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The Environmental Status of *Wetlands* in Rio de Janeiro State: An Analysis Based on Indicators Applied to the Wetlands of Rio de Janeiro State

O Estado Ambiental dos *Wetlands* Fluminenses: Uma Análise a Partir de Indicadores Aplicados as Paisagens Pantanosas do Estado do Rio de Janeiro

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Abstract

Marshy landscapes, internationally known as wetlands, perform vital ecosystem services, such as hydrological cycle regulation and biodiversity maintenance. However, they face increasing anthropogenic pressures that compromise their environmental stability. This research aimed to characterize the environmental status of wetland landscapes in the State of Rio de Janeiro, Brazil, through the integrated application of socio-environmental indicators. The methodology was based on the physical-geographic regionalization of the state's wetlands at a 1:50,000 scale. Four primary indicators were applied: Deforestation Index (DI), Anthropogenic Transformation Index (ATI), Rectilinear Channel Indicator (RCI), and Anthropization Index by Anthropogenic Elements (AIAE). The results were normalized to compose a synthetic index to weigh the environmental status of these areas. The findings revealed that most Rio de Janeiro wetland regions exhibit an unstable or critical environmental status, particularly in areas under strong urban and agropastoral influence, such as the North Fluminense and the Metropolitan Region. In contrast, only the Costa Verde region presented areas classified as stable, though still vulnerable due to fragmentation. It is concluded that the critical state of these landscapes demands immediate interventions and effective territorial management policies to mitigate irreversible damage and ensure the continuity of ecosystem services amidst a climate change scenario.

Keywords:
Wetlands, Geotechnologies, GIS, Spatial Analysis, Landscape Geoecology.

Resumo

As paisagens pantanosas, conhecidas internacionalmente como *wetlands*, desempenham funções ecossistêmicas vitais, como a regulação do ciclo hidrológico e a manutenção da biodiversidade,

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contudo, enfrentam crescentes pressões antrópicas que comprometem sua estabilidade ambiental. O objetivo desta pesquisa foi caracterizar o estado ambiental das paisagens de *wetlands* no estado do Rio de Janeiro através da aplicação integrada de indicadores socioambientais. A metodologia utilizou-se da regionalização físico-geográfica dos *wetlands* do Estado do Rio de Janeiro em escala 1:50.000. Foram aplicados quatro indicadores principais: Índice de Desmatamento (ID), Índice de Transformação Antrópica (ITA), Indicador de Canais Retilíneos (ICR) e Índice de Antropização por Elementos Antrópicos (IAEA), cujos resultados foram normalizados para a composição de um índice normalizado que ponderasse o estado ambiental desses ambientes. Os resultados revelaram que a maioria das regiões de *wetlands* fluminenses apresenta estado ambiental instável ou crítico, especialmente nas áreas sob forte influência urbana e agropastoril, como o Norte Fluminense e a Região Metropolitana. Em contraste, apenas a região da Costa Verde apresentou áreas classificadas como estáveis, embora ainda vulneráveis devido à fragmentação. Conclui-se que o estado crítico dessas paisagens exige intervenções imediatas e políticas de gestão territorial eficazes, visando mitigar danos irreversíveis e assegurar a continuidade dos serviços ecossistêmicos em um cenário de mudanças climáticas.
Palavras-chave:
Áreas úmidas, Geotecnologias, SIG, Análise Espacial, Geoecologia das Paisagens.

I. INTRODUCTION

The Ramsar Convention (1971) calls flooded landscapes "*wetlands*", defining them as: "Areas of marsh, peat or water, whether natural or artificial, permanent or temporary, with static or flowing water, fresh, fresh or salt, including areas of seawater, the depth of which at low tide does not exceed six meters".

Moore (2008) points out that these areas occupy around 6% of the world's surface, and are spread out, with a highly fragmented geographical distribution, present in large geographical areas, but distributed in small patches. This dispersed and fragmented behaviour, in addition to increasing the vulnerability of these areas, is one of the aspects that make it difficult to properly identify and characterize them for environmental management and planning purposes.

It should be noted that these areas have significant chorological diversity[1] (number of individuals) and typological diversity[2] (different types of landscapes), as well as a great diversity of environments in the state of Rio de Janeiro (fluvial, fluvial-marine, marine-lacustrine, tectonic, etc.).

Wetlands play a vital role in the subsistence of diverse communities and in maintaining environmental balance. According to Jaramillo et al. (2019), these areas function as strategic habitats that provide food and

[1] It refers to the quantity of chorological individuals conceived as landscape units (landscape contours), in relation to the total number of possible individuals (Rodriguez et al., 2017).
[2] It is calculated as the number of types that occur in a region, in relation to the total number of possible types (Rodriguez et al., 2017).

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refuge for aquatic and terrestrial biodiversity, as well as acting as natural hydrological buffers against floods and droughts. In addition, *wetlands* regulate water quality, sediment and nutrients, reducing peak flows and serving as essential sources of fresh water for domestic and agricultural use. Finally, their importance extends to local food security and long-term global carbon sequestration, consolidating them as multifunctional ecosystems of high environmental value.

In addition, *wetlands* have great environmental value, such as their importance in maintaining the water cycle and carbon cycles. Compared to all terrestrial ecosystems, *wetlands* have the highest carbon density, which makes them play an important role in global biogeochemical carbon cycles, helping to store and sequester carbon (Kayranli et al., 2010). In addition, these environments can help mitigate the impacts associated with climate change, in terms of flood control (Salimi et al., 2021).

Moore (2008) also points out that wetlands can act like giant sponges, absorbing excess water and slowly releasing it into rivers from which it can be extracted for use in agricultural irrigation, industrial processes or domestic consumption. These areas are susceptible to being occupied by infrastructure works or for agropastoral uses, due to the economic interest in these locations. It should be noted that with the change of use, their stability and natural function are interrupted, permanently changing their structure, which can cause irreversible damage.

It should be noted that in addition to natural *wetlands*, it is also possible to find artificial wetlands, i.e. those created by man, carrying out activities associated with aquaculture, and permanently or temporarily flooded agriculture, such as rice paddies, salt pans, reservoirs, impoundments, canals and sand pits.

The occupation processes in these areas can contribute to changes in the hydrogeological system, as many of these areas are zones of exudation or recharge of aquifers. In addition, the process of sealing the soil hinders the natural drainage of water, intensifying the occurrence of floods. In addition to economic losses, it is important to mention the risk of contagion of diseases and even the loss of human life that these events can cause for the residents of that locality (Seabra; Rocha-Leão, 2019). It is therefore essential to analyze the environmental status of these environments, which are sensitive and vulnerable.

Environmental status refers to the geoecological situation of the given landscape, determined by the type and degree of impact and the capacity of geosystems to react and absorb it (Rodriguez et al., 2017). The changes in the mechanisms of systemic formation and regulation, the degree and extent of the degrading processes, and the level of degradation determine the environmental state of the geosystem, considering the type and degree of impact and the capacity for reaction and absorption (Dias; Oliveira, 2012). Therefore, the

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environmental or geoecological state of landscapes is determined by the type and degree of anthropogenic modification and the absorption and reaction capacity of geosystems.

Methods for evaluating the environmental status of landscapes are generally based on criteria and indicators that make it possible to qualitatively describe or measure the properties of geosystems, related to their structure, functioning and evolutionary trajectory. Indicators are parameters or values that provide information or describe the state of a phenomenon.

The term index is understood as a numerical value that represents an interpretation of the reality of a simple or complex system, using scientific bases and appropriate methods in its calculation (Siche et al., 2007). Given its synthetic nature, an index can be used in decision-making and diagnostics, helping to analyze and interpret complex phenomena.

Indicators reflect natural potential, historical degradation trends, rates of change in natural resources, as well as the elements needed to adopt consistent policies for land use planning as a means of social progress and nature conservation (Palacio-Prieto et al., 2004). Among the main indicators associated with geosystems adopted by authors such as Lémechev (1982), Rodriguez and Martinez (1998), Palacio-Prieto et al. (2004), Santos et al. (2018) we can highlight those indicators associated with deforestation, the degree of anthropic transformation, the presence of anthropic elements, channel retilinization, urban expansion and changes in land use and cover.

Recent investigations in different global contexts have used integrated indicators to diagnose the geoecological integrity and conservation status of *wetlands* under pressure from accelerated urbanization and land use dynamics (Xu et al., 2019; Ghabayen et al., 2020). Such studies corroborate the urgency of methodological approaches applied on a regional scale, capable of subsidizing territorial planning and mitigating the loss of essential ecosystem services in wetlands (Hu et al., 2017).

Faced with the challenge of measuring and comparing the environmental status of different *wetland* landscape units, identifying stable, critical or unstable areas, environmental indicators play a central role. Thus, for this research, four indicators were selected that can provide an integrated analysis of the environmental status of these systems: (i) the Deforestation Indicator (ID), (ii) the Anthropogenic Transformation Index (ITA), (iii) the Straight Channel Indicator (ICR), and (iv) the Anthropization Index by Anthropogenic Elements (IAEA). All of these indicators had their results normalized so that they could be integrated into the formulation of a final index that would take into account the environmental status of *wetland* landscapes.

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Thus, the aim of this research is to characterize the environmental status of the marshy landscapes of the state of Rio de Janeiro, starting with the *wetland* landscape regions, through the integrated application of socio-environmental indicators.

II. MATERIALS AND METHODS

Study area

The study area for this research covers the entire territorial extension of the state of Rio de Janeiro (Figure 1). Compared to other territories in Brazil, the state of Rio de Janeiro has small and fragmented *wetlands*, but it does have significant flooded environments, made up of deltaic systems, coastal lagoons, alluvial, marine and palustrine wetlands, for example, which makes them of significant environmental interest.

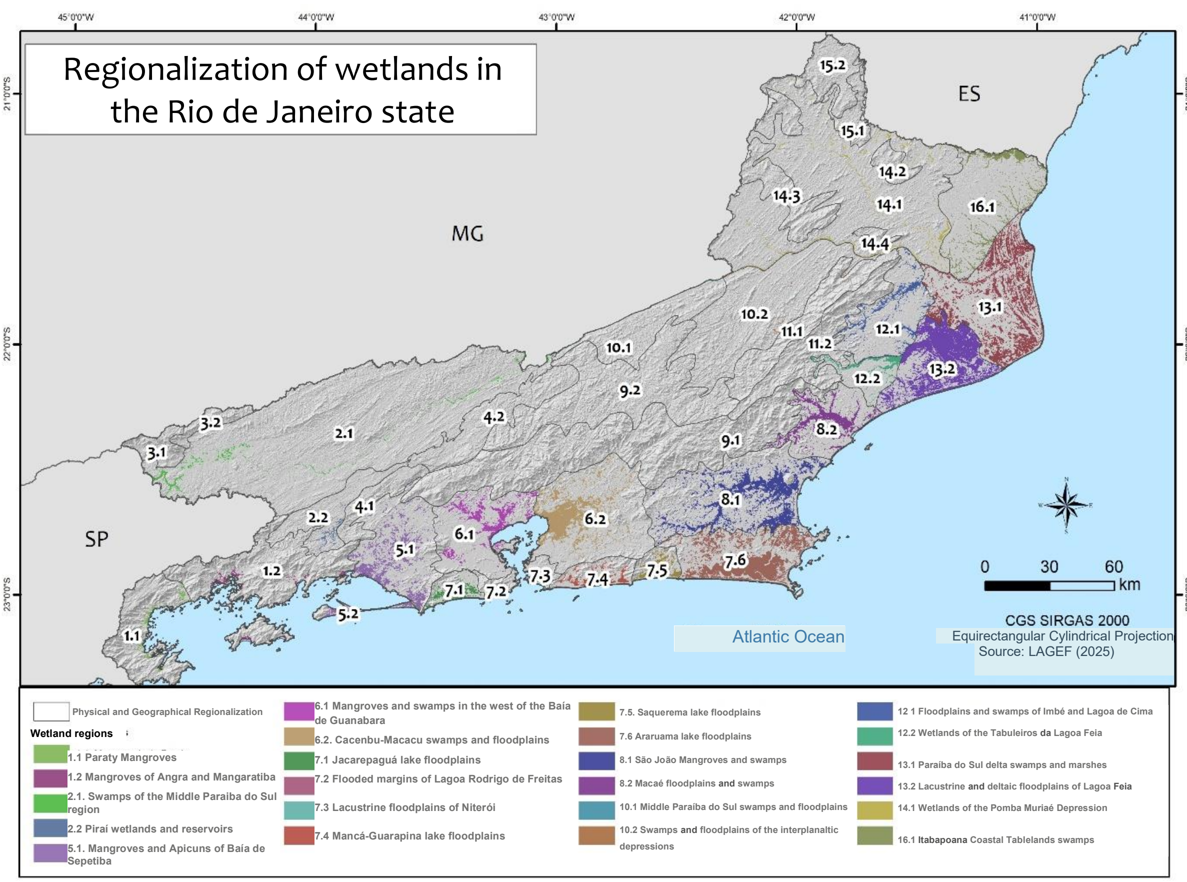

Figure 1 – Regionalization of *wetland* landscapes in the state of Rio de Janeiro (Source: Costa, 2025).

With an area of 43,778 km², the state of Rio de Janeiro is located in the Southeast region of Brazil, stretching between the Atlantic Ocean and the states of São Paulo, Minas Gerais and Espírito Santo. As one of the most mountainous states in Brazil, most of its area is made up of mountains and plateaus with steep slopes. The highest elevations exceed 2,000 meters in the intrusive mountain massifs of Serra da Mantiqueira and Serra

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do Mar, and vary between 500 and 1,500 meters in the reverse plateaus of Serra da Bocaina, Serra dos Órgãos and the Varre e Sai plateau. In the tectonic depression of the Rio Paraíba do Sul, the collinear terrain varies around 300 meters, and can reach up to 800 meters in the residual mountain ranges of the valley. The coastal lowlands between Baía de Sepetiba and the Rio Itabapoana, on the other hand, do not exceed 100 meters.

In terms of climate, the state of Rio de Janeiro is located in the Atlantic tropical zone, so the proximity of the sea and the relief are responsible for the variations in temperature and the distribution of rainfall over the months of the year. Thus, in the state of Rio de Janeiro, three types of climate predominate: the semi-humid tropical climate, the high-altitude tropical climate and the tropical climate (Sordi, 2020). Hydromorphic soils under conditions of temporal flooding or under intertidal regimes occupy 11.63% of the state's area (de Carvalho Filho et al., 2003), located on gentle gradient surfaces that favor the permanence of water, mainly flood plains, palustrine depressions, lagoon systems, coastal plains, deltas and estuaries and tidal flats. The remaining vegetation in 2024 was just over 80,000 ha of flooded fields and marshy vegetation, while almost 11,000 ha correspond to mangroves and halophytic vegetation on hypersaline surfaces (MapBiomas, 2025).

The geomorphology of the state of Rio de Janeiro means that the presence of *wetlands* is specifically restricted to areas with more flattened terrain, i.e. in areas of fluvial-marine, deltaic, alluvial, eolian-marine plains, valley bottoms and depressions, or even in areas of artificial reservoirs. The existence of *wetlands* in the study area is restricted to these areas, as this is where it is possible to maintain the concentration of flooding, due to their low slope.

This area of study was chosen because the state of Rio de Janeiro is an important spatial area in Brazil, whether from a strategic point of view, as it is located in an area of great social and economic dynamism, or from an environmental point of view, as it is home to different types of ecosystems and natural resources that supply the population of Eastern Rio de Janeiro and suffer from constant pressure and degradation.

In the state of Rio de Janeiro, various sanitation and infrastructure projects took place during the 1960s and 1970s, which channeled many swamps that existed along the rivers. An example of these interventions occurred in the São João river basin, located in eastern Rio de Janeiro, where the DNOS (National Department of Works and Sanitation) carried out hydraulic works. DNOS began work on the Rio São João basin in 1950, and between the 1970s and 1980s it carried out studies to straighten and channel rivers, drain swamps and flood areas and build the Juturnaíba reservoir. These interventions incisively modified the region's landscape, altering the entire geosystemic balance that had previously existed (Figure 2 - b).

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In the Lagos region, for example, the surroundings of the lagoon systems have been taken over by salt farming since the 19th century, with artificial channels for water intakes and the construction of tanks and dykes for this economic activity (Figure 2 - a). Also on the east coast, several "clogged" areas were channelized and drained by sanitation works, for example in Itaipuaçu.

Other locations in the state have undergone major changes, mainly in terms of straightening channels for urban growth, for example around Guanabara Bay (Figure 5 - d), and around the Jacarepaguá and Rodrigo de Freitas lagoon systems.

However, the main concentration of *wetlands* is in the Northern Eastern region of Rio de Janeiro, where there is an extensive deltaic plain. In this region, active or abandoned distributary channels are found, separated by shallow or partially submerged waters, such as tidal flats, marshes and mangroves (Martin et al., 1993). In this region, it is possible to find several active agricultural activities, where they compete for space with the *wetlands*, and are often drained and rectified so that they do not flood the areas used for grazing (Figure 2 - c) or crops.

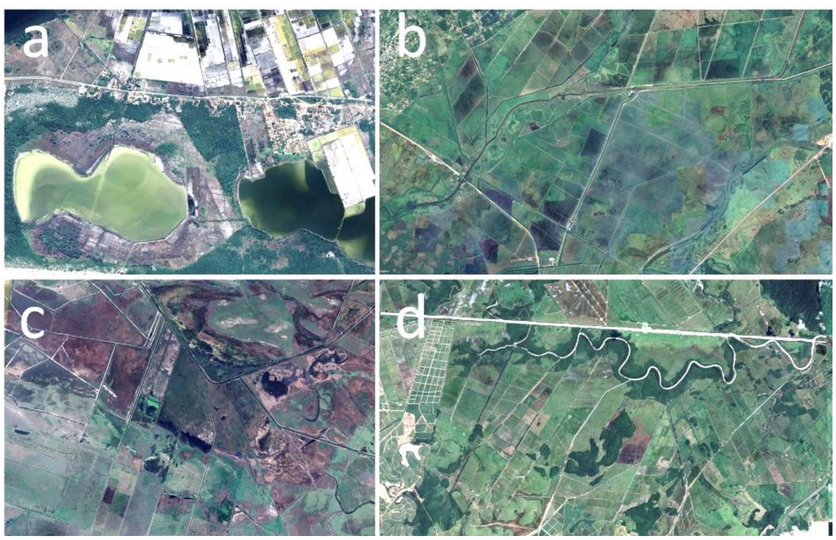

Figure 2 – Channeled *wetlands* in the state of Rio de Janeiro:
(a) Salt pans channeling flooded areas around the lagoon systems of the Lagos region, (b) retilinized canals in Itaboraí, near COMPERJ, (c) retilinized canals around Lagoa Feia for agropastoral activities, (d) retilinized canals in the Rio São João basin after DNOS works. Source: adapted from Google Earth (2021).

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Spatial data sources

Among the databases available for this study, we highlight the classification of *wetlands* in the state of Rio de Janeiro proposed by Costa (2025), for the period 2019 to 2021. This mapping, produced on a scale of up to 1:50.000, was developed using an innovative remote sensing methodology that integrates radar images from the Sentinel-1 Synthetic Aperture Radar (SAR) satellite with optical images from Sentinel-2, both with a spatial resolution of 10 meters.

The use of SAR data is an important methodological differentiator, as it allows information to be acquired from the earth's surface almost independently of atmospheric conditions, making mapping possible even during periods of heavy rainfall and under cloud cover. The integration of optical and radar sensors expands the set of images available and enhances the identification and characterization of *wetlands*, exploiting the spectral and structural properties of the different sensor systems in a complementary way.

Based on this classification of *wetlands*, Costa (2025) developed a physical-geographical regionalization of *wetland* landscapes in the state of Rio de Janeiro, based on the individualization and grouping of landscape typologies with similar physical characteristics, based on landscape geoecology (Rodriguez et al., 2017; Vicens, Rodríguez; Cronemberger, 2019). This regionalization aimed to bring together, in continuous spatial units, recurrent wetland landscapes in the territory, considering common physical-geographical attributes, giving rise to the so-called *wetland* landscape regions.

The regionalization process adopted in this research resulted in the identification of 16 first-order regional units, broken down into 37 second-order regional units, distributed throughout Eastern Rio de Janeiro's territory. These regional *wetlands* geoecological units constitute the main spatial database adopted in this research, and are used as a reference for carrying out spatial analyses and for the integrated application of socio-environmental indicators.

For the application of landscape indicators, aimed at analyzing the environmental status of wetland landscapes, secondary data was used, provided by institutions and private initiatives, such as the data made freely available by the National Spatial Data Infrastructure (INDE) and the MapBiomas initiative.

The indicators analyzed were constructed from different spatial databases. The deforestation indicator was based on land use and land cover data from the MapBiomas project, considering the time series from 1989 to 2023. The anthropogenic transformation indicator used the most recent MapBiomas land use and cover database (2024). The analysis of channel retilinization was based on the 1:25.000 scale hydrography database provided by the State Environment Institute (INEA) for 2015. Finally, the indicator for the presence of

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anthropogenic elements was based on the vector bases of roads, transmission lines, industries and mining processes, obtained from INEA (2024), the Brazilian Institute of Geography and Statistics (IBGE, 2018) and the National Mining Agency (ANM, 2024).

Deforestation

The rate of deforestation is an indicator of pressure on forest resources and is an essential element in assessing and diagnosing the behavior of other environmental variables (climate, soils, hydrology, among others) and socio-economic variables (population growth, population density, economic activities, among others) (Palacio-Prieto et al., 2004).

In order to map the deforestation indicator, we used the classifications of deforested areas from 1989 and 2023, referring to MapBiomas collection 9, which specifically refers to the classification of deforestation provided by the platform. This data was downloaded in matrix format from the Google Earth Engine (GEE) platform.

The deforestation indicator was then applied to each landscape unit following the methodology proposed by (Palacio-Prieto et al., 2004), which assesses the rate of growth or reduction in deforestation in the area under study. The deforestation index proposes an expression that includes the area deforested in the initial period and the area deforested in the subsequent period, in relation to the number of years between the periods. In this sense, we chose to work with 1989 and 2023, covering 34 years of analysis. The expression is calculated as follows:

$$\delta n = \left[\frac{S_2}{S_1}\right]^{\frac{1}{n}} - 1 \qquad (1)$$

Where: δn = rate of change; S_1 = area deforested in period 1; S_2 = area deforested in period 2; N = number of years between periods

Anthropogenic Transformation

According to Palacio-Prieto et al. (2004), the transformation index refers to the relationship between natural land cover and cover resulting from human activity. In this sense, the Anthropogenic Transformation Index (ITA) offers the possibility of analyzing the pressures resulting from changes in land use and cover on any environmental and spatial units.

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ITA was developed by Lémechev (1982) and put into practice by researchers such as Schwenk and Cruz (2008), Xavier et al. (2019), Seabra et al. (2019), Fushita et al. (2020), Silva et al. (2023) and Oliveira et al. (2023), who applied it in studies aimed at quantifying the pressures suffered by a component of the landscape. It can be applied to a watershed, protected areas, landscape units, municipalities, census sectors, among others.

ITA is applied in circumstances where the aim is to obtain quantified results on the pressures exerted on a given spatial area based on the percentage of land use and land cover, in addition to the weights established for each use class. Its analysis proposal is effective because, in addition to quantifying, this method makes it possible to assess the degree of pressure resulting from changes in land use and cover that occur in each component of the landscape analyzed.

To apply ITA, we used the land use and cover map of the state of Rio de Janeiro for 2022, obtained from MapBiomas collection 9. The mapping had the specific class legends systematized in order to summarize and reclassify the legends and classes used. The ITA is defined by the sum of the percentages of use in the landscape units (% use in the unit) multiplied by the weight of the class, which represents the degree of transformation), divided by 100, as shown in the expression below:

$$ITA=\sum (\%USE \times WEIGHT)/100 \quad (2)$$

Where: ITA = anthropogenic transformation index; USE = areas in percentage values of the use and cover class; PESO = weight given to the different types of use and cover in terms of the degree of anthropogenic alteration, ranging from 1 to 10.

To apply this index, it was necessary to assign weights to each of the land use classes available in the study area. Weights closer to its maximum value (10) represent areas of greater anthropogenic transformation, while values closer to 1 portray areas of low anthropogenic transformation. Based on recent research using ITA in the state of Rio de Janeiro (Seabra et al., 2019; Silva et al., 2023), weights were assigned to the land use and land cover classes according to the degree of human intervention in the study area. Classes with less anthropogenic influence, such as rocky outcrops, bodies of water, wetlands, sandy areas, forest formations and sandbanks, were given minimum weight. The forestry and agropastoral classes received intermediate weights (6 and 7, respectively), while the urban and mining classes, associated with greater intensity of anthropogenic transformation, received the maximum weight (10).

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River channel straightening

The first step in applying the straight channels indicator was to define the scale of analysis, which was set at 1:25.000. The basis for the analysis was obtained from the INEA database. However, the data provided does not include a description of natural drainages and those that have been anthropized and straightened by means of works. It was therefore necessary to classify the linear data in *ArcGis* software, assigning a descriptive element to the table of attributes based on the manual selection of each river and visual interpretation of the data using image interpretation techniques.

The most elongated shape, without sinuosities, was the main element to be highlighted as rectilinear. Subsequently, the location and context in which the drainage was inserted in the image was an important tool for identifying the anthropized channels. In addition to these, the constant and repeated pattern in agricultural areas, together with the standardized sizes, helped in the interpretation of these channels.

The channels were selected by visually interpreting the cartographic data, followed by the selection and classification of rectilinear drainage. This approach ensured that only rivers with straight characteristics were included in the analysis and that there were no mistakes in the classification. This stage used high spatial resolution images from the Google Earth Pro platform, as well as images made available from the *ArcGIS* software *basemap*.

Finally, to determine the straightness of the rivers, the density of straight channels was calculated for each landscape unit, which is represented by the ratio of straightened drainage to the total drainage network of the unit. The river channel transformation indicator corresponds to the ratio between the length of the retilinized channels and the existing *wetlands* in the landscape unit, as shown in the expression below:

$$CR = \text{channelized drainage}/\text{total drainage} \quad (3)$$

In this sense, the length of the straight channels in relation to the total length of the drainage network in the landscape unit was adopted as the parameter for this indicator.

Anthropic Elements

The Anthropization Index by Presence of Anthropic Elements (IAEA) was based on the methodology proposed by Bollo and Velasco (2018), which aims to classify landscapes into levels of anthropization using

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weights ranging from 1 to 5, allowing a variation in the degree of human modification (anthropization) per landscape region to be obtained.

The final weights result from the average of the weights assigned to the different anthropogenic elements, selected according to their spatial incidence and socio-economic relevance for the application of the indicator. The IAEA calculation takes into account the anthropogenic components of the landscape, understood as those introduced by human action to perform specific socio-economic functions. The indicator is based on the integration of variables representative of anthropogenic modification of the territory, including the density of industries (number of industries per area of the region, in km²), the density of transmission lines (length of power lines, in km²), and the density of the landscape. The density of the road network (length of roads, in km, per area of the landscape unit, in km²) and the density of mining (number of mining concessions per area of the landscape unit, in km²).

Finally, all the values assigned to the densities per region are summed up, resulting in anthropization ranges that can be defined, along with the % of natural cover in each region, according to the formula below:

$$IAEA = \sum^{n} p_i \qquad (4)$$

Where: Pi = weight given to indicator "i"; i = change indicators (densities); n = number of densities calculated

Next, the densities of the anthropogenic elements were formed for each unit, calculating the kilometers traveled in the case of linear data (roads and transmission lines) and, in the case of point data (industries and mining concessions), the sum of the points made with the join count, assigning proportional weights (Table 1).

Table 1 – Weights assigned to the densities of the variables used in the IAEA.

Industries (points/km²)	**LT (km/km²)**	**Mines (points/km²)**	**Roads (km/km²)**	**Pipelines (km/km²)**	**Airports (km/km²)**	**Ports (km/km²)**	**Weights**
0 - 0.006	0 - 0.052	0 - 0.003	0.399 - 0.924	0 - 0.012	0 - 0.000211	0	1
0.006- 0.015	0.052 - 0.326	0.003 - 0.008	0.924 - 1.300	0.012 - 0.058	0.000212 - 0.000684	0.000001 - 0.001036	2
0.015 - 0.027	0.326 - 0.774	0.008 - 0.014	1.300 - 2.056	0.058 - 0.091	0.000685 - 0.001499	0.001037 - 0.002999	3
0.027 - 0.047	0.774 - 5.870	0.014 - 0.025	2.056 - 3.787	0.091 - 0.164	0.001500 - 0.003509	0.003000 - 0.006708	4
0.047 - 0.093	5.870 - 9.659	0.025 - 0.053	3.787 - 5.882	0.164 - 0.274	0.003510 - 0.007606	0.006709 - 0.018093	5

Source: the authors (2025).

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Finally, the IAEA was calculated by combining all the weights and metrics adopted in each class. With the average values, it was possible to draw up the final map showing anthropization due to the presence of anthropic elements in each landscape region.

Classification and normalization of environmental status

Based on the attributes that make up the landscape, it is possible to analyze its environmental status by assessing its geoecological conditions, as well as identifying its degree of alteration and associated problems (Chart 1).

Chart 1 – Description of the classes assigned to environmental states.

Class	Description	Normalization
Stable	The landscape retains its original structure. Natural ecological processes. Little anthropogenic influence. No significant environmental problems	0 toa 0.2
Unstable	Few changes to the original structure. Geosystem maintains integrity. Some environmental problems, but of mild or moderate intensity	0.2 to 3
Critical	Major changes to the original structure. Alteration in geoecological functions. Overexploitation and falling productivity	0.3 to 0.5
Very critical	Loss of spatial structure. Human impact exceeds the capacity of the geosystem. Intense environmental problems	0.5 to 1

Source: adapted from Glazovskiy et al. (1998) and Rodriguez & Martinez (1999).

A stable landscape, i.e. one without degradation, retains its original structure and indicates that there are no significant environmental problems in natural geoecological processes. Therefore, anthropogenic interference is insufficient to unbalance this landscape.

An unstable landscape, i.e. one with low degradation, has little change to its original structure. Mild and moderate interference can occur which does not directly impact on the conservation of the geoecological system, i.e. it has low anthropogenic interference.

The critical landscape, on the other hand, has medium degradation and corresponds to a partial loss of the structure and function of the geoecological system. These landscapes face a serious environmental problem, as human interference compromises the dynamic balance of the system, resulting in negative impacts. Actions are needed in these landscapes to mitigate environmental impacts and recover the natural potential of the geosystems present.

Landscapes in a very critical environmental state are highly degraded, corresponding to the loss of their geoecological functions. These environmental systems are subject to high levels of anthropogenic interference and present major environmental problems. In this sense, the geosystems present in these landscapes need urgent intervention to return them to their environmental potential. However, the loss of these ecosystem

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services can have a major social, economic and cultural impact on the population in their immediate surroundings. This is not the case with *wetland* landscapes in the state of Rio de Janeiro.

In this sense, it is possible to analyze the environmental status of *wetlands* in the state of Rio de Janeiro, observing the existence of swampy regions in three different states, ranging from stable (low degradation) to unstable (medium degradation) and critical (high degradation). To make it possible to compare different variables with different scales and units, a statistical data normalization process was adopted. We opted for proportional linear scaling, in which each weight assigned to the thematic classes (Anthropization Index by Presence of Anthropic Elements, Deforestation Index, Straight Channels Index and Anthropic Transformation Index) was divided by the total sum of the weights.

This normalization procedure was adopted to ensure that the amplitude of the data was contained within a range between 0 and 1, preserving the fraction of importance of each class in the composition of the final index (Table 2). In this way, the normalized value represents the weighted weight of each indicator, making it easier to integrate variables of different natures without the distortion caused by different orders of magnitude.

Table 2 – Classification of indexes, according to the normalization assigned to the classes.

INDEX	THEMATIC CLASSES	WEIGHTS	NORMALIZATION
Deforestation	**Class**	**Weight**	**Normalization**
1 to 0	High	30	0.11
0 to -1	Low	0	0.00
Straight channels	**Class**	**Weight**	**Normalization**
0.5 to 0.85	High	40	0.15
0.25 to 0.5	Medium	30	0.11
0 to 0.25	Low	10	0.04
ITA	**Classification**	**Weight**	**Normalization**
5 to 7.5	High	30	0.11
2.5 to 5	Medium	20	0.07
0 to 2.5	Low	10	0.04
IAEA	**Class**	**Weight**	**Normalization**
4 to 5	Very High	40	0.15
3 to 4	High	30	0.11
2 to 3	Medium	20	0.07
1 to 2	Low	10	0.04
TOTAL		270	1.00

Source: the authors (2025).

It should be noted that the indexes for straight channels and anthropogenic elements were given the highest weights, given that these classes represent more direct impacts on *wetland* health.

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III. RESULTS AND DISCUSSION

Deforestation indicator (ID)

Analysis of the ID allowed us to identify the landscape regions impacted by deforestation between 1989 and 2023 (Figure 3). The results reveal a gradient where negative values indicate stabilization or regeneration, while positive values (0 to 1) point to the continued suppression of native vegetation.

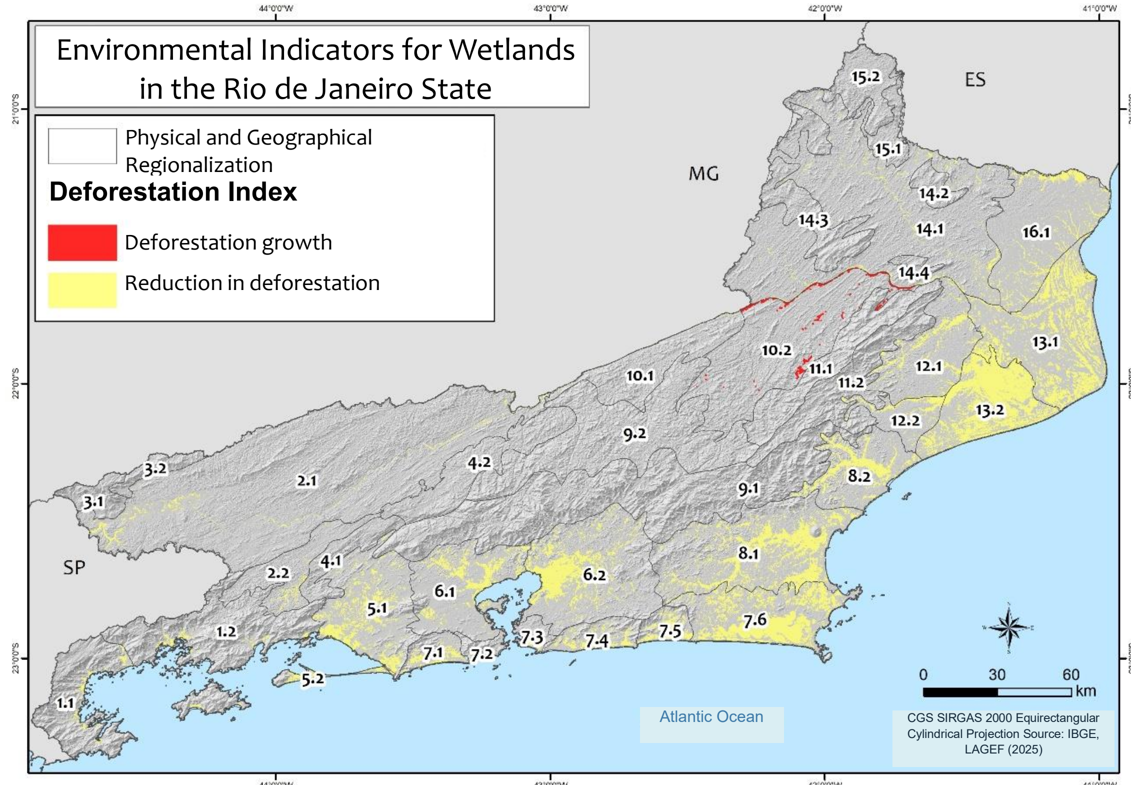

Figure 3 – Mapping of the deforestation indicator by *wetlands* region (Source: the authors, 2025).

The regions with negative values have seen a reduction in deforestation, since there has been no new deforestation since 1989. It should be noted that these areas are located in agricultural areas, or had increasing deforestation before the years analyzed, and stabilized between 1989 and 2023. Regions with growing deforestation, on the other hand, are represented by areas that obtained positive values, between 0 and 1, and show a growing demand for deforestation, closely associated with the process of agricultural expansion. This pattern can be analyzed in the region of the swamps and floodplains of the Interplanaltic depressions[3], which are increasingly deforested for agricultural production.

[3] It should be remembered that the term depression was redefined by the Brazilian Relief Classification System (CEN/SBCR, 2022) as a lowered surface, at the first taxonomic level (SALES; SANTOS; BOTELHO, 2025).

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It is possible to analyze, through comparisons between the land use and land cover map of MapBiomas and the deforestation index mapping, that the landscape regions most affected by deforestation are areas that were occupied by pastureland, or that were occupied through the process of urbanization. The areas that have seen a reduction in deforestation are occupied by temporary crops, forestry or *wetlands* and coastal lagoons. This can be explained by the fact that these areas had already suffered a great deal of deforestation in previous decades, or because they are still conserved.

The persistence of positive ID values in the North Eastern of Rio de Janeiro and on the lowered surfaces corroborates the global trend described by Davidson (2014), who identifies *wetlands* as the ecosystems most vulnerable to land use conversion in the 21st century. Wetlands in the interior of Eastern Rio de Janeiro face vegetation suppression that is often underestimated compared to forest clearing, a pattern also observed in multi-temporal monitoring studies by Baquero et al. (2025) and Ghobadi et al. (2012).

Anthropogenic transformation indicator (ITA)

The ITA revealed the heterogeneity of anthropogenic pressure on Eastern Rio de Janeiro's marshy landscapes (Figure 4). The predominance of high transformation classes (5 to 7.5) in a large part of the study area shows the advanced stage of land use conversion, corroborating the proposal by Mitsch and Gosselink (2015) on the vulnerability of wetlands inserted in dense anthropic areas. According to the authors, altering the surroundings compromises the self-regulation of *wetlands*, which lose their resilience and ability to provide essential ecosystem services, such as filtering pollutants and regulating water.

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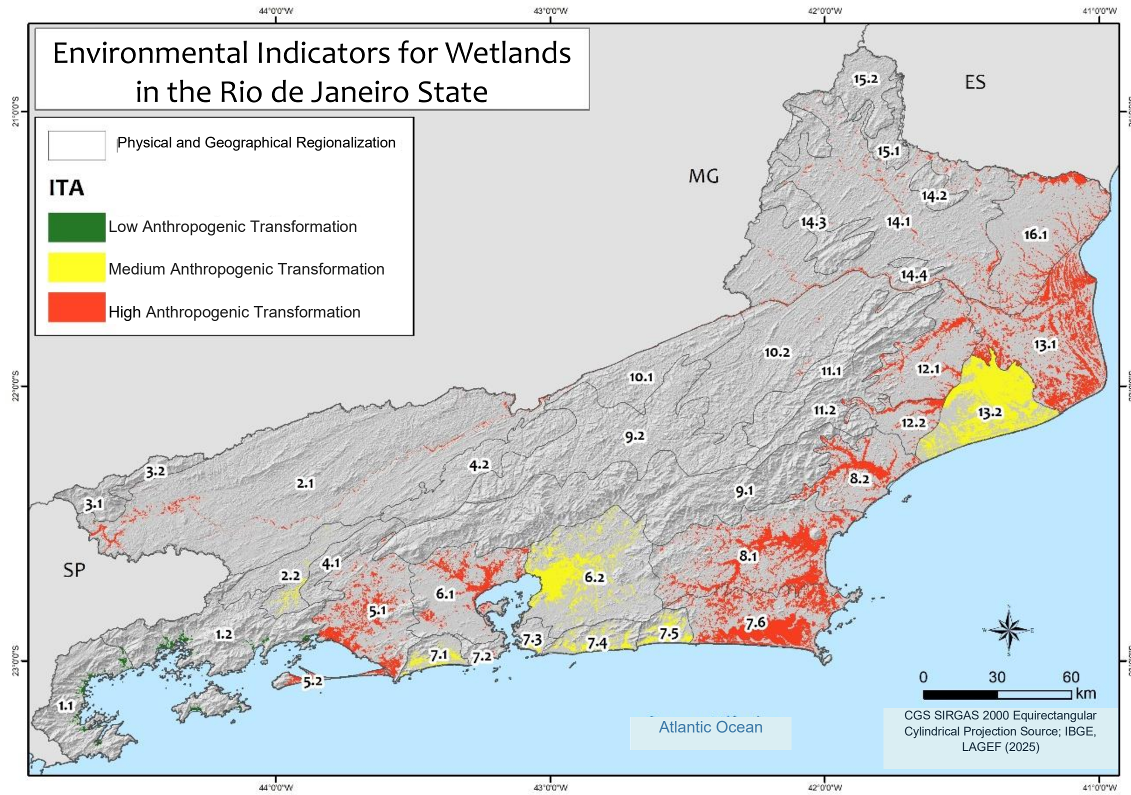

Figure 4 – Mapping of the Anthropogenic Transformation Indicator (ITA) by *wetland* region (Source: the authors, 2025).

It can be seen that the *wetlands* with low anthropogenic transformation are specifically located in the mangrove regions of Paraty, Angra and Mangaratiba. This is justified by the large forested areas found in the aforementioned regions. The regions with medium anthropogenic transformation are concentrated in the central axis of the state, in areas where there are growing urban occupations.

While the regions of high anthropogenic transformation are concentrated in the vast majority of the study area, specifically in the context of the North Eastern of Rio de Janeiro, where large fragments of wetlands are concentrated. This is in addition to other regions such as the Lagos-São João area, which is dominated by lake and floodplain *wetlands*, where there are significant amounts of urban areas. Other areas located in mangrove regions, further to the west of the state, were also classified as having high levels of anthropogenic transformation, given the urban context in which they are located. These observations suggest that these *wetland* regions are under great anthropogenic pressure, which tends to degrade the environmental systems of these objects. It should also be noted that no regions with very high anthropogenic transformations were identified in the study area.

The concentration of high anthropogenic transformation classes in the Metropolitan Region and the east-north axis of the state reflects what Mitsch and Gosselink (2015) define as the paradox of urban wetlands.

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Although protected by specific laws, changes in land use in the surrounding area compromise the hydrological functions and resilience of these systems. This high anthropogenic pressure, validated by data from MapBiomas (2024), indicates that the health of Eastern Rio de Janeiro's *wetlands* is directly conditioned by the density of occupation of the lowlands, where the replacement of natural cover with impermeable surfaces accelerates the environmental stress of these geosystems.

Straight channel indicator (ICR)

The ICR was classified into three levels, considering the proportion of artificial channels in the landscape: low (0 to 0.25), medium (0.25 to 0.5) and high (0.5 to 0.85), reflecting the degree of alteration to the natural drainage network. The mapping revealed a significant distribution of rectilinear channels, with a notable concentration in areas of agriculture, livestock and urbanization (Figure 5). Historically, the straightening of canals in the state of Rio de Janeiro, especially in the lowlands, was driven by public sanitation policies during the 20th century. As Goes (1934) points out, the elimination of meanders and swampy areas were seen as measures to control the fevers plaguing Eastern territory, as well as to optimize the productive integration of Eastern Rio de Janeiro's territory.

In agricultural and livestock areas, the practice of straightening channels in these regions is commonly adopted to make the land more practical and efficient for grazing, cattle breeding, crop management and irrigation. The linearity of the channels prevents the natural shape of the rivers from interfering with cultivation operations and minimizes the loss of pastures, thus improving productivity and land management. The presence of rectilinear canals in urban areas was also identified, such as in coastal towns that are close to the mouths of these bodies of water, such as lagoons and rivers. For the most part, the purpose of canalization is to facilitate the construction of roads, commercial and residential areas, maximizing land use.

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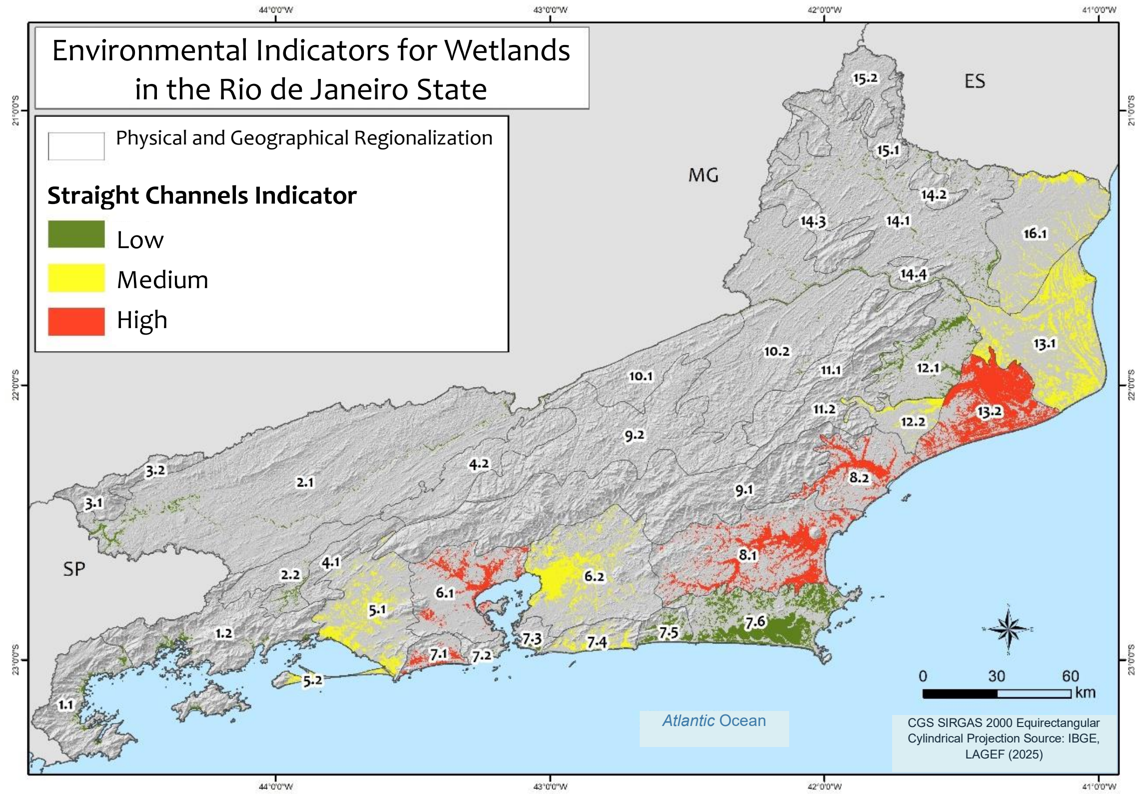

Figure 5 – Mapping of the River Channel Transformation Indicator by *wetland* region (Source: the authors, 2025).

The ICR showed critical levels (0.5 to 0.85) in the São João-Macaé axis, Macaé and the Metropolitan Region. The artificialization of drainage for agricultural purposes, as discussed by Junk et al. (2014), alters the flood pulse of *wetlands*, de-characterizing the water regime necessary for the maintenance of local biodiversity. In urban areas, channelization also ignores the flood buffering function of wetlands. In addition, channelization to enable farming and urban expansion not only accelerates surface runoff, but also disconnects rivers from their natural floodplains. As demonstrated by Grill et al. (2019) on a global scale, this fragmentation of the hydrographic network is one of the main drivers of biodiversity loss and water regulation services in tropical wetlands.

In the context of Rio de Janeiro, the fragmentation of the hydrographic network by rectifications is one of the main vectors of loss of water regulation services in wetlands.It exacerbates the risks of downstream flooding by accelerating the basin's time of concentration.

Anthropization indicator by presence of anthropic elements (IAEA)

The spatial distribution of IAEA in Eastern Rio de Janeiro reveals that the most severe pressures are concentrated in the lowlands to the west of Baía de Guanabara, driven by the densification of industries, ports,

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airports and energy infrastructure networks (Figure 6). This sector, together with the mangroves of Sepetiba Bay and the floodplains of Macaé, presents a scenario of cumulative impacts that characterizes these areas as technogenic landscapes, where anthropogenic modification overrides the natural regeneration capacity of ecosystems (Figure 6).

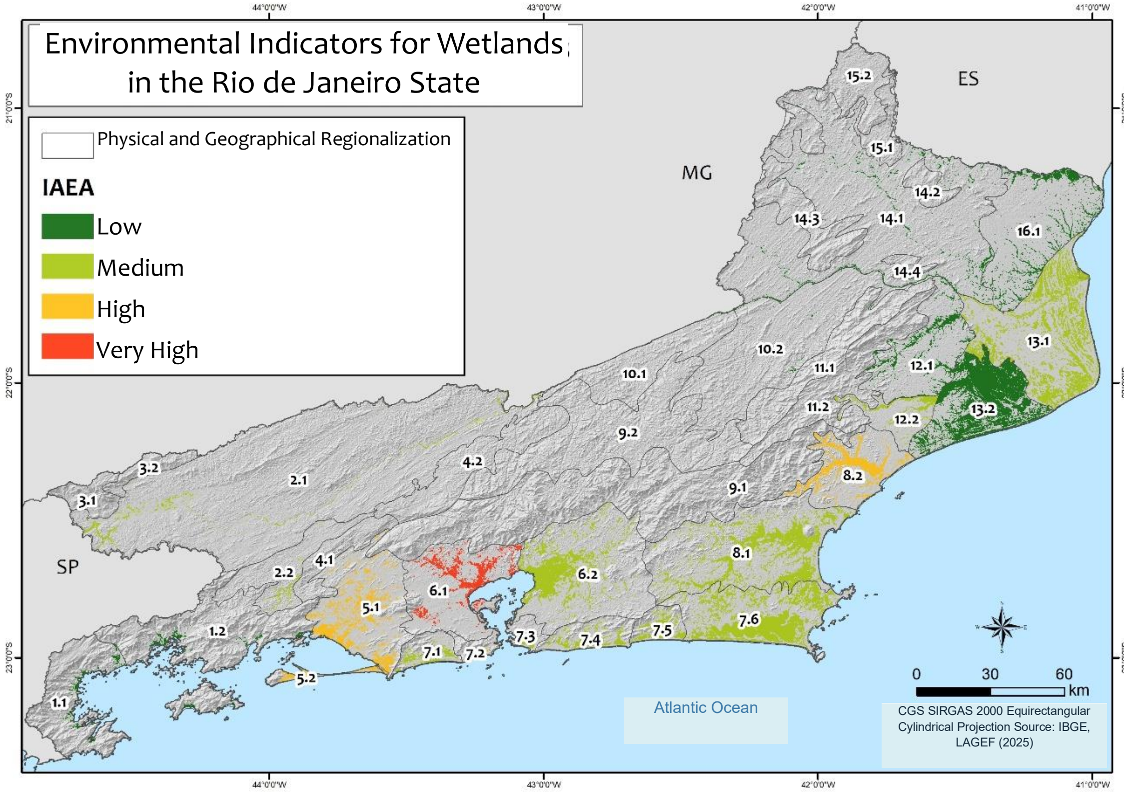

Figure 6 – Mapping of the anthropization indicator for the presence of anthropic elements (IAEA) by *wetland* region (Source: the authors, 2025).

The IAEA's spatial distribution reveals that the regions with the highest concentration of anthropogenic elements coincide with the state's historical and economic pressure centers. In Guanabara and Sepetiba Bays, this density of infrastructure (ports, airports and industries, transmission lines) characterizes technogenic landscapes where cumulative impacts override natural resilience. In this context, the degradation of the remaining mangroves and the loss of ecosystem services, as observed in Lagoa Rodrigo de Freitas and in the Sepetiba and Macaé port complexes, are reflections of anthropogenic pressure on these environments, processes that have been widely analyzed and discussed by Soares (1999) and Oliveira et al. (2019).

On a different scale of impact, Eastern Rio de Janeiro's lake plains have average levels of IAEA. In these areas, the pressure on *wetlands* is not only due to large industrial and urban centers, but also to the capillarity of highways, pipelines and mining activities that disrupt the connectivity of the landscape. This succession of impacts, ranging from fragmentation by linear infrastructures to urban saturation, is echoed in the spatial model

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by Halpern et al. (2008), which shows that no marine or coastal area is immune to human influence, and that the overlapping of multiple stressors increases environmental degradation. This degradation brings Eastern Rio de Janeiro's wetlands closer to the stage of 'functional extinction', in which the loss of ecosystem services severely compromises systemic integrity (Tockner; Stanford, 2002).

Classification of the environmental status of *wetlands*

By normalizing the indexes, it was possible to map the environmental status of the landscape regions in which the wetlands are located. Mitsch and Gosselink (2015) point out that indicators provide parameters for the resilience of the *weltland* system in general, reflecting its ability to sustain biodiversity and regulate water flows. Therefore, such data can contribute to the formulation of public policies promoting better environmental management for the most affected *wetland* regions. From the spatial distribution of the data (Figure 7[4]), it can be seen that stable landscapes can only be found in the Costa Verde region of the state, given the low presence of anthropogenic pressures in the regions where the *wetlands* are located. Despite being stable, these landscapes need to be secured and maintained in projects and inspection plans by environmental agencies, in order to ensure the ecosystem services provided in this region.

[4] Vector data and mapping PDF available at: https://github.com/evelyncastrogeo/wetlands/

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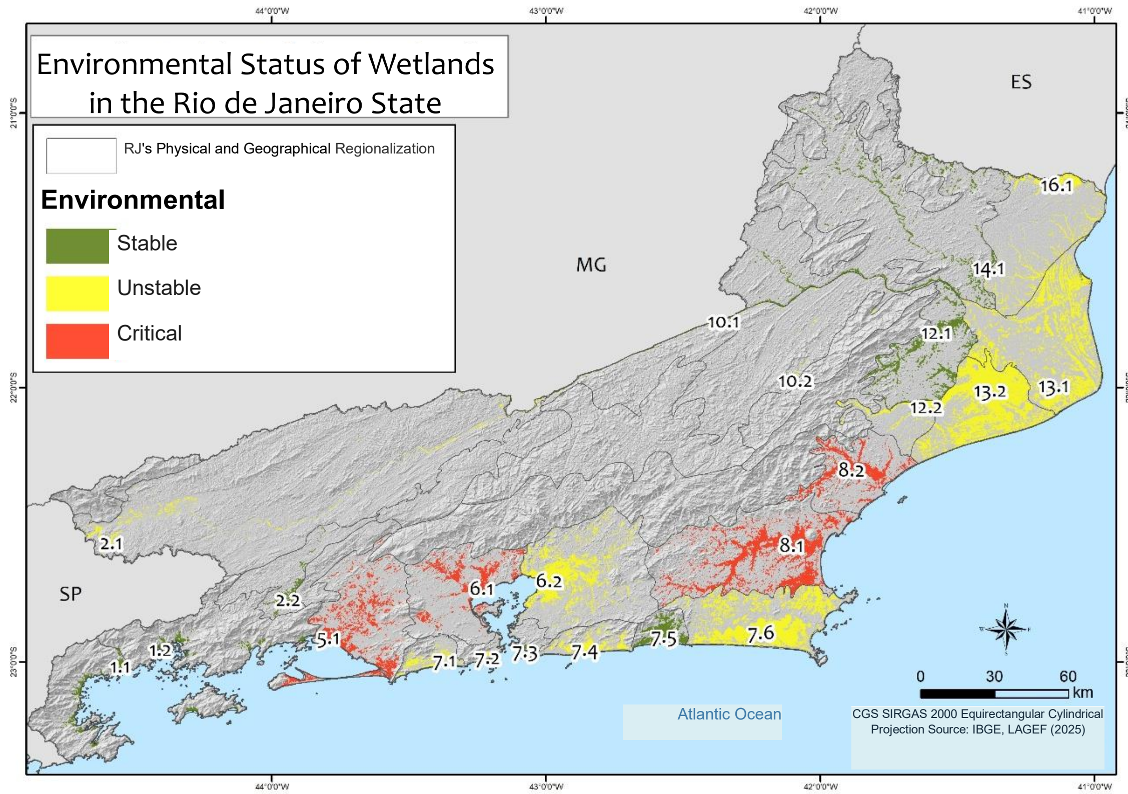

Figure 7 – Mapping of the environmental status of *wetlands* in the state of Rio de Janeiro (Source: the authors, 2025).

Although the Costa Verde *wetlands* have been classified as environmentally stable, they are highly vulnerable due to the small size and high fragmentation of *wetlands*, which makes them more susceptible to degradation, even in the absence of significant anthropogenic pressures, as shown by the indicators adopted in this research.

It is also possible to observe that a large part of the state's *wetlands* are in an unstable environmental state, i.e. medium degradation, due to the strong anthropogenic interference in these regions, where lake landscapes, swamps and mangroves are located. These regions stretch from the east to the north of the state and are found in landscapes that have been retilinized for urban occupation and agricultural production, as well as suffering constant pollution due to the dumping of sewage in their areas.

However, the worst environmental status, classified as critical, is found in areas of great urban and anthropogenic influence, transforming the natural character of these landscapes and incisively degrading these environments. The Mangroves and Swamps of the West of Baía Guanabara are in critical condition, followed by the Mangroves and Floodplains and Swamps of Macaé, as well as the Mangroves and Apicuns of Baía de Sepetiba and the Mangroves and Swamps of São João. These regions are subject to strong urban, port and agricultural pressures.

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In general, the *wetlands* present in Eastern Rio de Janeiro's landscapes are in constant degradation and suffer from constant anthropogenic interventions that disturb the health and dynamic balance of these landscapes. Therefore, these landscapes should be included in environmental recovery projects, given that their systems are overloaded and the ecosystem services provided by these geosystems are suffering significant losses and tending to be depleted.

Spatial correlation with Conservation Units

In addition to analyzing the environmental status of these landscapes, it is possible to correlate them with the spatial distribution of the conservation units (CU) created by the state (State Environmental Institute - Inea) and federal (Instituto Chico Mendes de Conservação da Biodiversidade ICMBio), located in Eastern Rio de Janeiro (Figure 8). By comparing these locations, it is possible to understand that the stable *wetlands* are located within the boundaries of the UCs, which corroborates their classification as stable. The *wetlands* classified as unstable, on the other hand, are outside the boundaries of the Conservation Units, which may indicate the need to create new conservation units in the state to protect the remaining *wetlands* in the state of Rio de Janeiro.

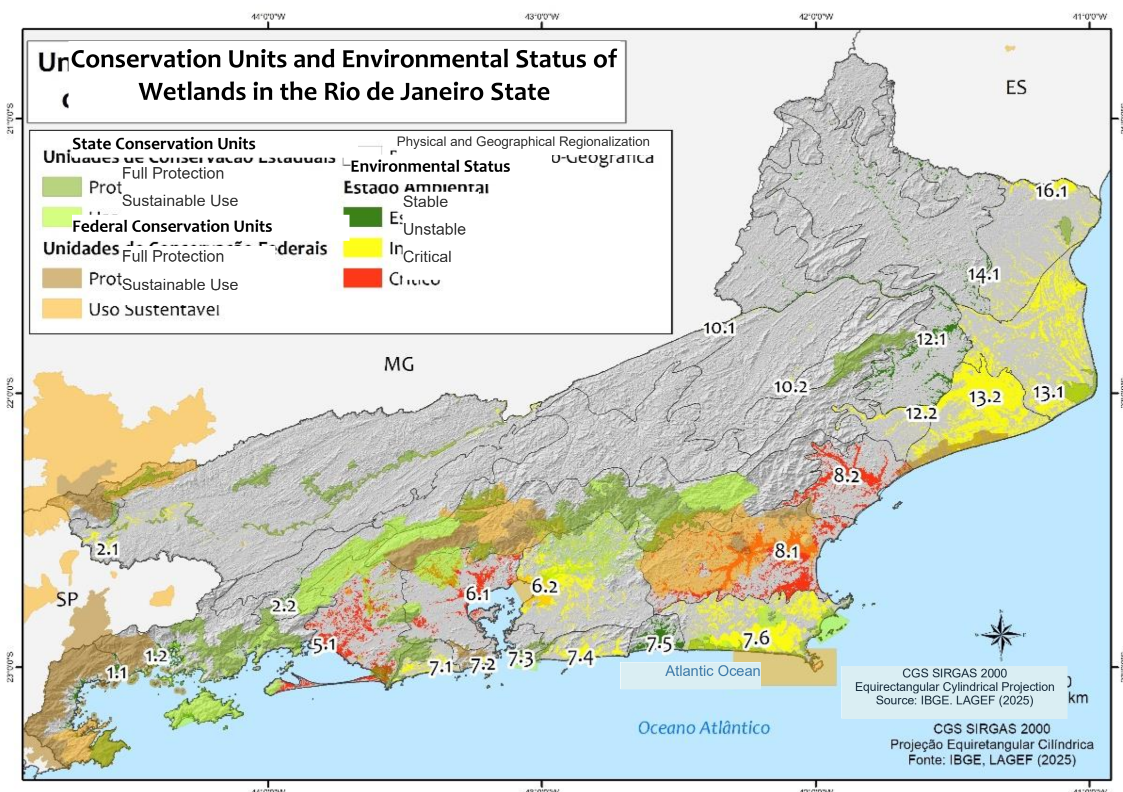

Figure 8 – Distribuição espacial das unidades de conservação e do estado ambiental dos *wetlands* do Estado do Rio de Janeiro (Source: the authors, 2025).

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It is estimated that the most compromised *wetlands* in the state of Rio de Janeiro today are those located in the metropolitan region and suffering from constant anthropogenic pressures. As well as *wetlands* in areas of strong urban growth, tourism and economic activities, located in the eastern and northern regions of Eastern Rio de Janeiro.

It should be noted that another demand that should be observed for the creation of UCs refers to the physical dimensions and connectivity of the existing *wetlands* in North Eastern Rio de Janeiro, which are currently outside the boundaries of state and federal conservation units, and deserve attention in view of their significant size. These areas deserve to be incorporated into emergency protection measures, given their significant contribution to society through ecosystem services.

Attention should be drawn to the Wetlands of the Tabuleiros da Lagoa Feia and the Lacustrine and Deltaic Floodplains of Lagoa Feia, in view of the size and continuity of the *wetlands* in these regions. These *wetlands* are currently partially protected by the Parque Nacional da Restinga de Juruobatiba, and should be better included in environmental preservation projects, given that this region suffers from constant agricultural and livestock activities that jeopardize the ecosystem support services that these environments provide to society.

In the region of the São João Mangroves and swamps, it should be noted that these *wetlands* are partially protected by the APA of the São João/Mico-Leão-Dourado River Basin and the stretches that are also to the south of the conservation unit deserve better protection. In view of the various river drainage channelization works, these *wetlands* are heavily compromised and deserve attention given their potential role in flood control.

The mangroves and swamps of western Baía de Guanabara are in critical condition and are outside the boundaries of federal and state protected areas, and deserve to be highlighted in view of their significant contribution to flood control in the lower Eastern Rio de Janeiro region. These *wetlands* are in critical condition and should be included in public environmental management action plans.

The mangroves and apicuns of the Baía de Sepetiba region are also in a critical state and suffer from constant anthropogenic pressure due to the port and economic activities carried out in the region. There are many artificial *wetlands* in the area, created from the excessive exploitation of sand. These areas must be properly managed so that the water table is not compromised. In addition, there are important fragments of mangroves in this region, which should be included in the proper management of the region's *wetlands*.

Another critical region, with no conservation units to protect its floodplains and swamps, is located in the Macaé Region. This area has *wetlands* in critical condition that should be included in public environmental

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management plans. Creating urgent measures could help reduce the coastal impacts that the region often suffers.

The analysis of the environmental status of *wetlands* in Eastern shows that, although UCs play a fundamental role in maintaining geoecological stability, legal protection alone does not guarantee the full integrity of these ecosystems. Global studies indicate that *wetlands* located in protected areas remain vulnerable to transboundary anthropogenic pressures and extreme climate events, which often exceed local management capacity (Reis et al., 2017).

Analysis of the spatial distribution of PAs in relation to the environmental status of Eastern wetlands reveals that legal protection, although fundamental, is not an absolute guarantee of systemic integrity. In this sense, the effectiveness of UCs in preserving wetlands has been widely discussed from the perspective of remote sensing monitoring, suggesting that fragmentation and loss of ecological functions can persist even under protection regimes. Global studies indicate that more than half of internationally important sites are severely affected by multiple impact drivers, with agriculture, pollution and the modification of natural systems being the main culprits in the suppression of river and lake wetlands (Xu et al., 2019).

In the context of Rio de Janeiro, the fragility of these geosystems is aggravated by the fact that ecological restoration rarely recovers the original integrity of already degraded areas. As demonstrated by Moreno-Mateos et al. (2012) in a global meta-analysis, even after decades of intervention, the biogeochemical functioning and biological structure of restored wetlands remain, on average, 23% to 26% below reference levels. Therefore, the critical state identified in several *wetlands* in the state reinforces that isolated protection is insufficient if there is no strict control over the occupation of adjacent areas.

IV. CONCLUSIONS

The typology and regionalization of Eastern wetlands made it possible to diagnose the integrity of these geosystems in the face of anthropic pressures, validating the methodology of physical-geographical indicators for the analysis of the current environmental state. The most degraded *wetlands* are located in and around the metropolitan region, specifically in the hydrographic regions of Baía de Guanabara, Macaé and Ostras, Lagos-São João and Baía de Guaratiba. The critical state of these regions is justified by the urban concentration, as well as the development of large-scale economic activities, such as tourism, oil and industrial activities and farming and cattle raising, predominantly.

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Although there are *wetlands* classified as stable, they all show some degree of degradation, as they have been disturbed and/or modified over the last few decades. Immediate intervention is therefore proposed to mitigate unstable areas and preserve stable remnants. The model adopted proved to be robust given the availability of data, although the inclusion of biotic and physical-chemical indicators could deepen analysis at more detailed scales.

As a follow-up to this research, we suggest analyzing the functional connectivity between these fragments in order to form ecological corridors, as well as the economic quantification of the ecosystem services provided by the different types of *wetlands.* In times of climate change, the importance of wetland landscapes becomes even more evident, both for their ability to regulate the hydrological cycle and for their role in sequestering and storing carbon. In short, the environmental characterization presented here provides the necessary technical basis for decision-making and safeguarding these essential services in the face of future climate scenarios.

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