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Research Article

Hydrogeomorphological compartmentalization in coastal wetlands - Lagoa do Peixe National Park, Brazil

Compartimentação Hidrogeomorfológica em Áreas Úmidas Costeiras – Parque Nacional da Lagoa do Peixe, Brazil .

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Abstract: Coastal wetlands play crucial roles in environmental processes due to their hydrogeomorphological characteristics. Despite their recognized significance, hydrogeomorphological analyses in these ecosystems remain relatively unexplored. The aim of this study was to establish hydrogeomorphic compartments in the wetlands of Lagoa do Peixe National Park (PNLP). The methods used were: (i) geomorphological compartmentalization (topographic variation using FABDEM); (ii) definition of landscape indicators (Sentinel-2 NDVI, soil samples); (iii) analysis of hydrodynamic. The FABDEM model effectively identifies altimetric variations and compartment boundaries, including those in the northern and southern sectors of PNLP, the Paleocliff of Barrier III, the eolic dunes of Barrier IV, and the interdunal wetlands. Hydrodynamics depend on precipitation, with a greater apparent water level during El Niño periods. Additionally, we analyze NDVI variations within these geomorphological compartments during La Niña, Neutral, and El Niño events, observing distinct spatial patterns between Lagoon Terrace II the Lagoa do Peixe site. Pedoenvironmental indicators reveal common pH levels across compartments, with sulfur concentrations specifically observed in Lagoon Terraces (salt marshes). Furthermore, the a, a′-dipyridyl dye indicated the presence of reduced iron characteristic of hydromorphic soils. Water variation is dependent on precipitation, with a larger apparent water surface during Neutral and El Niño events. In total, we establish nine hydrogeomorphological compartments: Eolic Dunes, Lagoon Fringe, Lacustrine Fringe, Lacustrine, Lagoon-Estuarine, Lacustrine Terrace, Lagoon Terrace, Depression, and Slope.

Keywords: FABDEM; Pedoenvironmental indicators; Marsches; Coastal Lagoon; Hydromorphic Soils.

Resumo: Áreas úmidas costeiras são sistemas hidrogeomorfológicos com importantes funções ambientais. Apesar da sua declarada importância, análises hidrogeomorfológicas nestes ambientes ainda são pouco exploradas. O objetivo deste estudo foi estabelecer compartimentos hidrogeomorfológicos nas áreas úmidas do Parque Nacional da Lagoa do Peixe (PNLP). Os métodos foram: (i) compartimentação geomorfológica (variação topográfica do FABDEM); (ii) definição de indicadores da paisagem (NDVI Sentinel-2, amostras de solo); (iii) análise da dinâmica hídrica. O modelo FABDEM foi eficiente para definir variações altimétricas e limites nos compartimentos geomorfológicos, nos setores norte e sul do PNLP, a Paleofalésia da Barreira III e Dunas eólicas da Barreira IV e as áreas úmidas interdunas. A dinâmica hídrica é dependente da precipitação, com maior lâmina de água aparente em períodos de El Niño. O NDVI nos compartimentos geomorfológicos mostrou diferenças relacionadas aos eventos La Niña e El Niño, com padrões espaciais distinto no Terraço Lagunar II, sítio da lagoa do Peixe. Os indicadores pedoambientais mostram o pH como elemento comum entre os compartimentos, e maiores concentrações de enxofre nos Terraços Lagunares (marismas). O corante a,a'-dipiridil indicou presença de ferro reduzido, característico de solos hidromórficos. Foram estabelecidos nove compartimentos hidrogeomorfológicos: Dunas eólicas, Franja Lagunar, Franja Lacustre, Lacustre, Lagunar-estuarino, Terraço Lacustre, Terraço Lagunar, Depressão e Encosta.

Palavras-chave: FABDEM; Indicadores Pedoambientais; Banhados; Lagoas Costeiras; Solos Hidromórficos.

1. Introduction

Wetlands can be configured as hydrogeomorphological systems saturated with water over the long term (BROOKS et al., 2012; GOMES; MAGALHÃES JÚNIOR, 2017). According to Brinson (1993), hydrogeomorphological classification is the starting point for functional assessments and the determination of environmental impacts.

The hydric dynamics, geomorphological aspects, and vegetation interact with each other and define their formation, characteristics, and functionalities (BRINSON, 1993, 2009; ABLAT et al., 2021). These components are key to hydrogeomorphological interpretation (MONTANÉ et al., 2016). There are a wide variety of characteristics of the hydrological regime related to frequency, duration, magnitude, location, and sources of water supply, which exert a dominant influence on the development of hydromorphic soils and/or adapted vegetation (NRC, 1995; MITSCH; GOSSELINK, 2015; GOMES, 2017).

Hydrogeomorphological approaches in the study of wetlands have been evaluated in Semeniuk (1987), Semeniuk and Semeniuk (1995; 2011), Brinson (1993; 1998; 2009), and Smith et al. (1995). Wetlands have been investigated in the context of hydrogeomorphology in Bahia (SOARES; LANDIM DOMINGUEZ, 2012); in Minas Gerais (GOMES, 2017, 2023; OLIVEIRA, 2021; GUIMARÃES, 2023); in the Chapada do Araripe between the states of Ceará, Pernambuco, and Piauí (SILVA; SOUZA; GUERRA, 2024); and in Rio Grande do Norte (SILVA; COSTA, 2022). On the international scene, investigations have been conducted in China (ASLAM et al., 2003; SINGH; SINHA, 2021; ZHOU et al., 2023), in France (MONTENÉ, 2014; MONTENÉ et al., 2016), and in the United States (BACKHAUS, 2022; HE et al., 2023). This approach has also been adopted in national inventories, such as in Western Australia (SEMENIUK; SEMENIUK, 1995; 2011), South Africa (OLLIS et al., 2013), Colombia (RICAURTE et al., 2019), and Argentina (MALVÁREZ; BÓ, 2004).

The fluctuation of hydrological levels is an important characteristic of wetlands. However, changes in climatic and hydrological patterns, common during El Niño and La Niña episodes (ILYAS et al., 2019), can cause water stress either directly or indirectly, whether through flooding or droughts (HARRISON et al., 2018;

COUROUBLE et al., 2021; XI et al., 2021). Extreme hydrological variations can lead to modifications in biogeochemical cycles, impacting the functions of wetlands. In this sense, characterizing wetlands through hydrogeomorphological criteria allows for an understanding of the health conditions of these ecosystems (SINGH; SINHA, 2021).

Remote sensing and geoprocessing are essential tools in the investigation, mapping, and classification of wetlands, as recommended by the Ramsar Convention (ARTIGAS; YANG, 2006; LOWRY et al., 2007; KLEMAS, 2008; DVORETT; DAVIS; PAPES, 2016; CUNHA-SANTINO et al., 2023). The radiometric, spectral, and temporal resolutions of Landsat and Sentinel satellite series (SHARPE; KNEIPP; FORGET, 2016; KAPLAN; AVDAN, 2017; MOHSENI et al., 2023), as well as Digital Elevation Models (DEMs), are among the remote sensing data frequently used in hydrogeomorphological investigations (HAWKER et al., 2022; DUSSEAU; ZOBEL; SCHWALM, 2023; BIELSKI et al., 2024).

Coastal and inland wetlands are characterized by the permanent or temporary obstruction of drainage, which creates environments adapted to high humidity conditions for most of the year (MITSCH; GOSSELINK, 2015). The ecosystem services provided by wetlands include habitat and food for wildlife (WANG et al., 2020), climate regulation, carbon retention (MITSCH; GOSSELINK, 2015), coastal protection, and the support of cultural practices (WITTMANN et al., 2015). The environmental values of the services provided by wetlands depend on their location (MITSCH; GOSSELINK, 2000), where the dominant hydrological and geomorphological characteristics define the spatial unit recognized as a hydrogeomorphological compartment (BRINSON, 1993; SMITH et al., 1995; BRINSON et al., 1998). According to Bisson and Lehr (2004), Babar (2005), and Alves (2020), riparian zones, slopes, fluvial systems, lacustrine systems, lagoon systems, and the various typologies of wetlands are the focus of hydrogeomorphological studies.

The Lagoa do Peixe National Park (PNLP) is located in the Coastal Plain, in low-elevation lands relative to sea level. The Lagoa do Peixe, a geomorphological feature of the lagoon type, with fresh to brackish water, has a direct and seasonal connection to the Atlantic Ocean and exhibits a strong tendency toward morphological segmentation due to wind action (SCHÄFER et al., 2013). The variability and mobility of the environment over short periods, due to weather conditions and the accelerated modification of the landscape by wind action, are striking characteristics of the region (TAGLIANI et al., 1992).

Due to its environmental significance, this region has been the subject of studies predominantly in the fields of biology (ROLON; ROCHA; MALTCHIK, 2011; COSTA, 2015; GARCIA et al., 2017), as well as coastal geology, geomorphology, and climatology (AREJANO, 2006; SBRUZZI; FONSECA; SALDANHA, 2015; SCHOSSLER, 2011, 2016; MANZOLLI et al., 2023). However, despite the stated importance of the wetland ecosystems of PNLP and their vulnerability to climate and environmental changes, there is a lack of inventories and mapping that provide information on the extent, conservation status, or types of wetlands, as well as monitoring plans for the medium to long term. Thus, the development of approaches capable of meeting the conservation demands of wetlands is highlighted as essential.

The application of the hydrogeomorphological approach in coastal wetlands is still underexplored. This is due to a set of factors: investigations focused on biological or ecological perspectives, challenges in delimiting compartments in areas of very flat morphology, and the emerging role of hydrogeomorphology in coastal studies. Hydrogeomorphological compartmentalization of wetlands allows for a more detailed analysis of these ecosystems, enabling the identification of local characteristics that affect ecology, hydric dynamics, and susceptibility to extreme events. This not only enhances the understanding of the functionality and health of ecosystems but also aids in the formulation of more effective conservation strategies tailored to the specific conditions of each compartment. In this context, given the challenges in defining hydrogeomorphological compartments in coastal wetlands and the need for more studies on this topic, this work aims to establish hydrogeomorphological compartmentalization in the Lagoa do Peixe National Park, located in the Coastal Plain of the state of Rio Grande do Sul, Brazil.

2. Study Area

The Lagoa do Peixe National Park (Figure 1) is located in the municipalities of Mostardas and Tavares, in the middle segment of the Coastal Plain of Rio Grande do Sul (PCRS), between the Lagoa dos Patos and the Atlantic Ocean. It is a Conservation Unit of full protection, established by the Federal Government in 1986 to preserve environments of ecological significance and scenic beauty. In 1993, it was recognized as a Ramsar Site

(Wetland of International Importance) for its importance in the conservation of wetlands, coastal ecosystems, and habitat for migratory birds. In 1999, it became part of the Atlantic Forest Biosphere Reserve and is currently part of the Hemispheric Network of Reserves for Shorebirds.

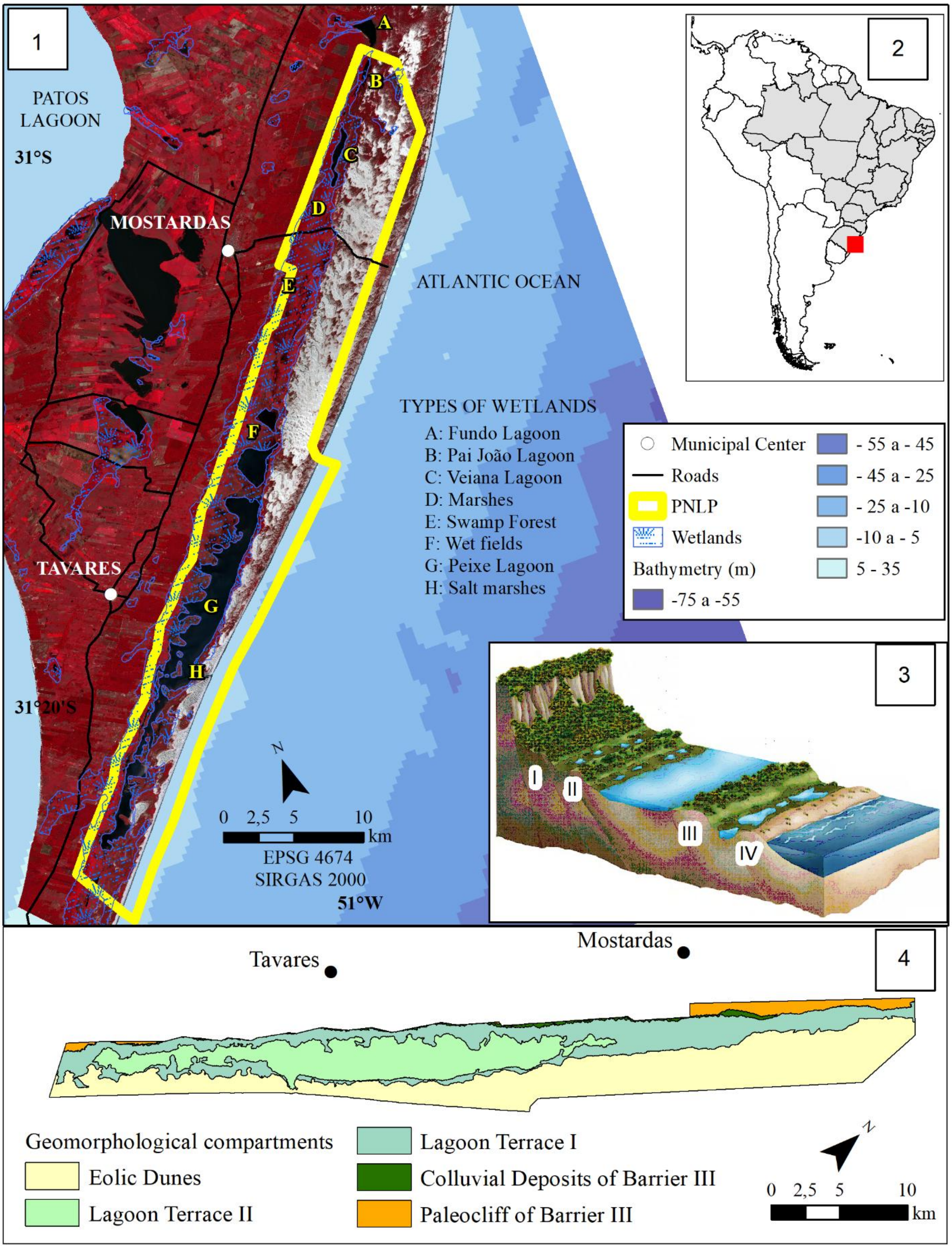


Figura 1. (A) e (B) Location of the Lagoa do Peixe National Park and Typologies of Wetlands; (C) Geological Model of Formation of the Barrier-Lagoon System; (D) Geomorphological Compartments. Sources: Colored Composition R8G4B3 Sentinel 2; Arejano (2006); Schäfer, Lanzer e Scur (2013); IBGE (2023); ICMBio (2024); Ramos et al. (2015).

The geological formation of the PCRS dates back to the transgressive-regressive episodes of the Quaternary (TOMAZELLI; VILLWOCK, 2000), which formed deposits of the Barrier-Lagoon System, including three Pleistocene ages (I, II, and III) and one Holocene age (IV). In this evolutionary process, water accumulated in the interdune depressions, giving rise to coastal lagoons and marshes (TOMAZELLI; VILLWOCK, 2000; SCHÄFER; LANZER; SCUR, 2013). The flat morphology reflects the paleoenvironmental changes of the Quaternary. According to Arejano (2006), the following geological-geomorphological features can be found in the Park: Paleofalésia of Barrier III; Colluvial Deposits of Barrier III; Lagoon Terraces I and II; and Eolic Dunes of Barrier IV (Figure 1D). Lagoon terraces and eolic deposits (dunes) cover approximately 80% of the Park's area. The marshes and the Lagoa do Peixe occupy the interdune space between barriers III and IV.

The geological-geomorphological features configure an extensive sandy plain with flat topography and low elevation. The highest points are represented by the Paleocliff of Barrier III and the Eolic Dunes of Barrier IV. The Paleocliff, a terrace composed of marine and eolic sediments of Pleistocene age, gradually widens from south to north, with elevations ranging from 7 to 21 meters (KNAK, 1999). Coastal dunes are prominent in the area, oriented perpendicularly to the direction of the northeast (NE) winds (MORAES, 2009). They reach heights exceeding 15 meters and vary along the coast of the Park, with dune fields reaching a maximum width of 5 km to the north and a minimum of 0.70 km to the south (MANZOLLI et al., 2023).

The predominant soil types are Argiluvic Plinthosol, Quartzarenic Neosol, and, more significantly, Melanic Gleysol. Melanic Gleysols are mineral, hydromorphic soils developed from unconsolidated recent sediments, composed of clayey, clayey-sandy, and sandy materials from the Holocene (STRECK et al., 2008). In the Park area, Gleysols occupy the Lagoon Terraces I and II. The hydrogeology consists of the Coastal Quaternary Aquifer I (MACHADO; FREITAS, 2005), composed of a succession of unconsolidated sandy layers ranging from fine to medium granulation, whitish, intercalated with silt-sandy and clayey layers that have high porosity and permeability, with good yield in wells (MACHADO; FREITAS, 2005; MARCUZZO; SIMON; KIRCHHEIM, 2014).

The lagoa do Peixe periodically connects with the Ocean and, along with the Veiana, Pai João, and Fundo lagoons, forms the water system of the Park. The wetlands occupy the Lagoon Terraces and part of the Colluvial Deposits of Barrier III, covering 47% of the total area of the PNLP. They are represented by lagoon bodies, wet fields, marsh vegetation, salt marshes, and marshes. They are distributed across all geomorphological compartments and are susceptible to flooding pulses associated with precipitation (KORB et al., 2023).

The volume of rainfall in the region is primarily conditioned by frontal rains, which result from the meeting of Tropical Maritime (mT) and Polar Maritime (mP) air masses, ranging between 1200 and 1500 mm annually. The average minimum and maximum temperatures vary between 11°C and 26°C (ROSSATO, 2020). The study area is also influenced by precipitation anomalies associated with climate variability phenomena such as El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), which can correlate (REBOITA; AMBRIZZI; ROCHA, 2009; SCHOSSLER, 2016). Rainfall is well-distributed throughout the year, with greater totals in winter and spring, and the highest accumulation occurring in September (Table 1). However, during El Niño years, rainfall exceeds the climatological normal (NC), while negative deviations occur during La Niña (FONTANA; BERLATO, 1997; BRITTO; BARLETTA; MENDONÇA, 2008; RODRIGUES, 2015; SBRUZZI, FONSECA; SALDANHA, 2015). During La Niña periods, there is a near-total reduction in water levels in lagoa do Peixe.

Table 1. Monthly Average Precipitation, Historical Series from 1992 to 2023, in the PNLP.

Months	J	F	M	A	M	J	J	A	S	O	N	D
(mm)	112,8	111,0	99,8	114,4	123,4	110,6	137,2	106,2	154,8	124,0	80,4	92,2

Source: Data CHIRPS.

The vegetation cover is composed of Pioneer Formations, or Restinga (SCHÄFER; LANZER; SCUR, 2013), with marine and lacustrine influences. Herbaceous species dominate the dunes, while tree, marsh, and herbaceous species are found on the Lagoon Terraces and the Paleocliff of Barrier III (KNAK, 1999; IBGE, 2023). There are also extensive areas of forestry with Pinus spp., an invasive species that spreads across the sandy lands of the Park (SIGNORI, 2018).

2. Materials and Methods

2.1. Data Acquisition

The following cartographic databases were acquired: (a) mapping of wetlands from the Zoobotanical Foundation of Rio Grande do Sul (RAMOS et al., 2015); (b) delineation of the lagoas do Peixe, Veiana, and Pai João from the Cartographic Base of Rio Grande do Sul at a scale of 1:25.000 - BCRS25, from 2018, by the Department of Environment and Infrastructure (SEMA-RS, 2006); (c) boundary of the PNLP from the Chico Mendes Institute for Biodiversity Conservation (ICMBio), at a scale of 1:250.000; (d) soil, vegetation, and political boundary maps from the Environmental Database and Information of the Brazilian Institute of Geography and Statistics (IBGE), at a scale of 1:250.000; (e) geological map of the state of Rio Grande do Sul from the Geological Service of Brazil (SGB), at a scale of 1:750.000; (f) hydrogeological map of the state of Rio Grande do Sul (MACHADO; FREITAS, 2005), at a scale of 1:750.000; (g) aerophotogrammetric surveys at scales of 1:60.000 from 1964 and 1:110.000 from 1975 from the Library of the Institute of Geosciences of the Federal University of Rio Grande do Sul; (h) precipitation data from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) product, using code structures in Javascript on the Google Earth Engine (GEE) platform; (i) evapotranspiration data from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS), MOD16A2GF, obtained on the GEE platform.

CHIRPS has a spatial resolution of 0,05º, approximately 5 km, near the Equator, with a geographical coverage from 50°S to 50°N, and data available from 1981 to the present. It is accessible in daily, pentadal, and monthly datasets in UCSB1 format, such as NetCDF, GeoTiff, and Esri BIL. The precipitation data from CHIRPS for Brazil show a high linear correlation with data from the National Institute of Meteorology, the Center for Weather Forecast and Climate Studies (INMET/CPTEC) and CHIRPS (95.4%), with an average linear correlation of 97% between the datasets (COSTA et al., 2019).

Terrestrial evapotranspiration MOD16 is calculated based on the Penman-Monteith equation (MONTEITH, 1965) and takes into account evaporation from wet and moist soil, evaporation of water intercepted by the canopy, and transpiration of water from leaf stomata (MU; ZHAO; RUNNING, 2011).

In the altimetric mapping, two global Digital Elevation Models (DEMs) were tested: (1) the Forest And Buildings Removed Copernicus (FABDEM) (HAWKER; NEAL, 2021), available from the University of Bristol; (2) the DiluviumDEM available in the Zenodo repository (DUSSEAU; ZOBEL; SCHWALM, 2023).

The FABDEM version 1.0, with a resolution of 1′ (approximately 30 m), does not have height bias from urban buildings and forests. These elements were removed using random forest machine learning from the Copernicus GLO-30 Digital Surface Model (DSM) (AIRBUS, 2020), reducing the mean absolute vertical error in built-up areas from 1.61 to 1.12 m, and in forests from 5.15 to 2.88 m (HAWKER et al., 2022).

The DiluviumDEM is a DEM developed for coastal areas, with a resolution of 1′ (approximately 30 m). Derived from COP30, the vertical errors were corrected using a machine learning algorithm, providing greater accuracy when compared to other global DEMs such as FABDEM, COP-30, and COASTALDEM. However, the height bias from urban buildings and vegetation was retained. DiluviumDEM has an estimated RMSE of 1.13 m for coastal areas with elevations less than 2 m above mean sea level (DUSSEAU; ZOBEL; SCHWALM, 2023).

Using tools from GEE, Sentinel-2 images were acquired from the MSI (Multispectral Instrument) sensor, with a spatial resolution of 10 m, in bands 2, 3, 4, and 8, which were atmospherically corrected and orthorectified. Images were collected between January 1, 2019, and April 18, 2024, encompassing El Niño, La Niña, and Neutral years, based on data from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA, 2024).

2.2 Acquisition of Landscape Indicators

On the GEE platform, a time series of images of the Normalized Difference Vegetation Index (NDVI) was generated (Equation 1):

$$NDVI = \frac{(\rho IVP - \rho V)}{(\rho IVP + \rho V)} \tag{1}$$

Where:
ρIVP is the near-infrared band (band 8 / Sentinel-2);
ρV is the red band (band 2 / Sentinel-2).
The NDVI value varies between -1 and 1. Negative NDVI values correspond to water; values close to 0 correspond to non-vegetated surfaces or vegetation under water stress due to soil moisture deficit; and values close to 1 indicate more vigorous vegetation (PONZONI; SHIMABUKURO; KUPLICH, 2015).

The NDVI was developed by Rouse et al. (1973) and exploits the contrast that vegetation shows in its spectral response, between reflectance in the near-infrared region and absorption by chlorophyll in the red region (CORDEIRO, 2014), facilitating the analysis of vegetation conditions (MAGALHÃES et al., 2023). NDVI patterns also reveal an association with the amount of water in the soil and have been used as indicators of hydrogeomorphological activities (MARCHETTI et al., 2013, 2016, 2020; LUAN et al., 2018; TERAMOTO et al., 2018; GANI et al., 2022).

Fields on NDVI were also collected using the GreenSeeker Handheld sensor, equipment based on optical remote sensing with an active light source that utilizes emitted radiation data in the red (650 nm) and near-infrared (770 nm) bands. The reflectance reading is calculated by an internal microprocessor, providing the NDVI value, which is transmitted to a portable computer adapted to the sensor. The collection points were the same as those used for soil sampling (Table 2).

As pedoenvironmental indicators, soil samples were collected from points distributed across geomorphological compartments (Figure 2, Table 2) in areas representative of wetland typologies, from profiles with depths of 60 to 80 cm when possible. A total of 32 soil samples were collected, with at least two collections per geomorphological compartment, verified beforehand using the GIS database of the Environmental Information Database (BDIA) from IBGE. The samples were analyzed in the Soil Analysis Laboratory (LABSOLOS) of the College of Agronomy at UFRGS to identify the following components: organic matter, hydrogen potential (pH), sulfur (S), and grain size analysis. Organic matter, pH, and S represent the main elements of soil hydromorphism in coastal regions with sharply flat topography (CANELLAS et al., 2008; NETO, 2010; AMENDOLA, 2017; SANTOS, 2023).

Indicators of hydromorphic soils, such as the presence of iron oxides, were used to aid in the interpretation of pedogenesis, weathering, and the biogeochemistry of iron in soils influenced by hydromorphism (NETO, 2010). The presence of hydromorphic soils was verified in the field using an indicator solution for reduced iron (Fe_{+2}) and applying a dye solution with a,a'-dipyridyl (CHILDS, 1981; CAMPOS et al., 2003; SANTOS et al., 2018; SCHULZ et al., 2021). If Fe_{+2} is present in the sample, the coloration varies from pink to red (Figure 3B).

To complement the hydromorphic characterization, we checked for the presence of standing or flowing water and indicator plant species in wetlands. The hydric variation of the compartments was analyzed through an integrated approach combining visual interpretation of satellite images over different climatic periods and direct observations on-site, in order to gain an understanding of the temporal changes in hydric conditions.

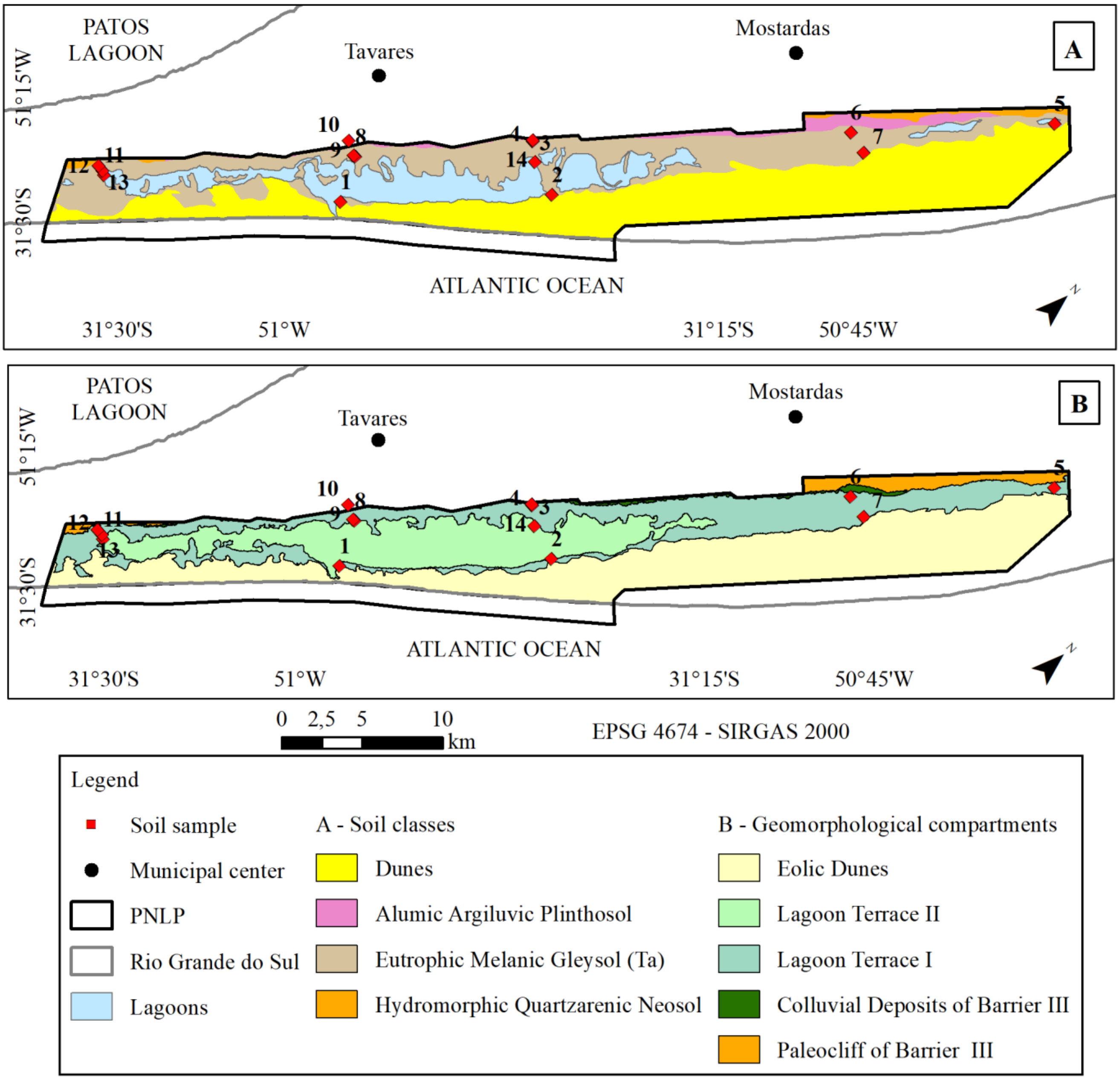


Figure 2. Spatial distribution of soil samples by: (A) soil classes; (B) geomorphological compartments. Sources: Arejano (2006); IBGE (2024); ICMBio (2024)

Table 2. Geographic coordinates of NDVI samples, obtained in the field with GreenSeeker, and soil samples, by geomorphological compartment and soil class.

Sample	Longitude	Latitude	Geomorphological Compartments	Soil Classes
1	-51,047330	-31,352647	Lagoon Terrace I	Melanic Gleysol
2	-50,958490	-31,261730	Lagoon Terrace I	Melanic Gleysol
3	-50,981660	-31,256510	Lagoon Terrace II	Melanic Gleysol
4	-50,992580	-31,249860	Lagoon Terrace I	Melanic Gleysol
5	-50,774220	-31,025920	Lagoon Terrace I	Melanic Gleysol
6	-50,858490	-31,114220	Lagoon Terrace I	Melanic Gleysol
7	-50,843110	-31,116260	Lagoon Terrace I	Melanic Gleysol
8	-51,062660	-31,329460	Lagoon Terrace I	Melanic Gleysol

Sample	Longitude	Latitude	Geomorphological Compartments	Soil Classes
9	-51,063950	-31,329620	Lagoon Terrace I	Melanic Gleysol
10	-51,073226	-31,326190	Lagoon Terrace II	Alumic Argiluvic Plinthosol
11	-51,163840	-31,440810	Lagoon Terrace II	Melanic Gleysol
12	-51,166390	-31,439880	Lagoon Terrace I	Melanic Gleysol
13	-51,170790	-31,439620	Paleocliff of Barrier III	Melanic Gleysol
14	-50,993429	-31,249375	Colluvial Deposits of Barrier III	Melanic Gleysol

Figure 3. Assessment of hydromorphic soil: A) sampling with an auger; B) application of a,a'-dipyridyl, a pedoenvironmental indicator for hydromorphic soils. Photo: by the authors.

2.3 Identification of Hydrogeomorphological Compartments

For the identification, the following references were adopted: (a) the hydrogeomorphological classification of wetlands by Brinson (1993) and Smith et al. (1995); (b) the recognition of wetland typologies by Cunha, Piedade, and Junk (2015).

A preliminary analysis of the definition of altimetric compartments, based on the FABDEM and DiluviumDEM models, and considering the flat characteristics of the terrain, showed that FABDEM was better able to express the definition of the boundaries of the hydrogeomorphological compartments.

For the interpretation of the compartments, the following aspects were considered: (a) the geomorphological compartmentalization of Arejano (2006); (b) the position of wetlands in the landscape; (c) the geology, soil type, hydric dynamics, hydrogeology, and vegetation; (d) the contour lines with a 1 m interval and the hypsometric map of FABDEM; (e) the aerial photographs from 1964 and 1975 from the Geographic Service Division of the Army (DSG); (f) the Sentinel-2 images (08.07.2021; 02.03.2022; 11.20.2023; 04.18.2024), in RGB color composition; (g) fieldwork (04 to 04/05/2023; 24 to 02/26/2024) for validation of the results.

The hydrogeomorphological compartmentalization was established through visual interpretation using satellite images, topographic variation and contour lines, aerial photographs, and NDVI images, with a scale set at 1:200.000 in ArcGIS Pro. The compartments and hydrogeomorphological systems were verified in fieldwork, checking for the presence of standing or flowing water, indicator species of wetlands, morphological characteristics, altimetric variation, and landscape patterns.

3. Results

3.1. Topographic Variation

Among the landscape patterns of the Park, a vast flat area is prominent, occupying the interdunal space between the Paleocliff of Barrier III and the Eolic Dunes of Barrier IV, with a predominance of altimetric levels of up to 5 m. The altimetric variation in PNLP (Figure 4) and the topographic profiles (Figure 5) obtained from the

FABDEM Digital Elevation Model show that this area is gently depressed in relation to its surroundings. This area hosts a hydrogeomorphological system composed of wet fields, marshes, lagoon bodies, and salt marshes, whose hydric flow is conditioned by the geomorphological compartments of higher elevation: the Paleocliff of Barrier III and the Eolic Dunes of Barrier IV (Figure 5).

Altimetric variations are also distinguished between the northern and southern sectors of PNLP. Between the channel of Lagoa do Peixe and the northern extreme, in the vicinity of part of the lagoon terraces, the current eolic dune ridges and part of the Paleocliff of Barrier III extend. In this area, altitudes can exceed 15 m. To the south of the channel, the altitude decreases, with elevations primarily below 5 m.

The Peixe Lagoon is characterized by its low depth, averaging 30 cm, although it can reach 2 m in the area near its outlet to the Ocean (PORTZ; GUASSELLI; CORRÊA, 2011; SCHOSSLER; TOLDO JR.; DANI, 2017).

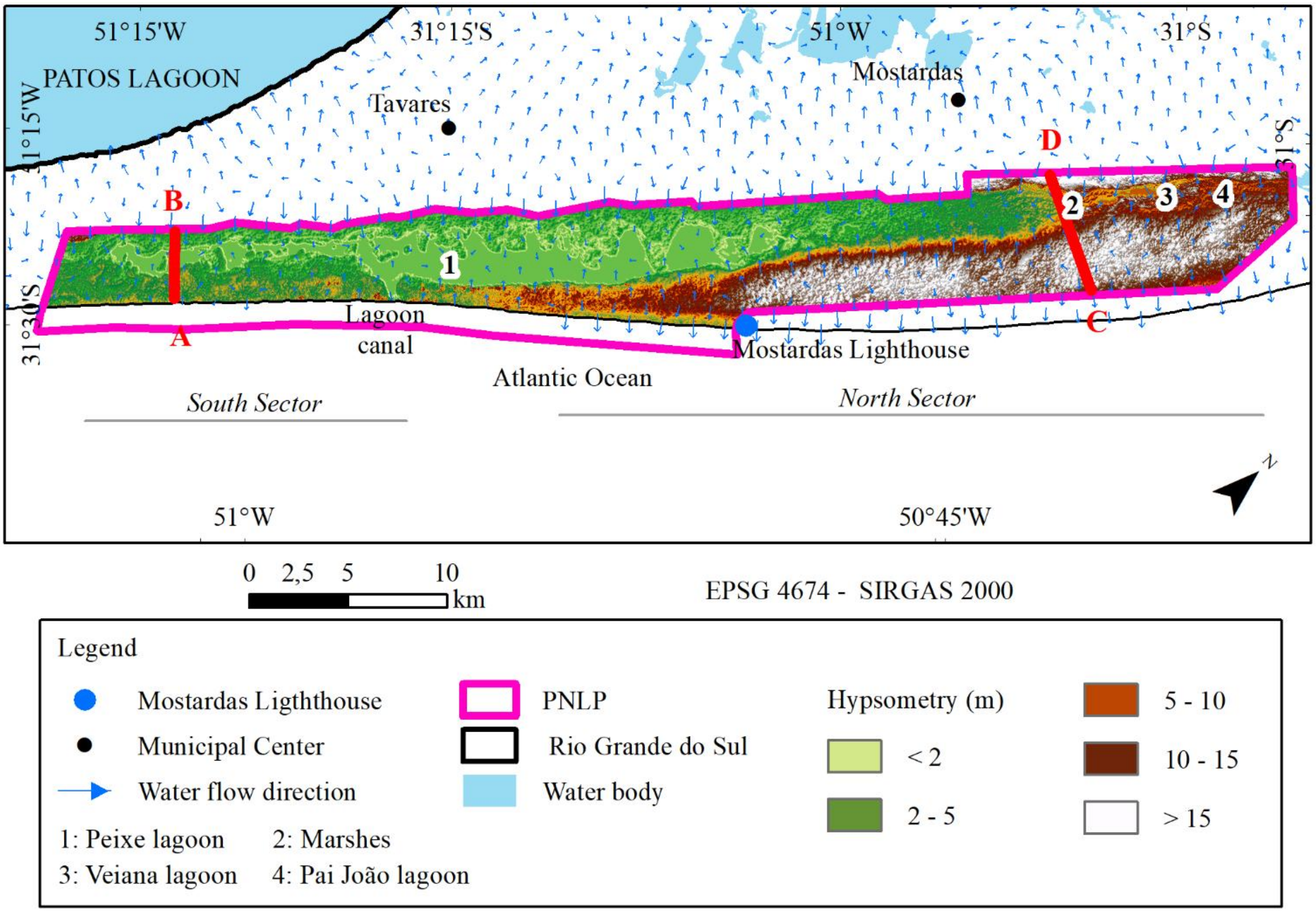
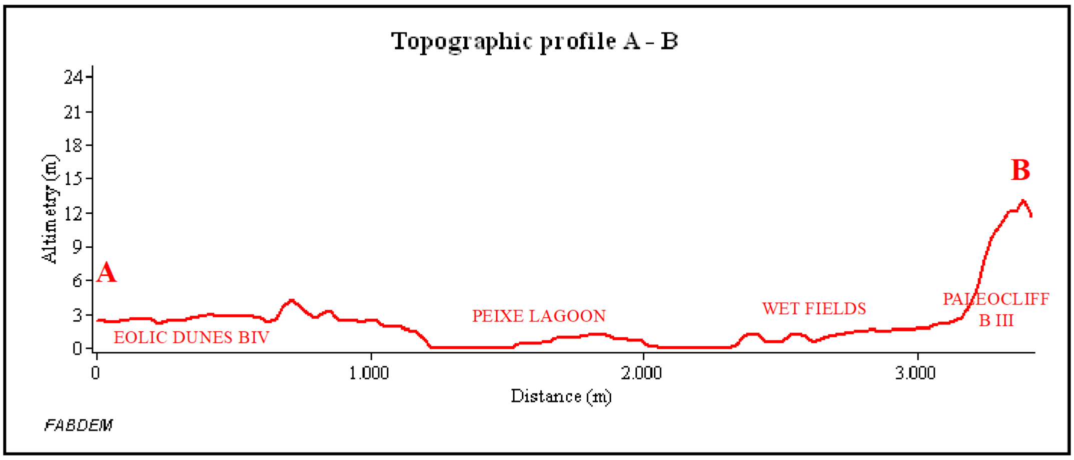


Figure 4. Hypsometry of PNLP. Sources: FABDEM (2023); ICMBio (2024); IBGE (2024).

SOUTH SECTOR (Profile A-B)



NORTH SECTOR (Profile C-D)

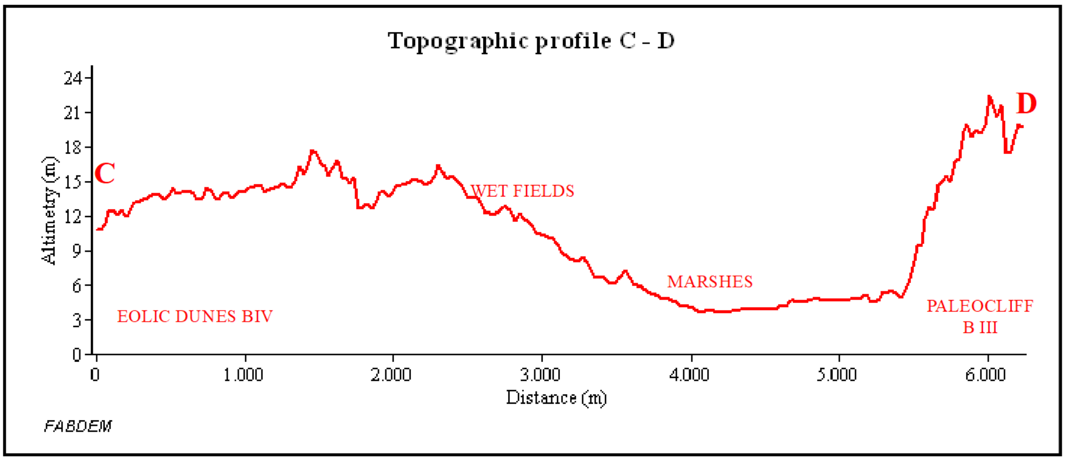


Figure 5. Topographic profiles of PNLP, Southern Sector (Profile A-B) and Northern Sector (Profile C-D). Sources: FABDEM (2023).

3.2. Hydric Dynamics

The water level of lagoa do Peixe, in images under different hydric conditions (Figure 6), is a result of climatic variability associated with ENSO, during La Niña (Figure 6A) and El Niño (Figure 6B). The image from February 3, 2022 (Figure 6A) represents a prolonged period with a strong predominance of La Niña. During this period, there was a continuous reduction in precipitation and an increase in water deficit, leading to an extreme decrease in the water level of the wetlands, especially lagoa do Peixe in Lagoon Terrace II, exposing the lagoon bottom.

Despite this reduction, the marshes and the Veiana and Pai João lagoons, located to the north of the park, still have water levels influenced by the proximity of the water table. The wetlands situated north of lagoa do Peixe, on Lagoon Terrace I, the Colluvial Deposits, and the Paleocliffs of Barrier III, at slightly higher elevations, contribute to the recharge of the downstream wetlands (lagoa do Peixe and wet fields). By maintaining apparent water levels, even during periods of water deficit, particularly in the La Niña phase, the Pai João and Veiana lagoons, along with the marshes, function as hydrological regulators of the landscape.

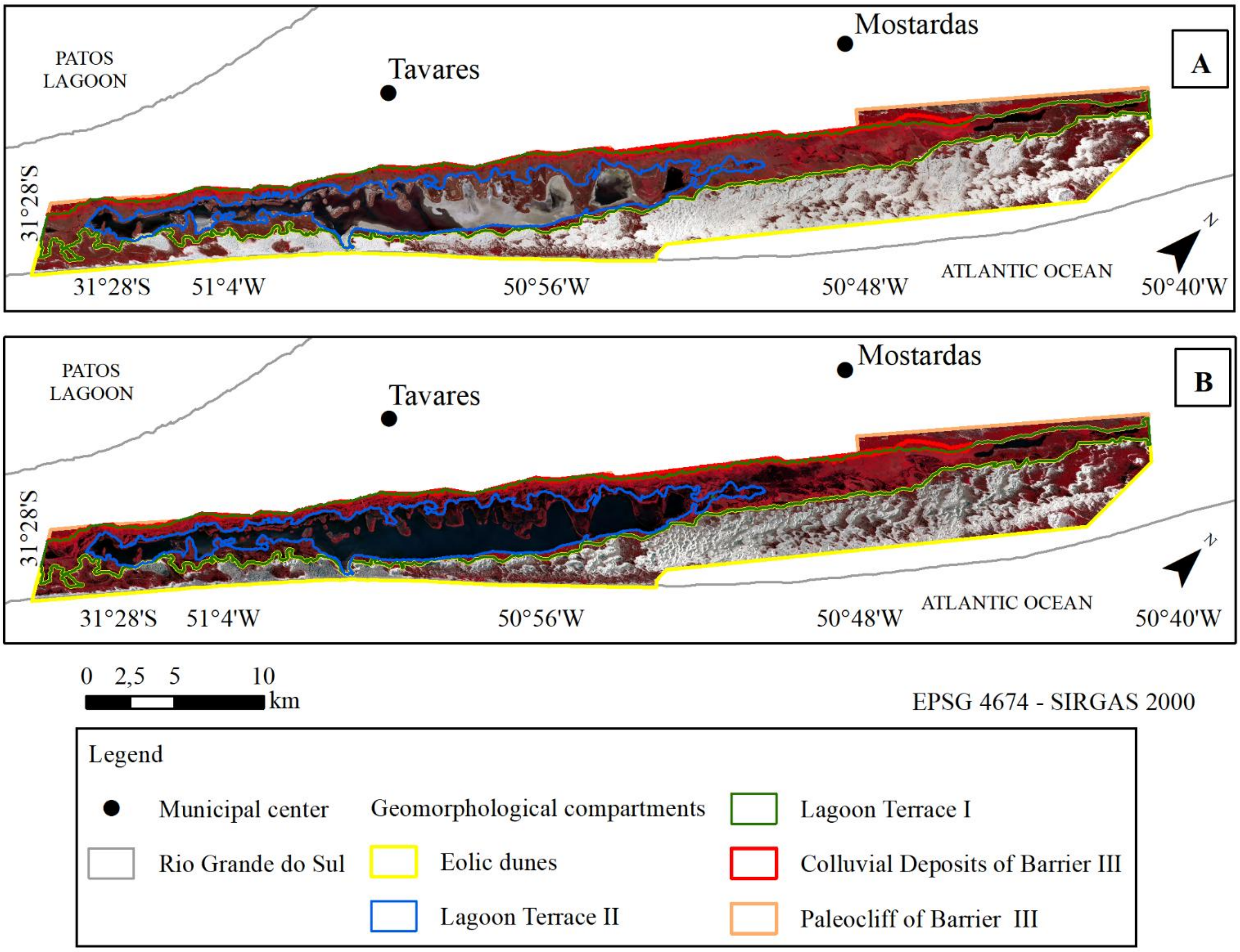


Figure 6. Images showing water dynamics under different rainfall conditions: A) La Niña, 03.02.2022; B) El Niño, 18.04.2024, in lagoa do Peixe. Sources: R8G4B3 Sentinel 2 color composite; Arejano (2006).

The image from April 18, 2024 (Figure 6B) shows the water dynamics of the wetlands during El Niño. The greater presence of water over the compartments floods Lagoon Terraces I and II in particular. In 2024, rainfall totals reached 487 mm, 251 mm in April alone, contributing to water accumulation and connectivity between the wetlands in this geomorphological compartment.

3.3. NDVI

The collection of images obtained from GEE, used to calculate the behavior of NDVI (Figure 7), covered rainfall conditions associated with climatic variability (El Niño and La Niña) and months of neutrality. This variability shows that (a) in 2019, NDVI values reflected a period of El Niño and neutrality; (b) in 2020, neutrality and the occurrence of La Niña; (c) in 2021, La Niña and neutral conditions; (d) in 2022, La Niña; (e) in 2023, La Niña, neutrality, and El Niño; and (f) in 2024, conditions of El Niño.

The average NDVI (Figure 7) shows that the Paleocliffs and Lagoon Terrace II compartments exhibited greater variation in relation to precipitation and the El Niño and La Niña phases. The Paleocliff, an area with the highest density of vegetation cover, also shows variation concerning the seasons of the year. However, the greatest variation in NDVI occurs in Lagoon Terrace II, where the reduction of water levels in the wetlands during the La Niña period results in a response pattern of exposed soil. On the other hand, in the areas of Lagoon Terrace I, a greater variation was expected due to the coverage of fields with low biomass and the influence of sandy soils on the spectral response, which did not occur.

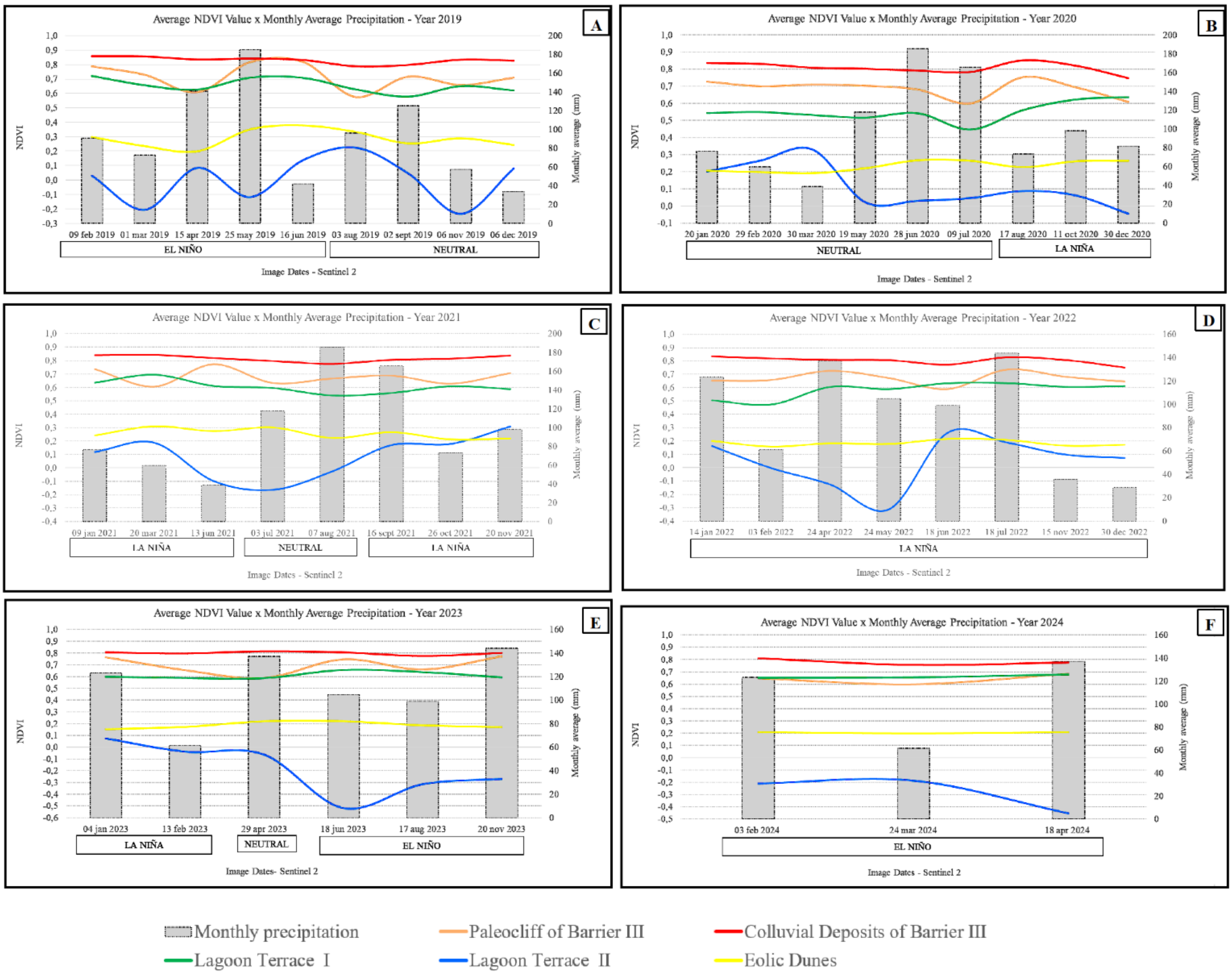


Figure 7. Average values and monthly precipitation averages by geomorphological compartments: A) Year 2019; B) Year 2020; C) Year 2021; D) Year 2022; E) Year 2023; F) Year 2024.

Figure 8 shows the estimated variables related to precipitation, evapotranspiration, water balance, and NDVI variation of the wetlands of PNLP. El Niño events cause positive anomalies in precipitation, mainly during spring and summer, resulting in a positive water balance (Figure 8). During La Niña, there is a reduction in precipitation, resulting in water stress in vegetation, an increase in evapotranspiration, and a consequent water deficit in the wetlands (Figure 8), especially in spring and summer (Figure 7D).

It should be noted that the decrease in NDVI values will only occur after a long period of reduced rainfall and water balance. This delay is related to the very low relief and the proximity of the water table, which allow for greater resilience of the wetlands in these areas.

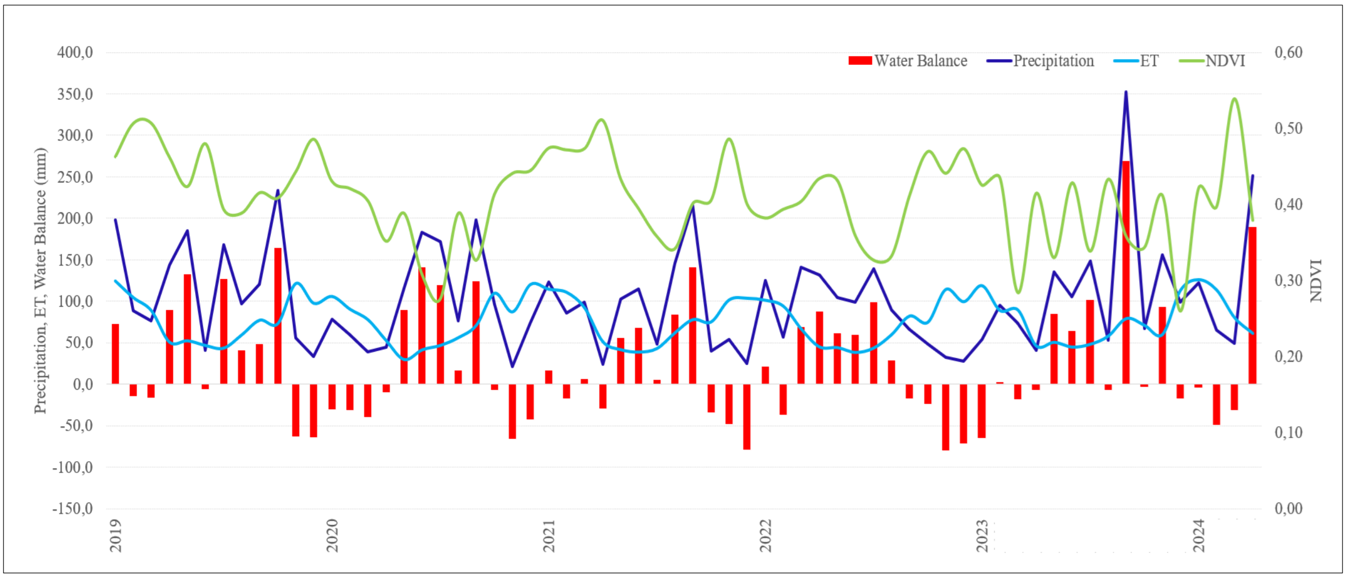


Figure 8. Estimated values of precipitation, evapotranspiration, water balance, and NDVI for Lagoon Terraces I and II. Source: CHIRPS and MOD16A2GF data.

The average NDVI values in each geomorphological compartment in the box diagram (Figure 9) show a distinct spatial pattern. There is the greatest variability in Lagoon Terrace II, the site of lagoa do Peixe, and in the Paleocliff of Barrier III. The data obtained with Greenseeker (Table 3) show similar patterns to those obtained with NDVI images in the period between 2019 and 2024.

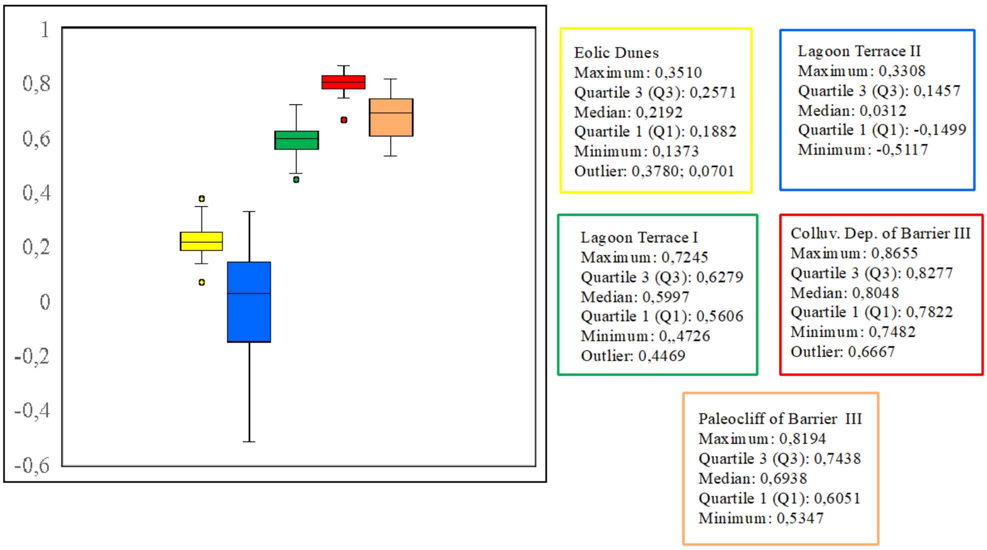


Figure 9. Box plot of NDVI variability from 2019 to 2024 by geomorphological compartment.

Table 3. NDVI samples obtained in the field with GreenSeeker.

Sample	NDVI	Geomorphological compartment	Sample	NDVI	Geomorphological compartment
1	0,45	Lagoon Terrace I	8	0,36	Lagoon Terrace I
2	0,59	Lagoon Terrace I	9	0,67	Lagoon Terrace I
3	0,32	Lagoon Terrace II	10	0,52	Lagoon Terrace II
4	0,72	Lagoon Terrace I	11	0,67	Lagoon Terrace II
5	0,43	Lagoon Terrace I	12	0,42	Lagoon Terrace I
6	0,62	Lagoon Terrace I	13	0,67	Paleocliff of Barrier III
7	0,69	Lagoon Terrace I	14	0,74	Colluvial Deposits of Barrier III

3.3. Pedoenvironmental indicators

The environmental indicators of the geomorphological compartments (Table 4) indicate the predominance of sandy-clay hydromorphic soil. The samples showed approximately 90% sand-sized grains and between 10% and 12% clay. Most of the samples have < 1% organic matter (Figure 10), with higher percentages in samples from Lagoon Terrace I (points 4, 6, 13).

In the Colluvial Deposits of Barrier III compartment (point 14), we identified a percentage of > 10% organic matter. The hydrogen potential (pH) varied between 4.5 and 8 across all compartments, with higher values predominantly found in Terrace I.

As for sulfur (S), we found that Terrace I (points 1, 2, 8) and Terrace II (point 3) had the highest concentrations. Lagoon Terrace I (points 4, 6, 13) and the Colluvial Deposits of Barrier III (point 14) had a higher concentration of organic matter and reacted to the dye solution with a,a'-dipyridyl.

Table 4. Particle size percentage of soil samples by geomorphological compartment.

Geomorphological compartment	Coarse sand + Fine sand	Clay	Silt
Lagoon Terrace II	86,4	12,4	1,2
Lagoon Terrace I	88	9,82	2,18
Colluvial Deposits of Barrier III	79	12	9
Paleocliff of Barrier III	89	10	1

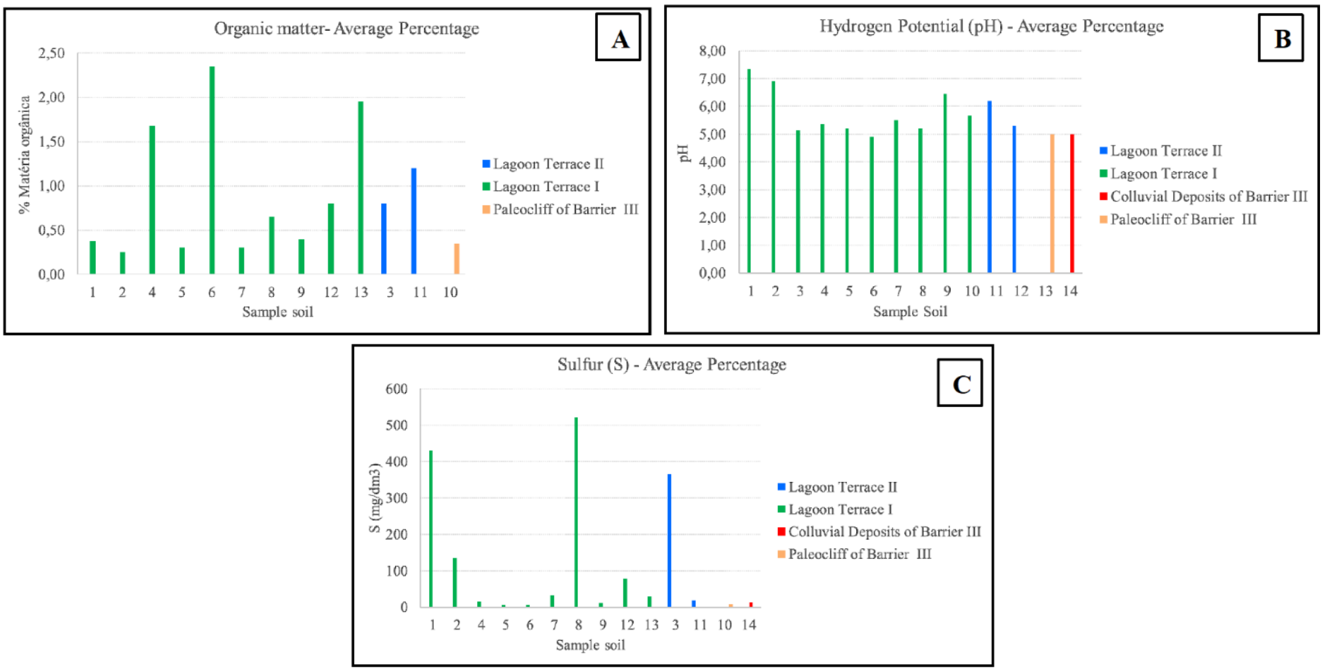


Figure 10. Pedoenvironmental indicators: A) Organic matter; B) Hydrogen potential (pH); C) Sulfur (S), by geomorphological compartment.

3.5. Hydrogeomorphological Compartments

Based on the interpretation of images and reference data, fieldwork, and the analysis of the adopted references, nine hydrogeomorphological compartments were established in PNLP: Eolic Dunes, Lagoon Fringe, Lacustrine Fringe, Lacustrine, Lagoon-Estuarine, Lacustrine Terrace, Lagoon Terrace, Depression, and Slope. Each compartment houses one or more hydrogeomorphological systems (Figure 11, Figure 12, Table 4).

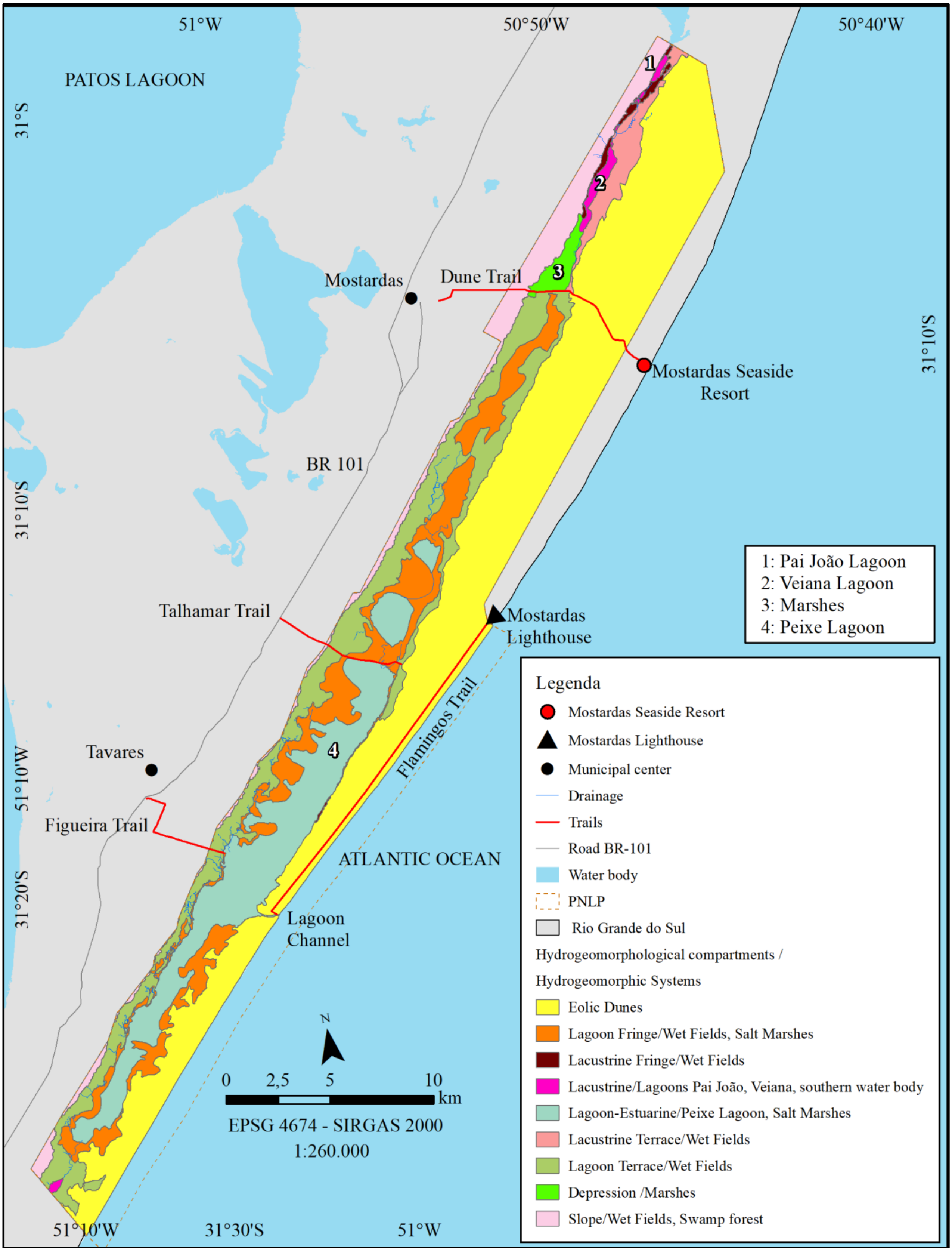


Figure 11. Hydrogeomorphological Compartments, Lagoa do Peixe National Park. Sources: DSG (2018), FABDEM (2023), IBGE (2024), ICMBio (2024), Image Sentinel - 2 (2024), SGB (2024).

Figure 12. Hydrogeomorphological Systems (Typologies of Wetlands) of PNLP: A) Pai João Lagoon; B) Wet Fields; C) Salt Marshes; D) Peixe Lagoon; E) Marshes. Photos: by the authors.

Table 5. Hydrogeomorphological Compartmentalization.

Hydrogeomorphological Compartment	**Hydrogeomorphological Systems (Typologies of Wetlands)**	**Main characteristics**
Eolic Dunes	Does not present wetlands.	Continuous eolic deposits along the coast. Unconsolidated quartz sands to the north of the Lagoa do Peixe channel, with heights ranging from 5 to 15 m. Orientation coincides with the direction of the northeast wind.
Lagoon Fringe	Wet Fields and Salt Marshes	Flat morphology is related to lagoonal erosion at the edge of Peixe Lagoon. Hydric dynamics are associated with flooding pulses and drainage channels in adjacent compartments. During periods of water deficit, there is increased evapotranspiration

Hydrogeomorphological Compartment	**Hydrogeomorphological Systems (Typologies of Wetlands)**	**Main characteristics**
		and a nearly complete reduction of water levels, exposing sandbanks. Herbaceous vegetation and the presence of bulrushes and cattails are observed.
Lacustrine Fringe	Wet Fields	Flat terrain along the margins of the Veiana and Pai João lagoons. Hydric dynamics associated with flooding pulses and the proximity of the water table. During these periods, there is greater connectivity between the lagoons, forming a single system, and the wet fields have higher water availability. The drainages are intermittent and vanish under La Niña conditions. There is a presence of grasses adapted to hydric fluctuations. Gleysols are predominant.
Lacustrine	Veiana and Pai João lagoons, and the water body to the south	Coastal freshwater lagoons. Hydric dynamics are related to water flow maintained by precipitation, the proximity of the water table, and drainage from the Slope compartment. In positive water balance (precipitation greater than evaporation), the Pai João and Veiana lagoons connect, and even during periods of water deficit, the water level is maintained.
Lagoon-Estuarine	Peixe Lagoon and Salt Marshes	Brackish or saline water compartment (Lagoa do Peixe and marshes) periodically connected to the Ocean. Hydric dynamics are associated with flooding pulses, when there is a positive water balance during the El Niño phase. During La Niña, characterized by water deficit, there is an almost total reduction in water levels, exposing the lagoon bottom, which remains moist in the lower layers. Marsh vegetation is found in intertidal areas, along with bulrushes at the edges of the lagoon. Bottom sediments are sandy and muddy facies.
Lacustrine Terrace	Wet Fields	Flat adjacent to the Eolic Dunes and the Pai João and Veiana lagoons. Hydric dynamics are associated with low elevation; when there is a positive water balance, there is a temporary accumulation of rainwater over the wetlands in the form of small ponds. Even during drier periods, water availability is preserved. There are intermittent drainages that disappear under La Niña conditions. Herbaceous vegetation and *Pinus spp*. are prevalent. Gleysols with sandy texture are predominant.
Lagoon Terrace	Wet Fields	In the interdunal compartment, between the Eolic Dunes and the Paleocliffs of Barrier III, there is flat morphology. Hydric dynamics are associated with periods of high rainfall during El Niño and neutral phases. There is intermittent drainage that flows from the wetlands to Lagoa do Peixe. Herbaceous vegetation adapted to the hydrological regime is

Hydrogeomorphological Compartment	Hydrogeomorphological Systems (Typologies of Wetlands)	Main characteristics
		present. Gleysols with a sandy texture are predominant.
Depression	Marshes	Concave morphology. Hydric dynamics are determined by the oscillation of water levels associated with precipitation and the proximity of the water table. During periods of positive water balance, apparent water levels occur due to flooding pulses, with drainage flowing into Peixe lagoon. Even during dry periods, water availability is maintained. There is a presence of amphibious macrophytes, including emergent, floating, epiphytic, and climbing plants. Soils (Gleysols) are permanently water-saturated.
Slope	Wet Fields and Swamp forest	Slightly elevated terrain with smooth morphology. Hydric dynamics associated with temporary drainage that flows from the Slope of the Paleocliff of Barrier III to the Lagoon Terraces. The hydrological regime is linked to precipitation (positive water balance), flooding pulses from the lagoons and marshes, which occasionally reach this compartment. Even in negative water balance, soil moisture is maintained in some sectors of the compartment. There is a presence of hygrophytic and herbaceous species adapted to the temporary hydric regime. Argiluvic Plinthosol and Melanic Gleysol, which are not permanently waterlogged, are predominant.

4. Discussions

The recent availability of free global DEM products has facilitated their use in geomorphological studies and is important for representing coastal sandy environments with low altimetric variation (ALMAR et al., 2021; EMMENDORFER et al., 2024). They are also relevant for assessing the hydrogeomorphological behavior of coastal zones (GESCH, 2023).

As a result of the factors influencing the topography of PNLP, the main altimetric differences correspond to depositional forms, with flat topographic features that exhibit little altimetric expression, showing similarities between compartments. When mapping the morphological features, these characteristics, combined with the presence of arboreal vegetation in the higher elevation compartments (Paleocliffs and Colluvial Deposits of Barrier III), make geomorphological delineation difficult. A more accurate representation of the elevation variation in the mapped area was obtained with the FABDEM model, which does not have the vertical bias from vegetation that was not removed in the DilluviumDEM. Thus, this model was adopted for the identification of hydrogeomorphological compartments, combined with visual interpretation of Sentinel-2 images.

However, according to the literature, there is no consensus on which model has greater accuracy in representing topography. Dusseau, Zobel, and Schwalm (2023) obtained better results using the DilluviumDEM compared to FABDEM, COP30DEM, and CoastalDEM in coastal areas of North and Central America, Europe, Oceania, and Asia. Gesch (2023) recorded a better performance of FABDEM when compared to other global DEMs (AW3D30, ASTER GDEM, NASADEM, CoastalDEM, Copernicus, MERIT, TanDEM-X, GLLDTM, and GEDI) in coastal areas of the United States. Meadows, Jones, and Renke (2024) achieved better vertical accuracy in coastal and continental areas worldwide with FABDEM when compared to COP30DEM, NASADEM, AW3D30, and SRTM. Therefore, it is ideal to assess which model shows better results for the analyzed area.

The combined use of remote sensing data in geomorphological analysis is an effective tool based on the visual and/or automatic interpretation of satellite images (MENESES; ALMEIDA, 2012). It has been recognized in the study of Ramsar Site AUs since 2006 at the Conference of the Parties (COP8) (GONÇALVES; CUNHA; JUNK, 2019).

Recent articles have explored coastal geomorphological mapping by combining global DEMs with satellite images (POLIZEL; ROSSETTI, 2014; NETO et al., 2019; COMERLATO; LAMOUR; SILVEIRA, 2020; BAGOT; HUYBRECHTS; SERGENT, 2021; RAMOS et al., 2021). Combined with the interpretation of satellite images with good spatial resolution, these are useful data for geomorphological mapping, especially in areas with very flat topography, where the similarity between morphologies can make it difficult to identify compartments (HOFFMANN; WINDE, 2010; GUASSELLI; SIMIONI; LAURENT, 2020). In coastal hydrogeomorphological studies, global DEMs have been compared by applying the Topographic Wetness Index (TWI) in AUs (GUASSELLI; SIMIONI; LAURENT, 2020); in coastal flood mapping (ZHANG et al., 2019); to estimate topographic attributes relevant to the mapping of vertical soil properties (METTERNICHT et al., 2022) in a low-lying sandy environment (EMMENDORFER et al., 2024).

Bitencourt et al. (2020) used the TanDEM-X model (0.4 arc-seconds spatial resolution) to produce altimetric profiles of a Holocene barrier (eolic dune compartment) between the southern and northern sectors of PNLP (Figure 5), which allowed for the description of a change in the orientation of the coastline, with a positive sediment balance in the northern sector of PNLP. The sand supply to the transgressive dune fields for the adjacent foreland (TOLDO et al., 2006; ABSALONSEN; TOLDO, 2007) shows that the coastal stretch of the PNLP region presents the highest net volume of sediments transported by longshore drift along the mid-coast (MOTTA et al., 2015; BITENCOURT et al., 2020).

The characteristics of wetlands are influenced by variations in water levels. These variations are related to the geomorphological and climatic characteristics of the region in which they are located (BRASSESCO, 2011). The hydric dynamics of the wetlands of PNLP are controlled by precipitation patterns and flat morphology, as they are not associated with a drainage network and do not receive inflow from rivers. The drainages are intermittent, a characteristic pattern of the landscapes of the Coastal Plain of Rio Grande do Sul. Korb et al. (2023) emphasized the greater influence of the El Niño-Southern Oscillation and the Southern Annular Mode on flooding pulses, with larger flooded areas in spring during El Niño years and Neutral years.

The El Niño-Southern Oscillation is a significant driver of hydric dynamics in the coastal wetlands of PNLP. El Niño and La Niña events can impact water levels both through direct oceanic effects and indirectly by altering precipitation patterns that affect the water balance and water flow of coastal watersheds (KAHYA; DRACUP, 1993; CLARK et al., 2001; GARCIA-LEÓN; BELTRÁN-VARGAS; ZAFRA-MEJÍA, 2023). The effect of the ENSO phenomenon on coastal wetlands has been verified by Goodman et al. (2018), Acosta et al. (2023), and on inland wetlands by Garcia-León, Beltrán-Vargas, and Zafra-Mejía (2023) and Saéz, Delgado, and Ramos (2023).

The water balance, obtained from the relationship between precipitation and evapotranspiration, demonstrated that the wetlands of PNLP face water deficit in the summer when La Niña occurs, during which evapotranspiration is higher. In contrast, positive balances are markedly observed in winter and spring, amplified by El Niño events. This climatic variability plays a crucial role in vegetation dynamics, influencing the spatial and seasonal distribution of plant species (LEE; KIM; KIM, 2020). Additionally, the recharge of the groundwater table is directly affected, with significant implications for the availability of groundwater in precipitation-dependent wetlands (DE LA FUENTE; MERIANE; SUÁREZ, 2021).

The interaction between hydrological cycles and biological activity in different seasons can provide essential information for conservation strategies and sustainable management (ZHANG et al., 2021; MAYILVAHANAM; GHOSH; OJHA, 2023). The stability of these ecosystems, in turn, is maintained by the ability of wetlands to adapt to these hydric dynamics, promoting ecological resilience (KOOL et al., 2022) and greater hydrological connectivity (SIMIONI, GUASSELLI, ETCHLAR, 2017). However, it can also interfere with biodiversity loss. According to Barros and Albernaz (2014) and Sandi et al. (2020), a reduction in rainfall can cause a rapid decline in species, while increased rainfall can lead to the replacement of plant species.

The variability of NDVI observed between 2019 and 2024 may be associated with El Niño and La Niña, primarily due to their influence on precipitation in the region, according to Jacobsen (2002) and Cordeiro (2014).

During positive precipitation anomalies of El Niño, higher NDVI values were recorded, especially in the Paleocliffs and Colluvial Deposits of Barrier III compartments, where there is greater vegetative vigor. On the other hand, the Lagoon Terraces (Depression, Lacustrine, Lagoon-Estuarine, Lacustrine and Lagoon Terraces, and Fringes) showed a greater NDVI range due to the presence of water on the surface, which reduces reflectance in the near-infrared (CORDEIRO, 2014). In marshes areas, the spectral response pattern is strongly influenced by the mixture of responses from aquatic macrophytes and water (GUASSELLI, 2005).

It is noteworthy that even during periods of water deficit, NDVI values close to 1 occur in the Depression compartment. The water dynamics in the Depression, where the main marshe of the PNLP is located, contributes water to the downstream compartments, such as the Lagoon-Estuarine (Peixe lagoon). NDVI values close to 1 are due to the presence of moisture in the compartment, possibly associated with the release of water from near the water table in coastal areas. This relationship was addressed by Wang et al. (2004), Chen et al. (2014), Teramoto et al. (2018), Zhou et al. (2023), and Liu et al. (2024), who correlated NDVI with aquifer behavior and concluded that seasonal fluctuations in NDVI reflect the availability of water in the soil.

In relation to the soils, the grain size analysis showed a sandy-clay pattern in the flat topography compartments, covering lagoon terraces susceptible to flooding pulses. The Gleysols reflect hydromorphism resulting from the process of iron compound reduction in the presence of organic matter, and oxidation alternation may occur due to fluctuations in the water table (EMBRAPA, 2018). According to Streck et al. (2008), Gleysols are widely found in the Coastal Plain, are predominantly sandy, hydromorphic, typical of lagoon plains, and originated from unconsolidated Holocene sediments.

The highest percentages of organic matter were obtained from Lagoon Terrace I (points 4, 6, and 13) and the Colluvial Deposits of Barrier III (point 14). These points represent the wet fields and marshes, hydrogeomorphological systems that tend to accumulate organic matter as a result of oxidation and reduction processes. According to Amendola (2017), in an oxidizing environment, organic matter tends to be rapidly consumed, while in a reducing environment, associated with the seasonality of the water table, it can remain in an anaerobic environment, responsible for its preservation.

The topographic conditions of these hydrogeomorphological systems tend, in addition to accumulating moisture, to deposit materials transported from geomorphological compartments with higher altimetry, such as the Paleocliffs of Barrier III. Thus, the process of adding organic matter is notably significant in the pedogenesis of these hydrogeomorphological systems. Sousa et al. (2011), Machado (2014), Sousa et al. (2015), Troian et al. (2015), Amendola (2017), and Cunha-Santino and Bianchini Júnior (2023) also analyzed the accumulation of organic matter in types of wetlands.

The reaction to the dye solution with a,a'-dipyridyl occurred at the same points of higher concentrations of organic matter and moisture (points 4, 6, 13, and 14), revealing that the redox environment influences the levels of pedogenic iron oxides (CORINGA; COUTO; TORRADO, 2015), unlike the points with soils where drainage and moisture are limited.

The pH analyses allowed for the classification of these soils as having a tendency toward acidity, a typical condition of materials rich in organic matter in hydromorphic conditions with partial decomposition of organic matter and the production of organic acids (NASCIMENTO; BERBET; RIBEIRO, 2015). The highest concentrations of sulfur were found in the Lagoon Terraces (points 1, 3, and 8), in marsh areas. Hydromorphic soils, specifically coastal-origin deposits, can exhibit varying sulfur levels due to their proximity to ocean waters (NETO, 2010).

The criteria for identifying, classifying, and delimitating wetlands vary, and various studies have been conducted to map these environments (SIMIONI; GUASSELLI, 2017). This highlights the importance of considering the spatial patterns they present in the landscape. Furthermore, it underscores the relevance of adopting regional or local terminologies based on theoretical and technical foundations that allow for grouping them into hydrogeomorphological compartments with similar functions (BRINSON, 2009; GOMES, 2017; RICAURTE et al., 2019). It is worth noting that the adoption of these criteria does not necessarily imply a rigid approach and can be applied to different landscapes (GOMES, 2023).

The adoption of hydrogeomorphological criteria for the compartmentalization of the wetlands in PNLP has allowed for an understanding of their main structural and functional characteristics. According to Brinson (1993), this classification approach for wetlands emphasizes hydrological and geomorphic controls, which are apparently responsible for maintaining many of the functional aspects of these ecosystems.

The hydrogeomorphological systems of the Park exhibit hydric dynamics associated with their flat and low morphology, related to variations in precipitation. This dynamics is connected to flooding pulses and periods of severe drought associated with climatic variability events. This compartmentalization allows for a detailed analysis of the hydrological and geomorphological processes that define the internal dynamics in these areas (MITSCH; GOSSELINK, 2015). With hydrogeomorphological compartmentalization, it is possible to understand the interactions between topography, water flow, and vegetation, providing a comprehensive framework for the effective management and conservation of these ecosystems (BRINSON, 1993; RIVERS-MOORE et al., 2020). Smith et al. (1995) and Gomes (2023) emphasize the importance of this methodology in maintaining the ecological functions of wetlands.

Analyses related to the extent of coastal wetlands, considering the application of the hydrogeomorphological approach, are still underexplored. Thus, this study's main contribution is to address these environments in the hydrogeomorphological compartmentalization of PNLP. We believe that the adopted references, Brinson (1993) and Smith et al. (1995), for the delineation and classification of wetlands based on hydrogeomorphological units, as well as Cunha, Piedade, and Junk (2015), with hierarchical levels and local terminologies, were suitable for the hydrogeomorphological compartmentalization of the wetlands in the Park.

5. Conclusions

The combination of remote sensing data (FABDEM model and Sentinel-2 images), landscape indicators (NDVI and hydromorphic soils), and water balance allowed for the definition of nine hydrogeomorphological compartments in the coastal wetlands of PNLP, in areas of flat topography and low elevation.

The model was more efficient in defining the altimetric variations and the boundaries between the geomorphological compartments. It better highlighted the differences between the northern and southern sectors of PNLP, between the Paleocliffs of Barrier III and the Eolic Dunes of Barrier IV, as well as revealing the interdunal wetland areas.

The hydric dynamics of the wetlands are directly related to precipitation, recording higher apparent water levels during neutral periods and the El Niño phase, and lower levels during La Niña periods.

The variability of the average NDVI values in each geomorphological compartment showed differences during the occurrence of La Niña, Neutral, and El Niño events. These values exhibited a distinct spatial pattern, particularly between Lagoon Terrace II, the site of Peixe Lagoon.

The pedoenvironmental indicators allowed for the identification of pH as a common element in all compartments with hydromorphic soils. Sulfur concentrations were found in the Lagoon Terraces and salt marsh areas due to their proximity to ocean waters. The dye solution a,a'-dipyridyl proved effective in indicating the redox environment that influences the levels of pedogenic iron oxides.

The hydrogeomorphological compartments in the PNLP occur where hydrological conditions, driven by the characteristics of the climate, geology, soils and flat topography, cause surface saturation lasting long enough to form hydromorphic soils and favor vegetation adapted to the wet conditions.

However, it is important to emphasize that establishing hydrogeomorphological compartmentalization in coastal wetlands remains a challenge, considering the similarity between markedly flat morphologies. It is essential to note that our analyses were specific to PNLP, located in the Coastal Plain of Rio Grande do Sul, in a segment of the coast that is quite unstable from a sedimentary perspective, both due to the dynamics imposed by the Ocean and by eolic and meteorological actions. Due to the geological and geomorphological formation, the hydrography is poorly developed and intermittent. The hydrological behavior is characterized by the overflow of lagoons due to flooding pulses, as well as by the proximity to the water table, connecting lagoons and marshes.

Finally, we hope that these analyses can contribute to expanding hydrogeomorphological knowledge in coastal AUs, and about the AUs of the PNLP in particular, in order to promote environmental protection policies for wetlands.

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