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Sediment deposition patterns in reservoirs with different water-level dynamics relevant for potential sediment reuse

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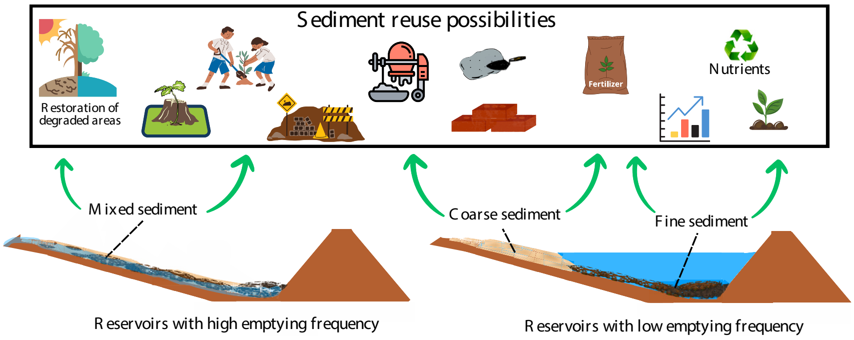
HIGHLIGHTS

- Spatial pattern of sediment grain size in reservoir bed is influenced by water level dynamics
- A hydrology-based Reservoir Emptying Index enables the assessment of sediment deposition pattern
- Fine grains strongly correlate with nutrients and serve as proxy for planning sediment reuse

GRAPHICAL ABSTRACT



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ABSTRACT

Reservoirs are essential for water supply in dry regions. However, siltation reduces their capacity and degrades water quality due to adsorbed pollutants. Assessing the spatial pattern of sediment deposition in reservoirs is crucial for the adoption of mitigating measures. We analysed sediments from eleven reservoirs in the semiarid Jaguaribe Basin, Brazil, aiming at understanding the deposition patterns and sediment attributes required for exploring the possibilities for sediment reuse. We adopted an approach with four methodological steps: (1) correlation analysis to explore the associations between grain size distribution and nutrients content; (2) cluster analysis to identify typical types of texture distribution of deposited sediments; (3) frequency assessment of sediment submergence to quantify accessibility of sediments; and (4) development of a Reservoir Emptying Index (REI) to be used as a proxy of sediment deposition patterns. The results revealed a clear correlation between fine grains and nutrient concentrations. Reservoirs with high emptying frequency exhibited greater sediment mixing. Conversely, reservoirs with low emptying frequency demonstrated granulometric segregation, with sand

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deposited near the delta and finer grains close to the dam. We demonstrated that water level dynamics can be used to estimate sediment deposition pattern and that grain size distribution can serve as an indicator for selecting sediments suitable for applications such as soil amendment, environmental rehabilitation, and additives of building material for civil construction. Our findings enhance the understanding of the spatial and temporal availability of sediments in reservoirs, supporting strategies for their removal and reuse, thereby contributing to more efficient reservoir management.

1. Introduction

Reservoirs play a crucial role at the global scale, providing essential benefits such as water supply, flood control, irrigation, hydropower generation, and recreation (Morris, 2020).

In dry regions, water scarcity has historically been mitigated through dam construction, with large government-managed reservoirs built to stabilize supply and smaller locally managed reservoirs often emerging in rural areas to store excess rainfall during the wet season (Medeiros and Sivapalan, 2020). This strategy has created dense reservoir networks (Pereira et al., 2025), but their effectiveness is increasingly threatened by reservoir siltation, which reduces storage capacity, water quality and, therefore, water availability (Lima Neto et al., 2022; Rabelo et al., 2025). In nested catchments, smaller upstream reservoirs retain sediments and help extend the lifespan of larger downstream structures (Bronstert et al., 2014). However, intensive water use and low overspill events accelerate sediment accumulation (de Araújo et al., 2023), especially in small farm dams which lack sediment-management infrastructure, such as bottom outlets. This paradox underscores that the implementation of new reservoirs alone cannot resolve water scarcity without integrated sediment management (Morris, 2020).

Soil erosion predominantly mobilizes finer particles that are transported to waterbodies and often trapped in reservoirs, leaving coarser fractions behind and degraded upstream soils (Pereira et al., 2022). The accumulation of sediments upstream of dams also alters the balance between storage and export, generating sediment deficits and compromising river connectivity (Shi and Qin, 2023). Disruption of the natural continuity of sediment transport reduces downstream sediment supply, altering channel morphology and affecting aquatic habitats (Fortesa et al., 2021).

To address the issue of siltation, several control measures can be implemented, including periodic desilting operations (Morris, 2020). Studies have highlighted the potential for reusing the extracted material, demonstrating its applicability for, e.g., soil amendment, construction material, or other innovative applications aligned with circular-economy principles (Bondi et al., 2016; Renella, 2021; Braga et al., 2024; Gomez et al., 2025). The high density of reservoirs in semiarid regions (Pereira et al., 2025) contributes to the availability of sediment at short distances (Braga et al., 2019). Furthermore, the temporal variability of precipitation and runoff, combined with water consumption and high evaporation rates, often results in a high frequency of reservoir emptying, which makes sediment readily available for desilting (Braga et al., 2025). As a result, desilting by regular excavation can align with the frequency of reservoir emptying during dry periods, potentially mitigating the impacts of sediment deposition (Silva et al., 2025) ensuring economic feasibility (Braga et al., 2019; Braga et al., 2025). However, attention must be given to the potential presence of pollutants such as heavy metals in deposited sediments, which might origin from runoff of urban or densely populated areas, as well as from regions with industrial activity (de Andrade et al., 2019), or in mining areas (García-Ordiales et al., 2016).

Sediment grain-size distribution plays an important role on sediment management: together with pedotransfer functions, it can be used to estimate hydraulic properties (such as hydraulic conductivity and water retention capacity) and promote understanding of the connections between sediments and other essential soil characteristics, such as nutrient content. This approach is particularly relevant given that comprehensive laboratory analyses of sediments can be time-consuming and resource-intensive (Carvalho et al., 2022). Simpler and faster grain size analysis enables the inference of physicochemical properties when their correlations are acknowledged, offering a practical pathway for the initial characterization of sediments. By understanding these relationships, it becomes possible to more accurately identify areas with higher sediment reuse potential, designating their allocation to specific applications such as agriculture, land restoration, or construction (Pereira et al., 2021; Renella, 2021).

Despite the recognised value of sediment reuse, the influence of water-level dynamics on the spatial deposition and granulometry of sediments remains poorly quantified. This knowledge gap limits the development of efficient strategies for selective sediment extraction and for predicting the quality of the material available for reuse.

In this study, we aimed to better understand how hydrological variability influences the spatial characteristics of reservoir sediments, providing information for their potential reuse. To this end, we assessed sediment properties and the pattern of their spatial deposition in reservoirs of the Jaguaribe Basin, in the semiarid region of Brazil, aiming to address this gap. We employed exploratory correlation analysis to investigate potential associations between sediment granulometry and physicochemical properties such as nutrient content (e.g., N, K, OM) and contamination risks (e.g., salinity), which can help to reduce the need for complex laboratory analyses. Additionally, we applied cluster analysis to identify preferential sediment deposition zones, to support the planning of its selective extraction and reuse for purposes such as agricultural fertilisation or civil construction. The pronounced temporal variability of reservoirs' water levels, with high frequency of depletion, led us to propose a novel hydrological approach based on the sediment submergence frequency to analyse the deposition patterns. This approach enables the identification of zones with different sediment characteristics, contributing to the adoption of sediment reuse as a measure for reservoir management.

2. Materials and methods

2.1. Study area

The study is based on a sediment database from eleven reservoirs of varying scales ranging between 0.01 and 118 hm^3 (Braga et al., 2024) located within the Jaguaribe River Basin, a semi-arid region in Northeastern Brazil (Fig. 1). The basin has an area of roughly 75,000 km^2 with an estimated population of approximately 2.5 million inhabitants. The average annual precipitation ranges between 500 and 1000 mm, while the potential evaporation exceeds 2000 mm per year. The rainfall regime is characterised by high intra- and inter-annual variability, with a well-defined rainy season between January and May, accounting for 80 % of the annual precipitation. The average monthly temperature ranges from 24 to 28 °C. The soils are generally shallow, with rock fragments, and the predominant soil types are Luvisols, Neosols, and Planosols. The rivers are ephemeral and intermittent, unable to meet the demand for water by the local population, which resulted in the construction of a dense network of reservoirs (one reservoir per 7 km^2 on average: Medeiros and Sivapalan, 2020). Among the studied reservoirs, five are located within the Madalena sub-basin ($\sim$124 km^2), an area that has been monitored in relation to hydrological and sedimentological variables (e.g., Braga et al., 2019; Zhang et al., 2021; Carvalho et al., 2022; Braga et al., 2024). These reservoirs are situated in rural areas where subsistence farming is predominantly. They are mainly used for human and livestock water supply, fishing, and small-scale irrigation (Coelho et al., 2017).

The geology of the Jaguaribe Basin exhibits lithological diversity, comprising extensive areas of metamorphic rocks (gneisses, metatexites, schists), igneous rocks (granodiorites, granites), and sedimentary formations (limestones and sandstones). In contrast, the Madalena sub-basin is characterised by more homogeneous crystalline basement units, composed predominantly of fine-grained gneisses, granodiorites, metatonalites, and granitoids, typical of metamorphic terrains (geological map of the study area in Fig. 2).

In the Brazilian semiarid region, water storage infrastructure has developed in response to persistent water scarcity caused by intermittent river flows and low groundwater availability. Beginning in the late 19th century, the government promoted the construction of large strategic dams, with a significant increase in implementation observed during the mid-1990s. Simultaneously, numerous small-scale reservoirs were built spontaneously by rural landowners to capture and store excess rainfall during the wet season (Medeiros and Sivapalan, 2020). These reservoirs, typically constructed with earth materials and without formal sediment management systems, now form a dense and heterogeneous network that plays a key role in regional water availability (Pereira et al., 2025).

2.2. Sediment sampling and characterization

Sediment samples were collected from the exposed reservoir surface layer (~2 cm depth) when the reservoirs were empty, following the removal of debris. A total of 197 sampling points were established across the reservoirs located in the Jaguaribe Basin, of which 131 samples are within the Madalena sub-basin. At each sampling point, an area with approximately 0.5 m in diameter was delineated, from which 3 to 5 subsamples were collected and combined to form a single composite sample weighing approximately 2 kg. The sediment samples were air-dried, disaggregated, homogenised, sieved to 2 mm, and subsequently sent to physicochemical laboratory analysis. The physicochemical analyses of the sediments were performed following the methods recommended in the Manual of Soil Analysis Methods by the Brazilian Agricultural Research Corporation (EMBRAPA, 2017). Sediment samples from Mel

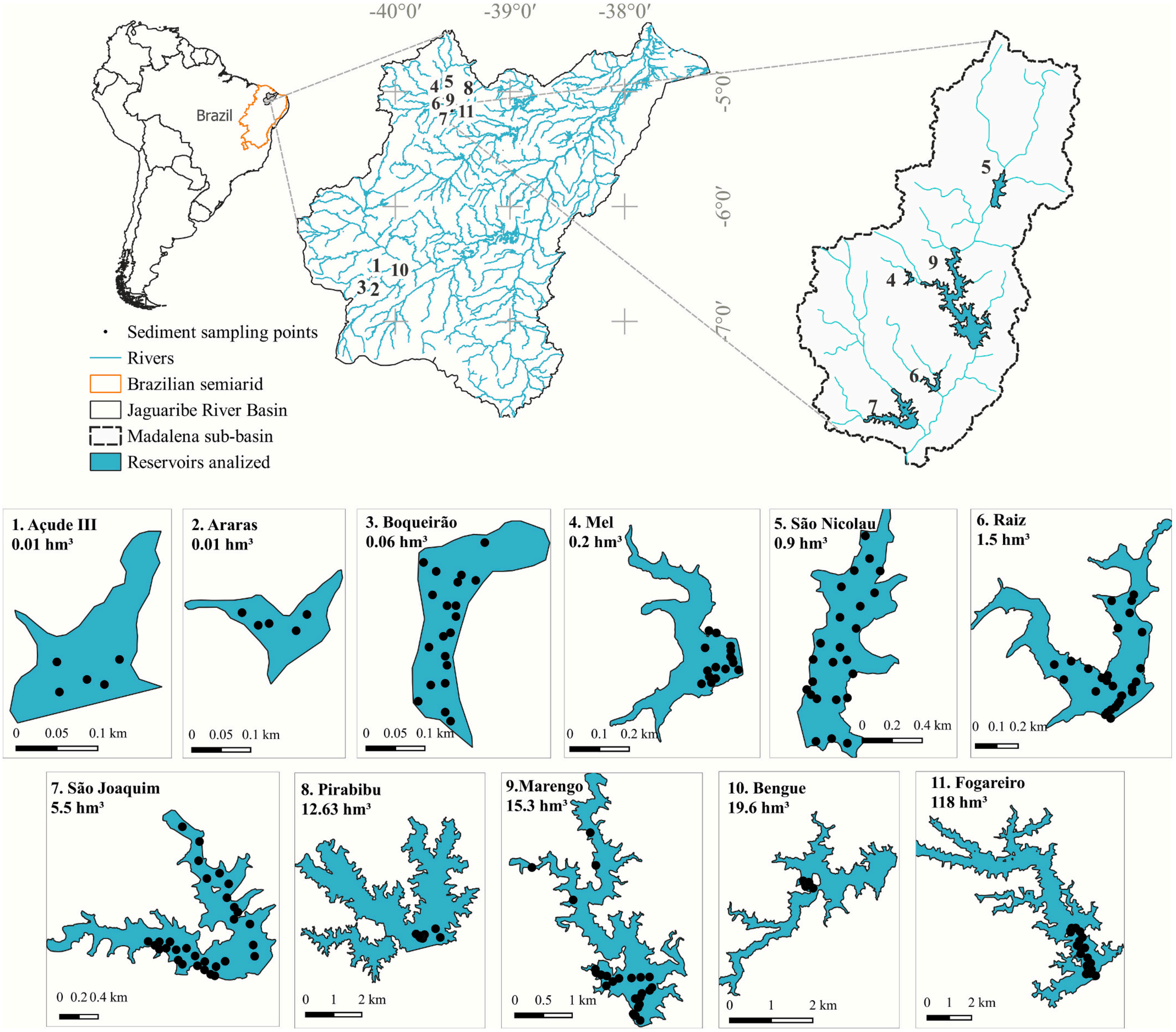
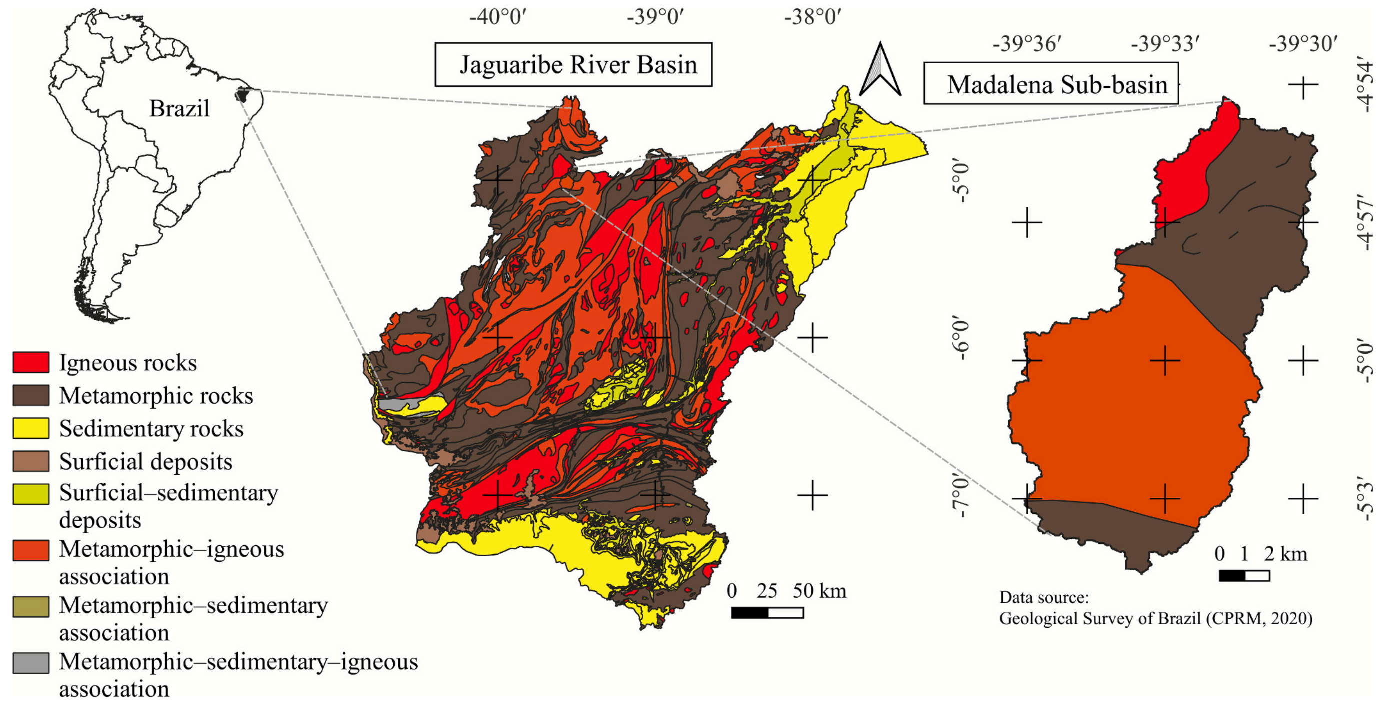


Fig. 1. Reservoirs studied in the Jaguaribe River Basin and the location of sediment sampling.



Data source:
Geological Survey of Brazil (CPRM, 2020)

Fig. 2. Generalized geological map of the Jaguaribe River Basin and Madalena sub-basin.

and Raiz reservoirs were collected in 2014, samples from the São Nicolau, São Joaquim, Marengo, and Fogareiro reservoirs were collected in 2016 and Araras, Açude III, Boqueirão and Benguê in 2017 (Carvalho et al., 2022), with updates including new sediment samples for the Boqueirão reservoir in 2021 (Silva et al., 2025), São Nicolau, São Joaquim and Pirabibu reservoirs in 2022 (Braga et al., 2024), and Marengo reservoir in 2024.

A total of 25 sediment properties were evaluated, including: coarse sand, fine sand, silt, clay, natural clay (N.clay), total carbon (C), total nitrogen (N), organic matter (OM) – all in $g \cdot kg^{-1}$, degree of flocculation (DF) in $g \cdot 100\ g^{-1}$, bulk density (BD) and particle density (PD) in $g \cdot cm^{-3}$, pH, calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), base sum (BS), available soil aluminium (Al), potential acidity (HAl), total cation exchange capacity (CEC) in $centimol \cdot kg^{-1}$, base saturation percentage (V), plant-available phosphorus (A.P) in $mg \cdot kg^{-1}$, total carbon/total nitrogen ratio (C.N), percentage of exchangeable sodium saturation (ESP), and electrical conductivity (EC) in $dS \cdot m^{-1}$. The data were used to investigate correlations between sediment texture (e.g., silt and clay) and other properties, to assess the potential of particle size distribution as an indicator of nutrient content (beneficial for agricultural use) as well as of limiting factors that may restrict sediment reuse (e.g., salinity). As the study area presents sediments with low metal concentrations, considered non-harmful for agricultural reuse (Braga et al., 2025), more detailed metal analyses were not conducted in this study. However, such analyses are essential in areas with potential contamination risk. This approach also contributes to understanding granulometric distribution patterns within the reservoirs, which is essential for identifying areas with reuse potential and guiding sediment extraction strategies for sustainable applications beyond agriculture.

2.3. *Data analysis and methods*

Data analysis comprises four methodological steps. The first one is exploring correlations between the sediment's physical and chemical properties to assess if it is possible to infer the presence of nutrients and other properties based on grain size distribution, therefore potentially reducing the need for more complex and costly laboratory analyses during sediment reuse applications. The second step involves a cluster analysis of the five reservoirs in the Madalena sub-basin, aimed at identifying granulometric groups with typical deposition patterns in the reservoirs. This analysis was conducted on a smaller scale, in the Madalena sub-basin, because reservoir bed elevation data were available, enabling a more detailed subsequent analysis of granulometric distribution within the reservoirs. In the third step, we conducted a water balance for the same five reservoirs to assess the water level dynamics and the frequency of submergence of the analysed sediment sampling points. Finally, in the fourth step we proposed a Reservoir Emptying Index (REI). We applied it to explain the granulometric deposition pattern using a hydrological approach, as an alternative to the hydrodynamic simulations usually employed for this purpose (Morris and Fan, 1997).

2.3.1. *Correlation analysis*

To determine the most appropriate correlation method, the Shapiro-Wilk test was used to assess whether the data followed a normal distribution. As the data exhibited a non-normal distribution (p-value <0.05), Spearman's correlation was applied to the 197 samples from the eleven reservoirs in the Jaguaribe River Basin to explore spatial correlations in a larger-scale context. Out of this total, a subset of 131 samples corresponds to the five reservoirs located within the Madalena sub-basin, which were analysed separately to assess whether correlation patterns varied according to changes in the catchment scale. Although the Madalena sub-basin is included within the Jaguaribe River Basin, these areas differ in both scale, geological characteristics, and data availability. This two-scale approach aimed to compare the correlation behaviour of sediment physicochemical data between reservoirs that are spatially more dispersed (Jaguaribe) and those situated in closer proximity to one another (Madalena).

2.3.2. *Cluster analysis*

The cluster analysis was conducted to identify typical grain size distribution patterns of sediments in the five reservoirs of the Madalena sub-basin, which was further used to assess the spatial distribution of the sediments within each reservoir. Statistical analysis was performed using the k-means algorithm in R, carried out using the factoextra package (Kassambara and Mundt, 2020), focusing on data for coarse sand, sand, silt and clay. To verify whether there were statistically significant differences among the three groups from each reservoir, the Kruskal-Wallis test was applied. This non-parametric test was chosen due to the absence of assumptions of normality and homogeneity of variances, as well as the unequal sample sizes. The analyses were conducted using a significance level of 5 % ($\alpha = 0.05$).

2.3.3. *Water balance in reservoirs and frequency of submergence of the sediment*

While regional flow information is available for large reservoirs monitored by the state water resources agency, local flow data are scarce. Due to the lack of hydrological monitoring for small reservoirs in the study area, the water balance approach was applied to characterize the hydrological regime and assess the frequency of sediment submergence in the reservoirs.

The water balance calculation and the submergence frequency analysis of the sediment sampling points within the five reservoirs of the Madalena sub-basin were conducted on a daily time step for the years 1974 to 2023. Rainfall data were obtained from the Brazilian National Water and Sanitation Agency (Agência Nacional de Águas e Saneamento - ANA), available at the Hidroweb platform (https://www.snirh.gov.br/hidroweb/serieshistoricas) - station code 539012, which ensured consistent and representative records for the study area. Evaporation data were estimated using the Penman method, based on meteorological data from the Quixeramobim station (code 82586), operated by the Brazilian National Institute of Meteorology (Instituto Nacional de Meteorologia - INMET). The dataset covered the period from 1974 to 2023, with any gaps filled using the monthly averages from historical records spanning 1961 to 2023. The surface runoff was estimated based on precipitation data and the empirical Curve Number (CN) method developed by the US Department of Agriculture. The average CN values for each of the reservoirs' catchments were obtained from the study conducted by the National Water and Sanitation Agency, which employed a soil mapping and land-use / land-cover data from 2014 to generate a comprehensive metadata for the entire Brazilian territory. CN values for normal conditions were considered for the five sub-basins – Mel, São Nicolau, Raiz, São Joaquim e Marengo - (averaging 79.9 to 82.7), resulting in initial abstraction values ranging from 12.8 mm to 10.6 mm (20 % of the potential storage), aligning with other values reported in the literature for the region, such as 12 mm (de Figueiredo et al., 2016) and 9.5 mm (Andrade et al., 2017). Water Height-Area-Volume (HAV) data were obtained from previous surveys conducted in the research area (Grin, 2014; Zhang et al., 2021).

Using the elevation data of each sediment sampling point in the reservoirs and based on the water balance calculations for the years 1974–2023, a sediment submergence analysis was performed, indicating the frequency at which the sampling points were under water and how this pattern could be used to explain the grain size distribution of the deposited sediment.

2.3.4. *Reservoir emptying index*

The Reservoir Emptying Index (REI) was developed to quantify the water storage conditions in the analysed reservoirs before the onset of the rainy season. For the application of the REI, historical series of reservoir volumes from 1974 to 2023 were used. The reference period for the calculation was the end of the dry season, just before the beginning of the rainy season, to capture the lowest water storage levels in each year when most of the runoff (and sediments) flowed into the reservoirs. Specifically, December 25th was adopted as the representative date for this dry-season threshold, as proposed by Soares et al. (2024) for the study region.

The REI is a standardised, quantitative measure of water storage conditions at the end of the dry season. It is based on probability theory and represents the historical cumulative frequency distribution of reservoir volumes on a specific reference date. Essentially, the index reflects the relative condition of the reservoir volume in relation to the maximum volume historically observed at the same period of the seasonal cycle. Calculation involves the numerical integration of the curve relating standardised volume (ratio between observed volume and maximum observed volume) to cumulative probability. The REI value is obtained by subtracting this integral from unity, as formalised in Eq. 1. Thus, a REI value of 1 indicates that the reservoir was empty on the reference date throughout the historical record, while an REI value of 0 indicates that the reservoir was continuously full.

$$REI = 1 - \int_0^1 \frac{\mathrm{V}\ (f)df}{Vo\ max} \tag{1}$$

Where:

REI: Reservoir Emptying Index (with a value of 1 representing a permanently empty reservoir and 0 representing a permanently full reservoir);

V(*f*): Observed reservoir volume corresponding to each cumulative frequency value *f* at the reference date (before onset of the rainy period);

Vo max: Maximum volume observed on December 25th throughout the historical series (1974–2023).

It is important to emphasise that the REI differs from predictive or process-based models used to estimate siltation and storage capacity loss. Process-based models such as WASA-SED (Mueller et al., 2010) and empirical sediment budget approaches (Lima Neto et al., 2011) simulate sediment generation, transport and deposition in order to estimate reservoir capacity loss. In contrast, the REI provides a simpler, more parsimonious hydrological indicator. Rather than predicting sediment inflow or accumulation rates, the REI quantifies reservoirs' historical water storage conditions at the end of the dry season. This reflects their vulnerability to water depletion and their potential exposure to sediment remobilisation during the first inflow events of the wet season.

The REI can be calculated directly from available reservoir volume time series, requiring minimal input data. This simplicity makes it particularly suitable for environments with limited data, such as many semi-arid regions, where long-term monitoring of sediment flows is not available. Therefore, the REI serves as a complementary tool to sedimentation models, offering a practical means of classifying reservoirs according to their hydrological behaviour and assisting in the planning of desilting and sediment reuse strategies.

For reservoir management, the REI provides a standardised assessment of vulnerability to drought, enabling comparisons between reservoirs of different sizes and hydrological dynamics. At the same time, REI serves as a physical indicator of a reservoir's exposure to sediment dynamics: Reservoirs with a high REI present reduced hydraulic buffering capacity at the start of the rainy season. Initial rainfall events encounter a substantially low water storage volume, predisposing the reservoir to the resuspension of deposited sediments and influencing the pattern of sediment accumulation. Conversely, reservoirs with a low REI maintain higher volumes, providing water buffering and favouring more stable delta deposition. Taking into account the need for desilting and the potential application of sediment reuse, it is our hypothesis that the REI may be a useful tool for inferring sediment deposition patterns and supporting management strategies in reservoirs.

3. Results

3.1. *Correlation between the physical and chemical sediment properties*

The following figures show the correlation between the physicochemical properties of the sediment samples. The variables are: coarse sand, fine sand, silt, clay, natural clay (N.clay), total carbon (C), total nitrogen (N), organic matter (OM) – all in $g \cdot kg^{-1}$, degree of flocculation (DF) in $g \cdot 100\ g^{-1}$, bulk density (BD) and particle density (PD) in $g \cdot cm^{-3}$, pH, calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), base sum (BS), available soil aluminium (Al), potential acidity (HAl), total cation exchange capacity (CEC) in $centimol \cdot kg^{-1}$, base saturation percentage (V), plant-available phosphorus (A.P) in mg·kg^{-1}, carbon/nitrogen ratio (C.N), percentage of exchangeable sodium saturation (ESP), and electrical conductivity (EC) in dS·m^{-1}.

Sediment particle sizes showed some correlation (*r* values usually higher than 0.5) with other physicochemical properties of the sediment from the eleven reservoirs in the Jaguaribe Basin (Fig. 3, in which larger font sizes correspond to stronger correlations). Fine materials (silt and clay) exhibit positive correlations with most nutrients, whereas coarser grains (coarse sand and fine sand) show negative correlations.

In the Madalena sub-basin, sediment particle sizes showed strong correlations (>0.7) between fine particles and cations, as well as good correlations with total carbon (C), total nitrogen (N), and organic matter (OM) – see Fig. 4. In general, this indicates that sediments rich in fine materials can be associated with high nutrient loads.

3.2. Cluster analysis and sediment deposition pattern

In the cluster analysis, three distinct groups of sediments were identified that exhibited distinct grain size distributions in the five reservoirs of the Madalena sub-basin: group 1 (yellow in the graphs hereafter) is predominantly composed of coarser fractions (sand), whereas group 2 (grey) represents a mixed distribution of coarse and fine materials, and group 3 (black) is characterised by a predominance of fine materials. The Kruskal-Wallis test indicated statistically significant differences in the grain size groups among the reservoirs, specifically in São Joaquim, Raiz and Marengo reservoirs. These differences occurred in grain size composition (sand, silt, clay) between at least two of the three groups, with *p*-values of 0.009, 0.010, and 0.0005 respectively. On the other hand, no statistical differences were found among the groups in Mel (p-value = 0.710) and São Nicolau (p-value = 0.253) reservoirs.

The distribution of the three groups of sediment samples within the reservoirs is shown in Fig. 5, with the corresponding granulometric concentration ranges depicted in Fig. 6. The largest fractions of sand in Group 1 and silt/clay in Group 3 were observed in reservoirs with larger surface areas and volumetric capacity (Marengo and São Joaquim), for which the groups are more distinct and present a spatial pattern within the reservoirs: siltation of coarser sediment (Group 1) occurs predominantly on the reservoirs' deltas, as this fraction deposits more rapidly once the flow velocity decreases in the lake, whereas fine particles (Group 3) tend to deposit on lower bed areas closer to the dam. In smaller reservoirs such as Mel and São Nicolau, there was not a clear spatial pattern of sediment deposition with distinction on the position of coarse (Group 1) and fine (Group 3) fractions.

3.3. Sediment characteristics versus frequency of submergence

The analyses for the five reservoirs in the Madalena sub-basin revealed distinct patterns of submergence (Fig. 7A) and sediment deposition (Fig. 7B). Smaller reservoirs, such as Mel (0.2 hm^3) and São Nicolau (0.9 hm^3) tend to dry out more rapidly and stay empty more frequently. In contrast, larger reservoirs, such as Marengo (15.3 hm^3), display more stable duration curves of water depth, indicating higher water retention capacity, highlighting the influence of reservoir size on the hydrological dynamics. In the large systems, the boxplots indicating the range of water level in which each group of sediment occurs (Fig. 7B), demonstrate clear stratification between the groups.

The spatial distribution of nitrogen (N), organic matter (OM), plant-available phosphorus (A.P), and electrical conductivity (EC) in the sediments of the studied reservoirs was assessed, as well (Fig. 8). Higher levels of N were predominantly observed in the São Nicolau reservoir, with critical points close to the reservoir's shore. High concentrations were also identified along the shore lines of Raiz and São Joaquim reservoirs. Organic matter concentrations varied widely, ranging from approximately 1 to 138 g·kg^{-1}, with values above 30 g·kg^{-1} considered high for soils according the Brazilian Agricultural Research Corporation. OM showed a spatial distribution similar to that of N, whose

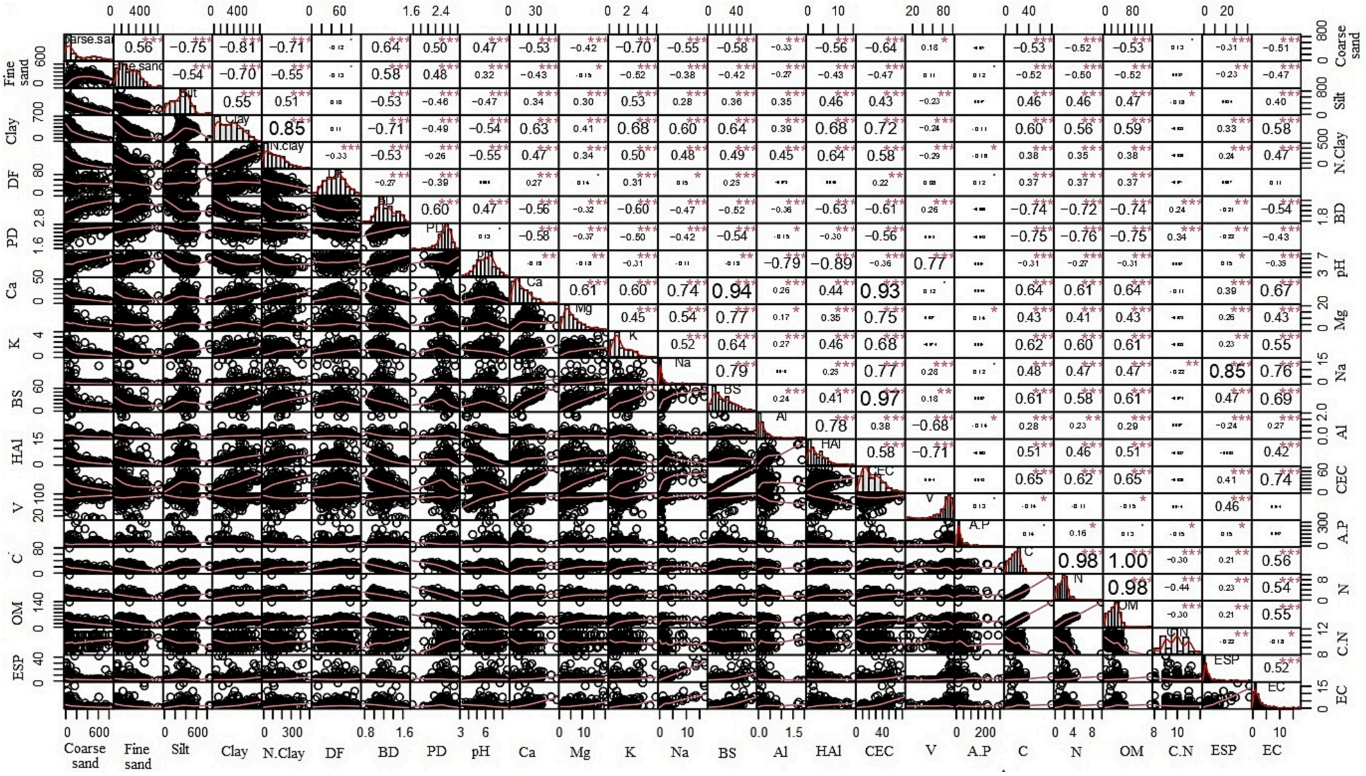


Fig. 3. Correlation of the 25 physicochemical sediment parameters with grain size (197 samples) collected between 2014 and 2024 in the eleven selected reservoirs of the Jaguaribe Basin. Significance levels: $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***), indicating 5 %, 1 % and 0.1 % probability of random occurrence, respectively.

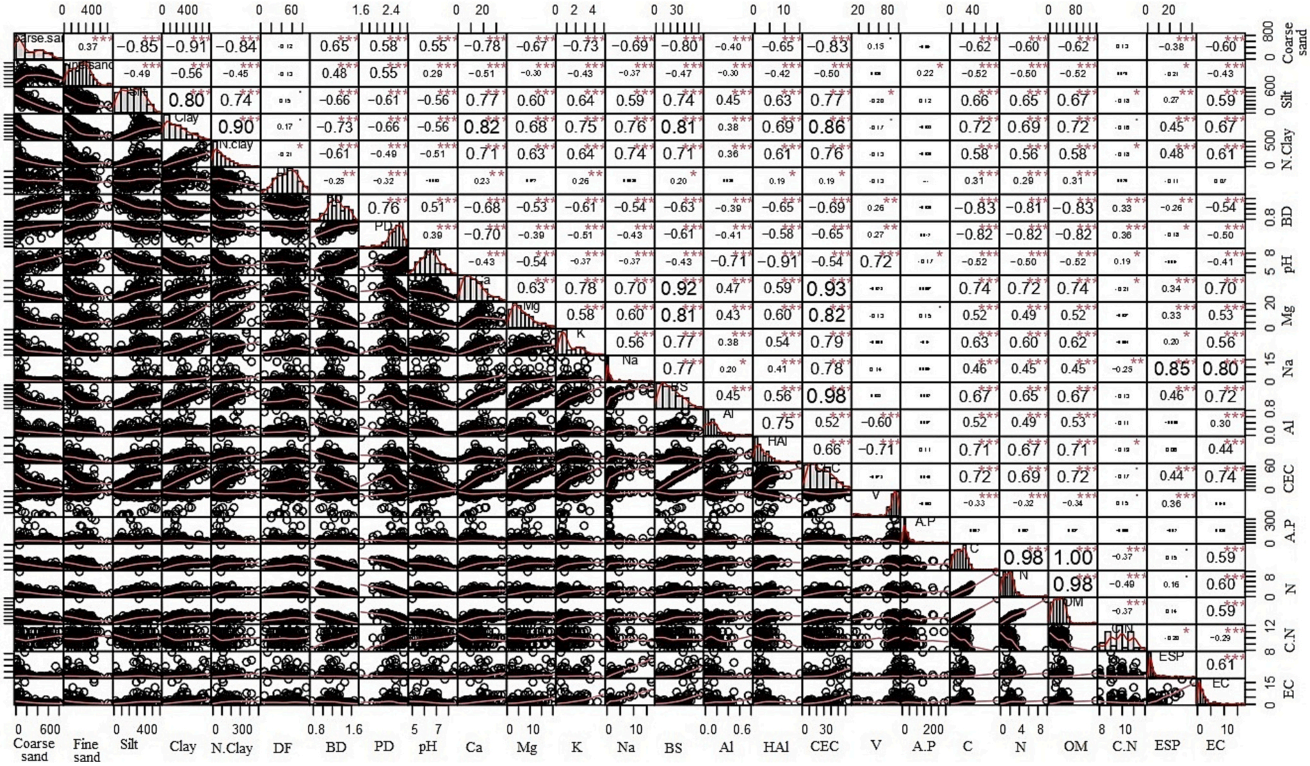


Fig. 4. Correlation of the 25 physicochemical sediment parameters with grain size (131 samples) collected between 2014 and 2024 in the eleven selected reservoirs of the Madalena subbasin reservoirs. Significance levels: $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***), indicating 5 %, 1 % and 0.1 % probability of random occurrence, respectively.

concentrations ranged from around 0 to 10 g·kg^{-1}. Since N is often associated with fine particles or incorporated into organic matter, areas with higher OM deposition also showed higher N concentrations. Plant-available phosphorus (A.P) concentrations ranged from approximately 1 to 316 mg·kg^{-1}, with the highest values occurring in reservoirs characterised by high emptying frequency, whereas those with high water accumulation and low emptying frequency exhibited lower concentrations. Electrical conductivity (EC) ranged from 0 to 17.24 dS·m^{-1}, with the highest values also associated with areas of high nutrient and OM accumulation.

3.4. Reservoir emptying index

Fig. 9 presents the Reservoir Emptying Index (REI) scale, ranging from 0 (always full reservoir) to 1 (always empty reservoir at the end of the dry season), where higher values indicate a higher degree of water depletion. Mel (REI = 0.97) and São Nicolau (REI = 0.82) reservoirs exhibited the highest values, indicating a critical state of water depletion before the onset of the rainy season. In these cases, runoff frequently flows into the empty reservoirs and transports all sediment particle sizes throughout the entire bed, resulting in a mixed sediment pattern. Conversely, Raiz (REI = 0.58), São Joaquim (REI = 0.57), and Marengo (REI = 0.39) displayed progressively lower indices. This indicates both a lower degree of depletion prior to recharge and greater grain-size selectivity of sediment deposition.

4. Discussion

4.1. Sediment characteristics impacted by the hydrological dynamics

The lithology of a river basin exerts influence on the particle size of sediments produced, which, in turn, affects transport and deposition processes, thereby influencing both the extent and nature of reservoir siltation (Rabelo et al., 2023). In this regard, the correlations between physical and chemical sediment properties, observed in the 124-km^2 Madalena sub-basin, may reflect the homogeneity of the predominant crystalline formations, resulting in homogeneous sediments across the studied area. In contrast, within the 75,000 km^2 Jaguaribe Basin, higher lithological and pedological diversity, combined with more complex hydrological conditions, tends to promote spatial variability in the sediment properties, potentially leading to weaker correlations among the physicochemical properties of the sediments. This effect on the correlation response was also noticed by Carvalho et al. (2022) when using diffuse reflectance spectroscopy to estimate sediment properties in the same study region. Furthermore, factors such as land cover and use (Rabelo et al., 2025), as well as the continuity of surface runoff (Fortesa et al., 2021), influence sediment mobilisation and delivery, impacting the nature of the material transported and the extent of deposition.

The higher correlations obtained (Fig. 4) for fine materials can be attributed to the fact that fine particles possess high specific surface areas and capacity to adsorb nutrients due to the presence of negative charges, which favours the adsorption of cations such as potassium (K) and sodium (Na), as well as organic matter (Amaro Filho et al., 2008). In addition, fine particles also include colloidal Fe and Al oxides, which provide positively charged sites capable of binding anions such as phosphate. However, this was not observed for plant-available phosphorus, although phosphorus is highly influenced by factors such as adsorption onto inorganic colloids (iron and aluminium oxides) and soil mineralogy (Santos et al., 2008).

These physicochemical interactions support the hypothesis that analysing sediment spatial patterns within reservoirs may provide an initial classification of sediment properties (Pereira et al., 2021). This initial analysis assists in the identification of areas with sediments suitable for targeted reuse (Carvalho et al., 2022). Despite the moderate to strong correlations (Mukaka, 2012) reported in our study, the initial exploratory analysis should not be interpreted as a definitive assessment

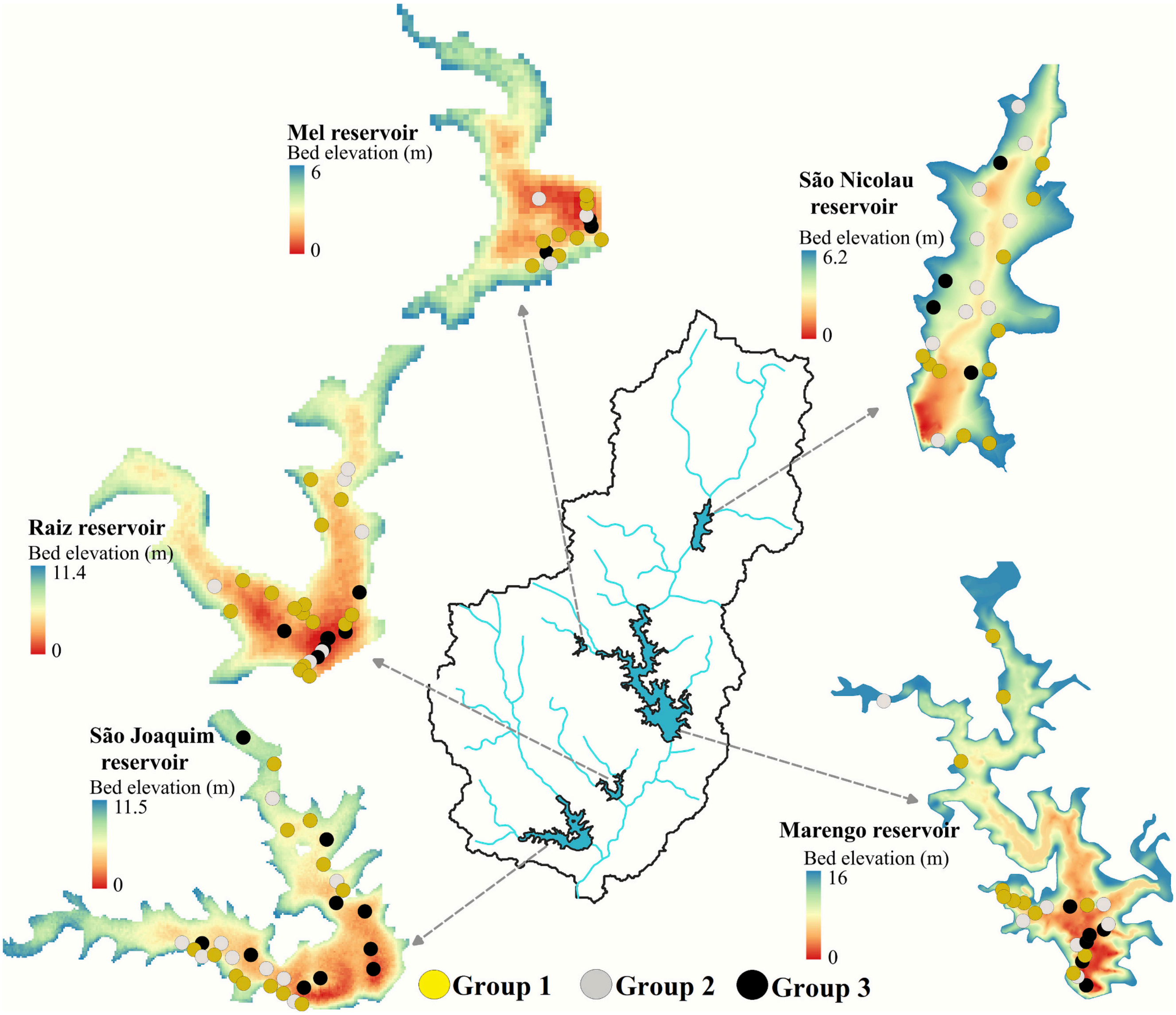


Fig. 5. Sediment deposition pattern by groups of grain size in the reservoirs of the Madalena sub-basin. Group 1: coarser fractions (sand); Group 2: mixed distribution of coarse and fine fractions; Group 3: fine fractions (silt and clay).

of characteristics, i.e., further sediment classification remains necessary.

Whereas sediment delivery is highly controlled by geomorphological factors (Rabelo et al., 2023), the dynamics of sediment deposition in reservoirs, specifically in dry regions, is strongly influenced by hydrological conditions. In these environments, which usually feature a dense network of reservoirs, those with a high frequency of emptying experience more intense mobilisation of sediment particles, promoting the transport and redistribution of finer materials when the reservoir is refilled. In contrast, reservoirs with low emptying frequency tend to favour the progressive deposition of fine sediments in deeper areas near the dam (Pereira et al., 2021). This filling and emptying dynamics play a crucial role in sediment redistribution and material mixing, as illustrated schematically in Fig. 10. For instance, a study conducted by Pereira et al. (2022) demonstrated that in a small reservoir (307 m^3 capacity), sediment concentrations remain continuously in suspension, suggesting significant particle mobility. In contrast, reservoirs with longer submersion cycles exhibit higher sedimentary stability and granulometric segregation, highlighting distinct patterns of deposition and sediment dynamics (Morris, 2020). Furthermore, the positioning of deltas within the reservoir may vary according to the stored water level: Pogorelov et al. (2021) observed that, during periods of higher water volume and depth, delta formation tends to advance towards more open and internal areas of the reservoir, whereas, during periods of lower water levels, deltas typically form in more restricted zones, which may lead to the compartmentalisation of the reservoir into distinct sectors. Thus, the water level during reservoir refilling can influence the positioning of deltas and the resuspension and redistribution of previously deposited sediments.

Pereira et al. (2021) observed in a 5 hm^3 reservoir located in a semi-arid region of Brazil the same pattern found in this study for larger reservoirs, where sediments exhibited higher fractions of fine particles near the dam and more sandy fractions along the reservoir margins. The authors also reported that phosphorus concentrations were higher at the reservoir margins, a pattern also observed in this study in the São Joaquim reservoir (5 hm^3). Conversely, plant-available phosphorus was significantly lower in the largest reservoir - Marengo (15 hm^3). Regarding nitrogen, Pereira et al. (2021) found higher concentrations near the dam and in the deeper central areas of the reservoir, a trend similarly observed in reservoirs with low REI in this study. However, high nitrogen concentrations were also recorded along the reservoir shoreline, which may be associated with land cover and use. In the specific case of the Madalena sub-basin, the area corresponds to a former

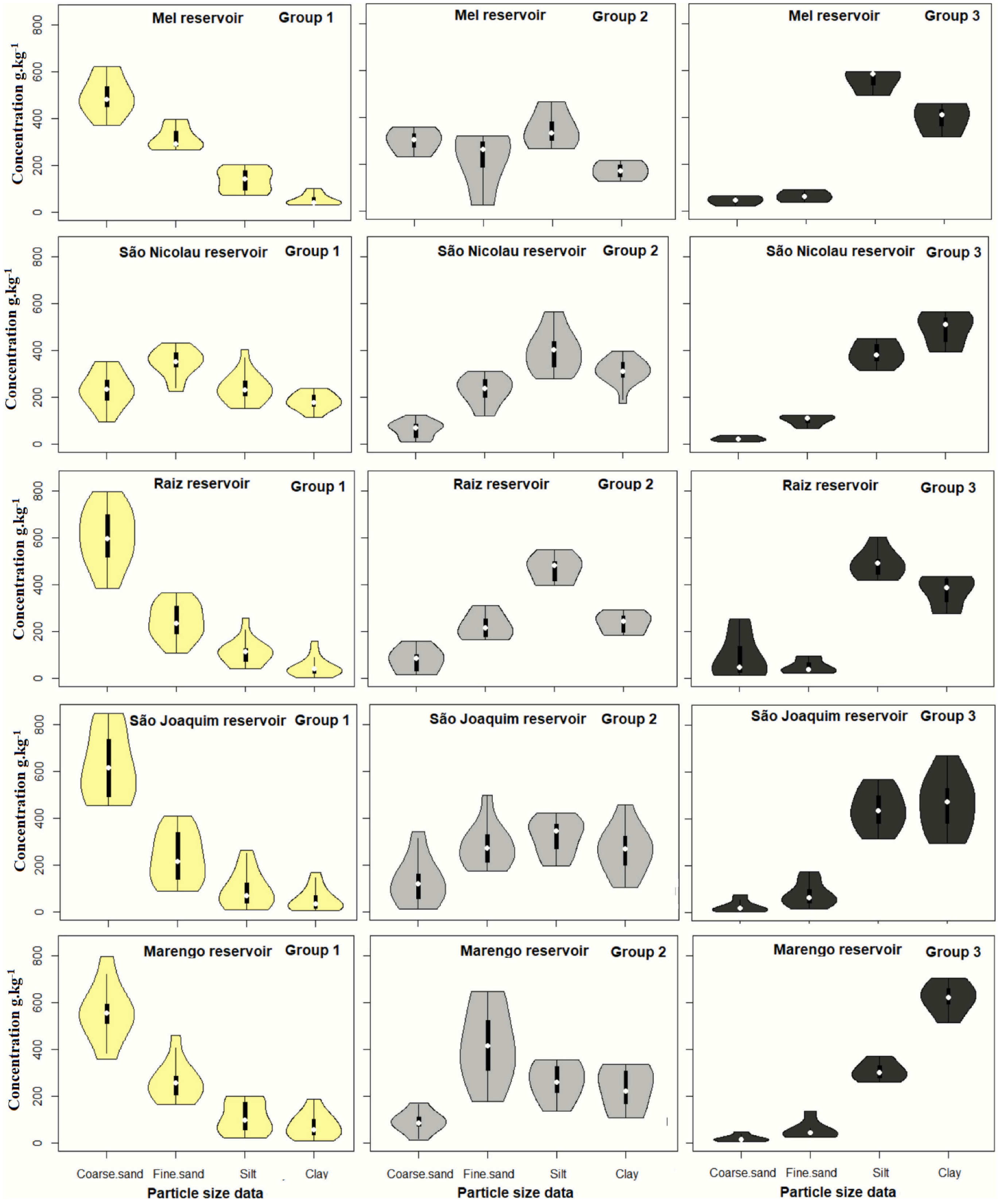


Fig. 6. Groups of sediment obtained in the cluster analysis, with their respective grain size distribution by reservoir in the Madalena sub-basin. Group 1 (yellow) is dominated by sand particles (coarse and fine sand), Group 2 (grey) presents a mixed distribution of sand and silt/clay fractions, and Group 3 (black) is characterised by a predominance of fine particles (silt and clay).

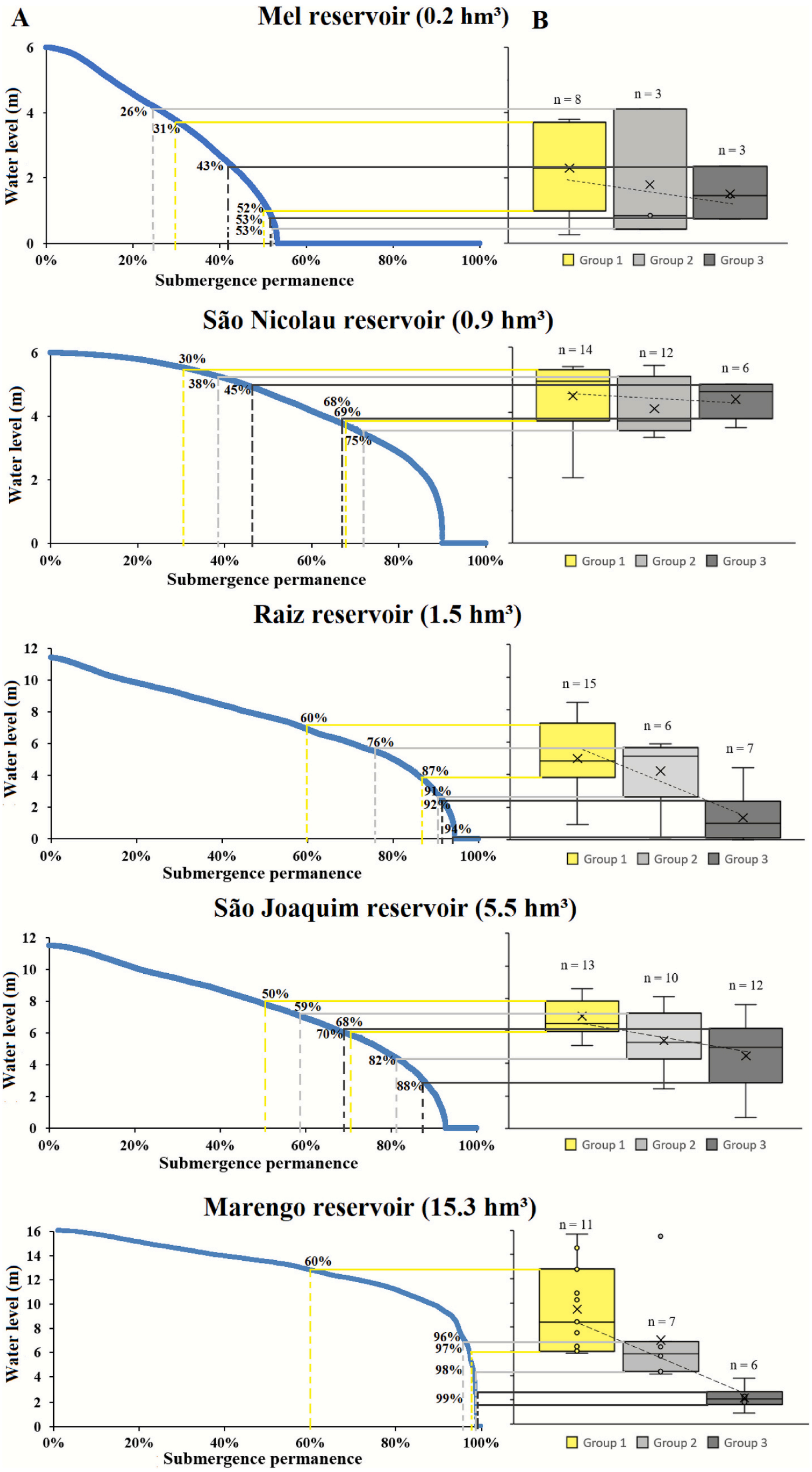


Fig. 7. Sediment submergence in the reservoirs of the Madalena sub-basin: A) duration curves of water level; B) sediment position in relation to water level, according to the sediment groups. Group 1: coarser fractions (sand); Group 2: mixed distribution of coarse and fine fractions; Group 3: fine fractions (silt and clay).

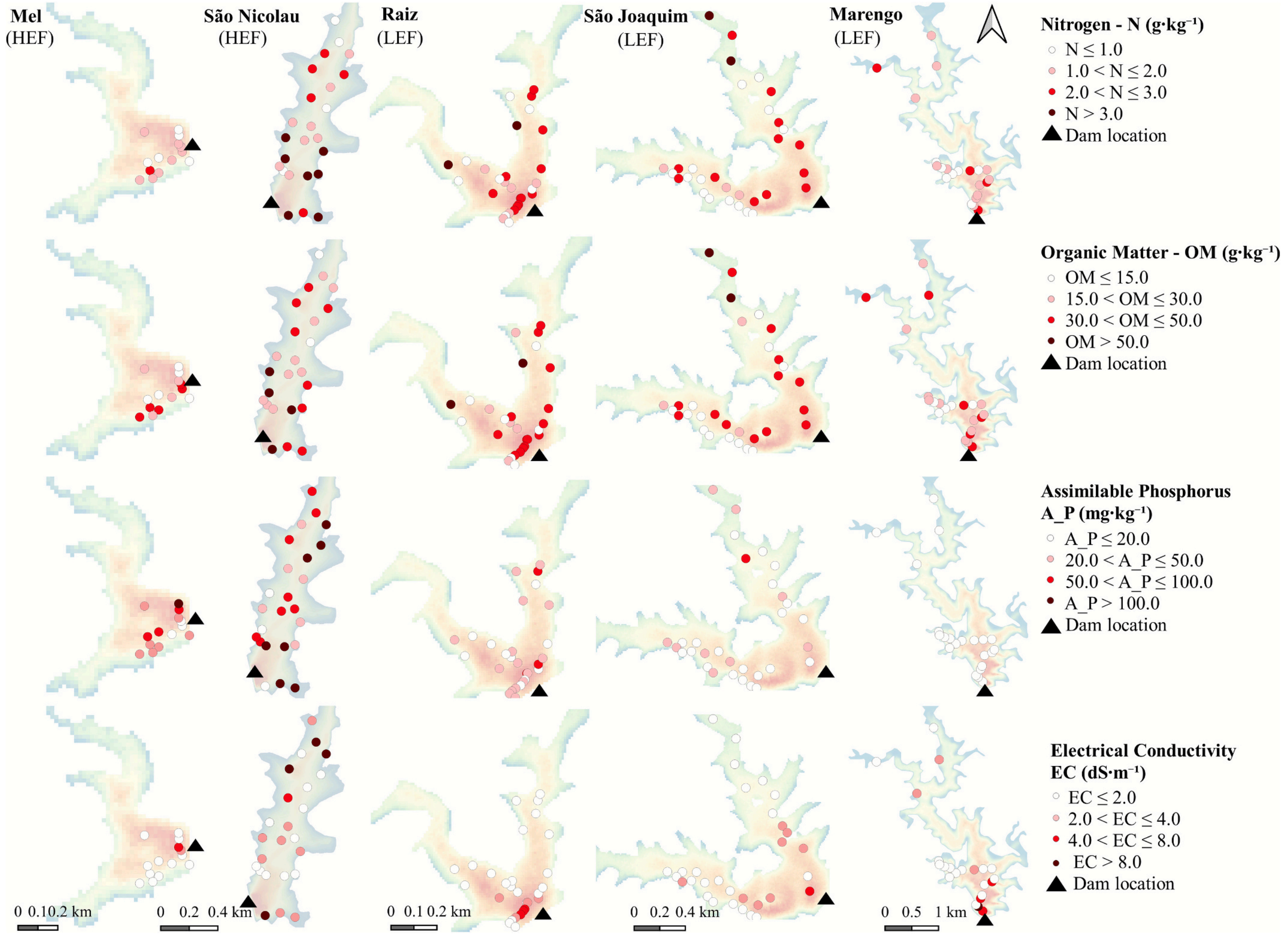


Fig. 8. Spatial distribution of nitrogen, organic matter, plant-available phosphorus, and electrical conductivity in the sediments of reservoirs with high (HEF) and low (LEF) emptying frequency in the Madalena sub-basin.

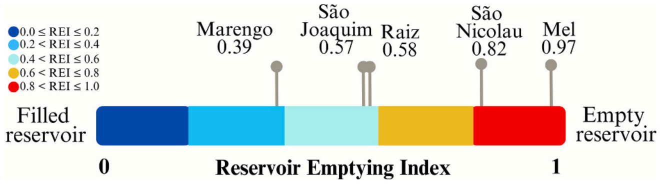


Fig. 9. Reservoir Emptying Index (REI) values computed for December 25th of each hydrological year (1974–2023), quantifying reservoir storage status (1 = always empty; 0 = always full).

farm converted into a rural settlement in 1989, with subsistence agriculture carried out mainly during the rainy season. In this area, unrestricted access of livestock to water bodies, floodplain crop cultivation and the use of agrochemicals is observed (Coelho et al., 2017). Anthropogenic activities such as crop cultivation and livestock breeding in the floodplains are usually associated with high emptying frequency reservoirs.

The highest EC levels were observed in the São Nicolau reservoir, particularly in the upstream portions and near the dam. In the other reservoirs, the highest EC concentrations were found near the dams, with EC > 4 $dS \cdot m^{-1}$ (shown in red – Fig. 8), which is classified as saline sediment and is not recommended for agricultural reuse (Braga et al., 2019).

Regarding the grain-size distribution (Fig. 7), reservoirs with a low REI exhibited higher heterogeneity of grain size deposition at different bed elevations, indicating a buffering effect of the residual water volume on sediment mixing. In these reservoirs, sediment of Group 3 (which consisted predominantly of clay) was in areas near the dam and other deeper zones. Group 2 was present in intermediate areas, typically at higher levels. In contrast, Group 1 (which corresponds to sediments with higher sand fractions) was predominantly found in upper bed areas, as indicated by other studies (Morris and Fan, 1997; Pereira et al., 2021). Conversely, reservoirs with a high REI (REI > 0.8 in this study) did not exhibit a clear granulometric deposition pattern, suggesting particle remobilisation, as observed in the study by Pereira et al. (2022).

In reservoirs with high REI, water recharge occurs in an exposed bed, where sediments previously deposited can be resuspended due to the rapid inflow during runoff events. This process promotes grain size mixing, resulting from the turbulence induced by the recharge flow in the onset of the rainy season. Previous studies suggest that empty reservoirs, upon receiving abrupt recharge, tend to undergo sediment fraction rearrangement, promoting particle homogenisation and redistribution of organic matter and nutrients within the water column (Leite and Becker, 2019). In contrast, in reservoirs with high water storage, the presence of a residual water volume acts as a hydrodynamic buffer, reducing fine sediment resuspension and promoting granulometric stability in the bed (Wang et al., 2019).

The deposition patterns and sediment composition of reservoirs are shaped by the complex interplay of lake hydrodynamics, valley geomorphology and human-induced pressures on river basins. Case studies

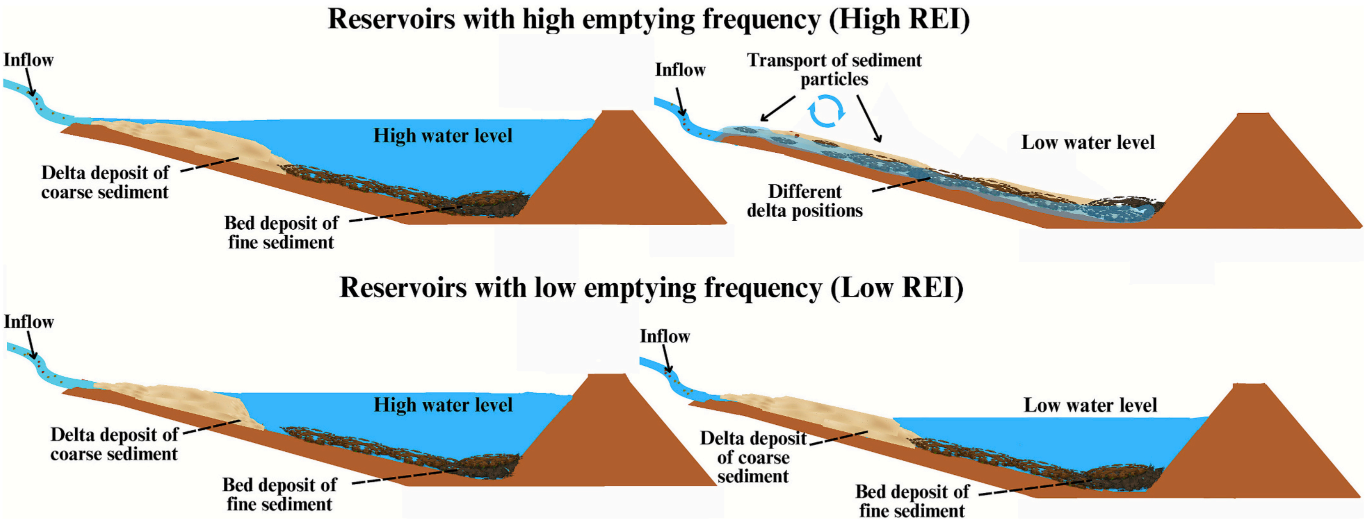


Fig. 10. Sediment deposition zones in reservoirs with high (top) and low (bottom) emptying frequency during high water-levels (left) and low water level (right).

from various regions demonstrate this phenomenon. For instance, in the Urft Reservoir in Germany, Stauch et al. (2024) documented a consistent sediment accumulation pattern, characterised by distinct segregation of coarse sediments in the upstream area and fine sediments in the downstream area. Remobilisation of consolidated sediments is a rare occurrence in this setting. By contrast, Bábek et al. (2020) observed a sound inflow delta subject to frequent remobilisation during flood events in the Les Království Reservoir (Czech Republic), which continually redefines the deposit architecture. Similarly, Molina et al. (2024) found that dam operation itself generates continuous sediment remobilisation in the Rules Reservoir (Spain), as evidenced by specific depositional forms.

Reservoir siltation is a global problem process, and necessitates sediment management, for which reuse is a promising solution (Bondi et al., 2016). However, the implementation of reuse strategies is complicated by site-specific deposition dynamics and widespread contamination, which is more evident in industrial countries, such as in Europe, rather than regions dominated by subsidence agriculture, as studied here.

In Europe, the reuse of sediments faces additional challenges due to persistent contamination and a fragmented regulatory landscape. Sediments act as sinks for a complex mixture of pollutants, including heavy metals (e.g., Pb, Cu, Zn), PAHs (polycyclic aromatic hydrocarbons) from pyrogenic and traffic sources, and microplastics from anthropogenic waste (Bábek et al., 2020; Stauch et al., 2024). Renella (2021) reports that sediment reuse and recycling have been trialled in various European sectors, including landscaping, road construction, and agriculture, although most efforts remain limited to pilot initiatives. Despite the technical feasibility of bioremediation, large-scale implementation is hindered by two structural barriers: persistent contamination inherited from decades of industrial activity and the absence of a unified European framework specifically addressing sediment management. The diffuse legacy of heavy industrialisation has left a long-term mark on Western European rivers, where Dendievel et al. (2022) documented that metals such as Cd, Pb, and Zn remain enriched in sediments, despite emission reductions and remediation efforts since the 1980s. This contamination, coupled with fragmented national regulations and stringent environmental limits, renders the agricultural reuse of sediments largely unviable.

Hydrological droughts have a strong influence on multi-purpose reservoirs in semi-arid regions, concerning both water quality and quantity. Rocha et al. (2024) observed that during drought periods, water quality deteriorates significantly, with nutrient dynamics showing higher temporal than spatial variability. Wiegand et al. (2021) reported that drought-induced volume reductions increased phosphorus and chlorophyll-a concentrations, leading to trophic state deterioration in 55.4 % (36 reservoirs) of the reservoirs studied by them, confirming that droughts exert a significant influence on the trophic status of semi-arid reservoirs. Sediment accumulation in reservoirs is an unintended feature of the system, given that most reservoirs are originally implemented to promote water availability and enable populations to cope with water scarcity (Medeiros and Sivapalan, 2020). However, siltation negatively impacts water quantity and quality at the waterbody level and requires management strategies to control storage loss and internal nutrient loads, sustaining the primary uses of reservoirs (Silva et al., 2025). De Araújo et al. (2023) demonstrated that, on average, the storage capacity of the regional reservoir network of the State of Ceará, where this study was conducted, declines by 2.7 % per decade due to reservoir siltation, indicating an apparent contradiction to the objectives of water resource management. Their study suggests, among other measures, the reuse of sediments as a potential strategy to mitigate the impacts of siltation.

4.2. *Reservoir Emptying Index (REI) as a proxy for sediment reuse*

In the pursuit of supporting sediment management in reservoirs, the Reservoir Emptying Index (REI) was developed as an indicator to predict sediment deposition patterns based on hydrological dynamics. This index can be used as a proxy to predict the grain size pattern of sediments deposited in reservoirs in regions with diverse water-level variations.

In this study, reservoirs with low REI values (< 0.6), typically associated with prolonged water storage (Fig. 9), tend to exhibit selectivity between coarse sediments (deposited in delta regions) and fine sediments (accumulated along the reservoir bed), as illustrated in Fig. 10. This natural segregation facilitates the reuse of sediments, with fine, nutrient-rich fractions suitable for agricultural applications (Braga et al., 2025), and coarse fractions applicable in civil construction (Kasmi et al., 2017). In contrast, reservoirs with high REI values (> 0.8 in this study), which experience frequent emptying-filling cycles (Fig. 9), are subject to continuous sediment remobilisation (Fig. 10), resulting in more homogeneous deposits and grain size mixing. Such conditions require adaptive management strategies, including seasonal monitoring to capture sediments during specific phases of the hydrological cycle.

Although sediment removal in large and deep reservoirs with low REI values can be costly and logistically challenging, several strategies can be adopted depending on reservoir morphology, hydrological conditions, and management objectives. Techniques such as dredging, flushing, and sluicing allow sediment removal under submerged conditions and can be particularly useful where emptying is not feasible (Morris, 2020). However, these methods are generally more costly and may cause ecological impacts associated with sediment resuspension and the release of contaminants previously isolated within the deposits (Yan and Li, 2023). In contrast, studies have shown that sediment removal by dry excavation, commonly adopted in small semiarid reservoirs, is a simpler and more cost-effective alternative. When sediment is removed during dry phases (exposed beds), the total costs of excavation, loading, transport and unloading over short distances (2–3 km) can be comparable to, or even lower than, the costs of conventional chemical fertilizers, resulting in up to 30 % savings (Braga et al., 2019). More recent data show savings of up to 68 % between 2018 and 2023 due to the increase in fertilizer prices (Braga et al., 2025). These results indicate that sediment reuse in the study area is financially feasible, especially when the reservoir is empty, which allows dry excavation/removal of the deposited material (Braga et al., 2019; Braga et al., 2025).

The relationship between the reservoir emptying frequency, sediment composition and its exposure for excavation supports the sediment reuse practice as a feasible reservoir management measure. Water agencies, such as the Ceará Water Resources Management Company - COGERH, which monitors 157 strategic reservoirs, could adopt this index as a proxy for planning of reservoir desilting. This enables more assertive management, based on emptying frequency and potential application of the removed sediment depending on the grain size fractions with distinct characteristics. Conversely, in smaller reservoirs not monitored by COGERH, which typically present high emptying frequency and textural mixing, sediments may be used locally for agricultural and degraded land restoration purposes. In such cases, studies have demonstrated both financial feasibility and satisfactory agronomic performance, with plant growth comparable to that achieved using chemical fertilizers (Braga et al., 2019; Braga et al., 2024). However, in Brazil, these practices are still mostly at pilot or local scale and have not yet been implemented as a widespread or standardised management policy. In terms of Brazilian legislation, Brasil. Conselho Nacional do Meio Ambiente (CONAMA), 2012 establishes guidelines for sediment management in port and waterway areas, including criteria for disposal and reuse, and permits utilisation of sediment provided that its characterization and classification do not result in environmental degradation. In our study area, which is predominantly rural with limited agrochemical inputs and no industrial activities, salinity is the main factor considered for agricultural reuse, but future studies should include a full assessment of metals, organic micropollutants and pathogens.

The application of the Reservoir Emptying Index as an approach to identify sediment deposition pattern, increasing the potential for sediment classification and reuse, represents a novel contribution of this study. By integrating hydrological dynamics with sediment accessibility and composition, REI provides a practical and scalable tool for reservoir management in dry regions.

As highlighted by Spadaro and Rosenthal (2020), sediment reuse is not merely a de-silting practice but an approach aligned with the principles of circular economy, transforming waste into a valuable resource for various sectors. This measure reduces the extraction of new natural resources, minimises environmental impacts, and optimises costs, fostering a sustainable sediment management model. Although the reuse of sediments can offset some dredging costs, studies show that economic viability is generally limited to uncontaminated materials. When it comes to contaminated sediments, technical, regulatory and market barriers often render reuse economically unfeasible, unless public funding or specific policies are in place.

4.3. *Limitations of the study*

The Reservoir Emptying Index (REI) thresholds (>0.8 and < 0.6) were effective in characterising the hydrological behaviour of reservoirs in this analysis. However, the dataset is regional in scope. These critical values therefore need to be validated in other climatic zones and management regimes. Hence, generalising the REI requires testing on a larger scale and in diverse environmental and operational contexts - a crucial step in consolidating the robustness and universality of the index.

Our study focused on the physical aspects of sediment deposition and its potential for reuse, rather than on ecological consequences, which we recognise as an important limitation. In semiarid regions such as Northeastern Brazil, the high density of reservoirs disrupts sediment connectivity and alters water quality, acting as internal sources of phosphorus that sustain eutrophication processes (Rocha et al., 2024; Rabelo et al., 2025). Such impacts on aquatic trophic structure and downstream ecosystems have also been reported in other parts of Brazil (Granzotti et al., 2018). On a global scale, recent reviews indicate that dam-induced sediment retention can have profound effects on water quality, river functioning and biotic communities, both within and downstream of reservoirs, and that sediment-removal operations also affect biota, although these impacts can be minimised under controlled conditions (Shi and Qin, 2023). A multidisciplinary approach in this context is therefore essential in future studies to achieve a more comprehensive understanding of these ecological consequences.

5. Conclusion

This study demonstrated that the frequency with which reservoirs are fully or partially empty plays a significant role in determining sediment deposition patterns and, therefore, their potential for reuse.

We found that the frequency with which reservoirs are emptied is an important factor in determining sediment deposition patterns. Reservoirs with a high emptying frequency (a Reservoir Emptying Index - REI > 0.8) exhibited mixed sediments without clear spatial stratification, suggesting that recharge over a dry bed had promoted remobilisation and homogenisation. Conversely, reservoirs with a low emptying frequency (REI < 0.6) exhibited more evident stratification, with coarse sediments being deposited in deltaic zones upstream and fine sediments accumulating in deeper areas downstream near the dams. Furthermore, moderate to strong correlations were identified between fine particles (silt and clay) and nutrients in the Madalena sub-basin ($\sim$124 km^2), which may be an indicator of potential sediment reuse in agriculture.

The REI can be used to assess the vulnerability of reservoirs to dry and sediment exposure dynamics. These findings highlight the feasibility of integrating sediment management and planned reuse into water resource planning in semi-arid regions, thereby transforming environmental liabilities into potential resources. In this sense, our study provides insights into the understanding of sediment deposition in reservoirs with diverse water level dynamics, providing a basis for the assessment of sediment reuse potential and contributing to sustainable water management in dry regions. However, further validation in reservoirs under different climatic and operational conditions is needed to strengthen its general applicability. Future research should also combine sediment characterization with ecological and hydrological monitoring to support more holistic approaches.

CRediT authorship contribution statement

Gabriela Domingos Lima: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José Carlos de Araújo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Brennda Bezerra Braga:** Writing – review & editing, Data curation. **Thayslan Renato Anchieta de Carvalho:** Data curation. **Eva Nora Paton:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Pedro Henrique Lima Alencar:** Writing – review & editing. **Pedro Henrique Augusto Medeiros:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Additional descriptions of sediment property analysis in the Supplemental Material. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.181088.

Data availability

Data will be made available on request.

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