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ARTICLE

MULTITEMPORAL ANALYSIS OF BANKLINE CHANGE AT THE CONFLUENCE OF THE AMAZON AND TAPAJÓS RIVERS USING GEOSPATIAL TOOLS

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Abstract

At the confluence of the Amazon and Tapajós rivers (Santarém), significant changes occur in the bed geomorphology, caused by fluvial dynamics that intensify the phenomena of erosion/retreat (¨terras caídas¨) and/or accretion (¨terras acrescidas¨). The Bankline (BL) is a geomorphological feature subject to topographical changes, which may occur over time, depending on the occurrence of high-energy, neotectonic or anthropic events. The position of the BL is an indicator of fluvial dynamics, whose position varies in time and space, producing movement towards the inner part of the lands (erosion); or towards the water (accretion) and the absence of recorded displacement suggests stability. This article analyzes the multitemporal variation (1995 to 2021) of the BL at the confluence of the Amazon and Tapajós rivers (Santarém), using the Digital Shoreline Analysis System (DSAS) and bathymetric methods. The results demonstrate that on the margins of the Tapajós River, the dynamics are different: on the left, erosion predominates with 91.38 % and on the right; accretion is very high with 74.35 %. In sectors I and II of the Amazon River, both margins are affected by erosion, respectively 60 % and 80 %. The average BL rates were -102.02 in the NSM, -3.91 in the EPR, and -4.42 in the LRR. Mean BL rates were -102.02 in NSM, -3.91 in EPR, and -4.42 in LRR.

Keywords: Lower Amazon; Landslides; Bankline; Raised land; DSAS.

Resumo / Resumen

ANÁLISE MULTITEMPORAL DAS MUDANÇAS NAS MARGENS FLUVIAIS NA CONFLUÊNCIA DOS RIOS AMAZONAS E TAPAJÓS USANDOFERRAMENTAS GEOESPACIAIS

Na confluência dos rios Amazonas e Tapajós (Santarém), ocorrem mudanças significativas na geomorfologia do leito, causadas pela dinâmica fluvial que intensifica os fenômenos de erosão/recuo (terras caídas) e/ou acreção (terras acrescidas). A Bankline (BL) é uma feição geomorfológica sujeita a alterações topográficas, que podem ocorrer ao longo do tempo, dependendo da ocorrência de eventos de alta energia, neotectônicos ou antrópicos. A posição da BL é um indicador da dinâmica fluvial, cuja posição varia no tempo e no espaço, produzindo movimento em direção ao interior dos terrenos (erosão); ou em direção à água (acreção) e a ausência de deslocamento registrado sugere estabilidade. Este artigo analisa a variação multitemporal (1995 a 2021) da BL na confluência dos rios Amazonas e Tapajós (Santarém), utilizando o Sistema Digital de Análise de Shoreline (DSAS) e métodos batimétricos. Os resultados demonstram que, nas margens do Rio Tapajós, as dinâmicas são distintas: à esquerda, a erosão predomina com 91,38% e, à direita, a acreção é muito alta, com 74,35%. Nos setores I e II do Rio Amazonas, ambas as margens são afetadas pela erosão, respectivamente 60% e 80%. As taxas médias de BL foram de -102,02 no NSM, -3,91 no EPR e -4,42 no LRR. As taxas médias de BL foram de -102,02 no NSM, -3,91 no EPR e -4,42 no LRR.

Palavras-chave: Baixo Amazonas; Deslizamentos; Margens de Margem; Terrenos Elevados; DSAS.

ANÁLISIS MULTITEMPORAL DEL CAMBIO DE LA MARGEN FLUVIAL EN LA CONFLUENCIA DE LOS RÍOS AMAZONAS Y TAPAJÓS UTILIZANDO HERRAMIENTAS GEOESPACIALES

En la confluencia de los ríos Amazonas y Tapajós (Santarém), ocurren cambios significativos en la geomorfología del lecho, causados por la dinámica fluvial que intensifica los fenómenos de erosión/retroceso (¨terras caídas¨) y/o acreción (¨terras acrescidas¨). La Línea de Banco (LB) es un accidente geomorfológico sujeto a cambios topográficos, que pueden ocurrir a lo largo del tiempo, dependiendo de la ocurrencia de eventos de alta energía, neotectónicos o antrópicos. La posición de la LB es un indicador de la dinámica fluvial, cuya posición varía en el tiempo y el espacio, produciendo movimiento hacia la parte interna de las tierras (erosión); o hacia el agua (acreción) y la ausencia de desplazamiento registrado sugiere estabilidad. Este artículo analiza la variación multitemporal (1995 a 2021) de la LB en la confluencia de los ríos Amazonas y Tapajós (Santarém), utilizando el Sistema Digital de Análisis de Línea de Costa (DSAS) y métodos batimétricos. Los resultados demuestran que en las márgenes del río Tapajós la dinámica es diferente: a la izquierda, predomina la erosión con un 91,38 %, y a la derecha, la acreción es muy alta, con un 74,35 %. En los sectores I y II del río Amazonas, ambas márgenes se ven afectadas por la erosión, con un 60 % y un 80 %, respectivamente. Las tasas medias de BL fueron de -102,02 en el NSM, -3,91 en el EPR y -4,42 en el LRR. Las tasas medias de BL fueron de -102,02 en el NSM, -3,91 en el EPR y -4,42 en el LRR.

Palabras-clave: Bajo Amazonas; Deslizamientos de tierra; Línea de ribera; Tierras elevadas; DSAS.

INTRODUCTION

There is a complex relationship at the confluence of the Amazon and Tapajós rivers, in the Santarém, which has recently shown significant changes in the bed geomorphology, which can be attributed to structural, neotectonic and climatic factors. In the ebb and dry period, where the rivers have less volume, the changes caused by erosion, transport and deposition processes are evident in the configuration of the larger bed. This dynamic in the Amazon has an important geomorphological role in the organization and spatial reorganization (BRANCHES FARIAS, 2012).

The Amazon Rivers represent the routes of internalization of human occupation since the floodplains present some of the best lands for the practice of agriculture. However, the main risk in urban agglomerations is the phenomenon of river erosion (¨fallen lands¨) which can promote the destruction of sections of these riverside cities; the phenomena of river accretion (¨accreted lands¨) occur in association with seasonal floods and elevation of the ground level (DANTAS and TEIXEIRA, 2013).

The Amazonian plain is characterized by extensive floodplains (several km) that occur along the channel of the Amazon River (DANTAS and TEIXEIRA, 2013). To understand the changes (erosion/accretion) in the study area, the term BL was used to indicate the river margin of the minor bed. In satellite images, the BL is identified with the physical interface between land and water. The BL changes continuously over time, depending on climatic conditions (precipitation rate, extreme events), hydrodynamics (vertical oscillation of water level, river flow, horizontal current), geological conditions (sliding of sediment masses and/or instability, neotectonic) and anthropic. The position of the BL is an indicator of fluvial dynamics, considering an average period, whose position varies in time and space, producing movement towards the inner part of the continent (erosion); or towards the water (accretion); however, the absence of displacement records suggests stability (GUIMARÃES, 2022).

One of the techniques that help detect changes in the BL is remote sensing, which enables the manual or semi-automatic extraction of the BL from the digital processing of satellite images with high quality, cost-effectiveness and reduction of manual error. To make this analysis more accurate, the Digital Shoreline Analysis System (DSAS) was used; is a software extension available and is compatible with ESRI Geographic Information System (ArcGIS) software, which generates statistical calculations of shoreline change rates for a series time of given vectors (MENEZES, 2021). Some investigations on erosion and accretion have been developed in the amazon region, such as: Influence of hydrological parameters on the fluvial erosion process in the region of Santarém (TEIXEIRA; SILVA and LOPES, 2018); Dynamics between water and land fall on the banks of the Amazon River based on the level data of the Tapajós River in the city of Santarém (VALE et al., 2019); Fluvial erosion risk analysis: an amazon study case (NASCIMENTO BANDEIRA et. al., 2021). DSAS is suitable for calculating the change in shoreline position over time. It is used worldwide and has recently been introduced in the Amazon region: CONTI and RODRIGUES (2011); RANIERI and EL-ROBRINI (2015); BAÍA; RANIERI and ROSÁRIO (2021); MENEZES (2021); GUIMARÃES (2022). Understanding the multitemporal evolution of the shoreline and the dynamics that influence the erosion and/or accretion process is fundamental for efficient management, aiming to find adaptive and mitigating solutions (GUIMARÃES, 2022). This article analyzes the multitemporal variation of BL (1995-2021) at the confluence of the Amazon and Tapajós rivers in Santarém and identifies areas in the process of erosion and/or accretion, using DSAS.

MATERIAL AND METHODS

STUDY AREA

The study area is located in the Lower Amazon (municipality of Santarém) on the right bank of the Tapajós River, where the confluence with the Amazon River occurs, 807 km from Belém. Access to the area can be via road, river or air.

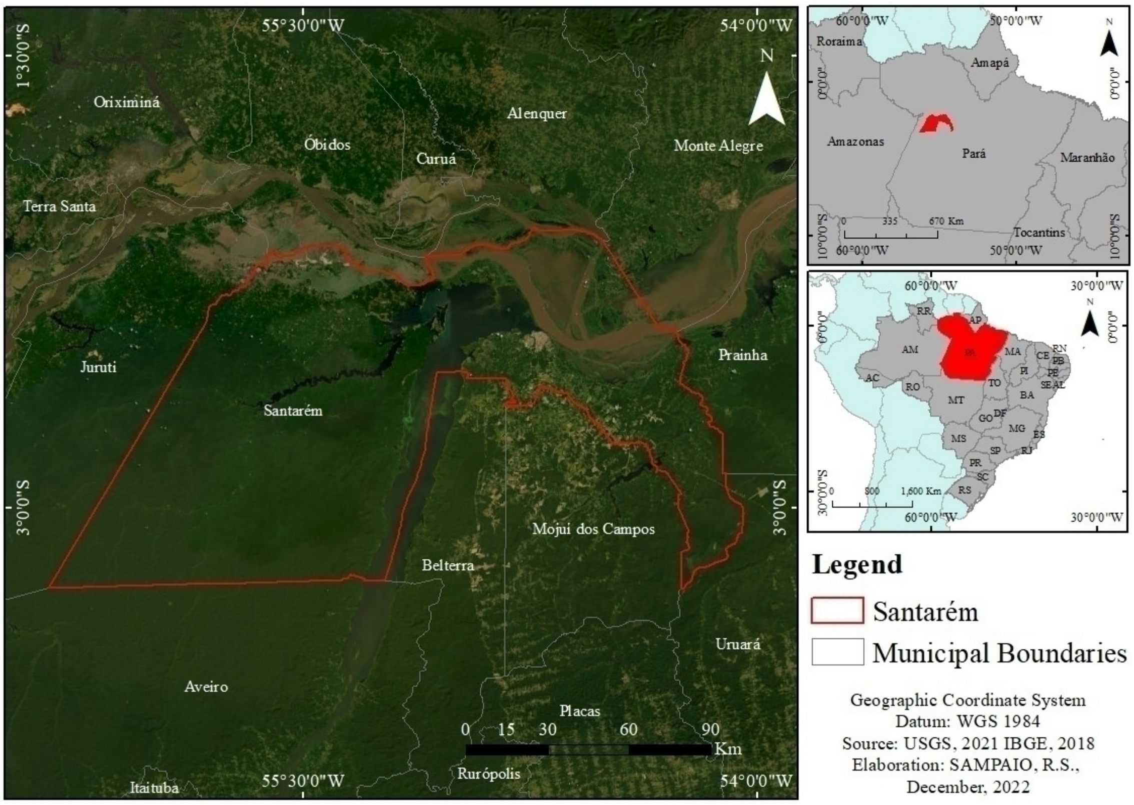

Figure 1 - Location of the study area (red box). Source: Elaborated by the author.

CHARACTERIZATION OF THE WORK AREA

The climate is type Am (hot and humid tropical), characteristic of Tropical Forests, with high average temperatures in the coldest month, with a shorter dry season that is compensated by a high level of rainfall (DUBREUIL et al., 2018). The average temperature and precipitation/year are 25.9 °C and 2150 mm, respectively. Average temperatures vary by 1.6 °C throughout the year. The difference between the precipitation of the driest month (September - 33 mm) and the wettest (March - 388 mm) is 355 mm. The average relative humidity is 86 %. Rains are heaviest in winter (December to May), with a monthly average of between 170 mm and 300 mm. June to November is the driest period (regional summer), with lower rainfall, with averages below 60 mm, between the months of August and October (ANA, 2022).

Extreme events were recorded during the research period of this paper. During 1995, El Niño/ Moderate occurred (CPC, 2022). In 2000 and 2008, it was the turn of La Ninã/ Strong. In 2015, El Niño returned with Very Strong intensity. However, in 2021, La Niña Moderate occurred.

The Amazon River basin is the largest on the planet (6,110,000 km²), with its source in the walls of the Andean chain and its mouth in the Atlantic Ocean (North and South channel of the Amazon River). The water network of the study area includes the Amazon, Arapiuns and Tapajós rivers. In addition to the floodplains, forming the lakes such as Pacoval, Itarim, Aramanai and Ituqui. The flow of the Amazon River at its mouth is 209,000 m³/s and that of the Tapajós River is 12,434 m³/s. The climate that prevails in Santarém interferes directly in the fluvial regime of the rivers, making the identification of the seasonal period easier. In the Tapajós River, the flood period occurs between the months of January and May and the ebb period between June and December, the dry season between August and October with peaks of flow between the months of February and May. The average flow is 8,103 m³/s, ranging from 3,103 to 30,103 m³/s (GUEDES, 2020).

In the Amazon River, there is a progressive increase in the flow, in a west-east direction, from February to May, reaching maximum values in mid-May, increasing the flooded area; however, from

June onwards, the flow and, consequently, the flooded area decreases, with a minimum value in November. The average difference between the water level during the period of maximum and minimum elevation is 6 m, reaching 7 m when considering the extreme values of maximum and minimum (CPRM, 2021a).

The work area is located in the geomorphological units of ¨Planalto¨ Tapajós-Xingu, ¨Planalto¨ do Tapajós and Planície Amazônica. This area is characterized by sediments from the Alter do Chão Formation (Meso-Cenozoic), associated with detrital-laterite covers from the Paleogene (Cenozoic), in addition to recent sediments, forming terraces and alluvial deposits (Holocene), formed by sediments associated with the Tapajós rivers. and Amazonas (CORTES; SZLAFSZTEIN and LUVIZOTTO, 2020). Due to the low topography of this river basin, mainly in the lower course, the tide advances beyond Óbidos (maximum amplitude of 10 cm), characterizing this segment (Foz of the Amazon River - Óbidos) as the upper estuary (river zone), where it occurs the dynamic tide (EL-ROBRINI et al., 2021).

ACQUISITION AND PROCESSING OF SATELLITE IMAGES

The research was carried out at the Ocean Geology Laboratory (LAGEOC), of the Marine and Coastal Studies Group (GEMC/CNPQ) at UFPA. Satellite images were acquired (1995, 2001, 2007 and 2020) georeferenced through the Earth Explorer websites of the U.S. Geological Survey (USGS) and the National Institute for Space Research (INPE). The criterion for choosing the images was the dry period (October - November), with low rainfall and with a lower percentage of clouds (from 0 to 50 %) in the study area for better visualization of the SL. Landsat satellite images were acquired (Table 1).

Sensor	Orbit-point	Data	Spatial Resolution (m)	Bands	Extreme Events /Classification
TM	227062	10/10/1995	30	3,4,5	El Niño/ Moderate
ETM +	227062	07/10/2000	30	3,4,5	La Ninã/Strong
ETM +	227062	30/11/2008	30	3,4,5	La Niña/Strong
OLI	227062	17/10/2015	30	4,5,6	El Niño/Very Strong
OLI	227062	17/10/2021	30	4,5,6	La Niña/Moderate
SRTM (02S555)	-	11/02/2000	30	-	La Ninã/Strong

Table 1 - Data from the acquired Landsat satellite images. Source: USGS, 2021; CPC, 2022.

For digital processing of images, ArcMap 10.1 software was used. The composition of the spectral bands in the raw images was created using digital image processing (PDI) techniques through the composition of RGB images, which facilitates interpretation, as it highlights the characteristics of the surface. In the LANDSAT 5 and 7 image, bands 3 (visible red), 4 (near infrared) and 5 (mid infrared) were used, while in LANDSAT 8 bands 4 (red), 5 (near infrared) and 6 (SWIR) were used.

In order to ensure the margin of accuracy of the measurements based on the errors of the images, the geometric errors were calculated from the simple rule of three, which establishes the linear and area geometric error margin. The cumulative errors were determined from the sum of the geometric errors. As a result of the cumulative errors 35.223 m for linear measurements and 1054.8 m² for area measurements. The average error was 7.045 m for linear measurements and 210.96 m² for area measurements. The third procedure was the direct vectorization of the SL over the images. After the vectorization of the SL in all images, the vectors are superimposed.

EXTRACTION OF BATHYMETRIC DATA THROUGH NAUTICAL CHARTS AND INTERPOLATION

The bathymetry analysis involved digitizing depths on nautical charts (NOAA-BSB version 3.0 format. - 2011-2014) covering the area, from Costa do Ituqui to Ilha do Meio and Rio Tapajós (scale 1:100,000) (CHM, 2022). The digitization of the maps in ArcGis 10.5 and later the method of interpolation of natural neighbors was applied, which allowed the elaboration of the bathymetric chart, as well as the visualization of the river channel.

DIGITAL SHORELINE ANALYSIS SYSTEM - DSAS

DSAS is an extension to ArcMap software, which works with ESRI Geographic Information System (ArcGIS) software. DSAS calculates rate of change statistics for a time series of SL vector data. It is a software of great value for coastal management and studies on erosion and accretion, which allows the measurement of rates of change in a given region with greater reliability, reducing geoprocessing errors (MENEZES, 2021).

From the vectorization of the SL of all years, the use of DSAS begins, which was based on the creation of quantitative parameters of SL variation from the generation of transects orthogonal to a baseline determined by the user (baseline) with a defined spacing (MENEZES, 2021). There are a number of quantitative parameters that express the horizontal variation of SL determined over time (MENEZES, 2021) (Table 2).

DSAS PARAMETERS	DESCRIPTION
SCE - ***Shoreline Change Envelope***	Shoreline Change Envelope describes the distance between the extremes of SL (erosion and accretion). It represents the total movement and does not take into account dates.
NSM - ***Net Shoreline Movement***	Net Shoreline Movement shows the distance between the most recent and oldest SL´s.
EPR - ***End Point Rate***	End Point Rate Determines the rate of change by simple ratio of distance by time of the dates of the SL´s (most recent and oldest) by the referred distance.
LRR - ***Linear Regression Rate-of-Change***	Linear Regression Rate-of-Change Shows a linear regression of the rate of change between the first and last SL.
JKR – ***Jacknife method***	Jacknife method calculates a linear regression between all possible variations of the SL.
WRL - ***Weighted Linear Regression***	Weighted Linear Regression calculates a regression between the SL´s with weight associated with position inaccuracies.

Table 2 - Quantitative parameters available in DSAS. Source: Menezes, 2021.

The NSM, EPR and LRR parameters were used because they were suitable for the necessary analysis of the change in the position of the SL, resulting in variations in meters over the 25 years of analysis (NSM) and average rates of change per year (EPR and LRR).

END-POINT RATE (EPR)

The endpoint rate component is calculated by dividing the SL by the elapsed time between the oldest and most recent SL. In this sense, the main advantage of using this method is that it needs only two vector components to carry out the analysis over the time studied.

However, there are disadvantages that correspond to the analytical issue of more data, that is, the intermediate SL's are ignored throughout the processing. It is important to emphasize that the data obtained from this method does not disqualify the analysis of the results (GUIMARÃES, 2022).

NET SHORELINE MOVEMENT (NSM)

The NSM is the distance between the oldest and most recent SL's for each transect, where a positive value indicates movement towards the water and a negative value indicates movement of the SL towards the land (GUIMARÃES, 2022).

LINEAR REGRESSION RATE (LRR)

The linear regression rate was determined by fitting a least squares regression line to all points for a transect generated in the processing. The line, which is based on the regression, is fitted so that the sum of the squared components (determined by squaring the distance offset of each data point from the regression line and adding the squared residuals together) is minimized.

The main features of LRR are that 1) all data are used, regardless of changes in trend or accuracy, 2) the method is purely computational, 3) the calculation is based on accepted statistical concepts, and 4) the method is easy to use. However, the linear regression method is susceptible to atypical effects and tends to underestimate the rate of change relative to other statistics, such as EPR (GUIMARÃES, 2022).

RESULTS

MULTITEMPORAL ANALYSIS IN DSAS

Using the vector generation tool, river lines were produced in images from 1995, 2000, 2008, 2015 and 2021 in the software. The results obtained were the multitemporal variability of SL in the working area (~247 km) with 476 transects. The rates representing positive DSAS quantifications characterize SL displacement parameters towards the river, configuring accretion values, and the negative SL values indicate components of change variation in continental direction, representing the erosive vector (Table 3).

	Left margin Tapajós River	Right margin Tapajós River	Left margin Amazon River (Sector I)	Right margin Amazon River (Sector I)	Left margin Amazon River (Sector II)	Right margin Amazon River (Sector II)
Number of transects	58	78	78	63	78	121
Lenght of BL (km)	27	35	38	30	38	57
Number of erosion transects	53	20	53	39	70	100
Number of accretion transects	5	58	25	24	8	21
Rate of erosion transects (%)	91,38	25,65	67,95	61,90	89,74	82,65
Rate of accretion transects (%)	8,62	74,35	32,05	38,09	10,26	17,35

Table 3 - Calculated summary of the SL change rates of the sectors of Santarém. Prepared by the author.

The work area has a trend of erosion of SL because the values obtained from the parameters: NSM, EPR and LRR characterized predominantly positive values, except in the left margin of the Tapajós River, which does not present any positive data.

The NSM rates had an average retreat indicated with the negative rate of -202.67 m and a positive rate of 105.61 m. The total component of SL retreat comprised a total of 335 transects, representing a quantitative amount corresponding to 70.38 %, with a maximum negative rate of -1555.28, on the left margin of the Amazon River (sector I). In contrast, 141 transects indicated accretion rates, where this amount represents 29.62 %, with a maximum positive rate of 713.92 m, on the left margin of the Amazon River (sector I).

The EPR parameter accounted for rates that generated an average of -4.27 m/year. 335 transects with erosive behavior were calculated (70.38 % of the total); the maximum retreat value was -59.77 m/year and the average of all erosion rates is -7.78 m/year. In contrast, the total number of transects subjected to accretion was 141, indicating 29.62 % of the total transects. The maximum accretion was 27.44 m/year and the average of all accretion rates is 4.05 m/year.

The LRR has an average of -4.83 m/year. There were 344 transects identified with evidence of erosion, which corresponds to 72.27 % of the total transects. The maximum retreat value was -62.09 m/year and the average of all erosion rates was -8.21 m/year. In contrast, the total number of accretion transects amounted to 132, corresponding to 27.73 % of the total transects. The maximum accretion rate corresponded to 31.35 m/year, where the average of all accretion rates is 3.96 m/year. The work area was subdivided into 3 sectors for a better analysis of SL dynamics scenarios: Sector I of the Amazon

River without the influence of the Tapajós River - the greatest accretion and erosion processes occurred; Sector II at the confluence of the Tapajós and Amazon Rivers - is highly erosive; Sector III - only the Tapajós River - had erosive behavior (left margin) and accretion (right margin)

AMAZON RIVER SL TRENDS - SECTOR I

In Sector I, on the margins of the Amazon River (~68 km), of the 141 transects generated, 64.93 % represent erosion and 35.07 % accretion, indicating a greater tendency to erosion, however, the left margin had 91 % of the transects representing erosion and the right margin 74 % of the transects represented accretion. The average erosion and accretion rate was -381.49 m and 244.81 m, respectively. The average rates of variation are -6.49 m/year (EPR) and -7.15 m/year (LRR) (Table 4) (Figure 2).

	Right margin Amazon River (Sector I)			Left margin Amazon River (Sector I)		
	NSM (m)	EPR (m/ano)	LRR (m/ano)	NSM (m)	EPR (m/ano)	LRR (m/ano)
Max positive rate	603,1	23,18	19,21	713,92	27,44	31,35
Max negative rate	-190,66	-7,33	-7,73	-1555,28	-59,77	-62,09
Negative average positive rate	299,26	11,50	8,69	190,26	7,31	8,16
Negativa average rate	-93,71	-3,60	-3,59	-669,28	-25,72	-26,14
Overall average geral	55,99	2,15	1,28	-393,78	-15,13	-15,58

Table 4 - Rates of change of SL calculated by NSM, EPR and LRR parameters for the right and left margins of the Amazon River (Sector I). Left margin of the Amazon River (Sector I).

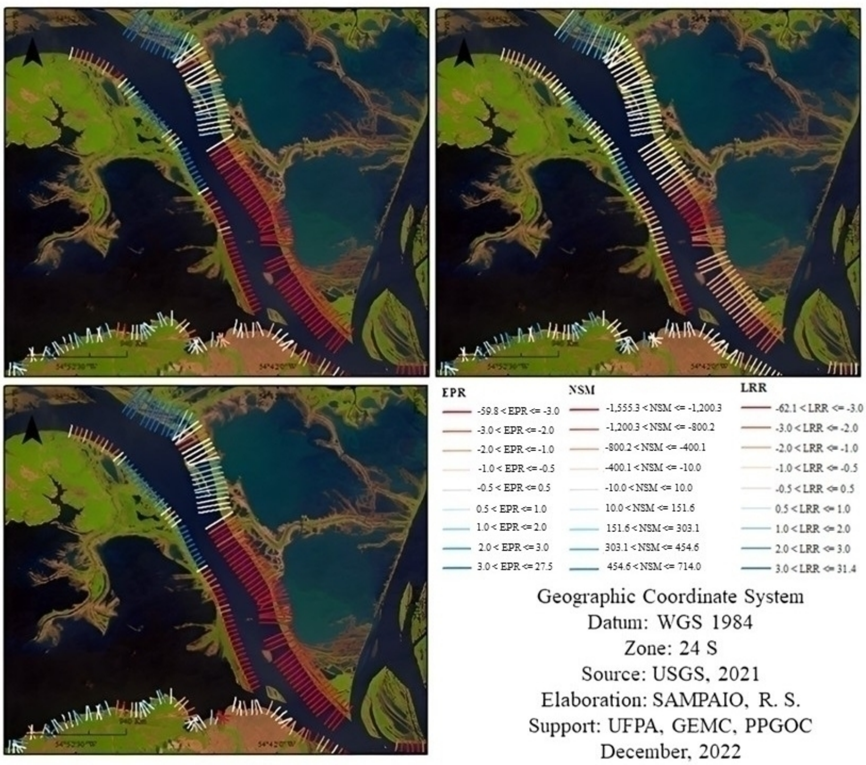

Figure 2 - End Point Rate (EPR), Net Movement (NSM) and Linear Regression Rate (LRR) respectively in the Amazon River (Sector I).

Maximum erosion rates reach -59.77 m/year at EPR and -62.09 m/year at LRR, while maximum accretion rates reach 27.44 m/year at EPR and 31.35 m/year at LRR, on the left margin.

AMAZON RIVER SL TRENDS - SECTOR II

On the margins of the Amazon River (Sector II) (~ 95 km), of the 199 transects generated, 86.19 % represent erosion and 13.81 % accretion, indicating a greater tendency towards erosion, with an average erosion rate of -148.56 m and an average accretion rate of 34.29 m. The average rates of change were -4.76 m/year (EPR) and -5.34 m/year (LRR) (Table 5) (Figure 3).

	Right margin Amazon River (Sector II)			Left margin Amazon River (Sector II)		
	NSM (m)	EPR (m/ano)	LRR (m/ano)	NSM (m)	EPR (m/ano)	LRR (m/ano)
Max positive rate	72,35	2,78	1,64	108,93	4,19	4,25
Max negative rate	-729,73	-28,05	-34,02	-709,87	-27,28	-30,04
Average positive rate	21,13	0,81	0,72	47,45	1,82	1,58
Negative average rate	-154,13	-5,92	-6,98	-143,97	-5,53	-5,73
Overall average rate	-123,71	-4,75	-5,89	-124,33	-4,77	-4,79

Table 5 - Rates of change of SL calculated by NSM, EPR and LRR parameters for the right and left margin of the Amazon River, sector II. Left margin Amazon River (Sector II). Fonte: Elaborado pela autora.

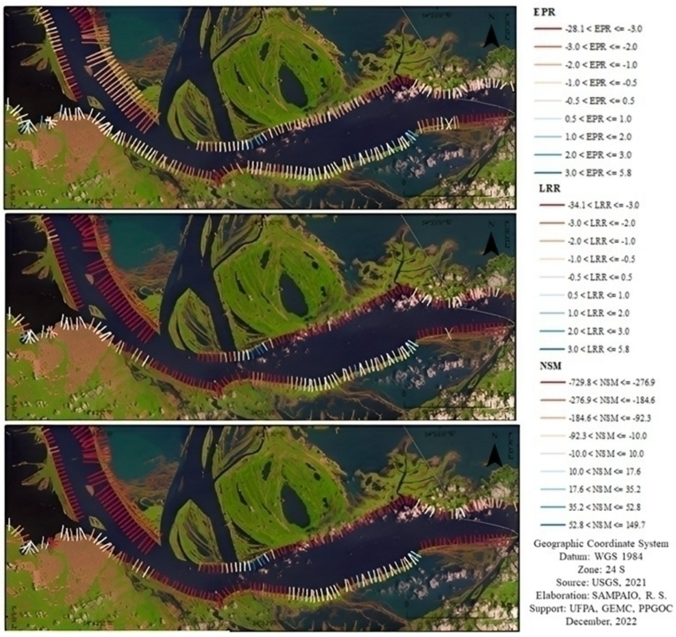

Figure 3 - End Point Rate (EPR), Net Movement (NSM) and Linear Regression Rate (LRR) respectively in the Amazon River (Sector II). Source: Elaborated by the author.

The maximum erosion rates reach -28.05 m/year in the EPR and -34.02 m/year in the LRR on the right margin, while the maximum accretion rates reach 4.19 m/year in the EPR and 4.25 m/year in the LRR on the left margin.

TAPAJÓS RIVER TRENDS

On the margins of the Tapajós River (~ 80 km), of the 136 transects generated, 58.52 % represent erosion and 41.48 % accretion, indicating a greater tendency towards erosion. The average rates of erosion and accretion are -40.54 m and 21.49 m, respectively. The average rates of change of -1.22 m/year (EPR) and -1.28 m/year (LRR) confirm the erosion trend (Table 6) (Figure 4).

	Right margin Tapajós River			Left margin Tapajós River		
	NSM (m)	EPR (m/ano)	LRR (m/ano)	NSM (m)	EPR (m/ano)	LRR (m/ano)
Max positive rate	149,63	5,75	5,77	17,48	0,67	0,46
Max negative rate	-124,41	-4,78	-14,46	-180,08	-6,92	-6,42
Average positive rate	36,11	1,38	1,47	6,88	0,26	0,46
Negative average rate	-30,97	-1,18	-1,77	-50,11	-1,92	-2,10
Overall average rate	18,91	0,72	0,51	-45,20	-1,73	-2,05

Table 6 - Rates of change of SL calculated by NSM, EPR and LRR parameters for the right and left margins of the Tapajós River. Source: Elaborated by the author.

Figure 4 - End Point Rate (EPR), Net Movement (NSM) and Linear Regression Rate (LRR) respectively in the Tapajós River. Source: Elaborated by the author.

The maximum erosion rates reach -6.92 m/year in the EPR on the left margin and -14.46 m/year in the LRR on the right margin, while the maximum accretion rates reach 5.75 m/year in the EPR and 5.77 m/year in the LRR, both on the right margin.

DISCUSSION

The effects of hydrological conditions are high in the work area in 2007-2008, La Niña with moderate intensity, influenced the rainfall regime and in 2008, it had a large index in March with 825.10 mm. In 2020-2021 there were La Niña events of moderate intensity that influenced the elevation of the fluviometric quota with 5.75 m in 2021, and during the May flood season it reached a flow of 273143.34

m³/s, one of the highest rates ever recorded. Bathymetric data (Figure 5) and terrain elevation (SRTM images) with topographic profiles (Figure 6) have been contributing to the understanding of the relationship between channel geometry and fluvial erosion and accretion processes. In the Tapajós River, the average channel width is 15.5 km, the maximum and average depth is respectively 39 m and 10.69 m. On the left margin, the average depth is 21.42 m and on the right margin an average of 34 m. This sector is formed by the Tapajós ¨Patamares¨ that include terraces or pediments at different altitudes and reach 150 m in Santarém.

In sector I of the Amazon River, the average width of the channel is 5.13 km, the maximum and average depth is 53 m and 11.87 m respectively. On the left margin, the average depth is 7.33 m and on the right margin 11 m. In sector II of the Amazon River the average width of the channel is 4.38 km, the maximum and average depth is respectively 62 m and 14.05 m. On the left margin, the average depth is 10.61 m and on the right margin 7.55 m. Sectors I and II of the Amazon River occur in the Amazon Plain, characterized by a flat topography, resulting from periodic or permanently flooded river accumulations (floodplains), where the highest regional altitudes are close to 20 m.

The overall average depth is 12.11 m. The depth range between 0-5 m, 5-10 m, 10-15 m, 15-20 m, 20-25 m, 25-30 m, >30 m is respectively 27.53 %, 14.34 %, 22.46 %, 13.76 %, 7.24 %, 6.66 % and 7.97 %, this shows that in the region, the 0-5 m depth range is predominant.

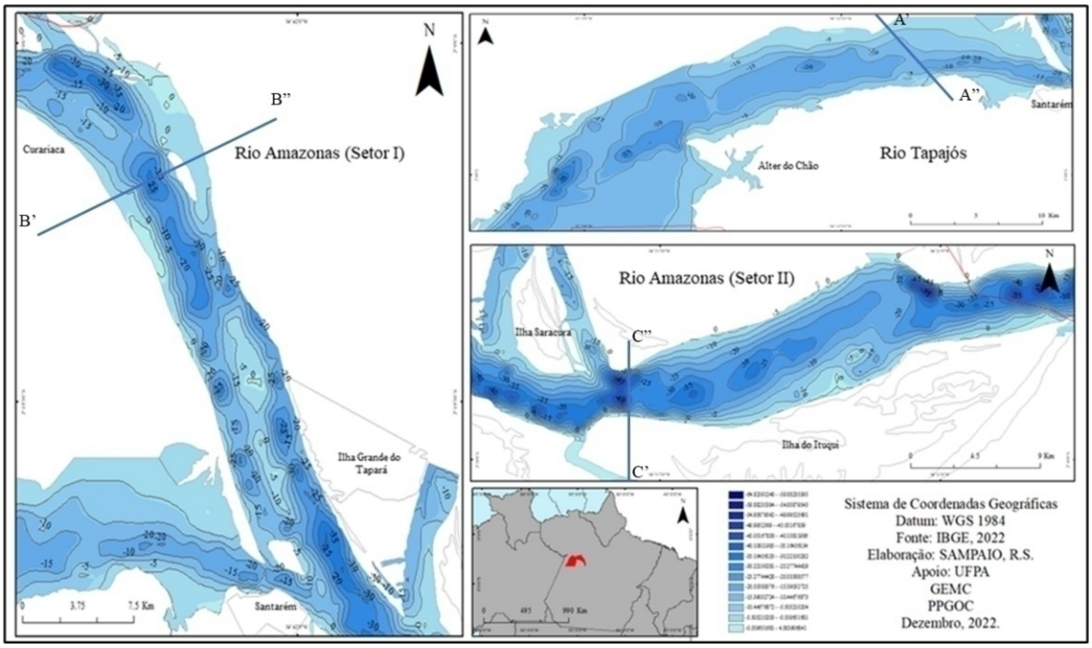

Figure 5 - Bathymetry of the study area subdivided into sectors: I and II (Amazon River) and Tapajós River. Source: CHM, 2022.

On the Tapajós River, the dynamics are different on the margins: left with 91.38 % (erosion) and right with 74.35 % (accretion) with average rates of erosion and accretion, respectively of -40.54 m and 21.49 m. According to Cortes (2020), there is inequality between the margins, the land is higher on the east margin than on the west margin of the Tapajós channel. The orientation of the channel in relation to the eastern margin of the basin and the differentiation of the valleys between the left and right margins suggest an inclination of the basin towards the east. Sector I of the Amazon River showed 64.93 % erosion and 35.07 % accretion, indicating a greater tendency towards erosion. To the north of the left margin of this sector it is possible to observe accretion processes that reach 713.92 m and erosion processes of -1,555.28 m. Teixeira, Silva & Lopes (2018) showed that the greater depths along the left margin resulted in a difference in the energy distribution within the channel, where the highest velocities were measured at around 2.3 m/s. In this sector, the slope of the left margin reaches a depth of 32.2 m and is almost vertical.

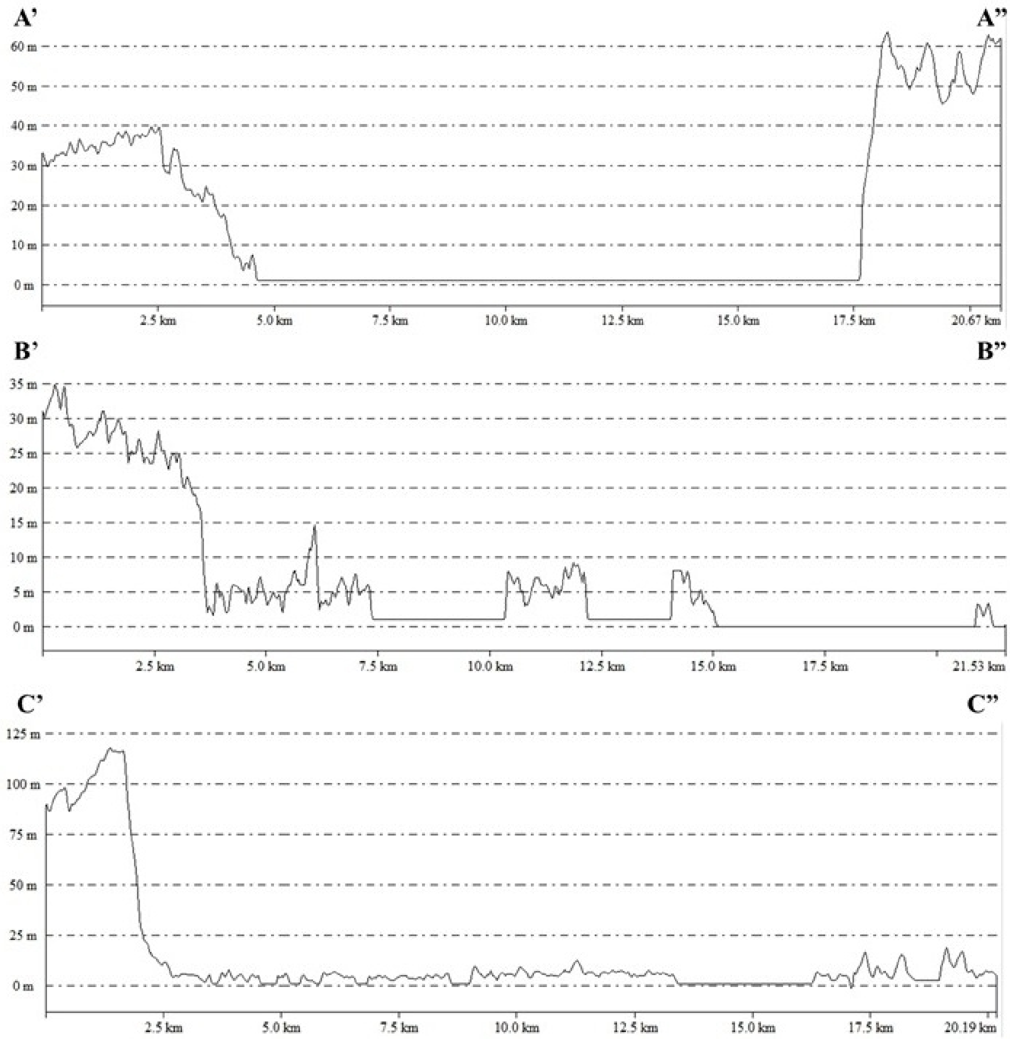

Figure 6 - Topographic profiles of the sectors. Source: Prepared by the author.

According to the same authors, this type of geometry favors the occurrence of accelerated lateral and vertical erosion, which justifies the large volume of eroded sediments. For NASCIMENTO BANDEIRA et al. (2021), the EPR result is an erosion rate ranging from 0.5 to 77 m with some accretion points up to 3 m, but the result calculated for the left margin, the maximum positive rate was 27.44 m/a and the maximum negative rate was -59.77 m/year.

Sector II of the Amazon River presented the highest erosion rates being 86.19 % in erosion and 13.81 % in accretion. With the highest maximum positive rate on the left margin (108.93 m) and the highest maximum negative rate on the right margin (-729.73). It is also the sector where the greatest depths occur, maximum of 62 m near the Saracura island (left margin) and the Ituqui island (right margin). The height of the left margin has an average of 10.61 m and the right margin average of 7.55 m.

In the floodplain (sectors I and II of the Amazon River), formed by the Amazon Plain, the rates of both erosion and accretion are higher compared to the areas formed by the Tapajós ¨Patamares¨ (sector of the Tapajós River). The results obtained in this article corroborate in part with the assessment of CPRM (2021b), however, the erosion rates of 1 to 2m/year presented are relatively lower than the rates that reach -15.13 (EPR) and -15.58 (LRR) on the left margin of the Amazon River (sector I) and -4.75 (EPR) and -5.89 (LRR) on the right margin of the Amazon River (sector II). In the analysis of risk of natural phenomena, only one area was out of line, presenting high risk for erosion (¨terras caídas¨) and accretion (¨terras acrescidas¨), while the area presented only accretion rates.

Data (erosion and accretion) from the work area were compared with other regions of the Amazon River basin. In the Acre River (Acre, border between Brazil and Bolivia), the loss exceeded 10 m/8 years, and the distance from one margin to the other is 20 m (ALMEIDA, SANTOS and ARCOS, 2014). In Rondônia, Curicacas Island disappeared (extension > 5 km) in the period of 38 years, however, the Madeira River migrated by 900 m towards the left margin (DELLA-JUSTINA and SAMPAIO, 2016). In the Branco River (Roraima), it was estimated at 1m/year and the average rate of channel margin accretion of ~1m/year (CREMON, 2016). In the Solimões River (Amazonas), accretion predominated in a river segment, with annual averages of 3.94 km² and 3.20 km² (PASSOS and SOARES, 2015). However, in the Amazon River (Parintins), the process of lateral migration of the river influenced erosion (88.56 km²) and accretion (49.64 km²), with rates of 2.95 km²/year and 1.65 km²/year respectively for the last two decades (MARQUES, 2017). In the Porto de Moz region (Pará), the margin retreated from 0.5 to 3 m/year (NASCIMENTO BANDEIRA et al., 2021).

			Accretion			Erosion		
Authors	Place	Period	AL	TA	TL	AL	TA	TL
Almeida, Santos & Arcos (2014)	Brasiléia - AC (Rio Acre)	2005 - 2013	***	***	***	+10 m	***	***
Della-Justina & Sampaio (2016)	Porto Velho RO (Madeira River)	1976-2014	+ 5 km	***	***	900 m	***	***
Cremon (2016)	Roraima (Branco River)	1985-2014	***	***	1m/a	***	***	-1m/a
Passos & Soares (2015)	Manaus – AM (Solimões River)	1995-2011	***	3,94 km²	***	***	3,20 km²	***
Marques (2017)	Parintins – AM (Amazonas River)	1985-2015	***	49,64 km²	1,65 km²/a	***	88,56 km²	2,95 km²/a
Nascimento Bandeira et al. (2021)	Porto de Moz PA (Amazonas River)	2003-2014	***	***	***	***	***	0.5 a 3 m/a

Table 7 - Synthesis of erosion and accretion results found in other parts of the Amazon River basin. AL (Linear change); TA (Rate per area); TL (Linear rate per year). Prepared by the author.

Studies carried out in other regions such as Roraima (CREMON, 2016) and Porto de Moz (NASCIMENTO BANDEIRA et al., 2021) had relatively lower rates and indices than those presented in this article, highlighting the high dynamics in the upper estuary and at the confluence of the Tapajós and Amazon rivers.

CONCLUSION

DSAS has been used worldwide, and recently in the Amazon; it is a very useful tool for analyzing the variations that occur at the limits of certain sedimentary environments, such as beaches, lakes and rivers. DSAS facilitates the process of calculating SL variations and provides information about the rate of change and statistical data necessary to establish the reliability of the calculated results.

This article aimed to analyze SL variations in the Lower Amazon over a period of 26 years. The results achieved are relevant, as the analysis considered that the SL in Santarém does not present the same dynamics in its extension, since in the floodplain areas the rates of both erosion and accretion are higher compared to the areas formed by the Tapajós ¨Patamares¨ showing the instability of the floodplains. The confluence of the Amazon and Tapajós rivers is also a relevant factor because the Amazon River dams the waters of the Tapajós river during the Amazon winter and La Niña. The bathymetry data also show that areas with greater depths are associated with sections of the SL with greater erosion, however, those with shallower depths are related to the accretion process.The analysis carried out in Santarém corroborates an integrated analysis of the processes that act in the SL of this, being only a fragment for the understanding of a more complex dynamics. The same may contribute with theoretical and methodological subsidy for future investigations on the fluvial dynamics of the municipality, which serve as a model of prediction of environmental changes, on the same, of large temporal and spatial scale.

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