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Eutrophication in Water Bodies in the Semi-arid Region of Northeast Brazil

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1 INTRODUCTION

Freshwater is a finite and irreplaceable resource, fundamental to ecosystems, economies, and human well-being. It sustains life through the hydrologic cycle of evaporation, precipitation, recharge, and runoff, while providing critical habitats and enabling agriculture, industry, and energy production (Cooke *et al.*, 2005). Yet, despite its renewal capacity, freshwater resources are increasingly degraded by human activities, contributing to a growing global freshwater crisis (Wetzel, 2001). The Millennium Ecosystem Assessment (2005) emphasized that the crisis is not only about scarcity in quantity, but also about declining water quality, which limits safe access and exacerbates risks of disease, food insecurity, and ecosystem collapse.

Aquatic ecosystems, particularly reservoirs, hold profound social, environmental, and economic importance. They serve as crucial sources of drinking water, regulate hydrological flows, support diverse fisheries, and act as strategic reserves, especially vital during periods of drought. However, their effective management is inherently complex, demanding interdisciplinary approaches that meticulously balance competing uses, mitigate adverse impacts, and ensure long-term sustainability. In this intricate context, education for sustainability and integrated water governance emerge as critical tools, fostering the collective capacity to address environmental problems holistically rather than in isolation, and to plan effectively for both immediate needs and future challenges.

Among the most pressing threats to water quality is eutrophication, defined as the excessive enrichment of water bodies with nutrients such as nitrogen and phosphorus (OECD, 1982). While these nutrients are indispensable for biological productivity, their uncontrolled accumulation profoundly disrupts ecological balance, diminishes ecosystem resilience, and triggers a cascade of detrimental effects. These impacts range from the prolific growth of aquatic plants and algae to severe oxygen depletion (hypoxia or anoxia) and significant losses in biodiversity (Wetzel, 2001; Chin, 2006; Schindler, 2006). A particularly severe consequence of eutrophication is the proliferation of harmful algal blooms (HABs). These blooms, frequently dominated by cyanobacteria, not only impair water usability for recreation, drinking, and fisheries but also release potent toxins that pose substantial dangers to human and animal health (Huisman *et al.,* 2018). The frequency, magnitude, and duration of these cyanobacterial blooms are increasing globally, a trend exacerbated by ongoing eutrophication and the broader effects of climate change (Huisman *et al*., 2018).

The problem of eutrophication is further aggravated by both external nutrient inputs, such as diffuse pollution from agricultural runoff and livestock operations, and internal loading from sediments. These sediments can accumulate significant quantities of phosphorus and subsequently release it slowly into the water column over extended periods, acting as a persistent source of nutrients (Carpenter, 2008; Cavalcante et al., 2018). Even when these external inputs are reduced, water bodies often fail to recover due to internal nutrient loading, where phosphorus accumulated in lake sediments is released back into the water column, perpetuating a cycle of nutrient enrichment. This internal recycling mechanism creates a form of "fertilization from within," implying that water quality degradation may persist or even worsen even after external nutrient inputs have been substantially reduced. For example, studies on Lake Ringsjön, Sweden, reveal that high phosphate concentrations in sediment pore water sustain elevated phosphorus levels in the lake, even after external nutrient inputs were significantly curtailed, highlighting the challenge of internal loading in shallow lakes (Granéli, 1999). Such complex dynamics render reservoir ecosystems especially vulnerable to long-term degradation once eutrophication processes become established, often requiring comprehensive management strategies that go beyond simple nutrient input reduction (Lurling *et al*., 2016; Räsänen *et al*., 2006).

These risks are particularly acute in semi-arid regions, where reservoirs are indispensable for water supply but are simultaneously exposed to fragile soils, limited vegetation cover, irregular rainfall patterns, and intense storm events. These combined factors accelerate nutrient inflows and increase the susceptibility to eutrophication compared to more humid tropical systems. According to Bates *et al.* (2008) in the IPCC Technical Paper on Climate Change and Water, semi-arid basins such as the Northeast of Brazil (NEB) are among the most water-stressed regions in the world, with per capita water availability frequently falling below the critical threshold of 1,000 m^3 per year. The report further warns that climate change is expected to intensify these pressures, contributing to reduced streamflow, drying of lakes, and increased pollutant concentrations in already scarce water bodies.

The Northeast of Brazil, home to more than 54 million people, exemplifies these vulnerabilities. It stands as the world's most densely populated semi-arid zone, characterized by recurrent droughts, high evapotranspiration rates, and highly irregular rainfall patterns (Marengo, 2008). Within this region lies the Caatinga biome, a unique seasonally dry tropical forest covering nearly a million square kilometers, which provides critical ecological services (Queiroz, 2017; Da Silva *et al.,* 2020). Yet, this biome is increasingly under stress from land use change, agricultural expansion, and climate extremes. The combined effect of water scarcity, external nutrient loading, and persistent internal nutrient recycling makes reservoirs in NEB highly vulnerable to eutrophication, with cascading effects on ecosystems, local economies, and human livelihoods, including the potential for toxic cyanobacterial blooms impacting aquatic communities (Bouvy *et al.,* 2001).

In light of these multifaceted challenges, this thesis investigates the complex drivers, dynamic interactions, and far-reaching consequences of eutrophication in the semi-arid Northeast of Brazil (NEB), a region uniquely vulnerable to water quality degradation due to its climatic, ecological, and socio-economic constraints. By situating this analysis within the broader context of the global freshwater crisis, the study underscores the urgent need to address nutrient enrichment in water bodies amidst increasing pressures from climate change, land use intensification, and population growth. The NEB, characterized by recurrent droughts, fragile soils, and limited water availability, exemplifies how external nutrient inputs and internal sediment recycling can exacerbate eutrophication, threatening critical ecosystem services such as water supply, fisheries, and biodiversity conservation. This research aims to unravel the interplay of anthropogenic activities, climatic variability, and ecological processes in driving eutrophication, while highlighting the socio-economic implications for local communities reliant on reservoirs for their livelihoods and well-being. By focusing on the NEB's distinct environmental and social conditions, the thesis seeks to contribute to global efforts to mitigate water quality degradation, offering insights into sustainable management strategies that address both local vulnerabilities and universal challenges in aquatic ecosystem restoration.

1.2 Objectives of the Thesis

General objective is to develop a comprehensive synthesis and multiscale assessment of eutrophication dynamics in semi-arid freshwater systems of Northeast Brazil, integrating hydrological, climatic, ecological, and governance dimensions, supported by reservoir monitoring data, long-term drought analysis, and multivariate statistical methods.

The specific objectives are:

- Contextualize eutrophication in the framework of global freshwater decline and the unique vulnerability of semi-arid regions to hydrological stress and nutrient enrichment.
- Characterize the climatic, hydrological, ecological, and socioeconomic features of the semi-arid Northeast Brazil that shape water availability and trophic responses.

- Review and systematize scientific evidence on nutrient inputs, internal loading, trophic state evolution, cyanobacterial dynamics, and climate-driven feedbacks in semi-arid aquatic systems.
- Assemble, filter, and map reservoir data from national monitoring platforms to evaluate spatial storage patterns and identify critical water-scarcity zones.
- Integrate government reservoir monitoring data (COGERH) and peer-reviewed limnological datasets to compare trophic conditions across systems and hydrological periods.
- Analyze the long-term hydrological trajectories of major reservoirs and their link to eutrophication intensification during prolonged droughts.
- Apply Principal Component Analysis (PCA) to identify dominant environmental gradients structuring water quality across reservoirs and hydrological phases.
- Examine climate-driven drought persistence, recovery lag, and reservoir memory effects as drivers of chronic eutrophication and bloom persistence.
- Identify management and governance strategies, including technological, biogeochemical, watershed-level, and institutional tools, adapted to semi-arid hydrology and socioeconomic constraints.

2 LITERATURE REVIEW

Understanding eutrophication in semi-arid freshwater systems requires situating the problem within a broader body of scientific knowledge. While the global drivers of eutrophication have been extensively studied, regional contexts such as the Northeast of Brazil (NEB) present unique combinations of climatic, ecological, and socio-economic pressures that demand closer attention. The literature demonstrates that eutrophication is a complex, multi-scalar process influenced not only by nutrient inputs, but also by interactions with land use practices, climate variability, hydrological cycles, and internal ecosystem dynamics.

The purpose of this chapter is to provide a critical synthesis of the scientific literature relevant to this thesis. It will examine the conceptual and mechanistic foundations of eutrophication, assess the roles of external and internal nutrient sources, and explore the broader ecological and social implications of water quality degradation. Special attention is given to reservoirs and other aquatic systems in semi-arid environments, where nutrient accumulation and hydrological stress create distinctive vulnerabilities. The review will also highlight how different land use practices, such as agriculture, livestock, and urbanization, intersect with climatic extremes to intensify eutrophication processes.

By organizing the discussion from global perspectives to regional case studies, the chapter aims to clarify both the universal and context-specific dimensions of eutrophication. This review not only establishes the scientific foundation for the analysis developed in subsequent chapters but also identifies knowledge gaps that this thesis seeks to address, particularly regarding the interplay of land use, drought dynamics, and internal nutrient cycling in the reservoirs of Northeast Brazil.

2.1 Freshwater Ecosystems and Reservoirs

Freshwater ecosystems such as lakes, rivers, and wetlands constitute only a small fraction of global water resources. Despite Earth's abundant water coverage, only a tiny portion is freshwater, and an even smaller amount exists as accessible surface water (Kalff, 2002). Most freshwater is stored in ice or deep aquifers, and smaller, shallow water bodies dominate the global landscape rather than large lakes (Dodds & Whiles, 2020).

Where natural lakes are insufficient, particularly in dry regions, reservoirs serve as critical infrastructure for water supply and management. Constructed primarily by damming rivers, they provide water for agriculture, household use, energy production, and recreation, and their operation involves anthropogenic control of water levels and flow (Cooke et al., 2005).

Reservoir location within large drainage basins results in inflows carrying considerable sediment and nutrient loads. These inputs often occur through concentrated, channelized pathways rather than gradual filtration, producing irregular pulses of particulate and dissolved materials. Their elongated, branching morphology further contributes to spatially complex water circulation, stratification patterns, and potential release of deeper, low-oxygen or nutrient-rich waters (Wetzel, 1990).

In semi-arid regions such as Northeast Brazil, limited and irregular rainfall combined with high evaporation intensifies these dynamics. Pronounced fluctuations in water levels and residence times, episodic runoff events, and sediment inputs promote conditions that favor elevated primary productivity and frequent algal blooms, making these systems highly susceptible to eutrophication (Kalff, 2002).

2.2 Eutrophication

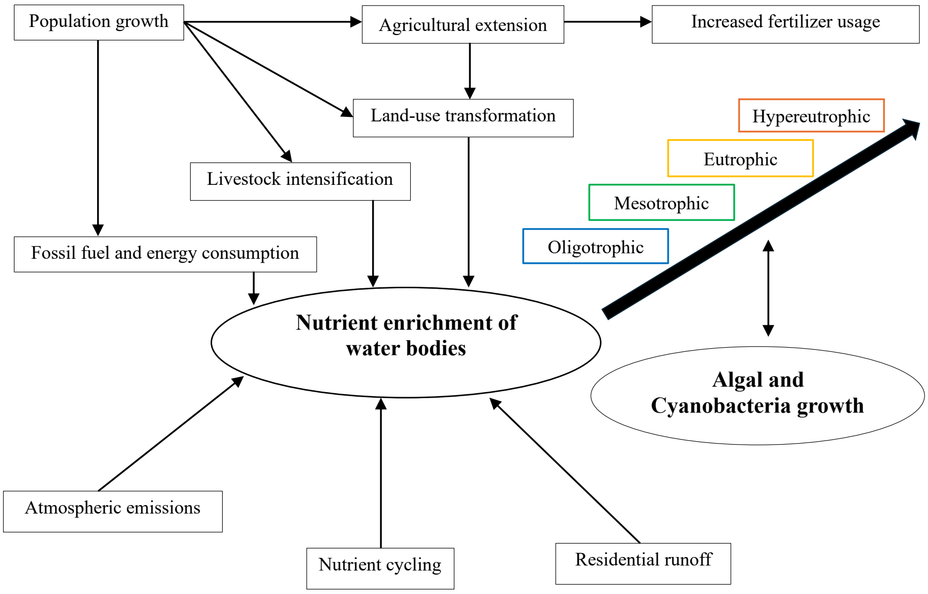
Eutrophication in freshwater systems has intensified largely because of agricultural, industrial, and urban nutrient inputs that expanded dramatically during the twentieth century (Harper, 1992). Although lakes naturally receive nutrients through catchment drainage and internal sediment recycling, human-driven land-use change, such as the conversion of forests to pasture and the expansion of settlement in lake catchments, has substantially increased nutrient export (Harper, 1992). Furthermore, phosphorus accumulation in soils, combined with erosion during periods of heavy rainfall, highlights the strong interaction between terrestrial nutrient dynamics and aquatic loading (Carpenter, 2008).

Nitrogen and phosphorus differ markedly in their environmental behavior, which has important implications for eutrophication processes. Reactive nitrogen moves readily through groundwater and atmospheric pathways, creating spatially and temporally variable nutrient pressures across landscapes (Carpenter, 2008). In contrast, phosphorus typically binds to soils and sediments, entering lakes primarily through erosion rather than rapid hydrological transport (Harper, 1992). These contrasting pathways emphasize the need for catchment-specific nutrient management strategies that account for local environmental conditions.

Long-term whole-ecosystem research provides compelling evidence that controlling phosphorus inputs is central to reducing eutrophication. When nitrogen inputs were reduced while phosphorus loading remained unchanged, nitrogen-fixing cyanobacteria compensated for nitrogen limitation, and algal biomass continued to increase in direct response to phosphorus availability (Schindler *et al.*, 2008). Consequently, strategies focused solely on reducing nitrogen inputs are insufficient, and sustained reductions in phosphorus loading are necessary to support ecological recovery in freshwater systems (Schindler *et al.,* 2008). Taken together, this evidence shows that although both nutrients contribute to eutrophication, phosphorus plays a dominant role in regulating algal productivity and therefore represents the most critical target for management and restoration efforts.

Eutrophication results from the accumulation of nutrients in aquatic systems due to natural processes and, increasingly, human activities. Elevated nutrient inputs stimulate excessive algal and cyanobacterial growth, degrade water quality, and shift ecosystems toward eutrophic and hypereutrophic states. Figure 1 presents a simplified conceptual pathway illustrating the main drivers of eutrophication and the resulting trophic condition of water bodies.

Figure 1.Drivers and progression of eutrophication leading to trophic state categories. Adapted from Khan and Mohammad (2014).



2.2.1 Nutrient Loading in Freshwater Systems

Research across diverse aquatic systems consistently shows that nutrient enrichment is the primary driver of lake eutrophication, with both natural and human-derived sources contributing to nutrient loads. However, the overwhelming evidence presented in recent studies indicates that anthropogenic inputs play the dominant role in accelerating eutrophication. In shallow lake environments, agricultural land conversion and urban expansion are identified as major contributors of nitrogen and phosphorus, whereas forested and natural landscapes export substantially lower nutrient loads (Zhou *et al.,* 2022). Although natural processes such as rainfall, evaporation, internal biogeochemical cycling, and sediment nutrient release occur, their contributions are comparatively minor and largely outside of management control (Yu *et al.*, 2020). In contrast, domestic sewage, agricultural runoff, and industrial discharges are consistently highlighted as the primary external drivers of nutrient enrichment. These pressures have intensified alongside population growth, fertilizer demand, and land-use change (Yu *et al.,* 2020; Zhou *et al.*, 2022).

Empirical case studies further reinforce the predominance of anthropogenic nutrient inputs. In Lake Titicaca, isotopic evidence shows clear signatures of wastewater-derived nitrogen and allochthonous organic matter originating from upstream urban and agricultural discharges, with δ15N and δ13C patterns demonstrating the spatial influence of sewage and runoff inputs (Heredia *et al.*, 2022). Nutrient signatures decline gradually with distance from discharge points, suggesting both the strength of external nutrient loading and the limited capacity of the lake to dilute and assimilate these inputs within short spatial scales (Heredia *et al.*, 2022). Similarly, water bodies in the semi-arid region of Ceará, Brazil, exhibit heightened eutrophication risk driven by climatic extremes. Prolonged drought reduces reservoir volume and concentrates nutrients, while intense rainfall events mobilize accumulated materials from surrounding basins, increasing turbidity, biochemical oxygen demand, and nutrient pulses into reservoirs (Laurent *et al.,* 2023).

Long-term historical analyses of regulated lake systems also show that hydrological manipulation exacerbates nutrient accumulation. Engineered water-level control and reduced flow increase water residence times and favor eutrophic conditions, particularly since the mid-twentieth century, when fertilizer use and water extraction intensified (Liang *et al.,* 2024). Agricultural intensification elsewhere produces similar pressures, with fertilizer use, livestock production, and soil erosion contributing nitrogen, phosphorus, pesticides, and organic matter into waterways and stimulating algal blooms and ecological imbalance (Vero & Fenton, 2022).

Taken together, these studies demonstrate that although natural nutrient cycling processes remain present, it is the sustained and expanding influence of anthropogenic nutrient inputs, particularly those associated with agriculture, wastewater discharge, and hydrological alteration, that underpins modern eutrophication trajectories (Zhou *et al.*, 2022; Yu *et al.*, 2020; Heredia *et al.,* 2022; Laurent *et al.*, 2023; Liang *et al.,* 2024; Vero & Fenton, 2022).

2.2.2 Trophic State Index and Classification

The Trophic State Index (TSI) proposed by Carlson (1977) provides a numerical approach to assess eutrophication. It uses chlorophyll-a concentration, Secchi depth, and total phosphorus to rank lakes on a continuous scale, supporting consistent comparison between water bodies and across monitoring periods (Carlson, 1977; Mäkelä & Meybeck, 1996). High TSI values correspond to nutrient-rich, algae-dominated waters with low clarity; low values indicate clear, low-productivity conditions.

Carlson (1991) later refined the index by distinguishing between “harmonic” lakes, where algal growth matches nutrient levels, and “disharmonic” lakes, where factors such as turbidity, grazing, or acidity restrict productivity despite nutrient availability. When TSI values calculated from phosphorus, chlorophyll, and Secchi depth agree, the system is typically nutrient-controlled. When they diverge, other limiting mechanisms are likely involved. In this way, the TSI functions not only as a descriptive tool but also as a diagnostic metric for understanding eutrophication drivers.

Since Carlson's original formulation was developed for temperate lakes, it does not fully capture the metabolic and nutrient-cycling characteristics of tropical systems (Carlson, 1977). To address this, Toledo Jr. *et al.* (1983) modified the TSI equations for tropical conditions. Their adapted version proved more suitable for evaluating trophic status in tropical environments like in NEB and is now widely used in studies of tropical lakes. The equations (1), (2) , and (3) adapted by Toledo Jr. *et al.* (1983) for tropical systems are shown below, followed by the trophic-state thresholds they proposed (Table 1), in which 24 < TSI ≤ 44 indicates oligotrophic conditions, 44 < TSI ≤ 54 mesotrophic, 54 < TSI ≤ 74 eutrophic, and TSI ≥ 74 hypereutrophic.

$$TSI\ (S) = 10\left(6 - \frac{0.64 + \ln S}{\ln 2}\right) \qquad (1)$$

$$TSI\ (P) = 10\left(6 - \frac{\ln(\frac{80.32}{P})}{\ln 2}\right) \qquad (2)$$

$$TSI\ (Chla) = 10\left(6 - \frac{2.04 - 0.695(\ln Chla)}{\ln 2}\right) \qquad (3)$$

Table 1. Trophic state classification for reservoirs following Carlson (1977), with adaptations by Toledo Jr. *et al*. (1983).

Trophic Class	TSI Range	Secchi Depth (m)	Total P (µg/L)	Chl-a (µg/L)
Ultra-oligotrophic	TSI ≤ 24	> 6.39	< 6.62	< 0.52
Oligotrophic	24 < TSI ≤ 44	6.39 – 1.60	6.62 – 26.50	0.52 – 3.82
Mesotrophic	44 < TSI ≤ 54	1.60 – 0.80	26.50 – 52.99	8.82 – 10.35
Eutrophic	54 < TSI ≤ 74	0.80 – 0.20	52.99 – 211.97	10.35 – 70.06
Hypereutrophic	TSI ≥ 74	< 0.20	> 211.97	> 70.06

2.2.3 Ecological and Environmental Consequences

Eutrophication across aquatic systems is consistently linked to nutrient enrichment that stimulates harmful algal blooms and degrades ecological conditions. In freshwater environments, elevated nutrient loads promote cyanobacterial dominance, reduce water clarity, alter pH and stratification, and suppress other phytoplankton groups, resulting in biodiversity losses and weakened trophic transfer (Amorim & Moura, 2021; O'Neil *et al.*, 2012).

Eutrophication in freshwater systems promotes shifts from non-toxic to toxic phytoplankton communities and increases the risk of harmful algal blooms, particularly in urban ponds, leading to oxygen depletion, fish mortality, and water quality deterioration that threatens aquatic life and human water use (Quadra *et al.*, 2019; Pereira *et al.,* 2024). Climate-driven warming and altered hydrological regimes intensify eutrophication impacts and amplify spatial–temporal variability, increasing ecological vulnerability in hotspot regions (Vasilakou *et al.*, 2025).

In transitional tropical systems, eutrophication is characterized by elevated chlorophyll-a, reduced water transparency, and altered physicochemical structure, driven by nutrient enrichment and hydrodynamic conditions that influence nutrient residence time and bloom persistence (Sá *et al.*, 2022). Urban sewage and agricultural runoff intensify these processes, degrading the ecological integrity of estuaries and lagoons (Sá *et al.*, 2022). Mangrove soils exposed to nutrient inputs exhibit shifts toward algal-derived organic matter, enhanced heterotrophic remineralization, and elevated CO_2 emissions, indicating reduced carbon storage efficiency and altered sediment biogeochemistry (Barroso *et al.*, 2022). Together, these findings show that eutrophication destabilizes ecosystem structure and function across freshwater, estuarine, and mangrove environments, with additive stress from warming and human-driven nutrient inputs amplifying ecological consequences.

2.3 Characteristics of Semi-Arid Regions in Northeast Brazil

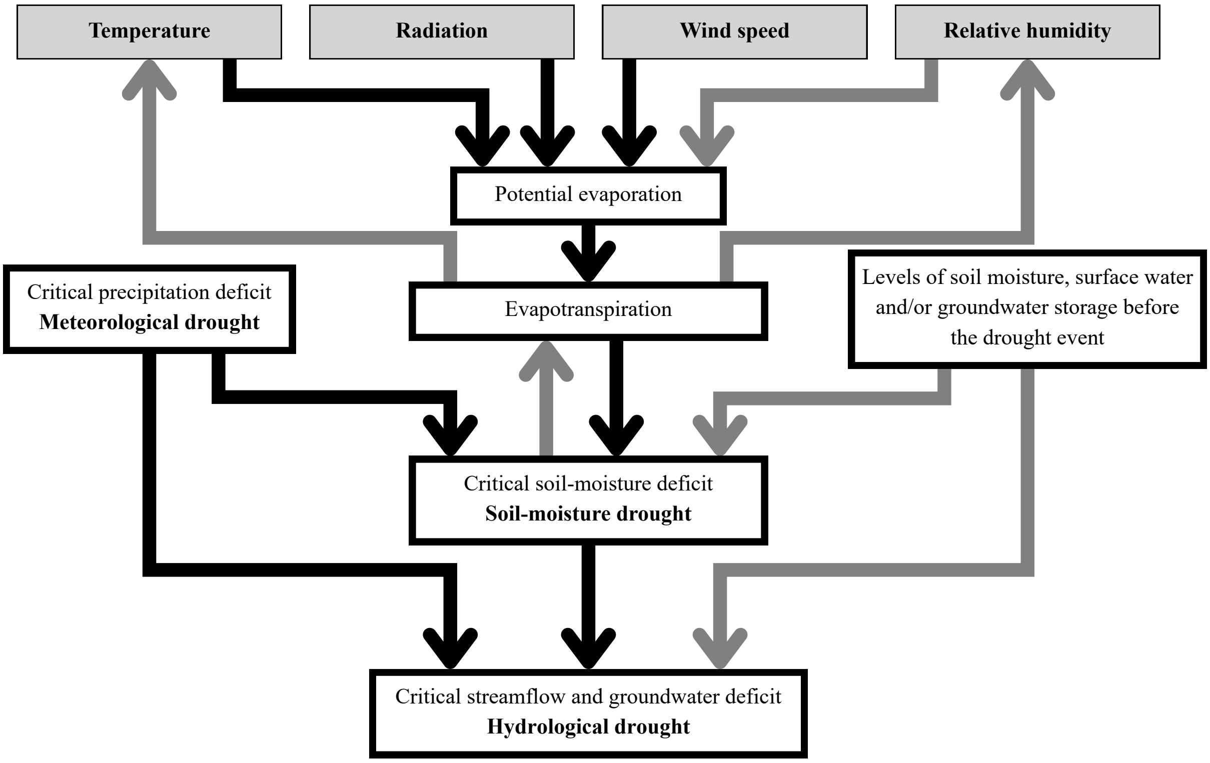
The semi-arid region of Northeast Brazil, predominantly comprising the Caatinga biome, represents a unique and complex socio-ecological system. Covering approximately 912,529 km^2, or 10.7% of Brazil's territory (Silva *et al.*, 2017), this vast area is characterized by a delicate interplay of climatic, hydrological, and anthropogenic factors that shape its environmental and social landscape. Understanding these characteristics is fundamental to comprehending the mechanisms and drivers of eutrophication in the region's water bodies. The inherent variability of the semi-arid climate, coupled with a history of intensive land use and water management challenges, creates a predisposition for nutrient enrichment and the degradation of aquatic ecosystems. This literature review synthesizes key findings on the environmental, climatic, hydrological, and socioeconomic characteristics of Northeast Brazil's semi-arid region, providing the necessary context for a detailed analysis of eutrophication.

2.3.1 Climatic and Hydrological Characteristics

The climate of Northeast Brazil is defined by its semi-aridity, with low and irregular rainfall, high temperatures, and intense evapotranspiration rates. As Campos (2015) notes, the region is not characterized by an absolute scarcity of water, but rather by the high variability and unpredictability of its rainfall. This variability is driven by large-scale ocean-atmosphere interactions, such as the El Niño-Southern Oscillation (ENSO) and the Atlantic dipole, which can lead to prolonged and severe droughts (Campos, 2015). The spatial distribution of rainfall is also highly heterogeneous, with the interior sertão experiencing the most extreme water deficits.

The concept of drought itself is complex, defined as a deficiency in precipitation over an extended period, leading to water scarcity (Wiegand, 2015). Seneviratne (2012) further elaborates that drought is a multifactorial process influenced by insufficient precipitation and/or excessive evapotranspiration, with soil moisture deficits amplifying local temperatures through heat-drought feedbacks. Semi-arid regions are particularly sensitive to small precipitation changes due to high evaporative demand and limited soil moisture capacity (Seneviratne, 2012). The intricate interplay of these factors, including temperature, radiation, wind speed, and relative humidity, alongside critical precipitation deficits and initial water storage levels (Figure 2), collectively drive the progression from meteorological drought to soil-moisture drought and ultimately to hydrological drought (Seneviratne, 2012).Í

Figure 2. Drought drivers aÍnd their propagation through the hydrological system. Black arrows indicate factors that contribute to drought, and grey arrows show factors that counteract it. Adapted from Seneviratne (2012).



The hydrological response to these climatic conditions is characterized by intermittent rivers and a high dependence on surface water storage in reservoirs. The concept of drought in this region is multifaceted, propagating through the hydrological system from precipitation deficits to soil moisture depletion, and finally to reductions in groundwater and surface water levels (Peters *et al*., 2006). Oliveira *et al.* (2024) highlights the distinct temporal scales of drought response, with soil moisture droughts being frequent and short-lived, while groundwater droughts are more prolonged and severe, dominating the region's overall hydrological variability. This is exacerbated by the fact that groundwater, which acts as a crucial buffer during dry periods, is slow to recover from prolonged deficits, a phenomenon Peters *et al.* (2006) describe as a “memory effect”.

2.3.2 Soil and Land Use

The soils of the semi-arid region are diverse, but are often shallow and have low organic matter content, making them susceptible to erosion and degradation, particularly when vegetation cover is removed. The native Caatinga vegetation, a mosaic of seasonally dry tropical forests and scrublands, is adapted to the harsh climatic conditions, but has been extensively modified by human activities. The widespread conversion of native vegetation to pasture and agricultural land has profound implications for the region's water and energy balance.

Cunha *et al.* (2015) demonstrate that land use and land cover change (LULCC) significantly alters regional climate processes. The replacement of native vegetation with pasture, for instance, increases surface albedo and reduces evapotranspiration, leading to complex and spatially variable changes in rainfall and temperature. These changes in land use also have a direct impact on nutrient runoff. The removal of natural vegetation cover, coupled with agricultural practices that often involve the use of fertilizers, increases the transport of nutrients such as phosphorus and nitrogen into water bodies, a key driver of eutrophication.

Dos Santos *et al.* (2024) further elucidate the impact of land use change on the local energy balance. Their research shows that while sensible heat flux dominates in all land use types, deforestation leads to lower net radiation and evapotranspiration. Such alterations in local energy and water balances may influence broader climatic and hydrological processes, potentially contributing to additional challenges for water management.

2.3.3 Hydrological Regime and Water Bodies

The hydrological regime of Northeast Brazil is characterized by a high degree of intermittency, with most rivers flowing only during the brief rainy season. To cope with this, a vast network of reservoirs has been constructed to store water for human consumption, irrigation, and industry. While these reservoirs are essential for the region's socioeconomic development, they are also highly susceptible to eutrophication.

Hydrological extremes, including both floods and droughts, significantly impact water quality. Hrdinka *et al.* (2012) emphasize that droughts, due to their persistence and chronic stress conditions like reduced dilution capacity and higher temperatures, are particularly hazardous in aquatic systems. These conditions promote the accumulation of dissolved substances and can lead to stratification and oxygen deficits. While floods cause acute, transient impacts by mobilizing sediments and pollutants, droughts generate sustained chemical imbalances, directly influencing nutrient concentrations and the potential for eutrophication (Hrdinka *et al.,* 2012).

Raulino *et al.* (2021) highlight the dual challenges of water scarcity and eutrophication in these reservoirs. Their modeling studies show that under future climate change scenarios, reduced streamflow and increased evaporation will lead to lower reservoir storage volumes. This, in turn, will concentrate nutrients and exacerbate eutrophication. The study projects that total phosphorus levels can rise sharply when reservoir volumes fall below 20% of their capacity, underscoring the tight coupling between drought and water quality.

The intermittent nature of the rivers and the reliance on reservoirs also mean that the flushing of nutrients from these systems is often limited. This allows for the accumulation of nutrients over time, creating a persistent state of eutrophication in many of the region's water bodies.

2.3.4 Socioeconomic and Environmental Context

The semi-arid region of Northeast Brazil is home to a population of 28.6 million people (Silva *et al.*, 2017), many of whom live in conditions of socioeconomic vulnerability. The region has historically been marked by high levels of poverty and inequality, with a heavy reliance on subsistence agriculture and government transfers. This socioeconomic context is a critical factor in understanding the region's environmental challenges.

Campos (2015) argues that drought in Northeast Brazil is not just a natural phenomenon, but also a socially constructed hazard. The impacts of drought are amplified by the vulnerability of the population, which has limited capacity to adapt to water scarcity. Human factors, such as water demand and management, can exacerbate the impacts of drought (Wiegand, 2015). Historically, public policies have focused on large-scale “hydraulic solutions,” such as the construction of dams and canals, which have often failed to address the root causes of vulnerability and have had significant environmental and social costs (Silva *et al.,* 2017).

The combination of population pressure, poverty, and limited water management capacity appears to place considerable stress on the region’s natural resources. Practices such as deforestation, overgrazing, and the discharge of untreated sewage into water bodies are frequently observed and may contribute to environmental degradation and elevate the risk of eutrophication. The semi-arid region of Northeast Brazil, with its variable climate, intermittent hydrology, vulnerable ecosystems, and complex socioeconomic conditions, presents a setting where these factors may interact to influence eutrophication processes, which will be further examined in the following sections.

2.4 Climate Change and Hydrological Variability

Climate change has profoundly altered hydrological regimes worldwide, particularly in semi-arid regions where natural water scarcity amplifies climatic sensitivity. A synthesis of studies across diverse spatial and temporal scales reveals a consistent pattern of increasing hydrological variability expressed through intensified droughts, irregular precipitation, and more frequent extreme events. These changes affect not only water availability but also the ecological and socioeconomic systems dependent on hydrological stability. Together, the literature underscores that both natural climate oscillations and anthropogenic influences interact to shape evolving drought dynamics and water-resource vulnerability.

2.4.1 Conceptual Foundations and Climatic Forcing

At the conceptual level, drought represents a temporary imbalance between precipitation and evapotranspiration rather than a permanent climatic state. Paulo & Pereira (2006) distinguish drought from aridity and other forms of water scarcity, framing it as a transient natural event characterized by duration, intensity, and recurrence. Their comparative analysis of drought indices demonstrates that standardized measures such as the Standardized Precipitation Index (SPI) provide the most consistent and spatially comparable characterization of drought evolution. This methodological clarity underpins later assessments of meteorological and hydrological droughts under climate change.

Large-scale atmospheric and oceanic drivers play a central role in determining precipitation and runoff variability. The analyses by Souza Filho & Lall (2003) in Ceará illustrate that streamflow behavior in semi-arid Brazil is governed by coupled interactions between the tropical Atlantic and Pacific Oceans. Variability in sea surface temperature (SST) anomalies, particularly through the Equatorial Atlantic Dipole and ENSO, modulates the position of the Intertropical Convergence Zone (ITCZ), which in turn regulates the onset and intensity of the rainy season. These teleconnections explain the pronounced interannual and interdecadal oscillations in regional hydrology, highlighting the predictability of drought and flood regimes through SST-based forecasting systems. The mechanisms identified align with broader assessments of global drought dynamics, where ENSO and related oceanic modes serve as primary sources of hydroclimatic variability (Hao *et al.*, 2018; Lavell *et al.*, 2012).

Hao *et al.*, (2018) extend this understanding by demonstrating that climate change intensifies such variability through alterations in large-scale circulation, land–atmosphere feedbacks, and energy balance. Their synthesis identifies feedback loops between soil moisture and surface temperature as amplifiers of drought persistence. Reduced soil moisture suppresses evapotranspiration and enhances sensible heat flux, reinforcing local warming and extending drought duration. This interaction between atmospheric forcing and terrestrial processes creates a self-sustaining mechanism that links meteorological anomalies to hydrological impacts. Similar processes are recognized in global assessments by Seneviratne *et al.* (2012), who document the growing frequency of temperature and precipitation extremes, noting that higher evapotranspiration rates and prolonged dry spells constitute robust signals of climate change in semi-arid regions.

2.4.2 Regional Evidence from Northeast Brazil

Empirical studies from Northeast Brazil provide consistent evidence that these global-scale mechanisms are manifesting regionally through heightened hydrological stress. De Medeiros & de Oliveira (2022) demonstrate that both dry and heavy rainfall days are projected to increase in frequency based on CMIP6 simulations for Northeast Brazil. Their analysis reveals a dual trajectory of climatic change, prolonged dry spells coupled with intensified rainfall extremes, indicating greater temporal irregularity in precipitation. While the drying trend is more robust across model ensembles, the concurrent rise in heavy rainfall events suggests an increasingly erratic hydrological regime characterized by longer droughts punctuated by short but intense rainfall episodes. Such conditions amplify flood and drought cycles and complicate water-resource planning, particularly in semi-arid zones already constrained by low storage capacity.

A parallel pattern emerges in Rio Grande do Norte, where de Medeiros *et al.* (2022) identify a persistent decline in precipitation and a rise in drought frequency over recent decades. Historical analyses using Standardized Precipitation Index (SPI) confirm that droughts have become longer and more severe since the 1980s, culminating in the extreme 2012–2017 event. Climate projections further indicate continued drying and warming, with more frequent negative precipitation anomalies under high-emission scenarios. These findings reinforce that meteorological drought is evolving into a chronic hydrological condition, with cumulative effects on reservoirs and surface storage. The convergence of rising temperature and reduced rainfall points to a structural water deficit likely to dominate future hydrological regimes.

At the basin scale, de Carvalho *et al.* (2023) provide complementary evidence linking climatic variability to land-use transformation and declining water yield in the Paraíba River watershed. Their long-term analysis identifies a significant reduction in forest and surface water areas, driven by agricultural expansion and vegetation loss. The strong correlation between forest cover and water body extent underscores the hydrological role of native Caatinga vegetation in regulating runoff and maintaining flow stability. Despite the absence of uniform rainfall decline, reduced vegetation and altered land cover have intensified water scarcity by decreasing runoff efficiency and soil moisture retention. These results highlight the interactive effects of climatic and anthropogenic drivers, revealing how land degradation compounds the impacts of variable precipitation.

2.4.3 Vegetation and Ecosystem Responses to Drought

The sensitivity of vegetation to hydrological variability is particularly evident in the Caatinga biome, where drought acts as both a climatic and ecological stressor. Barbosa *et al.* (2019) show that vegetation greenness, as captured by Normalized Difference Vegetation Index (NDVI), tracks rainfall anomalies closely, with a short lag reflecting plant physiological response times. During the multi-year drought of 2012 to 2015, widespread reductions in NDVI indicated severe vegetation stress and loss of productivity, affecting more than a quarter of the biome. Although some regions displayed localized greening, these were largely associated with irrigated agriculture rather than natural vegetation recovery. Hence, Barbosa *et al.* (2019) demonstrate that prolonged droughts cause cumulative degradation, while anthropogenic pressures such as overgrazing and deforestation exacerbate ecosystem vulnerability. Overall, these patterns confirm that vegetation dynamics in the semi-arid Northeast are tightly coupled to rainfall variability and that recurrent droughts are accelerating ecosystem decline.

Comparable responses have been observed beyond Brazil. Ibáñez & Caiola (2013) document similar ecological disruptions in Mediterranean systems, where flow reductions and recurrent droughts have transformed riverine and wetland environments. Reduced discharge and prolonged water scarcity alter flow permanence, connectivity, and water quality, driving structural changes in aquatic communities. Sensitive and endemic species decline while tolerant and invasive taxa proliferate, leading to homogenized biotic assemblages. In estuarine and lacustrine environments, reduced inflows promote salinization, eutrophication, and hypoxia, often resulting in long-term loss of ecosystem function. These findings provide a broader ecological context for the hydrological transformations observed in semi-arid Brazil, illustrating that climatic and hydrological variability generate similar patterns of ecosystem stress across water-limited regions.

2.4.4 Climatic Extremes, Feedbacks, and Water Quality Implications

The intensification of hydrological extremes under climate change creates feedbacks that extend beyond water quantity to water quality and ecosystem metabolism. Seneviratne *et al.* (2012) report that semi-arid regions are expected to experience both more prolonged droughts and more frequent heavy rainfall events. These alternating extremes generate compound impacts, with prolonged dry periods concentrating nutrients and promoting eutrophication, while intense rainfall introduces pulses of nutrient-rich runoff that destabilize reservoir dynamics. Elevated temperatures further exacerbate these effects by enhancing stratification and promoting cyanobacterial dominance, linking atmospheric warming directly to deteriorating water quality. The combination of episodic floods following droughts represents a new mode of hydrological variability, one that magnifies nutrient cycling and bloom intensity within reservoir systems.

Lavell *et al.* (2012) similarly emphasize that climate extremes function as risk multipliers, amplifying existing hydrological vulnerabilities rather than introducing new hazards. Their framework identifies drought as a slow-onset event whose impacts accumulate through soil degradation, vegetation loss, and declining water quality. Rising temperatures and irregular precipitation contribute to alternating periods of dryness and flooding, reducing groundwater recharge and destabilizing catchment hydrology. The authors highlight ENSO as a primary natural driver of such variability, but note that anthropogenic warming increasingly modulates its regional expression, making extremes more persistent and spatially extensive. The implications extend to risk management, where adaptive capacity and early-warning systems are essential to mitigate cascading drought impacts in resource-limited settings.

2.4.5 Emerging Patterns and Thematic Synthesis

Across these studies, several recurring trends are suggested. Many authors indicate that hydrological variability may be increasing, influenced by large-scale climate patterns and regional land-use change. Precipitation also appears to be becoming more irregular, with intense rainfall events occurring alongside longer dry periods, suggesting a shift toward more frequent drought–flood conditions. These shifts are often linked to ecological impacts, including possible changes in vegetation productivity, runoff, and water quality. Overall, the literature points toward a movement from relatively stable seasonal hydrology to more variable and extreme regimes.

In addition, land-surface processes and human activities are frequently discussed as amplifying climatic effects. Vegetation loss, agricultural expansion, and reservoir reliance may weaken system resilience, while warming and increased evapotranspiration could intensify water deficits. This has been described as a feedback cycle in which drought stresses vegetation, reducing hydrological buffering capacity and reinforcing water scarcity in semi-arid regions.These processes align with global assessments indicating that drought frequency and persistence are increasing as a consequence of warming-induced shifts in the hydrological cycle (Hao *et al.*, 2018; Seneviratne *et al.*, 2012).

The integrated body of evidence demonstrates that climate change is transforming hydrological dynamics in semi-arid and water-limited regions, particularly in Northeast Brazil. Historical analyses confirm the growing persistence of droughts, while projections indicate an intensification of both dry and extreme rainfall events. Land-use changes exacerbate these climatic pressures by diminishing natural hydrological regulation, accelerating water loss, and reducing ecosystem resilience. Together, these findings portray a future of heightened climatic instability, where water availability and quality fluctuate under increasingly extreme and unpredictable conditions. The convergence of climatic, hydrological, and ecological stressors underscores the need for adaptive water management and integrated land–climate monitoring to sustain hydrosystem function in an era of intensifying variability.

2.5 Eutrophication Management and Governance in Semi-Arid Regions

The management of eutrophication in semi-arid regions presents a unique and complex challenge, driven by the convergence of hydrological scarcity, high evaporation rates, and intense anthropogenic pressures such as agriculture and urbanization. The literature reviewed highlights that effective solutions require a shift from purely technical remediation to integrated, watershed-level governance frameworks that are specifically adapted to the climatic and socio-economic realities of these vulnerable environments.

2.5.1 Technical Strategies for Remediation and Nutrient Control

Technical approaches to eutrophication management in semi-arid systems can be broadly categorized into in-lake remediation and watershed-level nutrient source control.

2.5.2 In-Lake Remediation and Water Treatment

In-lake remediation efforts focus on mitigating the effects of existing eutrophication, particularly the internal nutrient load and the proliferation of harmful algal blooms. Pereira & Mulligan (2023) provide a comprehensive review of practices for shallow lake restoration, emphasizing that successful projects require a holistic and region-specific approach that addresses both external nutrient inputs and the internal legacy of nutrients continuously released from sediment. Their review covers a range of physical (e.g., dredging), chemical (e.g., phosphorus inactivation with lanthanum-modified bentonite), and biological (e.g., biomanipulation) methods. They stress the importance of stakeholder participation and ongoing monitoring for long-term success.

A specific focus in semi-arid regions, particularly in Brazil, is the removal of cyanobacteria and their associated toxins, which pose significant public health risks. Albuquerque *et al.* (2020) critically evaluate Advanced Oxidation Processes (AOPs) as a viable alternative or complement to conventional water treatment, where AOPs, such as Fenton and photocatalytic reactions, are shown to be highly efficient in degrading microcystins, offering a sustainable and scalable technology for managing water quality in reservoirs where conventional methods often fail under high toxin loads. Similarly, Pérez (2015) investigates the use of biofilm and macrophytes as a bioremediation tool, particularly in the semi-arid regions of Brazil. The study affirms that the strategic use of engineered bioremediation systems, combining biofilm with rooted macrophytes, is a promising approach for nutrient absorption and environmental recovery in eutrophic aquatic ecosystems.

2.5.3 Watershed-Level Nutrient Management

Addressing the root cause of eutrophication requires controlling nutrient loads from the surrounding watershed, with a particular focus on agricultural activities. Studies in semi-arid, intensively irrigated areas demonstrate the necessity of integrated Best Management Practices (BMPs).

Wei & Bailey (2021), using a coupled flow and reactive transport model in the Lower Arkansas River Valley, found that single BMPs (e.g., moderate fertilizer reduction) yield limited improvements. Instead, they advocate for a system-level approach where multiple measures, including irrigation management, nutrient management, water conveyance efficiency, and land-use practices, are combined. Their modeling showed that the most effective strategy involved a combination of reductions in irrigation, fertilization, and canal seepage, alongside conservation tillage, achieving substantial reductions in both nitrate and phosphorus loading. Crucially, they highlight that spatially optimized, integrated management is more effective than uniform interventions.

This finding is echoed by Özcan *et al.* (2017), who evaluated BMPs in the semi-arid Lake Mogan watershed in Turkey. While a combination of fertilizer reduction, no-tillage, and terracing achieved the greatest load reductions, the overall improvements were modest. They conclude that high levels of nutrient reduction could not be achieved solely through agricultural BMPs, underscoring the need for integrated watershed management strategies to effectively improve water quality in semi-arid agricultural regions.

2.6 Governance and Institutional Challenges

The foundational regulatory framework for water quality management in Brazil is established by the *Conselho Nacional do Meio Ambiente* (National Environment Council, CONAMA) Resolution No. 357, of March 17, 2005. This resolution represents a cornerstone of Brazilian environmental policy, defining the classification of surface water bodies, fresh, brackish, and saline, according to their intended uses and setting the mandatory conditions and standards for water quality and effluent discharge (CONAMA, 2005). It provides the legal and technical basis for the control of eutrophication in inland waters by explicitly establishing maximum permissible limits for key indicators such as Total Phosphorus, Chlorophyll *a*, and Cyanobacteria density. These limits are organized into a tiered system corresponding to water body classes (Class 1, 2, 3, and Special), as well as differentiated according to hydrological typology, distinguishing between lotic (flowing) and lentic (standing) systems. By directly linking nutrient loading to biological response and public health risk, Resolution 357/2005 operationalizes eutrophication prevention within Brazil's water governance framework. Consequently, any assessment of water quality or ecological status in Brazilian semi-arid regions must be referenced against the parameters and thresholds established by this regulatory standard, which serves as both a scientific benchmark and an enforcement tool for managing nutrient enrichment and maintaining ecosystem integrity.

Khorasani *et al.* (2018) propose a comprehensive, interdisciplinary framework for eutrophication management in off-stream artificial lakes in arid and semi-arid regions. Their framework integrates technical solutions with robust governance mechanisms, structured around four core components: system identification (characterizing the lake and stakeholders), advanced simulation modeling, development of diverse management scenarios, and selection of the preferred scenario using social choice methods (e.g., Borda counts). This approach formally integrates stakeholder preferences and addresses the inherent uncertainties in environmental modeling, underscoring that effective management requires decentralized decision-making and active engagement.

The institutional context of water management is further explored by Studart *et al.* (2021), who developed a typology of water governance-related conflicts in Northeast Brazil. Although their focus is on conflict resolution, they provide direct evidence that eutrophication is a significant driver of water-quality disputes. They explicitly link pollution-driven degradation to governance failures, such as insufficient regulation and limited integration of environmental controls into water management institutions. Their analysis suggests that effective eutrophication governance requires coordinated institutions, cross-sectoral regulation, and participatory mechanisms, such as the Negotiated Water Allocation Mechanism (NWAM), to resolve conflicts and prevent ecological crises.

Finally, the foundational ecological research by Callisto *et al.* (2014) on Brazilian freshwater systems provides critical evidence for policy design. Their findings demonstrate that eutrophication in semi-arid reservoirs is intensified by a combination of climatic constancy (low rainfall, high evaporation, long water residence times) and anthropogenic pressure (e.g., fish farming, sewage). They conclude that conventional models and indicators developed for temperate lakes are often inadequate, as phosphorus alone is not a good indicator of trophic level in these systems. This highlights the need for governance to adapt by using locally calibrated indicators and continuous biomonitoring, advocating for a focus on preventive rather than remedial measures due to the self-reinforcing nature of eutrophic conditions in semi-arid environments.

The literature on eutrophication management and governance in semi-arid regions reveals a consensus that successful intervention must be integrated, context-specific, and participatory. Technical solutions, ranging from advanced oxidation processes to combined agricultural BMPs, are essential but insufficient without a parallel focus on governance. The key challenge lies in developing and implementing frameworks that can effectively: 1) Integrate hydrological, agricultural, and socio-economic data to model and predict nutrient fate (Wei & Bailey, 2021; Khorasani *et al.*, 2018); 2) Adapt monitoring and management indicators to the unique limnological dynamics of semi-arid systems (Callisto *et al.,* 2014); and 3) Establish robust, participatory governance mechanisms that resolve conflicts, ensure cross-sectoral regulation, and formally incorporate stakeholder preferences into decision-making (Studart *et al.,* 2021; Khorasani *et al.,* 2018). The future of eutrophication control in these water-stressed regions depends on the successful synthesis of these technical and institutional imperatives.

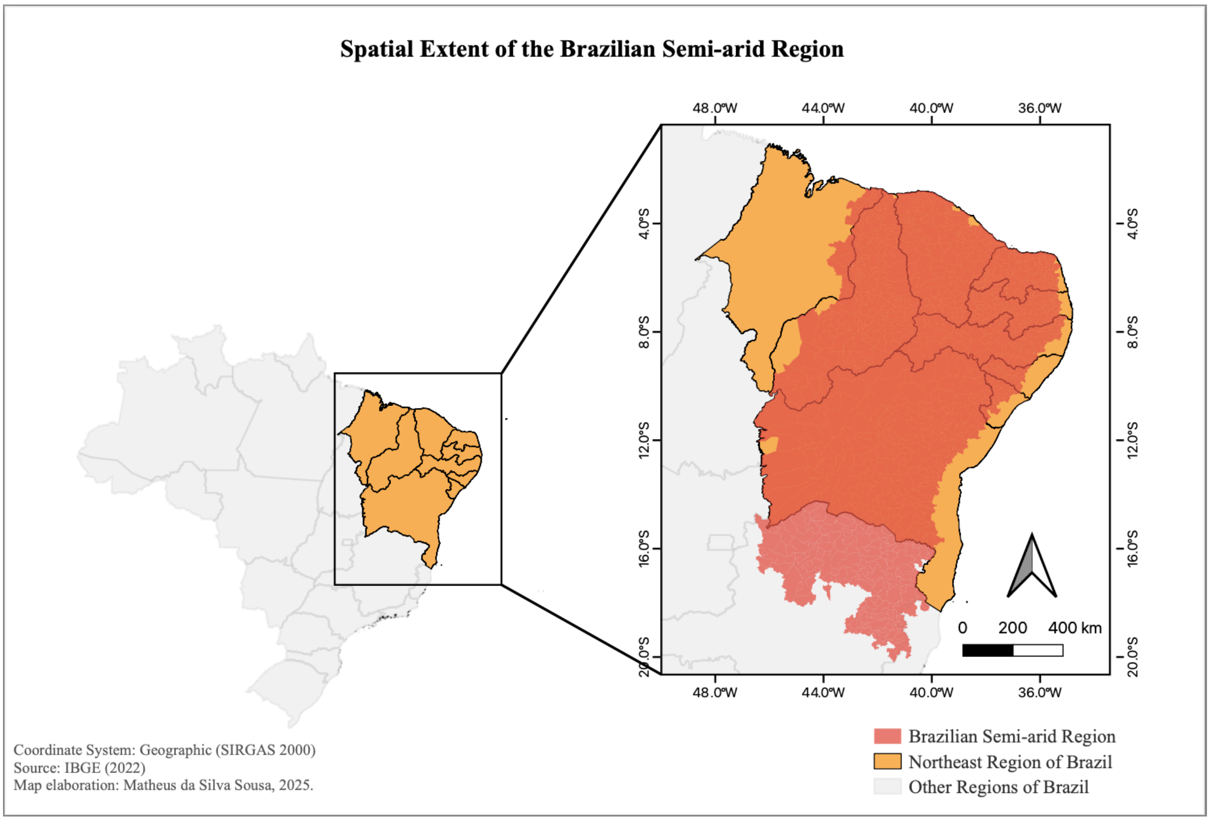
3 MATERIALS AND METHODS

3.1 Study Area

The present study focuses on the Brazilian Northeast (NEB), the region is geographically situated between approximately 01° S and 18° S latitude and 32° W and 48° W longitude. A deeper focus is given to the Semi-arid region (SAB), an extensive area that covers parts of nine states: Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, and Bahia. Overall, the SAB encompasses about 12% of the national territory and is home to approximately 28 million inhabitants, with the population distributed across urban (62%) and rural (38%) areas. The official delimitation of this region follows the criteria established by the Superintendência do Desenvolvimento do Nordeste (SUDENE). This area encompasses municipalities that simultaneously meet thresholds of low average annual precipitation, high potential evapotranspiration, and recurrent droughts.

The spatial data used to delineate the region were obtained from publicly available geographic datasets provided and IBGE (2022). These layers were processed and integrated in QGIS 3.40.11, and the final map (Figure 3) was produced using standardized cartographic procedures, including the use of color differentiation for national, regional, and semi-arid extents and the addition of a zoomed inset to emphasize the study area. The map shows the spatial extent of the semi-arid zone (red) within the broader Northeast region (orange) and the rest of Brazil (gray). The zoomed inset highlights the detailed boundaries of the semi-arid area, as defined by the Superintendência de Desenvolvimento do Nordeste (SUDENE) according to Resolutions nº 155/2022 and nº 163/2022

Figure 3. Figure 3. Location of the Brazilian Semi-Arid Region. Data source: IBGE, 2022 . Map elaboration: Author (2025).



Spatial Extent of the Brazilian Semi-arid Region

Coordinate System: Geographic (SIRGAS 2000)
Source: IBGE (2022)
Map elaboration: Matheus da Silva Sousa, 2025.

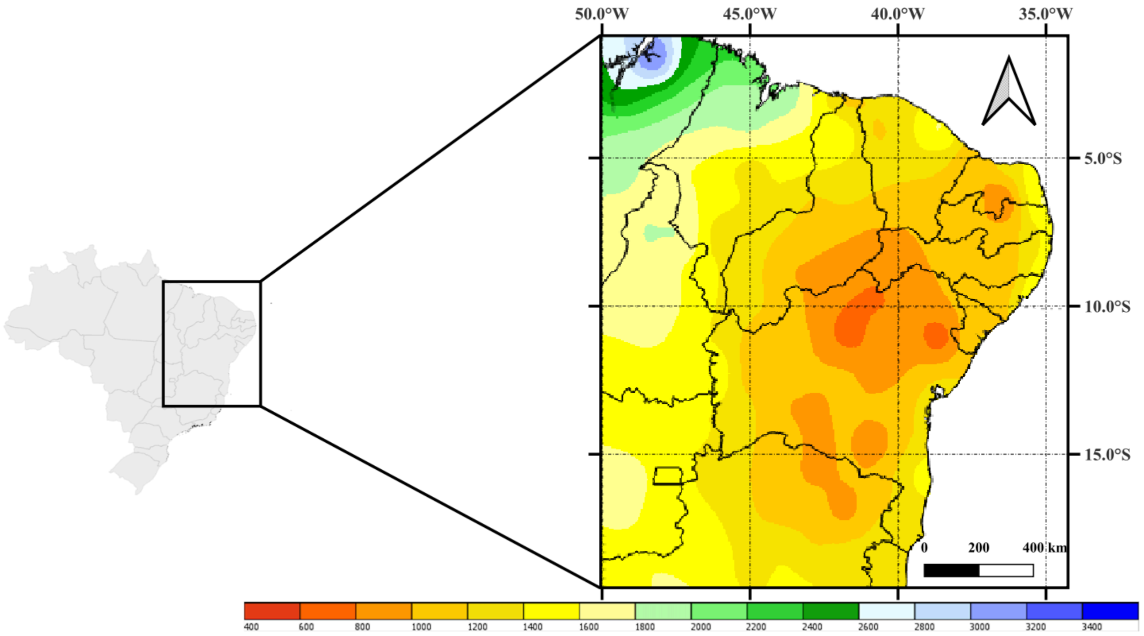
3.2 Climate Characteristics

Climatically, the region is predominantly classified as BSh (semi-arid; low latitude and altitude) according to the Köppen–Geiger system (Alvares *et al.,* 2013; Köppen, 1936). Average annual precipitation varies between 300 and 800 mm, with high interannual variability and strong spatial contrasts and the rainy season is typically concentrated between February and May, followed by an extended dry period lasting up to eight months (INMET, 2020). Mean annual temperatures remain high, usually above 25°C, and potential evapotranspiration rates exceed precipitation during most of the year, resulting in chronic water deficit conditions.

To illustrate the regional rainfall regime, a climatological map of accumulated annual precipitation (1991–2020) developed by the National Institute of Meteorology (INMET) was used (Figure 4). This map shows the spatial distribution of total precipitation across the Northeast and Semi-Arid region (SAB), emphasizing the marked gradient from the wetter coastal areas to the drier interior zones.

Figure 4. Annual accumulated precipitation climatology for Northeastern Brazil during the 1991–2020 reference period, obtained from INMET (N. d.) and processed in QGIS. Map elaboration: Author (2025).

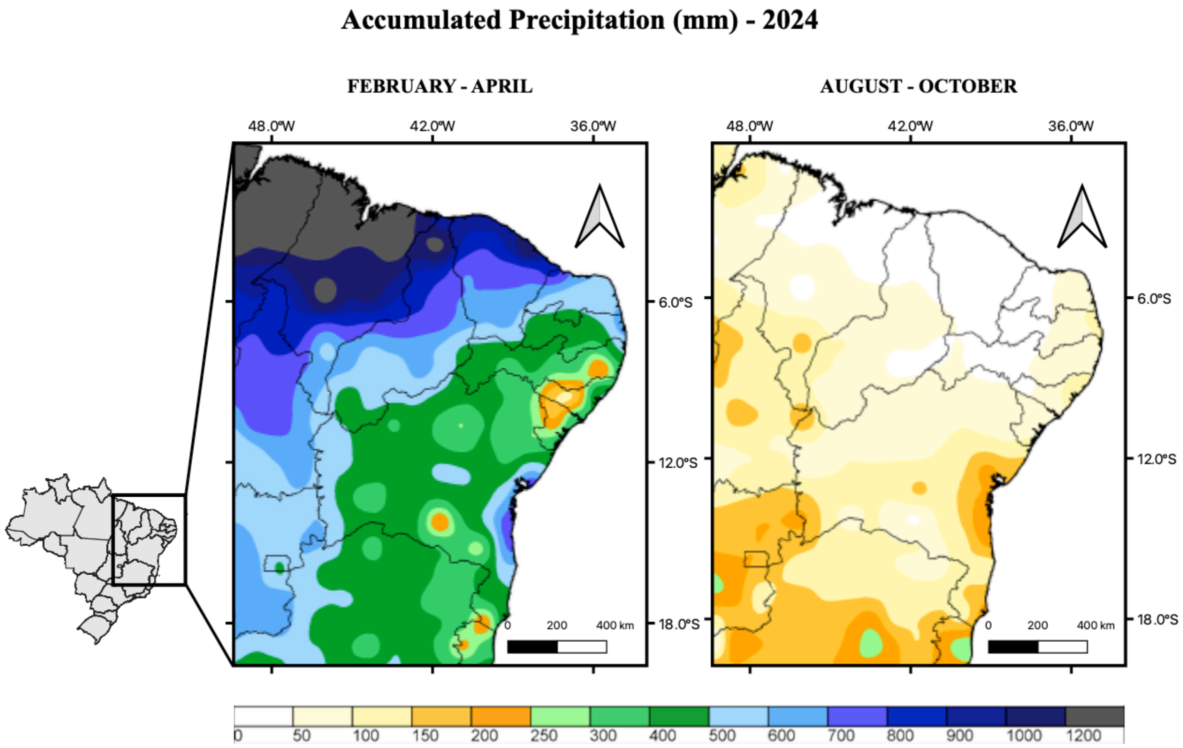
Annual Precipitation Climatology (1991–2020) — Northeastern Brazil (mm)



Coordinate System: Geographic (SIRGAS 2000)
Source: INMET (2020)
Map elaboration: Matheus da Silva Sousa, 2025.

In addition, seasonal climatological maps for the rainy trimester (February–April) and the dry trimester (August–October), obtained from INMET and processed in QGIS (Figure 5), highlight the strong intra-annual rainfall contrasts characteristic of the semi-arid climate. Rainfall during the rainy trimester is concentrated in localized areas, contributing to reservoir recharge, while the dry trimester shows minimal precipitation, reinforcing prolonged water deficit. These patterns are essential for understanding hydrological dynamics and informing water resource management in the region.

Figure 5. Seasonal climatological maps of accumulated precipitation in the semi-arid Northeast region for the rainy trimester (February–April) and dry trimester (August–October), obtained from INMET (N. d.) and processed in QGIS. Map elaboration: Author (2025).



Coordinate System: Geographic (SIRGAS 2000)
Source: INMET (2024)
Map elaboration: Matheus da Silva Sousa, 2025.

3.3 Data Acquisition and Reservoir Selection

Data on reservoirs located in the Northeast (NEB) and Semi-Arid Region (SAB) of Brazil were obtained from the National Water and Sanitation Agency (ANA) through the SAR - Sistema de Acompanhamento de Reservatórios platform. The dataset includes information for approximately 400 reservoirs, encompassing attributes such as geographic coordinates, storage capacity, surface area, and current water levels. Reservoirs were filtered according to specific selection criteria summarized in Table 2 to focus on the most hydrologically and environmentally significant systems.

Table 2. Selection criteria applied to reservoirs in the Northeast (NEB) and Semi-Arid Region (SAB) of Brazil.

Criterion	Description	Purpose /Rationale
Location	Within SAB limits defined by SUDENE (Resolutions 155/2022 and 163/2022)	Ensure geographic relevance
Data completeness	Available and consistent data on location, capacity, and operational level	Ensure dataset reliability
Hydrological relevance	Storage capacity >10 hm³	Focus on reservoirs serving regional water supply
Temporal coverage	≥5 years of monitoring records	Enable temporal comparisons
Scientific literature	Mentioned in peer-reviewed studies on water quality or eutrophication	Ensure environmental significance

This filtering ensured that the dataset represented the most hydrologically and environmentally significant reservoirs in the region, capturing spatial and temporal variability across diverse sub-basins of the NEB.

3.4 Geospatial Data Processing and Mapping

Spatial data were processed in QGIS 3.40.11. Reservoir coordinates from the ANA-SAR database were projected to SIRGAS 2000, and attribute tables were standardized to include reservoir name, basin, state, municipality, coordinates, maximum storage capacity, elevation, and current storage level. Reservoirs with incomplete or outdated information were excluded to maintain dataset consistency. The remaining reservoirs were visualized using thematic maps of storage capacity classes and relative storage levels (%) to identify geographic patterns and potential links with climate and eutrophication dynamics. All spatial layers were validated through visual inspection and cross-referenced with official cartographic bases from IBGE and SUDENE.

3.5 Bibliographic Search and Selection of Reservoir Case Studies

A systematic literature search was conducted to identify peer-reviewed studies on eutrophication in reservoirs of the Northeast and Semi-Arid Region of Brazil. Searches were performed between April and October 2025 using the following Boolean combinations: (“eutrophication” OR “water quality” OR “cyanobacteria” OR “trophic state”) AND (“reservoir” OR “lake”) AND (“Northeast Brazil” OR “semi-arid” OR “Caatinga”).

Papers were linked to reservoirs in the ANA database when possible. Table 3 summarizes the inclusion and exclusion criteria applied to select reservoir case studies. Selected studies were categorized by type (observational, modeling, experimental), temporal coverage, and key indicators to facilitate comparative and correlation analyses.

Table 3. Inclusion and exclusion criteria applied to select reservoir case studies.

Type	Criteria
Inclusion	- Reservoir explicitly identified or with geographic coordinates - Located within the Semi-Arid Region (SAB) as per SUDENE Resolutions 155/2022 and 163/2022 - Contains data on nutrients (P, N), chlorophyll-a, cyanobacteria, or Trophic State Index (TSI) - Provides temporal data (multi-year) or quantitative eutrophication parameters
Exclusion	- Studies focused exclusively on non-lentic environments (rivers, estuaries, etc.) - Reports without accessible methodological details - Reservoirs outside the officially defined SAB

3.6 Data Analysis and Principal Component Analysis (PCA)

To identify the main environmental gradients and relationships among limnological variables in the studied reservoirs, a Principal Component Analysis (PCA) was performed. This multivariate approach was used to reduce data dimensionality and highlight the principal factors explaining variation in water quality between rainy and dry seasons across the semi-arid reservoirs.

The combined dataset integrated measurements from both hydrological periods, comprising the following quantitative variables:

- Volume (hm^3): representing reservoir storage capacity and dilution potential;
- Chlorophyll-a (Chla, $\mu g\ L^{-1}$): indicator of phytoplankton biomass;
- Total Phosphorus (TP, $\mu g\ L^{-1}$) and Total Nitrogen (TN, $\mu g\ L^{-1}$): nutrient concentrations associated with eutrophication processes;
- Transparency (Transp, m): Secchi depth, reflecting light penetration and turbidity.

All variables were standardized (z-score normalization) to equalize their scales and avoid dominance by parameters with larger numerical ranges, such as volume. The PCA was carried out using Python (Jupyter Notebook). The analysis produced a biplot displaying the first two principal components (PC1 and PC2), which together represent the main axes of variation in the dataset.

Reservoirs were coded by season, red for the dry season (D) and blue for the rainy season (R), to visualize potential clustering patterns and seasonal differentiation within the multivariate space. Arrows in the biplot indicate the loadings (correlations) of each environmental variable with the principal components, allowing for interpretation of their relative influence on the overall variance.

The percentages of variance explained by PC1 and PC2 were used to assess the robustness of the analysis and the representativeness of the two-dimensional projection. All graphical outputs were exported in high-resolution formats for integration into the results section.

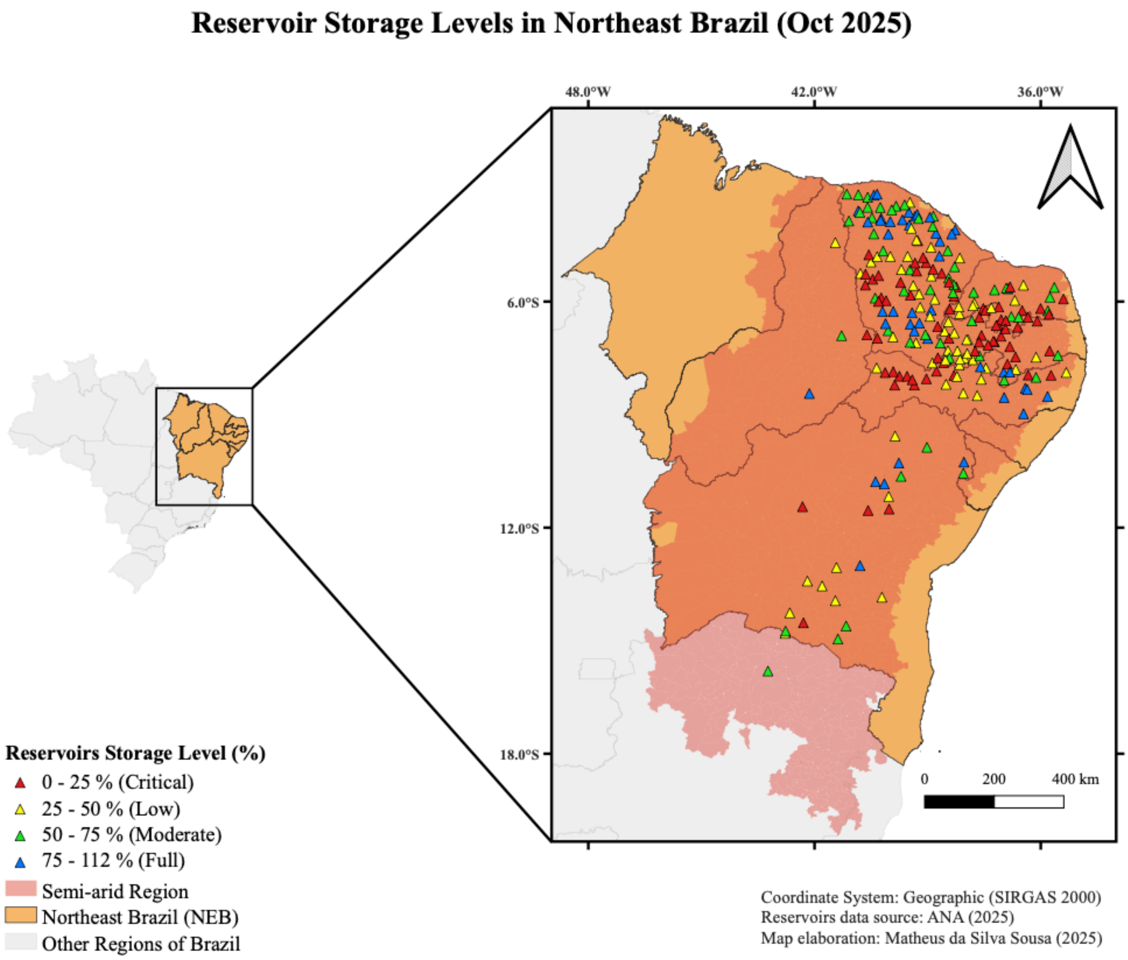
The PCA served as an exploratory statistical tool to reveal the dominant environmental gradients influencing reservoir conditions under different hydrological regimes, without implying causal relationships among variables.

4 RESULTS AND DISCUSSION

4.1 Reservoir Storage Conditions in the Semi-Arid Northeast (Dry Season, 2025)

The spatial distribution of reservoir storage across the Semi-Arid Northeast is shown in Figure 6. The map represents conditions during a month within the dry season, a period naturally characterized by reduced rainfall, high evaporation rates, and declining reservoir volumes. These climatic conditions make this phase of the year critical for understanding regional water security and the vulnerability of aquatic systems.

Figure 6. Storage percentage of major reservoirs in Northeast Brazil (Oct. 2025). Source: ANA (N. d.). Map elaboration: Author (2025).



Coordinate System: Geographic (SIRGAS 2000)
Reservoirs data source: ANA (2025)
Map elaboration: Matheus da Silva Sousa (2025)

A total of 226 reservoirs, all located within the official Semi-Arid Region and with storage capacities greater than 10 hm³, were included in this assessment. Their storage levels were expressed as a percentage of total volume and categorized to facilitate interpretation of water availability across the region.

To provide a clearer overview of storage conditions, reservoirs were grouped into storage classes based on the percentage of their current volume relative to total capacity. These results are summarized in Table 4.

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Table 4. Distribution of reservoirs by storage class in October 2025

Storage class (%)	Number of Reservoirs
0–25% (Critical)	71

25–50% (Low)	61
50–75% (Moderate)	52
75–112% (Full)	42
Total	226

More than half of the reservoirs (58%) were storing less than 50% of their capacity during the dry-season period. The largest group, with 71 reservoirs, was classified as 0–25% (Critical), indicating systems close to minimum operational levels. These conditions often imply reduced water depth, exposed shorelines, higher water temperature, and increased vulnerability to water quality deterioration.

Reservoirs in the 25–50% (Low) class (61 systems) also showed limited storage but retained some buffer capacity. In contrast, only 42 reservoirs (19%) were classified as 75–112% (Full). These are likely strategic water sources with larger drainage basins or favorable hydrological conditions.

Storage conditions observed during the dry season are essential for understanding water security in the Semi-Arid Northeast. Low reservoir levels at this time of the year not only represent diminished water availability but also create conditions that may favor eutrophication. Reduced volumes result in longer water residence times, higher temperatures, and lower dilution capacity, all of which intensify nutrient concentration and increase the likelihood of cyanobacterial blooms.

Reservoirs in the Moderate and Full classes (50–112%) represent hydrologically more stable systems and are less prone to these mechanisms. However, the spatial concentration of critically low reservoirs highlights areas of particular concern for public supply, ecosystem health, and future water quality monitoring.

4.2 Limnological Characteristics and Principal Component Analysis (PCA) of Semi-Arid Reservoirs

This section examines the main limnological patterns observed across reservoirs in the semi-arid Northeast and explores how their physical and chemical characteristics reflect different stages of eutrophication. By analyzing data collected during contrasting hydrological periods, it highlights how reservoir morphometry, nutrient levels, and water transparency interact under conditions of variable water storage. To identify the dominant environmental gradients influencing these systems, a Principal Component Analysis (PCA) was applied to a compiled dataset representing reservoirs of diverse hydrological and geographic contexts.

To provide a broader context for the PCA and to characterize the limnological conditions of the main reservoirs in the semi-arid Northeast, a consolidated dataset was assembled combining field data from the Water Resources Management Company of Ceará (COGERH) and complementary measurements reported in peer-reviewed studies. COGERH conducts bimonthly water quality monitoring across the state's principal reservoirs, allowing for consistent comparisons between rainy and dry seasons COGERH (2014; 2016; 2017; 2018; 2019; 2020; 2021). Additional data from scientific publications were integrated to expand spatial coverage beyond Ceará, encompassing reservoirs across different sub-basins of the semi-arid region.

The compiled dataset includes key limnological parameters (reservoir storage percentage, chlorophyll-a (Chl-a), total phosphorus (TP), total nitrogen (TN), and Secchi depth)representing fundamental indicators of trophic status and eutrophication intensity. These values, summarized in (Table 5), provide a comparative overview of seasonal variability and nutrient dynamics across reservoirs of differing hydrological and morphometric characteristics. The combined information forms the empirical foundation for the subsequent PCA, which identifies the main environmental gradients governing water quality under contrasting hydrological regimes.

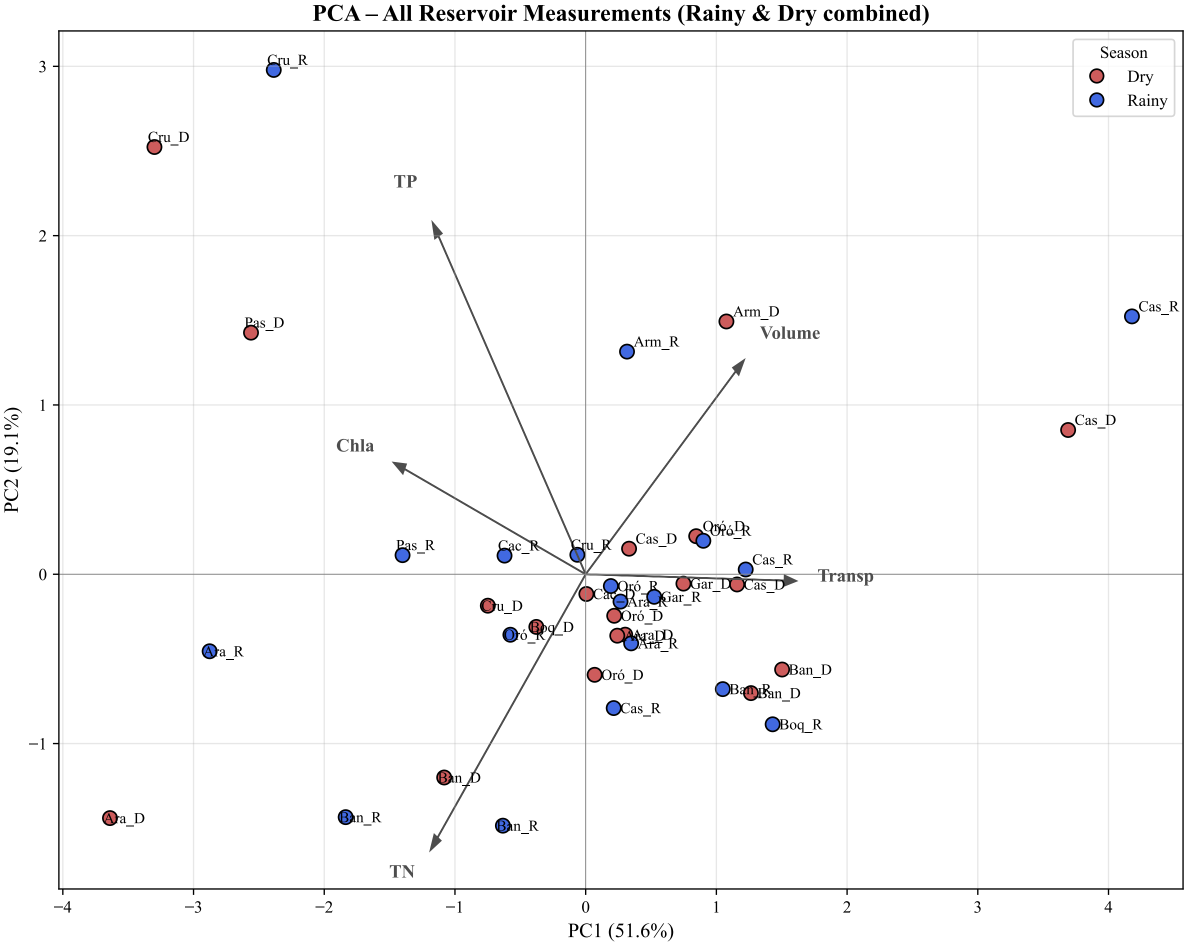
Table 5. Summary of hydrological and trophic characteristics of semi-arid Brazilian reservoirs during rainy and dry seasons. Values represent reported storage conditions, nutrient concentrations (TP, TN), chlorophyll-a (Chl-a), and water transparency (Secchi depth), along with trophic state classifications as described in the original studies and institutional monitoring reports. Source: data compiled from literature and COGERH monitoring bulletins.

Reservoir	**Storage % (rainy - dry)**	**Chl-a µg.L^{-1} (rainy)**	**Chl-a µg.L^{-1} (dry)**	**TP µg.L^{-1} (rainy)**	**TP µg.L^{-1} (dry)**	**TN µg.L^{-1} (rainy)**	**TN µg.L^{-1} (dry)**	**Secchi (m) Rainy**	**Secchi (m) Dry**	**Trophic State**	**Reference**
Castanhão	72.01 – 48.32	3.7	5.2	17.2	20.6	397	481	2.3	2.5	Mesotrophic - Eutrophic	Lacerda *et al.* (2018)
	12.78 – 10.68	15.18	25.20	93	64	1060	890	1.4	1.3	Eutrophic	COGERH (2021)
	6.08 – 4.99	54.08	51.80	64	120	2199	960	1.2	1.0	Eutrophic	COGERH (2017)
Orós	100 – 83.37	5.0 – 22.2	3.8 – 26.5	50 – 110	52 – 140	–	–	0.4 – 1.4	0.52 – 1.05	Eutrophic	Batista *et al.* (2014)
	10.49 – 6.90	66.64	25.95	107	88	1787	1712	0.50	0.80	Eutrophic	COGERH (2017)
	27.79 – 22.39	31.43	43.41	122	82	1425	1340	0.80	0.80	Eutrophic	COGERH (2020)
Banabuiú	7.5 – 6.91	11.73	7.08	80	74	1650	1325	1.70	2.0	Oligothrophic	COGERH (2019)
	0.5 – 0.5	21.40	64.13	87	106	3237	3175	0.70	0.60	Eutrophic	COGERH (2016)
	4.49 – 5.96	50.29	2.42	169	60	4225	1413	0.30	1.70	Mesotrophic	COGERH (2018)
Araras	77.64 – 59.22	25.00	63.10	100.00	40.00	–	–	–	–	Eutrophic	Sousa *et al.* (2014)
	5.31 – 3.46	187.57	219.62	209	183	3662	5412	0.20	0.30	Hypereutrophic	COGERH (2016)
	26.23 – 23.15	33.36	28.16	85	64	1450	1100	1.0	0.70	Eutrophic	COGERH (2018)
Arm. Ribeiro	100 – 95.29	31.5	62.0	218.0	230.0	1232.0	1085.0	0.4	1.5	hypereutrophic	Câmara *et al.* (2015)
Cruzeta	1.23 – 1.95	41.26	264.1	712.3	479.3	–	–	0.3	0.3	Eutrophic	Monicelli *et al.* (2023)
	74.18 – 68.54	36.76	65.96	144.23	126.33	953.94	1526.19	0.66	0.34	Eutrophic	Bezerra *et al.* (2014)
Gargalheiras	53.80 – 53.08	43.32	13.02	78.16	98.77	772.17	645.93	1.05	1.06	Eutrophic	Bezerra *et al.* (2014)
Boqueirão	50 – 19.48	11.64	63.32	29.06	85.97	–	–	1.89	0.5	Eutrophic	Santos *et al.* (2021)
Passagem das Traíras	40.0 – 6.0	156.79	233.3	116.76	297.9	–	–	0.31	0.24	Eutrophic	Santos *et al.* (2021)
Cachoeira II	22.97 – 19.69	79.9	23	166.5	148.5	–	–	–	–	Eutrophic	Diniz and Melo-Júnior (2017)

4.2.1 Principal Component Analysis: Results and Interpretation

The Principal Component Analysis (PCA) integrating all reservoirs and both hydrological periods (rainy and dry seasons) explained 70.7% of the total variance, with PC1 accounting for 51.6% and PC2 for 19.1% (Figure 7).

Figure 7. Principal Component Analysis (PCA) of reservoir measurements during dry and rainy seasons. The biplot represents the first two principal components (PC1 = 51.6%, PC2 = 19.1%) showing the distribution of reservoir samples from dry (red) and rainy (blue)



These two axes summarize the main gradients of limnological variability across the studied systems. The first principal component (PC1) represents a trophic state gradient, ranging from nutrient-rich, chlorophyll-dense, and turbid reservoirs (negative PC1) to larger, clearer, and low-nutrient systems (positive PC1). Variables such as chlorophyll-a (Chla), total phosphorus (TP), and total nitrogen (TN) load strongly on the negative side of PC1, whereas reservoir volume and transparency (Secchi depth) align positively. This opposition indicates that reservoirs with greater storage capacity tend to exhibit lower nutrient concentrations and higher transparency, while smaller systems are more susceptible to eutrophic conditions, particularly under high nutrient loading.

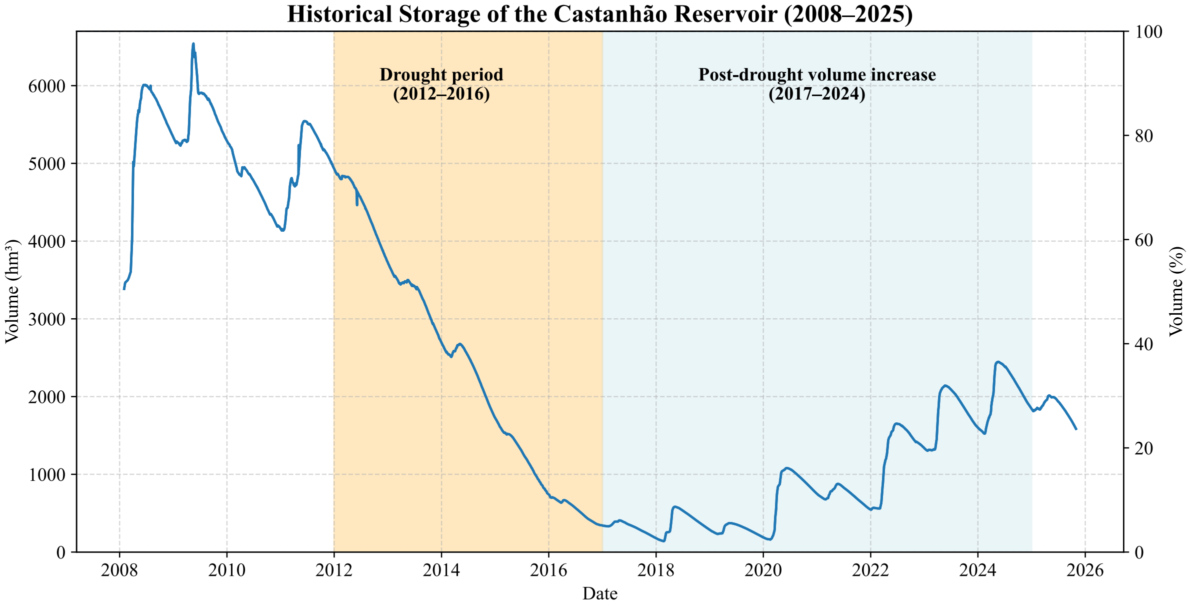
However, unlike what would be expected in systems with well-defined hydrological seasonality, reservoir samples did not cluster consistently by season in the PCA space. Samples from different reservoirs taken during the same hydrological period did not group together, and neither dry-season nor rainy-season observations formed clear clusters across systems. This pattern likely reflects the prolonged multi-year drought in the region, during which the typical hydrological recharge associated with the rainy season was limited or absent. As a result, many reservoirs remained under hydrological stress even during nominal wet periods, with reduced dilution capacity and persistently elevated nutrient concentrations. Consequently, seasonal differences in water quality were muted or overridden by the cumulative effects of sustained low water storage, meaning that hydrological period alone did not structure the distribution of samples in the PCA.

The second component (PC2) captures additional variation in the nutrient structure, separating reservoirs with high phosphorus concentrations (TP, upper-left) from those with higher nitrogen influence (TN, lower-left). This suggests subtle differences in nutrient limitation or source dynamics, which may vary according to watershed characteristics or local management regimes.

4.2.2 How Storage Decline Shapes PCA Positioning and Trophic State Evolution

To better understand this hydrological pattern, the long-term storage history of the Castanhão Reservoir offers a clear picture of how water levels changed over time (Figure 8). From 2008 to 2012, the reservoir stayed relatively full, but once the 2012–2016 drought began, storage dropped sharply to record lows. Even after rains returned, the reservoir only recovered gradually and never regained its earlier volume.

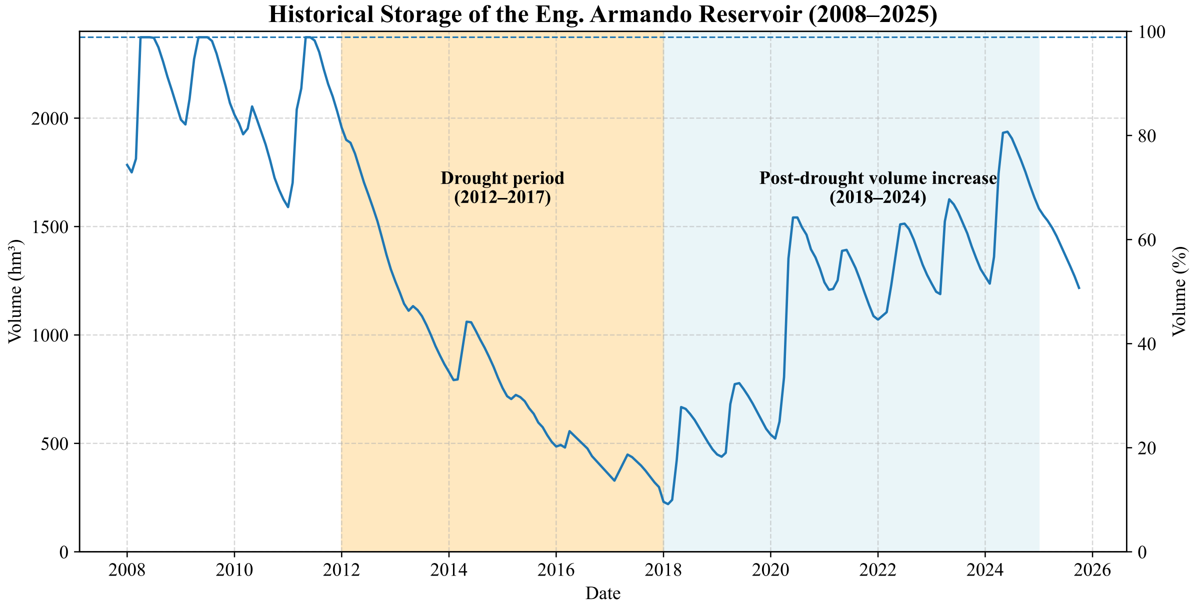
Figure 8. Temporal evolution of the Castanhão Reservoir storage (2008–2025), expressed as absolute volume (hm³) and percentage of capacity. The upper limit of the y-axis corresponds to the reservoir's full-supply storage level (≈6,700 hm³). Shaded intervals deno



Similarly, the long-term storage history of the Engenheiro Armando Ribeiro Gonçalves Reservoir provides an additional perspective on regional water availability (Figure 9). Prior to the drought, the reservoir maintained high volumes, with a full-supply capacity of approximately 2,737 hm³. Storage declined steadily and persistently between 2012 and 2017, reaching some of the lowest levels in the historical record. Even as rainfall improved after 2018, recovery was only partial: storage increased through 2024 but did not return to pre-drought conditions. The shaded periods in the figure highlight this trajectory, marking the 2012–2018 decline and the subsequent partial refill/stabilization phase (2018–2024). This extended low-storage period reflects the lasting hydrological imprint of the drought and the slow recovery dynamics characteristic of large semi-arid reservoirs, even in years classified as rainy.

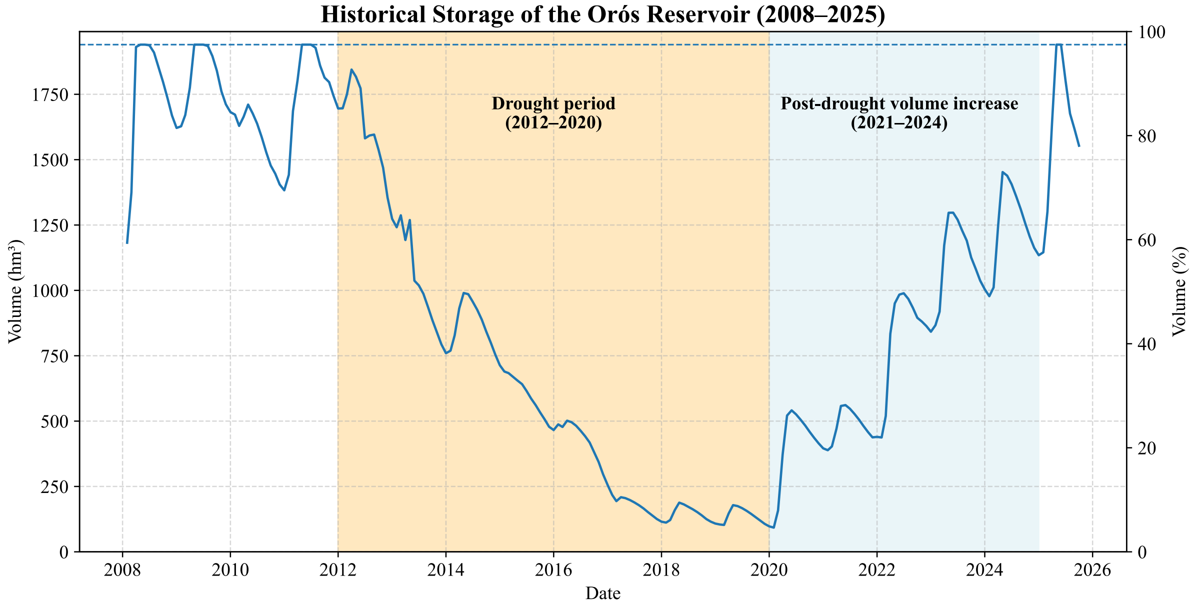
Figure 9. Temporal evolution of the Engenheiro Armando Ribeiro Gonçalves Reservoir storage (2008–2025). Data obtained from the Agência Nacional de Águas e Saneamento Básico

(ANA), Sistema de Acompanhamento de Reservatórios (ANA-SAR). Figure prepared by the Autho



Likewise, the storage trajectory of the Orós Reservoir reinforces the prolonged hydrological stress experienced in the region (Figure 10). With a maximum storage capacity of approximately 1,940 hm³, Orós sustained relatively high volumes until the onset of the 2012 drought. Storage then declined steadily and remained low for an extended period, with the most pronounced depletion occurring between 2012 and 2020. Only after 2020 did the reservoir begin to show signs of recovery, although, similar to Castanhão and Eng. Armando, this rebound has been gradual rather than a full return to pre-drought conditions. The shaded intervals in the figure highlight this long decline followed by a slow refill phase, illustrating the persistent hydrological legacy of multi-year droughts and the limited short-term resilience of large semi-arid reservoir systems.

Figure 10. Temporal evolution of the Orós Reservoir storage (2008–2025). Data: ANA-SAR. Figure prepared by the Author (2025).

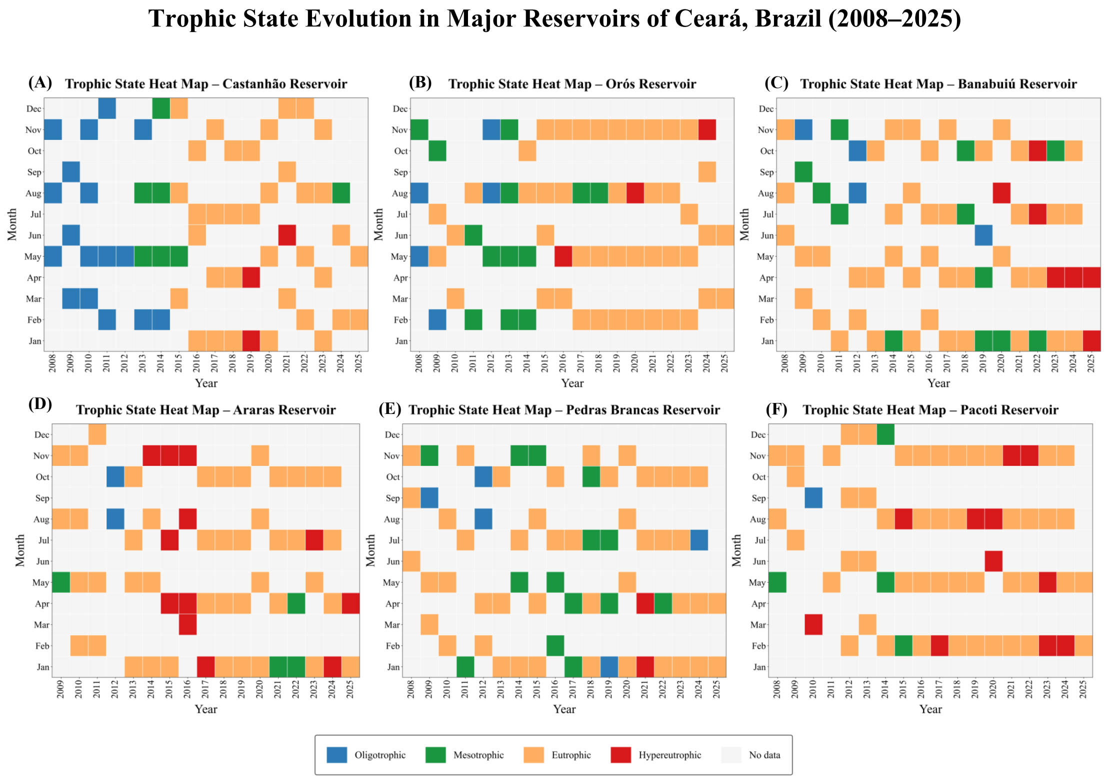


This persistent low-water phase helps explain the PCA results: when water levels fall and stay low for years, dilution capacity decreases and the system becomes more prone to eutrophication.

The temporal evolution of trophic states in the major reservoirs of Ceará (Figure 11) complements the PCA interpretation by illustrating how drought-induced hydrological stress translated into progressive eutrophication. Between 2008 and approximately 2013, most reservoirs, particularly the largest ones such as Castanhão and Orós, remained predominantly oligotrophic to mesotrophic, consistent with the positive side of PC1, where higher volumes and greater water transparency prevail. However, following the onset of the severe multiannual drought between 2010 and 2016, the most intense and prolonged event recorded in Northeast Brazil (Marengo *et al.*, 2018; Tomasella *et al.*, 2023), a marked deterioration in water quality occurred, driving these systems toward eutrophic and occasionally hypereutrophic states. This transition coincided with pronounced declines in reservoir volume, echoing the inverse relationship captured in the PCA, where the volume vector points to the upper right (positive PC1) while eutrophication-related variables (Chla, TN, TP) load strongly to the left.

Figure 11 uses monthly trophic state classifications from routine limnological monitoring conducted by Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) for Ceará's major reservoirs between 2008 and 2025, provided directly by the agency (J. Gonçalves Filho, personal communication, 28 October 2025).

Figure 11. Monthly variation in trophic states of (A) Castanhão, (B) Orós, (C) Banabuiú, (D) Araras, (E) Pedra Branca, and (F) Pacoti reservoirs, Ceará, Brazil, from 2008 to 2025. Data source: (FUNCEME, 2025, pers. comm.). Figure prepared by the Author (2025).



Trophic State Evolution in Major Reservoirs of Ceará, Brazil (2008–2025)

(A) Trophic State Heat Map – Castanhão Reservoir

(B) Trophic State Heat Map – Orós Reservoir

(C) Trophic State Heat Map – Banabuiú Reservoir

(D) Trophic State Heat Map – Araras Reservoir

(E) Trophic State Heat Map – Pedras Brancas Reservoir

(F) Trophic State Heat Map – Pacoti Reservoir

Similar to the patterns reported by Cortez *et al*. (2022) for the Cruzeta reservoir in the Brazilian semiarid, prolonged drought periods intensified nutrient concentrations and algal biomass, shifting the system from eutrophic to hypereutrophic even after reflooding. Their PCA results also revealed that despite rainfall recovery, low storage volumes and nutrient-enriched runoff from the watershed continued to sustain eutrophic conditions. This behavior highlights that water renewal after drought does not necessarily restore pre-drought quality, especially when sediments release accumulated phosphorus and external inputs surge with the first rains. In the Ceará reservoirs, the same process likely occurred: reduced dilution capacity and increased internal nutrient loading during the drought promoted a long-term shift along the trophic gradient.

Overall, the combination of the PCA evidence and the temporal trophic evolution suggests that extended droughts amplify eutrophication pressure by reducing water volume, concentrating nutrients, and altering biogeochemical cycling. The persistence of these patterns, also observed regionally (Marengo *et al.,* 2018; Tomasella *et al.,* 2023; Cortez *et al.,* 2022), underscores the vulnerability of large semiarid reservoirs such as Castanhão to climate variability, where prolonged low-water conditions can override their natural buffering capacity and push them into sustained eutrophic or hypereutrophic states.

De Lucena Barbosa *et al.* (2021) demonstrated that large-scale inter-basin water transfers, such as the São Francisco River Integration Project, can markedly alter trophic dynamics in receiving reservoirs of the semiarid Northeast. While upstream systems showed temporary water quality improvement due to dilution, downstream reservoirs accumulated higher nutrient loads and algal biomass, suggesting that the reestablishment of hydrological connectivity after prolonged drought may initially mobilize nutrients trapped in dry channels and sediments. Complementary to this, Costa *et al.* (2019) examined 16 reservoirs across the Piancó and Seridó sub-basins and found that prolonged drought led to lower water levels, reduced transparency, and higher turbidity, driving shifts in phytoplankton structure.

As photosynthetic efficiency decreased, cyanobacteria lost dominance to mixotrophic taxa such as Cryptophyceae and Euglenophyceae, indicating an adaptive response to simultaneous light and nutrient limitations. Similarly, Vanderley *et al.* (2021) showed that in six shallow semiarid lakes, low water levels and elevated phosphorus concentrations sustained perennial cyanobacterial blooms, with *Microcystis* dominating under clearer conditions and *Raphidiopsis* in more turbid, nutrient-enriched waters. These findings together highlight how hydrological stress and nutrient accumulation interact to promote eutrophic and bloom-prone conditions in semiarid systems.

At broader spatial and temporal scales, Ventura *et al.* (2022) analyzed two decades of chlorophyll-a data derived from MODIS imagery in large reservoirs such as Castanhão and Orós, revealing that chlorophyll-a peaks consistently coincided with drought periods, particularly the 2012–2016 event, when low inflows and high evaporation increased nutrient concentration and phytoplankton biomass. This pattern aligns with Freitas *et al.* (2011), who found that in the Cruzeta Reservoir, phosphorus and suspended sediment loads increased sharply during rainy periods but were largely retained within the reservoir, sustaining eutrophic conditions during dry seasons through internal nutrient recycling.

Long-term phosphorus monitoring in the Castanhão Reservoir by Lima Neto (2025) further confirmed that extreme volume fluctuations between 2008 and 2022 intensified internal phosphorus accumulation, with TP concentrations rising 22-fold in the water column and 7-fold in sediments. External loading, aquaculture effluent, and sediment release were identified as the main phosphorus sources, and model projections indicated that without significant load reductions, eutrophication will continue to intensify until 2050. Consistent with this, Cavalcante *et al.* (2021) highlighted that internal P release can persist for many years even after external contributions decline, meaning sediment phosphorus pools may continue fueling eutrophication under future warming and drought scenarios characteristic of semiarid environments. Collectively, these studies reveal a consistent pattern across different systems and scales: hydrological variability, nutrient retention, and internal recycling act together to maintain or enhance eutrophic states in semiarid reservoirs, even when hydrological conditions temporarily improve.

Altogether, the findings in this chapter illustrate how hydrological context, nutrient dynamics, and reservoir morphology interplay to shape water quality outcomes in the semi-arid Northeast. Periods of reduced storage were consistently accompanied by changes in trophic structure, shifts in transparency and phytoplankton patterns, and higher susceptibility to eutrophic states, while temporal variability highlighted the influence of both seasonal cycles and multi-year drought conditions. These observations provide a coherent picture of the ecological behaviour of reservoirs under sustained hydrological stress, offering a grounded basis from which broader implications and interpretive discussion can proceed in the following chapter.

5. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

Eutrophication in semi-arid reservoirs of Northeast Brazil results from the combined influence of hydrological variability, nutrient accumulation, and limited dilution capacity. During the 2012–2016 drought, reservoirs reached critically low storage levels and consistently shifted toward more eutrophic conditions. Even after rainfall resumed and volumes increased, water quality did not recover at the same pace. This slow response indicates the strong influence of internal nutrient release, extended water residence times, and the decomposition of accumulated organic matter, which sustain eutrophic conditions beyond the drought period.

The multivariate analysis supported these dynamics. The reservoirs did not form distinct clusters in the PCA, which is expected given that all systems were sampled during a drought-stressed period. However, the direction and strength of the variable loadings clearly reflected the underlying processes: higher storage and greater transparency aligned with lower nutrient concentrations and chlorophyll-a, while reduced volume aligned with eutrophic conditions. These vector relationships confirm that water availability, dilution capacity, and retention time are core drivers of trophic behavior in semi-arid reservoirs. The results are consistent with observations from large regional systems such as Castanhão and Orós and echo patterns documented in other semi-arid environments globally.

Catchment pressures further intensify this situation. Reservoirs influenced by degraded vegetation, agricultural runoff, livestock production, or insufficient wastewater treatment exhibit faster deterioration and slower recovery. Although Brazilian regulations, including CONAMA Resolution 357/2005, provide reference values for water quality, enforcement remains inconsistent and basin-level coordination is limited. Current water-resource governance prioritizes water supply and operational storage over integrated nutrient management, ecological thresholds, and drought-phase environmental protection.

Taken together, the findings show that eutrophication in semi-arid reservoirs is driven not only by external nutrient inputs but also by prolonged drought, internal nutrient cycling, and governance gaps. The system does not automatically return to pre-drought conditions after rainfall; instead, a legacy effect persists, requiring active management and adapted monitoring approaches. Protecting water quality in these systems demands attention to hydrological realities, climate uncertainty, land-use dynamics, and long-term ecological feedbacks.

5.1.2 Key conclusions

- Reduced storage amplifies eutrophication by concentrating nutrients and increasing residence time.
- Multi-year droughts produce long-lasting ecological changes, with slow recovery after refilling.
- PCA loadings confirmed that high storage and transparency align with lower nutrient concentrations and chlorophyll-a; reservoirs did not cluster because all were drought-affected.
- First-flush rainfall events mobilize accumulated nutrients and can trigger algal blooms.
- Land-use change and insufficient sanitation accelerate water-quality decline and delay recovery.
- Hydrological context must accompany trophic indicators to accurately assess reservoir status.
- Current management is centered on water supply, with insufficient focus on nutrient control and ecological resilience.

5.1.3 Final reflection

This work demonstrates that eutrophication in semi-arid reservoirs is fundamentally tied to hydrology, climate variability, and land-use pressures. Scientific understanding and policy frameworks must move beyond traditional nutrient-centric models and explicitly incorporate drought dynamics, catchment management, and internal nutrient cycling. Strengthening wastewater treatment, restoring riparian zones, improving monitoring, and integrating water-quality goals into drought planning are essential steps to ensure long-term ecosystem resilience and water security in the Northeast region.

6.2 Suggestions

6.2.1 Research and monitoring

- Integrate reservoir volume, residence time, and hydrological indicators into monitoring routines.
- Quantify sediment phosphorus release during drought and refilling to identify priority reservoirs for intervention.
- Conduct high-frequency sampling during the first rains to capture nutrient pulses and bloom onset.
- Expand cyanotoxin monitoring in drinking-water reservoirs during low-storage periods.

6.2.2 Technological and operational measures

- Pilot phosphorus-binding treatments in systems with confirmed internal loading.
- Promote decentralized sanitation and nature-based treatment solutions in small municipalities.
- Adopt operational rules that maintain minimum ecological storage thresholds during drought.
- Implement satellite-based chlorophyll monitoring for early-warning bloom detection.

6.2.3 Policy and basin-level management

- Establish basin-scale nutrient load limits tied to land-use licensing and aquaculture operations.
- Include water-quality targets and ecological thresholds in drought-response plans.

- Strengthen watershed committees and enforcement mechanisms for sanitation and land-use control.
- Prioritize riparian restoration and soil-stabilization practices in vulnerable catchments.

6.2.4 Methodological development

- Combine trophic classification with hydrological stress indicators.
- Institutionalize multivariate tools such as PCA in routine assessment programs.
- Develop semi-arid-specific trophic guidelines that reflect dilution loss and internal nutrient cycling.
- Advance ecological and hydrological modeling tools to simulate reservoir responses under climate-change scenarios.

7. SUMMARY

This thesis analyses the drivers, dynamics, and impacts of eutrophication in freshwater reservoirs in the semi-arid region of Northeast Brazil (NEB), a water-stressed area where reservoirs are essential for public supply, agriculture, and economic activities. The study rationale is based on increasing climatic pressures in the region, characterized by prolonged droughts, irregular rainfall, and high evaporation, combined with nutrient inputs from agricultural runoff, domestic wastewater, and land-use change across the Caatinga biome. These combined factors intensify nutrient accumulation and algal proliferation, threatening water security and ecosystem health.

A mixed methodological approach was applied. Reservoir data were obtained from the National Water and Sanitation Agency (ANA-SAR), state monitoring programs (COGERH), and peer-reviewed studies. Major reservoirs above 10 hm^3 located within the official semi-arid boundary defined by SUDENE were selected. Geospatial processing was conducted in QGIS to map reservoir distribution and storage patterns. Temporal analysis evaluated long-term storage trajectories. Limnological data (total phosphorus, total nitrogen, chlorophyll-a, Secchi depth) were standardized and assessed using Principal Component Analysis (PCA) to identify dominant gradients in water quality. Seasonal conditions during rainy and dry periods were compared.

Results show that more than half of the analysed reservoirs were below 50 percent capacity during the dry season, reflecting persistent hydrological stress. Storage records reveal sustained depletion following the severe 2012-2016 drought, with slow and incomplete recovery in subsequent years. Lower reservoir volume was strongly associated with higher nutrient concentrations, elevated chlorophyll-a, and reduced transparency. PCA indicated a clear contrast between larger, clearer, low-nutrient reservoirs and smaller, eutrophic systems with high nutrient loads and algal biomass. Seasonal clustering was weak, suggesting that prolonged drought conditions diminish typical seasonal patterns and sustain eutrophic states even during wetter months.

The study concludes that eutrophication in NEB reservoirs is driven by the combined effects of external nutrient inputs, internal sediment nutrient recycling, and chronic low water storage intensified by climate variability. Once established, eutrophication persists due to hydrological instability and limited dilution capacity. Effective management requires integrated watershed planning, expansion of sanitation and wastewater treatment, reduction of agricultural nutrient export, and adaptive governance suited to the socio-climatic context of semi-arid regions. Strengthening monitoring systems, improving regulatory enforcement, and adopting basin-scale, participatory water management approaches are essential to safeguard water quality and long-term water security in the NEB.

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DECLARATION

the public access and authenticity of the thesis

Student's name:	**Da Silva Sousa Matheus**
Student's Neptun code:	**A2P5SV**
Title of thesis:	**Eutrophication in Water Bodies in the Semi-arid Region of Northeast Brazil**
Year of publication:	**2025**
Name of the consultant's institute:	**Institute of Environmental Sciences**
Name of consultant's department:	**Department of Environmental Analysis and Technologies**

I declare that the thesis submitted by me is an individual, original work of my own intellectual creation. I have clearly indicated the parts of my thesis or dissertation which I have taken from other authors' work and have included them in the bibliography. Furthermore, I declare that the artificial intelligence tools (e.g. text generation, linguistic correction, translation, data analysis) used during the preparation of the thesis did not substitute my own research and creative work; their use was indicated either in the list of sources or in the methodology section, and I acted in accordance with professional and ethical expectations.

If the above statement is untrue, I understand that I will be disqualified from the final examination by the final examination board and that I will have to take the final examination after writing a new thesis.

I do not allow editing of the submitted thesis, but I allow the viewing and printing, which is a PDF document.

I acknowledge that the use and exploitation of my thesis as an intellectual work is governed by the intellectual property management regulations of the Hungarian University of Agricultural and Life Sciences.

I acknowledge that the electronic version of my thesis will be uploaded to the library repository of the Hungarian University of Agricultural and Life Sciences. I acknowledge that the defended and

- not confidential thesis after the defence

will be available publicly and can be searched in the repository system of the University.

Budapest, 2025/11/02

Student's signature

DECLARATION

Da Silva Sousa Matheus (Neptun code: **A2P5SV**)
as a consultant, I declare that I have reviewed the thesis and that I have informed the student of the requirements, legal and ethical rules for the correct handling of literary sources.

[✓ **I recommend**] **/ do not recommend** the **thesis** to be defended in the final examination.

The thesis contains a state or official secret: yes [✓ **no**]

Budapest, 2025/11/02

insider consultant

Declaration of Students and Doctoral Candidates on the Use of Artificial Intelligence (AI)”

1. general information:

Name of the student:	**Da Silva Sousa Matheus**
Neptun ID:	**A2P5SV**
Level of program (mark with X):	**BSc/BA**
Name and code of the subject*:	**Environmental Engineering** **B-GOD-N-EN-KORNY**
Title of the work:	**Eutrophication in Water Bodies in the Semi-arid Region of Northeast Brazil**

* Not required to be completed in the case of a doctoral dissertation.

2. Declaration on the Use of AI

I, the undersigned, fully aware of my ethical responsibility, make the following declaration:

(Please choose one of the options below!)

A) I have not used any artificial intelligence system or service.

(If you selected this option, completing the subsequent tables is not required.)

☐ B) I have used an artificial intelligence system or service.

(Please fill in the relevant tables!)

3. Details of Artificial Intelligence Usage

TABLE I: Assistant or Minor Usage (e.g., translation, language proofreading, brainstorming, etc.)

(For these uses, attaching the specific prompts and responses is not required.)

Purpose of Use	**Name and Version of the AI Tool Used**	**Affected Section (if not applicable to the entire text)**

TABLE II: Significant Content Contribution (e.g., generating an entire figure or a longer text section)

(In these cases, documenting the key prompts used and the raw responses provided by the AI, and attaching them as an appendix to the work, is required.)

Purpose of Use	Name, Version, and Access Information of the AI Tool Used	Exact Number of the Affected Chapter / Figure / Table	Entry Number of the Appendix Containing the Prompt Log

3/A. Additional Rules Prescribed by the Lecturer (if any)

If the instructor or supervisor of the course has established specific rules or expectations regarding the use of AI tools, please summarize them in the field below:

For example: prohibition of AI use for certain types of tasks; only specific tools are permitted; different citation requirements; documentation format, etc.

Rules Prescribed by the Lecturer or Supervisor

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4. Declaration Applicable to All Students:

I declare that I have critically reviewed, edited, and incorporated any content potentially generated by AI in all cases. I take full responsibility for every element of the submitted work, including its originality and scientific validity. I acknowledge that the Hungarian University of Agriculture and Life Sciences may check the submitted work with an artificial intelligence detector and may initiate proceedings if my declaration is found to be false or incomplete.

Place and Date: Budapest, 2025/11/02

………………………………………………………… ……………………………………………………………

Signature of the Student **Signature of the Advisor/Supervisor**