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RECENT COASTLINE TRENDS ON THE EAST MARGIN OF THE MIDDLE PARÁ ESTUARY

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Guimarães, D.K.M [a]* - El-Robrini, M. [b] - Rosário, R.P. [c]
Menezes, R.A.A. [d]

(a) Master in Geography.
ORCID: http://orcid.org/0000-0002-8894-5783. **LATTES:** http://lattes.cnpq.br/4259495348605314.
(b) PhD in Marine Geology
ORCID: http://orcid.org/0000-0001-7850-1217. **LATTES:** http://lattes.cnpq.br/5707365981163429.
(c) PhD in Geophysics.
ORCID: http://orcid.org/0000-0003-2913-0514. **LATTES:** http://lattes.cnpq.br/8003860457518342.
(d) PhD Student in Geography.
ORCID: http://orcid.org/0000-0001-5324-8008. **LATTES:** http://lattes.cnpq.br/4681123810496065.

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(*) CORRESPONDING AUTHOR
Address: UFRJ. Av. Athos da Silveira, 274, Cidade Universitária, CEP: 21941916, Rio de Janeiro (RJ), Brasil. Phone: (+ 55 21) 25901880
E-mail: guimaraesdiandra@gmail.com

Abstract

The main objective of this article is to quantify the erosion and accretion rates on the eastern margin of the middle Pará Estuary within 32 years (1987, 1993, 1999, 2004, 2008, 2013, and 2019) with the use of remote sensing and data Digital Shoreline Analysis System (DSAS) extension. These methodological procedures recently applied in the Amazon region are effective in the search for intended results. To calculate with significant accuracy the rates of CL changes, select the parameters Net Shoreline Movement (NSM), Linear Regression Rate (LRR), and End Point Rate (EPR) to obtain the variations. In the middle estuary, the rates showed a tendency towards CL retreat in the onshore direction, with an average rate of -38 m and an average accretion rate of 22.97 m prevailing on Mosqueiro Island, related to average rates of variation of -0.58 m/ year (EPR) and -0.54 m/year (LRR) and in Santo Antônio do Tauá with LRR and EPR parameters identifying average rates of variation of -1.67 m/year (LRR) and -1.55 m/year (EPR). Only on Colares island, there was a tendency to accretion, with an average erosion rate of -96.29 m and an average accretion rate of 116.49 m, where the maximum accretion and erosion rates are 405.61 m and -396.87 m, respectively.

Keywords: Eastern Amazon, Coastal Dynamics, Estuarine Environment, LANDSAT.

Resumo / Resumen

TENDÊNCIAS RECENTES DA LINHA DE COSTA NA MARGEM LESTE DO ESTUÁRIO MÉDIO DO RIO PARÁ

O principal objetivo desse artigo é quantificar as taxas de erosão e de acreção na margem leste do Estuário médio do Pará no decorrer de 32 anos (1987; 1993; 1999; 2004; 2008; 2013 e 2019) com a utilização do sensoriamento remoto e da extensão Digital Shoreline Analysis System (DSAS). Esses procedimentos metodológicos recentemente aplicados na região amazônica se mostraram eficazes na busca dos resultados pretendidos. Para calcular com acurácia significativa as taxas de mudanças da LC foram selecionadas os parâmetros Net Shoreline Movement (NSM), Linear Regression Rate (LRR) e End Point Rate (EPR) para a compreensão das variações. No estuário médio, as taxas apresentaram uma tendência à retração da LC em sentido onshore, predominando na Ilha de Mosqueiro uma taxa média de -38 m e taxa média de acreção de 22,97 m, relacionados às taxas médias de variação de -0,58 m/ano (EPR) e -0,54 m/ano (LRR) e em Santo Antônio do Tauá com LRR e EPR identificando taxas médias de variação de -1,67 m/ano (LRR) e -1,55 m/ano (EPR). Apenas na ilha de Colares houve tendência a acreção, com taxa média de erosão de -96,29 m e taxa média de acreção de 116,49 m, onde a taxa máxima de acreção e de erosão, são de 405,61 m e -396,87 m, respectivamente.

Palavras-chave: Amazônia Oriental, Dinâmica Costeira, Ambiente Estuarino, LANDSAT.

TENDENCIAS DE LA COSTA (1987-2019) EN LA MARGEN ESTE DEL ESTUARIO MEDIO DEL RÍO PARÁ

El objetivo principal de este artículo es cuantificar las tasas de erosión y acreción en el margen oriental del estuario medio del Pará en 32 años (1987; 1993; 1999; 2004; 2008; 2013 y 2019) con el uso de sensores remotos y extensión del Sistema Digital de Análisis de Costas (DSAS) de datos. Estos procedimientos metodológicos recientemente aplicados en la región amazónica son efectivos en la búsqueda de los resultados esperados. Para calcular con una precisión significativa las tasas de cambios de LC, seleccione los parámetros Net Shoreline Movement (NSM), Linear Regression Rate (LRR) y End Point Rate (EPR) para obtener las variaciones. En el estuario medio, las tasas tendieron a una retracción de la LC en dirección tierra adentro, con una tasa promedio de -38m y una tasa de acreción promedio de 22,97 m predominando en Ilha de Mosqueiro, relacionado con tasas de variación promedio de -0,58 m /año (EPR) y -0,54 m/año (LRR) y en Santo Antônio do Tauá con parámetros LRR y EPR identificando tasas de variación promedio de -1,67 m/año (LRR) y -1,55 m/año (EPR). Solo en la isla de Colares se presentó una tendencia a la acreción, con una tasa de erosión promedio de -96.29 m y una tasa de acreción promedio de 116.49 m, donde la tasa máxima de acreción y erosión son 405.61 m y -396.87 m, respectivamente.

Palabras-clave: Amazonía Oriental, Dinámica Costera, Ambiente Estuarino, LANDSAT.

INTRODUCTION

Estuaries are defined as the lower reaches of a river where fluvial and marine processes interact. They are dynamic transition environments, influenced by hydrological (river discharge, salinity) and hydrodynamic (tides and currents) parameters that act and shape this environment (ELLIOTT and MCLUSKY, 2002; FLEMMING, 2011; LIMA et al., 2015; VALLE- LEVINSON, 2011).

These estuarine complexes can be subdivided into three sectors: lower, middle, and upper estuary (MIRANDA et al., 2017). The middle estuary is a zone of mixing of saline water with fresh water, where muddy sediments (a mixture of mud and sand) predominate, with preferential deposition of mud resulting from flocculation, coagulation, and aggregation of suspended matter (FLEMMING, 2011).

The mouth of the Pará estuary communicates with the Amazon River through the ¨Estreitos¨ region and receives river contributions from the Tocantins and Guamá/Guajará rivers. Amazon estuaries have dynamics influenced by aerodynamic (rain, wind) and hydrodynamic conditions (currents, macrotides, waves). The middle Pará estuary is dominated by the meso and macro-tidal regime, where the meso-tidal predominates just before the transition with the upper estuary and the macro-tidal in the vicinity of the lower estuary, where the height of the spring tide is 5.7 m (RIBEIRO and VALADÃO, 2021).

Several factors, such as river discharge, determine an estuary's salinity level. The Pará estuary is classified as having a well-balanced saline regime, ranging from limnetic to mesohaline. Saline intrusion increases during low discharge and decreases during high discharge. Another factor that affects salinity is precipitation. During the rainy season, the estuary receives more fresh water; in the dry season, the water remains saltier. This information is supported by studies conducted by MENEZES et al. (2013), RIBEIRO and VALADÃO (2021), and ROSÁRIO et al. (2016).

The coastline (CL) of the estuary banks undergo short, medium, and long-term temporal transformations related to geological, climatic, oceanographic, and anthropogenic factors that occur in the CL (FRANÇA and SOUZA FILHO, 2003). The most widely used interpretation of CL is as the intersection between water and land, and its delimitation can be made by geomorphological limits, vegetation, tide level, beach contour, or other delimitation, depending on the study area (MARTINS; TABAJARA and FERREIRA, 2004; TOURE et al., 2019; VASCONCELOS et al., 2020).

One of the techniques that help detect changes in the CL is remote sensing, which enables manual or semi-automatic extraction of the CL from the digital processing of satellite images with high quality, cost-benefit, and reduction of manual error (APOSTOLOPOULOS and NIKOLAKOPOULOS, 2021; TOURE et al., 2019; WANG et al., 2020). In order to improve accuracy in analysis, the Digital Shoreline Analysis System (DSAS) was developed. This software extension is compatible with the Esri Geographic Information System (ArcGIS). It can generate statistical calculations that measure rates of change over time for vector data of CL´s. This system has been referenced in studies by HIMMELSTOSS et al. (2018), MISHRA et al. (2020), and TOURE et al. (2019).

In the Pará state, a series of research was carried out in the Pará coastal zone using remote sensing and DSAS, and were carried out mainly in the estuarine sector (BAÍA; RANIERI, and ROSÁRIO, 2021; CONTI and RODRIGUES, 2011; NEVES; FRANÇA and SILVA, 2019; RODRIGUES; SOUZA FILHO, 2011) and the Atlantic Coast sector of Pará (RABELO; SILVA and GORAYEB, 2021; RANIERI and EL-ROBRINI, 2015).

The detection of the CL's erosion and/or accretion areas becomes interesting to observe changes on the east margin of the middle Pará estuary. Understanding the behavior of the CL and the forcings that contribute to the erosion process is fundamental for the management of the coastal zone in order to assist in the search for adaptive and mitigating solutions (MATOS et al., 2022). This article aims to perform a multi-temporal analysis (1987-2019) of the East margin (Mosqueiro and Colares islands and Santo Antônio do Tauá) of the middle Pará Estuary and quantify the erosion and/or accretion areas.

LOCATION OF THE STUDY AREA

The research area is located on the east margin of the middle Pará Estuary, in the stretch: Mosqueiro island, Santo Antônio do Tauá and Colares island (Figure 1).

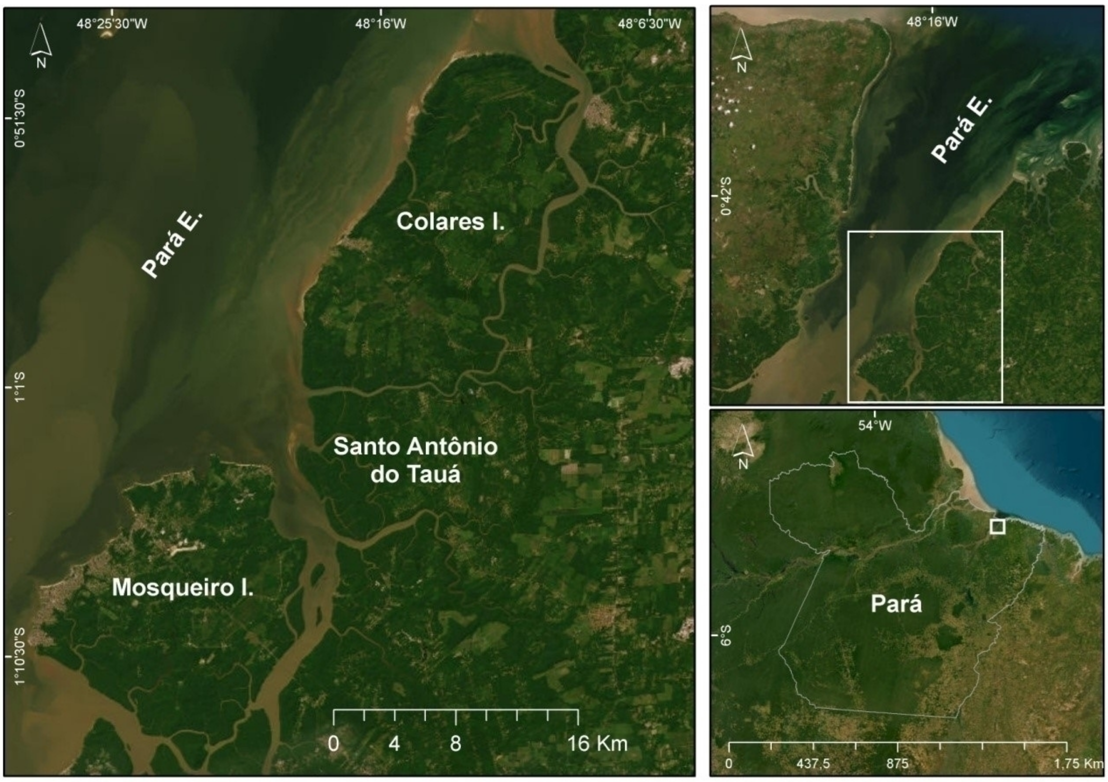


Figure 1 - Location of the East margin (Mosqueiro and Colares Islands, Santo Antônio do Tauá) of the middle Pará Estuary. Prepared: authors

CHARACTERIZATION OF THE STUDY AREA

The Mosqueiro Island is located in the northern part of Belém, with an area of 212 km2 and 27,000 inhabitants. It is the most urbanized sector in the study area. The island can be accessed via BR-316, PA-391 and the Sebastião Raimundo de Oliveira Bridge over ¨Furo¨ das Marinhas, integrating this island with the Metropolitan Region of Belém (IBGE, 2022).

Santo Antônio do Tauá's location is more sheltered than the two islands. There is no population on the margin of the Pará Estuary, including the mangrove forest. The municipal headquarters is located in the interior, with an area of 537,618 km² and 26,674 inhabitants (IBGE, 2022). To reach Colares Island from Belém, take BR-316 and enter PA-140. Pass through Santo Antônio de Tauá and follow PA-241 until Colares Island. There are 101.6 km of route with an average duration of 1h and 35 m of travel. The Colares Island occupies an area of 384,068 km², with 11,381 inhabitants (IBGE, 2022).

The weather in this area is classified as humid equatorial, with an average temperature ranging from 25 ºC to 27 ºC annually. The amount of rainfall typically falls between 2,000 to 3,000 mm/year and is directly impacted by the Intertropical Convergence Zone (ITCZ) seasonal migration towards the south. The rainy season typically occurs from December to May, while the dry season falls between June and November (INMET, 2021).

The study area was influenced by the extreme events of El Nino (EN) during 1987, 1993, 2004, and 2019. La Niño (LN) in 1999 and 2008. The change in the surface temperature of the Equatorial Pacific Ocean has global effects on the wind, cloudiness, temperature, and precipitation patterns (CAI et al., 2020; CPTEC/INPE, 2021; MOURA et al., 2019). Research into the influence of El Niño and La Niña in the Amazon basin has shown that the most significant impacts are related to changes in rainfall and the river flow.

During the occurrence of a moderate EN, precipitation tends to be less than normal; during a moderate LN event, precipitation tends to be greater than normal. These changes in precipitation will influence river discharge, reflecting on the region's hydrodynamic transport and deposition processes, vegetation cover, economic activities, and mainly the region's climate (MOREIRA et al., 2018; MOURA et al., 2019).

The Barreiras and Post-Barreiras formations make up the geological base of the study area, where alluvial deposits and coastal deposits occur above them (EL-ROBRINI et al., 2018b; ROLLNIC et al., 2020). The Barreiras Formation is composed of deposits of varied and non-fossiliferous siliciclastic sediments (conglomerates, sandstones, and claystone) and its layers exhibit laminated or massive stratifications, with a predominance of fine sandstones to siltstones (5 to 10 m thick) occurring in the central part of the Mosqueiro Island and the interior of São Caetano de Odivelas (BARBOSA and FRANÇA, 2006; EL-ROBRINI et al., 2018a; PICANÇO, 2013).

Post-Barreiras sediments occur in most of the research area, are deposited on the Barreiras Formation (erosive unconformity), and consist of sandy-clayey sediments (Pleistocene). These incorporate at least two different sedimentation episodes informally referenced from Post-Barreiras I and II sediments, the first being up to 10 m thick and the second being 2 to 5 m thick (BARBOSA and FRANÇA, 2006; EL-ROBRINI et al., 2018a; PICANÇO, 2013; RIBEIRO and VALADÃO, 2021).

Alluvial deposits occur just southeast of the Mosqueiro island, in ¨Furo¨ das Marinhas, and are made up of unconsolidated clayey and sandy sediments related to the current alluvial plains of the main water courses, which constitute channel deposits (point bars and channels) and floodplains (CPRM, 2008; EL-ROBRINI et al., 2018a).

Coastal deposits of beaches, dunes, mangroves, and saline swamps are found in the CL of Vigia and São Caetano de Odivelas and constitute the coastal plain of the municipalities. They are made up of sandy (beaches and dunes) and muddy (mangroves and saline marshes) sediments (CPRM, 2008; EL-ROBRINI et al., 2018a).

The morphology of the bottom in the section close to the Colares island is quite irregular with the presence of channels (18 m deep), covered by medium sand to coarse silt grading into very fine silt and even clay. In the section of Mosqueiro Island, the presence of a channel with -27 m depth, covered by medium sand to coarse silt, can be noted. According to CORRÊA (2005), the sediments on the eastern margin are deposited by decantation, showing low hydrodynamics.

Salinity in the Pará Estuary alternates its gradient, considering three periods: low flow, transition, and high discharge (Figure 2). The most extensive saline intrusion occurs during low flow at approximately 130 km. In the transition period between low and high discharge, saline intrusion occurs up to approximately 110 km. During high discharge, saline intrusion occurs at approximately 70 km from the mouth of the estuary (ROSÁRIO et al., 2016).

The net discharge of the Pará River is 20,946 $m^3.s^{-1}$. High and low river discharge occur respectively in the rainy and dry seasons (PRESTES et al., 2020). The tide is semi-diurnal, with a mesotidal regime, with 3.4 m near the Mosqueiro island, and macro tide, with 4.7 m near the Colares island (DHN, 2022; RIBEIRO and VALADÃO, 2021; ROSÁRIO et al., 2016). The flow of the local currents is influenced by both the river discharge and tidal currents, with current speeds reaching up to 2 $m.s^{-1}$ River currents are induced by river discharge flows, where tidal currents are 2 $m.s^{-1}$ (PRESTES et al., 2020).

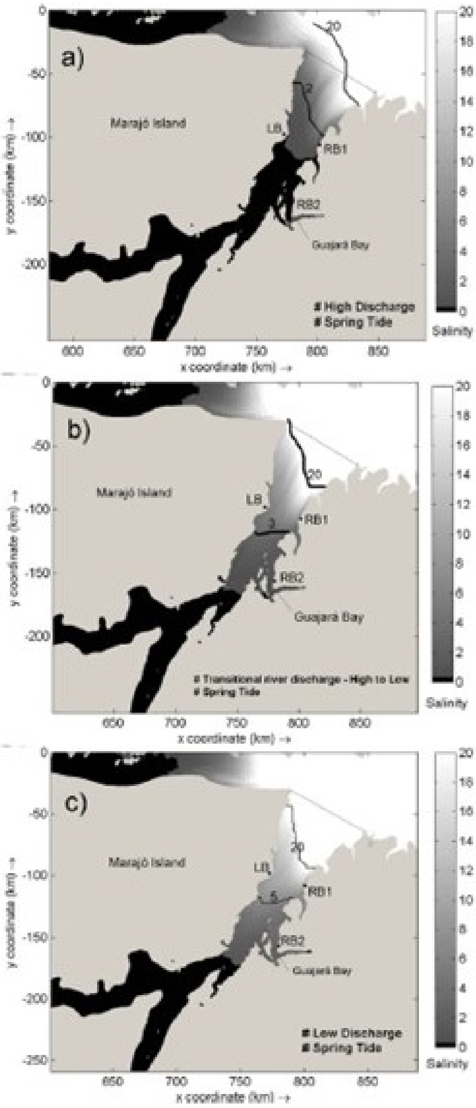


Figure 2 - Salinity result in: a) high discharge; b) transition period and c) low discharge. The straight line at the mouth of the Pará Estuary is the reference point for distances. Source: Rosário et al. (2016).

MATERIALS AND METHODS

ACQUISITION OF SATELLITE IMAGES

To achieve the results, Landsat TM (1987; 1993; 1999; 2004; 2008) and Landsat OLI (2013 and 2019) satellite images were acquired to take advantage of a 32-year analysis, where the satellite database was acquired from the United States Geological Survey (USGS), and these were projected onto datum WGS84 (UTM). After acquisition, all images were reprojected to the WGS84 22S datum to assign the orbit point of the study area (Table 1).

Year	Satellite	Sensor	Orbite/point	Spatial Resolution (m)	Date acquired
1987	Landsat -5	TM	223-061	30	17/05
1993	Landsat -5	TM	223-061	30	20/07
1999	Landsat -5	TM	223-061	30	13/07
2004	Landsat -5	TM	223-061	30	19/08
2008	Landsat -5	TM	223-061	30	14/08
2013	Landsat-8	OLI/TIRS	223-061	30	27/07
2019	Landsat-8	OLI/TIRS	223-061	30	26/06

Table 1 - Data from acquired images. Source: adapted from Landsat images (USGS data); National Institute of Meteorology (2020); Kayano et al. (2016) and Center for Weather Forecasting and Climate Studies (2021).

The choice of Landsat images in this region has some limitations, as in the rainy season the cloud coverage in the study area can reach 99 %, so the selection of the years analyzed took into account the lowest percentage of clouds. The time interval is 4, 5 and 6 years and images were selected based on the lowest cloud cover, corresponding to the months of the dry season where the percentage of clouds is from 0 % to 30 %, for better visualization of the CL. The scenes from orbit/point 223-061 cover the entire study area.

CL VECTORIZATION

To begin the process of interpreting the change in CL, it was vectorized and shapefiles were also created to extract the CL from the corresponding images (Figure 3), through the visual interpretation of these images based on the contact of vegetation with water. A baseline was also created for all images to help analyze the CL variation. These procedures were carried out in the ArcMap 10.5 program of ArcGis software.

Figure 3 - Layout of coastlines, referring to the years of analysis (1987; 1993; 1999; 2004; 2008). Preparation: authors.

DIGITAL SHORELINE ANALYSIS SYSTEM (DSAS)

The Digital Shoreline Analysis System (DSAS) was used to calculate the CL change rates with greater precision. On the east margin of the middle Pará Estuary, the parameters Net Shoreline Envelope (NSM), Linear Regression Rate-of-Change (LRR) and End Point Rate (EPR) were applied as they suit the necessary analysis, taking as a baseline the continental part and transects aligned every 100 m.

These parameters are necessary to understand the variation in CL, because: the NSM calculates the distance between the oldest and youngest CL´s for each transect; the EPR obtains its parameters from the rate component of the endpoint is calculated from the division of the CL from the time elapsed between the oldest and the most recent line in the analysis component: the LRR will be determined by adjusting the line least squares regression at all points on the coast for a transect generated in DSAS processing (HIMMELSTOSS et al., 2018; KABIR et al., 2020).

Therefore, the results of variations in meters over the 32 years of analysis (NSM), together with the average rates of variation/year (LRR) fall within positive values indicating displacement of the CL towards the sea along the transect and negative values indicate a displacement of the CL towards the earth.

RESULTS

TRENDS OF THE COASTLINE OF MOSQUEIRO ISLAND

The edge of the Mosqueiro Island exposed to the middle Pará Estuary is formed by Pleistocene Terraces and Alluvial Plains, where cliffs and ¨restingas¨ occur. Hydrodynamics has a direct influence on the entire western part of the island, which implies the formation and wide distribution of beaches (NEVES; FRANÇA and SILVA, 2019). The vegetation cover is made up of rainforest, floodplains and mangroves (MOURA et al., 2021). On the other hand, the western part is the most urbanized, with better infrastructure and services (FRANÇA et al., 2020; NEVES; FRANÇA and SILVA, 2019).

On the Mosqueiro Island (37 km) of the 350 transects generated (2-365) 70 % represent erosion and 30 % accretion, indicating a greater tendency to erosion, with an average erosion rate of -38 m and the average accretion rate is 22, 97 m. The average rates of variation of -0.58 m/year (EPR) and -0.54 m/year (LRR) confirm the erosion trend (Table 2).

	Mosqueiro Island		
	NSM (m)	EPR (m/ano)	LRR (m/ano)
Maximum accretion rate	518,22	16,14	10,35
Maximum erosion rate	-219,03	-6,82	-5,35
Average accretion rate	22,97	0,67	0,61
Average erosion rate	-38	-1,21	-1,03
Average rate of change	-18,67	-0,58	-0,54

Table 2 – Rates of shoreline change calculated by the NSM, EPR and LRR parameters for the Mosqueiro island. Source: authors.

The maximum erosion rates do not exceed -6.82 m/year in the EPR and -5.35 m/year in the LRR, while the maximum accretion rates reach 16.14 m/year in the EPR and -5.35 m/year in LRR (Figure 4a). The graphs show average erosion and accretion rates with some peaks of high erosion and accretion (Figures 4b and 4c).

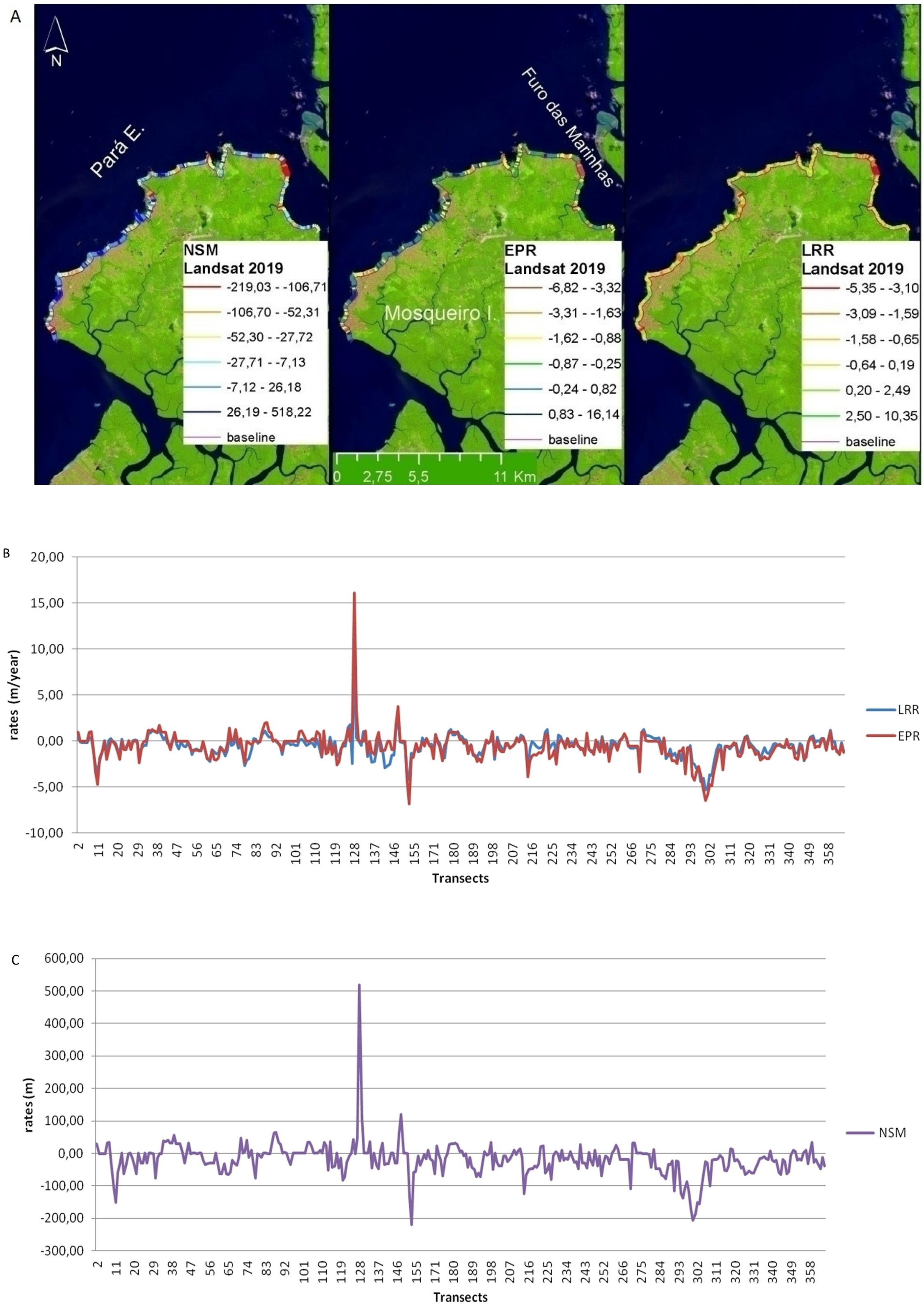


Figure 4 - Transects with the NSM, EPR and LRR rates of the CL (a) and graphs with the rates of variation of the LRR and EPR (b) and NSM (c) of the CL on the Mosqueiro Island. Preparation: authors.

The Mosqueiro Island has four different sectors. Sector A (Southwest of the island) shows average variation rates between -0.25 to -1.11 m/year. The maximum accretion rate of the NSM is in sector B (Northwest of the island) (transect 128), with 518.22 m and LRR and EPR rates, respectively, of 10.35 m/year and 16.14 m/year. In Sector C (North of the island) the highest erosion rate is -123.62 m (transect 214), with EPR and LRR rates, respectively, of -3.85 m/year and -3.10 m/year. Sector D (Northeast of the island) has high erosion rates (red transects) on the margin of ¨Furo¨ das Marinhas (transects 294 to 304). Transect 300 shows the highest erosion rate in this area, with -206.71 m (Figure 5).

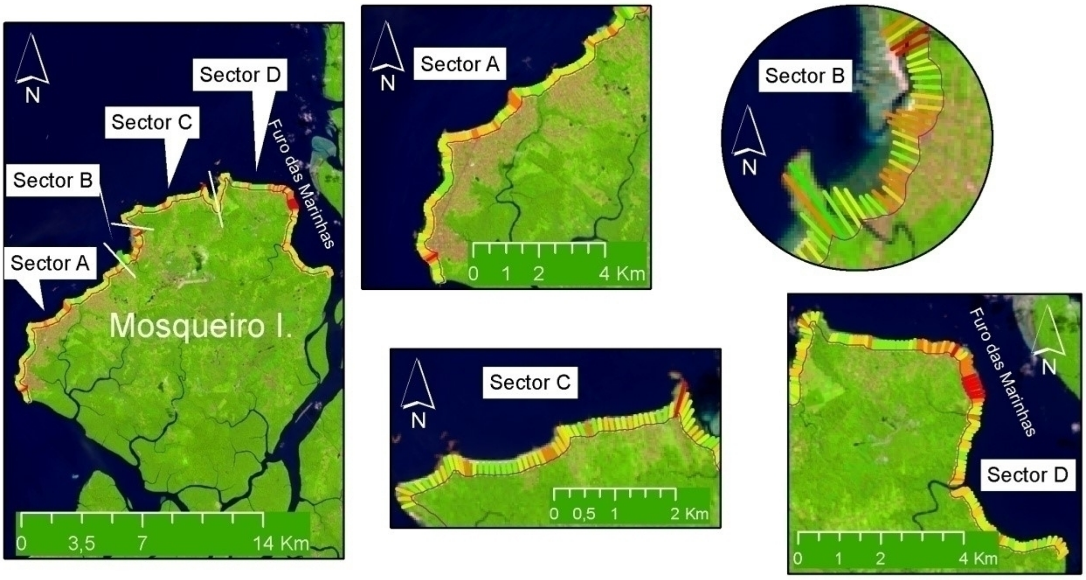


Figure 5 - Sectors A, B, C, D of Mosqueiro Island. Beaches are present in each sector: Sector A - Areião, Bispo, Praia Grande, Prainha, Farol, Chapéu Virado, Porto Arthur, Murubira, Ariramba and São Francisco; Sector B – Carananduba; Sector C - Marahú, Caruara, Paraíso; Sector D - Baía do Sol. Prepared by: authors.

TRENDS OF THE SANTO ANTÔNIO DO TAUÁ COASTLINE

The Santo Antônio do Tauá CL occupies a more sheltered area on the East margin of the Pará Estuary, compared to the Mosqueiro and Colares Islands. In this area, there are alluvial plains composed of gravel, sand and unconsolidated clay, colonized by well-preserved mangroves. The CL is cut by small tidal channels and is delimited by ¨Furo¨ das Marinhas (Southwest) and ¨Furo¨ da Laura (North) (BARBOSA, 2007; COSTA and ANDRADE, 2020; RODRIGUES et al., 2004).

In this section, 111 transects (406-537) were generated in the 13 km of CL. The percentage of transects in accretion is higher (59.46 %), but erosion presents a maximum erosion rate of -694.23 m in Sector A (transect 480), with an average rate higher than the average accretion rate, with -157 .09 m and 38.41 m, respectively (Table 3).

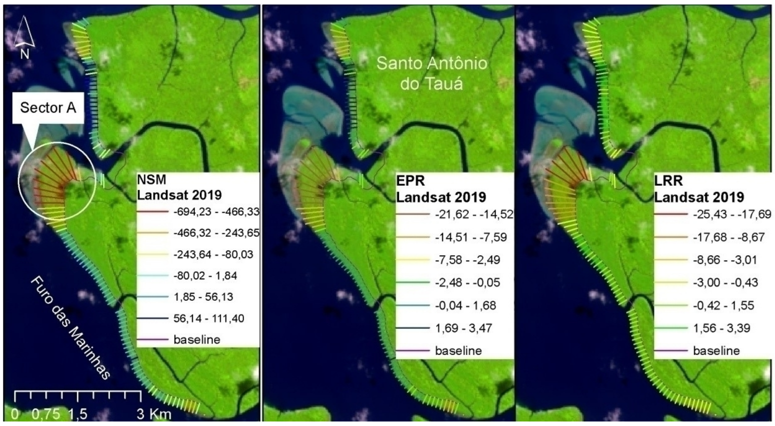
The areas to the south and north of Santo Antônio do Tauá mostly present medium and high accretion rates (light and dark blue transects, respectively) and some specific areas with medium erosion rates (yellow transects), where the maximum accretion rate of 111.40 m occurs (transect 514), with an LRR rate of 3.26 m/year and an EPR rate of 3.47 m/year in the northern part (Figure 6a). From the LRR and EPR parameters, average rates of variation of -1.67 m/year (LRR) and -1.55 m/year (EPR) were identified.

	Santo Antônio do Tauá		
	NSM (m)	EPR (m/ano)	LRR (m/ano)
Maximum accretion rate	111,40	3,47	3,39
Maximum erosion rate	-694,23	-21,62	-25,43
Average accretion rate	38,41	1,19	1,27
Average accretion rate	-157,09	-4,89	-5,98
Average rate of change	-49,65	-1,55	-1,67

Table 3 – Coastline change rates calculated by NSM, EPR and LRR parameters for Santo Antônio do Tauá. Source: authors.

High erosion rates occur in the central region of the LC of Santo Antônio do Tauá due to the strong influence of the waters at the mouth of "Furo" das Marinhas, the maximum erosion rates are -21.62 m/year (EPR) and -25.43 m/year (LRR), a value well above the maximum accretion rates of 3.47 m/year (EPR) and 3.39 m/year (LRR). However, the average rate of variation was -49.65 m (Figures 6b and 6c).

6A



6B

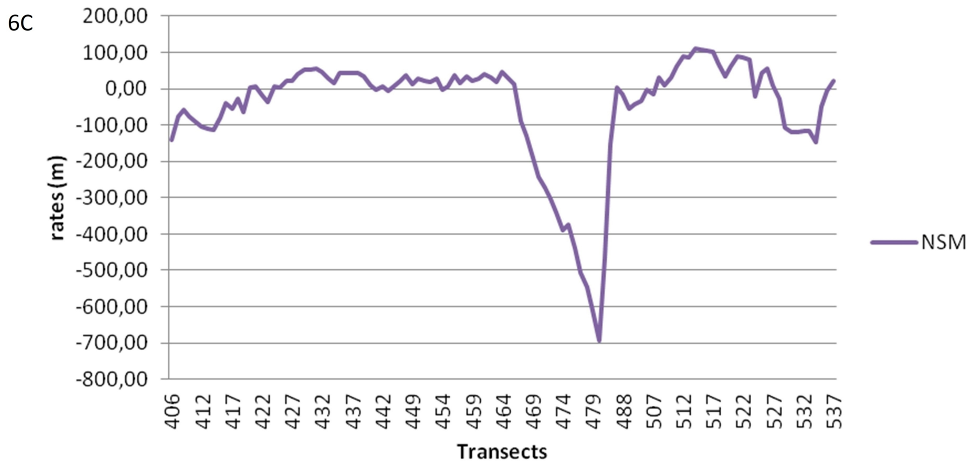


Figure 6 - Transects with the NSM, EPR and LRR rates of the CL (a) and graphs with the rates of variation of the LRR and EPR (b) and NSM (c) of the CL and highlights of sector A of Santo Antônio do Tauá. Preparation: authors.

LC TRENDS OF THE COLARES ISLAND

Colares Island occupies an area of 384,068 km², and is separated from the mainland by ¨Furo¨ da Laura. This island is mainly made up of floodplains with mangroves. Just to the southwest of the island, there is the Coastal plateau, exposed in the form of cliffs, at the seat of the municipality (BRAGA et al., 2018; RIBEIRO et al., 2021).

With 36 km of CL, the Colares island, based on the 352 transects generated (554-909), presents a tendency to accretion, with an average rate of 3.57 m/year (LRR) and 3.62 m/year (EPR) and average erosion rates of -3.35 m/year (LRR) and -3.01 m/year (EPR) (Table 4).

	Colares Island		
	NSM (m)	EPR (m/ano)	LRR (m/ano)
Maximum accretion rate	405,61	12,63	13,35
Maximum erosion rate	-396,37	-15,13	-9,23
Average accretion rate	116,49	3,62	3,57
Average erosion rate	-96,29	-3,01	-3,35
Average rate of change	3,45	0,10	0,11

Table 4 – Coastline change rates calculated by NSM, EPR and LRR parameters for the Colares Island. Source: authors.

The NSM statistical rates show an average rate of change of 3.45 m (Figure 7a). With the EPR and LRR methods, an average rate of variation of EPR of 0.10 m/year and LRR of 0.11 m/year was recorded (Figure 7b). The average erosion rate is -96.29 m and the average accretion rate is 116.49 m, with a maximum, respectively, of 405.61 m (transect 715) and -396.87 m (transect 909) (Figure 7c).

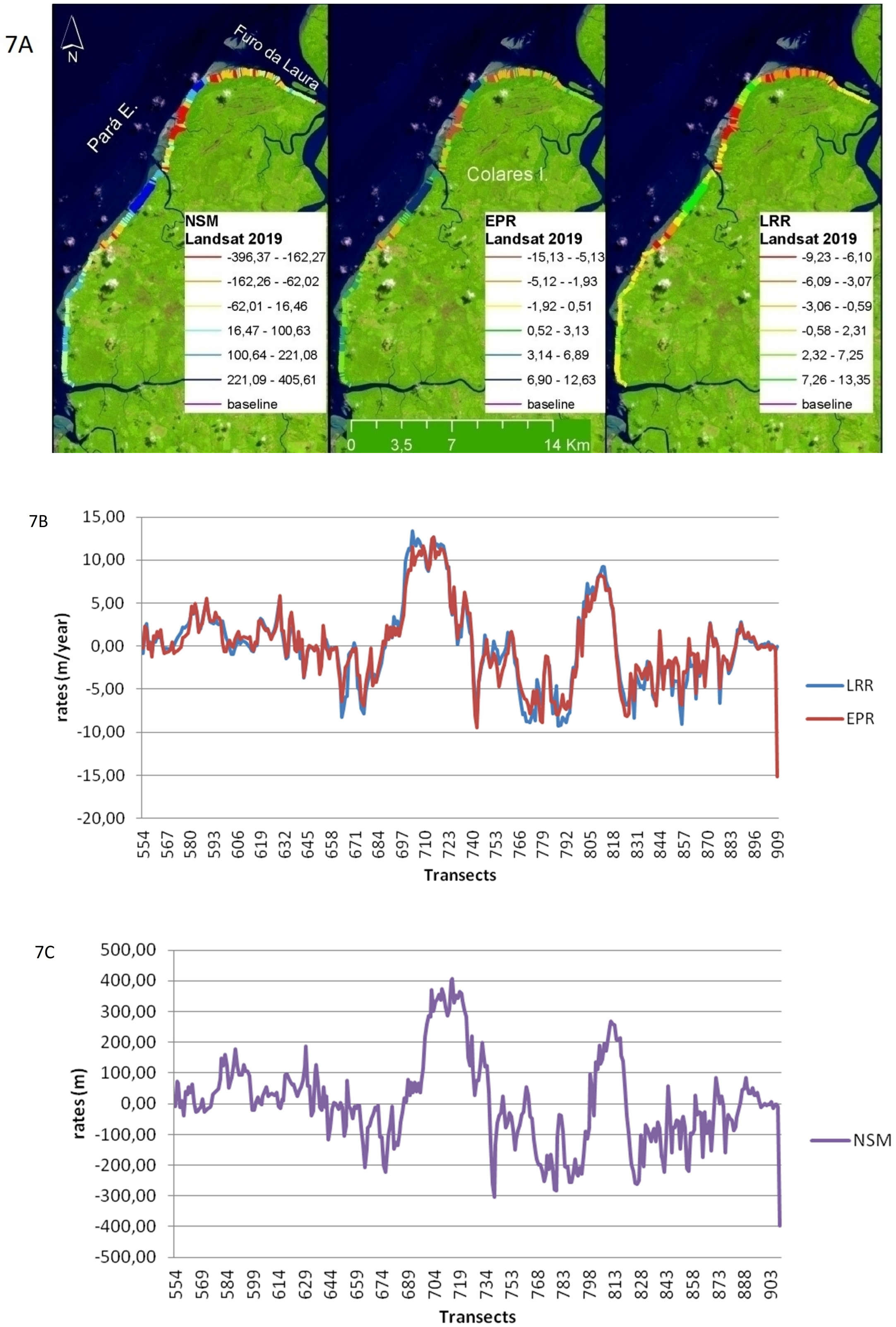


Figure 7 - Transects with the NSM, EPR and LRR rates of the LC (a) and graphs with the rates of variation of the LRR and EPR (b) and NSM (c) of the CL on the Colares Island. Preparation: authors.

The transect with the maximum erosion rate occurs in Sector D on the margins of ¨Furo¨ da Laura and the transect with the maximum accretion rate in Sector A. It is observed that the average erosion rates (yellow transects) and average accretion rates (green transects) are predominant. There are two areas (Sectors A and C) that stand out for presenting high accretion rates (transects 700 to 723; transects 799 to 818) (green transects). Furthermore, there are two areas (Sectors B and D) with high erosion rates (transects 741 to 798, transects 821 to 877) (Figure 8).

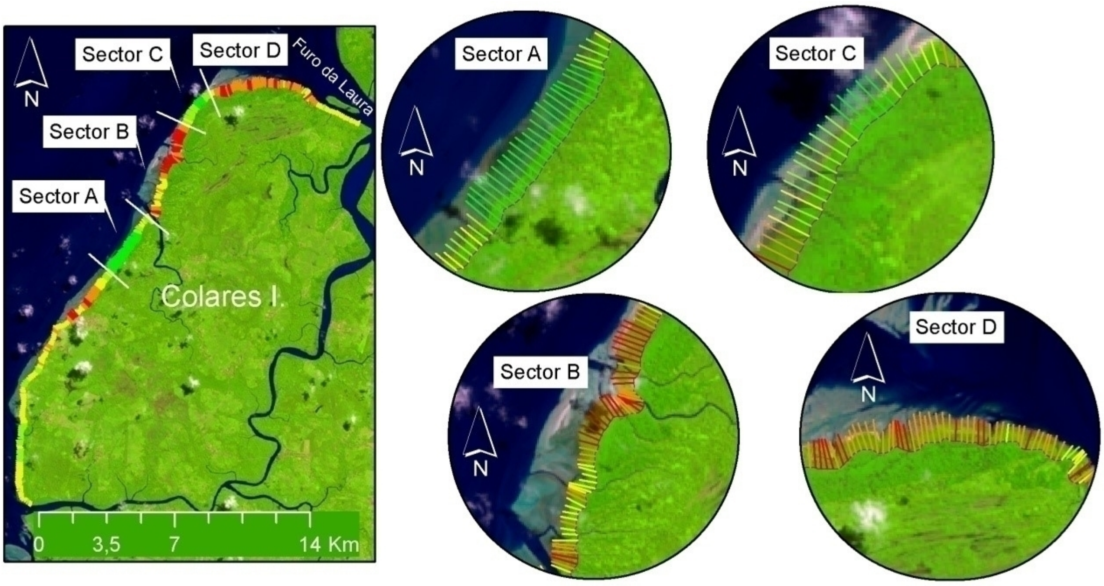


Figure 8 - Sectors A, B C and D of the CL on the Colares Island. Preparation: authors.

DISCUSSION

Remote sensing combined with tools such as DSAS proved to be an excellent option for analyzing changes related to coastal geomorphology. This methodology used in coastal zone of different countries, despite its limitations (medium resolution, periods with a high percentage of clouds) allowed the high precision diagnosis of erosion and accretion areas and the evolution of the CL on a larger temporal scale (APOSTOLOPOULOS and NIKOLAKOPOULOS , 2021).

The location of each erosion and/or accretion sector is related to its exposure and intensity of forcing in the middle Pará Estuary. The estuarine zone is characterized by the combination of water masses (salt and fresh) and forcing such as tides, currents and river discharge, contributing to erosion and/or accretion processes acting in the area.

The eastern margin of the middle Pará Estuary presents alternation of successive areas of erosion and accretion, but erosion rates are predominant. On the Mosqueiro Island, the 17 km long CL is characterized by a succession of headlands and coves, totaling 15 beaches (RAMOS and RANIERI, 2021).

The most exposed beaches have a greater tendency to erosion and those sheltered have a greater tendency to accretion, similar to what Santos et al. (2021) point out for the CL of the João Pessoa city, where these phenomena are influenced by waves that will diverge in the bay area and converge on the headlands due to wave refraction.

In sector A of the Mosqueiro Island, where the Areião, Bispo, Grande, Prainha, Farol, Chapéu Virado, Porto Arthur, Murubira, Ariramba and São Francisco beaches are located, accretion rates are higher with some erosion points, mainly in the Porto Arthur beach. França et al. (2020) point out that on the Grande and Bispo beaches the tendency to erosion is explained by tidal currents, the influence of NE-SW waves and the runoff of rainwater along the edge of the cliffs.

Sector B is made up of Carananduba beach, which is more protected and is influenced by the waters of the Pará Estuary and two channels parallel to CL, with less intensity. In sector C, the Marahú, Caruara and Paraíso beaches suffer from erosion (highest rate of -123.62 m). This sector is exposed, where tidal currents, winds and waves have intensified erosion, mainly in the CL section, with human occupation.

The accreting areas occur on the margins of coves protected by headlands and in the central area of Marahú in a ¨restinga¨ zone (NEVES; FRANÇA and SILVA, 2019; RAMOS and RANIERI, 2021). Finally, sector D comprises Baía do Sol beach, where the largest area of erosion was observed in ¨Furo¨ das Marinhas. However, the area of high accretion occurs in the central part of this beach, with low anthropogenic occupation.

In Santo Antônio do Tauá, the hydrodynamics of the Pará Estuary and Marinha and Laura ¨Furo´s¨ control the CL change. Its shape and morphology (alluvial plain) makes it more susceptible to erosion (rate of 2 m/year in the central part). The tidal currents in ¨Furo¨ das Marinhas help remove sediment. Similar processes occur in sections of the sector of Pará estuary.

Baía, Ranieri and Rosário (2021) in the Marapanim estuary found that on the west bank the variation in CL between 1988 and 2016 depends on the degree of exposure of the Santa Maria, Crispim and Marudá beaches. Crispim has the highest erosion rates (-9.82 m/year) due to its greater exposure to the open ocean, while Santa Maria is more sheltered and has suffered less oceanic influence.

On the Colares Island there are successive areas of erosion and accretion. Sector A in the central part of the CL is the point with the greatest number of high-accretion transects, followed by an area with the greatest number of high-erosion transects, close to a tidal channel. Sector C also has high accretion, receiving large volumes of sediment from sources outside the Pará Estuary (CORRÊA, 2005). Sectors B and D are characteristic of high erosion, where hydrodynamics are strong (Pará Estuary and ¨Furo¨ da Laura) (LIMA et al., 2015).

The erosion and accretion processes in the CL of the middle Pará Estuary are directly linked to the reach of semidiurnal tidal currents (2 $m.s^{-1}$) and river currents. The winds (2 $m.s^{-1}$) and waves (1 m) that occur in the estuary also contribute to the CL variation process (NEVES; FRANÇA and SILVA, 2019; RAMOS and RANIERI, 2021). The geomorphological aspects of the study area, the human occupation in some sections of the CL, mainly on the Mosqueiro Island, are other relevant and responsible factors in the variation of the CL on the east margin of the middle Pará estuary.

CONCLUSION

The main objective of this article is to quantify the erosion and accretion rates on the eastern margin of the middle Pará Estuary over 32 years (1987; 1993; 1999; 2004; 2008; 2013 and 2019) using remote sensing and DSAS extension. These methodological procedures recently applied in the Amazon region proved to be effective in achieving the intended results. The analysis showed a combination of natural forcings and anthropic agents influencing the change in the LC of the eastern margin of the middle Pará Estuary. The areas in successive erosion and accretion show that the position of each stretch in the estuary is another determining factor in changes in the LC, being more exposed or sheltered from natural forces. Erosion and accretion trends contribute to an understanding of the changes that occur in this section and assist in the construction of measures that seek solutions to the effects of erosion. DSAS is the tool that researchers used most to analyze CL variation between 2000 and 2019 (APOSTOLOPOULOS and NIKOLAKOPOULOS, 2021), as it provides relevant results for understanding the evolution of CL in coastal and estuarine environments. These results become relevant mainly when, in addition to forcing (tides, winds, currents and waves), according to Williams (2013), sea level rise emerges as a dominant driving force of change for coastal regions, and is becoming a negative impact factor for urban areas in the coastal zone. During the 20th century, sea levels began to rise at a global average rate of 1.7 mm/year. Due to this, low-altitude coastal plain regions, deltas and most islands are highly vulnerable, as is the case in the research region.

The results presented in this article may contribute to a set of measures seeking to achieve a healthy, resilient and safe ocean, such objectives present in the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), of the Organization of Nations United (UN). In Brazil, these data can contribute to applicability in Coastal Management (GERCO) and the Orla Project, with greater understanding of coastal dynamics.

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Author's Affiliation

Guimarães, D.K.M - Federal University of Para, Para (PA), Brazil.
El-Robrini, M. - Professor at Federal University of Para, Para (PA), Brazil.
Rosário, R.P. - Professor at Federal University of Para, Para (PA), Brazil.
Menezes, R.A.A. - Federal University of Para, Para (PA), Brazil.

Authors' Contribution

Guimarães, D.K.M - The author elaborated the entire text.
El-Robrini, M. - The author elaborated the entire text.
Rosário, R.P. - The author elaborated the entire text.
Menezes, R.A.A. - The author elaborated the entire text.

Editors in Charge

Jader de Oliveira Santos
Lidriana de Souza Pinheiro