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Characterization of the environmental systems of municipalities in water collapse in the state of Paraíba

Caracterização dos sistemas ambientais de municípios em colapso hídrico no estado da Paraíba

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Abstract: The Brazilian Semi-Arid region, especially the Northeast, faces the phenomenon of droughts, whose adverse effects are exacerbated by the degradation of water quality and inadequate water resource management. The state of Paraíba has the lowest per capita water availability index in Brazil, with a critical classification. Thus, the study aims to map and characterize the environmental systems of the reservoirs that supply small municipalities in Paraíba: Bananeiras, Casserengue, Esperança, Picuí, Pocinhos, Remígio, and Solânea. Remote sensing tools, information systems about the watersheds, and water quality data from 2010 to 2020 were utilized. The data analysis revealed that the reduced intensity of the rainfall regime, combined with the replacement of native vegetation by pasture areas, resulted in various consequences for the environmental systems of the studied municipalities, affecting the well-being and quality of the local biota. Insufficient water recharge negatively impacted water quality in these reservoirs, notably increasing turbidity and total phosphorus levels. Therefore, the study highlights the importance of sustainable practices and integrated water resource management to ensure the long-term sustainability of local environmental systems.

Keywords: Brazilian semi-arid; Watersheds; Water quality.

Resumo: O Semiárido Brasileiro, especialmente a Região Nordeste, enfrenta o fenômeno de secas, que tem seus efeitos adversos potencializados com a degradação da qualidade da água e gestão inadequada dos recursos hídricos. O estado da Paraíba apresenta o menor índice de disponibilidade hídrica per capita do Brasil, com classificação crítica. Assim, o estudo busca mapear e caracterizar os sistemas ambientais dos reservatórios que abastecem pequenos municípios da Paraíba: de Bananeiras/PB, Casserengue/PB, Esperança/PB, Picuí/PB, Pocinhos/PB, Remígio/PB e Solânea/PB. Utilizou-se ferramentas de sensoriamento remoto, de sistemas de informações sobre as bacias hidrográficas e e dados sobre qualidade da água, entre os anos de 2010 a 2020. A partir da análise dos dados, verificou-se que a redução de intensidade do regime pluviométrico associada a substituição de vegetação nativa por áreas de pastagem acarretou diversas consequências para o sistema ambiental dos municípios estudados, afetando o bem-estar e a qualidade da biota local. A recarga hídrica insuficiente alterou negativamente a qualidade da água nesses reservtórios, com destaque para o aumento da turbidez e do fósforo total. Desse modo, o trabalho ressalta a importância de práticas sustentáveis e de uma gestão integrada dos recursos hídricos para garantir a sustentabilidade a longo prazo dos sistemas ambientais locais.

Palavras-chave: Semiárido brasileiro; Bacias hidrográficas; Qualidade da água.

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1. Introduction

Water is a fundamental natural resource and is present in various physical, chemical, and biological processes that occur on the planet. The availability of water, in sufficient quantity and of good quality, is indispensable for living beings, as well as for the development of society and the economy of a region.

Some regions of the world are characterized by low rainfall, such as the Northeast Brazil, most of which is located in the Semi-Arid region. These physical and climatic conditions lead to the formation of a hydrographic network composed of intermittent water bodies, making the territory highly vulnerable and susceptible to the adverse effects of drought (LEMOS, 2020; MENDES *et al.*, 2022). This reality is exacerbated by the degradation of water quality and the inefficient management of water resources in this region, in the face of growing demands for human supply and, especially, for industrial activities and agriculture.

Challenges related to water security and water quality tend to intensify across the three dimensions of drought implications: environmental, social, economic, and political (BRITO *et al.*, 2020; BRITO *et al.*, 2022). Thus, integrated studies play an important role in nature, which is justified by the numerous works that seek a systemic view of the environment (COSTA; OLIVEIRA, 2019). Interdisciplinarity, in addition to contributing to the understanding of environmental systems, can aid in the decision-making process to reduce or eliminate the negative impacts caused by this extreme event, allowing for a more comprehensive approach and more effective confrontation.

In recent years, some municipalities in the state of Paraíba have been experiencing a water crisis resulting from the combination of various factors: climatic variations, long periods of drought, uncontrolled water use, and the lack of management of water sources (SOUSA *et al.*, 2023). In addition to compromising the population's supply and the economy of the municipalities, the low volume of reservoirs causes changes in the environment in which they are inserted, from vegetation changes to the degradation of water quality in the water bodies (FREITAS; ARAÚJO, 2021; PEREIRA *et al.*, 2020). According to the study by Alves *et al.* (2024), which estimated the Water Security Index (WSI) of 20 municipalities in the state of Paraíba, with populations of up to 20,000 inhabitants, there is water vulnerability in the area, with 50.0% of the municipalities presenting a medium WSI and the rest obtaining a low classification.

Therefore, the objective of this work is to map and characterize the environmental systems of the currently collapsed reservoirs that supply the small municipalities of Bananeiras/PB, Casserengue/PB, Esperança/PB, Picuí/PB, Pocinhos/PB, Remígio/PB, and Solânea/PB, using remote sensing tools, information systems on hydrographic basins, and water quality databases of the analyzed water bodies. Thus, the study not only addresses the physical and geographical characterization of the study areas but also evaluates the environmental systems in the context of integrated landscape analysis, land use and occupation, and changes in the water quality of the reservoirs.

2. Methodology

In order to achieve the proposed objective, the study is based on four methodological steps presented in the flowchart in Figure 1 and detailed this section.

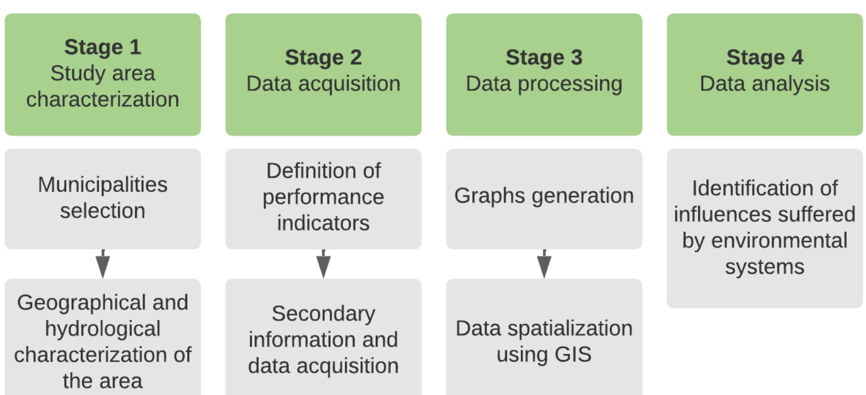

Figure 1 – Methodological flowchart of the study.
Source: Authors (2024).

2.1 Study area characterization

Paraíba is located in Northeastern Brazil and has 223 municipalities, of which 213 (95.5%) have populations under 50,000 inhabitants. The state's territory spans two biomes: the Atlantic Forest and the Caatinga, with the latter being predominant throughout the state, while the Atlantic Forest is concentrated only in the coastal region. It is important to highlight that anthropogenic urbanization activities dominate the state, occupying about 65% of its territory. The hydrogeological characteristics of Paraíba are unfavorable, as it has the second-lowest per capita water availability index in Brazil, classified as being in a critical situation (AESA, 2006).

Given the study's objective of identifying the consequences suffered by environmental systems in municipalities experiencing water collapse during droughts recorded over the past decade, the sample was limited to small municipalities (those with less than 50,000 inhabitants, according to the classification used in the 2010 IBGE Census), participating in the Decentralized Execution Agreement (TED) nº 003/2019, signed between the National Health Foundation (Funasa) and the Federal University of Campina Grande (UFCG) for the development of Municipal Basic Sanitation Plans. The situation of water collapse in these municipalities was identified based on a study conducted during the technical-participatory diagnostic stage of the TED (FUNASA; UFCG; 2021).

The map in Figure 2 shows the selected municipalities, followed by their geographic and rainfall characterization.

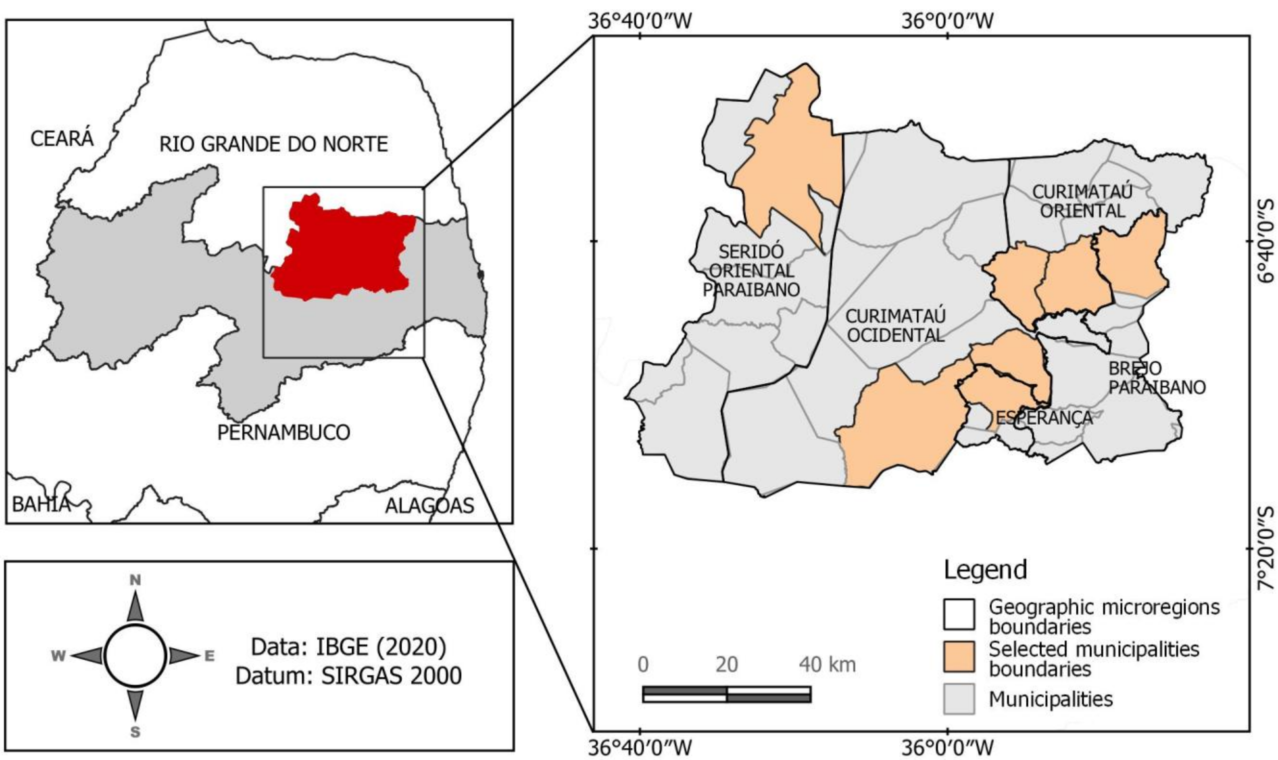

Figure 2 – Location of the municipalities studied in Paraíba.
Source: Authors (2024).

The municipalities included in the study are located in two mesoregions of Paraíba: Borborema and Agreste. The municipality of Picuí/PB, located in Borborema, is part of the Seridó Oriental Paraibano microregion. The other municipalities are part of the Agreste Paraibano, with Pocinhos/PB and Remígio/PB situated in the Curimataú Ocidental microregion, Casserengue/PB and Solânea/PB in Curimataú Oriental, Bananeiras/PB in Brejo Paraibano, and Esperança/PB in the Esperança microregion, as shown in Figure 2. Table 1 presents population data as well as economic data (gross domestic product - GDP per capita) and the Municipal Human Development Index (MHDI) for each of the studied municipalities.

Table 1 – Total population and GDP per capita by municipality.

Municipality	**Total Population (inhabitants - 2010)**	**GDP per Capita (R$/inhabitant/year – 2019)**	**MHDI (2010)**
Bananeiras/PB	21,851	10,316.32	0.568
Casserengue/PB	7,058	8,200.40	0.514
Esperança/PB	31,095	13,352.01	0.623
Pocinhos/PB	17,032	13,069.68	0.591
Picuí/PB	18,222	10,316.32	0.608
Solânea/PB	26,693	11,395.82	0.595
Remígio/PB	17,581	8,884.28	0.607

Source: IBGE (2010; 2019).

As shown in Table 1, all the municipalities have populations ranging from 7,000 to 32,000 inhabitants, classifying them as small municipalities. The GDP per capita of these municipalities, which reflects the economic output per inhabitant, is below the state average of R$ 16,108.00 per inhabitant per year. Regarding the MHDI, Paraíba presented a score of 0.658, indicating that the municipalities under study have values below the state's average.

Regarding rainfall in the study area, the map in Figure 3 shows the isohyets with the average annual rainfall, based on data collected from the Hydroweb Portal (ANA, 2024). It is noticeable that the municipalities of Picuí/PB and Pocinhos/PB belong to an area of very low rainfall (400 to 600 mm). In contrast, the municipalities of Bananeiras/PB and Solânea/PB experience higher rainfall, with an average annual rainfall index ranging from 800 to 1100 mm. The other municipalities (Casserengue/PB, Remígio/PB, and Esperança/PB) are located in an area with rainfall indices ranging from 600 to 800 mm per year.

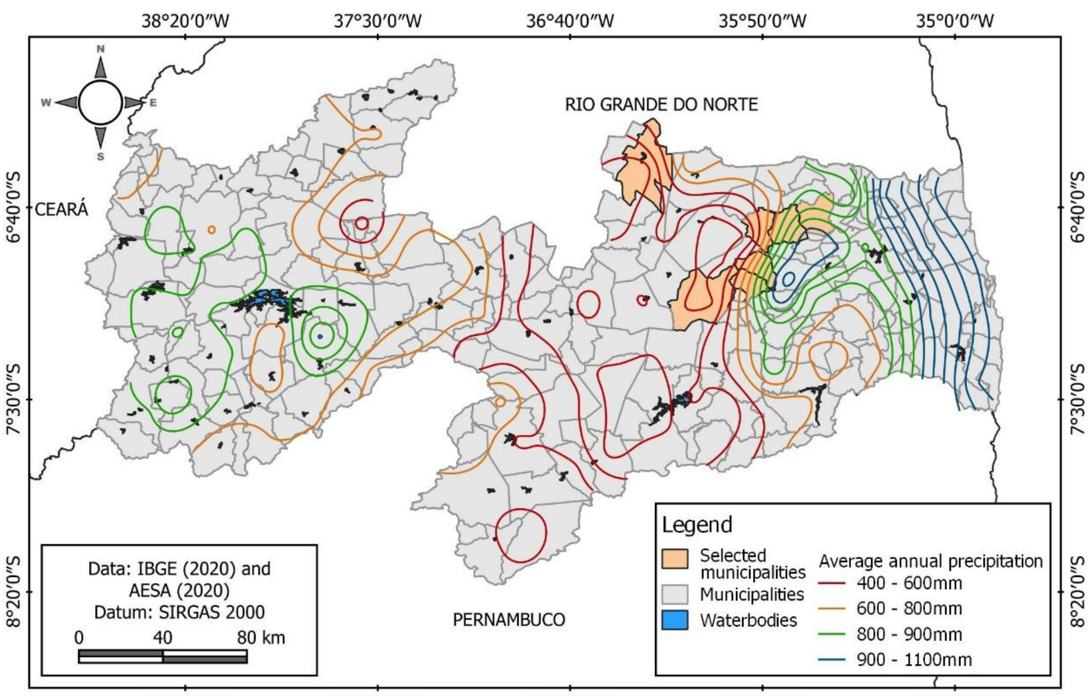

Figure 3 – Map of average annual rainfall in the state of Paraíba.
Source: Authors (2024).

2.2 Data collection

To understand the dynamics of the environmental systems in the region concerning the reduced occurrence of hydro-meteorological events, indicators and information were selected to reflect physical, biological, and anthropogenic aspects in the study area between 2010 and 2020, a period that includes the drought interval, similar to the studies by Farias and Mendoça (2022), Mendes *et al.* (2021), and Oliveira and Cestaro (2016). Most of these indicators were obtained through databases such as the Brazilian Institute of Geography and Statistics (IBGE), the Executive Agency for Water Management of the State of Paraíba (AESA), MapBiomas, and the National Water and Basic Sanitation Agency (ANA). The list of indicators used can be found in Table 2.

Table 2 – Indicators used for the analysis of aspects.

Analyzed aspect	Indicator	Description	Source
Water availability	Surface water	Area of the territory occupied by water bodies	MapBiomas (2022)
Cimatology	Average annual precipitation	Average amount of precipitation accumulated annually	AESA (2006)
Vegetation	Pasture quality	Level of degradation of pasture based on indices calculated using remote sensing techniques	MapBiomas (2022)
Fauna	Cattle production	Heads of cattle produced annually	IBGE (2020)
Anthropic occupation	Land use and occupation	Stratification of land use according to type	MapBiomas (2022)
Water quality	Phosphorus concentration	Average levels of the mentioned quality parameters in reservoirs of the microregion	ANA (2020) and AESA (2022)
	Biochemical Oxygen Demand		
	Dissolved Oxygen		
	Turbidity		

Source: Authors (2024).

Other physical natural aspects, important for the analysis conducted, were also considered during the data collection stage. However, during the research, a lack of data to measure these aspects was noted, especially in the case of small municipalities located in the Northeast.

2.3 Data processing

The analysis of the data collected in the previous stage was carried out through the generation of graphs and maps. The graphs showing the historical series of indicators for each of the selected municipalities were generated using Microsoft Excel. In the produced graphs, the average indicators for the state of Paraíba were also added as a comparison parameter with the other municipalities. Additionally, to facilitate the visualization of the effects on the analyzed aspects, the values for the year 2010 were considered as the baseline for the historical series.

For the purpose of analyzing the influence of the drought period on aspects of water availability, climatology (average annual rainfall indices), vegetation, and anthropogenic occupation, the obtained indicators were spatialized through maps produced in QGIS 3.16 and correlated with the boundaries of the selected municipalities for the study.

2.4 Data analysis

With the data, graphs, and maps produced, reflections were made regarding the existence and level of impacts on environmental systems caused by the period of water scarcity in the study area. In this stage, an effort was made to correlate the different aspects raised through data confrontation, aiming to identify patterns among them.

In this study, the average values of the parameters turbidity, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), and Total Phosphorus (TP) from reservoirs that experienced water collapse in the microregions of Paraíba were also analyzed, based on data obtained from the National Water and Basic Sanitation Agency (ANA). Additionally, values from reports prepared by the Executive Agency for Water Management of the State of Paraíba (AESA) were used.

According to the National Environmental Council (CONAMA) Resolution No. 357/2005, which addresses the classification of water bodies and environmental guidelines for their classification and establishes conditions for the discharge of effluents, water quality control aims to protect user health and ensure the balance of aquatic life.

As noted by Von Sperling (2014), turbidity represents the degree of interference with the passage of light through water. Turbidity is a characteristic that depends on the presence of organic particles (sand, silt, and clay) and organic debris, bacteria, and plankton in general. At elevated levels, it can affect water bodies biologically, chemically, and physically by reducing sunlight penetration, thereby limiting photosynthesis and the oxygen replenishment in water (TOMPERI *et al.*, 2020).

Dissolved Oxygen (DO) is essential for aerobic organisms, which survive in the presence of oxygen. In the stabilization of organic matter, bacteria utilize oxygen in their respiratory processes, which can lead to a reduction in its concentration in the environment. Depending on the magnitude of this phenomenon, various aquatic organisms, including fish, may die. If oxygen is completely consumed, anaerobic conditions (absence of oxygen) occur, resulting in unpleasant odors (VON SPERLING, 2014). Furthermore, according to Raj *et al.* (2021), DO plays a fundamental role in the self-purification process of water bodies, and its concentration varies spatially and temporally.

Biochemical Oxygen Demand (BOD) reflects the amount of oxygen required to stabilize carbonaceous organic matter through biochemical processes. Von Sperling (2014) states that BOD indirectly determines the organic matter content in water bodies, thus serving as an indication of the potential for Dissolved Oxygen consumption.

The accumulation of phosphorus is one of the limiting factors for productivity in water bodies, and along with nitrogen, is identified as a major cause of eutrophication in aquatic ecosystems. This nutrient can originate from natural sources (present in rock composition, carried by surface runoff from rainwater, particulate material in the atmosphere, and resulting from the decomposition of allochthonous organisms) or from human interference, through the discharge of sewage, industrial effluents, and leaching from agricultural areas (CETESB, 2018; JUPP *et al.*, 2020). Table 2 presents the standard values established for the parameters turbidity, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), and Total Phosphorus (TP) by CONAMA Resolution No. 357/2005 for the freshwater category.

Table 3 – Water quality standards for water bodies.

Parameters	Class I	Class II	Class III
Turbidity (UNT)	Up to 40	Up to 100	Up to 100
Dissolved Oxygen (mg/L O_2)	Greater than 6	Greater than 5	Greater than 4
Biochemical Oxygen Demand (mg/L)*	Up to 3	Up to 5	Up to 10
Total Phosphorus (mg/L P)	Up to 0,02	Up to 0,03	Up to 0,05

Source: Adapted from CONAMA (2005).

3. Results and discussion

Among the consequences of a water crisis resulting from drought periods is the deterioration of water quality in sources, leading to an imbalance in the aquatic system. The reduction in the volume of water bodies can influence the chemical reactions in the medium, trigger pollution processes, and cause negative impacts on the quality of life of living beings (ROCHA JÚNIOR *et al.*, 2018). Thus, monitoring the physical and chemical parameters of water is essential for protecting this natural resource and determining whether it is suitable for its intended uses.

Figure 4 presents the average turbidity values in the reservoirs of the collapsed microregions. It is evident that, between the years 2016 and 2020, the parameter showed elevated values, reaching approximately 92 NTU, about 56.5% higher than the limit allowed for class I waters. This is likely due to the lower water volume in the reservoirs and, consequently, a lower dilution of suspended matter present in the water sources, as observed by Sousa et al. (2020) and Silva et al. (2020).

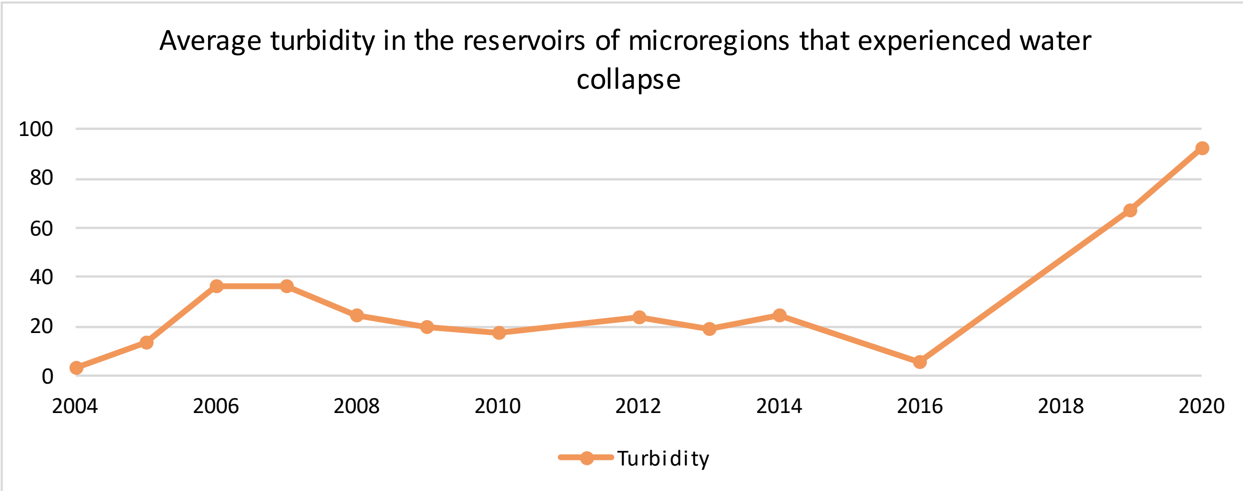

Figure 4 – Average values of turbidity between 2004 and 2020.
Source: Authors (2024).

Although it is within the standard established by CONAMA Resolution No. 357/2005 for freshwater classes II and III, high turbidity levels can reduce the penetration of solar radiation in the water body and hinder photosynthesis, reducing oxygen replenishment in the environment and causing an imbalance in the aquatic system (TOMPERI *et al.*, 2020).

Moreover, the particles causing the high turbidity can interfere with the efficiency of water treatment processes for human consumption, providing protection for pathogenic organisms, which prevents the disinfectant from acting on them. This risk is evidenced in the Technical-Participatory Diagnostics of the Municipal Basic Sanitation Plans (FUNASA; UFCG, 2021), as the municipalities of Bananeiras, Esperança, Remígio, and Solânea presented values outside the potability standards established in Ministry of Health Ordinance No. 888/2021, between 2016 and 2019.

Another parameter that showed alarming behavior in all analyzed years was Total Phosphorus. According to Figure 5, the average TPvalues ranged from 0.171 mg/L P to 0.583 mg/L P, averaging 94.7%, 92.0%, and 86.7% above the standards established in CONAMA Resolution No. 357/2005 for freshwater classes I, II, and III, respectively. Ferreira *et al.* (2023) reinforce that, in addition to being an indicator of the presence of wastewater in water sources, elevated TP levels can result in eutrophication caused by excess nutrients, leading to excessive growth of organisms such as algae and cyanobacteria. An eutrophic environment acquires turbid coloration, increased turbidity, and decreased oxygen levels, resulting in the death of various aquatic species.

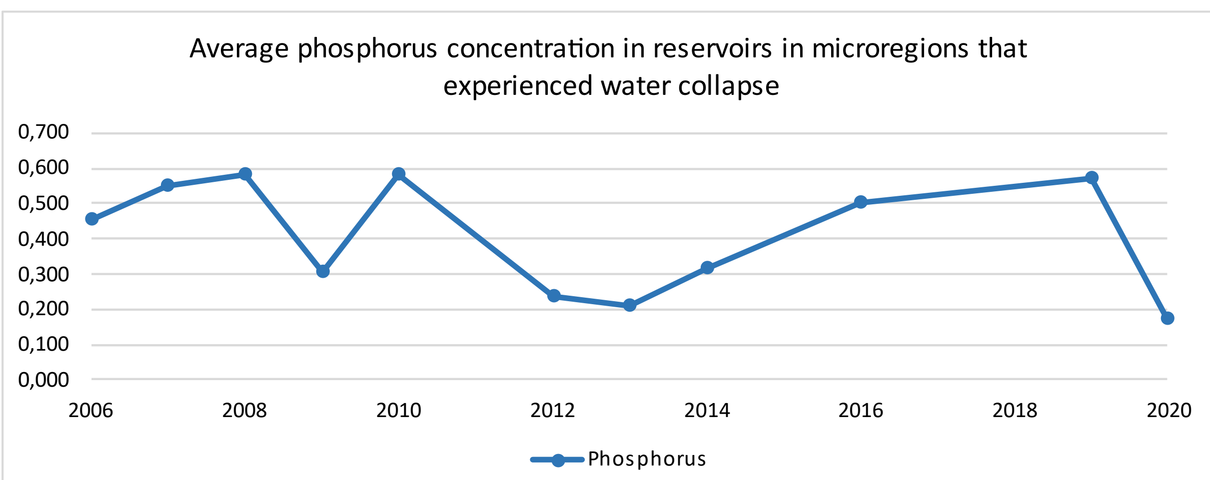

Figure 5 – Average values of total phosphorus concentration between 2004 and 2020.
Source: Authors (2024).

Regarding Biochemical Oxygen Demand and Dissolved Oxygen, both parameters were within the standards required by CONAMA Resolution No. 357/2005 for freshwater, as presented in Figures 6 and 7. The average values of Dissolved Oxygen remained above 6 mg/L, which may have contributed to maintaining the balance of the aquatic environments in the reservoirs throughout the entire period of collapse. There is a resilience of the reservoirs to the impacts of the water crisis, with a compensation between the levels of biodegradable organic load (BOD) and its degrading agent (DO), despite the possible eutrophication indicated by the levels of total phosphorus (Figure 5).

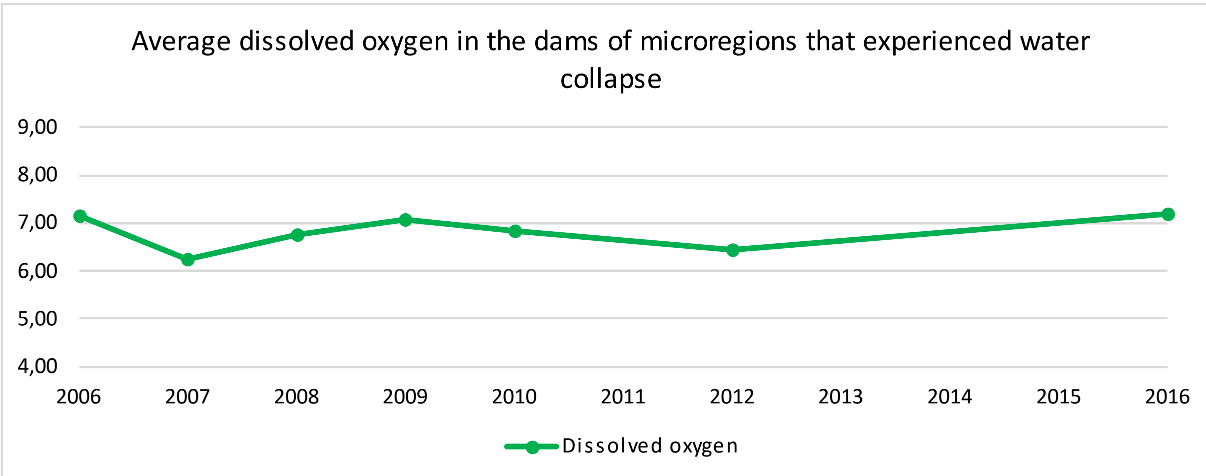

Figure 6 – Average values of Dissolved Oxygen between 2004 and 2020.
Source: Authors (2024).

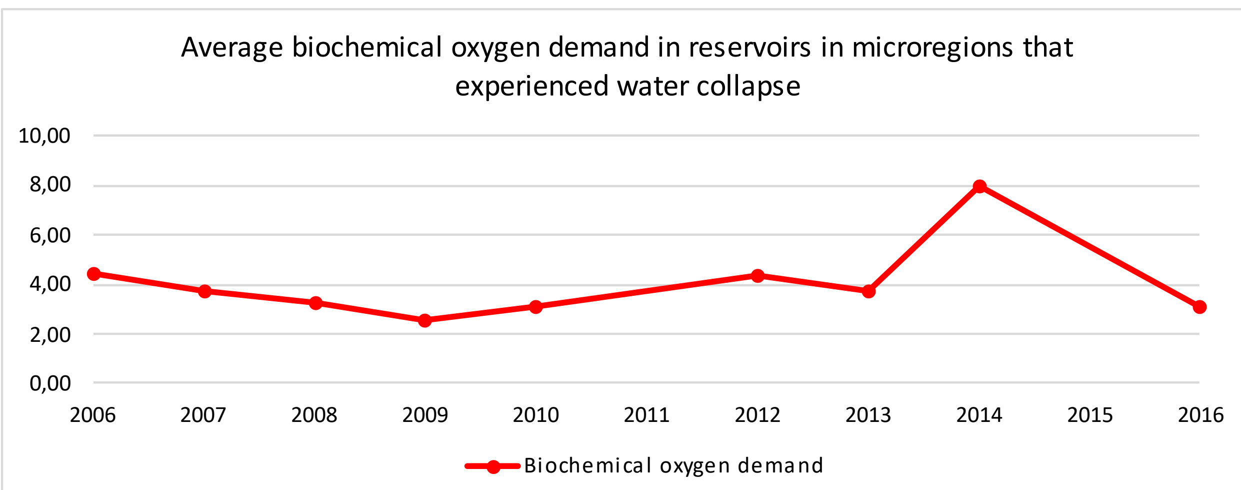

Figure 7 – Average values of Biochemical Oxygen Demand between 2004 and 2020.
Source: Authors (2024).

The anthropic dynamics of land occupation in the region during the drought period can be observed through Figure 8. There is a regression process of savanna natural formation from 2010 until the peak of the water collapse in the municipalities of the Seridó Oriental and Curimataú Ocidental microregions, such as Picuí/PB and Pocinhos/PB, while large areas of pasture emerge. The replacement of native vegetation with pastures can lead to deforestation and soil erosion, resulting in increased sedimentation in reservoirs. This can negatively affect water quality and hinder water recharge due to changes in infiltration and evaporation patterns (Oliveira *et al.*, 2023). On the other hand, the municipalities of Curimataú Oriental and Brejo Paraibano showed an increase in their natural formations.

There is also the disappearance of water bodies in a large part of the region due to low rainfall during the analyzed period, which hinders the development of agriculture and livestock along their banks. The graphs shown in Figure 9 help visualize the transition process of land use by presenting the percentages of each land occupation class in the selected municipalities for the three analyzed years.

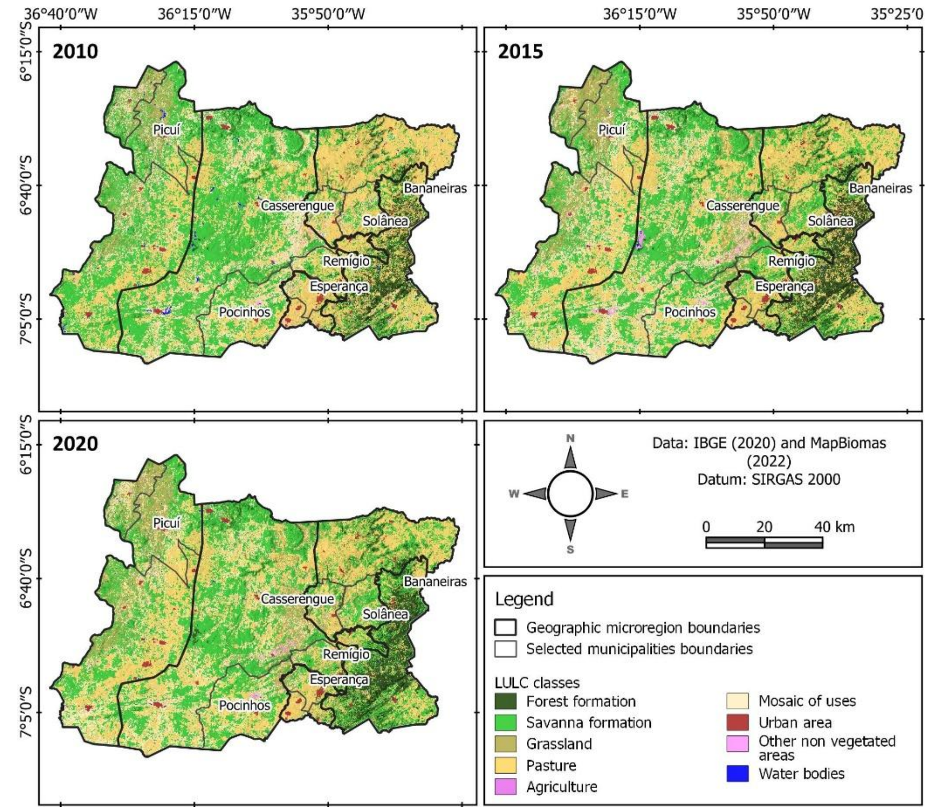

Figure 8 – Land use and occupation for the studied municipalities.
Source: Authors (2024).

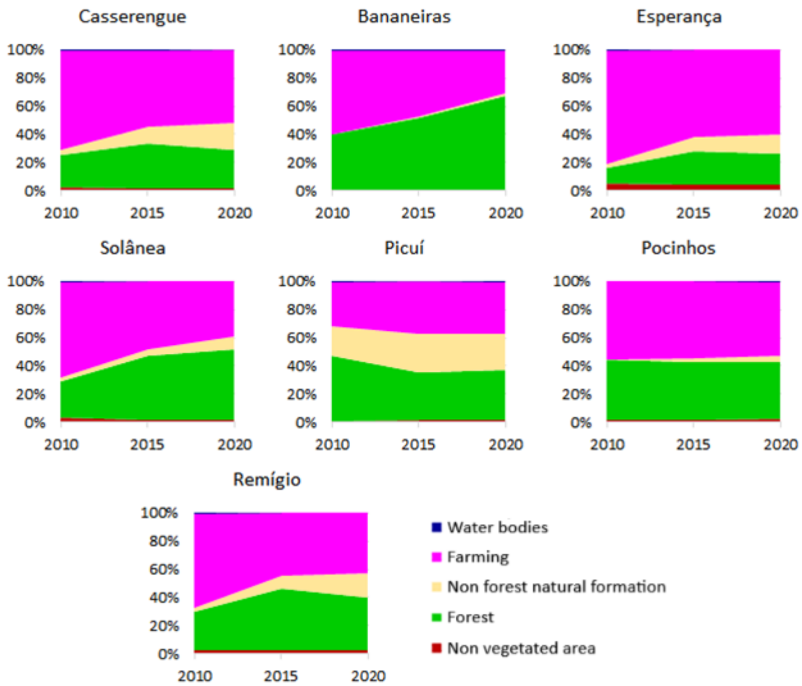

Figure 9 – Proportion of land use and occupation classes in the studied municipalities.
Source: Authors (2024).

It is evident that with the improvement in the rainfall regime in the region starting in 2015, there is a slight easing of the process of losing agricultural areas, caused by the increase in non-forested natural formation areas. In none of the analyzed municipalities, except for Picuí/PB, where agricultural areas increased during the drought period, did productive areas return to the levels prior to the water collapse. Thus, it is understood that the occurrence of extreme events of this type directly affects production and anthropogenic land occupation, with no immediate reestablishment post-event.

In Figure 10, it is noticeable for the year 2015, the peak of the water collapse in the municipalities, a significant increase in severe pasture degradation compared to 2010, predominantly in the municipalities of Picuí/PB, Pocinhos/PB, and Esperança/PB. The decline in pasture quality between these years may be related to the lack of water availability for maintaining plant species, given that water collapse involves not only water supply but the entire environmental system of the locality.

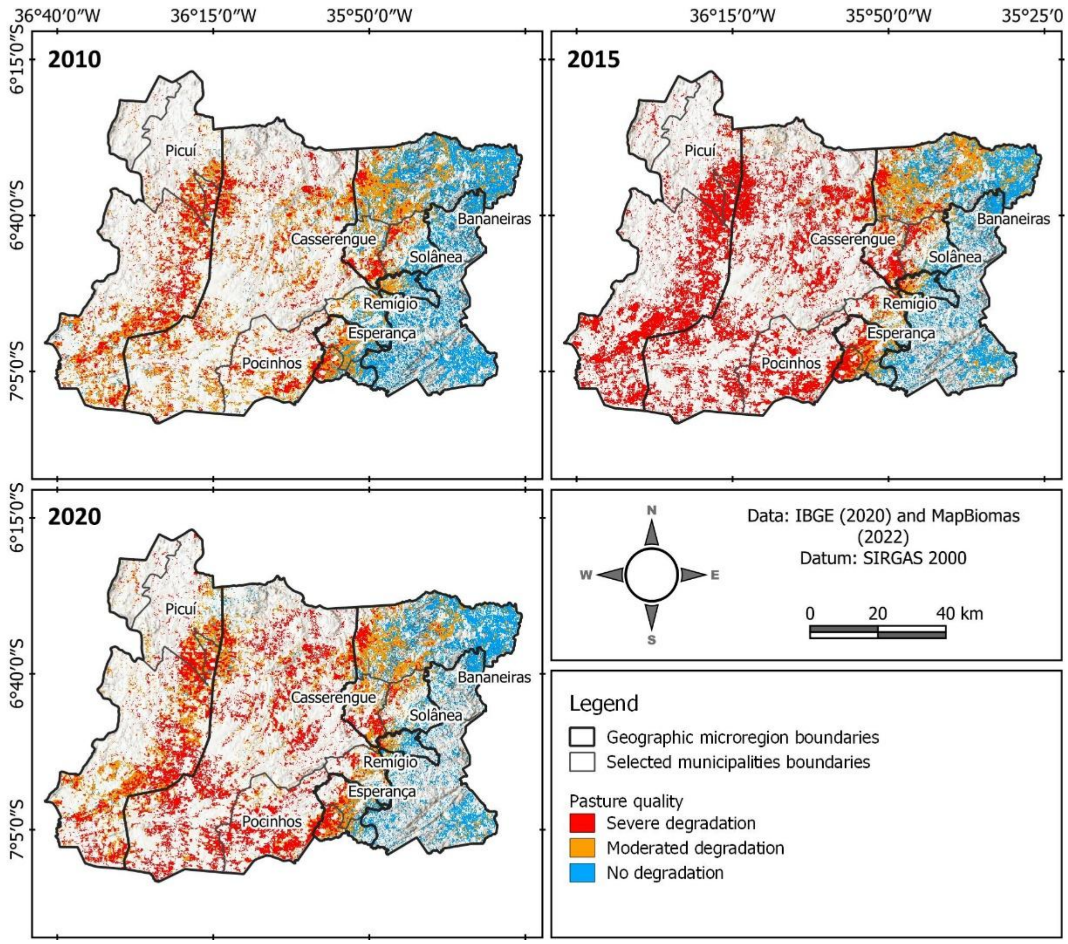

Figure 10 – Quality of the pasture in the study area.
Source: Authors (2024).

For the municipalities of Solânea/PB and Bananeiras/PB, the area without degradation remained proportional, indicating that in these municipalities, the onset of water collapse had little effect on vegetation quality. Between 2015 and 2020, a period during which there was an improvement in the rainfall regime in the northeastern region, pasture quality improved considerably across the territory; however, there was still a reduction in areas without degradation. Thus, to understand the quantification of degradation in the territory, Figure 11 presents the graph showing the percentage of pasture with severe degradation for each of the municipalities over the three years.

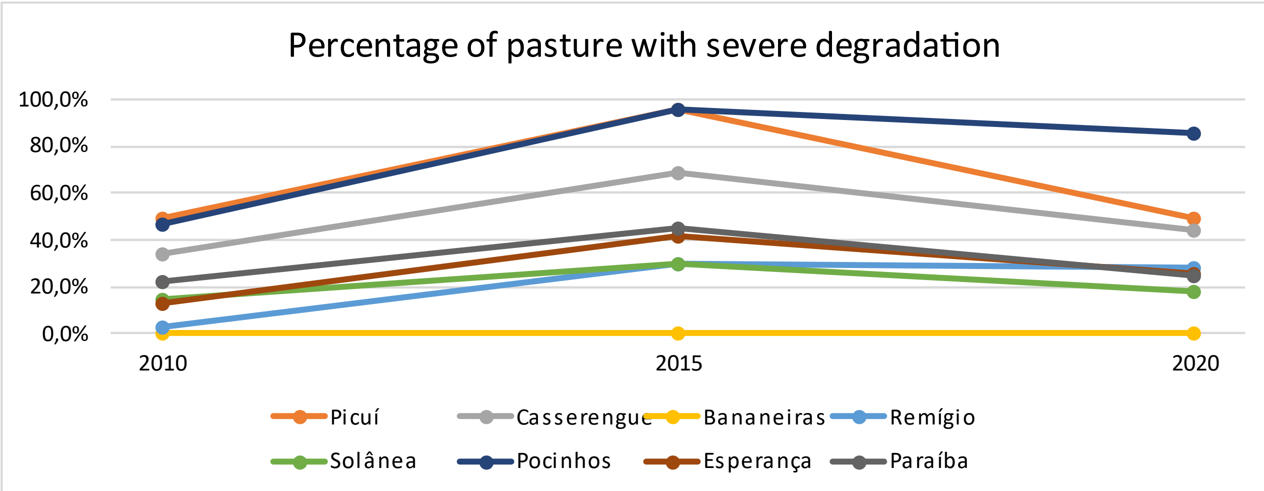

Figure 11 – Percentage of pasture with severe degradation for the municipalities studied.
Source: Authors (2024).

It is noticeable that the municipality of Bananeiras/PB had no areas of severe degradation from 2010 to 2020, indicating that the water collapse did not affect pasture quality in this municipality. The municipalities of Pocinhos/PB and Picuí/PB already had the highest rates of severe degradation among the studied municipalities in 2010, reaching severe pasture degradation rates above 90% by 2015. With the intensification of precipitation from 2015 to 2020, there was a reduction in severe degradation of the pasture, except for the municipality of Remígio/PB, which showed a slight increase in its rate.

4. Final considerations

As a consequence of the reduced intensity of the rainfall regime, the water collapse led to several consequences for the overall environmental system of the studied microregions, affecting the quality of life for both animals and plants . Regarding land use and occupation, there was a regression in natural formations between 2010 and 2015 in parts of the territory, despite the caatinga vegetation showing greater resilience to water consumption. From 2015 to 2020, there was a slight easing of the loss of agricultural areas, due to the increase in areas of non-forest natural formations.

Concerning pasture quality, there was a sharp increase in severe degradation between 2010 and 2015, predominantly in the microregions of Seridó Oriental and Curimataú Ocidental. However, in the Curimataú Oriental and Brejo Paraibano microregions, there were few changes in pasture quality, as indicated by the proportional maintenance of areas without degradation, with little influence of the water collapse on the pasture. From 2015 to 2020, a clear improvement in pasture quality was observed, related to the maintenance of rainfall regimes in the region.

It is important to highlight that vegetation conditions in the semi-arid region can be influenced by various factors, such as the presence of sparse and heterogeneous vegetation, leading to misinterpretations by low-resolution satellites regarding pasture degradation. Additionally, temporal resolutions pose challenges for environmental analyses in the semi-arid region, as data may not accurately capture short-duration events that result in landscape changes. To improve accuracy and overcome these limitations in the use of remote sensing for studies in the semi-arid region, the adoption of different data sources and the integration of multiple factors in the analysis are recommended.

Regarding the reservoirs that experienced water collapse in the region, a noticeable reduction in their volumes was observed from 2010 to 2020, as they were used more frequently; however, there was insufficient water recharge due to a lack of precipitation in the drainage basins. This reduction in volumes caused an increase in average turbidity levels due to the lower dilution of suspended matter in the water sources.

Additionally, there was an increase in total phosphorus and BOD (Biochemical Oxygen Demand) levels, linked to the amount of organic matter present in the water bodies, as well as eutrophication of these bodies. Despite variations in the mentioned parameters, BOD levels remain within the limits established by the ordinance on water quality for surface water bodies.

The findings of this study can complement public policies for water resource management in Paraíba, highlighting the need for adaptation to climate change and the mitigation of the effects of water collapse. The results obtained can guide water planning, assisting in the creation of contingency plans, revitalization of aquatic ecosystems, and more sustainable agricultural practices, ensuring the environmental and social resilience of the affected regions.

Thus, recognizing the limitations of the evaluations conducted, it is suggested that future studies encompass other components of the environmental system and other water quality parameters of surface bodies to analyze the influence of the rainfall regime and water collapse on the aquatic biosphere. Additionally, studies on the economic impacts of the environmental system during periods of water collapse can be conducted. Moreover, the use of environmental system modeling methodologies is recommended to better understand the system dynamics in critical situations.

Acknowledgments

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