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Papers

Multitemporal Assessment of Anthropogenic Pressure Through Land Use Change and the Anthropic Transformation Index (ATI) in the Piratininga Lagoon System Watershed, Brazil

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GIS
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Abstract
This study used remote sensing and geographic information systems to perform a multitemporal analysis of land-use changes and assess anthropogenic pressure using the Anthropic Transformation Index (ATI) in the Piratininga lagoon system watershed in the municipality of Niterói, Rio de Janeiro, Brazil. We used a multitemporal approach with aerial photographs from 1976 (FAB-DRM) and high-resolution satellite images from 2003, 2013, and 2022 obtained from Google Earth Pro. The data were processed through georeferencing, manual vectorization, and classification into nine (9) land use classes based on the MapBiomas Collection 8 classification legend. The results show a continuous expansion of urban areas throughout the period analyzed, particularly in environmentally sensitive areas near the margins of the lagoon system, leading to the suppression of riparian vegetation and increased pressure on the aquatic system. Although forest cover has increased in recent years, this change is mainly associated with the regeneration of secondary vegetation rather than effective ecological restoration. The ITA value of 5.292 classifies the watershed as degraded, reflecting high anthropogenic alteration. These findings highlight the need to combine spatial indicators with environmental management strategies to support urban planning and ecosystem conservation. The proposed approach provides a robust framework for monitoring anthropogenic impacts on coastal lagoon systems and supports decision-making for sustainable watershed management.

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INTRODUCTION

In recent decades, water resources have become increasingly vulnerable to anthropogenic pressures, especially in coastal areas, where uncontrolled population growth, intense land use changes, and poor sanitation services pose serious risks to environmental sustainability (Patra *et al.*, 2018). These pressures drive significant changes in aquatic and terrestrial ecosystems, including degraded water quality, silting of water bodies, biodiversity loss, and altered natural geomorphological and hydrological processes (Fearnside, 2022).

Coastal lagoon systems are among the most sensitive environments; they occur along the entire coastline, act as ecological interfaces between terrestrial and marine environments, and provide various ecosystem services (Tuholske *et al.*, 2021; Koboević *et al.*, 2021).

The Piratininga lagoon system, located in the Oceanic Region of Niterói, Rio de Janeiro, is a Brazilian coastal lagoon system of considerable ecological, social, and landscape significance. Historically connected to the sea by natural channels and fed by several watercourses, the Piratininga lagoon system has long played a central role in the region's environmental dynamics. However, in recent decades, disorderly urbanization, extensive paving, and the replacement of native ecosystems with built-up areas have intensified anthropogenic transformations and seriously compromised the lagoon system's ecological integrity (Ribeiro *et al.*, 2021; Vellozo *et al.*, 2022).

In the Oceanic region of Niterói, the housing deficit has led low-income populations to occupy environmentally sensitive areas, and these settlements (slums) often lack formal sanitation infrastructure. However, it is important to understand that multiple systemic factors, including inadequate urban planning, insufficient public investment in infrastructure, and socioeconomic inequality, contribute to the degradation of the lagoon system. The spatial relationship between informal settlements and lagoon degradation therefore requires careful contextualization and should not be interpreted without recourse to broader structural drivers (Patra *et al.*, 2018).

To understand the dynamics of this degradation, the watershed should be adopted as the spatial unit of analysis and planning, as recommended by Brazil's National Water Resources Policy (BRASIL, 1997). Activities within the watershed directly influence hydrological and biogeochemical cycles, affecting water quality and quantity (Araújo *et al.*, 2018). Therefore, assessing changes in land use and land cover that affect aquatic ecosystems is essential to support environmental management policies and strategies (Silva *et al.*, 2022).

In this context, Geographic Information Systems (GIS) and Remote Sensing have become indispensable tools for identifying spatial and temporal patterns of degradation, contributing to the achievement of the Sustainable Development Goals (SDGs), as defined by the United Nations General Assembly (United Nations, 2015) in particular SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water).

To quantify these transformations over time, researchers have developed several anthropization indices at international and national levels. The Anthropic Transformation Index (ATI), conceived by Lémechev (1982) and disseminated in Brazil by authors such as Rocha and Cruz (2002) and Gouveia *et al.* (2013), has proven to be an effective tool. This index allows for a quantitative assessment of the intensity of anthropic pressures on the landscape based on land use and land cover percentages.

Internationally, Cheng *et al.* (2022) conducted a comprehensive review of the relationship between land use and land cover and water quality, highlighting remote sensing's role in assessing environmental impacts. This study synthesized more than 200 international studies and showed that indices such as the Human Footprint Index and Human Modification effectively assess and quantify anthropogenic changes and predict spatial patterns of water pollution. Similarly, Chen *et al.* (2023) used a composite index of anthropogenic activities (CAAI), based on variables such as population density, built-up areas, agricultural use, and vegetation cover, to assess how water quality responds to multiple human pressures on urban rivers. The results showed that increased soil permeability and urban expansion intensify pollutant loads and alter the chemical composition of surface waters.

Similarly, Jiang *et al.* (2024) used the Human Footprint Index (HFI) to assess how habitat quality evolved and affected aquatic systems in Chinese watersheds. This study demonstrated that the continuous growth of the human footprint compromises the ecological integrity of water ecosystems, reducing the natural regulatory capacity of watersheds and the environmental quality of surface waters.

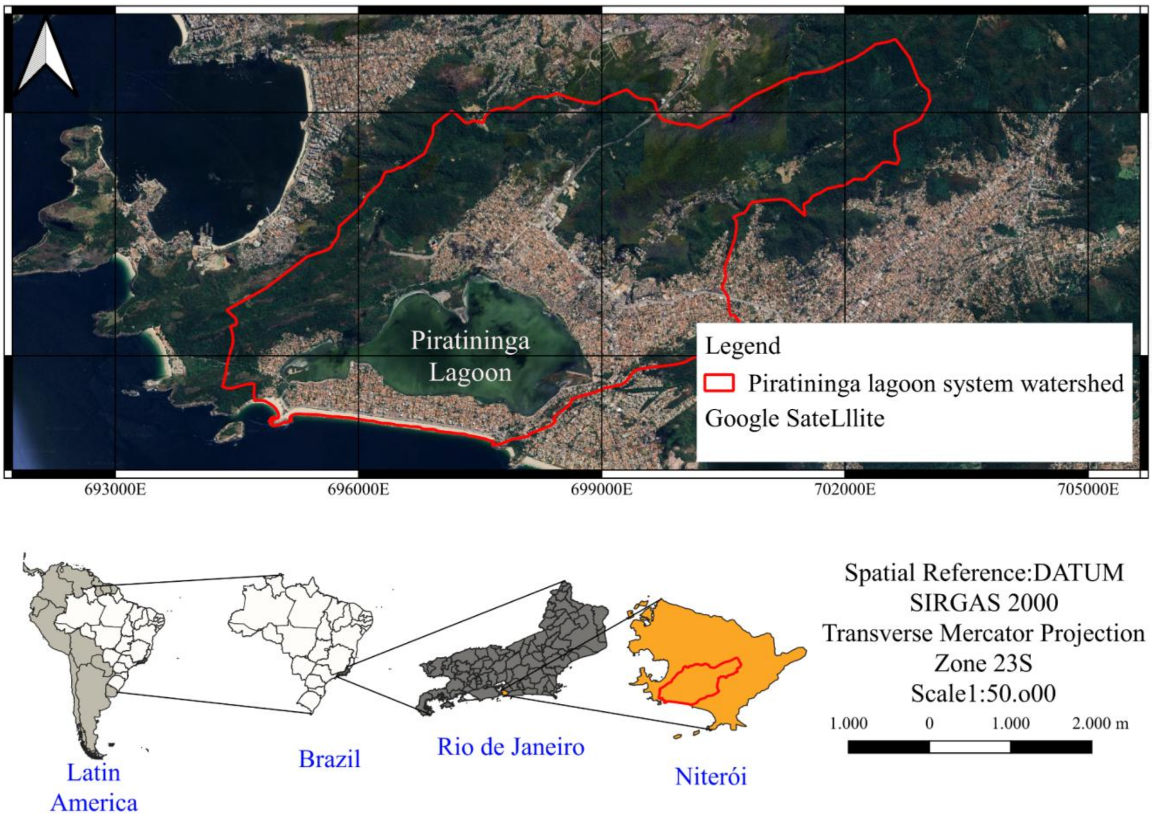
More recently, Zhang *et al.* (2025) applied an integrated human footprint model, based on metrics derived from the Human Modification Index, to analyze natural and anthropogenic influences on water quality in Chinese rivers, demonstrating that regions with higher population density, intensive agricultural use, and urbanization show marked deterioration in water quality, including water quality parameters such as turbidity, nutrients, and dissolved oxygen.

Within this scenario, the research aims to analyze the multitemporal evolution of land use and occupation in the Piratininga lagoon system watershed. Four distinct moments were analyzed in the period from 1976 to 2022, not as a continuous series, but as an initial 27-year snapshot, followed by approximately 10-year intervals (1976, 2003, 2013, 2022), captured via high-resolution remote sensing imagery. The study is structured into four sections: 1- the present introduction; 2-the methodological procedures, encompassing a characterization of the study area, the data sources employed, land use classification, procedures, ATI calculation, and sanitation analysis; 3- the presentation and discussion of results; and 4- the conclusions, with emphasis on environmental planning and management of lagoon systems.

MATERIAL AND METHODS

The Piratininga neighborhood in Niterói is part of the Oceanic Region and has approximately 18,492 inhabitants in 2022, with a high Municipal Human Development Index (MHDI) of 0.942. The area is characterized by strong social diversity, with middle-class residents in more valued areas and low-income populations, especially in irregular settlements near the lagoon system.

Figure 1 – Geographical location of the Piratininga Lagoon system

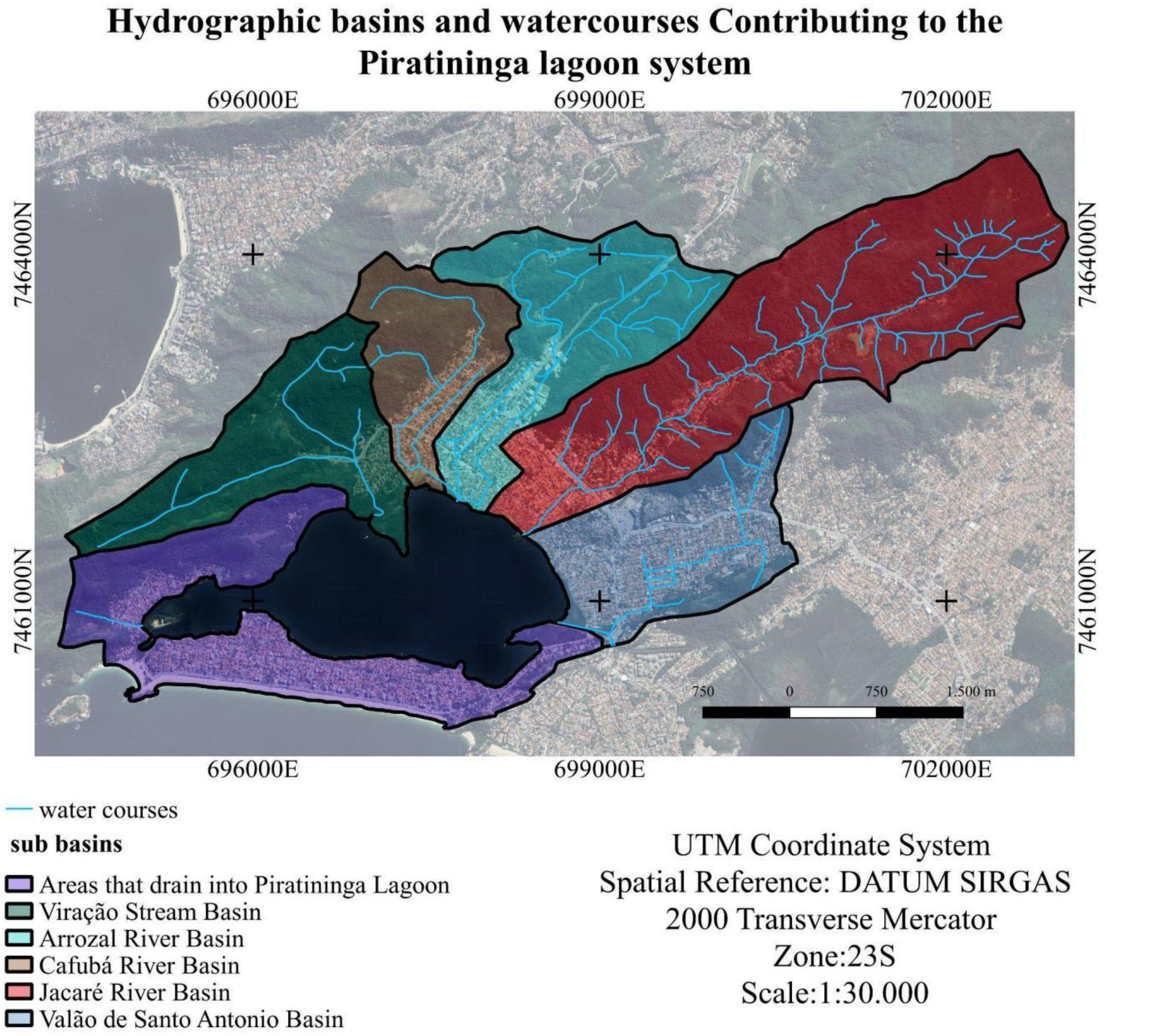


Source: The authors (2026).

The Piratininga lagoon system extends approximately 10 km east - west and 1.3 km in width, with an area of approximately 2.87 km² and an average depth of 0.5 m, according to the Comitê da Bacia Hidrográfica - CBH (2024) (Watershed Basin Committee WBC, 2024). It has three islands: Pontal, located to the north; Modesto, to the east; and a third island to the west, called Tibau.

The Piratininga lagoon system receives water from rivers and streams such as the Viração stream, the Valão de Cafubá, the Arrozal River, the Jacaré River, and the Santo Antônio. The springs of these watercourses are in preserved Atlantic Forest areas in the region's hills. Although they originate in preserved Atlantic Forest areas, these watercourses suffer degradation from domestic sewage and increased sediment loads due to urbanization. Figure 2 shows the main hydrodynamic basins and watersheds that flow into the Piratininga lagoon system.

Figure 2 – watersheds that feed the Piratininga lagoon system



Source: The authors (2026).

The water exchanges with the Atlantic occur mainly through the Itaipu Channel. However, sediment accumulation and sandbank growth have reduced this flow, negatively affecting water quality, increasing organic matter, and accelerating eutrophication (Rocha, 2019). Urban pressure and alterations to drainage Channels, including the Camboatá Channel, have modified lagoonal hydrodynamics, reduced water levels, and compromised ecosystem services. Figure 3 illustrates the channels that connect the Piratininga lagoon system with the Atlantic Ocean, allowing for water exchange.

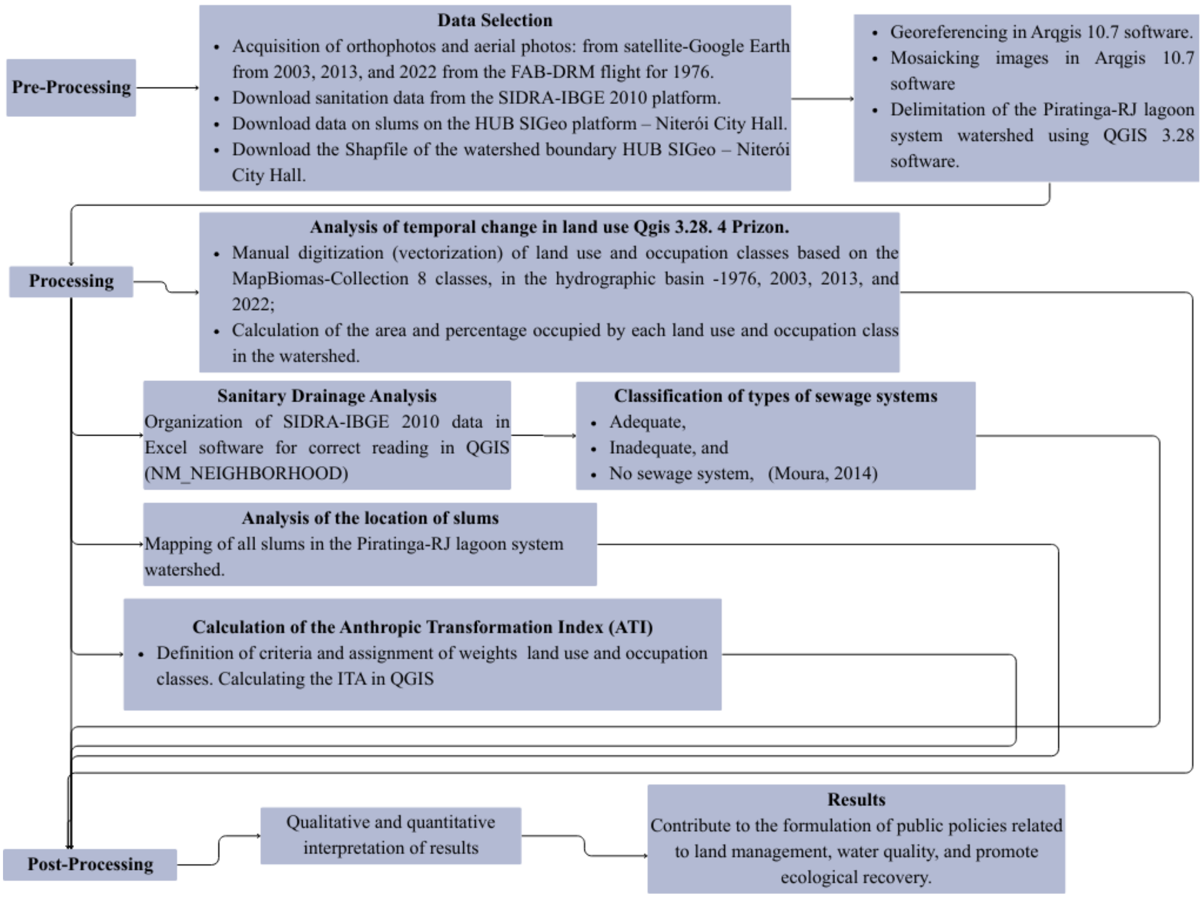
Figure 3 – Channels that allow the Piratininga lagoon system to exchange water with the Atlantic Ocean

Source: The authors (2026).

Image Processing and Classification

Figure 4 shows the flowchart of the methodology used in the research.

Figure 4 – Flowchart of methodological steps



Source: The authors (2026).

Images from 2003, 2013, and 2022 were obtained from Google Earth Pro at an observation viewpoint altitude of 5.66 km, and a spatial resolution of 30 cm, and aerial photographs from 1976 from the FAB-DRM flight of the Department of Mineral Resources-RJ. The georeferencing datum used was WGS 84 (World Geodetic System 1984), Universal Transverse Mercator projection, zone 23S. We projected these orthophotos to SIRGAS 2000, zone 23S, to accurately calculate polygonal areas. We selected these four temporal snapshots (1976, 2003, 2013, and 2022) based on the availability, quality, and internal consistency of the imagery needed for multitemporal analysis.

We georeferenced the captured images using ArcGIS 10.7 (ESRI, 2019), achieving a root mean square (RMS) error of 0.23 pixels to ensure spatial accuracy. The images were mosaicked to integrate adjacent imagery into a single continuous representation, then exported for import into QGIS (2023) (version 3.28.4 Firenze) software (version 3.28.4'Firenze') for the following steps.

The boundary shapefile of the Piratininga lagoon system watershed was obtained from the SIGEO (Niterói, [s.d.]) municipal geospatial platform in ESRI shapefile format (.shp), with the original coordinate Reference System (CRS) SIRGAS 2000, UTM, Zone 23S (EPSG:31983), requiring no additional reprojection. The watershed delineation and imagery were imported into QGIS. The area of interest was delimited using the QGIS vector clipping tool, with the mosaic image as the input layer and the basin boundary as the clipping mask.

The images were manually digitized (vectorized), and the different land use and occupation classes were visually delimited on the cropped images. Digitization was performed in QGIS at a working scale of 1:30.000, using topological snapping rules to prevent polygon overlaps or sliver gaps. To minimize inter-period classification bias, all digitization sessions used contrast-enhancement tools to ensure color consistency across the four temporal images. The classification followed the MapBiomas Brazil (2023) Collection 8 classification legend. MapBiomas is a platform that uses high-resolution satellite imagery and manual validation to generate land-use data. Thus, we defined nine (9) classes: Flooded Field, Sandy Area, Pasture, Arboreal Sandbank, Other Non-Vegetated Areas, Urbanized Area, Lagoon, Exposed Soil, and Forest Formation.

With the vectorized and corrected file, we created fields in the attribute table for each polygon representing a land use class, storing information such as the class code, class name, and calculated area occupied in km2. Chart 1 details the nine land use and occupation classes defined to optimize the analysis.

Chart 1 – Land use and land cover classes of the Piratininga Lagoon system, Niterói, Rio de Janeiro

Class	Description	Interpretation Guide	Image
Wetland	Areas that are permanently or periodically flooded, with vegetation adapted to humid environments and hydromorphic soils.	**Texture:** Smooth **Color:** Dark shades of green or blue-green **Shape:** Irregular or amorphous, with diffuse contours	
Sand Spot	Areas predominantly covered by sand, which may be natural (such as dunes and sandbanks) or the result of human activities.	**Texture:** Rough **Color:** Light tones (white, beige, or yellowish) **Shape:** Irregular or rounded, may form continuous spots	
Pasture	Area covered by grasses and low vegetation, which can be used for raising animals or other agricultural activities, with little or no trees.	**Texture:** Rough **Color:** Shades of light green to yellowish **Shape:** Regular or fragmented, with contours defined by fences or divisions	
Wooded Sandbank Vegetation	Vegetation characteristic of coastal regions, composed of trees and shrubs adapted to sandy soils and saline conditions, with high biodiversity.	**Texture:** Rough **Color:** Medium to dark green **Shape:** Irregular, following the coastline	
Other Non-Vegetated Areas	Areas without significant vegetation cover, including vacant lots, areas exposed by erosion, or human infrastructure without associated vegetation.	**Texture:** Rough **Color:** Brown, grayish, or reddish tones **Shape:** Irregular or angular	
Urban Area	Spaces transformed by human use, including occupation by buildings, urban infrastructure, avenues, paved roads, and other permanent anthropogenic modifications.	**Texture:** Rough **Color:** Grayish, white, or reddish tones **Shape:** Regular, with defined geometric patterns (squares, streets)	
Lagoon	Continental water bodies, natural or artificial, are essential for ecological balance and hydrological cycles.	**Texture:** Smooth **Color:** Black (depending on turbidity) **Shape:** Regular or oval, with smooth edges	
Exposed Soil	Bare ground surfaces without significant vegetation cover, resulting from deforestation, erosion, or human activities.	**Texture:** Smooth **Color:** Shades of brown or beige **Shape:** Irregular, with scattered areas	
Forest Formation	Dense, closed, medium to large vegetation, usually associated with preserved or recovering ecosystems.	**Texture:** Rough **Color:** Dark green **Shape:** Irregular or compact, forming large continuous blocks	

Source: The authors (2026).

At the same time, we incorporated socioeconomic data to complement the analysis. We mapped the slums using geospatial data from the Geographic Information System of Niteroi (SIGeo) platform maintained by the Niteroi city hall. The spatial layers were downloaded as shapefiles (.shp) and reprojected from their original local coordinates to the

Geocentric Reference System for Americas (SIRGAS 2000, UTM, Zone 23S EPSG:31983) to enable precise geometric computations of polygonal areas.

This platform provides validated geospatial data for the municipality of Niteroi. To extract only the informal settlements located within the Piratininga neighborhood, it was necessary to use the "Cut" tool in QGIS 3.28.4, using the neighborhood boundary polygon as the clipping mask, yielding a new Shapefile that was subsequently used to generate the spatial distribution map of informal settlements.

To calculate overage distance from each intervention settlement (Slum) perimeter to the *Parque Orla de Piratininga* (POP) we used QGIS 3.28.4. The spatial algorithm was configured to calculate the shortest Euclidean distance from the absolute vector boundary (edge-to-edge) of each settlement polygon to the nearest point on the outer perimeter coordinates of the POP. We selected this boundary-to-boundary metric instead of a centroid-to-centroid approach to better represent the immediate physical proximity and potential direct edge effects of each settlement on the park's buffer zone.

In addition, we analyzed sanitary sewage data for the neighborhoods within the Piratininga lagoon system watershed using the SIDRA-IBGE (2010) platform. The SIDRA-IBGE platform provides tabular data on municipalities and neighborhoods across the national territory, enabling more thorough analysis.

The data were organized in Excel software for correct reading in QGIS. The neighborhood names were organized in the NM_BAIRRO column, corresponding to the attribute table of the municipality's neighborhood boundaries. Sanitary sewage data were classified as adequate, inadequate, or without sanitary sewage, following the methodology proposed by Moura (2014), and linked to each neighborhood. After classification, the data were merged in QGIS using the "Unions" tool, associating the sanitary sewage data with each neighborhood polygon.

Anthropic Transformation Index

To assess the anthropogenic transformation of the Piratininga lagoon watershed, we used the Anthropogenic Transformation Index (ATI) developed by Lémechev (1982), modified by Mateo (1984), and applied by Richter (2004), Gouveia *et al.* (2013), and Seabra *et al.* (2018). The ATI quantifies pressures on landscape components such as watersheds, protected areas, municipalities, or census tracts based on each land use class's proportional contribution, weighted by its degree of anthropogenic impact.

The index was calculated using the formula:

$$ATI = \sum P\,i \;\times (\,A\,i\,/\,A\,T\,)$$

Where: (Ai) represents the area of each land use class; (Pi) corresponds to the weight assigned to each class; and (AT) indicates the total watershed area.

The ATI was applied according to Galvanin and Neves (2019) and Silva *et al.* (2023), who classified the ATI as slightly degraded (1 - 2.5), regular (2.6 - 5), degraded (5 - 7.5), and very degraded (7.6 - 10), as shown in Table 1.

Table 1 – Weight for ATI classification

State of conservation	ATI Intervals
Little degraded	1-2.5
Regular	2.6-5
Degraded	5-7.5
Very degraded	7.6-10

Sources: The authors (2026).

The weight assigned to each land-use class reflects how strongly that class affects the environment: the higher the weight (maximum value 10), the greater the negative impact; conversely, lower weights (close to 1) indicate less influence on environmental degradation. The weight values were determined using an expert-based approach, grounded in two complementary sources: (a) existing peer-reviewed literature, namely: Gouveia *et al.* (2013), who justify higher urban weights due to progressive densification and surface imperviousness, and Galvanin and Neves (2019), who demonstrate that reclassification of land-use weights is necessary when categories transition to more intensive uses over time; and

(b) field knowledge of the study area, as recommended by Silva *et al*. (2023). Chart 2 details the weights assigned to each class for each period and justifies changes between periods.

Chart 2 – Land use and cover classes and their respective weights and justification in relation to the degree of anthropogenic transformation used in the analysis of the Piratininga Lagoon System watershed, Niterói-RJ

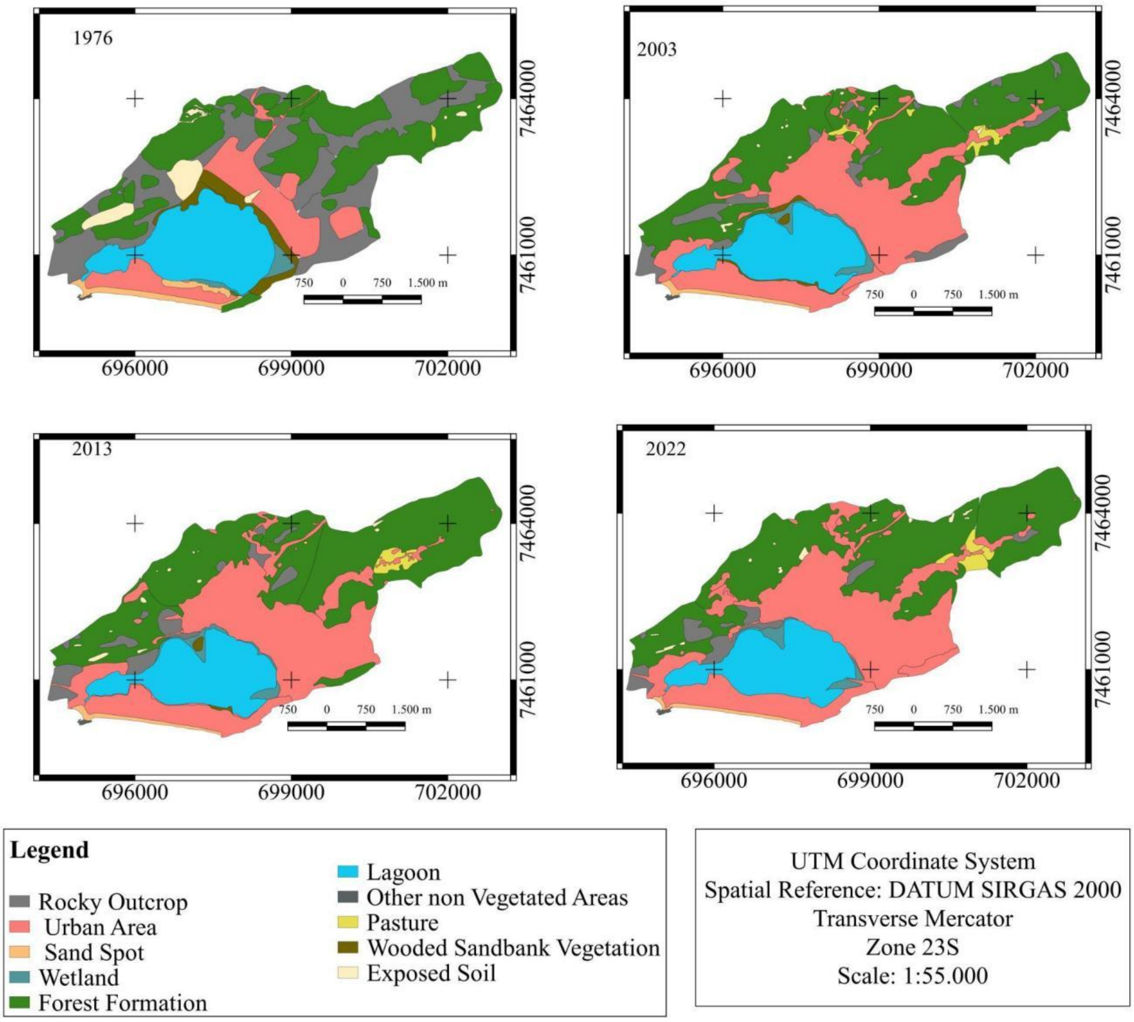
Classes	Weigh 1976	Weigh 2003	Weigh 2013	Weigh 2022	Criteria for Weight change	Justification
Wetland	2	3	3	4	Drainage/Vulnerability	In 1976, they were still well represented, though small. In 2003, they underwent initial drainage and anthropogenic changes. In 2013, urban pressure intensified, increasing their vulnerability. In 2022, they persist in a reduced area but are very susceptible to occupation.
Sand Spot	3	3	4	5	Anthropogenic Pressure	In 1976, these were relatively stable areas of exposed sand. In 2003, they began to be incorporated into urban expansion. By 2013, they had been greatly reduced and fragmented. In 2022, only small fragments remained under pressure from tourism and coastal urbanization.
Pasture	5	6	7	7	Soil Degradation	In 1976, it occupied the minimum area. In 2003, it expanded significantly, replacing native vegetation. In 2013, it remained stable but was already showing signs of soil degradation. In 2022, it remained present, reflecting agricultural use and pressure on ecosystems.
Wooded Sandbank Vegetation	2	2	3	3	Fragmentation	In 1976, it still occupied continuous areas. In 2003, it shrank sharply due to urban expansion. In 2013, it was quite fragmented. In 2022, it disappeared almost entirely, replaced by urbanized areas.
Other non Vegetated Areas	5	6	7	7	Degradation	In 1976, they appeared as small, isolated patches. In 2003, they grew sporadically, associated with construction work and land clearing. In 2013, they remained small. In 2022, they persisted with little variation but represented localized degradation.
Urban Area	7	8	9	10	Density/Sealing	In 1976, the urbanized area was initially scattered, with only streets and a few houses. In 2003, urbanization expanded, and in 2013, it intensified, reaching hillsides and previously undeveloped areas. In 2022, growing and denser urbanization occupied even the main roads, areas that were previously tree-covered sandbanks and rocky outcrops, which are important natural elements.
Lagoon	1	2	3	4	Degradation	In 1976, environmental conditions were better preserved. By 2003, pollution and silting were already evident. In 2013, these processes intensified, especially due to the influx of domestic sewage. In 2022, the area remained the same, but environmental quality was compromised by irregular occupation of the banks.
Rocky Outcrop	1	1	1	1	Stability / Inaccessibility	In 1976, it occupied significant areas and formed part of the natural landscape. In 2003, urbanization began to replace it. In 2013, the reduction was more pronounced. In 2022, only small, isolated patches remain, already under considerable pressure from urban growth.
Forest Formation	1	1	2	2	Ecological succession/Integrity	In 1976, the area was preserved with natural vegetation. In 2003, urban expansion began around the forested areas, but natural vegetation remained. From 2013 to 2022, public policies supported forest regeneration. In 2019, the Ecological Restoration project began, but the structural quality and diversity do not match those of the native forest, so the weight doubled from 1 (1976) to 2 (2013 and 2022).
Exposed Soil	6	7	8	8	Erosion Risk	In 1996, exposed soil was already linked to deforestation and construction work. In 2003, it decreased but remained in sensitive areas. In 2013, it reappeared due to construction activities. In 2022, these areas were gradually replaced by other classes, such as urban areas.

Sources: The authors (2026).

RESULTS

The data presented here are analyzed jointly, taking into account the land use and land cover classes identified in the Piratininga lagoon system watershed. Figure 5 shows the spatial classification of land use and occupation, and Table 2 presents the area (km²) and percentage for each land use and occupation class.

Figure 5 – Land use map for the years 1976, 2003, 2013, and 2022 for the Piratininga lagoon system watershed



Source: The authors (2026).

Table 2 – Class measurement of land use and occupation in the watershed area of the Piratininga lagoon system, Niterói-RJ from 1976-2022

Classes	1976 (km²)	%	2003 (km²)	%	2013 (km²)	%	2022 (km²)	%
Urban Area	3.100	14.015	7.233	32.700	7.434	33.609	8.033	36.317
Lagoon	3.807	17.211	3.218	14.549	3.110	14.060	3.148	14.232
Rocky Outcrop	5.653	25.557	1.350	6.103	1.127	5.095	0.947	4.281
Forest Formation	7.325	33.116	9.310	42.091	9.572	43.275	9.152	41.376
Exposed Soil	0.703	3.178	0.059	0.267	0.089	0.402	0.111	0.502
Sand Spot	0.489	2.211	0.219	0.99	0.202	0.913	0.184	0.832
Wetland	0.244	1.103	0.325	1.469	0.271	1.225	0.257	1.162
Wooded Sandbank Vegetation	0.763	3.450	0.158	0.714	0.066	0.029	0.00	0.000
Pasture	0.022	0.099	0.242	1.094	0.231	1.044	0.283	1.279
Other non-vegetated areas	0.013	0.059	0.017	0.077	0.017	0.006	0.019	0.502
TOTAL	22.119	100	22.119	100	22.119	100	22.119	100

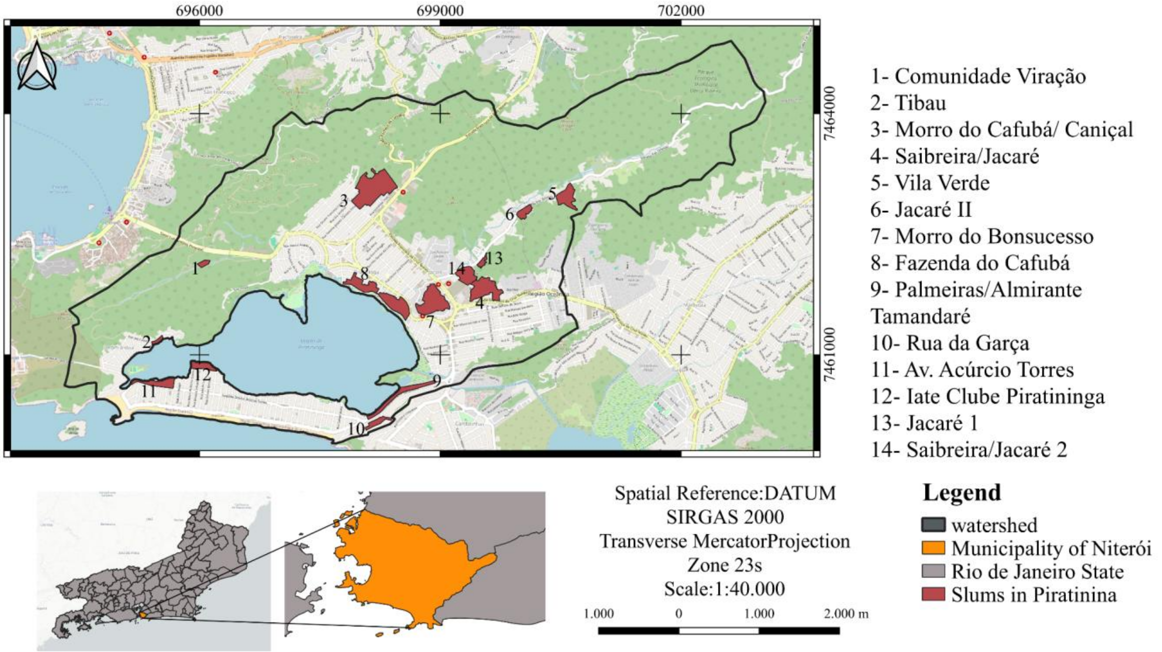
Source: The authors (2026).

The watershed of the Piratininga lagoon system evolved from a predominantly natural and preserved landscape in 1976 to an environment heavily altered by human activity in 2022. The urban area expanded from 3.10 km² (14.0% of the watershed) in 1976 to 8.03 km² (36.3%) in 2022. This expansion occurred primarily at the expense of ecologically sensitive transition ecosystems: rocky outcrops decreased from 5.65 km² (25.6%) to 0.95 km² (4.3%), a reduction of more than 83%, and tree cover on the sandbars was virtually eradicated, decreasing from 0.76 km² (3.5%) in 1976 to 0.00 km² (0.0%) in 2022.

Forest cover increased from 7.33 km² (33.1%) in 1976 to 9.15 km² (41.4%) in 2022. This increase, however, should be interpreted with caution: it is mainly attributable to the secondary regeneration of vegetation within the boundaries of the *Parque Orla de Piratininga* (POP) (Piratininga Coastal Park) and the Niterói Environmental Protection Area (EPA of Lagoons and Forests), and not to the effective restoration of the original Atlantic Forest cover. The increase in forest cover does not, therefore, indicate forest preservation in the ecological sense, but rather a process of ecological succession on previously degraded or rocky land. This trend is consistent with national surveys by MapBiomas (2023), which indicate that much of the apparent gain in native vegetation corresponds to secondary forests in the Southeast and Northeast regions.

To provide context for these spatial results, we mapped the informal settlements (*favelas*) within the watershed. Figure 6 shows the spatial distribution of these settlements, which are concentrated along the shores of the lagoon system.

Figure 6 – Distribution of slums in the Piratininga-Niterói neighborhood, Rio de Janeiro



Source: The authors (2026).

Table 3 – Area of each slum and its distance from the POP

Name of the Slums	Area in hectares	Average distance (m)
Comunidade Viração	0.804	733.802
Tibau	0.658	65.587
Morro do Cafubá/ Caniçal	14.868	1031.158
Saibreira/Jacaré	7.505	956.740
Vila Verde	4.419	2555.077
Jacaré II	1.833	2066.074
Morro do Bonsucesso	8.980	296.244
Fazenda do Cafubá	10.336	94.352
Palmeiras/Almirante Tamandaré	4.075	45.398
Rua da Garça	1.756	137.407
Av. Acúrcio Torres	3.323	36.535
Iate Clube Piratininga	2.208	37.819
Jacaré 1	0.878	1269.321
Saibreira/Jacaré 2	4.005	964.353

Source: The authors (2026).

Regarding demographic and infrastructural parameters, the spatial mapping of irregular settlements (Slums) within the Piratininga neighborhood identified 14 distinct sectors (Figure 6). The absolute surface areas and their exact shortest Euclidean distances to the perimeter of the *Parque Orla de Piratininga* (POP) are presented in Table 5. The largest settlement, *Morro do Cafubá/Caniçal*, spans 14.868 hectares and has an average distance of 1.031015 m from the POP boundaries. In terms of absolute spatial proximity to the environmental intervention park, the closest communities are *Av. Acúrcio Torres* (3.323 ha; 36.535m), *Iate Clube Piratininga* (Iate Clube Piratininga 2.208ha; 37.819m), *Palmeiras/Almirante Tamandaré* (4.075ha; 45.398m) and Tibau (0.658ha; 65.587m).

Sanitation Conditions: Sanitary sewage

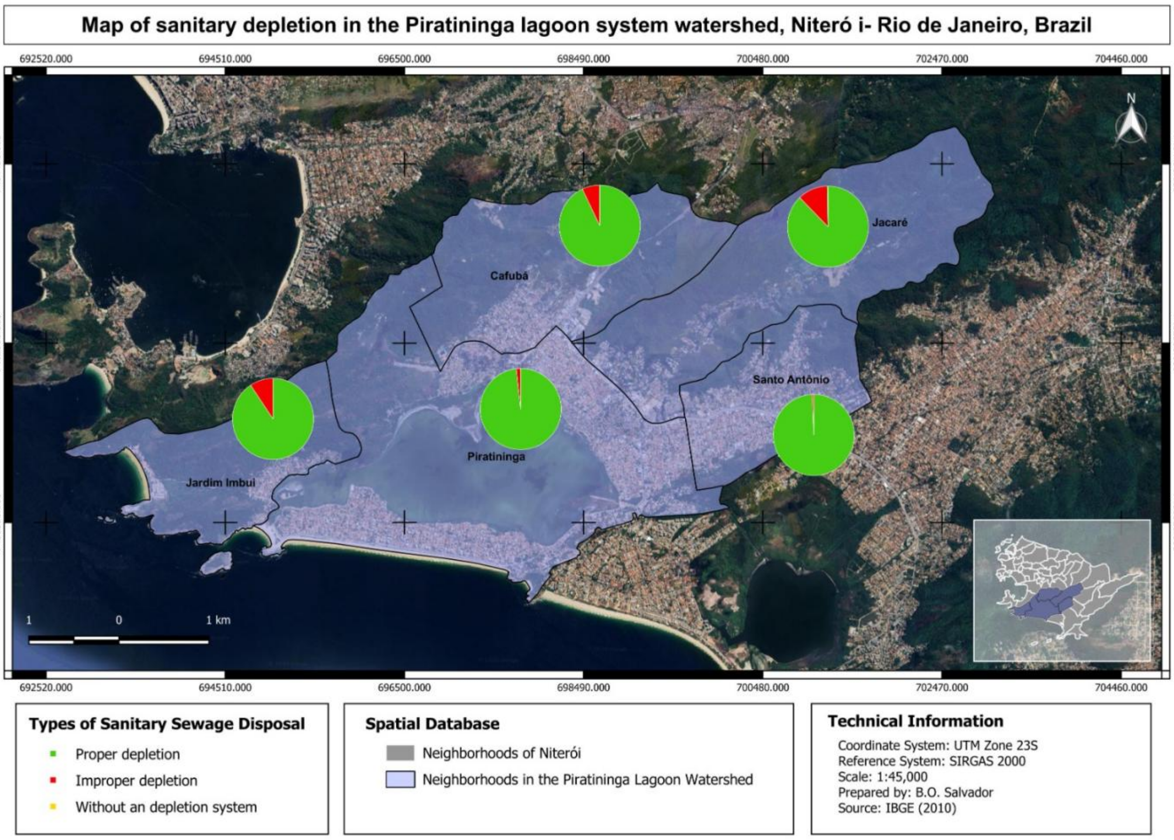
We analyzed sanitary sewage in neighborhoods within the *Piratininga-Niterói* lagoon system watershed, as shown in Table 4. We spatialized these data as shown in Figure 7.

Table 4 – Classification of sanitary sewage systems

Neighborhood	Adequate	%	Inadequate	%	without sewage disposal	%
Cafubá	923	92.95	69	6.95	1	0.10
Jacaré	881	87.74	120	11.96	3	0.30
Jardim Imbuí	341	90.69	35	9.31	0	0.00
Piratininga	4957	98.28	82	1.63	5	0.10
Santo Antônio	1450	99.38	9	0.62	1	0.00
Total	8.552	96.36	315	3.54	10	0.11

Source: The authors (2026).

Figure 7 – Classification of Sanitary Wastewater Treatment in the Piratininga Lagoon System Watershed, Niterói, Rio de Janeiro



Source: The authors (2026).

Socioeconomic data on sanitation collected at the neighborhood level (Table 4 and Figure 7) indicate that adequate and formal sanitation infrastructure is highly prevalent, accounting for an aggregate average of 96.36% (8,552 households) across the entire watershed. In contrast, 3.54% were classified as inadequate, and 0.11% lacked a sewage system. These results are consistent with data from the Instituto Trata Brasil sanitation ranking (2021), which ranks Niterói as the city with the highest sewage collection rate in Brazil.

Among the neighborhoods assessed, Santo Antônio and Piratininga had the highest internal percentages of adequate coverage, reaching 99.38% and 98.28%, respectively. In contrast, Jacaré had the highest proportion of inadequate sanitation (11.96%), followed by Jardim Imbuí (9.31%) and Cafubá (6.95%). Households completely lacking any sewage collection system represent a marginal fraction (0.11%, or 10 households) across the entire study area.

Anthropogenic Transformation Index

Table 5 presents the ATI results.

Table 5 – Anthropic Transformation Index (ATI) of the Piratininga Lagoon System watershed from 1976 to 2022

Classes	ATI 1976	ATI 2003	ATI 2013	ATI 2022
Urban Area	0.981	2.615	3.025	3.629
Lagoon	0.344	0.436	0.422	0.569
Forest Formation	0.331	0.421	0.866	0.827
Rocky Outcrop	0.256	0.061	0.051	0.043
Pasture	0.005	0.066	0.073	0.09
Wetland	0.022	0.044	0.037	0.046
Sand Spot	0.066	0.03	0.037	0.042
Exposed Soil	0.191	0.019	0.032	0.04
Wooded Sandbank Vegetation	0.069	0.014	0.009	0.000
Other non-Vegetated Areas	0.003	0.005	0.006	0.006
TOTAL	2.268	3.711	4.558	5.292
Classification	Little degraded	Regular	Regular	Degraded

Source: The authors (2026).

The Anthropogenic Transformation Index (ATI) showed a steadily rising trend of degradation over time (Table 5). The total ATI value increased steadily from 2.268 in 1976 to 3.711 in 2003, rising to 4.558 in 2013, and finally reaching 5.292 in 2022. Consequently, the categorical ecological status of the Piratininga Lagoon system's watershed shifted from "Slightly Degraded" in 1976, through a persistent "Fair" status in 2003 and 2013, until it officially crossed the "Degraded" classification threshold in the 2022 assessment.

Urban areas contributed most to ATI growth, increasing from 0.981 in 1976 to 3.629 in 2022, accounting for 69% of the total ATI and becoming the primary driver of change. In contrast, rocky outcrops declined, falling from 0.256 to 0.043 during the same period.

DISCUSSION OF RESULTS

The multitemporal analysis of the Piratininga lagoon system watershed revealed transformation between 1976 and 2022. While the forest regenerated in areas of rugged terrain and protected slopes such as the *Parque Natural Municipal de Niterói* (PARNIT; Niterói Municipal Natural Park), urbanization expanded from 3.100km² to 8.033km² (14.0% to 36.3%), occupying areas of coastal plains and the banks of the lagoon system, destroying important transitional ecosystems such as riparian forests. This structure created an imbalance in water flow: protective vegetation sat in higher areas, while pollution originated in lower areas, preventing the forest from filtering polluted water from urban areas before it reached the lagoon system.

Research conducted by Rezende *et al.* (2018) points out that forest regeneration has been responsible for the current predominance of secondary forests in biomes such as the Atlantic Forest and the Amazon, a phenomenon also described by Brancalion and Chazdon (2017) and Almeida and Gouveia (2024), where they emphasize that vegetation growth in remote sensing images does not always reflect the preservation of original biomes, and may cover up processes of degradation and ecological replacement. The observed increase in forest formation in the Piratininga watershed is consistent with this cautionary assessment.

The near-total disappearance of rock outcrops and the wooded sandbank vegetation interface ecosystem between terrestrial and aquatic environments resulted in the loss of natural sediment filtration and bank-stabilization functions, leaving the lagoon directly exposed to diffuse urban runoff. This finding corroborates Oliveira *et al.* (2023), who identified urban area expansion as a central driver of basin degradation in the Urussanga River catchment, Santa Catarina, over 1986, 2005, and 2020.

The spatial patterns identified through ATI analysis align with findings by Friede (2020), who noted that population growth adversely affects environmental quality, and by Aguiar *et al.* (2023), who documented intensifying anthropogenic pressure on urban peripheries in Mato Grosso. Gouveia *et al.* (2013), applying ATI to the *Bezerro Vermelho* stream basin, further demonstrated the index's efficacy in capturing not only the intensity but also the spatial pattern of anthropic transformation over time.

The sanitation data, which indicate that 96.36% of households in the watershed are classified as having an adequate sewage collection system (IBGE, 2010), appear, at first glance, to be inconsistent with the water quality results documented for the same period. The Instituto Estadual do Ambiente (INEA)- State Environmental Institute Water Quality Index (IQANSF) assessments (2013–2022) consistently classified the water bodies of the Piratininga basin as "Very Poor" or "Poor," mainly due to high biochemical oxygen demand (BOD), high concentrations of total nitrogen and phosphorus, and recurrent episodes of algal blooms (INEA, 2023).

This discrepancy between the sanitation indicator and the ecological indicator is not a methodological error; it reflects a well-documented structural dissociation between wastewater collection and treatment, identified in multiple Brazilian urban watersheds (Von Sperling, 2014; Instituto Trata Brasil, 2021). In Niterói, this decoupling warrants careful analysis, given the data generated by this study.

Several non-mutually exclusive hypotheses may explain the discrepancy between the high collection rate and the lagoon's poor ecological condition. First, the IBGE census methodology classifies a household as having "adequate sewage disposal" if it is connected to the general sewage collection network, regardless of whether the collected effluent is subsequently treated (IBGE, 2010). This means the 96.36% figure reflects connection to the network, not actual treatment. Von Sperling (2014) showed that, in medium-sized Brazilian cities, the proportion of collected sewage that actually receives secondary treatment can be 30–50 percentage points lower than the collection rate, because treatment infrastructure is phased and often implemented incompletely relative to collection systems. Second, the Icaraí Sewage Treatment Plant (ETE) in Niterói, the main facility receiving effluents from the Oceanic Region, operates at design capacity levels established in the early 2000s (Niterói, 2022). Urban densification in the watershed between 2003 and 2022 documented here as a 36% increase in built-up area (from 5.50 km² to 8.03 km²) likely generated hydraulic loads that exceed the original design parameters, reducing hydraulic retention time and, consequently, the efficiency of biological treatment, particularly for the removal of nitrogen and phosphorus Von Sperling (2014) e (Metcalf & Eddy *et al.*, 2014). Third, the phenomenon of illegal cross-connections, in which stormwater drainage pipes are illegally connected to the sanitary sewer system (and vice versa), is widely documented in Brazilian coastal municipalities (Chagas *et al.*, 2020; ANA, 2017) and produces two adverse effects: during rainfall events, it dilutes and bypasses sewage treatment by overloading the network; and during dry periods, it generates diffuse wastewater discharges directly into stormwater outlets that drain into the lagoon. Fourth, point-source contributions from commercial and industrial establishments such as restaurants, car washes, and small industries may not be adequately captured by household-level census data but can represent significant organic and nutrient loads in a predominantly urban watershed (Chagas *et al.*, 2020). Fifth, contamination inputs from the neighboring Itaipu basin, whose stormwater and sewage overflows partially drain into the Piratininga system during heavy rainfall events, cannot be ruled out as a complementary pathway (Rocha, 2019).

The scope of the treatment infrastructure deserves special attention. In Brazil, municipal investment in sanitation has historically focused on collection networks rather than treatment capacity, since collection infrastructure is more politically visible and yields faster improvements in household-level sanitation indicators (Instituto Trata Brasil, 2021; SNIS, 2022). According to the National Sanitation Information System (SNIS, 2022), the average per capita investment in sewage treatment in Brazilian state capitals was R$ 28.70/inhabitant/year, compared to R$ 89.40/inhabitant/year for collection—a ratio of approximately 1:3. If this pattern applies to the Niterói Coastal Region, the existing WWTP may be structurally undersized relative to the volume of sewage collected, regardless of its nominal design capacity. Furthermore, tertiary treatment for nutrient removal (nitrogen and phosphorus) is rarely included in Brazilian WWTPs of this generation (Von Sperling, 2014), which means that, even at full capacity, the treatment would discharge nutrient-rich effluents capable of sustaining eutrophication in a shallow, low-flow system such as Piratininga's. The combination of a growing urban load (documented by the increase in the ATI from 2,268 in 1976 to 5,292 in 2022), a treatment infrastructure not designed for tertiary nutrient removal, and compromised hydrodynamic renewal due to the Tibau tunnel (INEA, 2023) creates a self-reinforcing cycle of nutrient accumulation from which the lagoon system cannot recover through natural renewal alone.

CONCLUSION

The study showed that the Piratininga Lagoon System Watershed underwent a marked process of anthropogenic transformation between 1976 and 2022. The application of the Anthropogenic Transformation Index (ATI) made it possible to show this evolution, highlighting the transition from slightly degraded (ATI = 2.268) in 1976 to a degraded state (ATI = 5.292) in 2022, with urbanization as the main vector of impact.

Spatial patterns demonstrated paradoxes between the apparent recovery of the forest and the deterioration of water quality in the lagoon system. It was concluded that the increase in forest formation, associated with secondary regeneration, was not sufficient to reduce the impacts caused by the degradation of ecosystems that connect land and water, such as sandbanks (coastal strips) and flooded fields, which protect the margins of the lagoon system.

The integration of databases such as MapBiomas, with manual vectorization on high-resolution images, proved to be a strategy for correcting limitations for complex urban areas and transition zones, such as slopes, water bodies, and mosaics of use. This combined approach was essential for identifying informal land uses and mixed occupation patterns that automatic classification methods may fail to capture adequately.

Although official census data indicate advances in sanitation, the environmental reality (hyper-eutrophication) shows that the sanitation problem still exists and causes negative impacts. The restoration of the Piratininga lagoon system cannot be limited to the conservation of slopes (nature-based solutions implemented on the banks, such as the Orla Park), but must also include adequate basic sanitation, interrupting sources of diffuse pollution, and the immediate recovery of the lagoon's direct connectivity with the sea.

REFERENCES

ABREU, F. B.; BORGES, E. F. Análise espacial do uso e cobertura das terras no município de São Gabriel-Bahia, 2007 e 2018. **Revista Ibero-Americana de Ciências Ambientais**, v. 12, n.7, 535-548. 2021. https://doi.org/10.6008/CBPC2179-6858.2021.007.0046

AGÊNCIA NACIONAL DE ÁGUAS (BRASIL). **Conjuntura dos recursos hídricos no Brasil**: relatório pleno 2017. Brasília, DF: ANA, 169 p., 2017.

AGUIAR, J. C.; SILVA, N., SANDRA M. A.; COSTA, R, L. Antropização da paisagem do município Matogrossense de colíder-Amazônia brasileira. **Revista Equador**, v. 12, n.3, 156-177. 2023. https://doi.org/10.26694/equador.v12i3.14034

ALMEIDA, B. V.; GOUVEIA, R. G. L. Uso e ocupação da terra na bacia hidrográfica do ribeirão Frutal de 1990 até 2020. **Revista de Ciências Agro-Ambientais**, v. 22, n. 1, p. 39-45,2024. https://doi.org/10.30681/rcaa.v22i1.12364

APOLINÁRIO, S. Lagoas da Região Oceânica de Niterói estão com mortandade de peixe. **Jornal A Seguir-Niteroi**. 2022. Available: https://aseguirniteroi.com.br/noticias/meia-tonelada-de-peixe-morto-boia-na-lagoa-de-piratininga/. Accessed on: jun. 26, 2025.

APOLINÁRIO, S. Lagoas da Região Oceânica de Niterói estão com mortandade de peixe. **Jornal A Seguir-Niteroi**. 2023 Available: https://aseguirniteroi.com.br/noticias/lagoas-da-regiao-oceanica-de-niteroi-estao-com-mortandade-de-peixe/. Accessed on: jun. 26, 2025.

ARAÚJO, P. L. Relação entre a qualidade da água e o uso do solo em microbacias do reservatório Billings, na Região Metropolitana de São Paulo - SP. **Revista de Gestão de Água da América Latina**, v. 15, e2, 2018. https://doi.org/10.21168/rega.v15e2

BERWANGER, D.; SCCOTI, A. A. V.; ROBAINA, L. E. D. S. Dinâmica espaço-temporal da cobertura e uso da terra e as modificações no ambiente no município de São Gabriel, RS. **Geopauta**, v. 8, e15586. 2024 https://doi.org/10.21168/rega.v15e2

BRANCALION, P. H. S.; CHAZDON, R. L. Beyond restoration: recovery of biodiversity and ecosystem functions in secondary forests. **Science Advances**, v. 3, n. 11, e1701340, 2017. https://doi.org/10.1126/sciadv.1701340

BRASIL. [Lei nº 9.433, de 8 de janeiro de 1997]. Institui a Política Nacional de Recursos Hídricos, cria o Sistema Nacional de

Gerenciamento de Recursos Hídricos, regulamenta o inciso XIX do art. 21 da Constituição Federal e altera a Lei nº 8.001, de 13 de março de 1990. **Diário Oficial da União**: seção 1, Brasília, DF, 9 jan. 1997.

BRASIL. MINISTÉRIO DO DESENVOLVIMENTO REGIONAL. SECRETARIA NACIONAL DE SANEAMENTO. **Sistema Nacional de Informações sobre Saneamento – SNIS**: diagnóstico temático: serviços de água e esgoto: visão geral: ano de referência 2022. Brasília, DF: Ministério do Desenvolvimento Regional, 2024.

CHAGAS, P. F.; LUCENA, K. O. C. de; CASTRO, M. P. S.; SANTOS, S. H. L. dos; SILVA, F. J. A. da; ARAÚJO, J. K. de. Índice de estado trófico de um manancial receptor de efluente de estação de tratamento de esgoto baldo–RN. **Brazilian Journal of Development**, v. 6, n. 2, p. 6253-6260, 2020. https://doi.org/10.34117/bjdv6n2-069

CHEN, X.; WANG, Y.; JIANG, L.; HUANG, X.; HUANG, D. Water quality status response to multiple anthropogenic activities in urban rivers. **Environmental Science and Pollution Research**, v. 30, n. 2, p. 3440-3452, 2023 2023. https://doi.org/10.1007/s11356-022-24468-1

CHENG, C.; ZHANG, F.; SHI, J.; KUNG, H. T. What is the relationship between land use and surface water quality? A review and prospects from remote sensing perspective. **Environmental Science and Pollution Research**, v. 29, n. 38, p. 56887-56907, 2022. https://doi.org/10.1007/s11356-022-21348-x

COMITÊ DA BACIA HIDROGRÁFICA DA BAÍA DE GUANABARA. Subcomitê Lagoas de Itaipu e Piratininga. **Relatório de Gestão e Monitoramento**. Rio de Janeiro: CBH Baía de Guanabara, 2024.

ESRI. **ArcGIS Desktop**: version 10.7. Redlands: Environmental Systems Research Institute, 2019.

FEARNSIDE P. M. Desmatamento na Amazônia brasileira: história, índices e consequências. **Destruição e Conservação da Floresta Amazônica**, V. 1, P. 7-19, 2022.

FRIEDE, R. Aumento populacional e degradação ambiental: a conta que não quer fechar. **Revista Augustus**, Rio de Janeiro, v. 25, n. 52, p. 82–93, 2020. https://doi.org/10.15202/1981-1896.v25n52p82

GALVANIN, E. A. S.; NEVES, S. M. A. S. Índice de transformação antrópica como instrumento de planejamento ambiental em bacias hidrográficas. **Revista Brasileira de Geografia Física**, v. 12, n. 5, p. 1806–1822, 2019. https://doi.org/10.26848/rbgf.v12.5.p1806-1822

GONTIJO, H. M.; RIBEIRO, S. D. S.; LIMA S. C. R. B. D. Water and sanitation sewage management in Divinópolis/MG: the current discourse on urban/rural fragmentation. **Revista de Economia e Sociologia Rural**, v. 62, p. e265399, 2024. https://doi.org/10.1590/1806-9479.2023.265399pt

GOUVEIA, R. G. L.; GALVANIN, E. A. S.; NEVES, S. M. A. S. Application of anthropic transformation index for multitemporal analysis of the Córrego do Bezerro Vermelho basin, Tangará da Serra-MT. **Revista Árvore**, Viçosa, v. 37, n. 6, p. 1045–1054, 2013. https://doi.org/10.1590/S0100-67622013000600006

IBGE – INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo Demográfico 2010**: características da população e dos domicílios: resultados do universo. Rio de Janeiro: IBGE, 2011.

INSTITUTO ESTADUAL DO AMBIENTE (RIO DE JANEIRO). **Boletins de qualidade das águas**: Bacia do Sistema Lagunar de Itaipu e Piratininga. resultados referentes ao ano de 2022. Rio de Janeiro: INEA, 2023.

INSTITUTO TRATA BRASIL. **RANKING DO SANEAMENTO 2021**. São Paulo: Instituto Trata Brasil, 2021. Available: https://tratabrasil.org.br/estudos/estudos-itb/itb/ranking-do-saneamento-2019. Accessed on: mar. 2, 2021.

JIANG, Y.; HE, J.; ZHAI, D.; HU, C.; YU, L. Analysis of the evolution of watershed habitat quality and its drivers under the influence of the human footprint. **Frontiers in Environmental Science**, v. 12, p. 1431295, 2024. https://doi.org/10.3389/fenvs.2024.1431295

KOBOEVIĆ, Ž.; MIŠKOVIĆ, D.; CAPOR HROŠIK, R.; KOBOEVIĆ, N. Analysis of sea pollution by sewage from vessels. **Sustainability**, v. 14, n. 1, p. 263, 2021. https://doi.org/10.3390/su14010263

LÉMECHEV, T. On hydrological heterogeneity catchment morphology and catchment response. **Journal of Hydrology**, v. 100, n. 1, p. 357–375, 1982.

MAPBIOMAS. **Projeto MapBiomas** – Coleção 8 da Série Anual de Mapas de Cobertura e Uso de Solo do Brasil. Available: https://brasil.mapbiomas.org/. Accessed on: oct. 10, 2025.

MATEO, J. M. **Apuntes de geografía de los paisajes**. La Habana: Editorial André Voisin, 470 p., 1984.

MELO, D. S.; GONTIJO, E. S.; FRASCARELI, D.; SIMONETTI, V. C.; MACHADO, L. S.; BARTH, J. A.; MOSCHINI-CARLOS, V.; POMPÊO, M. L.; ROSA, A. H.; FRIESE, K. Self-organizing maps for evaluation of biogeochemical processes and temporal variations in water quality of subtropical reservoirs. **Water Resources Research**, v. 55, n. 12, p. 10268-10281, 2019. https://doi.org/10.1029/2019WR025991

METCALF & EDDY; TCHOBANOGLOUS, G.; STENSEL, H. D.; TSUCHIHASHI, R.; BURTON, F. L. **Wastewater engineering**: treatment and resource recovery. 5. ed. New York: McGraw-Hill Education, 2014. 2048 p.

MOURA, L.; LANDAU, E. C.; LUZ, W. V. Esgotamento sanitário nas áreas de maior concentração da agricultura familiar: situação da Região Nordeste. *In*: Simpósio Regional de Geoprocessamento e Sensoriamento Remoto, 7., 2014, Aracaju. **Anais** [...]. Aracaju: UFS, 2014.

NITERÓI (MUNICÍPIO). **Saneamento**: Niterói receberá mais de R$ 100 milhões até o fim de 2023. Niterói: Prefeitura Municipal de Niterói, 31 ago. 2022.

NITERÓI (MUNICÍPIO). **SIGEO**: Sistema de Informações Geográficas de Niterói. Niterói: Prefeitura Municipal de Niterói, [s. d.].

OLIVEIRA, A. J. M. DE; LADWIG, N. I.; SILVA, J. G. S. DA; SUTIL, T. Índice de transformação antrópica da bacia hidrográfica do Rio Urussanga, Santa Catarina, Brasil. **Revista Geotemas**, Pau dos Ferros, v. 13, n. 1, e02321, 2023. https://doi.org/10.33237/2236-255X.2023.4710

PATRA, S.; SAHOO S.; MISHRA P.; MAHAPATRA S. C. Impacts of urbanization on land use/cover changes and its probable implications on local climate and groundwater level. **Journal of urban management**, v. 7, n. 2, p. 70-84, 2018. https://doi.org/10.1016/j.jum.2018.04.006

PEREIRA, J. DA S.; NEVES, S. M. A. DA S.; SILVA, J. DOS S. V. Antropização da paisagem da Bacia Hidrográfica do Córrego Jacobina em Cáceres/MT, Brasil. **Revista Equador**, Teresina, v. 12, n. 2, p. 48–71, 2023. https://doi.org/10.26694/equador.v12i2.14050

PERIM, M. A.; COCCO M. D. A. Efeito das transformações antrópicas às margens do rio Una, Taubaté, São Paulo, Brasil. **Ambiente & Água-An Interdisciplinary Journal of Applied Science**, v. 11, p. 1163-1171, 2016. https://doi.org/10.4136/ambi-agua.1918

QGIS ASSOCIATION. **QGIS Geographic Information System**: version 3.28.4 Firenze. [S. l.]: QGIS Association, 2023.

REZENDE, C. L.; SCARANO, F. R.; ASSAD, E. D.; JOLY, C. A.; METZGER, J. P.; STRASSBURG, B. B. N.; TABARELLI, M.; MITTERMEIER, R. A.; RODRIGUES, R. R. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. **Perspectives in Ecology and Conservation**, v. 16, n. 4, p. 208–214, 2018. https://doi.org/10.1016/j.pecon.2018.10.002

RIBEIRO, P. E. A. M.; CARVALHO, T. S. DE; SANTOS, L. C. M. DOS; DIAS, L. L.; SANTOS, G. M. F. dos. Monitoramento quali-quantitativo das águas superficiais do Sistema Lagunar Urbano de Itaipu-Piratininga – Niterói-RJ. *In*: Congresso Brasileiro de Gestão Ambiental, 12., 2021, Salvador. **Anais** [...]. Salvador: IBEAS, 2021.

RICHTER, M. **Geotecnologias no suporte ao planejamento e gestão de unidades de conservação**: estudo de caso: Parque Nacional do Itatiaia. 2004. 162 f. Dissertação (Mestrado em Geografia) – Programa de Pós-Graduação em Geografia, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2004.

ROCHA, A. V. **Foraminíferos bentônicos e biopolímeros como indicadores ambientais em ecossistema hipersalino**: Laguna de Araruama, Rio de Janeiro. Dissertação (Mestrado em Geociências) – Universidade Federal Fluminense, Niterói, 2019.

ROCHA, S. D.; CRUZ, C. Monitoramento da cobertura vegetal nas APAs da Mantiqueira e Serrinha do Alambari, no município de Resende com auxílio do sensoriamento remoto. *In*: Encontro Nacional de Geógrafos, 13., 2002, João Pessoa. **Anais** [...]. [S. l.: s. n.], p. 357, 2002.

SANTOS, B. Fish Kill Outrages Fishermen at Piratininga Lagoon in Niterói. **A Tribuna newspaper**. 2025. Available: https://atribunarj.com.br/materia/mortandade-de-peixes-indigna-pescadores-da-lagoa-de-piratininga. Accessed on: jun. 26, 2025.

SANTOS, M. V.; MENEZES, J. A.; SILVA, D. A. P.; DUARTE, M. L.; FLORESTA, A. C. Uso e ocupação do solo e qualidade da água do rio Crato no município de Humaitá-AM, Brasil. **Revista Valore** v. 5, 2020. https://doi.org/10.22408/reva502020447e-5040

SEABRA, V. S.; XAVIER, R. A.; DORNELLAS, P. C.; DAMASCENO, J. Índice de transformação antrópica por bacias de primeira ordem nas bacias do Rio Taperoá e Alto Paraíba-PB. *In*: Simpósio Nacional de Geomorfologia, 12., 2018, Crato. **Anais** [...]. Crato: [s. n.], p. 1–13, 2018.

SILVA JUNIOR, L. C. S.; AZEVEDO, J. P. S. Influência do saneamento na qualidade de água em rios: uma análise através da modelagem de qualidade de água. **MIX Sustentável**, Florianópolis, v. 8, n. 1, p. 41–52, 2022. https://doi.org/10.29183/2447-3073.MIX2022.v8.n1.41-52

SILVA PEREIRA, J.; DA SILVA NEVES; S. M. A.; SILVA, J. D. S. V. Antropização da paisagem da Bacia Hidrográfica do Córrego Jacobina em Cáceres/MT, Brasil. **Revista Equador, Teresina-PI**, v. 12, n. 2, p. 48–71,2023. https://doi.org/10.26694/equador.v12i2.14050

SILVA, D. C. C.; OLIVEIRA, R. A.; SIMONETTI, V. C.; TONIOLO, B. P.; SALES, J. C. A.; LOURENÇO, R. W. Creation of an environmental sustainability index for water resources applied to watersheds. **Environment, Development and Sustainability**, v. 25, n. 10, p. 11285-11305, 2022. https://doi.org/10.1007/s10668-022-02527-9

SILVA, J. G. S.; LADWIG, N. I.; BACK, Á. J. Índice de transformação antrópica (ITA) aplicado à bacia hidrográfica do rio Araranguá, Santa Catarina, entre os anos de 1985, 2005 e 2019: Anthropic Transformation Index (ATI) applied to the Araranguá river hydrographic basin, Santa Catarina, between 1985, 2005 and 2019. **Revista de Geociências do Nordeste**, v. 10, n. 2, p. 51-65, 2024. https://doi.org/10.21680/2447-3359.2024v10n2ID33545

SILVA, P. N.; COSTA, E. D. C. P.; SILVA SEABRA, V. Índice De Transformação Antrópica Por Unidades De Paisagem Na Bacia Do Macacu-Guapiaçu-Rj. v. 19, n. 2, p. 24-44, 2023. https://doi.org/10.12957/tamoios.2023.71054

TUHOLSKE, C.; HALPERN, B. S.; BLASCO, G.; VILLASENOR, J. C.; FRAZIER, M.; CAYLOR, K. Mapping global inputs and impacts from of human sewage in coastal ecosystems. **PloS one**, v. 16, n. 11, p. e0258898, 2021. https://doi.org/10.1371/journal.pone.0258898

UNITED NATIONS. **Transforming our world**: The 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015, A/RES/70/1. United Nations. 2015. Available: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1. Accessed on: sep. 8, 2024

VELLOZO, L. D.; OLIVEIRA SANTOS, L. C. DE; WEINS, N. W. Dissemination of ideas of Nature-Based Solutions: an analysis of the implementation of the Orla de Piratininga Park, Niterói (RJ). **Revista LABVERDE**, São Paulo, v. 12, n. 1, p. 100–128, 2022. https://doi.org/10.11606/issn.2179-2275.labverde.2022.189324

VICENS, R. S. **O transporte de sedimentos em suspensão como parte da análise ambiental da bacia hidrográfica do Rio Mazomba**. 117 f. Dissertação (Mestrado em Geografia) – Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 1998.

VON SPERLING, M. **Introdução à qualidade das águas e ao tratamento de esgotos**. 4. ed. Belo Horizonte: Editora UFMG, 470 p., 2014.

ZHANG, H.; SUN, H.; LI, J.; LI, Y.; ZHANG, L.; ZHAO, R.; HU, X. Natural and anthropogenic imprints on seasonal river water quality trends across China. **npj Clean Water**, v. 8, n. 1, p. 49, 2025. https://doi.org/10.1038/s41545-025-00481-3

AUTHORS CONTRIBUTION

Minércia Job Macamo: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing original draft and Writing review & editing; Braian de Oliveira Salvador: Data curation, Methodology and Visualization; Fábio Ferreira Dias: Supervision, Conceptualization, Validation and Writing review & editing.

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DATA AVAILABILITY: The data that underpin the results of this study may be made available by the corresponding author, upon duly justified request. [Minércia Job Macamo].