REVISTA GEONORTE

FLUVIAL EROSION RISK ANALYSIS: AN AMAZON STUDY CASE

Análise de risco a erosão fluvial: um estudo de caso na Amazônia

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ABSTRACT: In the Amazon region, there are more than 69.000 people living in areas at risk of fluvial erosion processes. In addition to the large number of people impacted, studies have shown that the erosion patterns identified on the margins of mega rivers in the Amazon region are distinct due to the fact they are related the mass movement leading to great soil displacement known as 'Terras Caidas'. In this context, this study aims to evaluate quantitatively the degrees of risk in areas subject to fluvial erosion in three communities: Itanduba, São Braz, and Fátima de Urucurituba. The methods include hazard attributes, as well as vulnerability aspects, through the Analytic Hierarchy Process (AHP). A multitemporal analysis were made to validated the marginal erosion at the studied areas. The results indicated a high risk of fluvial erosion on these areas. The local families lives under high and very high social vulnerability in conditions with little infrastructure and very close to the susceptible erosive riverbank. The riverbank is composed of poorly consolidated sediments, show instability indicators, and are usually associated to drainages with flow rates above 100.000m^3/s. The results and methodology brings an important contribuition to territorial planning of the region.

Keywords: Analytic Hierarchy Process - AHP, Hazard, Vulnerability, Pará, Brazil.

RESUMO: Na região amazônica, existem mais de 69.000 pessoas vivendo em áreas de risco a processos de erosão fluvial. Além do grande número de pessoas impactadas, estudos têm mostrado que os padrões de erosão identificados nas margens dos mega rios da região amazônica são distintos, por estarem relacionados ao movimento de massa que causam grandes deslocamentos de terra, denominados como "Terras Caidas". Nesse contexto, o presente estudo tem como objetivo avaliar quantitativamente os graus de risco de áreas sujeitas à erosão fluvial, em três comunidades: Itanduba, São Braz e Fátima de Urucurituba. O método utilizado inclui avaliação dos atributos do perigo, assim como aspectos de vulnerabilidade que foram hierarquizados através do Processo Analítico Hierárquico (AHP). Uma análise multitemporal foi feita para validar a erosão marginal nas áreas estudadas. Os resultados indicaram alto risco de erosão fluvial nessas áreas. As famílias locais vivem em situação de vulnerabilidade social alta e muito alta, em condições de pouca infraestrutura e muito próximas à margem de rio susceptível à erosão. Essas margens são compostas por sedimentos pouco consolidados, apresentando indicadores de instabilidade que geralmente estão associados a drenagens com vazões acima de 100.000m^3/s. Os resultados e metodologia trazem uma importante contribuição para o planejamento territorial da região.

Palavras-chave: Processo Analítico Hierárquico, Perigo, Vulnerabilidade, Pará, Brasil.

INTRODUÇÃO

Erosion is the third more common disaster in Brazil (TOLEDO; LANA, 2019) and is the third more common in the Amazon (TEXEIRA et al., 2019). In addition to being susceptible to erosion, the margins of the Amazon river also have a high potential for mass movement events such as land falls and landslides. The erosive process that occurs due to the high speed of the river flow modifies the geomorphology and increases the inclination and height of the riverbanks (CHARMAN; GRIFFITHS, 1993; OMNR, 2002; THORNE; OSMAN, 1988). Depending on the geometry of the margins (height and inclination) (MACFALL et al., 2014) and the geotechnical characteristics there can be a higher or lower potentiality for landslides (THORNE, 1991). Also, according to Aly El-Dien et al. (2014) and Bandeira et al. (2018) mass movement might also occur either when the river is in the flood period causing slumps or when it is in the ebb period, associated to lowering water levels of the river leading to landslides and creeps.

The riverbank erosion is considered as a geological type of natural disaster according to the Brazilian Classification for Disaster (COBRADE). After majors Brazilian municipalities affected by mass movement, inundation, floods and erosion processes in 2011, the Federal Law 12.608/2012 was created. It instituted the National Policy on Protection and Civil Defence - PNPDEC as well as the National Plan for Risk Management and Natural Disaster Response (BRAZIL, 2012) aiming to prevent and, as a consequence, reduce social and economical losses related to natural disasters. Such plan instituted the execution of the mapping, description and classification of areas of high and very high geological risk in municipalities from all units of the federation.

This activity has been officially performed by Geological Survey of Brazil – CPRM resulting in 1605 municipalities mapped throughout Brazil (GEOLOGICAL SURVEY OF BRAZIL - CPRM, 2020). From that amount two hundred and twenty-three municipalities were mapped in the hydrographic region of the Amazon river and 74 of them host areas with high and very high risk of fluvial erosion. On the mapped areas there are more than 69.000 people living along the margin of rivers at risk of experiencing material losses and physical damage related to fluvial erosion processes. The main losses refer to home appliances, properties and sometimes losses of lives (ANDRADE; SZLAFSZTEIN, 2019; BANDEIRA et al., 2018a). To aggravate the

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situation, this region shows low economic and social development indexes in comparison to other regions of Brazil (INSTITUTO DE PESQUISA ECONÔMICA APLICADA, 2019).

In order to map such risks, the methodology of qualitative analysis and risk characterization (SUN et al., 2020) of the Ministry of Cities and the Institute for Technological Research (CARVALHO; GALVÃO, 2006; CARVALHO et al., 2007; PIMENTEL et al., 2020) has been applied to the entire national territory. This methodology was elaborated to satisfactorily assist the cases of mass movement and inundations. However, it still poses a challenge to objectively apply it on the Amazon hydrological and geomorphological systems and dimensions (SZLAFSZTEIN, 2018). Particularities from large rivers system are: extensive alluvial deposits susceptible to fluvial erosion, high precipitation index, fluvial hydrodynamics related to big and mega rivers (LATRUBESSE, 2008; ASHWORTH; LEWIN, 2012), and localised erosion as well as large soil displacements (slumps, creep and landslides) regionally known as *Terras Caidas* (BANDEIRA et al., 2018).

Despite the existence of the studies on the fluvial erosional processes, their triggering factors and the risk faced by people who occupy the margins of the Amazon rivers, such as: Carvalho (2006), Passos; Soares (2017), Magalhães and Vieira (2018), Bandeira et al. (2018), Souza (2019), Silva; Andrade (2019) and on the sectorization of the risk from 2012 to 2019 conducted by Geological Survey of Brazil - CPRM (2020), there are no studies on risk assessment mapping taking into consideration Amazon geological, hydrological and socioeconomic features in the fluvial erosion processes, in their analysis. In this context, the study aim to analyse riverbank risk erosion in three areas in the Amazon.

STUDY AREA

Location

The study area includes three communities located at the lower course of the Amazon river: (i) Itanduba, (ii) São Braz and (iii) Fátima de Urucurituba (Figure 1). These areas are in the rural zone of Prainha, Porto de Moz and Santarém, respectively, located in the state of Pará. The criterio for selection this study areas where due to their locations at the margin of large rivers, and because it presents a high or very high risk of river erosion.

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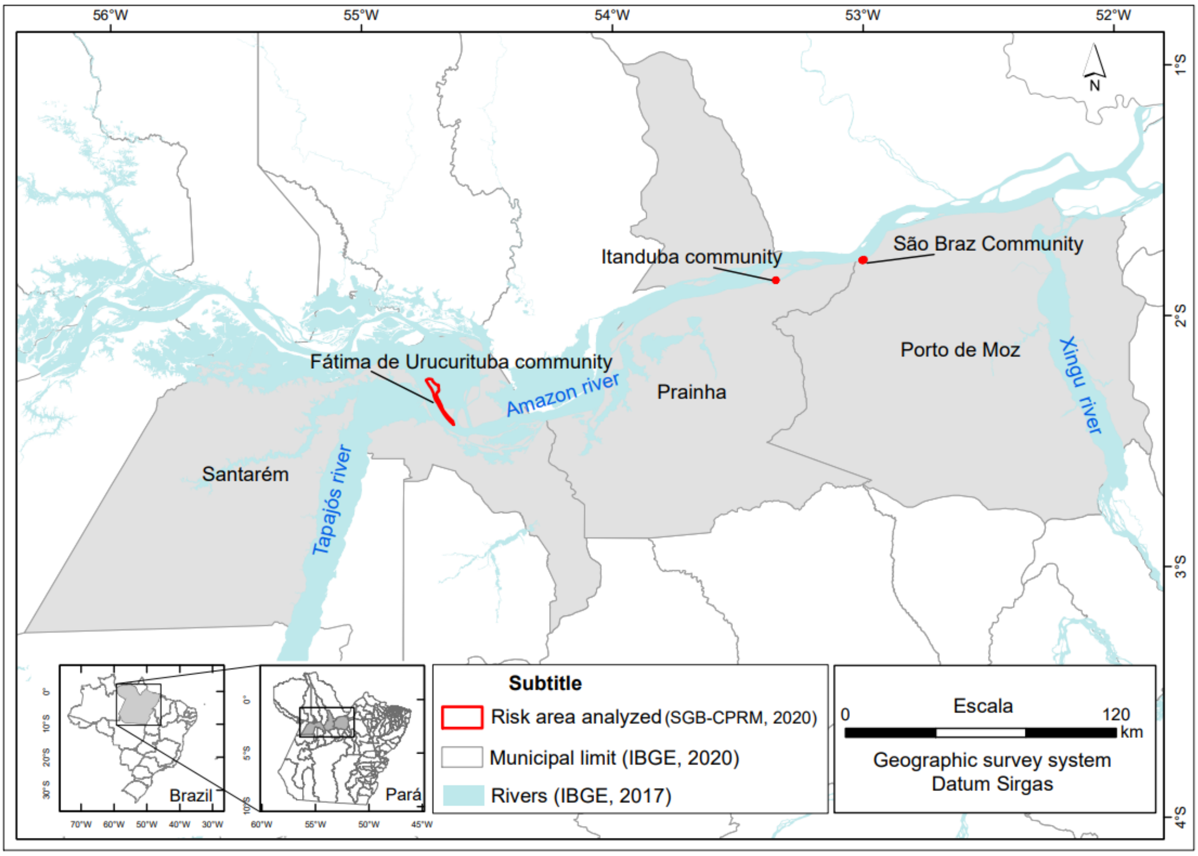

Figure 1. Location of areas at risk of fluvial erosion in the lower Amazon river.
Source: Autor (2021).

Physiography

Geomorphologically, the three areas of study are included in the Amazon Plain and in the hydrographic basin of the Amazon river, the greatest river in the world with the greatest flow rate (ALBERT et al., 2018). The fluvial system displays river channel with anabranching pattern whereas its tributaries show meandering to straight forms; its margins are straight, concave and convex; 3 to 8 km wide; average flow rate between 59.000m³/s and 160.000m³/s and an approximate average depth of the river channel between 25 and 70m (MARINHA, 2020). The fluctuation of the water level in the period of lower river flow (September to February) is that of 3m whereas in the period of higher water level (March to August) it is 1,50m (AGÊNCIA NACIONAL DE ÁGUAS, 2019). The study area is slightly influenced by the dynamic tide with amplitude variations between 10 to 50cm/ day depending on the ebb and flow periods of the river (GALLO; VIZON, 2005). Such fluvial hydrodynamics are associated to a tropical climate whereas the highest precipitation indexes occur from February to May with a monthly average above 300 mm whereas the lowest average rates occur from August to November, sometimes below 40 mm (AGÊNCIA NACIONAL DE ÁGUAS, 2020).
The areas bordering the Amazon river on all three stretches focused on this study, are geologically characterized by extensive alluvial deposits (VASQUEZ; ROSA-COSTA, 2008) composed of sandy and silty-clayey sediments of low geomechanical resistance and low to moderate cohesion. The Land Use and Land Cover includes pasture lands where there is low to moderate forest formation overall the studt areas (MAPBIOMAS, 2019).

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Socio-economic aspects

The municipality of Santarém is the third largest by population in the state of Pará with a population of 294.580 where 73.2% are in the urban area IBGE (2010a). Approximately 3.340 live along the margins of the Amazon river near areas where several cases of fluvial erosion have occurred. The economy of Santarem is based on services, commerce, agropecuary, agroindustry and ecotourism (IBGE, 2010a). Porto de Moz is that of 33.956 inhabitants where 57% in the rural zone (IBGE, 2010b) noting that approximately 5.247 people live near the margins of the river with high susceptibility to fluvial erosion processes. The economic activities of the municipality are based on farming, pecuary, plant extractivism and subsistence fishing (IBGE, 2010b). Around 29.349 inhabitants lives in Prainha is that of where 69.5% in the rural zone (Brazilian Institute of Geography and Statistics, 2010c) noting that approximately 531 people live near the margins of the river. The economy of Prainha is linked to agropecuary, industry and general services (IBGE, 2010c).

METHODOLOGY

The study was divided into the following steps: (1) Definition of the hazard and vulnerability criteria and attributes for the study area; (2) Application of the multi-criteria analysis (AHP); (3) Assessment and classification of the risk of fluvial erosion and (4) Validation of the degrees of risk related to the erosion rate. Also the number of affected people in each community were counted by visual analysis.

Criteria and attributes used in the hazard and vulnerability assessment

The criteria for fluvial erosion hazard assessment considered the particularities for the event in the Amazon region according to Bandeira et al. (2018). Therefore, the following criteria were selected: lithology of the margin, morphology of the margin, height of the riverbank slopes, instability indicators, flow rate, waves and vegetation (Table 1).

According to Couper (2003) the composition of the lithology plays a very important role in relation to the stability of the riverbank where the rate of erosion increases as the silt/clay content along the sandy margins submitted to the same flow speed decreases. For the study area, the expansive clay poses a greater risk of erosion than sediments that, in turn, are more susceptible than clay-bearing sediments. The latter posing more risk of erosion than rocks. The lithology on the river margins is one of the factors that distinguishes the fluvial erosion in Amazon and associates this process to the mass movement processes (BANDEIRA et al., 2018).

The flow rate of the rivers is higher in the river channel and plays a role in the erosion rate when is near the margin riverbank. The highest flow rates occur during the flood period and are related to areas where the most intense erosional processes occur (BANDEIRA et al., 2018). Once the prossess is in course, instability indicators tend to occur. The morphology of the drainage influence in the resistance to fluvial erosion (AVILA et al., 2014). According to these authors different susceptibility to marginal erosion dependes on the hydrodynamics of the river, as well as curvier forms, straighter or the width of the drainage.

According to Aly El-Dien et al. (2014) and Bandeira et al. (2018) mass movement might also occur either when the river is in the flood period causing slumps or when it is in the ebb period. The authors alo associated to lowering water levels of the river leading

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to landslides and creeps related to fluctuations of the piezometric surface causing changes in the physical and hydraulic features, the pore pressure, decrease in the matrix suction, and decrease of the resistance to shear. Since the inclination of the riverbank in the study area is usually higher than 70^0, therefore only its height was used as one of the geometrical criteria to be added to the hazard assessment.

For waves attribute, this study classification criteria uses waves associated to the wind the Beaufort wind force scale (MARINHA, 2019). As for the vegetation, according to Coppin; Richards (1990) and field observations revealed that the existence of vegetation along the margins of large rivers can cause positive or negative impacts on the stability of the riverbanks. But it will have little influence on the erosional process when compared to other conditioning factors analysed.

The criteria for vulnerability assessment consider type of housing, distance of the riverbank, retaining works and family income. The type of housing, wooden or bricken houses, influences how the material responds to the hazard pressure (MINISTÉRIO DAS CIDADES, 2007). The distance of the riverbank takes into account the erosion rates analysed in this study and the data achieved by Teixeira (2017) and Teixeira et al. (2018). Proximity of the houses and facilities to the riverbank maximize the consequences caused by the contact of the population and hazards (GHOSH; SAHU, 2019). Retaining works are included as structutral measure to prevent or adapt facing erosion (SILVA; ANDRADE, 2019). For Amazon, the income has been considered in previous studies for vulnerability analysis in natural hazard context (ANDRADE et al., 2010; ANDRADE; SZLAFSZTEIN, 2018).

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Table 1. Criteria and attributes used in the Risk

	Criteria	Atributes	Obtaining the data	Justification	References
Hazard	Lithology	Sedimentary saprolite or profile of alteration, Clay sediments, Silt sediments, Sandy sediments, Expansive clay	Field observations, granulometric analysis using the laser light scattering method, sieving and x-ray diffraction assays were conducted. Also, indirect calculations of the soil erodibility factor were carried out.	The composition of the lithology plays the most important role in relation to the stability of the riverbank where the rate of erosion increases as the silt/clay content along the sandy margins submitted to the same flow speed decreases.	Thorne (1991); OMNR (2002); Maskare (2015); Abidin et al. (2017); Couper (2003); Bandeira et al. (2018).
	Flow rate	500 to 999m3/s, 1.000 to 9.999m3/s, 10.000 to 49.999m3/s, 50.000 to 99.999m3/s, above 100.000m3/s.	Field data collected using a 600KHz ADCP - Acoustic Doppler Current Profile and databank of agência Nacional das Águas Agency (2019) and information Molinier et al. (1994).	The flow rate besides being responsible for the transportation of sediments it defines, to a greater or lesser degree, both the depositional and erosional rates of the margins and increases the excess shear stress on the riverbank.	FEMA (1999); OMNR (2002); Knighton (1998); Stevaux; Latubresse (2017); Nardi et al. (2013).
	Instability indicators	Small stepped landslides called terracettes, cracks in the soil and in the houses, failure scars, erosional features, inclined trees and utility posts.	Observation and recorded on site.	The instability indicators also contribute to the risk assessment of a given area mainly the fluvial erosion in large rivers. Thus, the greater the number of indicators the greater the hazard degree. However, it has been noted there exist areas that show no indicators and yet they are affected by land slumps.	Carvalho et al. (2007); Bandeira et al.(2018).
	Height of the riverbank	Height is subdivided into the following categories: below 2m, between 3 and 6m, between 7 and 10m and above 10m.	Preliminarily identified based on bathymetric charts (MARINHA, 2020) and obtained during field work.	Depending on the geometry of the margins (height and inclination) there can be a higher or lower potentiality for erosion and landslides.	Charman; Griffiths (1993); OMNR (2002); Thorne; Osman (1988); Macfall et al., (2014); Thorne (1991).

	Criteria	Atributes	Obtaining the data	Justification	References
Hazard	Morphology	River confluences, concave margins, convex and straight morphologies.	Was obtained by visually analysing Geoeye imagery from years 2000, 2017 and 2018.	The morphology of the drainage is intrinsically related to erosion. Areas that have the same resistance to fluvial erosion might show different susceptibility to marginal erosion depending on the hydrodynamics of the river, as well as curvier forms, straighter or the width of the drainage. It is also noted that at places of drainage confluence there is a high potential to erosion.	Thorne (1991); Curran; Mcteague (2011); Derruau (1966); Avila et al. (2014).
	Waves	Categories: grade 0 to 3 (Calm to gentle breeze) associated to mirrored water until 1m high undulations; 4 to 6 (Moderate breeze to very fresh wind) corresponding to 1m high undulations up to waves approximately 3.6m high; and above 7 (Strong wind to storms) relating to waves higher than 3.6 m.	Was gathered on site based on the analysis of the Beaufort scale (MARINHA, 2019).	The fluvial erosion is also affected by the impact of waves breaking at the margin of the river. In the study area where the rivers are very wide, kilometric at times, such waves exist due to two factors: intense wind and the transit of vessels. This study considers only waves caused by the wind as there are no studies evaluating waves generated by vessels.	Bhowmik et al. (1982); Analysis of the Beaufort scale MARINHA (2019).
	Vegetation	Areas with no vegetation and areas with large to medium-sized vegetation.	Field observation and visual analysis of satellite imagery (WorldView from 2014 and Geoeye from 2018) according to Monteiro et al. (2016).	Large to medium-sized shrub species represent the most hazard as they can overload the soil and cause landslides, as well as trees exposed to the wind transmit dynamic forces to the soil favouring the destabilization of the marginal riverbank. However, it is noted that in areas with no vegetation the susceptibility to fluvial erosion is also high due to the increase of the surface runoff. However, the small-sized species accrete more resistance to the soil due to their light weight in relation to large- sized ones as well as roots.	Coppin; Richards (1990); Sutili (2007); Mulyono et al. (2018); Gray; MacDonald (1989); Monteiro et al. (2016); Luna (2016); Peixoto et al. (2009); Maffra et al. (2017).

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	Criteria	Atributes	Obtaining the data	Justification	References
Vulnerability	Type of housing	Wooden houses Bricken houses	Field observation and visual analysis.	The quality of the material used to build houses is important as the structure has to withstand pressure and threat.	Carvalho et al. (2007)
	Distance of the riverbank	Edifications built more than 50 m away from the riverbank; distances between 20 and 50m; distances between 10 and 20m and very high vulnerability - edifications built less than 10m away from the riverbank	Field observation and measuring.	The distance between the houses and the marginal riverbank was also included, taking into consideration that the closer to the eroded margin the higher the vulnerability in occupied areas.	Mollah; Ferdaush (2015)
	Retaining works	no retaining works; existing and inefficient retaining works; and existing and efficient retaining works.	Field observation and visual analysis.	The retaining works criterion lessens the vulnerability and, consequently, the risk, as it minimizes the impacts on the terrain.	Andrade; Szlafstein (2019).
	Family Income	Less than the amount of 1 monthly minimum wage in Brazil; between 1 and 2 times the amount of the monthly minimum wage in Brazil, between 2 and 3 times the amount of the monthly minimum wage in Brazil and more than 4 times the amount of the monthly minimum wage.	Information provided by inhabitants who occupy the risk area.	The income is related to the ability to recover during the post-disaster phase.	Cutter et al. (2003), Andrade et al. (2010)

Source: Autor (2021).

Analytic hierarchy process (AHP)

After establishing criteria and attributes, the degree of absolute relevance that rests on each one of them in the processes of risk of fluvial erosion and vulnerability was conducted using the AHP methodology by assigning grades and weights. This method is used to organise the criteria, subcriteria and alternatives of an analysis, in a descending order of importance. The given hierarchy contains relevant details that define the problem as completely as possible. This methods provides a general overview of the complexity related to the situation as well as assisting the decision maker analyse whether the problems have the same order of magnitude (SAATY, 1988).

The Hierarchical Decision Process was built on three hierarchical levels, adapted according to Bathrellos; Skilodimou (2007): Level 1, object of the classification that is the risk assessment of fluvial erosion; Level 2, identification and relation between the criteria established to reach the goal; Level 3, identification and relation between the attributes or subcriteria. To perform that it was used the AHP online calculator from BPMSG (BUSINESS PERFORMANCE MANAGEMENT SINGAPORE). It is an online free tool used to implement the AHP available at https://bpmsg.com/ahp/ahp-calc.php.

The hierarchy of relevance is created by a pairwise comparison square matrix n x n where the intensity of the relations between the rows and columns of such matrix is determined (VAIDYA; KUMAR, 2006).

The comparisons are carried out following a scale that indicates how many times one variable is more important or more dominant than another, with respect to a given property on which they are compared. Based on this scale, 1 indicates an equal importance where both variables contribute equally to the objective and 9 indicates the maximum importance where a variable is that of the highest order of importance in relation to another (SAATY, 2008).

The first step of the analysis is the fulfilment of the comparative judgements, therefore, the calculation of the Consistency Index (C.I) becomes necessary and represents the degree of reliability of the assessment, given by: I.C. = $\frac{\lambda_{max} - n}{n-1}$ (1).

Where *n* is the order of the matrix and λ_{max} is the maximum eigenvalue (comparative judgement scale) that can be reached by multiplying the judgement matrix by the priorities column vector. Exemplifying the AHP calculations applied to the previous case (Table 2).

Table 2. Exemplifying the AHP calculation

	Lithology	Flow rate
Lithology	1	2
Flow rate	0,5	1

Source: Autor (2021).

Applying the mathematical principle to calculate the eigenvalue on a second order matrix: $\begin{bmatrix} 1-\lambda & 2 \\ 0,5 & 1-\lambda \end{bmatrix} = (1-\lambda).(1-\lambda) - 2.(0,5) = \lambda^2 - 2\lambda$

Then, λ=0 or λ=2 are eigenvalues (comparative judgement scale) that correspond to consistency numbers. Considering v_1 = Lithology and v_2 = Flow rate.

For λ=0, we have:

$$\begin{bmatrix} 1 & 2 \\ 0,5 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$1.v_1 + 2.v_2 = 0$$
$$0,5.v_1 + v_2 = 0$$

So: $v_1 = -2v_2$

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For λ=2, we have:

$$\begin{bmatrix} -1 & 2 \\ 0{,}5 & -1 \end{bmatrix} . \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$-1.v_1 + 2.v_2 = 0$$
$$0{,}5.v_1 - 1v_2 = 0$$

So: $v_1 = 2v_2$

Therefore, the eigenvalues obtained correspond to the priority order corroborating the analysis of the decision maker, i.e., the lithology (v_1) is twice more important than the Flow rate (v_2).

Based on that, one can say that: I.C. = $\frac{2-2}{2-1} = 0$ ou 0,00%

In percentage:

$$v_1 + v_2 = 100\%$$
$$2v_2 + v_2 = 100\%$$
$$3v_2 = 100\%$$
$$v_2 = 33{,}33\% \text{ (weight)}$$

Then,

$$v_1 = 66{,}66\% \text{ (weight)}$$

The second and third criteria are associated to the assemblage of the pairwise comparison matrix assigning values from the comparative judgement scale in a pair to pair relation aiming to establish grades (for the criteria) and weights (for the attributesto prioritize the alternatives. The AHP online calculator from BPMSG (BUSINESS PERFORMANCE MANAGEMENT SINGAPORE) was applied to this study. It is an online free tool used to implement the AHP available at https://bpmsg.com/ahp/ahp-calc.php

Risk assessment and classification

In order to classify the risk, the grades and weights of the criteria and attributes obtained from the multicriterial analysis were applied to the Hazard, Vulnerability and Risk equations (Table 3).

Such equations were included in the software used for calculations (Excel) and the analysis of the results for the Hazard criteria.

Table 3. Formulas for hazard, vulnerability and risk.

Equation 1	Equation 2	Equation 3
$\boldsymbol{H_{ij}} = \sum_{\boldsymbol{k=1}}^{\boldsymbol{a}} (\boldsymbol{W_k} \times \boldsymbol{G_k})$ Where: $\boldsymbol{H}$ = Hazard $\boldsymbol{a}$ = Number of threat criteria used $\boldsymbol{Wk}$ = Weight of each attibute within the Threat criterion $\boldsymbol{Gk}$ = Grade of the threat criterion	$V_{ij} = \sum_{z=1}^{v} (W_z \times G_z)$ Where: V = Vulnerability v = Number of vulnerability criteria used Wz = Weight of each attibute within the vulnerability criterion Gz = Grade of the vulnerabilidade criterion	Risk = HxV

Source: Rebelo (2001).

Validation of the risk degree associated to the erosion rate

The erosion rate was applied to validate the results for the following reasons: (i) the eroded areas in the Lower Amazon river undergo a continuous erosional process with an average recess greater than 1,4km/year according to multitemporal analysis of satellite LANDSAT for a period of 31 years (TEIXEIRA, 2017; TEIXEIRA et al., 2018); (ii) it allows for an estimate of how much the river is eroding as its channels are continuously adjusting their morphology by means of erosional and depositional processes associated the effects of tectonism, climate change and sea level change

(MERTES; DUNNE, 2007) ; and (iii) unavailability of high spacial and temporal resolution imagery in the entire.

A timeline analysis from 3 to 10 years based on Maxar Technologies and Digital Globe imagery, available on Google Earth PRO, on a 1:5000 scale was applied to the three study areas. The erosion rate was estimated from graphical inferrence analysis using the software Digital Shoreline Analysis System – DSAS 5.0 adapting the methods from Thieller et al. (2005). DSAS amplifies the use of software ArcGIS10.7 automating great part of the tasks related to the quantitative analysis of the evolution of the erosional and depositional trends from statistics on time series and multiple positions of the shoreline. This tool applies the analytical method End of Point Rate – EPR to calculate vector rate-of-change data between two shoreline horizons, by dividing the distance of shoreline movement between two distinct periods by the time period elapsed, thus, providing the annual rate of shoreline change (HIMMELSTOSS et al., 2018) (Table 4) .

Table 4. Images used to analyze the fluvial erosion rate at the margins of the Amazon river.

Municipality	Satellite	Year	Spacial resolution
Porto de Moz	WorldView-1	08/2003	50cm
	WorldView-2	07/2014	47cm
Prainha	WorldView-2	10/2010	47cm
	WorldView-3	09/2018	37cm
Santarém	WorldView-2	08/2015	50cm
	Geoeye-1	07/2018	42cm

Source: Autor (2021).

The transects between the shoreline and the baseline to calculate the erosion rate were 5m apart in the Porto de Moz and Prainha studies and 20m apart in the Santarém studies. Based on the results on the shoreline changes on the investigated areas the erosion rate was subdivided into 4 intervals: lower than 1m/year, low index; 1 to 2m/year, moderate index; 2 to 3m/year, high index and higher than 3m/year, a very high index.

RESULTS AND DISCUSSION

Analytic hierarchy process (AHP) value

Considering the attributes for risk analyses the pairwise comparison matrix and assigning values from the comparative judgement scale in a pair to pair, it was possible to establish grades (for the criteria) and weights (for the attributes) to prioritize the alternatives (Tables 5 and 6).

Table 5. Pairwise comparison matrices for Hazard and Vulnerability to fluvial erosion criteria.

Hazard criteria	Grade	Vulnerability criteria	Grade
Lithologyof the margin	0,183	Type of housing	0,35
Flow rate	0,169		
Instability indicators	0,158	Distance house/ riverbank	0,27
Morphology of the margin	0,143		
Height of the riverbank	0,136	Retainment works	0,2
Waves	0,111		
Vegetation	0,1	Family income	0,18

Source: Autor (2021).

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Table 6. Pairwise comparison matrices for Hazard and vulnerability to fluvial erosion attributes

Hazard		Vulnerability	
Lithology of the margin	**Weight**	**Type of housing**	**Weight**
Expansive clay-bearing sediments	0,32	Brick house	0,55
Sediments or soils with higher sand content	0,3		
Sediments or soils with higher silt content	0,2		
Sediments or soils with with higher clay content	0,15	Wooden house	0,45
Sedimentary saprolite or profile of alteration	0,03		
Flow rate		**Distance house/riverbank**	
Above100.000m^3/s	0,35		
50.000 to 99.999m^3/s	0,3	0 to 10 m	0,4
10.000 to 49.999 m^3/s	0,2		
1.000m to 9.999 m^3/s	0,1	10 to 20 m	0,3
Between 500 e 999 m^3/s	0,05		
Instability indicators		20 to 50 m	0,2
More than 3 indicators	0,4		
2 indicators	0,3		
1 indicator	0,2	More than 50 m	0,1
0 indicator	0,1		
Morphology of the margin		**Retaining works**	
Confluence of drainages	0,4		
Concave drainage	0,3	No retaining works	0,5
Convex drainage	0,2		
Straight drainage	0,1	Existing and Inefficient retaining works	0,3
Height of the riverbank			
Higher than 10m	0,4		
7 to 10m	0,3	Existing and efficient retaining works	0,2
3 to 6m	0,2		
Lower than 2m	0,1		
Waves		**Family income**	
Higher than 3,6m	0,5	Less than the amount of 1 monthly minimum wage in Brazil	0,4
1m high undulations to 3.5m high waves	0,3		
Mirrored water to 1m high ondulations	0,2	Between 1 and 2 times the amount of the monthly minimum wage in Brazil	0,3
Vegetation			
Inexistent	0,35	Between 2 and 3 times the amount of the monthly minimum wage in Brazil	0,2
Large size – taller than 3m	0,3		
Medium size - 1,5 to 3m tall	0,25	More than 4 times the amount of the minimum wage in Brazil	0,1
Small size – shorter than 1,5m	0,1		

Source: Autor (2021).

The results for the Hazard criteria showed values ranging from 0,08984, representing the lowest value on the hazard scale that indicating irrelevant to null danger, to 0,38301

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representing the maximum hazard degree where all attributes are potentialized. In terms of vulnerability criteria, values vary between 0,067, indicating the lowest vulnerability degree in the assessment and 0,208, the maximum vulnerability. Finaly the risk yielding results that can vary between 0,0060193 indicating the lowest or inexistent risk degree and 0,07966608, the maximum risk verified in the assessment.

Applications of AHP in the Itanduba community, municipality of Prainha

The community of Itanduba islocated on a fluvial island between Amazon and Pará do Uruara rivers closer to the margin of the latter. The margin is convex in shape, associated to a subvertical riverbank (80 to 85°), approximately 7m high, composed of sandy-silty material and covered by grass- like vegetation. On this stretch of the river, the flow rate is that of 147.000m^3/ s showing waves up to 1m high that form erosion features and terracettes on the riverbank. The area is occupied by 15 (fifteen) wooden stilt houses placed between 1 and 12m away from the margin of the drainage.
This is a hazardous and vulnerable area with high risk of erosion (Table 7). Such result is confirmed by the multitemporal analysis conducted on the risk area at the Itanduba community, that revealed a continuous and accelerated erosional process as well as the margin retreat at a rate of 0,5 to 3m/year (Figure 2). The result obtained is consistent with the risk level mapped by Bandeira; Costa (2019).

Table 7. Classification of risk of fluvial erosion for the study area in the Itanduba community.

Hazard criteria	**Grade**	**Attributes**	**Weight**
Lithology of the margin	0,183	Sediments or soils with higher sandy content	0,30
Flow rate of the drainage	0,169	Above 100.000m^3/s	0,35
Instability indicators	0,158	2 indicators	0,3
Morphology of the river margin	0,143	Convex	0,2
Height of the riverbank	0,136	7 to10m high	0,3
Waves	0,111	Mirrored water to 1m waves	0,2
Vegetation	0,1	Nonexistent	0,35
Hazard Classification		0,28805 (High)	
Vulnerability criteria	**Grade**	**Attributes**	**Weight**
Type of housing	0,35	Wooden house	0,45
Distance margin/riverbank	0,27	10 to 20 m	0,3
Retaining Works	0,2	No retaining works	0,5
Family income	0,18	Less than the amount of 1monthly minimum wage in Brazil	0,4
Vulnerability Classification		0,181 (Very High)	
Risk		**0,05213705 (High)**	

Source: Autor (2021).

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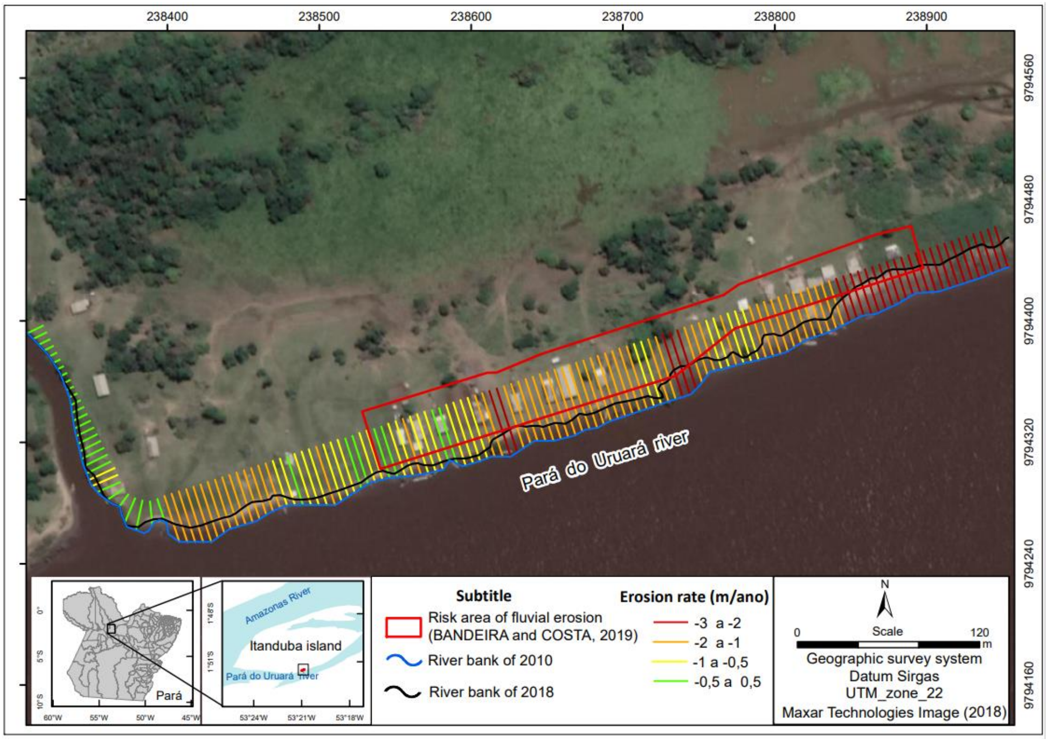

Figure 2. Map showing the placement variation of the river margin associated to its retreat caused by erosional processes in the Itanduba community, in the municipality of Prainha, state of Pará. **Source:** Organized by Authors (2021).

Applications of AHP in the São Braz community, municipality of Porto de Moz

The socio-economic vulnerability of São Braz community is very high as the income of the 10 families that occupy the area stays under the amount of 1 monthly minimum wage in Brazil leading them to subsistence fishing and buffalo raising. These families live in wooden stilt house very close to the marginal riverbank which has no form of retainment.

Considering the hazard criteria presented, the margin in the study area is concave, covered by low to medium-sized vegetation, lithologically composed of silty-clayey material, high erodibility rate and no expansive clay. The inclination and height of the marginal riverbank are approximately 80° and 3.5m, respectively. It stays submerged during the flood period of the Amazon river (March to August), inundating the entire community area, whereas during the ebb period of the river (September to February) the riverbank emerges 1.6m. In this region, the flow rate has reached 109.000m^3/s in the flood period and small wind and vessel-generated waves were noted.

The greatest indicator of instability observed in the terrain refers to an event that occurred very close to the risk area in August, 2016 when a massive amount of earth (relative to an area 400m long x 1000m wide) collapsed submerging 14 edifications that were dragged by the river stream. Due to this event, many personal belongings were lost and part of the community disappeared, in a few hours, in the water. There were no deaths or injured inhabitants only the loss of material goods and the relocation of 31 people (Bandeira et al., 2019).

By assigning grades and weights to the hazard and vulnerability criteria it was possible to identify a high-risk condition (Table 8). Such result is confirmed by the multitemporal analysis conducted on the risk area at the São Braz community that revealed a continuous and accelerated erosional process as well as the margin retreat at a rate

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of 0.5 to 3m/year (Figure 3). The result obtained is consistent with the risk level identified by Bandeira; Simões (2017).

Table 8. Classification of risk of fluvial erosion presented for the São Braz community.

Hazard criteria	Grade	Attributes	Weight
Lithology of the margin	0,183	Sediments or soils with higher silt content	0,2
Flow rate of the drainage	0,169	Above 100.000m³/s	0,35
Instability indicators	0,158	1 indicator	0,2
Morphology of the river margin	0,143	Concave	0,3
Height of the riverbank	0,136	3 to 6m	0,2
Waves	0,111	Mirrored water to 1m waves	0,2
Vegetation	0,1	Small size – shorter than 1,5m	0,1
Hazard Classification		0,22965 (High)	
Vulnerability criteria	**Grade**	**Attributes**	**Weight**
Type of housing	0,35	Wooden house	0,45
Distance margin/riverbank	0,27	0 to 10 m	0,4
Retaining Works	0,2	No retaining works	0,5
Family income	0,18	Less than the amount of 1monthly minimum wage in Brazil	0,4
Vulnerability Classification		0,208 (Very High)	
Risk		**0,0477672 (Very High)**	

Source: Autor (2021).

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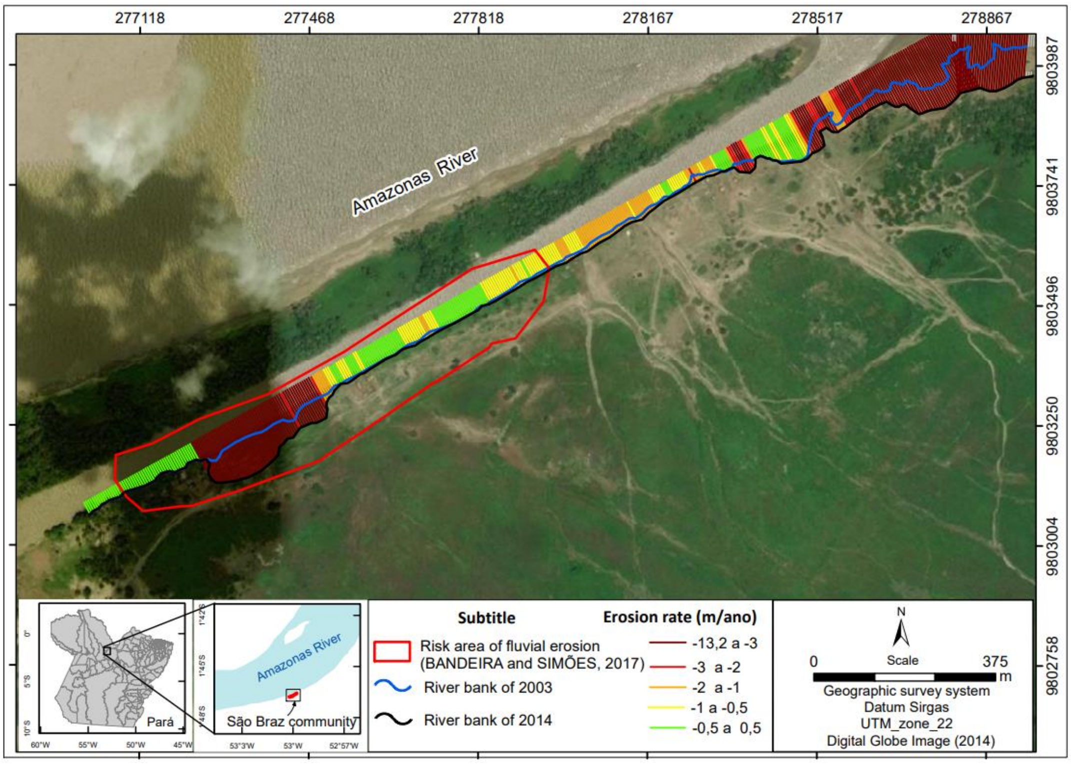

Figure 3. Map showing the placement variation of the river margin associated to its retret caused by erosional processes in the São Braz community, in the municipality of Porto de Moz, state of Pará. **Source:** Organized by Authors (2021).

Applications of AHP in the Fátima de Urucurituba community, municipality of Santarém

The study area is a riverside community with high socio-economic vulnerability where approximately 46 families live on an income between 1 and 2 times the amount of the monthly minimum wage in Brazil. These families live in wooden stilt houses at a distance of 40 to 100m away from the marginal riverbank that has no type of retaining works.

The region is defined as a rectilinear side bar or a marginal dyke that separates the Amazon river from Pacoval lake near its confluence with the Tapajos river. At this location the marginal riverbank is subvertical, approximately 35m deep, composed of interlayered silty-sandy sediments and expansive clay-bearing material, covered by small to medium-sized vegetation. The area is affected by small undulations associated to the frequent transit of large vessels causing turbulence in the water, as well as wind-generated waves up to 2m high. During the ebb period (mainly between September and November) the silty-sandy deposits and water-saturated clay slide as the water level gets lower generating subaqueous mass movement followed by high energy waves that hold great destructive power. This phenomenon is accelerated by the action of wind-generated waves and the transit of large vessels, the moon tide and mainly by the high flow rate of the Amazon river that registered 157.366m^3/s for this stretch.

Instability indicators such as cracks or fractures due to traction on the soil were found as well as terracettes and the consequent reduction of exposed land. In addition to

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these indicators, the inhabitants of the region have already registered significant material losses such as the destruction of the local school and several houses in Ouctuber, 2010, due to the erosion of an extensive area (LUZARDO; TEIXEIRA, 2012).
The degree of risk is high (Table 9) and it is the same verified by Luzardo and Teixeira (2012). The result is consistent with the erosion rate that varies from 0.5 to 77m with some accretion spots up to 3m (Figure 4).

Table 9. Classification of risk of fluvial erosion for the Fátima de Urucurituba community.

Hazard criteria	**Grade**	**Attributes**	**Weight**
Lithology of the margin	0,183	Expansive clay - bearing sediments	0,32
Flow rate	0,169	Above 100.000m^3/s	0,35
Instability indicators	0,158	More than 3 indicators	0,4
Morfology of the margin	0,143	Concave	0,3
Height of the riverbank	0,136	Higher than 10m	0,4
Waves	0,111	1m high ondulations up to 3,5m high waves	0,3
Vegetation	0,1	Short size – shorter than 1,5m	0,1
Hazard Classification		0,321151 (Very High)	
Vulnerability criteria	**Grade**	**Attributes**	**Weight**
Type of housing	0,35	Wooden house	0,45
Distance margin/ riverbank	0,27	20 to 50 m	0,2
Retaining works	0,2	No retaining works	0,5
Family income	0,18	1 to 2 times the amount of the monthly minimum wage in Brazil	0,3
Vulnerability Classification		0,154 (High)	
Risk		**0,04951254 (High)**	

Source: Autor (2021).

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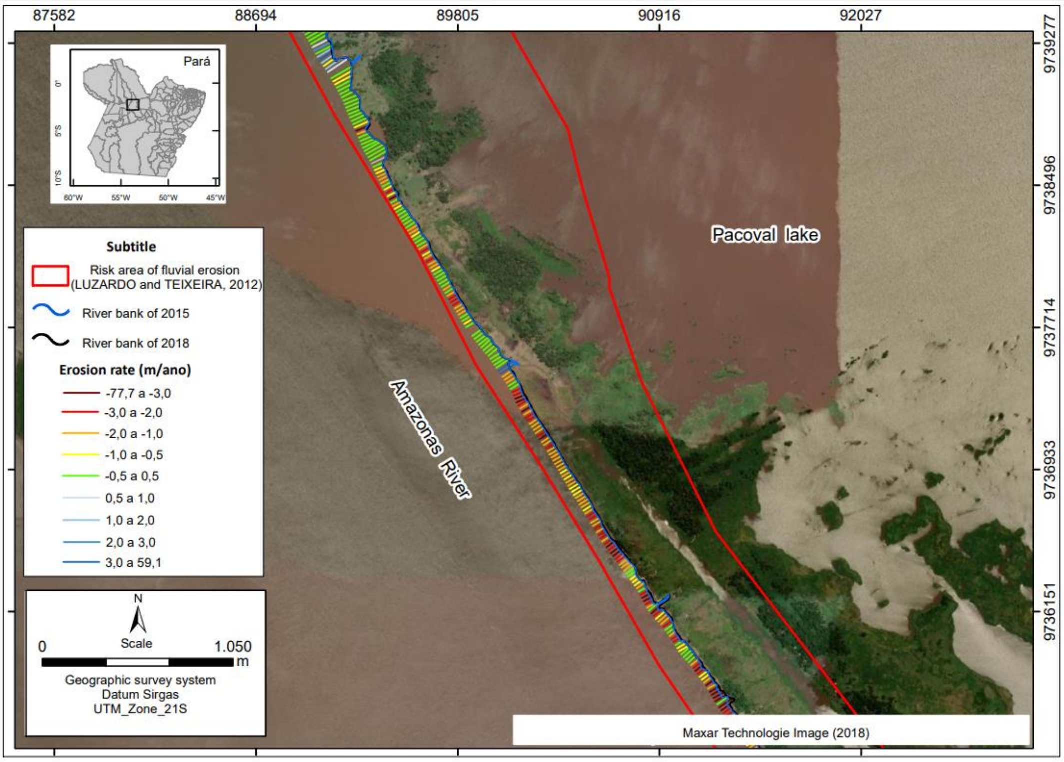

Figure 4. Map showing placement variation of the river margin associated to its retreat caused by erosional processes in the Fátima de Urucurituba community in the municipality of Santarém, state of Pará. **Source:** Organized by Authors (2021).

These regions at risk of river erosion are also affected by seasonal floods, due to the elevation of the level of the Amazon River. Mainly in the period from May to July this region reaches its highest level. Even being on stilts with high heights, in periods of great floods, as the events that occurred in 2009, the residents use diverse measures to cope and adapt. Some of these measures are temporary wooden structures that elevate the floor of the houses and also help to protect animals (locally called as marombas). Other measures are access ramps in front of houses, Suspended vegetable gardens, and temporary bridges on the street (ANDRADE; SZLAFSZTEIN, 2019). However, even so, water enters homes, causing material damage to families, such as animal deaths, destruction of floodplain plantations, and destruction of homes (SOUZA et al., 2010).

FINAL CONSIDERATIONS

The methodology applied to the risk mapping of fluvial erosion in the lower Amazon river in the state of Pará was considered satisfactory. The conditioning factors such as: lithology, flow rate, instability indicators, morphology of the margin, height of the riverbank, waves, vegetation, type of housing, distance house/ riverbank, type of retaining works and socio-economic status of people, made it possible to differentiate degrees of risk. The degree of risk assessed by the methodology applied to this study, taking into consideration quantitative criteria, comes close and many times is equal to the degrees of risk mapped by Geological Survey of Brasil - CPRM from 2012 to 2019. It is important to highlight that the using AHP induces to stricter systematization of risk assessment as it considerably reduces the subjectivity the analyst. Once it is done, enables a more appropriate comparison, and consequently generating data, between different risk areas. However, in more complex assessments, the experience of the

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analyst is indispensable. Therefore for refine this methodology there are some suggestiond, such as:

- Multitemporal analysis of satellite images from different periods in the entire Amazon region to obtain a history of values that allows the classification, in different levels, of the erosion rate at the margins of the rivers.
- Systematic survey on the resistance to shear of the material along the margins and its relation to the geomorphological and hydrological variables (flow rate and fluctuation of the water level).
- Quantification of the sedimentary load of the rivers and its influence on the eroded areas.
- Evaluation of the tectonics influence on the process and its relation to seisms and the trigger of processes that cause mass movements associated to fluvial erosion.
- Research on the potentiality of the waves caused both by the wind and the navigation of vessels, in the fluvial erosion process.
- Statistical studies related to the rainfall data to verify the soil saturation during direct precipitations on the area undergoing erosional processes and during the elevation of the water level in the rivers, which, in this region, usually occurs 2 to 3 months, on average, after a heavy rainfall and, thus, evaluate what precipitation levels can influence the erosional process of the margins. Note that this information was not used as a hazard criterion due to the low density of hydrometeorological stations in the lower Amazon region. The ideal scenario for this project would be the construction of at least 3 (three) more stations to be placed in the area between the municipality of Obidos and Porto de Moz as the information generated by these stations would be more specific and representative.

The vulnerability vector can also be refined by adding other information such as: the exact number of people composing the local population, since the more populous the area is the higher the vulnerability, as a greater number of people can be affected. Variables such as age criteria, physically disabled people with difficulties to move and educational level are also widely used in studies that take vulnerability into consideration on risk mapping. However, at a local level, these data are obtained using Social Sciences methods and that would require more time and budget to acquire and treat such data.

The application of this methodology in other regions can lead to a revaluation of the grades and weights, besides removal, hierarchy changes or addition of new criteria according to the local peculiarities.

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