1}), whereas TP showed no significant seasonal variation (1.13–1.81 mg L^{-1}). TC levels were extremely high during the dry season (3.5×10^6 MPN 100 mL^{-1}). The Water Quality Index (WQI) classified the river as fair (39–45), with very poor conditions in urban stretches and relative improvement in rural areas. The Trophic State Index (TSI_{PT}) indicated eutrophic to hypereutrophic conditions (60–77), especially in urban sites. Overall, the Salgado River exhibits selective and seasonal degradation, with critical urban hotspots, partial self-purification reaches, and high eutrophication risk.

Highlights

Urban hotspots lowered WQI to poor/very poor during the dry season

TSI revealed eutrophic to hypereutrophic conditions in urban sector

Hydrological seasonality modulated pollution: dilution in rainy, concentration in dry

Integrated WQI–TSI analysis showed selective degradation and high eutrophication risk

INTRODUCTION

Water is an essential resource for ecosystem functioning and socioeconomic development, playing a central role in sectors such as agriculture, industry, domestic and livestock supply, power generation, transport, and recreation (UNESCO/UN-Water 2023). Driven by population growth, the intensification of productive activities, and rising consumption standards, the increasing global water demand has intensified the pressure on both surface and groundwater resources (Palácio et al. 2009; Wada et al. 2016; Silva et al. 2021). On a global scale, competition among conflicting water uses has escalated, particularly in regions where water availability is naturally limited or subject to sharp climate variability (Vörösmarty et al. 2010; Mekonnen and Hoekstra 2016).

Surface water constitutes one of the most vital elements for maintaining ecological processes, while also representing one of the most strategic commodities in the modern world (UNESCO/UN-Water 2023). However, the intensification of anthropogenic activities, such as agricultural expansion, uncontrolled urbanization, industrialization, and changes in land use and land cover, has caused significant alterations in water quality, especially within hydrographic basins of arid and semi-arid regions (Palácio et al. 2009; Pak et al. 2021). These alterations include increased nutrient loading, the introduction of organic and inorganic contaminants, elevated turbidity, and microbiological degradation, thereby compromising the multiple uses of water and the integrity of aquatic ecosystems (Kumar et al. 2015; Wang et al. 2015; Paula Filho et al. 2019; Acuña-Alonso et al. 2020; Da Silva et al. 2026).

In addition to anthropogenic pressures, water quality is modulated by climatic, hydrological, and biogeochemical factors operating across different spatiotemporal scales. Climate variability, for instance, directly influences hydrological dynamics, water availability, and the transport and dilution processes of pollutants (Mosley 2015; Li et al. 2022). In semi-arid regions, predominated by prolonged dry periods interspersed with concentrated and irregular rainfall, these processes become even more complex, promoting the concentration of contaminants and the intensification of eutrophication processes (Zhang et al. 2021; Li et al. 2022; Silva et al. 2023).

Maintaining adequate water quality is, therefore, a global challenge, primarily due to the coexistence of point and non-point sources of pollution, which complicate the control and integrated management of water resources (Giri and Qiu 2016; UNESCO/UN-Water 2023). Within this context, the continuous and systematic monitoring of physicochemical, biological, and microbiological parameters is essential to support public policies, guide management actions, and ensure the sustainability of multiple water uses. The international literature emphasizes that long-term monitoring programs are fundamental for detecting trends, identifying critical events, assessing trophic status, and informing predictive models (Ferreira et al. 2011; Acuña-Alonso et al. 2020).

Water quality monitoring involves analyzing parameters that reflect both natural composition and the influence of pollution sources. Among the most widely used physicochemical parameters are pH, turbidity, electrical conductivity, dissolved oxygen, total solids, nutrients (nitrogen and phosphorus), and biochemical oxygen demand. Concurrently, microbiological parameters, such as thermotolerant coliforms and *Escherichia coli*, are essential for assessing sanitary risks and evaluating the suitability of water for domestic supply and recreation (Kumar et al. 2015; Paula Filho et al. 2020).

Continuous and high-temporal-resolution monitoring, particularly in environments subject to intense seasonal variations, is fundamental to understanding biogeochemical dynamics and improving water resources management. Studies conducted in Mexico, Chile, and Argentina demonstrate that climate variability and land use are determining factors in water quality dynamics, requiring integrated monitoring approaches (Acuña-Alonso et al. 2020; Martínez – Santos et al. 2021a,b). Globally, research in arid regions of Africa and Asia also highlights that the combination of water scarcity and anthropogenic pressures intensifies the degradation of aquatic systems (Khan et al. 2020).

The systematic collection of these data enables the detection of trends, assessment of trophic status, identification of critical events, and support for predictive models. Ferreira et al. (2011) emphasize that the relationship among nutrients, chlorophyll-a, and primary production is crucial for comprehending eutrophication processes, rendering it indispensable in monitoring programs (Paula Filho et al. 2020).

In semi-arid regions, such as the Brazilian Northeast, the need for continuous monitoring is even more evident. The defining hydrographic characteristic of these regions is river intermittency, where surface flow occurs exclusively during the rainy season, leaving the rivers dry or reduced to isolated pools during the dry period (Palácio et al. 2009; Maltchik 1999; Da Silva et al. 2026). This unique hydrological dynamic promotes the concentration of pollutants, reduces self-purification capacity, and intensifies the vulnerability of aquatic ecosystems.

Studies conducted in the Brazilian semi-arid region demonstrate that excessive nutrient loading, particularly nitrogen and phosphorus, in rivers and reservoirs is associated with agricultural activities, livestock farming, fish farming, and the discharge of untreated domestic sewage (Kumar et al. 2015; Paula Filho et al. 2019, 2020; Da Silva et al. 2026). The combination of low water turnover, high temperatures, and continuous nutrient inputs creates ideal conditions for cyanobacterial blooms, water quality degradation, and significant risks to human health (Richardson et al. 2019; Paerl et al. 2020).

The insufficiency of sewage collection and treatment systems further exacerbates this situation, resulting in microbiological contamination, increased organic loading, and the degradation of both surface and groundwater bodies. This scenario underscores the imperative for studies that evaluate water quality on a seasonal basis, considering the hydrological particularities of the semi-arid region and the influence of anthropogenic activities (Palácio et al. 2009; ANA 2021; UNESCO/UN-Water 2023).

The use of composite indices, such as the Water Quality Index (WQI) and the Trophic State Index (TSI), facilitates data interpretation and enables clear and objective communication regarding the environmental condition of a water body (Paula Filho et al. 2020; Silva et al. 2021). WQI integrates multiple parameters into a single value, simplifying assessments and enabling spatial and temporal comparisons (Uddin et al., 2021). Conversely, TSI is widely applied to diagnose the degree of enrichment, especially in environments subject to continuous nutrient inputs (Carlson 1977; Lamparelli 2004; Cunha et al. 2013). Giri and Qiu (2016) emphasize that quality indices are essential tools for managers and policymakers, as they translate complex biogeochemical interactions into accessible information, even for non-specialist audiences.

The Salgado River, located in southern Ceará, is one of the main tributaries of the Jaguaribe River and plays a strategic role for the Cariri Metropolitan Region. However, rapid urban growth, industrial expansion, untreated domestic effluent discharge, and intensive land use have severely compromised water quality throughout its basin (Paula Filho et al. 2019; Santos et al. 2026). The vulnerability of the Salgado River is further aggravated by the deficit in sanitation infrastructure, culminating in microbiological contamination, organic overload, and the degradation of strategic surface and groundwater resources (Paula Filho et al. 2019; Marques et al. 2024; Santos et al. 2026).

In this study, an evaluation of the water quality of the Salgado River was performed across seasonal campaigns distributed between the dry and rainy periods, utilizing physicochemical and microbiological monitoring alongside the application of WQI and TSI_{PT} indices. This approach provides a comprehensive understanding of seasonal water quality dynamics and identifies the most vulnerable reaches, thereby supporting targeted management and conservation actions.

Consequently, this study aligns with the framework of the UN 2030 Agenda by contributing to targets related to sustainable water use, sanitation, ecosystem protection, and the strengthening of integrated water resources management. By generating qualified data on seasonal water quality dynamics in the semi-arid region, this work supports planning, conservation, and water security efforts, aspects that are vital for the sustainable development of the region and for achieving the Sustainable Development Goals (SDGs) focused on water, resilient cities, and environmental protection (UN 2015; UNESCO/UN-Water 2023).

METHODOLOGY

Study area

This research was conducted in the Salgado River basin, a sub-basin of the Jaguaribe River Hydrographic Basin, located in the southern region of the state of Ceará. The sub-basin encompasses a drainage area of 12,865 km^2, spanning 23 municipalities with an estimated population of one million inhabitants (IBGE 2022). The Salgado River, extending 308 km, originates at the Batateira Geosite in the municipality of Crato, at the foothills of the Araripe Plateau. It flows through densely populated urban areas, receiving substantial loads of domestic and industrial effluents along its upper reach, particularly within the municipalities of Crato and Juazeiro do Norte (Fig. 1). Recent studies indicate that this section of the basin experiences high anthropogenic pressure, characterized by the discharge of untreated sewage, rapid urban expansion, and intensive land use, factors that have contributed to the degradation of water quality and the reduction of the river's self-purification capacity (COGERH 2021; SRH- CE 2022).

The primary environmental impacts in the Salgado River Basin include deforestation, biomass burning for firewood and agriculture, river damming that alters fluvial courses, excessive pesticide application, and water contamination by raw sewage (COGERH 2021). The stretch traversing the Cariri Metropolitan Region (Crato, Juazeiro do Norte, and Missão Velha) concentrates both population and industries, which exacerbates pollution from solid waste and effluents. Moreover, the removal of riparian vegetation intensifies siltation and water loss, while the occupation of the Araripe Plateau slopes causes soil sealing (impermeabilization) and the burying of headwaters, thereby promoting desertification processes (SRH-CE 2020). The low coverage of sewage collection networks and treatment facilities for domestic and industrial effluents, such as tanneries and slaughterhouses, further compromises the quality of strategic surface and groundwater resources in this sector (SNIS 2022). After flowing past the Missão Velha Waterfall, the river runs through peri-urban and rural areas until it discharges into the middle Jaguaribe River, contributing to the recharge of the Castanhão Reservoir, one of the largest water

reservoirs in Latin America and the primary source responsible for the water supply of the Fortaleza Metropolitan Region.

The Salgado River basin exhibits a surface water accumulation potential of 447.41 million m^3, representing a strategic asset for regional socioeconomic development (ANA, 2021; Santos et al. 2026). This study encompasses the municipalities of Crato, Juazeiro do Norte, Missão Velha, Aurora, Lavras da Mangabeira, and Icó. The first three cities are characterized by high urbanization rates and low sewage collection network coverage, whereas the latter three span areas dominated by typical rural land use. The 11 sampling sites were distributed from the headwaters to the river mouth, representing gradients of land use and land cover, as recommended by recent monitoring studies in semi-arid regions (Acuña-Alonso et al. 2020; Silva et al. 2023) (Fig. 1).

Sampling Design

Between 2023 and 2024, five sampling campaigns were conducted across the dry and rainy seasons at 11 sampling sites, totaling 55 samples evaluated over the biennial period. Table S1presents the geographic coordinates and description of the sampling sites monitored between 2023 and 2024 in the Salgado River, northeastern Brazil (Supplementary material). Subsurface water samples were collected at a depth of approximately 30 cm using a Van Dorn bottle. For physicochemical analyses, 1L polyethylene bottles, previously washed and decontaminated, were utilized. The samples were stored in isothermal boxes at ~ 4°C and transported to the Analytical Central facility at UFCA. Microbiological analyses were performed at the Water and Effluents Microbiology Laboratory (LAMAE/CENTEC). All collection, preservation, and transport procedures followed the recommendations established by the *Standard Methods for the Examination of Water and Wastewater* (APHA 2017).

Analytical Procedures

Table 1 presents the evaluated physicochemical and microbiological variables alongside their respective methodologies. Parameters measured directly in the field included pH, temperature, dissolved oxygen, electrical conductivity, and turbidity, which were determined using previously calibrated multiparameter probes (APHA 2017). In addition to *in situ* measurements, laboratory analyses were conducted for BOD_5, total suspended solids (TSS), total nitrogen, total phosphorus, and thermotolerant coliforms. For compliance monitoring purposes, the water quality standards established by the Brazilian environmental legislation under CONAMA Resolution 357/2005 were considered (Brasil, 2005). The selection of these parameters aligns with recommendations for monitoring hydrographic basins subject to anthropogenic pressures, particularly in semi-arid regions, where nutrient loading, hydrological variability, and the influence of land use exert a strong control over water quality (Wang et al. 2015; Paula Filho et al. 2019; Zhang et al. 2021; Li et al. 2022).

Table 1
Physicochemical and biological variables considered in the water quality assessment of the Salgado River, northeastern Brazil.

Variables	Acronym/Unit	Technique	Reference
pH	pH	Potentiometric	(APHA, 2017)
Temperature	T(°C)	Thermometric	(APHA, 2017)
Electrical conductivity	EC (µS cm^{-1})	Potentiometric	(APHA, 2017)
Turbidity	NTU	Nephelometric	(APHA, 2017)
Dissolved oxygen	DO (mg L^{-1} O_2)	Potentiometric	(APHA, 2017)
Biochemical Oxygen Demand	BOD_5 (mg L^{-1} O_2)	Standard Bottles (Incubation)	(APHA, 2017)
Total dissolved solids	TDS (mg L^{-1})	Electrometric	(APHA, 2017)
Total suspended solids	TSS (mg L^{-1})	Gravimetric	Strickland and Parsons 1972
Total nitrogen	TN (mg L^{-1})	Spectrophotometric	Valderrama 1981.
Total phosphorus	TP (mg L^{-1})	Spectrophotometric	Valderrama 1981.
Thermotolerant Coliforms	TC (MPN $100mL^{-1}$)	Multiple Tubes	(APHA 2017)

Water Quality and Trophic State Indices

To evaluate the water quality at the monitored sites along the Salgado River, the Water Quality Index (WQI) and the Trophic State Index for Total Phosphorus (TSI_{TP}) were determined, both calculated in accordance with Brazilian National Water Agency (ANA 2026). The WQI was determined based on nine variables considered critical for water quality assessment (pH, temperature, turbidity, dissolved oxygen, BOD, total suspended solids, total nitrogen, total phosphorus, and fecal coliforms), with its primary determinant centered on suitability for public supply. The relevance of the WQI as a synthetic environmental assessment tool is widely recognized in recent literature (Uddin et al. 2021; Silva et al. 2021). The WQI is calculated using the weighted product of the water quality scores corresponding to the variables that integrate the index, as expressed in Eq. 1.

$$WQI = \prod_{i=1}^{n} q_i^{w_i} \quad \text{Eq. (1)}$$

Where the generated WQI is a value ranging from 0 to 100, increasing as water quality improves. Table S2 shows the water quality scale as calculated using the water quality index (Supplementary material).

The term *qi* represents the quality score of the *i-th* parameter, a number between 0 and 100 obtained from its respective "mean quality variation curve" as a function of its concentration or measurement. The term *wi* is the weight assigned to the *i-th* parameter, ranging from 0 to 1, which reflects its relative importance to the overall quality framework and *n* denotes the total number of variables. The Table S3 presents the relative weights of the parameters used in the Water Quality Index (WQI) (Supplementary material).

The IET_{PT} was calculated based on the total phosphorus concentration for tropical environments, with total phosphorus (TP) expressed in µg/L (Lamparelli 2004; Cunha et al. 2013). Total phosphorus is the primary nutrient driving eutrophication in semi-arid ecosystems, particularly in lotic environments subject to a continuous input of point and non-point loads (Silva et al. 2022). The corresponding results should be understood as a measure of the eutrophication potential, since this nutrient acts as the causative agent of the process. For lotic environments, Eq. 2 was utilized.

$$IET_{PT} = 10 \times \left[6 - \left(\frac{(0.42 - 0.35 \times (lnPT)}{ln2}\right)\right] \quad \text{..... Eq. (2)}$$

Table S4 presents classification of the trophic status (TSI_{PT}) values associated with the different trophic state categories (Supplementary material).

Statistical Analysis

The statistical analysis was conducted in multiple stages, beginning with the assessment of data distribution. Normality was evaluated using the Shapiro–Wilk test, which guided the selection of the most appropriate inferential approach. Based on the distribution behavior, either parametric or non-parametric tests were applied to investigate seasonal differences among the environmental variables. To measure the degree of association among the hydrogeochemical parameters, Spearman's rank correlation coefficient was employed, as it is appropriate for non-normally distributed data or monotonic relationships.

Following the laboratory stage, the data were organized into an electronic spreadsheet and analyzed using Jamovi software (version 2.6.44). Descriptive statistics (minimum, maximum, mean, and standard deviation), boxplots, normality tests, correlation analyses, and Kruskal–Wallis tests for seasonal mean comparisons were performed. This set of procedures aligns with consolidated practices in studies on water quality within semi-arid aquatic systems, which recommend the integration of univariate and inferential analyses for a robust interpretation of spatial and temporal patterns (Khan et al. 2020; Martínez – Santos et al. 2021a,b).

RESULTS AND DISCUSSION

Dynamics of Physicochemical and Microbiological Parameters

Table 2 shows the descriptive statistics for the concentrations and measurements of the physicochemical attributes analyzed in this study during the dry and rainy seasons between 2023 and 2024. The results reveal that the Salgado River is strongly influenced by the typical seasonality of the semi-arid region and by urban discharges along the fluvial gradient. Comparisons with the maximum permissible values (MPV) for Class II waters highlight multiple points of non-compliance, particularly in urban (P3–P7) and peri-urban (P8–P11) stretches. The Shapiro–Wilk normality test demonstrated that only dissolved oxygen follows a Gaussian distribution ($p > 0.05$); therefore, non-parametric statistical methods were applied to analyze the data.

Table 2
Descriptive statistics of the concentrations and measurements of physicochemical and bacteriological attributes at the sampling sites of the Salgado River during the dry and rainy seasons between 2023 and 2024.

Variable	Season	N	Mean	Variance	MPV*
pH	rainy	33	5.73–8.65 7.16 ± 0.61	0.368	6–9
	dry	21	6–8.65 7.08 ± 0.72	0.515	
T (°C)	rainy	33	23.8–30.5 27.6 ± 1.95	3.82	NA
	dry	22	25- 39.5 29.4 ± 3.29	10.8	
EC (µS cm^{-1})	rainy	33	38.6–905 397 ± 215	46232	NA
	dry	22	43–1285 723 ± 415	172295	
TDS (mg L^{-1})	rainy	33	27–634 278 ± 151	22654	≤ 500
	dry	22	30.1–897 506 ± 291	84425	
Turbidity (NTU)	rainy	33	6.69–724 108 ± 163	26421	≤ 100
	dry	22	1.95–222 43.2 ± 52.5	2756	
DO (mg L^{-1})	rainy	33	0.79–9.64 3.72 ± 1.88	3.52	> 5
	dry	22	0.22–6.3 3.34 ± 1.85	3.41	
BOD (mg L^{-1})	rainy	33	0–28.5 4.81 ± 5.78	33.4	≤ 5

Variable	Season	N	Mean	Variance	MPV*
	dry	22	0.85–36.4 8.76 ± 9.31	86.7	
TSS (mg L^{-1})	rainy	33	1–578 103 ± 154	23637	NA
	dry	22	0–140 45.0 ± 43.5	1890	
NT (mg L^{-1})	rainy	33	0.5–8.54 1.07 ± 1.80	3.24	< 3.7
	dry	22	0.5–23.1 5.27 ± 7.52	56.6	
TP (mg L^{-1})	rainy	33	0.05–17.6 1.82 ± 3.65	13.3	≤ 0.05
	dry	22	0.01–4.55 1.14 ± 1.42	2.00	
TC (NMP 100 ml^{-1})	rainy	33	1300–23000 3521 ± 5510	$3.04x10^7$	< 1000
	dry	22	1600–$3.5x10^7$ $3.58x10^6$±$1.02x10^7$	$1.04x10^{14}$	

Table 2
Descriptive statistics of concentrations and measurements of physicochemical and bacteriological attributes at sampling sites along the Salgado River, during dry and rainy periods between 2023 and 2024.

Variable	Season	N	Min – Max Mean ± σ	Variance	MPV*
pH	rainy	33	5.73–8.65 7.16 ± 0.61	0.368	6–9
	dry	21	6–8.65 7.08 ± 0.72	0.515	
T (°C)	rainy	33	23.8–30.5 27.6 ± 1.95	3.82	NA
	dry	22	25- 39.5 29.4 ± 3.29	10.8	
EC (µS cm^{-1})	rainy	33	38.6–905 397 ± 215	46232	NA
	dry	22	43–1285 723 ± 415	172295	
TDS (mg L^{-1})	rainy	33	27–634 278 ± 151	22654	≤ 500
	dry	22	30.1–897 506 ± 291	84425	
Turbidity (NTU)	rainy	33	6.69–724 108 ± 163	26421	≤ 100
	dry	22	1.95–222 43.2 ± 52.5	2756	
DO (mg L^{-1})	rainy	33	0.79–9.64 3.72 ± 1.88	3.52	> 5
	dry	22	0.22–6.3 3.34 ± 1.85	3.41	

*Maximum permissible value (MPV) considering class II for inland waters according to CONAMA 357/2005.

Variable	Season	N	Min – Max Mean ± σ	Variance	MPV*
BOD (mg L^{-1})	rainy	33	0–28.5 4.81 ± 5.78	33.4	≤ 5
	dry	22	0.85–36.4 8.76 ± 9.31	86.7	
TSS (mg L^{-1})	rainy	33	1–578 103 ± 154	23637	NA
	dry	22	0–140 45.0 ± 43.5	1890	
NT (mg L^{-1})	rainy	33	0.5–8.54 1.07 ± 1.80	3.24	< 3.7
	dry	22	0.5–23.1 5.27 ± 7.52	56.6	
TP (mg L^{-1})	rainy	33	0.05–17.6 1.82 ± 3.65	13.3	≤ 0.05
	dry	22	0.01–4.55 1.14 ± 1.42	2.00	
TC (NMP 100 ml^{-1})	rainy	33	1300–23000 3521 ± 5510	$3.04x10^7$	< 1000
	dry	22	$1600–3.5x10^7$ $3.58x10^6±1.02x10^7$	$1.04x10^{14}$	

*Maximum permissible value (MPV) considering class II for inland waters according to CONAMA 357/2005.

*Maximum permissible value (MPV) considering Class II for inland waters in accordance with CONAMA Resolution 357/2005 (Brazil 2005).

The pH remained within the permissible range for Class II waters (6–9) in both periods (7.16 in the rainy season and 7.08 in the dry season); however, minimum values close to 5.7 in the headwaters (P1–P2) indicate natural acidification episodes. These episodes are associated with the geology of the Araripe Plateau, where sandier soils and poorly buffered organic matter favor chemical fluctuations. In rivers

located in semi-arid regions, this variability is widely documented and results from the interaction among natural processes, such as low alkalinity, high evaporation, and sharp discharge variations, and moderate anthropogenic influence, especially in stretches near urban areas (Khan et al. 2020; Martínez – Santos et al. 2021a,b). This behavior is consistent with patterns described for intermittent and non-perennial rivers in semi-arid environments, where pH tends to fluctuate more intensely between dry and rainy periods due to the alternation between solute concentration and rapid dilution during precipitation events. Recent studies highlight that pH dynamics in semi-arid systems reflect both local geology and the increasing influence of urban discharges along the fluvial gradient (Martínez – Santos et al. 2021a,b).

Temperature was higher in the dry season (29.4°C) than in the rainy season (27.6°C), a typical behavior of shallow rivers in semi-arid regions, where intensified evaporation and low discharge favor warming. Elevated temperatures reduce oxygen solubility and can aggravate hypoxic conditions in polluted stretches.

Electrical conductivity (EC) and total dissolved solids (TDS) exhibited a strong seasonal contrast. In the dry period, TDS exceeded the 500 mg L^{-1} threshold, indicating salt concentration by evaporation and a continuous input of urban effluents. This pattern is widely described in semi-arid rivers subject to discharge reduction and increased salinity.

Turbidity exceeded the limit established for Class II waters during the rainy season (mean of 108 NTU; maximum of 724 NTU), reflecting intense runoff of sediments, particulate organic matter, and urban waste, particularly in the P3–P7 stretches that cross the Cariri metropolitan region. This behavior is typical of semi-arid rivers during precipitation events, when surface runoff mobilizes large amounts of material from exposed soil, degraded areas, and urbanized zones (Silva et al. 2020; García – Rodríguez et al. 2022). Recent studies in fluvial systems of semi-arid regions emphasize that turbidity tends to increase abruptly during the rainy season due to low vegetative cover, accelerated erosion, and high hydrological connectivity between urban areas and the river channel (Khan et al. 2020). In the dry period, although the mean turbidity (43.2 NTU) was within the permissible limit, this does not necessarily represent an improvement in water quality. The lower turbidity coincided with a significant increase in electrical conductivity and total dissolved solids, indicating a higher concentration of solutes due to intense evaporation and low water turnover pattern widely described in semi-arid rivers under strong anthropogenic pressure (Medeiros et al. 2021). As observed by Martínez – Santos et al. (2021a,b), rivers in semi-arid climates frequently present clearer but chemically more concentrated water during droughts, resulting from the combination of discharge reduction, accumulation of urban effluents, and the intensification of salinization processes. This contrast between periods, high turbidity in the rainy season and high solute concentration in the dry season, is characteristic of intermittent and non-perennial fluvial systems, where hydrological dynamics strongly control water quality. In a comparative study on semi-arid rivers, Khan et al. (2020) highlighted that elevated turbidity during rainfall events is associated with the transport of particles and particulate nutrients, whereas the dry period favors the concentration of dissolved compounds, including salts, nutrients, and urban contaminants.

The mean DO values fell below the regulatory limit in both periods (rainy: 3.72 mg L^{-1}, dry: 3.34 mg L^{-1}), indicating hypoxic conditions detrimental to aquatic biota. At levels below 5 mg L^{-1}, fish and macroinvertebrates exhibit physiological stress, reduced metabolism, and mortality risks, particularly in environments subject to high temperatures and low water turnover, as is typical for semi-arid rivers (Khan et al. 2020). In urban stretches, the combination of low discharge, elevated temperatures, and continuous organic matter input favors anoxic conditions. These conditions intensify biogeochemical processes such as phosphorus release from the sediment, ammonia production via incomplete denitrification, and the increase of reduced compounds (H_2S, Fe^2, Mn^2), which are phenomena widely described in urban fluvial systems of semi-arid regions (Martínez – Santos et al. 2021a,b).

BOD exceeded the limit during the dry period (mean: 8.76 mg L^{-1}; maximum: 36.4 mg L^{-1}), indicating a heavy biodegradable organic load, typical of stretches receiving raw domestic sewage discharges. In the rainy season, the mean (4.81 mg L^{-1}) remained close to the threshold but still reveals a significant input of organic matter. This pattern is consistent with urban rivers in the semi-arid region, where prolonged drought intensifies effluent concentration and reduces self-purification capacity, resulting in higher oxygen consumption driven by microbial decomposition (Silva et al. 2020; Medeiros et al. 2021). In urban environments, high BOD is directly associated with the presence of untreated sewage and the accumulation of organic matter on the riverbed, especially in intermittent rivers (Costa et al. 2020).

The relationship between DO and BOD in the Salgado River evidence a typical scenario of organic degradation in semi-arid rivers under urban pressure. The high BOD, especially in the dry season, intensifies oxygen consumption through microbial decomposition, contributing directly to the low DO values observed along the fluvial gradient. This mechanism is amplified by low discharge, high temperatures, and elevated solute concentrations, which further reduce oxygen solubility and promote hypoxic and anoxic conditions (García – Rodríguez et al. 2022). Thus, the combination of high BOD and low DO reflects a system with a strong input of organic matter, low self-purification capacity, and the intensification of reducing processes in the sediment, a pattern widely documented in urban and intermittent rivers of semi-arid regions (Santos et al. 2014; Albuquerque et al. 2019; Khan et al. 2020; Martínez – Santos et al. 2021a,b).

The TN during the dry period showed very high values, reaching a maximum of 23.1 mg L^{-1}, indicating an accumulation of nitrogenous compounds due to low water turnover and the continuous input of urban and agricultural effluents. This behavior is typical of intermittent and semi-arid rivers, where nutrient concentrations increase drastically during droughts because of overconcentration, discharge reduction, and the intensification of point and non-point loads (Khan et al. 2020; Medeiros et al. 2021). Studies in semi-arid basins also show that the combination of exposed soils, low vegetative cover, and domestic sewage inputs favors nitrogen accumulation in urban and peri-urban stretches (Albuquerque et al. 2019; Silva et al. 2021).

The TP values were far superior to the regulatory limit in both periods, with mean values of 1.82 mg L^{-1} (rainy) and 1.14 mg L^{-1} (dry). These values are dozens of times higher than the MPV, indicating a severe risk of eutrophication. In semi-arid rivers, phosphorus is frequently transported within the particulate fraction during rainfall events, when surface runoff mobilizes phosphorus-rich sediments from degraded and urbanized areas (Silva et al. 2020; García – Rodríguez et al. 2022). Conversely, during the dry period, hypoxic and anoxic conditions favor phosphorus release from the sediment (internal loading), intensifying water quality degradation, a process widely documented in intermittent fluvial systems under anthropogenic pressure (Santos et al. 2014; Martínez – Santos et al. 2021a,b; Costa et al. 2020).

The relationship between TN and TP in the Salgado River reveals a typical framework of severe nutrient enrichment in semi-arid rivers under strong urban and agricultural influence. Nitrogen accumulation during the dry period, coupled with sediment phosphorus release under anoxic conditions, creates a highly favorable environment for eutrophication, particularly in urban and peri-urban stretches. The combination of low discharge, high temperatures, and continuous effluent input intensifies the concentration of both nutrients, reduces self-purification capacity, and promotes biogeochemical processes that feed back into the degradation cycle, such as accelerated organic matter mineralization and the mobilization of particulate nutrients (Kumar et al. 2015; Martínez – Santos et al. 2021a,b; Medeiros et al. 2021; García – Rodríguez et al. 2022). Thus, the synergy between high nitrogen and phosphorus concentrations constitutes one of the main drivers of water quality deterioration in the Salgado River, reflecting patterns widely described in intermittent and semi-arid rivers worldwide (Santos et al. 2014; Khan et al. 2020; Costa et al. 2020).

The results for thermotolerant coliforms indicate severe fecal contamination, incompatible with recreational uses and public supply without advanced treatment. Extremely high values, especially in urban and peri-urban stretches, reflect the continuous discharge of untreated domestic sewage. This situation has already been documented in recent studies within the Salgado basin, which also identified the presence of urban microcontaminants along the metropolitan stretches of the Cariri region (Silva et al. 2020; García – Rodríguez et al. 2022). In semi-arid rivers, the combination of low discharge, high temperatures, and effluent input favors the survival and proliferation of fecal bacteria, aggravating sanitary risks and compromising water quality (Khan et al. 2020). The elevated presence of coliforms is directly associated with increased biochemical oxygen demand (BOD), since the microbial decomposition of organic matter present in sewage consumes large amounts of dissolved oxygen. This contributes to the low DO values observed in the Salgado River, especially during the dry season, when low water turnover and high temperatures further reduce oxygen solubility (Medeiros et al. 2021; Martínez – Santos et al. 2021a,b). Furthermore, the input of domestic and agricultural sewage significantly raises total nitrogen and total phosphorus concentrations, nutrients that accumulate during the drought and intensify eutrophication and environmental degradation processes (Santos et al. 2014; Albuquerque et al. 2019; Costa et al. 2020). Thus, fecal contamination does not occur in isolation; rather, it integrates a set of anthropogenic pressures that simultaneously affect oxygenation, organic loading, and nutrient enrichment within the system.

The interaction among TC, DO, BOD, TN, TP, and temperature reveals a typical framework of organic degradation and eutrophication in semi-arid rivers under heavy urban pressure. The high sewage load increases BOD, promotes DO depletion, and intensifies reducing processes in the sediment, favoring phosphorus release and the accumulation of nitrogenous compounds. These mechanisms are further amplified by the overconcentration and high temperatures characteristic of the region (Martínez – Santos et al. 2021a,b; García – Rodríguez et al. 2022). This set of factors creates a negative feedback loop: more sewage → more coliforms → higher BOD → DO depletion → greater nutrient release → increased eutrophication, a pattern widely described in intermittent and urban rivers of semi-arid regions worldwide (Santos et al. 2014; Khan et al. 2020; Costa et al. 2020). Therefore, thermotolerant coliforms function as a key indicator that synthesizes the anthropogenic pressure exerted on the Salgado River and its environmental vulnerability.

Longitudinal Variation of Water Quality Parameters

The assessment of the spatial behavior of the variables can be performed using Fig. 2, considering the mean values obtained according to the seasonal period (rainy/dry). The monitoring data across the eleven sites (P1–P11) describe a well-defined fluvial gradient that follows the continuum of the Salgado River from its headwaters in the Araripe Plateau (P1–P2), crossing the heavily urbanized Crato–Juazeiro do Norte stretch (P3–P7), down to the peri-urban and crystalline areas of the Salgado Valley (P8–P11). This spatial pattern is typical of semi-arid watersheds, where the combination of water seasonality, land use, and anthropogenic pressures generates strong longitudinal heterogeneity (Acuña Alonso et al. 2020; Silva et al. 2023). The spatial structure observed in the Salgado River also reflects what the literature describes as "disruptions in the river continuum" within urban stretches of intermittent and perennial rivers (Santos et al. 2014; Medeiros et al. 2021; Martínez – Santos et al. 2021a,b).

Water pH values remain close to neutrality, with moderate alkalinity, while temperatures are milder, particularly during the rainy season, when diffuse recharge and reduced surface exposure decrease the thermal amplitude (Fig. 2a). At the headwaters (P1–P2), within the recharge area of the Araripe Plateau, the water exhibits lower EC and TDS (Fig. 2c, 2d), reflecting the contribution of sedimentary aquifers with low mineralization and higher dilution capacity, as observed in other sedimentary basins of the semi-arid region (Silva et al. 2014; ANA 2021). DO is higher (Fig. 2g), indicating predominantly oxic conditions, with low BOD (Fig. 2h) and a reduced TC load (Fig. 2k), a pattern typical of headwater stretches under low anthropogenic pressure (Medeiros et al. 2021; Martínez – Santos et al. 2021a,b). This behavior is consistent with classic studies on semi-arid aquatic ecosystems, which emphasize the greater ecological integrity of headwaters (Esteves et al. 1999; Maltchik 1999).

As the river advances into the urban and heavily anthropized stretch (P3–P7), where it intersects densely populated areas of Crato and Juazeiro do Norte, a clear disruption in the river continuum is observed. EC and TDS increase abruptly (Fig. 2c, 2d), reaching values typical of eutrophied urban semi-arid rivers, particularly during the dry period when evapoconcentration intensifies salinization. This pattern is widely documented in semi-arid basins undergoing accelerated urbanization, where low discharge and

continuous effluent input amplify mineralization (Khan et al., 2020; Da Silva et al. 2026). Turbidity and TSS also increase significantly (Fig. 2e, 2f), with peaks exceeding 200–270 NTU and 150–200 mg L^{-1}, respectively, thus surpassing the 100 NTU threshold established by CONAMA Resolution 357/2005 for Class II rivers. This behavior is consistent with studies showing that rainfall events in semi-arid urban areas mobilize large volumes of sediment, organic matter, and contaminants (Albuquerque et al. 2019; García – Rodríguez et al. 2022; Silva et al. 2020).

The most critical situation occurs within the oxygen and organic matter parameters. At P3–P4, DO drops to values near 0.5–1.0 mg L^{-1} during the dry period, falling far below the 5 mg L^{-1} minimum required by CONAMA Resolution 357/2005 and characterizing severe hypoxic conditions. Simultaneously, BOD reaches values between 19 and 30 mg L^{-1}, violating the 5 mg L^{-1} threshold for Class II waters and indicating a heavy input of untreated domestic sewage. This pattern is widely reported in urban semi-arid rivers, where the combination of high temperatures, low discharge, and continuous organic loading leads to rapid oxygen depletion (Wang et al. 2015; Silva et al. 2020; da Silva et al. 2026). Nutrient levels reinforce this scenario (Fig. 2i, 2j); TN and TP reach concentrations of 8–15 mg L^{-1} and 1–6 mg L^{-1}, respectively, which are well above the recommended values for multi-purpose rivers, establishing a framework of chronic eutrophication. Recent studies demonstrate that hydrological alterations and urban pressures intensify eutrophication in semi-arid basins, especially during prolonged dry periods (Li et al. 2022; Silva et al. 2022; Richardson et al. 2019; Paerl et al. 2020).

Thermotolerant coliforms reach extreme values, such as 3.5 x 10^7 MPN 100mL^{-1} at P4 during the dry period (Fig. 2k), surpassing the 1000 MPN 100mL^{-1} threshold for Class II waters by more than four orders of magnitude. This level of bacteriological contamination is typical of urban rivers receiving raw sewage, as documented in other cities within the Brazilian semi-arid region (da Silva et al. 2026; Santos et al. 2026). These results confirm that the urban stretch of the Salgado River operates as a core of sanitary and ecological degradation, with multiple parameters simultaneously failing to meet legal standards.

At the peri-urban sites of the Salgado Valley (P8–P11), which are situated within a crystalline bedrock domain and under the influence of multiple dams and agricultural uses, the water tends to exhibit moderate to high EC and TDS. This reflects greater mineralization associated with the crystalline geology and the return of water from reservoirs. This behavior is widely reported in crystalline basins of the semi-arid region, where water–rock interaction and the residence time within reservoirs increase hardness and alkalinity (Lira et al. 2014; Lopes et al. 2014). The presence of coliforms and nutrients remains significant, indicating that although there is a certain degree of spatial dilution relative to the immediate urban stretch, the continuum of degradation extends along the fluvial gradient, as previously observed in regional studies (SRH-CE 2020; COGERH 2021).

The comparison between the rainy and dry periods must be interpreted considering the recent rainfall regime. According to regional meteorological data, the average annual precipitation in the region was approximately 644 mm in 2023 and 761.4 mm in 2024; both values are below or near the lower limit of

the historical average for the Cariri region (FUNCEME 2026). This scenario is consistent with recent analyses showing that climate variability and the reduction of prolonged floods limit the self-purification capacity of semi-arid rivers (Zhang et al. 2021; UNESCO/UN-Water 2023). Thus, even during the rainy season, the river did not experience hydrological pulses sufficiently to restore water quality, remaining under strong anthropogenic pressure. The rainy campaigns show a reduction in EC, BOD, and, to some extent, TN and TP; however, they do not eliminate oxygen depletion in urban stretches or the high bacteriological load. Conversely, the dry campaigns evidence the worsening of salinization, hardness, alkalinity, and eutrophication, with DO frequently reaching critical levels, a pattern widely documented in intermittent and perennial semi-arid rivers (Maltchik 1999; Silva et al. 2023).

From the legal perspective classification, the results indicate that only the headwaters (P1–P2) consistently meet the CONAMA Resolution 357/2005 standards for Class II waters. Conversely, the urban stretch (P3–P7) exhibits multiple simultaneous violations of DO, BOD, turbidity, TP, and TC, practically approaching a Class IV condition, which is unsuitable for recreational uses, vegetable irrigation, and the protection of aquatic biota. The crystalline valley (P8–P11) presents intermediate conditions compatible with Class III standards, though still displaying critical parameters during specific campaigns. This pattern of longitudinal degradation is consistent with global analyses that identify urban rivers as hotspots of ecological and sanitary risk (Vörösmarty et al. 2010; Martínez – Santos et al. 2021a,b).

Thus, the spatial gradient of the Salgado River reveals a river continuum interrupted by a highly degraded urban stretch, followed by a crystalline reach that acts as a partial buffer but is unable to fully restore water quality. Integrated management must recognize this spatial structure and prioritize interventions at critical points, ensuring that legal classification serves not only as a regulatory instrument but as a feasible goal for environmental recovery.

Seasonal Dynamics of Water Quality Parameters

The comparison between the rainy and dry periods must be interpreted considering the recent rainfall regime, which was marked by annual totals below the lower limit of the historical average for the Cariri region (900 mm yr^{-1}), reaching 644 mm yr^{-1} and 761.4 mm yr^{-1} in 2023 and 2024, respectively. This reduction in prolonged floods consequently limited the self-purification capacity of the river. This context helps explain the Kruskal–Wallis test results, which indicated significant differences between seasons for temperature (°C) (p = 0.0187), EC (p = 0.00008), TDS (p = 0.0007), turbidity (p = 0.02537), BOD (p = 0.0325), TN (p = 0.04788), and TC (p = 0.00023). These parameters are directly influenced by dilution, discharge, and organic loading. In contrast, pH (p = 0.9222), DO (p = 0.0632), TSS (p = 0.5884), and TP (p = 0.9434) showed no significant differences, suggesting that during hydrologically dry years, these indicators remain relatively stable, controlled either by internal system processes or by continuous anthropogenic pressures throughout the year.

Figure 3 presents the box-plot representations for the dataset, considering the seasonal behavior across the rainy and dry periods. Box-plots constitute an essential graphical tool for interpreting the data in this study, as they allow for a clear visualization of the distribution, median, variability, and presence of outliers between the rainy and dry seasons. Within the context of the seasonal analysis of the Salgado River, their use is particularly relevant because it immediately highlights the shift in medians and the interquartile range of the parameters that exhibited significant differences in the Kruskal–Wallis test, such as temperature, EC, turbidity, BOD, TN, and TC, visually reinforcing the effects of discharge and dilution on these indicators. Likewise, the boxplots enable the observation of overlapping distributions for pH, dissolved oxygen, TSS, and total phosphorus, corroborating the absence of statistical differences between seasons. Thus, the boxplots not only complement the statistical analysis but also facilitate the communication of seasonal patterns, making the hydrological influence on water quality along the fluvial gradient more evident.

The box-plot results reveal seasonal patterns consistent with the recent hydrological behavior of the Salgado River, which was marked by annual precipitation near or below the lower limit of the historical average for the Cariri region. This, in turn, reduced the occurrence of prolonged floods and limited the self-purification of the system. The pH exhibited high stability between seasons, with virtually identical medians (7.04 in the dry period and 7.17 in the rainy period) and an extensive overlap of the quartiles, confirming the absence of statistical difference (p = 0.9222) and indicating that this parameter is poorly sensitive to discharge variations (Fig. 3a). In contrast, temperature showed a clear seasonal response (Fig. 3b), with a higher median in the dry period (29.4°C) compared to the rainy period (27.9°C). This reflects greater sunstroke, reduced shading, and overconcentration, which is consistent with the significant test result (p = 0.0187).

In Fig. 3c, EC exhibited one of the most striking differences between seasons: the median during the dry period (824.5 µS cm^{-1}) was more than double that observed in the rainy season (371 µS cm^{-1}), with Q3 exceeding 1000 µS cm^{-1} in the dry period, evidencing a strong concentration of salts under low flow conditions, which aligns with the highly significant p-value (0.00008). The same pattern is observed for TDS (Fig. 3d), whose medians were 577 mg L^{-1} in the dry period and 259 mg L^{-1} in the rainy period, reinforcing the effect of overconcentration. Turbidity, in turn, showed an inverse behavior (Fig. 3e). The median was higher in the rainy period (52.7 NTU) than in the dry period (27.8 NTU), with extreme values reaching 724 NTU, reflecting the input of sediments and particulate matter during rainfall events, in agreement with the significant p-value (0.02537). Conversely, TSS showed high variability in both seasons (Fig. 3f), with close medians (30 mg L^{-1} in the dry period and 28 mg L^{-1} in the rainy period) and a strong overlap of the boxes, justifying the absence of statistical difference (p = 0.5884).

DO presented similar medians between periods (3.36 mg L^{-1} in the dry period and 3.55 mg L^{-1} in the rainy period), with widely overlapping boxes, which explains the non-significant p-value (0.0632) (Fig. 3g). This result suggests that in hydrologically dry years, low reaeration capacity and high organic loading keep DO persistently reduced, regardless of the season. In contrast, BOD (Fig. 3h) showed a clear difference

between periods, with a median of 5.32 mg L^{-1} in the dry period and 3.00 mg L^{-1} in the rainy period, reflecting a higher concentration of organic matter under low flow conditions and confirming the significant p-value (0.0325). Despite presenting extreme values in the rainy period (maximum of 17.57 mg L^{-1}), TP (Fig. 3i) exhibited close medians (0.24 mg L^{-1} in the dry period and 0.526 mg L^{-1} in the rainy period) and a strong overlap of the quartiles, which explains the lack of statistical significance (p = 0.9434), suggesting that its dynamics are more associated with point-source inputs than with hydrological seasonality.

TN presented one of the most evident seasonal responses (Fig. 3j). The median in the dry period (1.68 mg L^{-1}) was much higher than that of the rainy period (0.28 mg L^{-1}), with Q3 reaching 6.35 mg L^{-1}, reflecting nutrient accumulation under low flow conditions and confirming the significant p-value (0.04788). Finally, thermotolerant coliforms exhibited the most expressive contrast between seasons (Fig. 3k). The median in the dry period (140,000 MPN 100 mL^{-1}) surpassed that of the rainy period (1,800 MPN 100 mL^{-1}) by several orders of magnitude, with a maximum of 3.5 x 10^7 MPN 100 mL^{-1} in the dry period, evidencing a strong influence of domestic sewage concentration under low dilution conditions, which aligns with the highly significant p-value (0.00023). These results reinforce that in years of low rainfall, hydrological seasonality exerts a selective influence on water quality parameters, intensifying concentration and degradation processes during the dry period, while other indicators remain relatively stable along the fluvial gradient.

Additionally, the results of the Spearman correlation analysis revealed contrasting scenarios between the rainy and dry periods, confirming that hydrological seasonality plays a central role in modulating the relationships among water quality parameters. In the rainy period, correlations were mostly moderate but statistically non-significant, reflecting the strong influence of hydrological dilution typical of the Cariri region. The positive relationship between pH and dissolved oxygen (r = 0.417; p = 0.165) suggests that slightly more alkaline waters tend to exhibit greater oxygenation, although the lack of statistical significance indicates that turbulence and water renewal are the primary drivers of DO (Khan et al. 2020; Medeiros et al. 2021). The negative correlation between temperature and DO (r = -0.399; p = 0.826), consistent with oxygen solubility, loses statistical strength due to increased natural aeration during rains (Martínez – Santos et al. 2021a,b). Correlations involving TSS with EC (r = 0.623; p = 0.388) and turbidity (r = 0.411; p = 0.929) reinforce that, although sediment transport increases during the rainy season, conductivity tends to decrease due to dilution, reducing the consistency of these associations (Albuquerque et al. 2019). Total phosphorus presented moderate correlations with pH (r = 0.490; p = 0.319) and BOD (r = 0.589; p = 0.132), reflecting predominantly particulate transport, whereas the significant correlation between thermotolerant coliforms and pH (r = 0.495; p = 0.004) indicates that more alkaline waters favor bacterial persistence (García – Rodríguez et al. 2022). In summary, the rainy period is dominated by hydrological variability, which reduces the strength of correlations between variables associated with organic and nutrient pollution.

In the dry period, by contrast, correlations became stronger and statistically significant, reflecting the intensification of overconcentration, salinization, and low self-purification capacity. Total nitrogen presented strong correlations with EC (r = 0.656; p = 0.039), turbidity (r = 0.722; $p < 0.001$), BOD (r = 0.855; $p < 0.001$), and TSS (r = 0.471; $p < 0.05$), as well as a negative correlation with DO (r = -0.748; $p = 0.039$), confirming its direct association with the degree of organic pollution and solute concentration (Khan et al. 2020; Medeiros et al. 2021). Total phosphorus showed very strong correlations with EC (r = 0.747; $p < 0.001$), turbidity (r = 0.846; $p < 0.001$), BOD (r = 0.825; $p < 0.001$$, TSS (r = 0.686; $p = 0.027$), and TN (r = 0.810; $p < 0.001$), in addition to a negative correlation with DO (r = -0.604; $p < 0.001$), confirming that it follows the behavior of other degradation indicators (Silva et al. 2020; Martínez – Santos et al. 2021a,b). EC strongly correlated with turbidity (r = 0.532; $p < 0.01$), BOD (r = 0.616; $p = 0.055$), TSS (r = 0.442; $p < 0.002$), TN (r = 0.656; $p = 0.039$), and TP (r = 0.747; $p < 0.01$), evidencing that the increase in salinity is directly associated with the input of urban and agricultural effluents (Albuquerque et al. 2019; Costa et al. 2020). BOD correlated strongly with turbidity (r = 0.831; $p = 0.036$), TN (r = 0.855; $p < 0.001$), TP (r = 0.825; $p < 0.001$), and negatively with DO (r = -0.555; $p < 0.05$), confirming that organic load is one of the main drivers of environmental degradation (Silva et al. 2020; García – Rodríguez et al. 2022). Turbidity presented very strong correlations with TSS (r = 0.880; $p < 0.001$), BOD (r = 0.831; $p = 0.036$), TN (r = 0.722; $p < 0.01$), and TP (r = 0.846; $p < 0.001$), confirming that the transport of sediments, organic matter, and nutrients occurs in an integrated manner, especially in urban stretches. In summary, during the dry period, TN, TP, EC, BOD, and turbidity form a core of highly interrelated variables, all associated with nutrient accumulation and organic pollution, while DO maintains negative correlations, reflecting hypoxic and anoxic conditions. This pattern is consistent with studies on urban and intermittent semi-arid rivers (Costa et al. 2020; Khan et al. 2020; Martínez – Santos et al. 2021a,b), confirming that the combination of low flow, high temperatures, and continuous sewage input creates a mutually reinforcing cycle of environmental degradation.

Water Quality Index (WQI) and Trophic State Index (TSI)

The integrated analysis of the mean WQI and TSI values for the years 2023 and 2024, considering three campaigns in the rainy season and two in the dry season, reveals a river continuum marked by degradation hotspots associated with urban areas in the Cariri Metropolitan Region. Regarding the WQI results, Fig. 4a presents the spatial behavior in terms of seasonal averages. At the headwaters (P1, P2), the values fall within the "good" category during the rainy season (52.9–54.3) and "fair" in the dry season (44.8–40.1), confirming that lower anthropogenic influence and higher discharge favor water quality. However, upon entering the urban zone (P3, P4), the indices drop drastically to "poor" and "very poor" during the dry period (22.1 and 17.9), reflecting the discharge of domestic, industrial, and hospital effluents. This pattern is consistent with the Kruskal–Wallis results, which indicated significant differences for turbidity, BOD, TN, and coliforms, as well as with the Spearman correlations, which showed a core of highly interrelated variables (EC, BOD, TN, TP, and turbidity) during the dry period, all associated with organic and nutrient pollution.

At P5, a relative improvement is observed (with WQI classified as "fair": 32.8 and 32.9 for the rainy and dry periods, respectively) due to the input of water from adjacent streams, suggesting the onset of self-purification. This process intensifies at P6, where the index rises to "fair/good" (42.4 and 39.4 for the rainy and dry periods, respectively) but drops again at P7 (31.4 and 24.6 for the rainy and dry periods, respectively). This sector receives the discharge of treated effluents from the largest municipal wastewater treatment plant. This decline in water quality may be related to the inefficiency of the stabilization pond that discharges effluents upstream. This behavior highlights the alternation between degradation and recovery reaches, characterizing urban hotspots interspersed with self-purification segments, a recurrent pattern in semi-arid rivers under strong anthropogenic pressure (Uddin et al. 2021; Chidiac et al. 2023).

In the rural and less populated stretches (P8–P11), WQI values remain within the "fair" range (39–45), with a significant improvement during the rainy season (up to 52.6 at P8), consistent with the effect of hydrological dilution. This seasonality confirms that the increase in discharge during the rainy period reduces pollutant concentrations and temporarily improves water quality, whereas overconcentration during the dry period intensifies salinization, organic loading, and eutrophication (Ribeiro et al. 2025; Duvoisin et al. 2025).

Regarding the TSI_{PT}, the spatial and seasonal behavior (Fig. 4b) confirms that the Salgado River exhibits a river continuum marked by eutrophication hotspots, particularly within the urban stretches of the Cariri Metropolitan Region. At the headwaters (P1, P2), the values fall into the mesotrophic category during the dry period (TSI_{PT} ~ 54) and progress to eutrophic in the rainy season (TSI_{PT} ~ 60–61), reflecting the particulate transport of phosphorus during rainfall events. This pattern is consistent with the obtained total phosphorus values, which remain near the lower limit of eutrophic, confirming that even areas with lower anthropogenic influence already present a risk of nutrient enrichment (Silva et al. 2023).

At the urban sampling sites (P3, P4), the indices reach supereutrophic to hypereutrophic levels (TSI_{PT}, 71–77) during both the rainy and dry periods, indicating strong anthropogenic pressure and a continuous input of effluents. This condition is consistent with the Kruskal–Wallis results, which indicated no significant difference for TP between the hydrological periods (p = 0.9434), related to elevated extreme values in both climatic seasons; this suggests that phosphorus is mobilized by both urban discharges and hydrological pulses. The Spearman correlation reinforces this diagnosis, showing that TP is strongly associated with EC, turbidity, BOD, TSS, and TN during the dry period, confirming that phosphorus follows the core of variables linked to organic and nutrient pollution (Martínez – Santos et al. 2021a,b).

In the subsequent stretches (P5–P7), high TSI_{PT} values (70–79) persist, with a particular emphasis on P7, which reaches hypereutrophic (TSI_{PT} = 79.2 in the rainy season). This result reflects the inefficiency of the municipal wastewater treatment plant, as previously discussed regarding the WQI values, and confirms the presence of a critical eutrophication hotspot. At P8, values remain between eutrophic and supereutrophy (62–70), indicating a relative improvement compared to the urban sites, yet remaining above mesotrophic thresholds. Along the crystalline valley stretch intersected by the Salgado River,

encompassing the municipalities of Aurora (P9), Lavras da Mangabeira (P10), and Icó (P11) (Fig. 1), the indices vary between 60 and 70, characterizing eutrophic conditions. This is consistent with urban stretches of lower population density and higher discharge, which favor dilution but do not eliminate the risk of eutrophication.

Seasonality is evident and well-defined between the hydrological periods. During the dry period, TSI_{PT} values remain elevated, reflecting overconcentration and the release of phosphorus from the sediment under anoxic conditions. In the rainy season, there is a relative improvement at certain sites, but particulate transport maintains the indices within eutrophic to hypereutrophic ranges. This pattern confirms that the Salgado River presents a vulnerability typical of semi-arid rivers, where the combination of low discharge, continuous sewage input, and climate variability intensifies the risk of eutrophication (Silva et al. 2023).

Conclusions

Based on the monitoring results and considering the fluvial gradient, a progressive degradation from the headwaters to the mouth of the Salgado River was observed across all campaigns. P1 and P2 at the headwaters in the Araripe Plateau presented the best conditions of compliance with the MPVs, notably with lower concentrations of TDS, nutrients, and coliforms. Downstream from the headwaters, the urban stretches between P3 and P7 exhibited multiple violations of the MPVs, primarily driven by the strong influence of sewage discharges and the consequent increase in BOD, nutrient concentrations, and the presence of coliforms. In peri-urban stretches (P8 to P11), degradation persisted through increased salinity and nutrient concentrations, despite signs of internal self-purification mechanisms taking effect, which led to the partial recovery of certain water quality parameters (turbidity/DO/BOD/TSS). This spatial pattern is typical of semi-arid rivers subjected to the combination of climate seasonality, urban pressure, and low self-purification capacity, as described in recent studies on non-perennial rivers and urban river systems in arid and semi-arid regions.

The set of physicochemical and microbiological variables reveals a hydrochemical gradient consistent with the river continuum and regional geology. At the sedimentary headwaters (P1–P2), the water is more diluted, less hard, and exhibits better oxic conditions. In the urban stretch (P3–P7), severe degradation is observed, with high BOD, nutrients, coliforms, turbidity, and oxygen depletion, especially during the dry period. In the peri-urban crystalline valley (P8–P11), high alkalinity, hardness, and mineralization are maintained, with the persistence of diffuse impacts and the return of water from dams. This pattern is consistent with previous diagnoses of the Salgado River basin and other rivers in the Brazilian semi-arid region, which point to the combination of irregular rainfall, the use of rivers as wastewater sinks, sediment transport during rainfall events, and overconcentration during dry periods as the central drivers of surface water quality loss.

This spatial diagnosis highlights clear priorities for management: (1) control of domestic sewage in densely populated urban areas (P3–P7), the primary source of BOD, nutrients, and TC; (2) urban

stormwater drainage management to reduce peaks in turbidity and TSS; (3) restoration of riparian vegetation along urban and peri-urban stretches; (4) continuous monitoring focusing on hotspots P3–P7; (5) realistic quality targets in line with classification into a less restrictive class (Class II), such as DO > 5 mg L^{-1}, BOD < 5 mg $L^{-1,}$ TP < 0.1 mg L^{-1}, and TC < 1000 MPN 100 mL^{-1}; (6) integration with water security policies aligned with the Sustainable Development Goals (SDGs) of the 2030 Agenda.

The WQI and TSI_{PT} results, combined with the Kruskal–Wallis analyses and Spearman correlations, reveal that the Salgado River exhibits a pattern of selective and seasonal degradation, with critical stretches of very poor water quality and hypereutrophic in urban centers, partial self-purification segments in transition areas, and mesotrophic to eutrophic conditions in rural zones. The integration of indices confirms that the river functions as a fluvial continuum, where urban pollution hotspots disrupt quality, but reaches with higher discharge and lower population density favor partial recovery. This seasonal dynamic, marked by dilution during the rainy season and pollutant concentration during the dry season, is widely documented in tropical semi-arid rivers. Therefore, water quality management in the Salgado River must simultaneously consider hydrological seasonality, urban pollution hotspots, and eutrophication processes to guide public sanitation and conservation policies compatible with the climatic and socio-environmental reality of the semi-arid region.

Declarations

Conflict of interest

The authors have no relevant financial or non-financial interests to declare.

Ethical Approval

This is not applicable

Clinical trial number

This is not applicable.

Consent to Participate

This is not applicable

Consent to Publish

This is not applicable

Competing Interests

The authors declare that they have no competing interests

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Authors' Contribution

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Data Availability Statement

https://www.kaggle.com/code/marcellaaraujomacedo/water-quality-data-for-the-salgado-sub-basin

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Figures

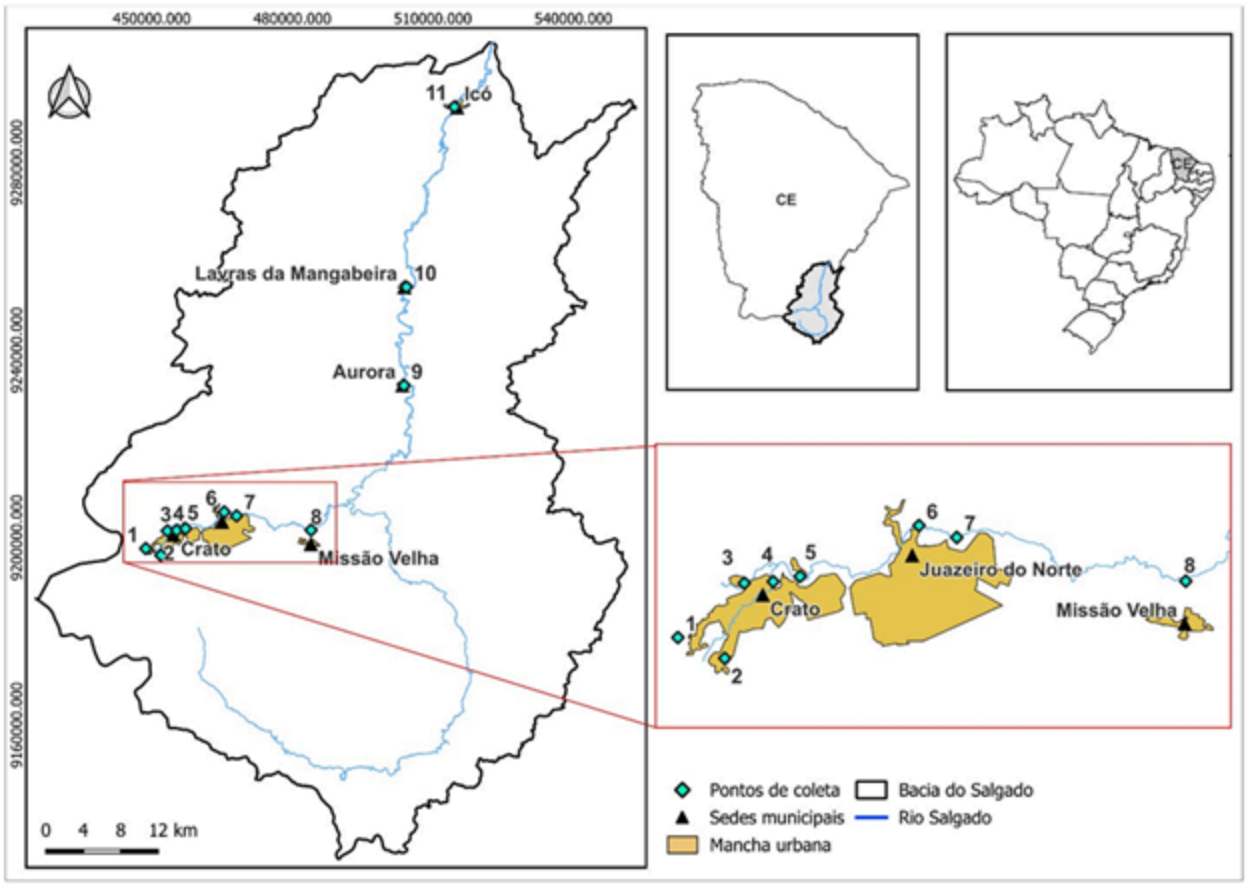


Figure 1

Location map of the sampling sites along the Salgado River, northeastern Brazil.

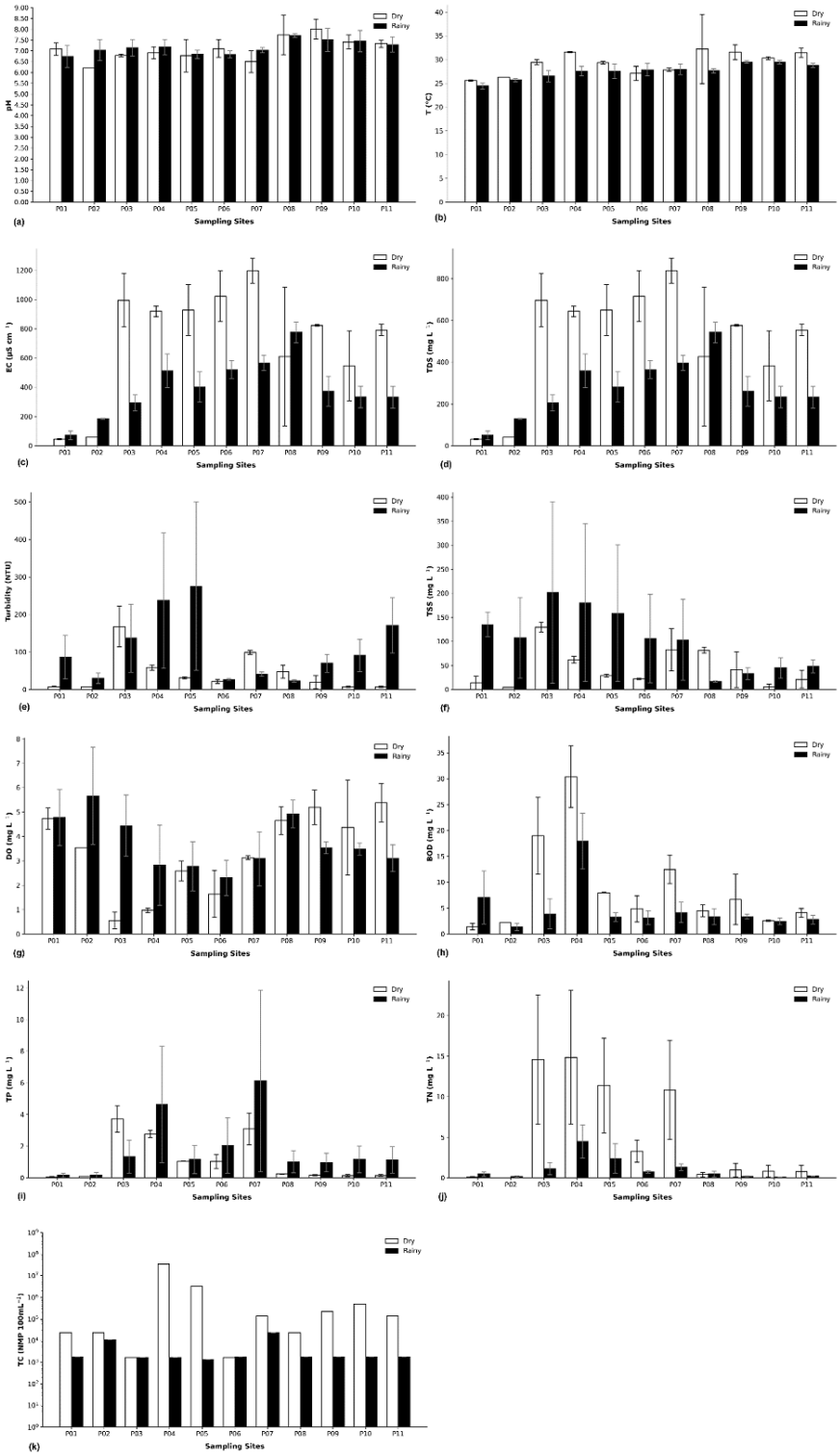


Figure 2

Behavior of Physicochemical and Bacteriological Variables across Sampling Sites in the Salgado River, Northeastern Brazil, during the Rainy and Dry Seasons (2023–2024)

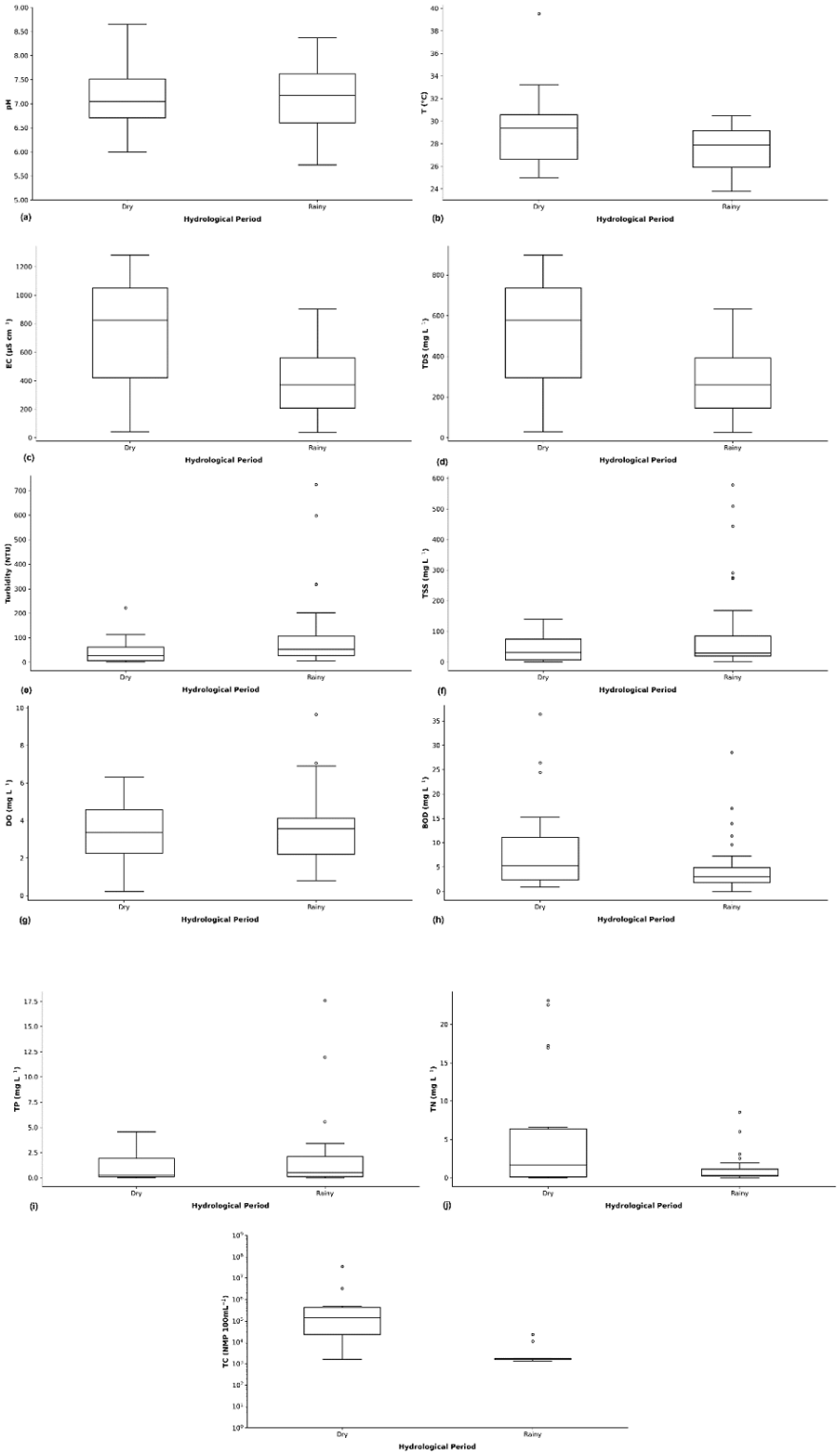


Figure 3

Box-plots of physicochemical and bacteriological variables across sampling sites in the Salgado River, Northeastern Brazil, during the rainy and dry seasons (2023–2024).

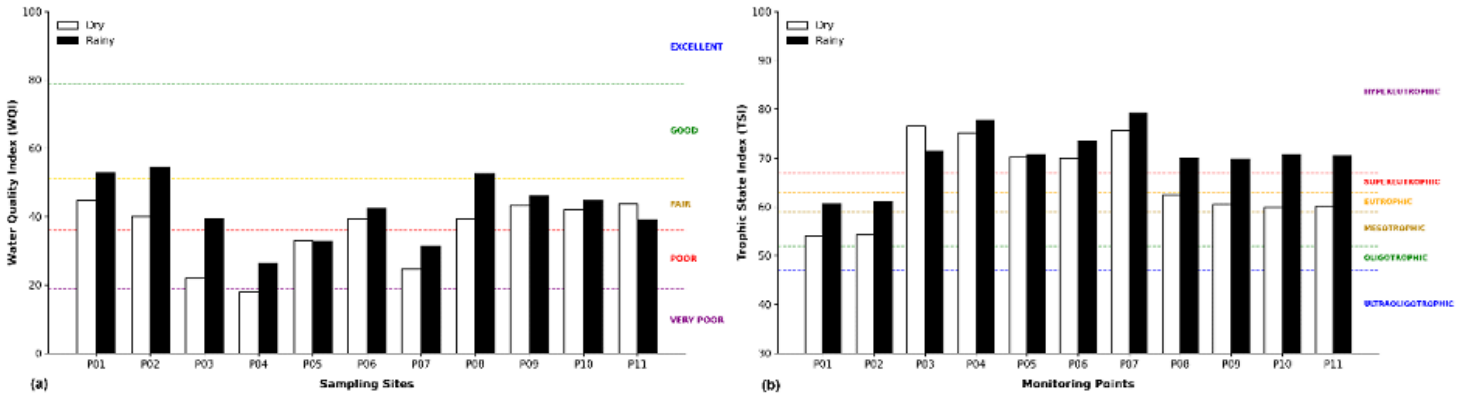


Figure 4

Spatial and Temporal Variation of the Water Quality Index (WQI) and Trophic State Index (TSI) across Sampling Sites in the Salgado River, Northeastern Brazil, during the Rainy and Dry Seasons (2023–2024)

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