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Geo-environmental Analysis of Watersheds on the Eastern Coast of the State of Maranhão, Brazil and Interface with Lençóis Maranhenses National Park

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ABSTRACT

Watersheds occupy a vulnerable position with regards to issues associated with anthropogenic changes. The state of Maranhão stands out in Brazil for its water resources. The Watersheds of the Eastern Coast of Maranhão (ECWSM) are located in the Hydrographic Region of the Western Atlantic. The present paper characterizes the physiography of the ECWSM of Maranhão, highlighting the components and natural potential (altimetry, declivity, soils, vegetation, water resources, geology and geomorphology), which were mapped using geotechnologies and secondary data. Thus, this paper provides information for the planning of socioeconomic development programs as well as land management plans. The geology, geomorphology, pedology and vegetation data were obtained from the IBGE database at a scale of 1:250,000. The Digital Elevation Model was obtained from the TOPODATA project. Water resources data were obtained from the IBGE, National Water Agency. The ECWSM analyzed were: the Hydrographic Basin System of the Rivers Itatuaba, Anajatuba, Axuí, Mapari, Periá, Grande and the Hydrographic Basins of the Negro and Preguiças Rivers. The morphological and physical attributes of the ECWSM and the relationships of ecological potential (geology, geomorphology, hydrology and climate), biological exploitation (soil and vegetation) and human actions reveal proxies of the evolution of the Holocene landscape. The natural resources and landscape of Conservation Units within these watersheds form immense nurseries for biological productivity that supports traditional economic activity. The mapping of the ECWSM contributes to the development of effective environmental zoning in the region.
Keywords: Geosystems; Amazon Biome; Cerrado Biome; Conservation units.

Análise Geoambiental das Bacias Hidrográficas do Litoral Oriental do Maranhão e Interface com o Parque Nacional dos Lençóis Maranhenses

RESUMO

As bacias hidrográficas ocupam uma posição vulnerável em relação às questões associadas às mudanças antrópicas. O estado do Maranhão se destaca no Brasil por seus recursos hídricos. As Bacias Hidrográficas do Litoral Leste do Maranhão (ECWSM) estão localizadas na Região Hidrográfica do Atlântico Ocidental. O presente trabalho caracteriza a fisiografia do ECWSM do Maranhão, destacando os componentes e potencialidades naturais (altimetria, declividade, solos, vegetação, recursos hídricos, geologia e geomorfologia), que foram mapeados utilizando geotecnologias e dados secundários. Assim, este artigo fornece informações para o planejamento de programas de desenvolvimento socioeconômico, bem como planos de gestão da terra. Os dados de geologia, geomorfologia, pedologia e vegetação foram obtidos do banco de dados do IBGE na escala 1:250.000. O Modelo Digital de Elevação foi obtido do projeto Topodata. Os dados de recursos hídricos foram obtidos do IBGE, Agência Nacional de Águas. Os ECWSM analisados foram: o Sistema de Bacias Hidrográficas dos Rios Itatuaba, Anajatuba, Axuí, Mapari, Periá, Grande e as Bacias Hidrográficas dos Rios Negro e Preguiças. Os atributos morfológicos e físicos do ECWSM e as relações de potencial ecológico (geologia, geomorfologia, hidrologia e clima), aproveitamento biológico (solo e vegetação) e ações humanas revelam proxies da evolução da paisagem holocênica. Os recursos naturais e a paisagem das Unidades de Conservação dentro

dessas bacias hidrográficas formam imensos viveiros de produtividade biológica que sustentam a atividade econômica tradicional. O mapeamento do ECWSM contribui para o desenvolvimento de um zoneamento ambiental efetivo na região.
Palavras-chave: Geossistemas; Bioma Amazônia; Bioma Cerrado; Unidades de conservação.

Introduction

Beginning in the 1970s, the protection of the environment, nature, biodiversity and landscapes became the reference for different planning models and ecological-environmental management plans, such as the following programs: Ecological Planning (Mcharg, 1969; Sahraoui et al., 2021), Landscape Planning (Fabos, 1985; Zhang et al., 2020), Environment Planning and Management (Takeuchi; Lee, 1989), Sustainable Territorial Planning (Leitão and Ahern, 2002; Assiri et al., 2021), Integrated Planning (Healey, 1998) and Integrated Watershed Management (Heathcote, 2009; Pourghasemi at al., 2020).

Watersheds occupy a vulnerable position with regards to issues associated with anthropogenic changes. Prior to human interference, hydrographic systems were in a state of dynamic equilibrium. In recent decades, the intensification of changes in land use and coverage in watersheds has altered the dynamics of hydrological systems in terms of evaporation, infiltration and erosion rates as well as surface and subsurface regimes, and has also compromised water availability and quality (Shrestha et al., 2018; Martins and Galvani, 2020).

The state of Maranhão stands out in Brazil for its water resources. The Watersheds of the Eastern Coast of Maranhão (ECWSM) are located in the Hydrographic Region of the Western Atlantic, which has large genuinely state basins (Bandeira, 2013) with high biodiversity (Ab'Saber, 1977). Three of the six biomes found in Brazil are present in Maranhão, along with ecotones that run from the Amazon to the *Cerrado* (savanna biome) and the transition from the *Cerrado* to the *Caatinga* (xeric shrubland and thorn forest) (Stella, 2011).

Watersheds are socioenvironmental systems with a high degree of complexity. Their integrating properties make these basins an integral system not only from the water standpoint, but also due to the interaction of characteristics in terms of geomorphology, geochemistry of the landscape and physical geography. Thus, watersheds are fundamental to the ecology of landscapes, serving as complex functional systems and the basis for the management of nature as socioeconomic, ethnodemographic and cultural entities (Korytny, 2017; Gou et al., 2021).

According to Soares et al. (2017), the integrated planning of watersheds is necessary, as it assists in the management of the land unit and its implementation depends on a set of interdisciplinary factors for a systemic assessment of environmental dynamics. Thus, the implementation of predictive complementary planning assists in the reduction of conflicts, strengthening recovery, preservation and conservation actions as well as the management of natural ecosystems to improve the quality of life of the communities.

The state of Maranhão is divided into 12 watersheds. This division was formalized by State Decree nº 27.845, from November 18th, 2011, following as study conducted by the State University of Maranhão. The state government took on the commitment to implement an integral water resource and watershed program. Despite the issuing of a summary report by the State Water Resource Plan in 2021, the watersheds of the eastern coast of the state have not yet been demarcated on a detailed scale. To date, only the watershed system of the Periá River and Preguiças River have been mapped.

There is a lack of studies on the water resources and socioenvironmental dynamics of the ECWSM, especially in the context of the ecology of the landscapes, planning and management. The region has high socioeconomic and environmental potential, as it establishes an interface with Lençóis Maranhenses National Park and the adjacent coastal zone, which is a fundamental tourism center for the social and economic development of the communities in the basins.

Historically, environmental management in the watershed is not part of the sectorial public polices of the state of Maranhão. Despite the fact that these areas have considerable importance on the national stage, with large reserves of natural resources, the natural and hydrological potentials are unknown. Water resources in Brazil, particularly in the state of Maranhão, are under severe pressure from both biotic and social factors. The main causes for this are the increase in the population, the loss of forest cover for other uses, the advance of itinerant agriculture, degradation caused by illegal deforestation, forest fires, etc. The set of problems that affect the ECWSM underscore the need for emergency action in the form of conservation policies for water resources in the region.

The characterization and territorial environmental zoning of watersheds are instruments of the National Environmental Policy of Brazil. Watersheds are the basis for proper territorial planning taking into account the physical and biological changes of the natural resources present in them (Fontes; Pejon, 2008). Alilou et al. (2019) demonstrate the importance of investigating the characteristics of watersheds in Iran in terms of climatic vulnerability, geology-erosion, morphometric characteristics, and water quality, showing the importance of geoenvironmental characterization of watersheds. Doad et al. (2021) state that there are specific natural and anthropogenic factors that affect geo-environmental quality and are the basis of assessment studies of any area, along with spatial database that affects the natural environment, such as watersheds, such as geology, pedology, geomorphology, hydrology, climate, relief, and vegetation.

The present paper characterizes the physiography of the ECWSM of Maranhão, highlighting the components and natural potential (altimetry, declivity, soils, vegetation, water resources, geology and geomorphology), which were mapped using geotechnologies and secondary data. Thus, this paper provides information for the planning of socioeconomic development programs as well as land management plans.

Material and methods

Study area

The state of Maranhão is environmentally characterized by its natural domains of a transition zone (the Cocais) situated predominantly in the central region of the state, the *Cerrado* biome in the eastern portion and the Amazon biome located in the southwestern region. The state has seven microregions and is bordered by the Atlantic Ocean to the north.

The ECWSM are important units for the state due to relevance in the national scenario of water resources. These watersheds occupy an approximate area of 10,238.90 km² and a perimeter of approximately 1,597.12 km.

Each watershed can be seen as a distinct system that results from the interaction of geological, geomorphological, oceanographic and climatic components, together with the flora and fauna, which mold social, cultural and economic factors. Considering the expansive water network of the state of Maranhão, the ECWSM were inserted in the Hydrographic Region of the Western Atlantic, offering the opportunity for studies that can contribute to the detailed mapping of these distinct territorial units (Figure 1).

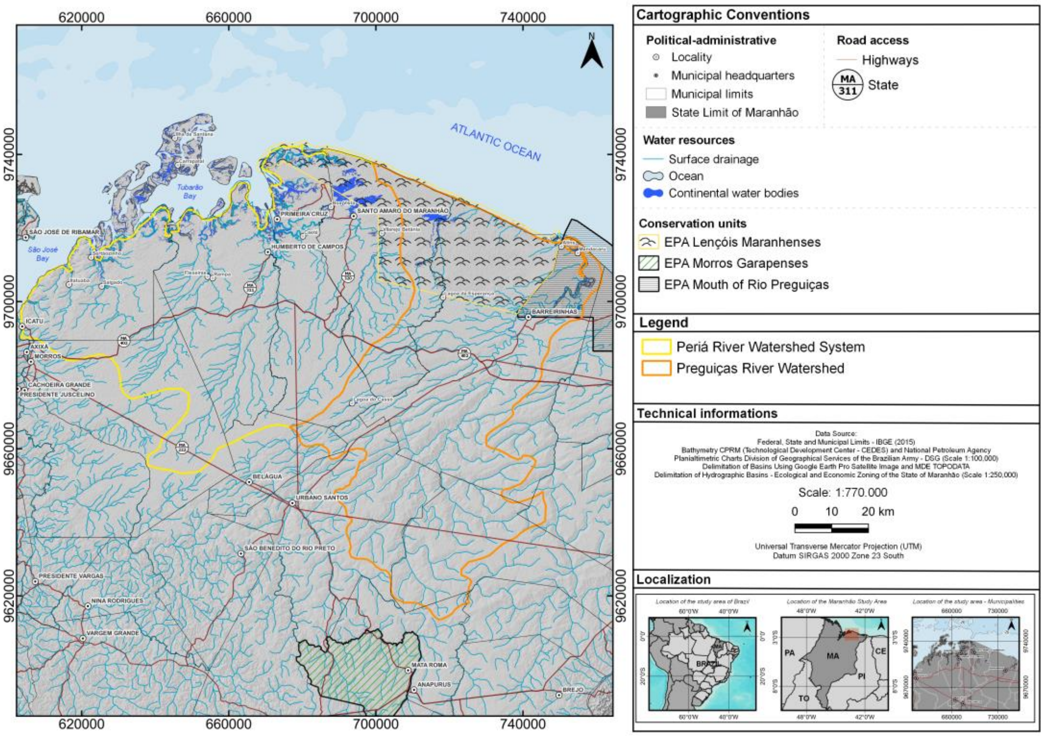

Figure 1. Location of ECWSM state of Maranhão, Brazil mapped by Cerrado Biome Ecological and Economic Zoning.

The state of Maranhão conducted technical studies to define zones of land management and planning of the Amazon and *Cerrado* biomes, known locally as Ecological and Economic Zoning (ZEE).

The ECWSM analyzed were the systems of the Itatuaba, Anajatuba, Axuí, Mapari, Periá and Alegre/Grande River as well as the watersheds of the Negro and Preguiças Rivers. These systems pass through the municipalities of Anapurus, Barreirinhas, Belágua, Cachoeira Grande, Humberto de Campos, Icatu, Morros, Paulino Neves, Primeira Cruz, Santa Quitéria do Maranhão, Santana do Maranhão, Santo Amaro do Maranhão and Urbano Santos (Figure 2).

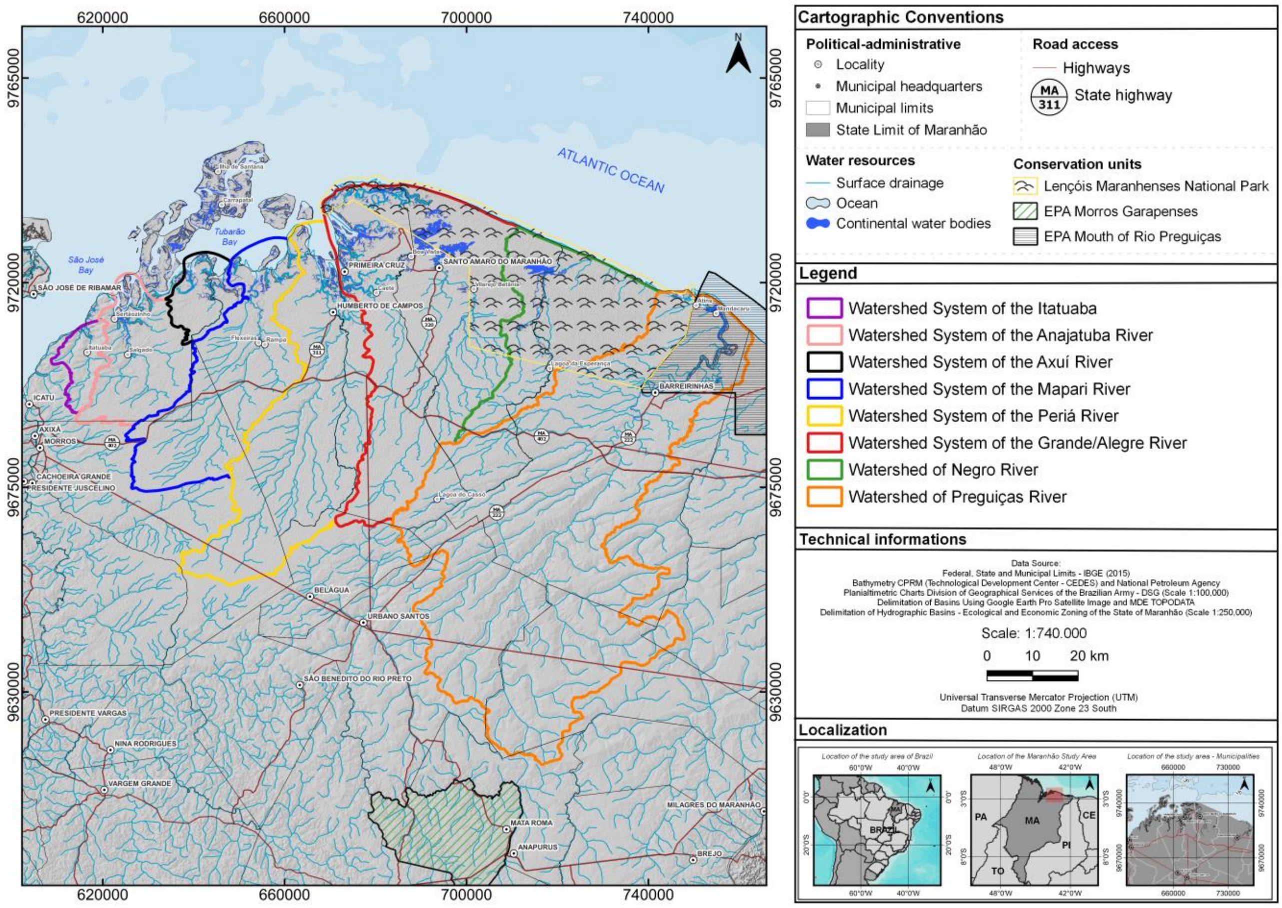

Figure 2. Location of ECWSM state of Maranhão, Brazil mapped by Cerrado Biome EEZ.

Mean annual rainfall in the region is 2000 millimeters, as indicated by the historical dataset (1975-2019). The two distinct periods are a rainy season, which normally occurs between January and June, and a dry season between August and December (INMET, 2020). Lençóis Maranhenses National Park also known as the “Brazilian Sahara”, is located on the eastern coast of the state and has an area of 155 thousand hectares that preserve a unique ecosystem of dunes, inter-dune lagoons, mangroves and coastal vegetation, with considerable potential for the development of studies directed at environmental conservation, management and monitoring (Parteli et al., 2006; Dos Santos et al., 2019; ICMBIO, 2020).

Data and methods

Methodologically, the research is classified as developing an applied approach, since "it aims to generate knowledge for practical application directed to the solution of specific problems that involve local truths and interests" (Prodanov; Freitas, 2013), in this research, at the level of watersheds.

Regarding the objectives, this study is classified as exploratory and applied at the level of watersheds, because "aims to provide more information on the subject, generating knowledge for practical application directed to the solution of specific problems and involving truths and local interests" (Prodanov; Freitas, 2013), is developed in order to approach and explore a subject with little accumulated knowledge. In addition to being exploratory, this research is also classified as having a descriptive character, because "its primary objective is to describe the characteristics of certain phenomena, establishing relationships between variables" (Gil, 2008).

In the design of technical procedures, the research is classified as a documentary and bibliographic research, substantiated with an empirical field approach, with on-site data collection in the study area (Lakatos; Marconi, 2021).

Theoretical-qualitative data were collected through the literature in the form of books, articles and other collections accepted by the scientific community. Data on geoenvironmental aspects of the study area as well as bibliographic and cartographic sources used for the regional and typological limits were provided by public institutions and are summarized in Table 1.

Table 1. Summary of databases used in present study.

Cartographic bases	Scale	Year	Sources	Address
Geology	1:250,000	2021	IBGE	https://geoftp.ibge.gov.br/informacoes_ambientais/geologia/levantamento_geologico/vetores/escala_250_mil/versao_2021/
Digital elevation model	30 meters	2005	INPE	SRTM - TOPODATA http://www.webmapit.com.br/inpe/topodata/ (Valeriano, 2005).
Geomorphology	1:250,000	2021	IBGE	https://geoftp.ibge.gov.br/informacoes_ambientais/geomorfologia/vetores/escala_250_mil/versao_2021/
Pedology	1:250,000	2021	IBGE	https://geoftp.ibge.gov.br/informacoes_ambientais/pedologia/vetores/escala_250_mil/versao_2021/
Vegetation	1:250,000	2021	IBGE	https://geoftp.ibge.gov.br/informacoes_ambientais/vegetacao/vetores/escala_250_mil/versao_2021/
Territorial limits	1:250,000	2019	IBGE	https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/15774-malhas.html?=&t=acesso-ao-produto
Roadways	1:250,000	2015	DNIT	https://servicos.dnit.gov.br/vgeo/
Hydrography	1:250,000	2019 2021	EEZ MA	Maranhão Ecological and Economic Zoning (EEZ) (http://zee.ma.gov.br/)
Hydrography	1:1,000,000	2017	ANA	https://metadados.ana.gov.br/geonetwork
Precipitation	~5 km	2001 to 2021	CHIRPS	Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY
Temperature of land surface	~1 km	2001 to 2021	MOD11A2	MOD11A2 Terra Land Surface Temperature and Emissivity 8-Day Global 1km https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD11A2
State of Maranhão Conservation Units	1:250,000	2019 2021	EEZ MA	Cartographic data of EEZ Maranhão (http://zee.ma.gov.br/)

The *Cerrado* Biome and Coastal System ZEEs show the scarcity of precipitation and fluviometric stations in the region. Thus, climate data were obtained using the Google Earth Engine platform (https://earthengine.google.com/). Climate graphs of the municipalities were created with data obtained from the precipitation database of the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) using the Python language, which is a precipitation dataset developed by the United States Geological Survey and Climate Hazards Group at the University of California, Santa Barbara (UCSB). CHIRPS has a spatial resolution of 0.05º (approximately 5 km) near the equator, geographic coverage of 50ºS to 50ºN, with data from 1981 to the present day and is available in a daily dataset as well as five-day and monthly mean data.

Day and night land surface temperature data were obtained from the MOD11A2 V006 product (Wan, 2013) made available by NASA (https://search.earthdata.nasa.gov/). MOD11A2 provides average soil surface temperature under clear-sky conditions of the MOD11A1 over an eight-day period and was selected due to the fact that its images have fewer invalid pixels as a result of cloud contamination. This product has a spatial resolution of 1 × 1 km in a sampling grid of 1200 × 1200 km.

These models resulted in summary tables and thematic maps on two scales: (i) regional

(1:250,000) and (ii) municipal — watersheds (1:100,000), revealing the potentials and limitations of the region, using QGIS software version 3.22.4 LTR. For such, the ECWSM were sectorized using data with ecological and landscape potential (geology, geomorphology, hydrology and climate), biological exploitation (soil and vegetation) and activities in conservation units.

Results and discussion

Altimetry

The aim of the altimetry analysis of watersheds is to enable observations on the stages of evolution of the relief and assess the influence of geological and tectonic factors on the topography and its modifications. The region has altitudes with a predominance of more plain surfaces and higher elevations in the southern portion of the study area. Some locations are up to 148.56 m in this region (Figure 3).

The terrain in the aera has distinct characteristics. In the lower course of the watersheds, the relief has low declivity, with a quite heterogeneous hydric characteristics and the drainage of ephemeral and intermittent channels due to the porous sedimentary typology (sand). In the middle and upper course of the watershed systems of the Itatuaba, Anajatuba, Axuí, Mapari, Periá, Grande and Negro Rivers, inter-dune lagoons are found, formed by shifting barchan and barchanoid dunes. In the wetlands adjacent to Lençóis Maranhenses National Park, the medium-size drainage channels are mainly perennial, with shallow inter-dune drainage valleys. These characteristics apply to all the ECWSM (Gastão and Maia, 2010).

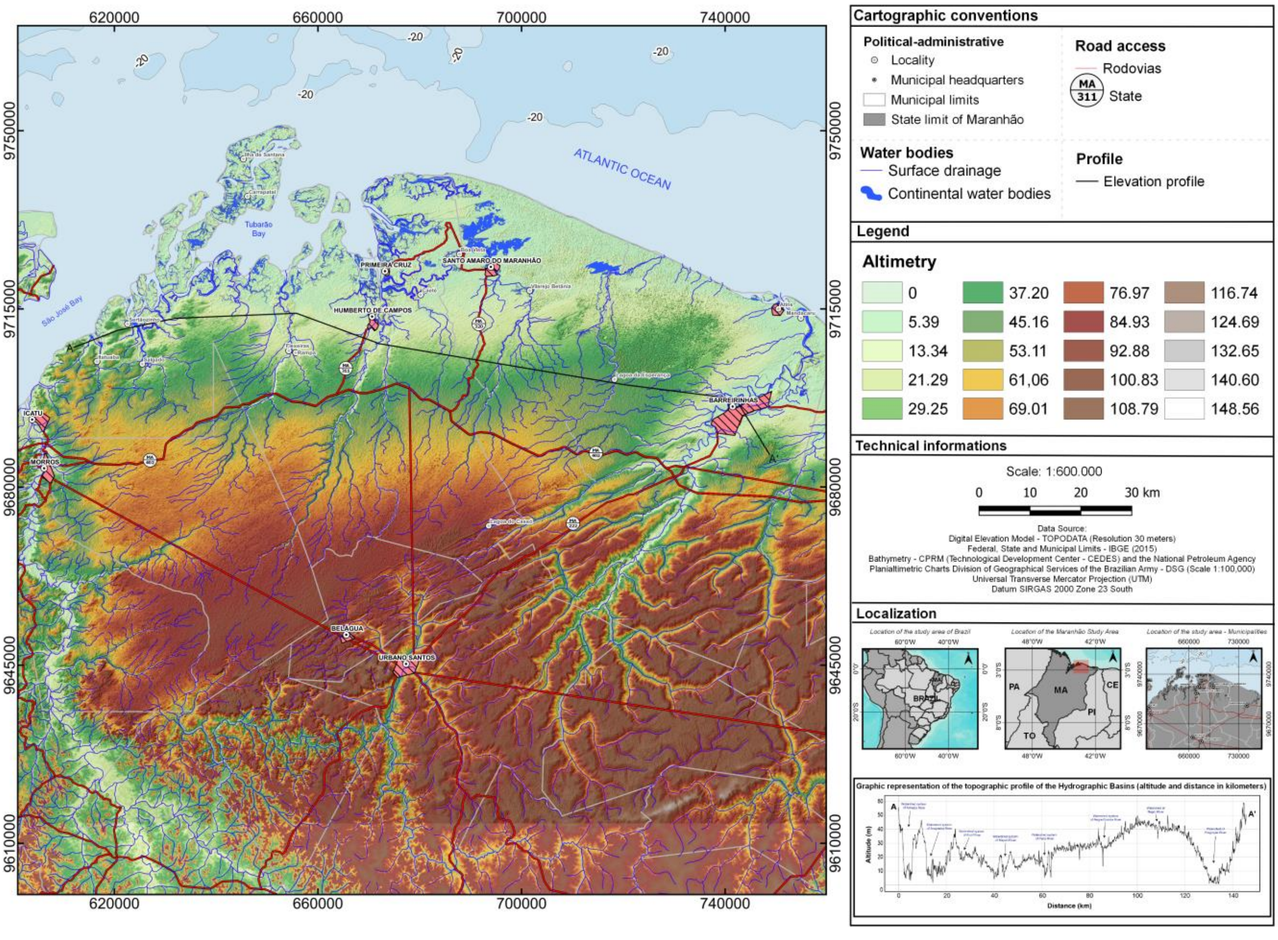

Figure 3. Altimetry map of eastern coast of state of Maranhão, Brazil.

The watershed of the Preguiças River has some distinctions from the others. A field of inactive dunes is found in the upper course of the river with arboreal-shrub vegetation and drainage channels, most of which are perennial, but also with the presence of intermittent and ephemeral channels. The right bank of the upper course has winding and straight channels, with a field of inactive paleo dunes, where the relief is quite smooth, with few undulations (Gastão and Maia, 2010; De Jesus and Barreto, 2021).

The graph of the profile of the ECWSM shows the difference in the relief throughout the study area, which ranges from approximately 2 m up to around 58 m (Figure 4). The longitudinal profile of the ECWSM shows the relief of the coastal zone, for which Ab'Saber (1977) describes the influence of structural lineaments possibly due to more recent tectonic events and formed by different reliefs, the presence of lineaments (columnar joints) and erosive process of the Barreiras Group induced by the drainage network of the region.

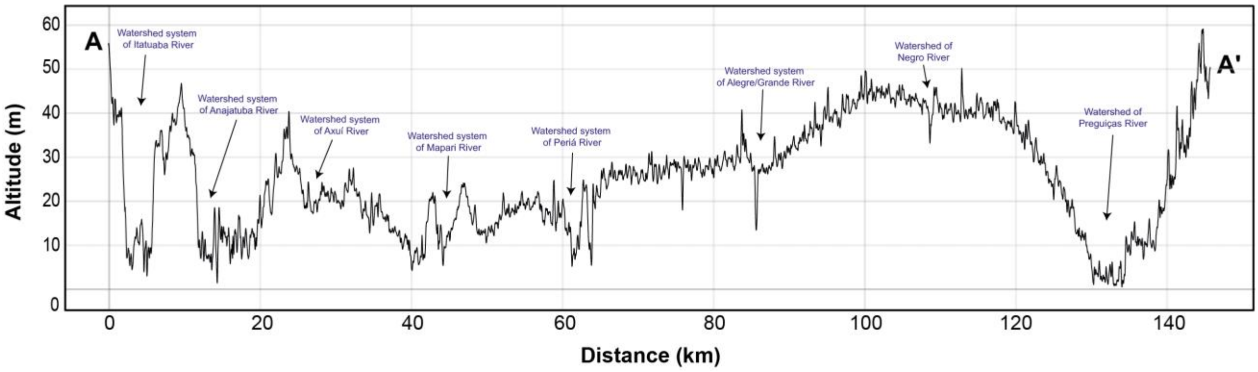

Figure 4. Topographic profile of ECWSM of state of Maranhão, Brazil.

Geology

The region has a formation geologically based on sedimentary basins, which are formed by rocky clusters with ages less than 600 million years, denominated phanerozoic (Figure 5), and are composed of the most diverse sedimentary rocks, such as sandstone, siltstone, mudstone, conglomerates and limestone, as well as a large diversity of animal and plant fossils from the period of 380 million years ago to the terminal Pleistocene (last 10,000 years). The recent alluvium (Pleistocene), which is deposited along the river valleys, is derived from fluvial activities (Santos, 2008; Bandeira, 2013).

Particularly in terrestrial environments, records of deposits from the Pleistocene constitute one of the most important archives for revealing atmospheric circulation patterns over thousands of years (Rossetti; Bezerra and Dominguez, 2013). In the region, shifting dunes (barchan, barchanoid, transverse and frontal) and the strip of beach form an interface with Lençóis Maranhenses National Park and ECWSM. The transport of sand by the wind plays an important role in the creation of new dunes and sedimentary composition, which assists in understanding the relation between the climate and the deposition of sediments during the Quaternary.

In the ECWSM, the chrono-stratigraphic aspect encompasses quaternary units with ages ranging from the Cretacean to the Quaternary, denominated Pleistocene Eolian Loess, Holocene Alluvium Deposits, Holocene Swamp and Mangrove Deposits, Pleistocene Littoral Dune System Deposits, Holocene Fluviomarine Deposits, Holocene Littoral Deposits, Itapecuru formation (Table 2 and Table 3).

Holocene Swamp and Mangrove Deposits have predominantly pelitic, clay-silty sediments with a large portion of organic matter, wood scraps and shells in fluvial-marine and/or coastal environments with mangrove vegetation. Holocene Coastal Eolian Deposits have well-rounded bimodal sand of fine to medium granulation and medium-size to large cross stratifications and a deflated surface, well-selected quartz sands of fine to medium granulation with rounded grains (Klein and Lopes, 2011).

The geological features that stand out for the dislocation zones and faults indicate that the ECWSM had a prolonged geological evolution that led to the development of various types of rocky beds and different structural zones and the erosion of the upper sedimentary package of the Parnaíba Sedimentary Basin, and influenced the evolutionary system of the continental margin sedimentary basins, some of which are still active (tectonic and neotectonic events) (Dantas et al., 2013).

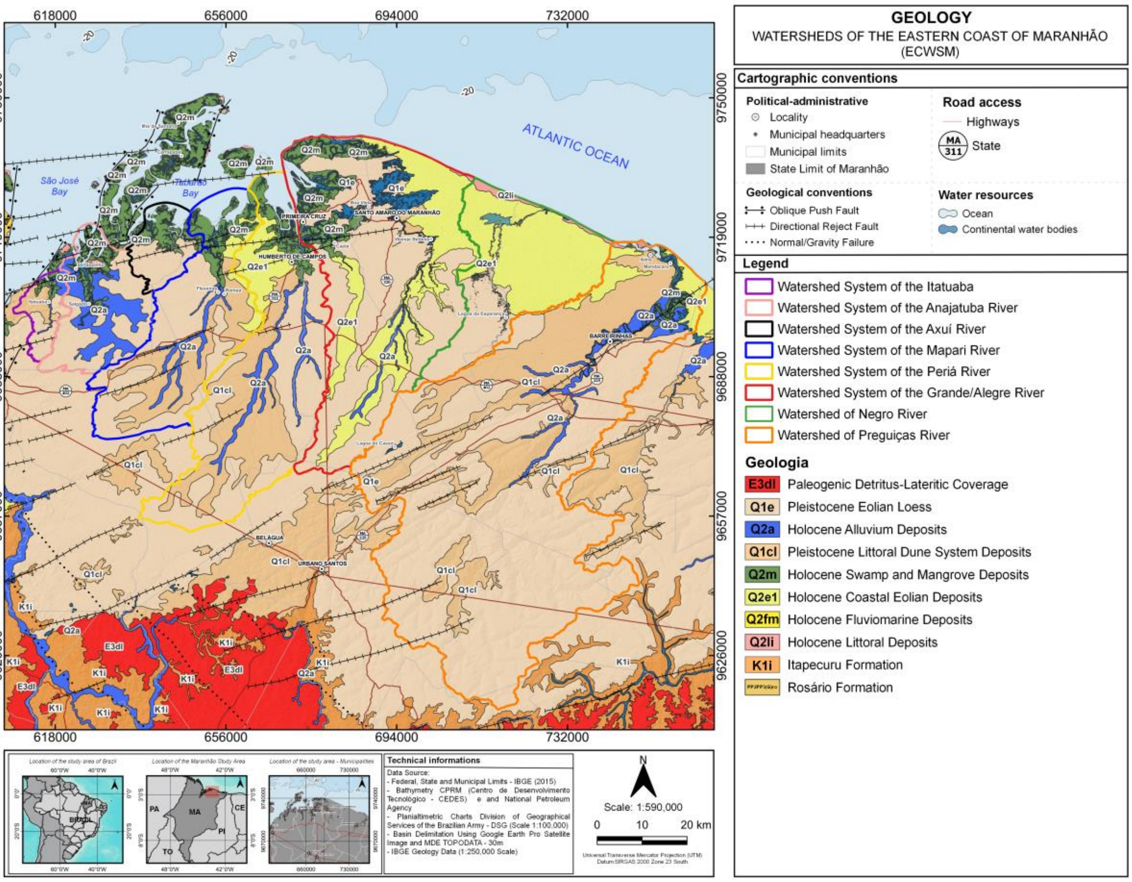

Figure 5. Geology das ECWSM of state of Maranhão, Brazil.

Table 2. Geological units of ECWSM, Brazil.

Watershed	Geological units
Watershed System of the Itatuaba River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Holocene Swamp and Mangrove Deposits, Pleistocene Littoral Dune System Deposits
Watershed System of the Anajatuba River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Holocene Swamp and Mangrove Deposits, Holocene Littoral Deposits
Watershed System of the Axuí River	Pleistocene Eolian Loess, Holocene Swamp and Mangrove Deposits
Watershed System of the Mapari River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Pleistocene Littoral Dune System Deposits, Holocene Coastal Eolian Deposits, Holocene Swamp and Mangrove Deposits
Watershed System of the Periá River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Pleistocene Littoral Dune System Deposits, Holocene Coastal Eolian Deposits, Holocene Swamp and Mangrove Deposits
Watershed System of the Alegre/Grande River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Pleistocene Littoral Dune System Deposits, Holocene Swamp and Mangrove Deposits, Holocene Coastal Eolian Deposits, Holocene Fluviomarine Deposits
Watershed of Negro River	Pleistocene Eolian Loess, Holocene Coastal Eolian Deposits, Pleistocene Littoral Dune System Deposits, Holocene Littoral Deposits
Watershed of Preguiças River	Pleistocene Eolian Loess, Holocene Alluvium Deposits, Pleistocene Littoral Dune System Deposits, Holocene Swamp and Mangrove Deposits, Holocene Coastal Eolian Deposits, Holocene Littoral Deposits, Itapecuru formation

Source: The authors.

The fluvial, fluvial-lacustrine or fluvial-marine plains, coastal plains and dune fields account for the largest part of the geology and geomorphology of the ECWSM.

In the coastal zone, these geological domains occur as Holocene terraces and are beach deposits with incipient pedogenesis that sustain *Restinga* vegetation (coastal vegetation on sand), corresponding to variations in sea level during the Quaternary. Littoral Eolian Deposits are generally characterized by low, slightly undulating surfaces with a smooth declivity toward the sea and occurring along beaches throughout the entire coastline (Klein and Lopes, 2011; Fernandez et al., 2019).

Table 3. Chrono-litho-stratigraphic sketch of the of ECWSM, Brazil.

	Eon	Era	Period	Epoch		10^6 years	Geological unit
	PHANEROZOIC	CENOZOIC	Quaternary	Holocene		0,01	Q2a – **Holocene Alluvium Deposits:** Thick deposits to conglomeratic from channel residuals, sandy relative to point bar, pelitic represented to those of overflow and fluviolacustrine, eolian when worked by wind.
							Q1cl – **Holocene Swamp and Mangrove Deposits:** Predominantly pelitic, clayey-silt sediments, with lots of organic matter, wood remains, and shells, in a riverine and/or coastal environment, with mangrove vegetation.
							Q2e1 – **Holocene Coastal Eolian Deposits:** Well rounded bimodal sand, matte grained, fine to medium grained and medium to large cross stratifications and deflation surface. Quartz sands of fine to medium grain size, well selected and with rounded grains.
							Q2li – **Holocene Littoral Deposits:** quartz sands of transitional coastal environments (coastal dunes, beaches, sandy plains, and old coastal ridges).
				Pleistocene		1,75	Q1e – **Pleistocene Eolian Loess:** Areia bimodal, bem arredondada, grãos fosco, de granulação fina a média e estratificações cruzadas de médio a grande porte.
							Q1cl – **Pleistocene Littoral Dune System Deposits:** Depósitos grossos a conglomeráticos de residuais de canal, arenosos relativos a barra em pontal, pelíticos representado àqueles de transbordamento e fluviolacustres, eólicos quando trabalhados pelo vento.
			Tertiary	Neog.	Pliocene	23,5	
					Miocene		
				Paleog.	Eocene	65	E3dl – **Coberturas Detrito-Laterítica Paleogênica:** at the base, kaolinitic clay zone; bauxite zone with concretions and gibbsite lenses; ferruginous concretionary zone; pisolitic nodular zone; clay capping (Latosols), at the top.
					Oligocene		
					Paleocene		
		MESOZOIC	Cretaceous	Upper	Maastrichtian	145	
					Campanian		
					Santonian		
					Coniaciano		
					Turonian		
					Cenomanian		
				Lower	Albian		K1i – **Itapecuru formation:** Constructed of reddish sandstones and siltstones, occurring in subordination whitish sandstones, grayish and purplish leaflets. Predominance of sandstones; predominance of argillites. Lagoonal environment, fluvial and tidal channel.
					Aptian		
					Barremian		
					Hauterivian		
					Valanginian		
					Berriasian		
			Jurassic			200	
		PALEOZOIC	Triassic			251	
			Permian			299	
			Carboniferous			359	
			Devonian			416	
			Silurian			444	
			Ordovician			488	
			Cambrian			542	
Pre-Cambrian	PROTEROZOIC	NEOPROTEROZOIC	Ediacaran			635	
			Criogenian			850	
			Tonian			1.000	
		MESOPROTEROZOIC	Stenian			1.200	
			Ectasian			1.400	
			Caliman			1.600	
		PALEOPROTEROZOIC	Staterian			1.800	
			Orosirian			2.050	
			Riacian			2.300	PP2PP 3(G)ro – **Rosário formation:** It is constructed of quartz diorites, tonalites, granodiorites and andesites.
			Siderian			2.500	
	Archaic					4.000	
	Hadean (Informal)					~4.600	

Source: Adapted from Dantas et al. (2013).

Geomorphology

The geomorphology is quite compartmented in the watersheds of the Itatuaba, Anajatuba, Axuí, Mapari, Periá, Alegre/Grande and Negro Rivers. Coastal plains are found in the lower course of the systems, whereas fluvial plains and terraces occur on the Barreirinhas Tableland in the middle and upper courses. In the middle and lower course, the watershed of the Preguiças River has similarities with systems of the eastern sector of the eastern coast, but the upper course has sublittoral tablelands (Figure 6).

The geomorphology of the ECWSM is directly influenced by morphogenetic processes of erosion, transport and deposition caused by the semiarid climate, which has higher rainfall indices in the months of March and April. The region is formed primarily by quartz with a large quantity of sand that has little tendency toward solidifying and is easily transported by the wind, which causes the formation of immense dune fields that spread throughout the middle of the tablelands of the Barreiras Group and extend 50 to 120 km inland (Soares; Santos; Szlafsztein, 2020).

The municipality of Barreirinhas is the largest in spatial context of the ECWSM and has a hydrogeological domain with unconsolidated sediments of swamp deposits, continental eolian deposits, littoral eolian deposits, and alluvium deposits (CPRM, 2011). The sedimentation patterns influenced by the geomorphological scenario of the mangroves in the lower courses of the watersheds are consolidated by physical forces in the coastal zone.

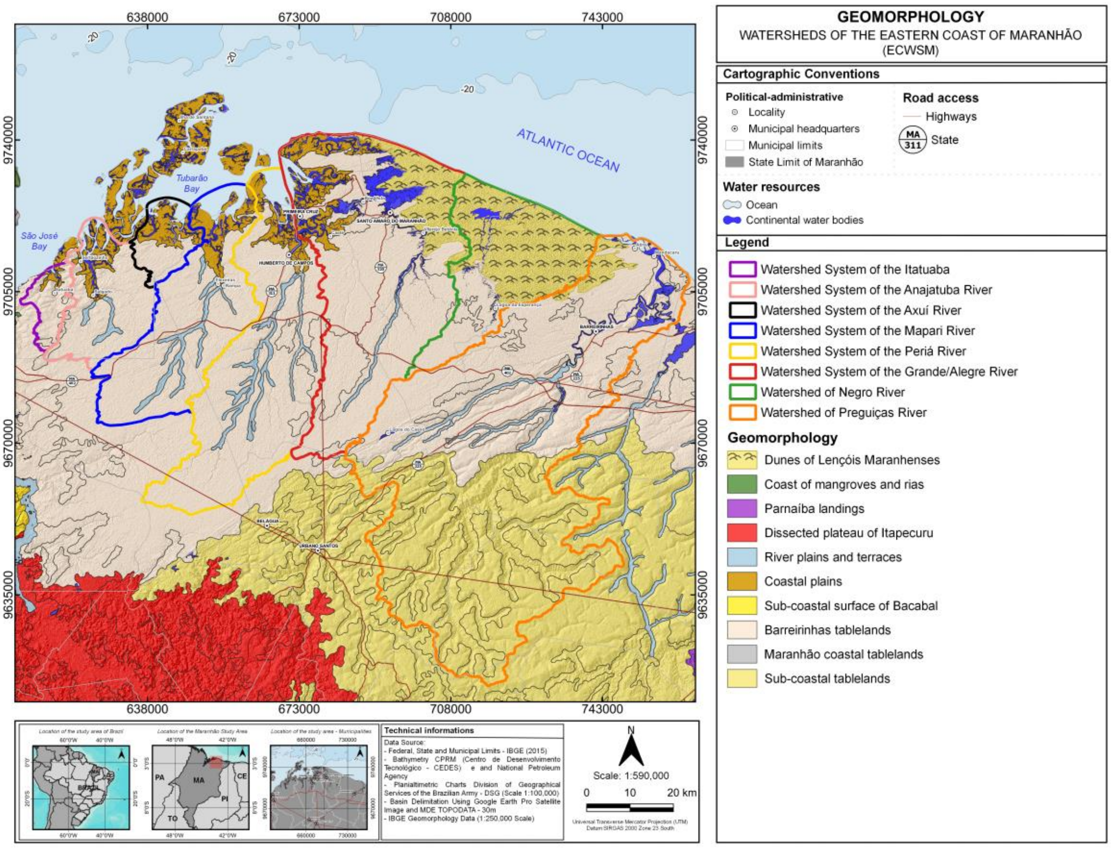

Figure 6. Geomorphology of ECWSM of state of Maranhão, Brazil.

The region of the eastern coast has tablelands, coastal plains and fluvial plains with altitudes less than 200 meters and declivities that do not surpass 30° (Table 4). The sedimentary cover of the Cenozoic region of the Holocene includes sediments of the Barreirinhas Tableland corresponding to the largest lithostratigraphic unit, encompassing quaternary sediments of the coastal strip and alluvial deposits from fluvial plains (CPRM, 2011).

In the ECWSM, the coastal tablelands represent the geomorphological domain. These units underwent progressive modifications, particularly during the recent Pleistocene-Holocene period, influenced by fluctuations in sea level. Paleodunes are also found at a distance of approximately 160 km from the coastline with a preferential NE/SW shifting and areas of well-developed vegetation that attenuate the impact of the wind and the flow of sediments. These tablelands are generally sustained by sedimentary rock with little lithification and characterized by forms of tabular relief that have extensive flat tops, with a predominance of processes of pedogenesis and the formation of thick, well-drained soils with little tendency toward erosive processes (Bandeira, 2013; Gorayeb et al., 2020).

Table 4. Declivity and topographic amplitude of forms of relief identified in ECWSM of state of Maranhão, Brazil.

Relief pattern	Declivity (degrees)	Topographic amplitude (m)
Fluvial and fluvial-lacustrine plains	0 to 3	0
Fluvial-marine plains	0	0
Coastal plains	0 to 5	2 to 20
Dune fields	3 to 30	5 to 40
Tablelands	0 to 3	20 to 50
Dissected tablelands	2 to 5	0 to 20
Conserved plain surfaces	0 to 5	0 to 10
Degraded plain surfaces	0 to 5	10 to 30

Source: Dantas et al. (2013).

Pedology

The soils of the ECWSM were mapped and interpreted according to the Brazilian Soil Classification System (SiBCs) of the Brazilian Agriculture and Livestock Research Company (EMBRAPA) (2018) (Figure 7). There is little diversification in the soils of the ECWSM. The soil classes were associated with the geomorphological compartmentation and grouped into morphopedological units according to Oliveira (2018) and Seara (1988). Predominant soils in the ECWSM: Dunes, orthic thiomorphic gleysol, dystrophic yellow latosol and orthic quartzarentic neosol.

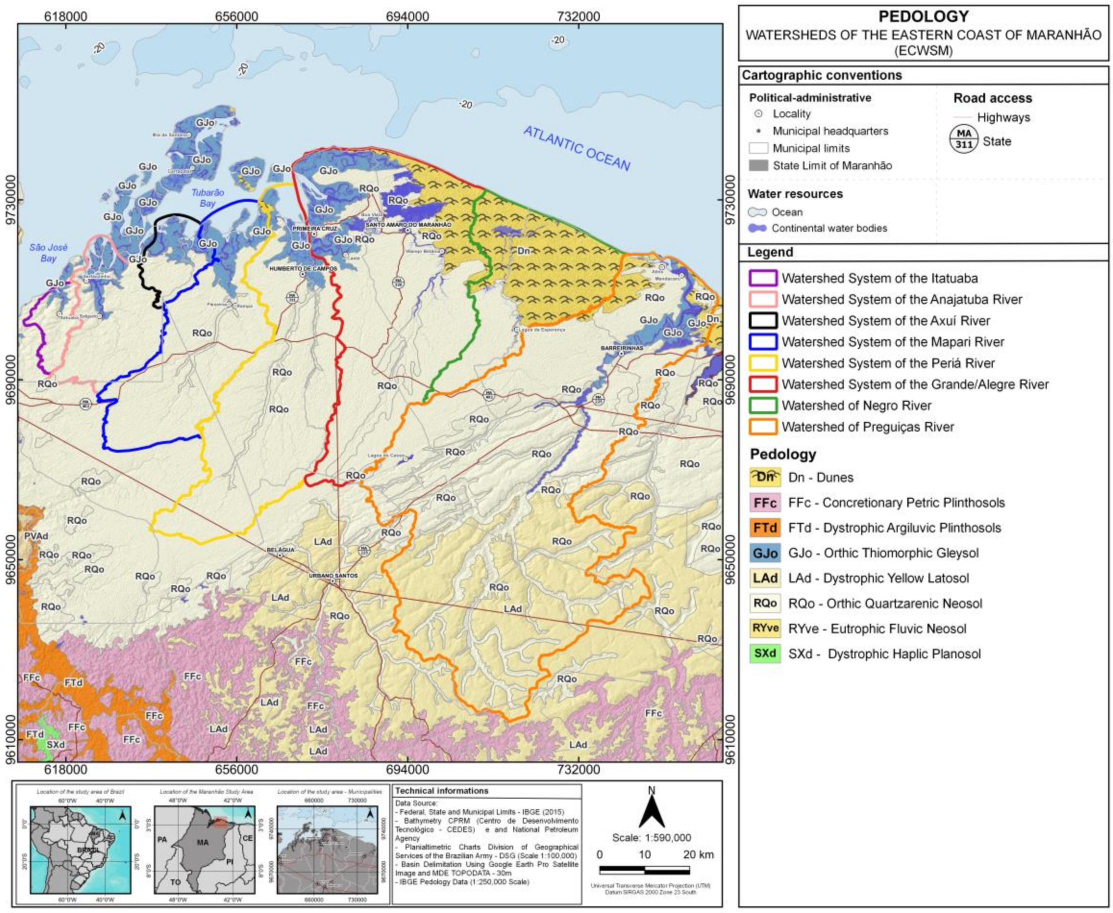

Figure 7. Pedology of ECWSM in state of Maranhão, Brazil.

The soils presented little spatial variation, as the ECWSM are composed mainly of orthic quartzarenic neosols, which, taxonomically, are soils of little development from the Barreiras Group of the Tertiary period and marine sediments of the Holocene period, shallow or of little depth, with no lithic contact within a depth of 50 cm, A-C horizon sequence, essentially quartzous, including coarse and fine sand fractions. Areas of fixed dunes, paleo dunes and pre-littoral tablelands are found in the ECWSM (EMBRAPA, 2018). Table 5 displays the taxonomy and morphopedological units of the ECWSM.

Table 5. Morphopedology of ECWSM of state of Maranhão, Brazil.

Geomorphologic units	**Features of morphology**	**Brazilian soil classification system (EMBRAPA, 2018)**
Coastal plain	Beach strip, marine terrace and shifting dune field	Terrestrial and marine quartzous sediments
	Fixed dune field and paleo dunes	Orthic Quartzarenic Neosol
	Fluvial-marine plain	Orthic Thiomorphic Gleysol
Fluvial-lacustrine plain, lacustrine plain and areas of floodable accumulation	Lacustrine and luvial-lacustrine plains	Combination of Fluvic Neosols and Dystrophic Yellow Latosol
	Areas of floodable accumulation	Orthic Quartzarenic Neosol
Fluvial plain	Fluvial pains of ECWSM	Orthic Quartzarenic Neosol
Fluvial plain of watershed of Preguiças River	Fluvial plain of watershed of Preguiças River	Combination of Orthic Thiomorphic Gleysol and Orthic Quartzarenic Neosol
Sublittoral tablelands	Sandy tablelands	Orthic Quartzarenic Neosol
	Sandy-clay tablelands	Combination of Orthic Quartzarenic and Dystrophic Yellow Latosol

Source: Adapted Oliveira (2018).

Regarding the relation between pedological aspects and the vegetational complex of the coastal plain, the fluvial-lacustrine plains, lacustrine plains and areas of floodable accumulation of the ECWSM occupy areas of orthic quartzarenic neosols, orthic thiomorphic gleysols and a combination of fluvic neosols and dystrophic yellow latosol. The *Cerrado* (savanna) occurs in lixiviated sandstone terrains that have shallow, nitrogen-poor soils and sparse small to medium-size trees with twisted branches and trunks (CPRM, 2011).

Gleysols are hydromorphic mineral soils that remain either permanently or periodically saturated by water, present a gley horizon within 50 cm from the surface or a depth greater than 50 cm and less than or equal to 150 cm provided that they begin immediately below the A or E horizons, do not have a clear division of horizons and are poorly drained (EMBRAPA, 2018). The pedogenesis of the lower courses of the ECWSM has sandy and silty-clay horizons that illustrate the dynamics of marine progradation and retrogradation.

In the ECWSM, orthic thiomorphic gleysols occur on coastal and fluvial-marine plains affected by the semi-diurnal macrotidal regime, with amplitudes that reach up to 7 m in the coastal zone adjacent to Tubarão Bay. These zones remain partially or completly submerged (El-Robrini et al., 2006). Mangrove/*apicum* soils exhibit a clay-silty to clay textural variation. The permanent or semi-permanent water saturation leads to the accumulation of organic matter and the formation of horizons of black coloration (Henriques et al., 2022). When dry, the soils form a massive, low-density structure and the accumulation of salt, if present, increases the firmness/hardness of the soil structure

Dystrophic yellow latosols are deep, non-hydromorphic soils, with A, latosolic B and C horizons. Fertility conditions are low, which explains the dystrophic properties and minimal productive capacity for agricultural use. These types of soil have low natural fertility due to deficiencies in phosphorus, potassium and calcium (EMBRAPA, 2018; Moura et al., 2019). With dystrophic yellow latosol pedological coverage, lithological and pedological conditions favor the infiltration and percolation of water, hindering the emergence of a dense drainage network (Souza and Silva, 2022). In the ECWSM, this class occurs near the drainage network in the upper course of the watershed of the Preguiças River, together with water dividers and near the class of orthic quartzarenic neosols.

Watershed climate graphs

Climate graphs are important to the understanding of the characteristic climate of a given region, identifying dry and wet months and the occurrence or not of well-defined seasons. According to the Köppen classification, the ECWSM have an Aw climate (hot and wet), with a drier period in winter. Based on the climate graphs (Figure 8), all the ECWSM are located in a semi-humid area, with four to five dry months.

The graphs show that nearly all watersheds have an average annual rainfall of approximately 2100 mm, with the exception of the watershed of the Preguiças River, for which the average is approximately 1473 to 1623 mm. The precipitation pattern has considerable variability on the temporal and spatial scales. In a watershed, this pattern determines the volume of river outflow.

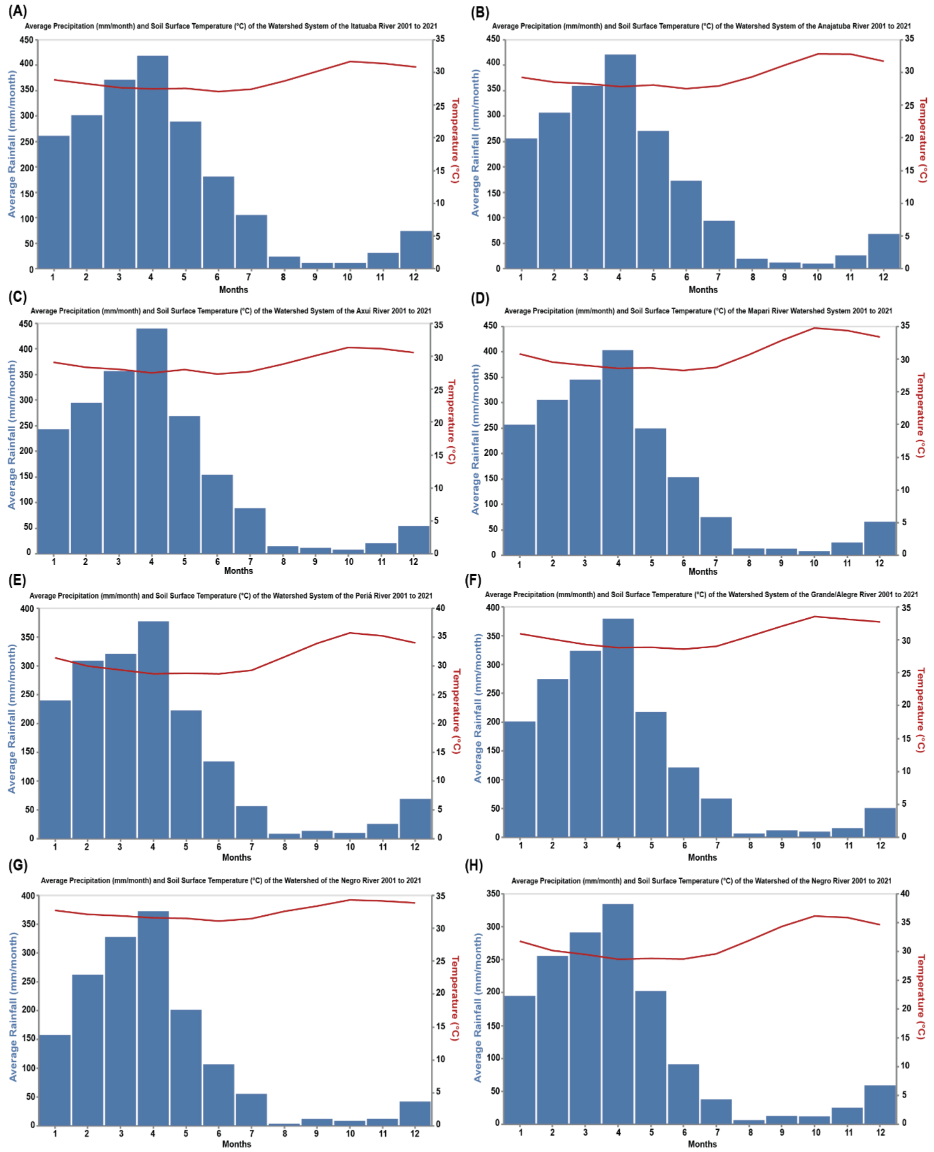

Figure 8. Climate graphs (2001 to 2021) of ECWSM. (A) Watershed system of Itatuaba River; (B) Watershed system of Anajatuba River; (C) Watershed system of Axuí River; (D) Watershed system of Mapari River; (E) Watershed system of Periá River; (F) Watershed system of Alegre/Grande River; (G) Negro River; (H) Watershed system of Preguiças River.

Atmospheric circulation in the region of the ECWSM is directly influenced by the Intertropical Convergence Zone (ITCZ), which is the zone of convergence of the trade winds and has latitudinal movement throughout the year, generating changes in in the heating and cooling patterns of the water surface temperature in the equatorial Pacific and Atlantic (Molion, 1987; Nobre and Shukla, 1996). In its southern movement, the ITCZ reached the latitudes of 2°S to 4°S from February to Abril, reaching 14°N from August to October in response to the increase or reduction in the sea surface temperature in the Atlantic and the variation in the intensity of the trade winds (Hastenrath and Heller, 1977).

Using data from CHIRPS and comparing data from more than 183 meteorological stations of Center for Weather Forecasting and Climate Study of the National Meteorology Institute (INMET/CPTEC), Costa et al. (2019) concluded that the data had high reliability, validating the CHIRPS data for Brazil in the period from 1998 to 2010. Thus, the use of such data for different purposes related to climate studies in Brazil is plausible.

Other atmospheric systems and mechanisms that influence the ECWSM are the El Niño-Southern Oscillation (Pezzi and Cavalcanti, 2001; Kayano and Andreoli, 2009), the variability in the sea surface temperature of the tropical and equatorial Atlantic (Kayano and Andreoli, 2009), lines of instability, which are convective systems that affect interannual variability on the northeast coast of Brazil, eastern waves or eastern undulatory disturbances (Ferreira and Mello, 2005; Coutinho and Fisch, 2007) as well as maritime and terrestrial breezes (Kousky, 1979).

Surface water resources

The surface drainage network was represented spatially using manual vectorization on a scale of 1:50,000, with correction of the sinuosity of the channels and establishing a pattern viewed in the satellite images. The figure 9 enables the determination of the visual difference in the watershed drainage density furnished by ANA, IBGE and the Ecological and Economic Zoning (EEZ) of the Amazon, *Cerrado* and coastal system in relation to the vectorized base in the present study (Table 6). Drainage density is an indicator of the degree of development of a river system and it is therefore important for its mapping to be done in a detailed way.

The fluvial plains in the ECWSM symbolize morphostructures molded by the river in the lower course, which constitutes an area of sedimentation subject to inundation during floods. These are lower zones with alluvial sediments and wetland vegetation distributed throughout the vast fluvial plain and low level of fluvial terraces (CPRM, 2011). The elements of significant importance to geodiversity linked to hydrology in the study area are represented by rivers, most of which are perennial and of touristic interest due to the scenic beauty.

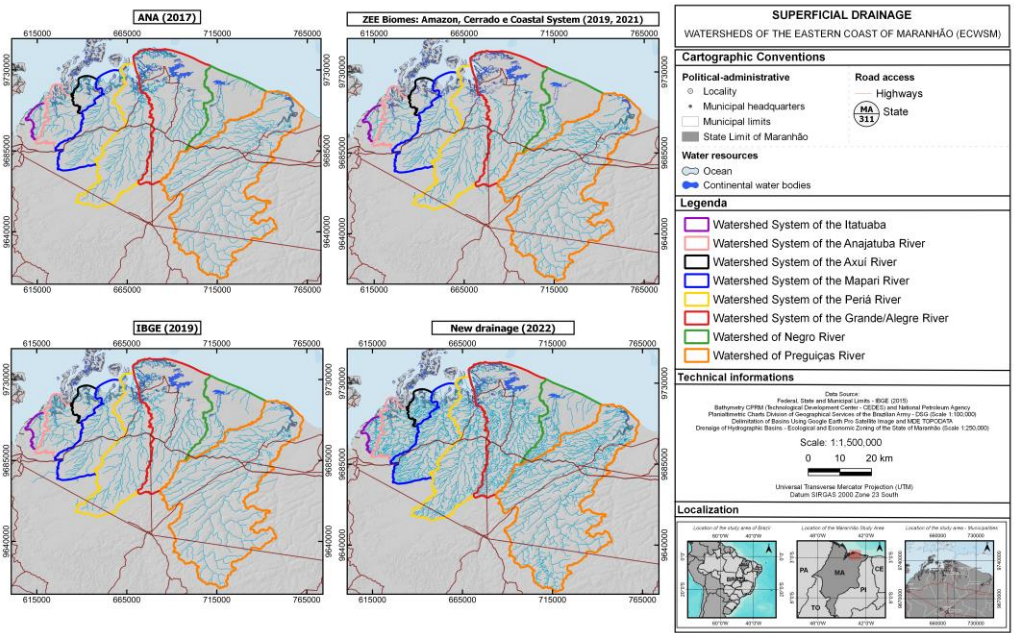

Figure 9. Comparation of water shed of ANA, IBGE, EEZs of Amazônia and *Cerrado* biome and coastal system in relation to that proposed in present study.

Table 6. Comparison of number of drainages stretches in ECWSM according to different databases: ANA, IBGE, EEZ and that proposed in present study.

		Drainage stretches			
Study area	**Watersheds**	ANA (2017)	IBGE (2019)	EEZs of Amazon, *Cerrado* and Coastal System (2019; 2021)	Novel proposal for ECWSM
Watersheds of Eastern Coast of State of Maranhão	Watershed system of Itatuaba River	14	19	10	108
	Watershed system of Anajatuba River	39	64	39	199
	Watershed system of Axuí River	5	60	4	180
	Watershed system of Mapari River	77	120	172	322
	Watershed system of Periá River	117	138		344
	Watershed system of Alegre/Grande River	98	138		552
	Watershed system of Negro River	33	22		129
	Watershed system of Preguiças River	239	183	319	696

Source: The authors.

Geomorphological parameters are considered preliminary indicators of the geology, relief, declivity, climate and hydrodynamics of a river system. Drainage density is defined as the proximity between channels. In the management of watersheds, it is important to determine the behavior of the drainage network and its interactions. For the ECWSM, the results of the analysis of the drainage network show that the relief is flat and with low drainage density in the lower courses.

The watershed system of the Alegre/Grande River has a drainage network with stretches of meandering and anastomosing channels as is endorheic, since it empties into Santo Amaro Lake. The drainage network to the southeast of the shifting dune field has perennial and ephemeral rivers, some of which compose radial drainage, which is an indication of structural control in its development. The watershed of the Negro River has small streams as tributaries, which account for the considerable outflow as well as the dendritic drainage pattern, with stretches of channels alternating from meandering to anastomosing (MMA/IBAMA, 2003; Santos, 2008).

De Jesus and Barreto (2021) analyzed the qualitative drainage properties of the watershed of the Preguiças River, compartmenting the basin spatially into six zones. Zone I has a low degree of integration, continuity and density, unidirectional and low angularity. Zone II has a high drainage density and degree of continuity. Zona III had a high degree of control and high angularity, with an oriented multidirectional, presenting elbow turn anomalies. Zone IV has a low drainage density, oriented multidirectional tropic and medium angularity. Zone V has high drainage density, tri-directional, a medium degree of control and low angularity. Zone VI had low drainage density, disoriented multidirectional, strong degree of control and medium angularity.

Conservation units

A total of 27% of the area of the state of Maranhão (approximately 92 mil km²) is comprised of conservation units, which are divided into Sustainable Use Conservation Units, which include Environmental Protection Areas (EPA) and Extractivist Reserves (RESEX), which occupy approximately 85.8% of this area, whereas Full Protection Conservation Units are represented by parks and biological reserves, which account for only 14.2% (Masullo et al., 2018).

The watersheds of the eastern coast of Maranhão have full protection (Lençóis Maranhenses National Park) and sustainable use Conservation Units (EPA of the mouth of the Preguiças River, Garapenses Hills EPA located in the proximities of the upper course of the Preguiças River, Tubarão Bay RESEX and Upaon-Açu/Miritiba/Upper Preguiças EPA) (Figure 10 and Table 7).

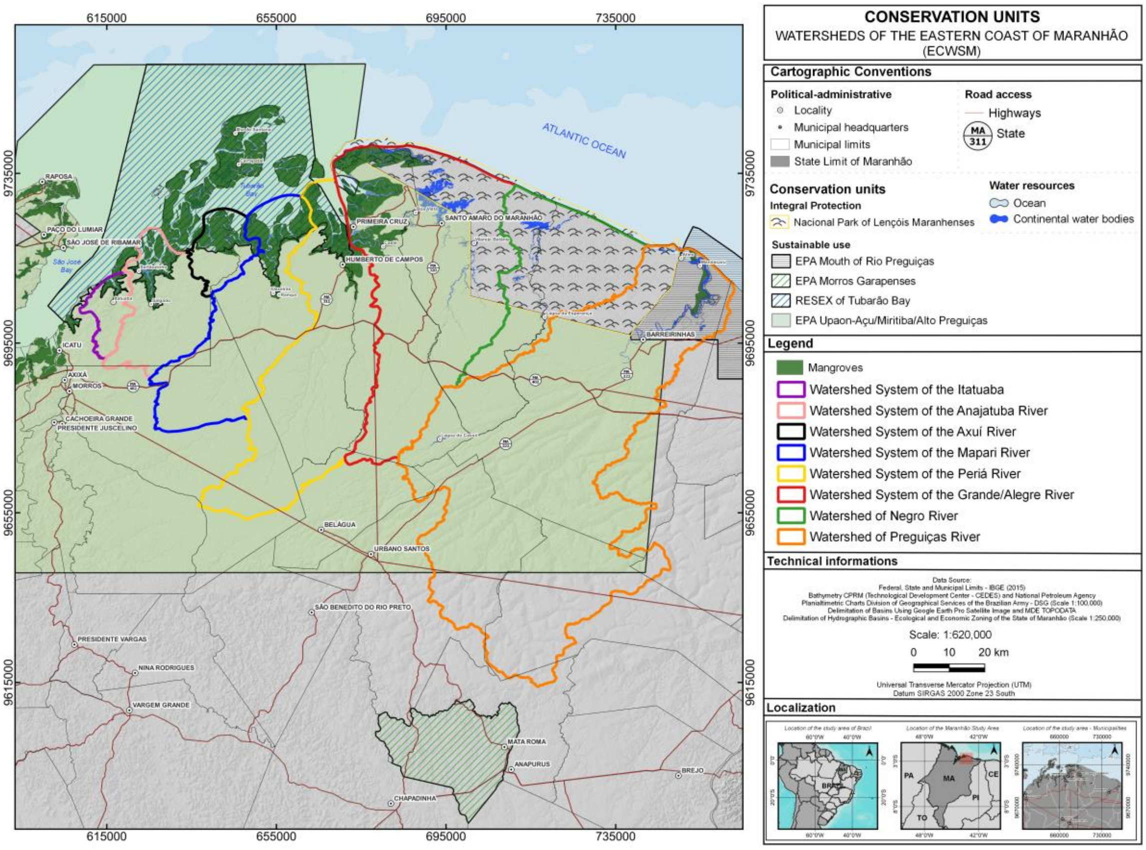

Figure 10. Conservation units on eastern coast of state of Maranhão, Brazil.

Table 7. Characterization of conservation units in ECWSM in state of Maranhão, Brazil.

Conservation unit	Creation	Protection level	Biome	Area	Municipalities (MA)
EPA – Mouth of Preguiças River	Decree - 11.899 – 11 June 1991	Sustainable use	Cerrado, Caatinga, Coast and Marine	2752 km^2	Água Doce do Maranhão; Araioses; Barreirinhas; Paulino Neves; Tutóia
EPA – Garapenses Hills	Decree – 25.087 – 31 Dec 2008	Sustainable use	Cerrado	2347 km^2	Afonso Cunha; Brejo; Brejo de Areia; Buriti; Buriti Bravo; Coelho Neto; Duque Bacelar
EPA of Upaon-Açu/Miritiba/Upper Preguiças	Decree - 12.428 – 5 June1992	Sustainable use	Amazon, Cerrado, Coast and Marine	15,353 km^2	Axixá; Bacabeira; Belágua; Barreirinhas; Cachoeira Grande; Humberto de Campos; Icatu; Itapecuru Mirim; Morros; Nina Rodrigues; Paço do Lumiar; Presidente Juscelino; Presidente Vargas; Primeira Cruz; Raposa; Rosário; Santa Quitéria do Maranhão; Santa Rita; Santana do Maranhão; Santo Amaro do Maranhão; São Benedito do Rio Preto; São José de Ribamar; São Luís; Urbano Santos
Lençóis Maranhenses National Park	Law n° 86.060 2 June 981	Full protection	Cerrado, Coast and Marine	1550 km²	Barreirinhas, Santo Amaro and Primeira Cruz
Tubarão Bay RESEX	Decree nº 9.340, 5 April 2018	Sustainable use	Amazon, Cerrado, Coast and Marine	2239 km²	Humberto de Campos and Icatu

Source: adapted from Masullo *et al.* 2018.

Even with the large number of Conservation Units, a total of 24.6 thousand km^2 of Amazon Forest in the state of Maranhão were cut down in the last 30 years, corresponding to 33% of all deforested areas, whereas 77% had been deforested previously. Currently, only 25% of the original forest cover remains (24.7 thousand km^2), 70% of which is in protected areas (indigenous lands and conservation units), 10% is in agrarian reform settlements and approximately 20% is dispersed among rural properties (Alencar et al., 2016).

Lençóis Maranhenses National Park forms an interface with some of the ECWSM, influencing the water dynamics. There is a moderate availability of surface water resources, such as the Periá, Marciano, Alegre/Grande, Santo Inácio, Baleia, Pequí, Maçangano, Negro and Preguiças Rivers. The watershed of the Alegre/Grande and Preguiças River are the two largest that have a direct interface with Lençóis Maranhenses National Park. Besides the waterbodies cited, there are also the Achuí, Tucuns, Bom Passar, Passagem do Canto, Baixão do Nuritizal, São Domingos, São Bento, Lagoa Grande and Pedro Reira Creeks and the Peixe, Azul, Urubú, Betânia and Bonita Lakes, among others, which exist due to the significant rainfall characteristic of the rainy period and the type of soil in the area (ICMBIO, 2020).

Vegetation

Vegetation and dunes function with a single pattern in the ECWSM. In areas near the mouths of the rivers, the plant-covered dunes have distinct characteristics from those in inland regions. The coastal zone has a vegetation complex that encompasses formations submitted to quite differentiated ecological conditions (Table 8; Figure 11).

Table 8. Vegetation units of ECWSM in state of Maranhão, Brazil.

Watersheds	Comprehensive vegetation units
Watershed system of Itatuaba River	Pioneering Formation with Fluvial-Marine Influence. Secondary Vegetation with palms.
Watershed system of Anajatuba River	Pioneering Formation with Fluvial-Marine Influence. Secondary Vegetation with palms. Arborized Savanna without Gallery Forest.
Watershed system of Axuí River	Pioneering Formation with Fluvial-Marine Influence. Secondary Vegetation with palms. Arborized Savanna without Gallery Forest.
Watershed system of Mapari River	Pioneering Formation with Fluvial-Marine Influence. Arborized Savanna without Gallery Forest.
Watershed system of Periá River	Pioneering Formation with Fluvial-Marine Influence. Arborized Savanna without Gallery Forest. Pastures.
Watershed system of Alegre/Grande River	Dune Field Vegetation. Pioneering Formation with Fluvial-Marine Influence. Pioneering Formation with shrub marine influence. Arborized Savanna without Gallery Forest.
Watershed system of Negro River	Campos de Dunas. Pioneering Formation with herbaceous Fluvial and/or Lacustrine Influence without palms.
Watershed system of Preguiças River	Pioneering Formation with shrub marine influence. Savanna Park without Gallery Forest. Pioneering Formation with herbaceous Fluvial-Marine Influence. Pioneering Formation with arboreal Fluvial-Marine Influence.

Source: The authors.

The composition of the vegetation in the study area can be considered mixed, with natural vegetation comprising species with a marine influence (*Restinga*), fluvial-marine influence (mangrove), fluvial influence (alluvial communities) and the presence of the *Cerrado* (arborized and field) (MMA/IBAMA, 2003). The region is influenced by the combination of evaporation and precipitation rates as well as fluvial and marine processes, with the tide plains colonized by arboreal (mangroves) and herbaceous vegetation (Santos, 2008; Bandeira, 2013; Gorayeb et al., 2020).

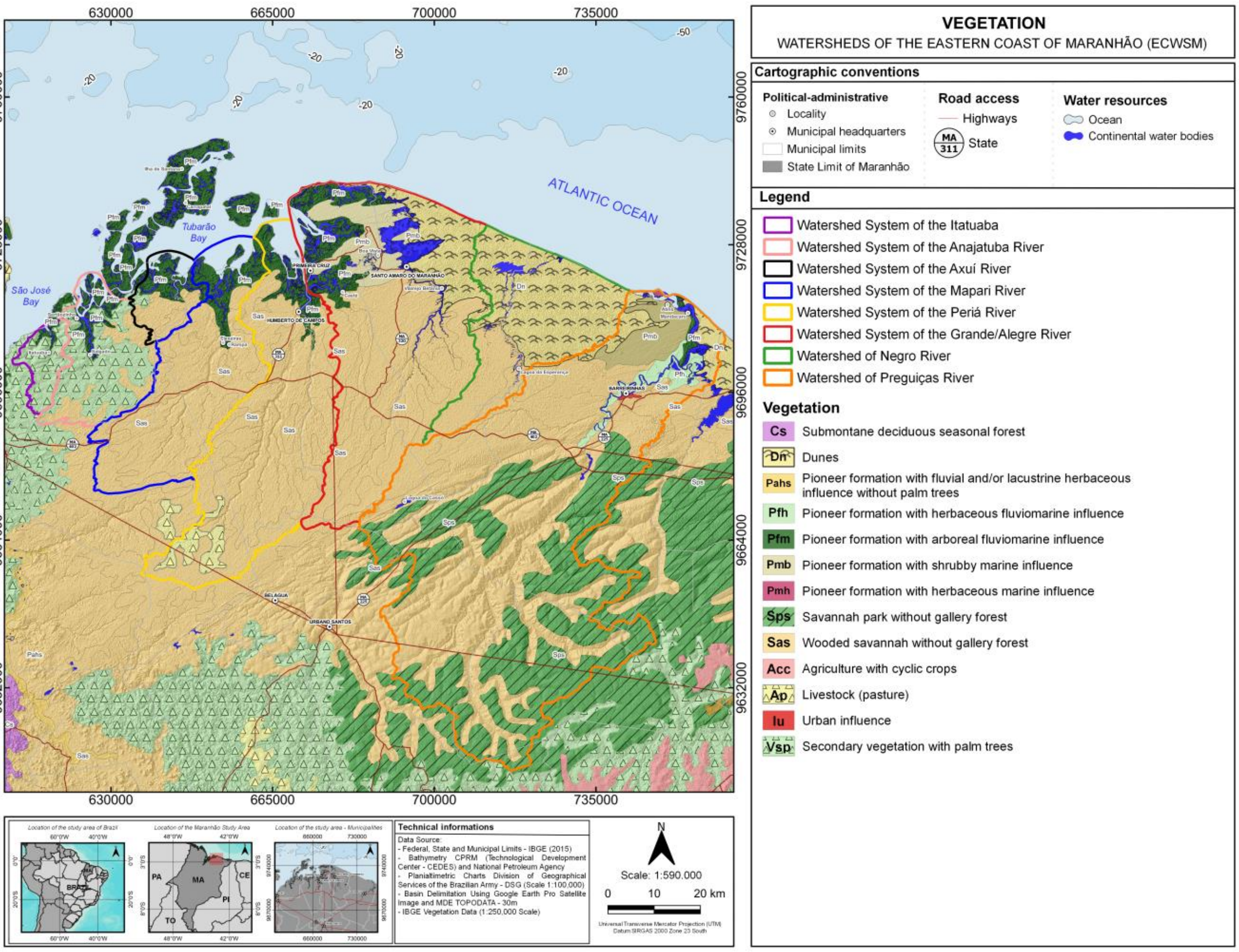

Figure 11. Vegetation units of ECWSM of state of Maranhão, Brazil.

The vegetation complex of the coastal zone of the ECWSM encompasses *Restinga* ecosystems associated with dunes. This type of vegetation is found in tropical and subtropical coastal areas, with individuals in the herbaceous, shrub and arboreal layers growing on plains that date back to the Quaternary period (Castro and Piorsk, 2002; Serra; Lima and Almeida, 2016; Pinto; Rego; Albuquerque, 2020).

The *Restinga* has typical species of this type of vegetation, but species are found from other biomes, such as the *Cerrado* (arborized savanna without gallery forests), *Caatinga* and riparian forest. Shrub species, such as *Humiria balsamifera* ("umiri"), have large herbaceous communities that surround lakes. This vegetational differentiation results from natural and/or anthropogenic processes. However, independently of which process prevails, a plant community is always associated with these natural, disturbed or degraded characteristics (Pinto; Rego; Albuquerque, 2020).

According to Castro and Piorsk (2002), Serra, Lima & Almeida (2016), Pinto, Rego & Gomes Fernandes (2020) and Albuquerque (2020), it is possible to define the following vegetation units for the study area based on phytogeographic units: Marine-Silty Edaphic Arboretum (mangrove vegetation), Pioneering Psamophyl Vegetation (partially corresponding to the coastal vegetation complex), Marine-Sandy Edaphic Arboretum (tableland vegetation), Fluvial Edaphic Arboretum (wetland vegetation) and *Cerrado*, which cover the lower course of the ECWSM.

On the map, the vegetation that occupies the lower course of the ECWSM is mainly Pioneering Formation with Fluvial-Marine Influence and Pioneering Formation with Marine-Shrub Influence, occupying the paleodune plateaus from the Pleistocene, denominated shrub *Restinga*, which occurs in low densities in the form of dispersed shrubs due to the low moisture content in the soil and low availability of nutrients. *Humiria balsamifera* ("umiri") and *Byrsonima sp* ("murici") occur in this region. On the banks of rivers, lakes and wetland areas subjected or not to flooding during the rainy season, herbaceous *Restinga* fields occur, which may be intercalated with shrubs and sparse trees (Figure 12) (Santos-Filho et al., 2010; Amaral et al., 2019).

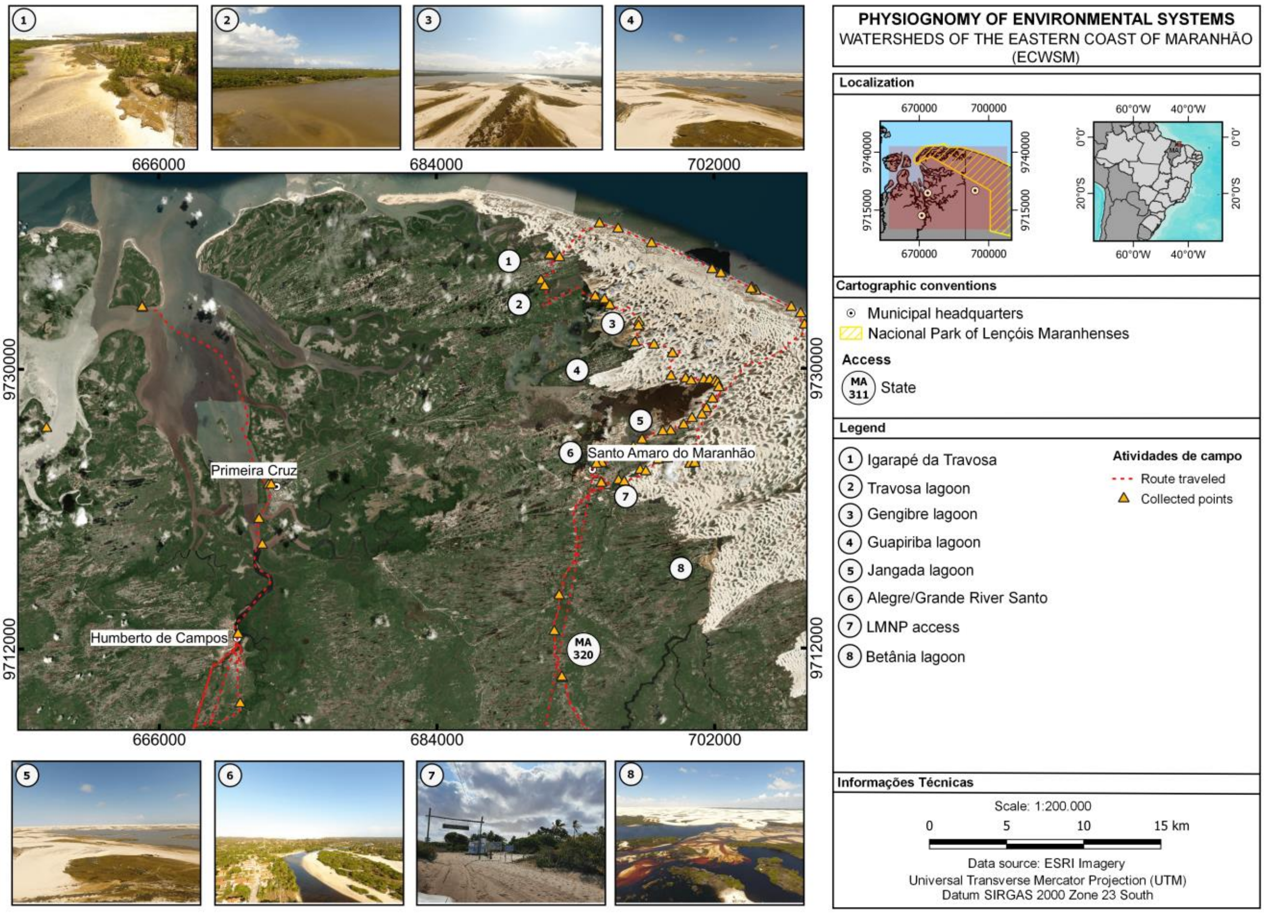

Figure 12. Physiognomy of environmental systems found in lower course of watershed system of Alegre/Grande River.

According to Santos-Filho *et al.* (2010) and Amaral *et al.* (2019), woody *Restinga* vegetation on the slopes of the valley develops distributed homogeneously with a closed canopy, varying between shrubs and trees, with the occurrence of *Hymenaea parvifolia* (“jatobá”) and *Anacardium microcarpum* (“cajuí”). The species *Mauritia flexuosa* (“buriti”), *Euterpe oleacea* (“açaí”) and *Scripus sp.* are common along all water courses. The species *Cyperus sp.* (“tiririca”), *Cassia rotundifolia* (“erva coração”), *Borreria* sp., *Copernicia prunifera* (“carnauba”) and *Astrocaryum vulgare* (“tucumã”) are found in these fields.

Also, in the geomorphological domain of the coastal plain, the Arboreal Pioneering Formation with Fluvial-Marine Influence or mangrove vegetation typical of the equatorial Americas occurs at the interface of the brackish environment situated at the mouth of rivers with marine influence. Specialized vegetation adapted to variations in salinity grows in the muddy sediments, such the following sequence: *Rhizophora mangle*, *Avicennia germinans* and *A. schaueriana*, the species of which vary with the latitude, and *Laguncularia racemosa*, which grows at taller locations only affected by the high tide (IBGE, 2012).

In the municipality of Humberto de Campos between the watersheds of the Mapari and Periá Rivers, shrimp farming ponds and deactivated saline ponds are found in areas of fluvial-marine plain domains.

More inland, the data collected for the mapping of vegetation units according to the classification proposed by the Brazilian Institute of Geography and Statistics (IBGE, 2012) show that the arborized savanna without gallery forests covers the largest part of the areas of the majority of the ECWSM. In the geomorphological unit of the Barreirinhas Tablelands, this vegetation has a physiognomy marked by low, spaced (isolated) tress amidst a continuous herbaceous stratum. Some species such as *Chrysobalanus icaco* (“guajiru”) are also widely found.

The atmospheric humidity is high throughout a large part of the year, favoring the development of dense, evergreen vegetation that plays a direct role in environmental eco-dynamic stability. On the alluvial plains, the vegetation reflects the effects of the flooding of the rivers in the rainy period or floodable depressions. Depending on the quantity of water accumulated and the time that it remains in an area on these alluvial terrains, the plant communities range from cryptophytic aquatic species (hydrophytes) to temporarily inundated terraces, where Arecaceae of the genera *Euterpe* and *Mauritia* aggregate in many places, constituting the *açaizal* and *buritizal* of the northern region of Brazil (IBGE, 2012).

Conclusions

The northern coast of Brazil requires considerable instruments for the analysis, monitoring and management of its natural resources and landscapes. In a world of increasing expansion, the planning and management of social and economic development is needed in watersheds. The morphological and physical attributes of the Eastern Coast Watersheds of Maranhão (ECWSM) and the relationships of ecological potential (geology, geomorphology, hydrology and climate), biological exploitation (soil and vegetation) and human actions reveal proxies of the evolution of the Holocene landscape.

A gamut of geomorphic processes driven by fluvial-marine dynamics exert a direct impact on soil formation processes. Moreover, anthropogenesis, the evolution of the relief, soil moisture/evaporation and vegetation also exert an influence on the morphological formation of the ECWSM.

The mangrove system in the lower courses of the ECWSM has well-developed saline-sodic soils. The extreme podzolization of ancient sand deposits occurred at the end of the Holocene, which the high precipitation and level of the water table resulted in the formation of organic matter in soils with iron-aluminum components. Currently, the sandy soils are covered by seasonal savannas, indicating a complex evolution in comparison to the majority of soils mapped.

The drainage network pattern and the morphological and hydrographic characteristics found in the different watersheds analyzed are linked to tectonics. The lithological resistance and arrangement linked to characteristics of tectonic adjustment should be analyzed in future geomorphological studies in watersheds located in the coastal zone. The drainage of the ECWSM exhibits patterns shaped by morphostructural influence. The lithology of the ECWSM determines fluvial processes of different intensities. The second element refers to the configuration of the relief itself, which is conditioned by lithology and is likely also linked to tectonics caused by the constant separation of South America from Africa.

The principal aim of the present study is the dissemination of geoenvironmental data of the ECWSM as distinct units on a more detailed scale compared to previous studies conducted in the state.

The natural resources and landscape of Conservation Units within these watersheds form immense nurseries for biological productivity that supports traditional economic activity, such as fishing, mollusk collecting and boating. The mapping of the ECWSM contributes to the development of effective environmental zoning in the region.

It is important to highlight the role of the Maranhão government in the conservation of state water resources. The generation of data for each watershed separately is of extreme importance to decision makers to fulfill the law, as their function is to “ensure the environmental quality of water resources and the soil and conserve biodiversity” (Federal Decree nº 4.297/2002), thereby acting in accordance with the Brazilian federal constitution, Article 225 of which stipulates that the public power and collectivity have the obligation to defend and preserve a balanced environment for present and future generations.

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