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Riverine communities in the Central Amazon are largely subject to erosion and sedimentation risk

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Sedimentary processes cause large changes in riverscapes and alter river banks and margins, leading to major hazards for riverine communities. However, regional mapping of the resulting risk remains scarce, especially in remote Amazon regions. Here, we combine environmental observations with regional socioeconomic information to map erosion and sedimentation risk for Central Amazon river-floodplain communities. We combine long-term trends of open water changes (sedimentation/erosion hazard) with exposure (population size) and social vulnerability (socio-economic indices) to estimate risk at each community. Half of the region's population, located either in uplands or floodplains, is subject to an unstable riverscape, with 18.5% of the communities affected by sedimentation processes and 26% by erosion. We identified four communities (out of 51 assessed) at very high risk, and seven at high-to-moderate risk. We highlight the need to include sedimentary processes in disaster management strategies in the changing river landscapes of the Amazon.

The transport of sediments along rivers is a natural process that leads to the continuous change of river beds, banks and margins, especially along water bodies with high sediment concentration such as in large tropical systems[1]. Along a river bend, while in the inside bend an intense sedimentation may take place, in the outside bend an erosion process may occur leading for instance to the loss of river banks[2]. In river reaches with human settlements such as riverine rural communities, these phenomena can turn into major disasters, through the loss of properties and crops or the isolation of entire communities due to increased distance to the river[3].

In the Amazon basin, millions of people live along rivers, and directly depend on their resources and ecosystem services for subsistence, e.g., through fishing and floodplain agriculture and transportation[4–6].

Yet the river's resources and ecosystem services are directly affected by sediment processes[7], and migrate together with a river, when it shifts. A large portion of Amazonian people live along rivers with intense meander migration[2,3,8] and are thus under major risk of either losing their homes and built infrastructure (erosion) or becoming each year more isolated from the main river (sedimentation), which is often the only means of transport and access to goods.

Historically, riverscape changes have led to multiple migration of these people, as described for many communities located along the Central Amazon region[9,10]. While it has been a long established adaptation practice, this also leads to many social challenges, including how to keep the community's history through a human memory that is largely dependent on the territory's spatial elements[11]. During extreme droughts, both erosion and sedimentation processes may exacerbate the impact of very low water levels and turn the disaster into a compound risk event. This has dramatically occurred in the 2023–2024 drought, the largest drought ever recorded in Central Amazon which led to the minimum water levels measured in the city of Manaus in more than 120 years. During the event, extreme cases of river erosion (regionally known as "terras caídas") caused the destruction of whole communities (including deaths[12]), schools[13] and ports of big cities such as Itacoatiara[14]. On the other hand, the large beaches that were formed largely contributed to isolate entire communities from the main rivers, leading to hunger and thirst due to lack of access to water and food[13].

Even with all these impacts, river erosion and sedimentation in Amazonian rivers are largely overlooked phenomena, usually not included in regional-scale disaster mapping in the region. One reason is the remoteness of a large portion of Amazon communities, associated with lack of resource investment in disaster management in the area[15]. To date, only a few initiatives have been carried out in this context, such as the risk mapping at community level made by the Brazilian Geology Survey[16], which mapped erosion in some Amazonian communities, and estimated that more than 69,000 people live

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in areas at risk due to river erosion in the Brazilian Amazon[17]. It is thus fundamental to improve our capability to map human risk (and its multiple components—hazard, exposure and vulnerability) at large scales. The importance of regional-scale risk mapping in the Amazon has been increasingly highlighted as a necessary step towards adequate risk management in the region[18].

Remote sensing is a major tool to map large-scale changes in river systems. These include advances in mapping changes and dynamics of surface waters[19–22], meander migration and geomorphology[23–28], floodplain vegetation[29,30] and sediment dynamics[31]. The Amazon River basin has been a particularly important region for the development of remote sensing techniques in this context[32,33].

Recent examples include the mapping of river erosion and sedimentation hazards in communities of the Juruá River[3], mapping of large-scale sedimentation processes[34], and the use of inundation datasets to understand changes in surface water dynamics along the Amazon River over the last decades[22]. Yet, most studies focus on the use of satellite data to map hazard only, while the more complete understanding of risk is hampered by the lack of social-economic information which allows the quantifying of human exposure and vulnerability and thus risk.

The goal of the study is to provide a regional-scale mapping of human risk to river erosion and sedimentation along a large portion of the Amazon river-floodplain system. We show that half of the assessed population lives close to an unstable riverscape, either due to erosion or sedimentation processes. The hazard analysis is combined with vulnerability and exposure indexes for the communities, revealing the location of communities under high to moderate risk. We then discuss the major challenges that these people are currently facing and highlight some of the major needs that must be addressed to improve disaster management in the largest river basin on Earth.

Results

Erosion and sedimentation hazard mapping

We combine satellite optical imagery processing with regionally-derived social-economic characteristics of communities in the Central Amazon, in the region of the Mamirauá Sustainable Development Reserve, the largest protected area in Brazil for inland wetlands (Fig. 1). The rationale behind the hazard mapping method relates to the fact that a long-term increase (decrease) in open water areas in the environment surrounding the community's built area can be attributed to river erosion[3,28] (sedimentation) (Fig. 2).

Among the 254 locations that were mapped in the hazard analysis, 18.5% are affected by sedimentation, with important impacts on mobility, 26% by river margin erosion, very hazardous for livelihoods, and 55.5% are in a stable situation (Fig. 1). Most of the communities suffering from erosion and sedimentation are located along the main channels of the Amazon (60% of the assessed communities being affected) and Japurá (26%) rivers, and in areas south of the Mamirauá Reserve, near the Japurá River mouth (Fig. 1).

Most communities in the region are located in floodplain areas (82%), with only 18% in uplands (Fig. 3b). Despite a general thinking that upland communities are not very subject to intense riverscape changes, for having more consolidated sediments than adjacent floodplains, our results indicate that these are also largely affected by river erosion or sedimentation (Fig. 1), which may be explained by the large water level amplitude at this river reach (around 11 m annually, on average)[35]. Furthermore, even very large communities (in terms of population size) are subject to erosion/sedimentation hazards, with no clear distinction between stable and unstable areas regarding the size of the locations (Fig. 3a).

A few examples illustrate how hazardous this riverscape can be. The Caburini community (Figs. 1a, b, 3b) stands out as one of the localities most affected by sedimentation, with the nearby creation of large beaches, which affect the local people's transport during the dry period. Because of the large distance between the community and the Amazon River, they have already migrated three times since 2000 (based on the Mamirauá Institute's socioeconomic census), and because of continuous sediment deposition in front of the community, they are already planning to move once again to be closer to the river. For this purpose, they rebuild each community's house a few hundred meters closer to the river, in a joint community effort that can last up to a few months. Such a collective effort translates into an important adaptation measure by Amazon riverine communities. Another example of intense impacts by sedimentation is provided by Nova Tapiira, a floodplain community on the left bank of the Japurá River which becomes isolated from the main channel during many months every dry season (Fig. 4c). On the other hand, the community of Coadi shows intense erosion, and is located in the Amazon River's margin in an upland area (Fig. 4a).

This location faces major risk of loss of houses by riverside erosion, in a dangerous margin river bank that can be several meters high during the dry season.

Erosion and sedimentation risk

Risk is obtained here by the multiplication of hazard (estimated with satellite data as shown in previous section), exposure (population size in each community, see Fig. 5a), and vulnerability. Vulnerability assessment is based on four factors (Fig. 5b–f, see "Methods"): (a) access to services and goods, based on distance from the communities to the largest urban area in the region (the city of Tefé) and to the nearest town; (b) number of recent migrations due to erosion or sedimentation processes (18% of the communities already migrated because of one of these two phenomena, according to Mamirauá Institute's census), as a measure of community's risk awareness and adaptation capability; (c) community social development based on social-economic indexes (education, properties and social organization), from the Mamirauá Institute's socioeconomic census (see Methods); and (d) number of women, children and elderly people of each community.

We mapped risk for a total of 51 communities (out of 254 with hazard mapping), for which all necessary social-economic information was available (Fig. 6). Considering a Jenks natural breaks categorization (Moreira et al., 2021), four communities (7.8%) were considered as having very high risk (Santa Domicia, Canariá, Boiador and Acapuri de Baixo communities), seven (13.7%) with high risk (Barroso, Porto Braga, Punã, Ingá, São Raimundo do Panauã, Triunfo and Caburini), seven with moderate risk (13.7%), eleven with low (21.6%) and twenty-two with very low risk (43.1%).

Communities at very high risk are located along the banks of the Amazon River, in regions with intense erosion and sedimentation processes, with significant hazard, exposure and vulnerability values (Fig. 6). A good example are the Acapuri de Baixo and Canariá communities, which have high hazard values, related to intense sedimentation that occurs in front of the communities, and which combined with high exposure and vulnerability values. Communities at high risk are also distributed along the banks of the Amazon River, and in the Aranapu Channel region, a region with intense erosion and sedimentation processes, with significant risk, exposure and vulnerability values (Fig. 6).

The communities with moderate risk are located in areas with intense geomorphological dynamics, along the banks of the Amazon and Japurá rivers and in the Aranapu Channel (Santa Luzia, Ponto X, Moura, São Raimundo do Jaraguá, Vila Alencar, São Sebastião Liberdade, Bate Papo). Low and very low risk communities are mainly in the inner portion of the Mamirauá Reserve, associated with floodplain environments that are less dynamic than the Amazon River banks (Fig. 6).

Discussion

Amazonian riverine people largely subject to erosion and sedimentation risk

From the surveyed socioeconomic information, we identify that, from a total of 11,483 people in the Mamirauá Reserve in the Central Amazon, 73% live in floodplain environments, and only 27% in uplands. Our analysis shows that half of the population lives in geomorphologically stable areas (5715 people). The remaining fraction is directly impacted by either erosion or sedimentation processes—27% and 23% of the total reserve's population, respectively, amounting to 5768 people. This proportion is similar to the one

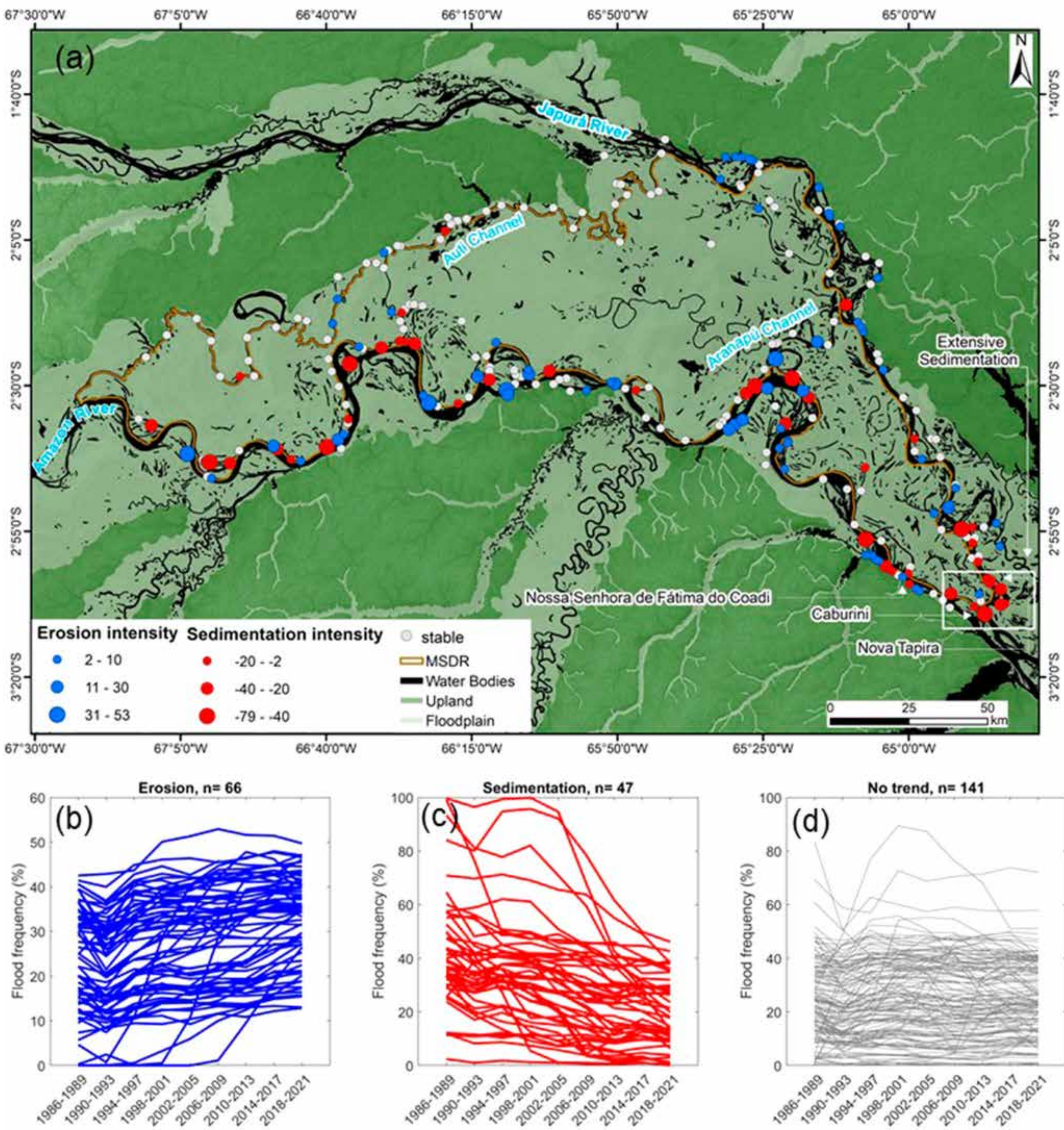


Fig. 1 | Percentage of surface water (%) changed over time, from 1986–1989 to 2018–2021, for all assessed communities. a Distribution of communities associated with predominant erosion and sedimentation processes. Background image shows the topography from the FABDEM Digital Elevation Model (Hawker et al., 2021). Lower panels show (**b**) increasing surface water trends (erosion), (**c**) decreasing trends (sedimentation) and (**d**) no trend (stability).

estimated in the Juruá River[3] (a major tributary of the Amazon), who found that 26% and 15% of the 369 communities are subject to sedimentation and erosion hazards, respectively.

The Mamirauá Reserve's portion of the Amazon floodplain comprises only around 10% of the whole Amazon River floodplain[36] (11,000 km² out of around 116,000 km), and even then a large number of almost 6000 people are under erosion/sedimentation risk in the area. This reinforces that a huge population along white-water river systems in Amazonia is under such a risk. The Brazilian Geological Survey, for instance, estimated 69,000 people to be under river erosion risk for 223 municipalities assessed in the Brazilian portion of the Amazon Basin[17]—and this number would get larger if sedimentation risk or more municipalities were considered.

An important output of this study is that erosion and sedimentation processes affect both upland and floodplain communities in the Central Amazon. This counteracts the common sense that would expect the floodplain environment to be much more dynamic and with more unconsolidated sediments, thus being more susceptible to these phenomena. However, the high annual water level amplitude at the region (around 11 m)[35] is partially responsible for destabilizing river banks and thus

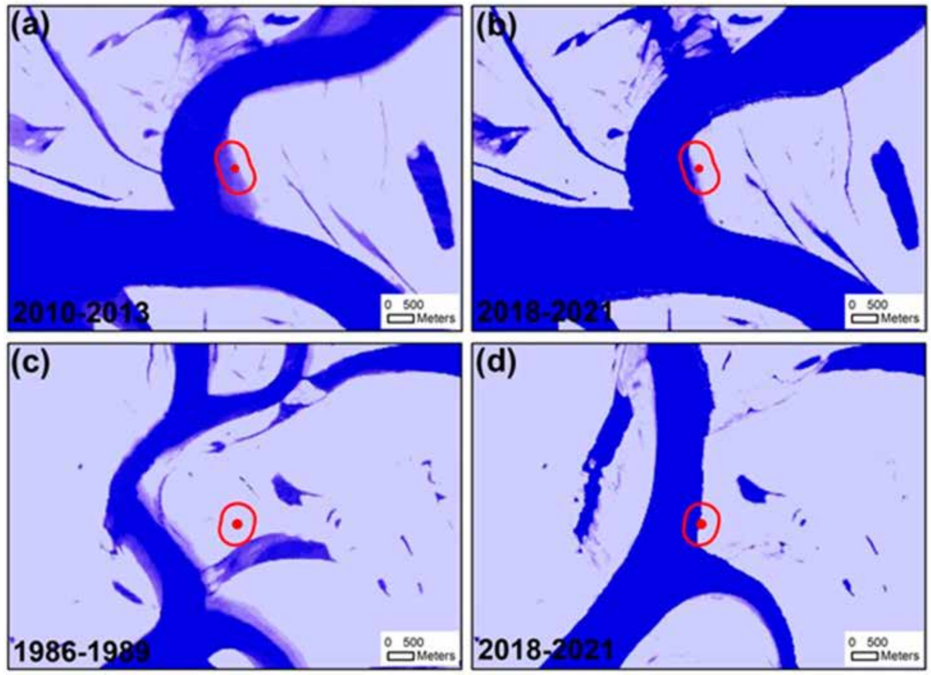


Fig. 2 | Changes in the riverscape around communities. Red polygon indicates the 300 m buffer showing (**a**, **b**) sedimentation in the Caburini community, based on Global Surface Water composites from 2010–2013 to 2018–2021, and (**c**, **d**) erosion in the Bate Papo community, from 1986–1989 to 2018–2021.

promoting erosion around upland communities (see, for instance, the major erosion in the Coadi upland community in Fig. 4a).

Still, it is fundamental to note the major differences in the impacts of erosion and sedimentation in upland and floodplain human settlements. For instance, while agriculture and forest management can be largely affected by erosion in the floodplain areas, these economic activities are usually at less risk in upland communities. This occurs because in their case there are forests and croplands areas that can be accessed or developed further in the upland area, while the floodplain ones usually extract timber and grow crops closer to the rivers (areas that can be under erosion risk).

In the assessed region, upland communities are also less impacted by sedimentation processes because they are generally located in higher areas on the banks of the Amazon and Japurá rivers (following somehow the bluff model of riverine settlement by Denevan (1996)), which tend to be more exposed to erosion than sedimentation processes. On the other hand, the complex wetlandscape dynamics in the Amazon floodplain with constant terrain migrations generate significant changes in the process of human occupation in floodplain areas[9,37]. Our socioeconomic census revealed that 37 (out of 203) communities reported to have migrated due to either erosion or sedimentation processes. Of these, 22 were due to erosion and 15 to sedimentation (formation of beaches that hampered access to rivers in the dry season). Interestingly, all these communities are floodplain ones, highlighting that upland communities live in areas where, even with these hazards taking place, they may find safe places in their territories to continue living there.

The need for improving the mapping of erosion and sedimentation risk in the Amazon

To our knowledge, this is the first study to perform regional-scale mapping of river erosion and sedimentation risk in the Amazon, a problem that is largely overlooked in the literature[17]—to date, studies addressed either the hazard component (e.g., through remote sensing data[3]) or the vulnerability one (e.g., reports on migration due to Amazon riverscape changes[10]). While detailed regional mapping of risks is a very challenging task[18], more investment from public agencies on large-scale vulnerability mapping is fundamental, in order to be combined with environmental satellite data and generate meaningful risk maps. This is a necessary step towards more robust public policies for disaster management in the Amazon.

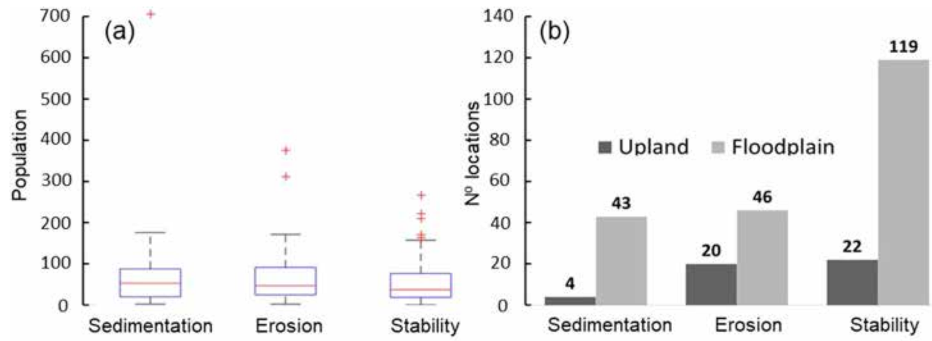
In Brazil, different initiatives for environmental risk management were developed in the last decade, especially after the major mass movements, floods and erosion processes that occurred in 2011 in the country's Southeast region[17]. The National Civil Protection and Defense Policy—PNPDEC and the National Plan for Risk Management and Response to Natural Disasters[38] were created with the objective of preventing and, consequently, reducing social and economic losses related to natural disasters[2,17]. Yet its applicability for the river erosion and sedimentation hazards that occur in Amazon whitewater rivers is far from optimal. For instance, the national plan established the implementation of mapping, description and classification of high and very high geological risk areas in municipalities of all Brazilian states.

This strategy was started by the Geological Survey of Brazil (SGB) resulting in 1605 municipalities mapped throughout the country, from which 223 municipalities located in the Amazon basin.

Within the Mamirauá Reserve, this survey identified 32 communities under erosion risk, most of which close to urban centers, while in some municipalities only areas within the municipal headquarters were considered. An overlay of the SGB mapping with our satellite-based results show that they converge in the locations mapped with erosive processes, yet our methodology yields many more communities under such a risk, revealing the general underestimation that national risk surveys have been subject to (Supplementary Fig. 1). While the SGB initiative is very welcoming and provides important insight into risk management in the Amazon, more investigation is needed to better portray the actual risk that Amazonian communities face. For instance, there is quite often a focus on urban areas as a priority, leaving many rural areas (and thus isolated communities) out of risk mapping initiatives.

It is also important to remark that our study focuses on a regional mapping with a rather simple satellite-based method, and does not exclude the need of local geomorphological studies such as those conducted locally by SGB. Studies which detail the morphodynamics and hydrosedimentary processes of erosion events identified on the banks of Amazonian rivers[17] are essential for better understanding and advancing erosion risk mapping in the Amazon. Expanding local-scale analyses is necessary, and our regional risk mapping has the potential to guide the region's civil defense authorities to identify priority areas to perform such detailed surveys. In turn, this should

Fig. 3 | Relationship between erosion and sedimentation processes and communities' characteristics. Relation with (**a**) population size and (**b**) number of communities located on floodplains and uplands.



be used to promote zoning and identify priority areas to invest in infrastructure resilience and assistance to local populations in more general terms.

While most concerns in the Amazon regarding natural hazards focus on the increase of floods and droughts in recent decades[39], it is fundamental that public policies more broadly encompass sedimentary processes in their risk assessments. Furthermore, the acute nature of erosion processes, which can quickly destroy large portions of communities' territories, make this phenomenon to have more focus than its counterpart—the sedimentation and formation of large beaches that isolate thousands of people, especially during droughts. Yet this process can also lead to major impacts and community migration[10,11], and also requires disaster management strategies. It is interesting to note that sedimentation is not even considered as a hazard within the Brazilian Classification and Coding of Disasters – COBRADE[38].

As a product of hazard, exposure and vulnerability, there are different ways to manage erosion and sedimentation risk in Amazon river-floodplain communities. This requires addressing the different perspectives of all stakeholders, who often have distinct risk perceptions and divergent understandings of drivers, feedback and results of vulnerability[40]. This can be especially true in the case of indigenous and traditional communities in the Amazon region, whose knowledge must be directly considered when proposing risk management solutions[41]. A better understanding of social vulnerability and its dynamics within Amazonian riverine communities is also needed, providing new ways of large-scale mapping of the susceptibility or fragility of society to external threats. Such susceptible conditions can be attributed to several aspects such as political relationships, rural-urban relationships, and demographic and socioeconomic inequalities between social groups within societies. For instance, many studies have found that localities with higher numbers of elderly people, children, and women, low illiteracy rates, and weak financial capacity are highly vulnerable[42–44]. For example, women can have a more difficult time during recovery than men, often due to sector-specific employment, lower wages, and family care responsibilities.

Extremes of the age spectrum affect the movement out of impacted areas. Parents invest time and resources caring for children when daycare facilities are affected; elderly may have mobility constraints or mobility concerns increasing the burden of care and lack of resilience[43,45–48]. Distance to main urban centers have also been acknowledged as a main source of vulnerability in remote urban areas in the Amazon[49], as also considered in our risk approach by addressing the distance from communities to the main regional center (Tefé) and the nearest urban areas. Understanding the interplay among these vulnerability factors along Amazonian communities is a needed step forward.

The migration of communities due to erosion and sedimentation processes is a common practice along the Central Amazon river[10]. While migrating is rarely a first option, the imposition of erosion and sedimentation hazards is so strong after a few years that not moving is barely a viable option for many communities – imagine, for instance, having to walk through a few kilometers during a drought because of formation of a major beach, or even having houses or schools destroyed by erosion. It is the perception of what occurs in the present, guided by the knowledge obtained from previous experiences, that allow local Amazonian communities to make forecasts about the future riverscape changes[10], ultimately guiding their migration to nearby areas that are perceived as less hazardous. Communities such as Caburini (Fig. 3b) have migrated several times in the past, and are already preparing their new migration to stay closer to the river. To deal with erosion, many community houses are built of wood instead of masonry being more easily dismantled, and agricultural crops are cultivated far from the river banks. Regarding sedimentation, many communities periodically migrate nearer to the river by rebuilding their houses by themselves using the same timber. With these acquired experiences they develop strategies to deal with future disasters. Future research should address what ultimately drives the decision of migrating, as well as the economic and psychological impacts of such migrations in the willingness to migrate again in the future. This is particularly important in a context of accelerating climate change. Another important element is to assess migration-induced impoverishment, although it should not be a major problem for the region since migrations typically occur over relatively long periods (e.g. each five to 10 years) and involve relatively low costs.

Compound risks: synergy with other environmental hazards

Current risk management needs to better integrate compound risk frameworks[8,50]. The Amazon River system is increasingly affected by multiple anthropic stressors such as dam construction and deforestation in highlands and floodplains[51–54]. On top of them, a significant increase in the frequency and intensity of droughts and floods, likely associated with climate change, as well as alterations in the hydrological cycle, has been reported in recent years in the Amazon region[22,40,55,56]. For instance, along the Amazon floodplains, increased maximum inundation extent has been reported[22], while record-breaking droughts have also taken place in recent years[57]. In June 2021, it occurred the highest water level ever recorded in the Negro River at Manaus, in Central Amazon, after more than 120 years of measurements[58]. Two years later, in October 2023[59], the same place experienced the lowest water level ever measured, which was later overpassed by the October 2024 drought. While integrating multi-hazard scenarios within regional-scale risk mapping is challenging[18], it is a needed advancement for the region, which could benefit from the multiple recent developments with remote sensing datasets in the Amazon[34].

It is thus imperative to understand Amazon natural hazards with a synergistic and holistic perspective. Sedimentation processes, such as the formation of river beaches, can turn into a major disaster during extreme droughts since the exposed beaches become very large and so does the community isolation. With the reduction in river water levels, river bank exposition promotes an intensification of bank erosion processes.

At Tefé, the river water levels decreased around 14 m in 2023, from July, during the flood peak, to October, during the drought peak. An unprecedented number of erosion disasters were reported by local news[12,14,60,61]. This may be further exacerbated by extreme air temperatures due to the intense drying of river banks – in 2023, temperatures broke records across the globe[61].

Finally, the unpredictability of extreme hydrometeorological events, currently reported by many traditional people across the Amazon[62], poses

Fig. 4 | Photos of erosion and sedimentation processes along the study region. a Erosion in the community of Coadi, and sedimentation processes with large beach formation in the communities of (**b**) Caburini and (**c**) Novo Tapiira. Photos: (**a**) Paula Silva, (**b**) João Paulo Borges Pedro and (**c**) André Zumak.

even more challenges to the management of erosion and sedimentation risks along the Amazon. Such uncertainty can also be affected by manmade interventions in the region's river systems, such as sediment trapping by dam expansion[63,64] and land use change[28,65–68]. The rate of river meander migration also depends on the river's sediment transport[1], which can also be affected by climate change, e.g., through increased rainfall rates in the headwaters of the Amazon in the Andes[69].

Conclusions

To our knowledge, this study presents the first regional-scale analyses of river erosion and sedimentation risk in the Amazon. We show that, in the region of the Mamirauá Reserve (around 11,000 km²) along the Amazon river-floodplain system, more than 5000 people are being impacted by erosion and sedimentation processes in both upland and floodplain environments. This population represents around half of the people that currently inhabit the area, and it highlights the need to improve basin-scale mapping of such risks, involving larger investment for understanding large-scale hazard, exposure and vulnerability of remote riverine communities.

Remote sensing techniques proved very useful to map erosion and sedimentation hazard based on trend analyses of open water areas. The integration of regional-scale socioeconomic data helped to identify communities under different risk classes (very high, high, moderate, low and very low). Thus, this study stresses the possibilities of merging global-scale datasets (open water data) with regional-scale socioeconomic data (Mamirauá Institute's census of the reserve) to provide useful information to assist disaster management strategies. Our study also highlights the need for large-scale and more consistent monitoring strategies related to these hazardous phenomena across Amazonia.

This study also contributes to the debate about practices and forms of usage of natural resources by traditional populations, since these practices are associated with local and unique knowledge about the river-floodplain environment. A deep understanding of the local ecological calendar and the particularities of the seasonal movement of river waters is fundamental for these populations to establish livelihood strategies, and improve their resilience to such disasters, e.g., through constant migration due to river erosion or sedimentation (formation of beaches). We showed that, from 254 surveyed communities, a total of 37 floodplain communities have already migrated because of these two types of natural hazards.

It is important to highlight that even though the methodology adopted here can be applied to other regions, there are several limitations that must be acknowledged. Remote sensing data may be affected, for instance, by cloud cover, geolocation errors, discontinuity in long-term series, and therefore field validation is still necessary, even for large-scale analyses. Similarly, socioeconomic information is not free of uncertainties, especially regarding our assumptions about the communities' vulnerability to risk and sedimentation risks. Nevertheless, here we present an important starting point that can guide risk mitigation efforts by regional civil defense authorities, based on global to regional-scale datasets, and especially to assist the identification of priority areas to develop more local, detailed risk surveys. We also stress that our methodology may be suitably applied to map erosion and sedimentation risk in other meandering rivers with similar channel patterns such as the Juruá and Purus rivers in the Amazon Basin. However, even within the basin, other channel patterns do exist (such as straight rivers with small meandering rates), for instance along black-water rivers, where our long-term hazard mapping approach with satellite data may not be adequate.

Finally, this study proposes that disaster risk management in the Amazon moves beyond the current paradigm that focuses mostly on increasing floods and droughts, encompassing more holistically different hazards and moving towards a compound hazard approach. The combination of multiple risks leads to major damages to local populations—this was particularly evident during the extreme 2023 drought, the largest one ever measured in the Central Amazon, when many communities became isolated due to formation of large beaches or lost their infrastructure and houses due to bank erosion. In a context of climate and other major environmental changes and degradations, including dam expansion, mining, deforestation and increased water and air pollution, the vulnerable people that inhabit the Amazonian rivers urge for better disaster management strategies.

Methods

Study area

The Mamirauá Sustainable Development Reserve is located in the Amazon lowlands at the confluence of the Amazon and Japurá rivers, near the

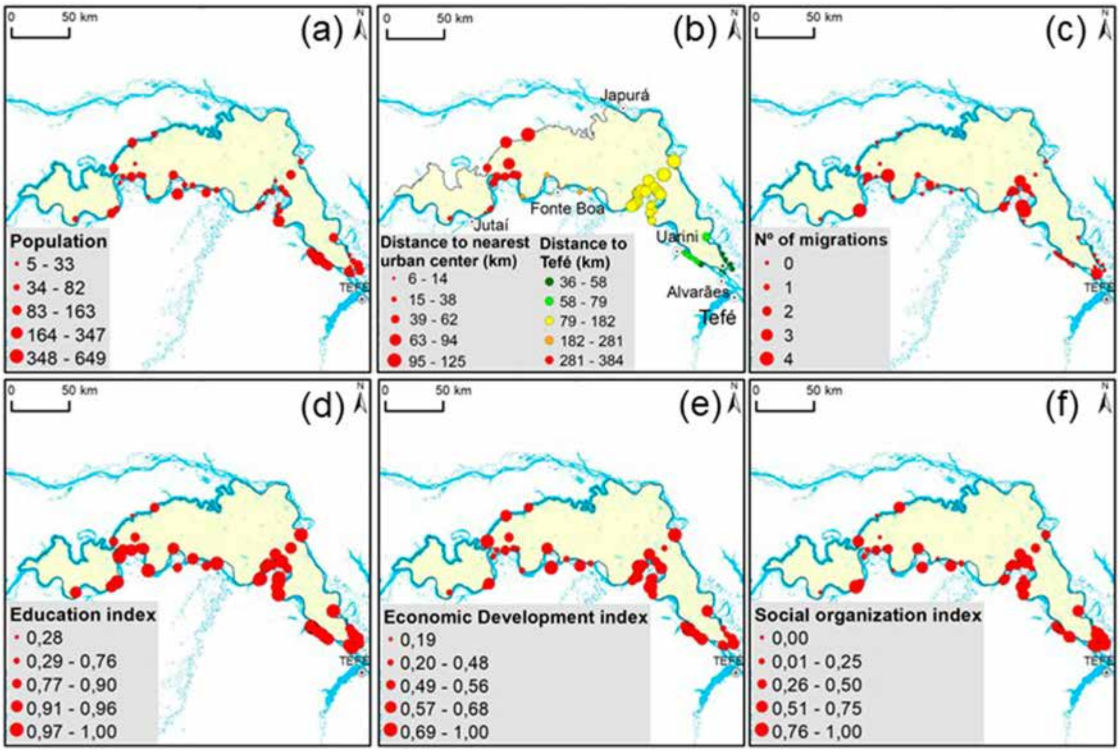


Fig. 5 | Maps of exposure and vulnerability indexes. a Exposure (here assumed as population size) and (**b**–**f**) vulnerability indexes per community.

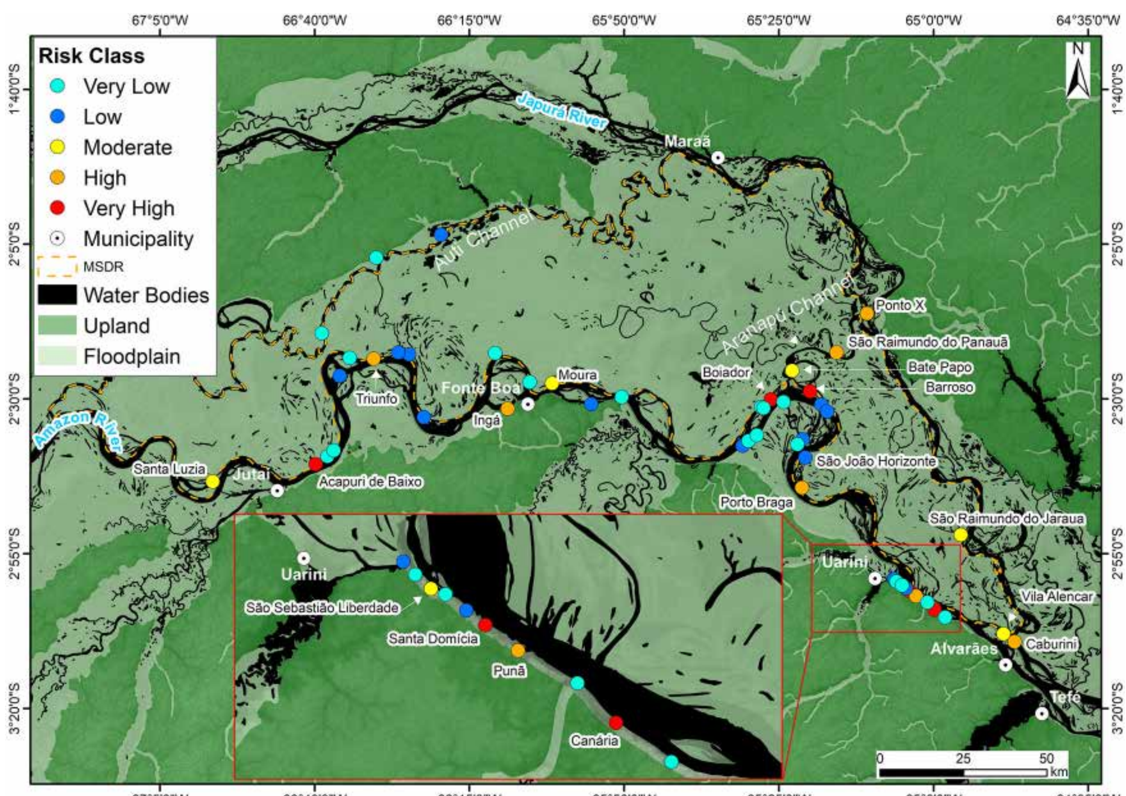


Fig. 6 | Map of risk for each community in the Mamirauá Reserve.

city of Tefé, in the Brazilian state of Amazonas, approximately 600 km upstream from Manaus (Fig. 7). It is one of the largest protected areas dedicated to the environmental conservation of Amazon wetlands, the largest protected inland wetland in Brazil. Supporting a wide range of socio-economic initiatives and biological studies on forestry, agriculture, fisheries and ecotourism, the reserve is a key center for research on sustainable development and conservation in Amazonian environments[30,69–72].

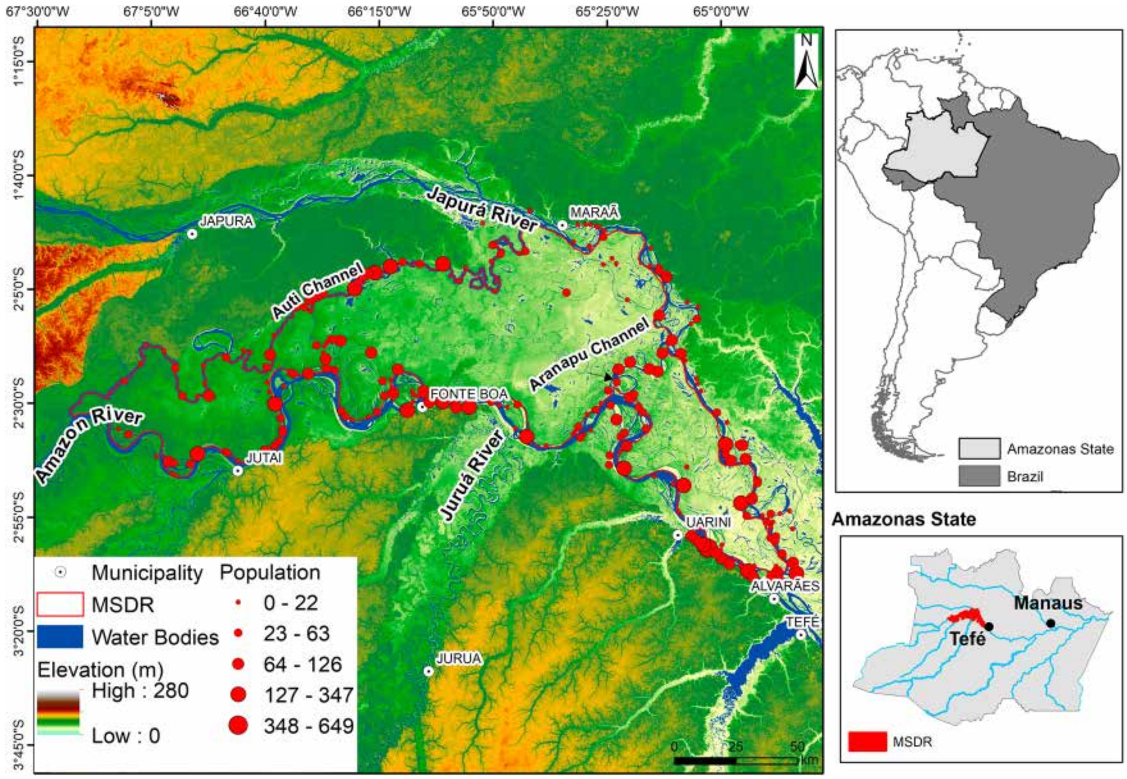


Fig. 7 | Location of the Mamirauá Sustainable Development Reserve. Located in Central Amazon. With the studied communities' population size depicted with red circles. Background image shows the topography from the FABDEM Digital Elevation Model[99].

According to a sociodemographic census carried out by the Mamirauá Institute in 2019, there is a population of 11,483 people living in the reserve (Mamirauá, 2019), inhabiting both floodplains (locally known as "várzea" in portuguese) and uplands ("terra firme"). The Mamirauá Reserve extends over five municipalities (Uarini, Fonte Boa, Japurá, Maraã and Tonantins), although its population is subject to political-administrative relationships with the municipalities of Alvarães, Jutaí and especially Tefé, which is the city with greatest economic influence in the region[73] (Fig. 7).

The local population is predominantly young, with gradual aging since 2010, reflected in the increase in median age and the proportional decrease in children under five[73]. In 2019, the predominant age group was 10–14 years, with a slight predominance of girls.

The communities' economy is characterized by high seasonality and reliance on natural resources, generating significant non-monetary income, while activities such as fishing and extractivism are strongly affected by seasonal variations. Monetary income shows considerable annual variability, making consistent recording challenging, and the circulation of money has increased recently with income transfer programs and social benefits.

The flood dynamics in the Mamirauá Reserve is characterized by a large monomodal flood pulse, reaching an annual water level amplitude of around 11 m. The flood season begins in May, extending until mid-July, followed by a receding phase that lasts until September. The dry season occurs from September to November, when the flooding process begins, lasting until May[35].

The landscape is a mosaic of recent linear river depositions interspersed with floodplain levees, old channel bar deposits, abandoned meanders and lakes, periodically interconnected with each other and with the river systems of the Amazon and Japurá rivers[74].

Both the Japurá and Amazon rivers are white-water watercourses (rivers with high sediment concentration) and are among the nine largest rivers on Earth, classified as "branched mega rivers", with relatively straight courses[75]. Large rivers such as the Amazon are dominated by "anabranching" patterns[76,77]. These are understood as multichannels that present a diverse group of alluvial rivers comprising multiple channels and are interconnected, separated by large and stable alluvial islands, which divide the flow. Even so, both rivers develop meanders in their upper stretches[29,77]. The alluvial geomorphology of white-water rivers along the Mamirauá Reserve is highly dynamic. Sedimentation and erosion processes are generally well balanced when monitored throughout a long period[29]. The channel changes are considerably greater along the Amazon River than in Japurá, due to the higher sedimentation concentration in the former. This occurs because of the central part of the Andes in Peru and Ecuador, where precipitation, weathering and erosion rates are higher[29,78–80].

A total of 113 localities were mapped along the Mamirauá Reserve region, based on the Mamirauá Institute's census (Fig. 7). Locally, they are called either communities (larger human settlements, up to several hundreds of people) or "sítios" (smaller ones); for simplicity, here we call all of them as communities. The "sítio" type accounted for 25% of the total mapped localities.

Risk computation

Overview. Our erosion and sedimentation risk analysis framework is based on the calculation of risk (R), which is the multiplication of the variables hazard (H), exposure (E) and vulnerability (V) (R = H x E x V)[81,82] (Tables 1, 2 and Fig. 8). The risk classes were obtained through the construction of an index that uses the normalization of indicators by dividing the unit value by a reference target (in most cases the maximum value)[83] (Tables 1, 2).

The hazard variable was estimated from the temporal trend of increase or decrease of open water areas around the communities – when these areas increase over time, erosion takes place; when they decrease, sedimentation is the main process occurring. This method of analysis was used for global investigation of erosion and bank accretion[28], and also to quantify the hazard associated with meander migration in Amazonian communities[3].

Exposure was estimated with the population size. Vulnerability was computed by the multiplication of four factors: (a) access to services and

Table 1 | Description of the risk dimensions and how they were computed in this study

Dimensions of risk	Variable /Indicator	Description	Methods	Data source
Hazard	Trend in open water area Percentage of open water (%)	Erosion processes: sedimentation (positive trend) and erosion (negative trend)	Remote sensing and GIS	Open water mask from Landsat satellite data[20]
Exposure	Population size (total number of people)	Population size in each community	Statistics and percentage calculation using GIS	Mamirauá Institute census[73]
Vulnerability	Distance to urban area (km) Distance to the nearest urban center (km)	Distance from the communities to the largest urban area in the region (Tefé) Distance to the nearest urban center	Cost path analysis[95]	Mamirauá Institute census[73]
	Number of past community migrations due to erosion/sedimentation processes (total number of community migrations)	Previous experience with the hazard	Statistics using GIS	Mamirauá Institute census[73]
	Socioeconomic data	Social Development Index based on thre dimensions: education, economic development and social organization	Statistics and calculation of percentage	Mamirauá Institute census[73]
	Number of women, children and elderly people in the communities (total number per community)	Total number of women, children and elderly people in the community	Statistics and percentage calculation using GIS	Mamirauá Institute census[73]

goods, based on distance from the communities to the largest urban area in the region (the city of Tefé) and to the nearest town; (b) number of recent migrations due to erosion or sedimentation processes, as a measure of community's risk awareness and adaptation capability; (c) community vulnerability based on social-economic characteristics; and (d) number of women, children and elderly people in each community.

For each community, the final risk value was computed from the multiplication of the hazard, exposure and vulnerability values. Finally, the risk was categorized into five classes (very high, high, moderate, low and very low), considering the method of Jenks natural breaks optimization, which is typically adopted in disaster risk analyses[84]. The next subsections present the detailed methods for each risk component.

Hazard computation

The detailed steps of risk mapping are summarized in Fig. 8. The first step consisted of estimating the hazard component. For that, the communities' built areas were manually mapped using images from the Planet satellite with 4.77 m resolution, through Norway's International Climate and Forest Initiative[85]. The communities' locations were obtained from the Mamirauá Institute census from 2018 and 2019[73].

Percentage of surface open water maps, which are a proxy of the fluvial topography[86,87], were derived for periods of four years (1986–1989; 1990-1993; 1994–1997; 1998–2001; 2002–2005; 2006–2009; 2010–2013; 2014–2017; 2018–2022) using Landsat-based water masks from the JRC Monthly Water History dataset (Global Surface Water Dataset; Pekel et al., 2016; available at: <https://developers.google.com/earth-engine/datasets/catalog/JRC_GSW1_4_MonthlyHistory>). Different from the static layers of the Global Surface Water Dataset, the adopted monthly database allows the mapping of water occurrence for a selected period. Open water area change over time was then extracted for each built area considering a 300 m buffer.

The main reason for using the Global Surface Water Dataset is that although water masks can be derived from fieldwork, drone observations, or aerial survey, these methods tend to be laborious, time-consuming, and difficult to replicate at frequent time scales for continuous monitoring[88]. Space-based Earth observations have emerged as a reasonable method for remotely generating inland water masks[88–90]. Indeed, the global coverage and fine temporal resolution of satellite imagery provide the opportunity to obtain time series of surface water extent at the global scale for almost all rivers[91].The Landsat water mask from the Global Surface Water dataset aggregated 3 million Landsat optical images to categorize water occurrence from 1984 to 2020 with 30 m spatial resolution and has been providing breakthrough information for understanding the dynamics of water globally[20].

From the nine estimates of open water frequency (4-yr averages from 1986 to 2022), the Mann-Kendall trend analysis test was performed to identify whether the area surrounding the community had experienced increased or decreased open water areas, considering a P-value of 0.95. As a result, the communities were characterized as having predominantly erosion processes (positive trend of increasing areas of water surfaces), sedimentation (negative trend) or stable areas (without significant trends). The process intensity was assessed through the magnitude of the trend (e.g., a very steep increase in open water areas means an intense erosion process is taking place). A similar methodology was applied for assessment of erosion and sedimentation in Amazon and global rivers, respectively[3,28].

The obtained results were validated through visual inspection, field visits to the reserve, conversations with local populations, and comparison with information on community erosion/sedimentation from the Mamirauá Reserve's census[73] and other studies published about the area's erosion and sedimentation impacts on local communities[10]. The final hazard value, for each community, was normalized between 0 and 1 using the "distance to target" approach[84], by dividing each community's trend value (e.g., a 30% increase in long-term open water areas surrounding the community-built areas) by the largest hazard value obtained from all assessed communities.

Table 2 | Description of the risk dimensions and how they were calculated and normalized in this study

Dimensions	Variable /Indicator	Maximum value in all communities	Normalization
Hazard	Increasing open water trends (erosion) Decreasing open water trends (sedimentation)	48.05 73.22	Increasing trends (erosion) / maximum values Decreasing trends (sedimentation) / maximum values
Exposure	Total number of people	649	Total number of people / maximum values
Vulnerability	Distance to Tefé's urban area (km)	384	Distance to Tefé's urban area / maximum values
	Distance to the nearest urban center (km)	124	Distance to the nearest urban center / maximum values
	Total number of community migrations due to either erosion or sedimentation	does not apply	Values were defined as 1 = no migration, 0.8 = 1 migration, 0.6 = 2 migrations, 0.4 = 3 migrations and 0.2 = 4 migrations. Considering that the highest values correspond to the most vulnerable locations, due to the lack of experience in dealing with changes.
	Number of women	305	Number of women / maximum values
	Number of children	254	Number of children / maximum values
	Number of elderly people	29	Number of elderly / maximum values
	Education index	Does not apply	2/3 (community people between 10–14 years that can read) + 1/3 (community people over 15 years old that can read).
	Economic Development index	Does not apply	Average number of equipments per house in a community / Maximum value in all communities
	Social Organization index	Does not apply	With Community Association = 0.25 + With community center = 0.25 + With school = 0.25 + With health agent = 0.25
	Social Development Index (SDI) based on three dimensions: education, economic development and social organization	does not apply	SDI = (Education Index + Economic Development index + Social Organization index) / 3The final value for risk computation is considered as (1 - SDI), to make communities with lower SDI values to have higher vulnerability
Total Vulnerability	Average of the values of the normalized variables mentioned above: Distance to Tefé's urban area, Distance to the nearest urban center, Number of migrations, Number of women, children, elderly and Social Development Index	does not apply	does not apply
Risk calculation	Multiplication of the variables hazard, exposure and total vulnerability	does not apply	does not apply

Computation of exposure and vulnerability

The communities' exposure and vulnerability to erosion and sedimentation were obtained mainly from socio-economic data available from the Mamirauá Institute's census[73] for the Mamirauá Reserve, which is carried out, on average, every five years. The most recent one was carried out during 2018-2019.

Exposure is computed considering the number of people in each community (Fig. 3a). The values were rescaled between 0 and 1 using the "distance to target" approach considering the largest community population size obtained from all assessed communities.

Vulnerability is computed by the average of four factors: (a) community distance to urban centers; (b) previous community's experience with erosion/sedimentation; (c) number of women, children and elderly people in the communities; and (d) Social Development Index, reflecting the community's education, economic and social organization level.

The first factor is the community distance to nearby urban centers, considering the Amazonian riverine rural populations' dependence on the urban areas to access different services and goods[92]. The factor considered two submetrics: distance to (1) the regional urban center (the city of Tefé) and (2) to the nearest town. The first one was designed reflecting that Tefé plays a central role in the region, being a service hub for the entire "Médio Solimões" region, exerting influence on various municipalities (Alvarães, Fonte Boa, Japurá, Juruá, Jutaí, Maraã, Tonantins, Japurá, Uarini)[93] with a total area of influence of 220,000 km² (similar to the area of the United Kingdom). The city of Tefé concentrates urban functions, and not only holds the majority of services, but, more importantly, it is the only city that holds these services if we consider the absence of some essential elements for the urban function, such as the financial system[92,94]. In this sense, Tefé is considered the only city of regional influence in the Solimões River (i.e. the Amazon River between the Brazil-Peru border and Manaus)[70], also called medium-sized city with territorial responsibility[92].

The community distance to the nearest town was also considered since this is usually the first option to access some services, especially for those communities located along the Japurá and Amazon rivers. For example, in the Santa Luzia community, located in the Amazon River, the along-river distance from the community to Tefé is 384 km, while to Jutaí town is only 24 km. However, unlike Tefé, the region's towns generally have small urban areas that provide basic services such as first access to health, secondary education, electricity, telecommunications and small markets[95], mand the main region's services are concentrated in Tefé.

The distances from the communities to Tefé and to the nearest urban center were computed using the methodology which considers the distance between two points along a river network, using a GIS cost-path function[95]. To create the river network for the study area, we used a 1:10,146 river base layer (polylines) extracted from the Brazilian Water Agency's hydrological database[96]. The Japurá and Amazon rivers and other several channels present in the study area cumulatively cost the travel of each cell in the raster to a source or a set of sources[97].

To do this, we generated 20-km buffers around the digitized river network, which incorporated the locations of the communities under investigation. The buffers and the simplified river lines were then converted to raster layers with a cell size of 30 m, projected to the UTM Zone 20S (WGS 1984). The next step was to combine both rasters and reclassify the output to create the cost raster to be used in the cost path analysis[100], giving a higher travel cost value to the buffer pixels and a value of 1 to river pixels. Since our analysis aimed to determine the distances of transportation routes that use the river network rather than the surrounding land, the relative costs were adjusted so that the results favored a path along the river network

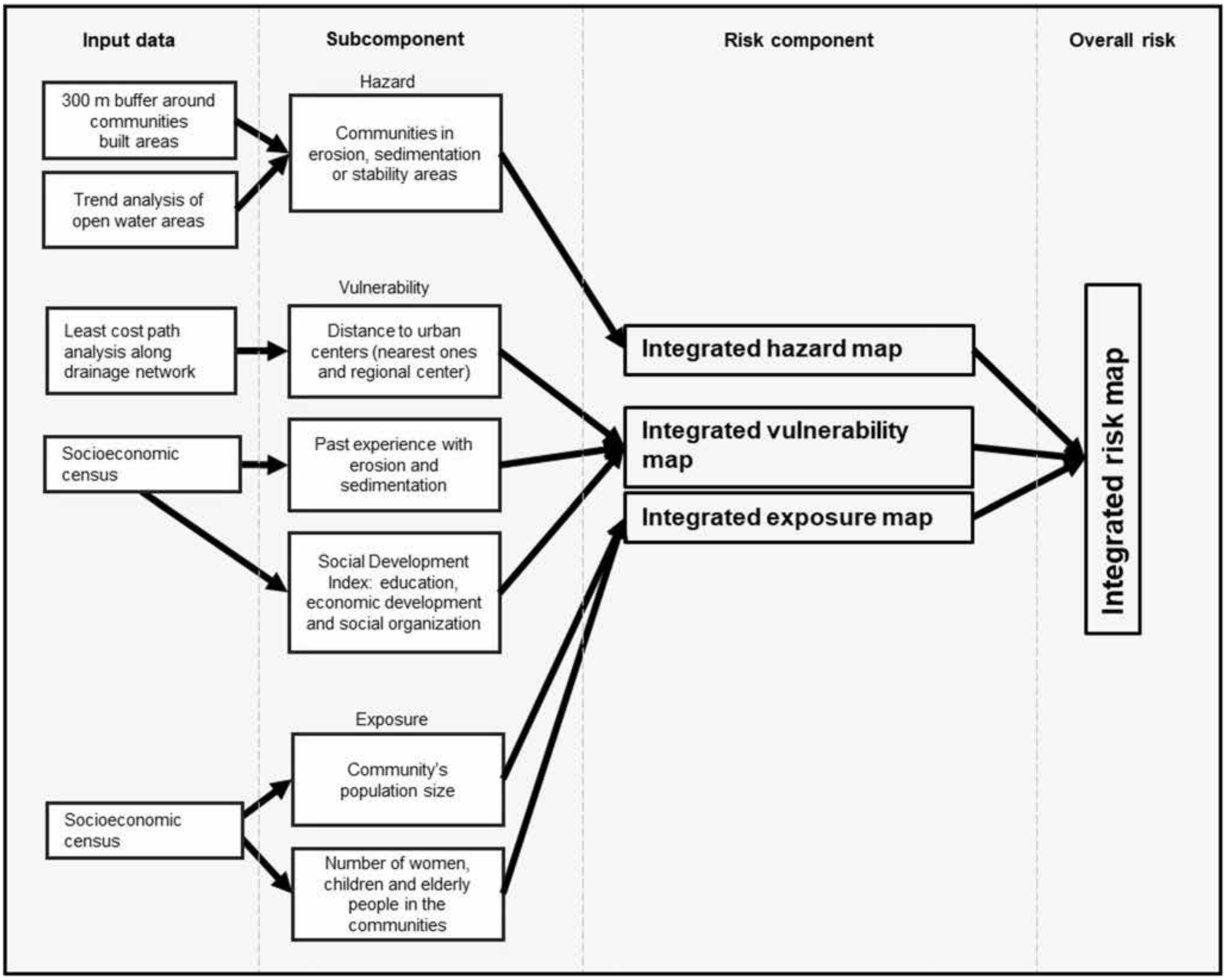


Fig. 8 | Flowchart with the study's working steps.

rather than through the buffer. The final distance values were rescaled using the "distance to target" approach considering the maximum distance obtained from all communities.

The second vulnerability factor considers the community's experience in dealing with erosion and sedimentation processes. This was assessed through the number of migrations (Fig. 3c) that the community performed due to erosion or sedimentation, which was computed by the Mamirauá census. Communities that have already migrated due to this process are assumed to be more prepared to deal with future disasters due to their improved knowledge of the impacts and the potential adoption of disaster prevention and response measures. The vulnerability value was normalized considering a maximum weight (1.0) for zero migrations, 0.8 for one migration, 0.6 for two, 0.4 for three and a minimum value of 0.2 for four or more migrations.

The third factor is the number of women, children and elderly people of each community. While gender imbalance generally puts women at higher risk during disasters (Cutter et al., 2003), age is also considered a factor of vulnerability due to challenges to cope with the disaster consequences[83]. The values were rescaled between 0 and 1 using the "distance to the target". Considering the largest numbers of people in the age group of 0 to 12 years (children) and people over 60 years (elderly)[93].

Finally, the fourth factor is based on the Social Development Index developed by Mamirauá Reserve[73,98], which considers three metrics (education, economic development and social organization) and was designed to account for the social diversity between localities across the heterogeneous landscape of the reserve. The final Social Development Index is the average of the three metrics (education, economic development and social organization), and ranges from 0 to 1.

The education metric is based on the fact that access to education is a fundamental step toward empowerment of local people to deal with social challenges and inequalities. The adopted metric gives a 2/3 weight for the fraction of the community people between 10–14 years that can read and a 1/3 weight for the fraction of the community over 15 years old that can read.

The economic situation of the communities was evaluated through the economic component of the social development metric, by considering the average number of equipment (fridge, oven, boat engine, bed, mobile telephone, television, etc.) per house. This metric has been considered adequate to assess riverine communities due to difficulties in obtaining other more typical metrics, such as income per capita/per family, as non-monetary income is common (e.g. direct extraction of natural resources), commercial relationships are usually not registered by them, and the high seasonality of local production makes it difficult to accurately compute the annual average monetary incomes[98]. Thus, the consumption of durable goods, as computed by the economic index within the social development index, was deemed by these authors as the most suitable pattern to assess the economic situation of these social groups. This approach thus addresses the complexities of data collection in remote areas by using proxies and simplified statistical techniques to maintain the relevance of the index[98].

The social organization metric is related to the importance of having organized local communities to promote the locality's welfare and social development. In remote rural communities such as in Amazonia, the relevance of social organization has unique particularities, associated with the environment's dynamics, the reduced number of people, parental relationships and the community's history. The adopted metric considers the existence of services and infrastructure in the communities, including a local association, a health agent, a school, and a community center. Specifically, the presence of a local association guarantees the legal recognition of the community, allowing it to access public services and carry out financial transactions. A health agent indicates a formal integration into the health system, while the presence of a school addresses educational needs, sometimes including both adult and youth education.

Finally, the community center serves as a venue for cultural, social, and political activities, reflecting the community's organizational capacity. A 0.25 weight is given to each of these social organization infrastructures.

Data availability

Hazard estimates were performed using the Landsat-based classification of surface waters, freely available from the Global Surface Water Explorer (https://global-surfacewater.appspot.com/).

Socioeconomic data from the census developed by the Mamirauá Institute for Sustainable Development for riverine communities in the Mamirauá Reserve can be obtained through an official request to the institute (mamiraua@mamiraua.org.br).

Code availability

All codes used in this research are readily available through request to the main author.

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Author contributions
A.Z. conceived and designed the project, performed most of the analysis, interpreted the results, and wrote the manuscript. A.S.F., A.F.A. and F.P. supervised the study, designed the project, interpreted the results and contributed to the manuscript writing. P.S. interpreted the results and contributed to the manuscript writing. H.C. and A.C. provided the sociodemographic database and helped integrate it into the overall analysis, interpreted the results, and contributed to the manuscript writing.

Competing interests
The authors declare no competing interests.

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