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Severe droughts reduce river navigability and isolate communities in the Brazilian Amazon

Letícia Santos de Lima[1,2], Francisco Eustáquio Oliveira e Silva[2,3], Paula Rosana Dorio Anastácio[4], Marina Marcela de Paula Kolanski[4], Ana Carolina Pires Pereira[5], Marianne Stéfany Resende Menezes[4], Evandro Landulfo Teixeira Paradela Cunha[6] & Marcia Nunes Macedo[7,8]

The Amazon basin is experiencing severe droughts that are expected to worsen with climate change. Riverine communities are especially vulnerable to these extreme events. This study investigates the experiences of Brazilian Amazonian communities during droughts occurring from 2000-2020. We assess the distribution of settlements at risk of prolonged isolation during extreme low-water periods, along with impacts reported in digital news outlets. Using historic time series of river levels from 90 gauges, we look at how long droughts lasted in regions with reported impacts. Results indicate that the droughts in 2005, 2010, and 2016 were the most severe, with over an additional month of low water levels in those years. Such drought events routinely disrupt inland water transport and isolate local populations, limiting access to essential goods (food, fuel, medicine) and basic services (healthcare, education). Given this new reality, Amazon countries must develop long-term strategies for mitigation, adaptation, and disaster response.

The Amazon River basin covers an area of around 7 million km^2, encompassing a vast tropical rainforest and freshwater ecosystems that extend over 14–29% of its total area[1]. The Pan-Amazon region spans nine countries, including the largest expanse of remaining tropical rainforests and all major tributaries of the Amazon River. The area is home to approximately 47 million people, including Indigenous and non-Indigenous populations, as well as urban and rural dwellers[2]. Most Amazonians rely on navigation as part of their daily lives since rivers are the region's primary means of medium- to long-distance transportation[3]. Yet today this vast river system and the surrounding floodplains and forests are under immense pressure due to the compounding effects of climate change, deforestation, and fire[4,5].

Climate projections suggest that the Amazon will experience increasingly drier conditions and more frequent extreme events, including droughts and floods[6–8]. Indeed, the hydroclimatic record already shows an intensification of the hydrological cycle, with recent droughts (as in 2005, 2010, 2015-2016, and 2023) occurring more frequently than in previous decades[3,9,10]. These drought years are associated with anomalously low rainfall, which translates to low-water level events that can have cascading impacts on local populations and the freshwater ecosystems they depend upon.

The 2023 drought proved to be an unprecedented example of these extreme events—with abrupt decreases in water levels and abnormally high air temperatures triggering fish kills, river dolphin mortality, disrupted navigation, isolation of rural dwellers, and massive wildfires in the central Amazon[10–13]. Given its dependence on predictable water levels, inland water transport (i.e., by river boats and vessels) is substantially more sensitive to droughts than other modes of transport[14]. Hydrological droughts – defined as sustained periods of below-normal water levels[15,16]—can therefore impact inland navigation by forcing reduced vessel speed and course changes to avoid obstacles (e.g., sand bars and rocks); limiting access to ports and moorings; or requiring reduced vessel loads[17].

In the context of the Amazon, extreme droughts can also completely halt navigation, disproportionately impacting rural communities. The consequences of these extreme events include the total isolation of villages

[1]Institut de Tecnologia i Ciencias Ambientals (ICTA-UAB), Universitat Autònoma de Barcelona, Cerdanyolla del Vallès, Catalunya, Spain. [2]Programa de Pós-graduação em Saneamento, Meio Ambiente e Recursos Hídricos (SMARH), Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. [3]Hydraulic Engineering & Water Resources Department, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. [4]Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. [5]Espace-DEV, IRD, Univ. Montpellier, Univ. Guyane, Univ. Reunion, Montpellier, France. [6]Faculty of Letters, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. [7]Woodwell Climate Research Center, Falmouth, MA, USA. [8]Instituto de Pesquisa Ambiental da Amazônia, Brasília, DF, Brazil.
e-mail: leticia.lima@uab.cat

for weeks to months[3,18], leading to shortages of food and medical supplies[19–21], as well as limited access to health services and education facilities[22]. Severe droughts may also reduce protein sources for local families[23,24], given degraded water quality and restricted access to fishing sites during these extreme events.

Few studies have examined the direct and indirect effects of severe droughts on local Amazonian people through disruptions to navigation. Although some studies have described the various impacts of droughts on riverine communities (known as "ribeirinhos" in Portuguese), these were only able to address a small number of cases[20,25–27]. Others have focused on the hydrological impacts of drought events, highlighting the critical importance of inland water transport for local people[3,19,21]. To the best of our knowledge, there has been no systematic, spatially explicit analysis of these impacts at the scale of the Amazon basin.

Large-scale studies on cross-sectoral impacts of droughts have been constrained by data availability[28,29]. In response, several drought observatory initiatives have emerged[30,31] and research groups have begun exploring media content (e.g., newspaper articles) as a source of information for qualitative assessments of widespread cross-sectoral drought impacts[28,29,32–35]. Here we assess the impacts of droughts occurring from 2000 to 2020 on the local populations of the Brazilian part of the Amazon basin, focusing on impacts related to limited accessibility and mobility in the region. To do so, we first assessed the extent to which communities rely on rivers and wetlands for transport. We then analysed the impacts of past droughts reported in media outlets, comparing them with the available academic literature and exploring the hydrological conditions that accompanied those events.

Results and discussion

Proximity to rivers and roads

The Brazilian part of the Amazon basin encompasses 3671 non-Indigenous localities, which can be subdivided into 3259 remote rural settlements, 251 cities (including 5 state capitals), and 161 villages[36]. In addition, there are 2521 Indigenous villages ("aldeias")[37] (Supplementary Fig. 1). To identify the non-Indigenous localities and Indigenous villages most prone to isolation during droughts, we quantified and compared the nearest straight-line distance from these settlements to major water bodies and roads (see Supplementary Table 1 for data sources).

Non-Indigenous localities: Our results show that 89% of non-Indigenous localities ($n = 3259$) are up to 5 km away from the nearest major water body during the high-water season, but this number drops to 84% during the low-water season. About 77% of all localities ($n = 2841$) are situated <1 km away from major water bodies during the high-water season, compared with 73.6% in the low-water season. The average straight distance is 1.7 km (high water) and 2.6 km (low water), with median values of 0.4 and 0.5 km, respectively. In contrast, 48.5% of localities ($n = 1779$) are <5 km away from the nearest road (independent of road conditions), while the rest are located 5–200 km away (average straight-line distance = 18.6 km; median = 5.9 km). The localities closest to roads (<1 km away) represent only 38.4% ($n = 1411$) of the total. In sum, 2222 localities (60.5%) are closer to major water bodies than to roads during high water, compared with 2185 (59.5%) during low (Supplementary Note 1, Supplementary Tables 2–7).

To identify the geographical distribution of non-Indigenous localities prone to isolation during droughts, we selected those that are ≤5 km away from major water bodies (high-water season) and >5 km away from roads ($n = 1850$) (Fig. 1a). Most ($n = 1495$, 80.8%) are in the state of Amazonas, followed by 160 (8.6%) in Acre, 155 (8.4%) in Pará, 13 (0.7%) in Roraima, 11 (0.6%) in Rondônia, 10 (0.5%) in Amapá, and 6 (0.3%) in Mato Grosso. Assuming that an average human pace on forest trails is approximately 5 km per hour[38], settlers from these localities could face at least 1 h on foot (straight line distance) to reach the nearest roads. Even then, they might face constraints associated with the availability of vehicles, poor road conditions (even worse during the rainy season), and lack of connectivity. By relying on rivers and wetlands as paths for transport, they can access nearby communities, urban areas, and resources during average conditions. However, they might be more vulnerable during extreme droughts, when water levels fall and extensive floodable areas go dry.

Indigenous villages: Our results show that 92.2% of Indigenous villages ($n = 2325$) are <5 km away from the nearest major water body during the high-water season, dropping to 82.8% during the low-water season. An estimated 1971 (78.2% of total) of these are <1 km away from water bodies during high water, compared with 1736 (68.9%) during low water. The average shortest path is 1.3 km (high water) and 3.0 km (low water), with median values of 0.4 and 0.5 km, respectively. In contrast, just 44.8% of Indigenous villages ($n = 1131$) are located <5 km away from the nearest road (independent of road conditions), with the rest located 5–183 km away (average straight-line distance = 20.5 km; median = 7.9 km). Only one-third (30.1%, $n = 760$) of Indigenous villages are close to roads (<1 km away) (Supplementary Note 1, Supplementary Tables 8–13).

Our results indicate that 1671 (66.3%) Indigenous villages are closer to water bodies than to roads during high water, compared to 1584 (62.8%) during low water. Selecting Indigenous villages ≤5 km away from major water bodies (high-water season) and >5 km away from roads ($n = 1359$), we find that 755 (55.6%) are in the state of Amazonas, 225 (16.6%) are in Roraima, 152 (11.2%) in Pará, 125 (9.2%) in Acre, 16 (1.2%) in Rondônia, 13 (1.0%) in Amapá, and 73 (5.4%) in Mato Grosso (Fig. 1b).

Spatial and temporal perspectives on droughts

To evaluate the exposure of Amazonian communities to past extreme drought events, we collected and analysed digital news articles reporting the impacts of droughts from 2000 to 2020. We identified a total of 70 news articles, from which we extracted 142 statements reporting the effects of droughts and/or impacts on local populations. Of these, 117 statements reported some impact of droughts on the lives of local populations via effects on economic activities, whereas 26 only reported effects on water levels and/or the environment, such as increased fire occurrence or erosion along riverbanks due to low water levels. After accounting for each location mentioned in the statements (one statement could mention multiple locations), we documented 224 entries. Each statement could also include information about more than one category of impact (see Supplementary Data 1).

The years 2005, 2010, and 2016 were noteworthy in terms of the number of media articles reporting the impacts of droughts according to our analysis (Fig. 2). These years are recognised in the literature as the most affected by droughts since the beginning of the 21st century, with the effects reported in 2016 beginning with the drought in 2015[39–42]. Nevertheless, localised impacts of drier conditions were also registered via news outlets in other years (e.g., 2009 and 2019). Considering only media articles that mentioned specific months ($n = 69$), October was the month with the highest number of news pieces reporting droughts ($n = 19$), followed by September ($n = 15$) and August ($n = 11$). In terms of temporal distribution, the impacts of the droughts in 2005 and 2010 were mostly reported in the months of September, October, and November, while the 2015–2016 drought was more widespread, with news articles pointing to impacts across several months (Fig. 2).

Analysing the spatial distribution of these news articles, 2005 and 2010—two years marked by extreme droughts across the Amazon—registered substantial impacts on local populations, particularly in the central and western Brazilian Amazon. In 2005, we found news documenting impacts on rural areas of the Purus, and lower Negro River basins as well as southern tributaries of the Solimões River near the border between Brazil and Colombia. Most of this area was in Amazonas state, which has the highest number of localities and villages prone to isolation during droughts (Fig. 3). Amazonas is the largest state in the basin and contains the most pristine portions of the Amazon rainforest. The sub-basins reported in the news also covered the entire state of Acre.

Accounts indicate that the drought of 2010 might have affected over half of the Brazilian portion of the Amazon basin, covering the Madeira, Purus, Juruá, and Negro River basins, as well as the Solimões tributaries near the border between Amazonas state and Peru (Fig. 3). It is also the year with the largest number of collected news articles (Fig. 2).

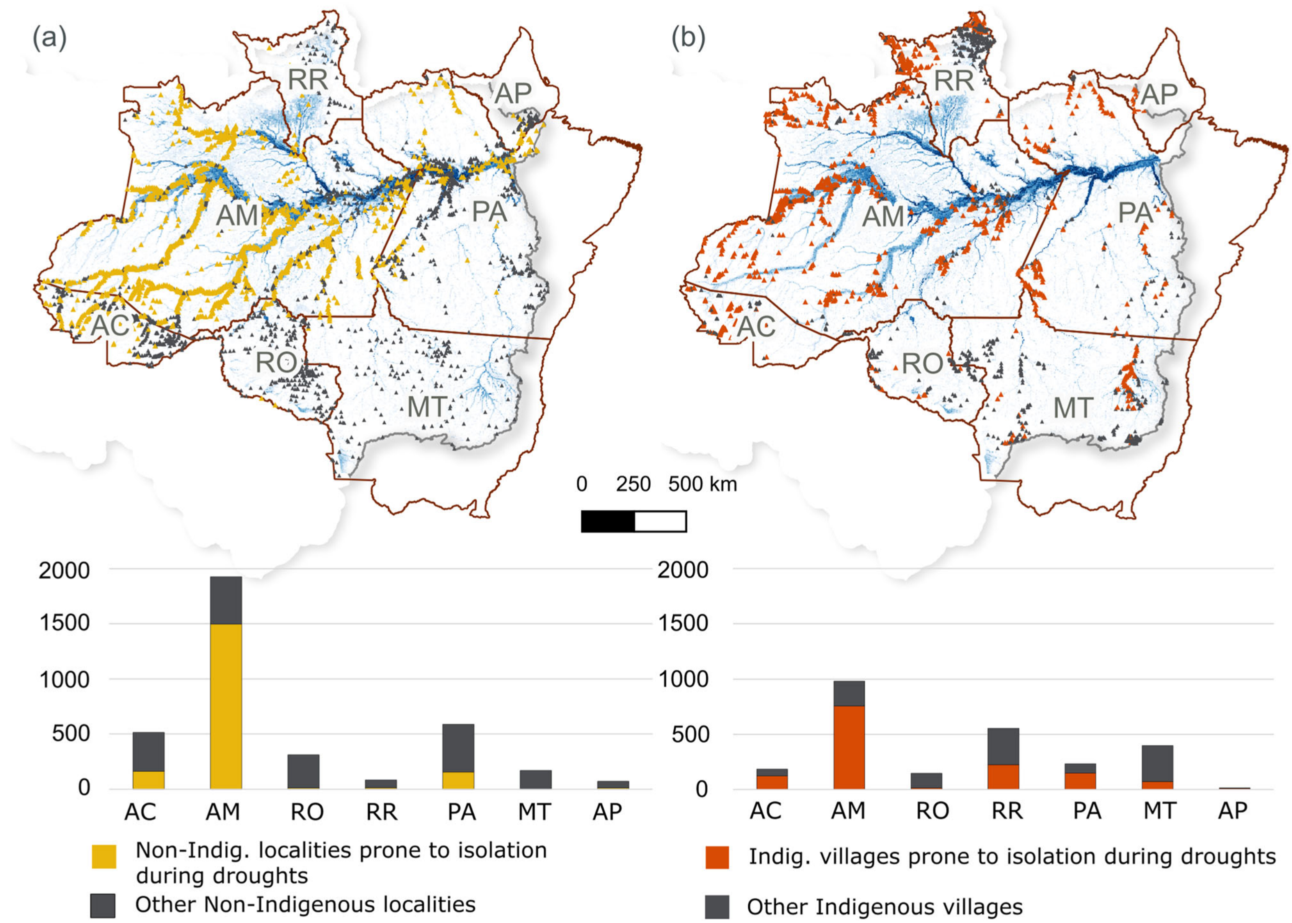


Fig. 1 | Human settlements are prone to isolation during severe droughts in the Brazilian portion of the Amazon basin. Yellow marks represent **a** non-Indigenous localities ($n = 1850$), and red marks represent **b** Indigenous villages ($n = 1359$) that are >5 km from roads and ≤5 km from major water bodies and are, therefore, considered prone to isolation during periods of severe drought. Dark grey marks represent the remaining localities ($n = 1409$) and villages ($n = 1162$). The distribution of settlements follows official datasets from 2021[36] and 2020[37], respectively. Brazilian Amazon state borders are delineated in brown, and states are labelled as follows: AC Acre, AM Amazonas, AP Amapá, MT Mato Grosso, RO Rondônia, RR Roraima. The basemap (blue) indicates the maximum inundated area[80]. Grey lines indicate the boundaries of the Amazon River basin in the Brazilian territory. Map design by Letícia Santos de Lima using QGIS version 3.28.6 from OSGeo, and Excel from Microsoft 365.

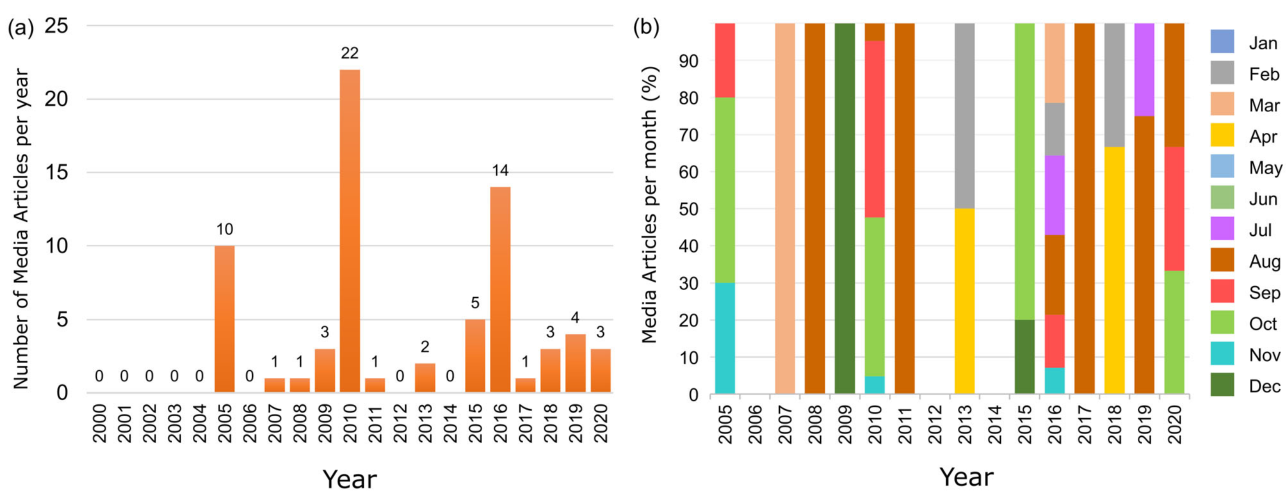


Fig. 2 | Distribution of media articles reporting drought impacts per year and month. The years 2005, 2010, and 2016 had the largest number of news accounts of drought impacts on the local population of the Brazilian part of the Amazon basin. October, September, and August are the months when most impacts were reported, although the dry period varies across different regions of the basin. **a** Bar chart showing the number of media articles per year, after our screening process. **b** Proportion (%) of media articles attributed to a given month each year of the study (the years 2000–2004 are omitted for simplicity, as we found no reports on drought impacts) (see Supplementary Data 1). Graphic design by Letícia Santos de Lima using Excel from Microsoft 365.

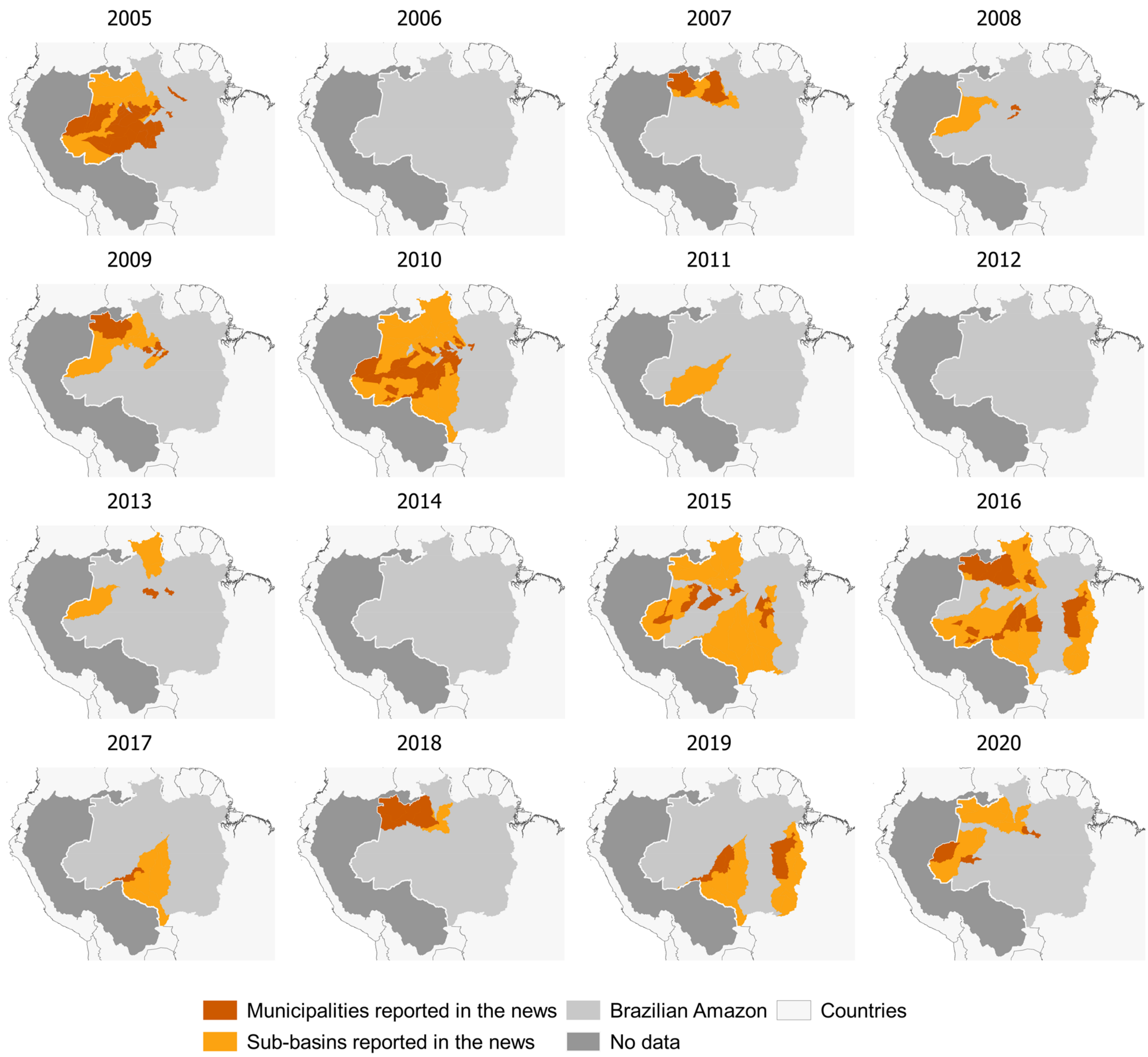


Fig. 3 | Spatial distribution of media accounts of drought impacts in the Brazilian portion of the Amazon basin. Collected news articles point to a large area affected by droughts, particularly in 2005, 2010, and 2015–2016. The years 2000–2004 are omitted here, as we found no reports on drought impacts in those years (see Supplementary Data 1). The darker grey area indicates the portion of the basin outside Brazil, which was beyond the scope of this paper. Administrative borders are provided by IBGE, and sub-basins are mapped by ANA (see Supplementary Table 1 for data sources). Map design by Letícia Santos de Lima using QGIS version 3.28.6 from OSGeo.

Our results also corroborate previous studies showing that 2015–2016 was a particularly strong drought[39]. Collected news accounts showed effects across the Amazon basin, including the Madeira, Xingu, Juruá, and Purus River basins. News collected from 2019 pointed to impacts in the northern Madeira and western Xingu River basins, while in 2020 impacts were mostly felt in the Negro and Juruá River basins, as well as some Solimões tributaries (Fig. 3). Notably, the Negro River basin made headlines in nearly half of the years from 2000 to 2020.

Hydrological records

To assess the hydrological conditions associated with reported drought impacts on Amazonian communities, we analysed data from 90 river gauges distributed across the affected area, as reported in media articles (Supplementary Note 2, Supplementary Fig. 2, Supplementary Data 2). We defined the hydrological year as beginning on December 1 of the previous year and ending on November 30 of the subsequent year (e.g., the hydrological year of 2016 is defined as starting in Dec 1, 2015)[43]. We adopted the long-term 80th percentile of the water level duration curve (P80) as the cutoff for low-water levels, counting the number of days in which water levels fall below this reference historical level in a given hydrological year. Levels below the reference represent the driest conditions experienced at a given river gauging station over the historical record.

Our results show that 2005, 2010, and 2016 saw the longest low-water periods at the analysed stations for the 2000–2021 interval (Fig. 4), coinciding with the highest numbers of media articles on local impacts. In these extreme drought years, the period with levels below P80 was ~36.8 days longer than the median for the whole historical time series, with some years exceeding 100 days below long-term P80 (median values for 2005 = 101 days; 2010 = 119.5 days; 2016 = 118 days). In terms of spatial distribution, a smaller dispersion around the median indicates more homogenous behaviour across regions. By that measure, 2005 and 2010 were relatively uniform events with more river gauging stations showing longer low-water periods. The years with the largest dispersion in terms of number of days below the reference were 2006 (StDev = 37.8), 2011 (StDev = 43.1), 2015 (StDev = 36.2), 2017 (StDev = 36.2), 2020 (StDev = 36.5), and 2021 (StDev = 42.7). The large dispersion values observed in the hydrological

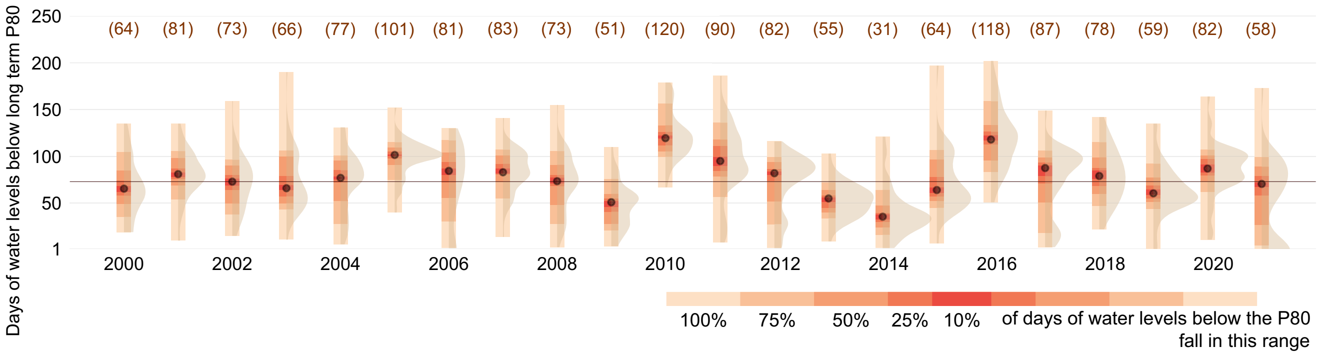
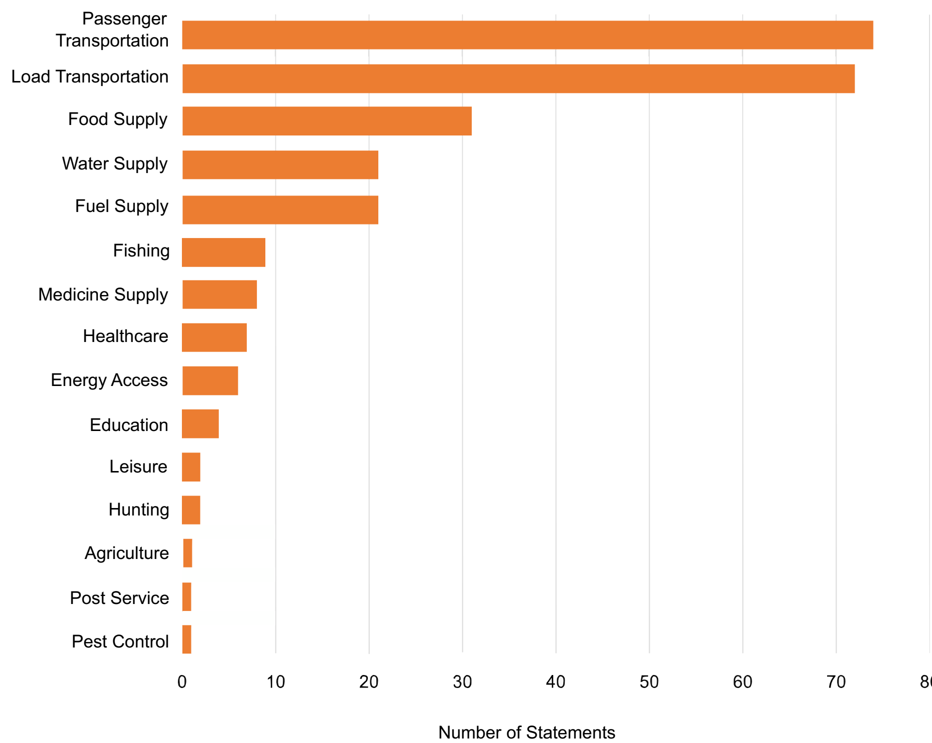


Fig. 4 | Distributions of days with levels below the long-term 80th percentile of the water-level duration curve (P80) across stations from 2000 to 2020. Low-water levels persisted for more than 100 days during severe drought years (e.g., 2005, 2010–2011, and 2016). The number of stations with available data under the selection criteria varies for each year (see Supplementary Data 2). Numbers in parentheses indicate the rounded median value (days per year). The bolded line highlights 73 days (20% of 365 days). Narrower distributions indicate that more stations show comparable duration of days with levels <P80. Year labels refer to the endpoint of hydrological years, which begin on December 1 of one year and end on November 30 of the following year. Graphic design by Francisco Eustáquio Silva, using R packages ggplot2, patchwork, and magrittr, based on the visualisation design scheme from Cédric Scherer's work[87]. Post-editing by Letícia Santos de Lima using Inkscape 1.3.2.

Fig. 5 | Media accounts of drought impacts categorised by type of activity. Passenger and load transport are the most affected activities during droughts, impacting access to goods and services. Orange bars indicate the total number of digital media statements extracted and categorised by the reported activity impacted by hydrological droughts (see Supplementary Data 1). Note that a single statement may report multiple types of impact. Graphic design by Letícia Santos de Lima, using Excel from Microsoft 365 and Inkscape 1.3.2 for post-editing.



years of 2006, 2011, and 2015 indicate the varied spatial response to the transition from/to the extreme hydrological droughts observed in 2005, 2010, and 2016, respectively (Supplementary Data 3).

A key finding of this study is that recent hydrological droughts have not only caused exceptional low-water anomalies across the Amazon basin but also dramatically increased the duration of the low-water period. The river gauge data shows over one additional month of low water levels during these severe droughts (Fig. 4), which has profound implications for aquatic fauna, freshwater ecosystems, and the riverine communities that depend on them. Today, riverine communities are being exposed to impaired conditions, with limited access to resources and services, both more frequently (i.e., recurrent events) and for much longer (i.e., during a given event) than in the past.

River flows in the Amazon basin are strongly influenced by El Niño and La Niña events[44]. However, the warming of the North Atlantic Ocean has also been associated with longer dry periods in the basin. For instance, the drought of 2005 was associated with a warmer subtropical North Atlantic Ocean[45], while the 2010 drought was connected to the combined effect of an El Niño, intensified by a subsequent warming of the Tropical North Atlantic[3]. The 2015–2016 hydrological drought, on the other hand, was mostly associated with an El Niño event, which produced a strong and widely distributed land surface warming during the months of October, November, and December of 2015[39]. Some of these drivers are also implicated in the extreme drought of 2023, which resulted in some of the lowest river levels on record for the central Amazon[10–12]. A recent article points to the combination of the transition phase from La Niña in late 2022 to El Niño in 2023 as the main climatic driver of this extreme drought[10], while a report suggests that, although El Niño played a role in this event, it was greatly amplified by precipitation and temperature anomalies attributed to global warming[46].

Consequences for inland water transport

Since hydrological droughts may directly impose navigational barriers, they have profound effects on mobility and transportation in the Amazon, as

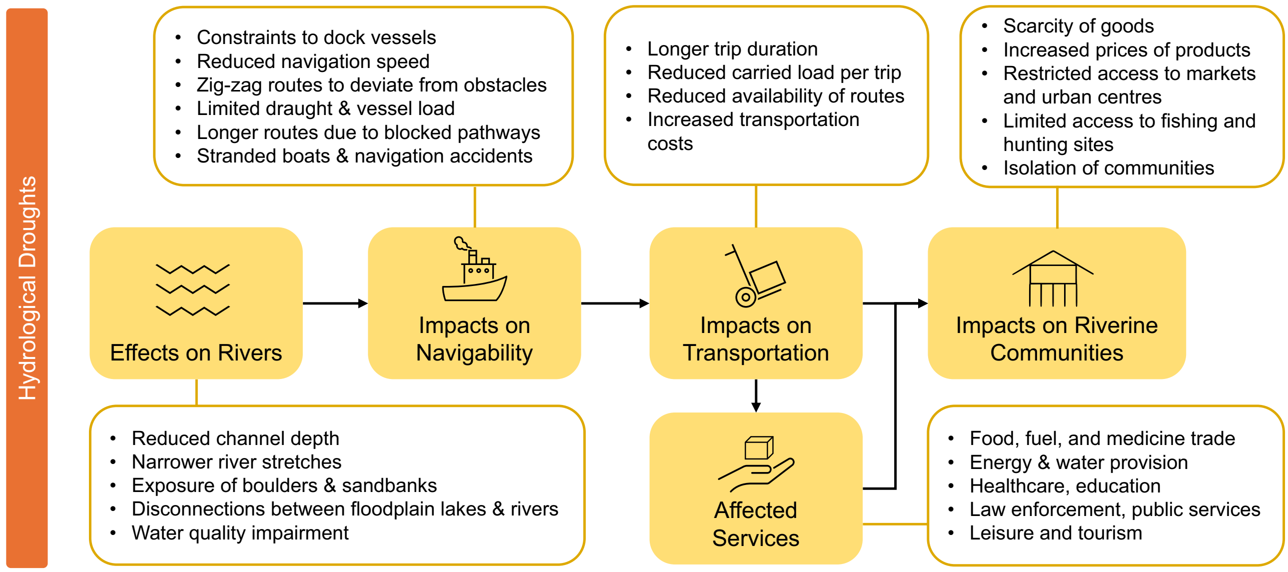


Fig. 6 | Cascading impacts of hydrological droughts on riverine communities of the Amazon basin. Reduced water levels change river morphology and sediment transport, exposing boulders and sandbanks, disconnecting river mainstems from floodplain lakes; and disrupting river navigability due to physical barriers. These constraints on inland water transport cause longer and more expensive trips, while reducing the total load capacity (either passenger load or merchandise) per trip. These impacts on transportation, in turn, affect the provision of goods and services, isolating riverine communities and impairing their quality of life. Conceptual diagram by Letícia Santos de Lima using PowerPoint from Microsoft 365, with design support from Markus Kreutzer. Clip-art icons are provided by Microsoft Office 365.

reflected by 97 statements (68.3%) out of 142 digital news statements catalogued in this study (Fig. 5). Of these, 25 statements addressed issues with passenger transportation only, while 23 were related to load transportation issues only. The other 49 statements mentioned both general transportation issues. This sectoral issue has important economic and social consequences. For instance, during the drought of 2005 and 2010, navigation was suspended in some sections of the Madeira River, as well as the upper and central Amazon River[41], both fundamental waterways for regional economies and for exporting commodities. While this problem was briefly mentioned in previous literature[21,25,26,41,47], we note the absence of systematic studies and policies focusing on this recurring climate risk.

Large sandbanks that prevent vessels from reaching harbours are a major navigational challenge brought on by low water levels. As sandbanks and boulders become visible, they narrow river courses and restrict access. As a result, boats and ships may resort to docking far from the riverbanks, making it difficult for passengers to reach land or forcing them to traverse enormous sandbanks on foot. Navigation speeds may be reduced as vessels search for safe routes, given the possibility of obstacles that could endanger people or damage boats (Fig. 6). The Brazilian Navy typically publishes warnings during droughts and enforces limits on nighttime navigation, maximum speed, and vessel draught values. Therefore, even if dry conditions do not completely block navigation on some rivers, they might lead to substantial delays and longer transit times. Difficulties in navigation, such as stranded boats and boat crashes were also reported in a previous study of riverine communities in the Solimões river[26].

Impacts on local populations

Our results indicate that hydrological droughts have cascading impacts on local populations of the Amazon, often triggered by their effects on river levels and resulting navigational constraints (Fig. 6). Reports indicated that droughts compromised access to essential goods such as food, fuel, and medical supplies, largely due to impacts on load transportation, particularly affecting riverine communities. Impacts were felt in the form of scarcity of goods, delays in product delivery, higher prices due to logistical constraints, and even the complete lack of products such as medicine in some regions. In total, there were 31 statements (21.8%) explicitly mentioning impacts on the food supply, including wholesale trade and retail of food, as well as grain trade. Logistical issues due to low water levels increased transportation costs and time, leading to an increase in food prices that affected local businesses and threatened food security. Remote rural areas are not only importers of food, but also essential providers of products like cassava, fish, nuts, and fruits, which supply nearby markets and urban areas. Transportation disruptions during low water thus restrict their ability to reach broader markets, often leading to losses or forcing local producers to offer products at lower prices. This result is consistent with previous research reporting production losses due to constraints on transport, as well as increased cost of merchandise[26].

Impacts on fuel supply were mentioned in 21 statements (14.8%), including impacts on wholesale trade and fuel retail markets associated with product scarcity and increased prices. Six statements mentioned issues with electric power generation. Since most rural communities and villages in the Amazon are not connected to the power grid, they rely on fossil fuels as their primary source of electric power (e.g., generators), leaving them in the dark when fuel provision is halted. This reduced access to fuel also limits mobility by boats and motorbikes. Medicine supply was also found to be affected by load transportation constraints. Eight statements mentioned medicine shortages due to supply restrictions during droughts. These statements coincided with the most intense droughts: 2005, 2010, 2015–2016.

Drought-related restrictions on passenger transportation had several consequences for the lives and livelihoods of remote rural communities in the Brazilian Amazon. Our analysis of news articles found several mentions of the isolation of communities for days or months due to low water levels. While searching for the word "isolated" in statements, we found 55 unique entries (38.7%). The isolation of communities was also briefly mentioned in scientific articles characterising these droughts[48–50]. Constraints on navigation affected access to many services, including health care ($n = 7$ statements), education ($n = 4$), leisure ($n = 2$), postal services ($n = 1$), and pest control ($n = 1$). Although Brazil has a robust public health system, access to healthcare has been a long-term issue in the Brazilian Amazon[22]. To benefit from health services, rural dwellers must reach nearby healthcare centres, which are usually only suitable for basic consultations, vaccines, and primary care. Accessing these centres may include terrestrial or inland water transport, but the latter is more common in remote areas. When droughts affect the rivers, not only are rural dwellers unable to reach the healthcare centres, but doctors, nurses, and dentists are incapable of accessing rural communities. These logistical issues also impair prevention measures, including control of disease vectors, as reported in one statement.

This is further aggravated by problems with the water supply, which were mentioned in 21 statements (14.8%). Surface water has various uses in the Amazon, although in remote rural communities, water supply for domestic use also comes from groundwater wells[47]. During droughts, surface and groundwater levels can decrease substantially, making it harder to meet household demand. River and lake margins become distant from households, requiring residents to walk long distances to obtain water for household uses. In addition, low surface water and groundwater levels can lead to substantial changes in water quality that may make water sources temporarily unsuitable for human consumption[51]. In some emergency situations, local government officials are compelled to deliver gallons of water to impacted communities.

Reports also show evidence of disease outbreaks due to degraded water quality and reduced access to potable water, as previously noted in the literature[25,41,47]. In our study, rotavirus outbreaks were reported in one media article during the 2005 drought. Previous studies showed evidence of an increase in hospital admissions in Acre state during the drier months of 2005, associated with both waterborne diseases and respiratory diseases due to air pollution from forest fires[41,52]. This is further aggravated by the effects of concomitant heat waves on human health[53].

For riverine communities, access to schools has always depended on predictable river conditions. School calendars are adjusted to the water levels to allow students to attend classes[20]. Whenever a drought occurs, basic education activities become compromised due to logistical disruptions, and schools may be forced to close for long periods while rivers are anomalously low. As reported in this study, extreme droughts prolonged low-water levels by as much as a month in many affected areas. This may have a particularly profound impact on youth from local communities, with potential long-term consequences in terms of mental health, food security, and poverty.

Only two statements reported disruptions to leisure activities, although many Amazon communities rely on river-based leisure activities and tourism (e.g., recreational fishing, navigation, and sightseeing) for income generation. Leisure/tourist vessels are regularly found in many towns and larger cities like Manaus and Belém. During droughts, ferries and recreational boats cannot dock in towns, suspending these services as well as the income and employment opportunities they afford.

News articles also documented drought-related disruptions to environmental governance and public services. For example, low water levels and subsequent constraints on passenger transportation have reportedly hindered data collection during Brazil's decadal population census in 2010. According to one statement, low water levels may even have affected elections by preventing citizens from reaching their electoral posts on election day. Moreover, limited river navigation compromised environmental law enforcement (e.g., against deforestation, hunting, or illegal logging) during droughts, as reported in one media article.

Aside from less effective enforcement, endangered species may become more vulnerable due to intensified hunting during droughts. With low water levels, animals such as manatees, freshwater porpoises, and turtles become easy prey for hunters, as reported in one news article. Likewise, issues with fishing were mentioned 9 times in our analysis. As with hunting, some media articles reported that drier conditions can facilitate fishing when fish get trapped in shallower water bodies, which was also noted in previous studies[20,21,47]. This situation can lead to overfishing in some circumstances.

On the other hand, low water levels can disrupt connections between the main stem of the river and floodplain lakes, making it difficult to access fishing sites[26]. Some statements reported that fishing was harder during droughts since there was high fish mortality associated with high water temperatures. Another statement reported the loss of shoals due to low oxygen levels in the water—a direct consequence of low water levels and higher temperatures, which increased organic matter and oxygen consumption and reduced the quality of fish habitat. Previous studies confirm that droughts can dramatically reduce fish stocks[21,23,26,47] and change species distributions for long periods after an extreme event[20,24,25,54], which may have serious consequences for food security, considering that fish is the main protein source for most riverine communities in the Amazon[55].

Policy implications

Over the last several decades, the population of the Amazon basin (both rural and urban dwellers) has been exposed to numerous severe weather events, including droughts and floods. These extreme events have already become more common than in the past and are expected to increase in frequency, intensity, and duration over the near-term[6,10]. Our results show that past extreme droughts caused low water level periods to last about a month longer than usual, with cascading impacts on local populations. Rural settlements near rivers and their floodplains—particularly Indigenous peoples and "ribeirinho" communities—will be more vulnerable to such extreme events, given their distance from urban centres where vital services are offered[49] and reliance on rivers and wetlands for their livelihoods and mobility. While previous studies have described the potential exposure and sensitivity of some Amazon riverine communities to droughts[20,25,26,47], this study contributes to the literature by providing a spatiotemporal perspective of the impacts of hydrological droughts on their lives and livelihoods, as well as a detailed assessment of the cross-sectoral cascading effects.

Remote rural communities in the Amazon are often overlooked in public policies and climate adaptation strategies. Understanding the growing challenges they face is a critical step towards devising more inclusive adaptation and emergency response strategies. Currently, disaster management in Brazil is performed by civil defence agencies operating at municipal and state levels, with emergency funds provided by the federal government through the National System for Civil Protection and Defence[20,56]. Historically, disaster-relief policies related to droughts have been directed to the driest region of the country (e.g., the "sertão" region of NE Brazil[57,58]), since extreme drought events in the Amazon were relatively infrequent. As a result, actions to cope with recent droughts in the Amazon have been reactive rather than proactive and grounded in preparedness and adaptation principles. These emergency strategies are failing to provide sufficient, timely support for affected communities. Coordinated efforts to address climate-driven disasters have only recently become a focus of Brazil's Interministerial Committee on Climate Change[59], following years of abandonment of the initiative by the Bolsonaro administration. Still, progress towards long-term, coordinated, cross-sectorial strategic planning is in its infancy.

The recent 2023 drought[10–12,46] serves as a stark reminder of how unprepared policymakers are to deal with Amazon extreme events. Several organisations (Brazilian and international bodies) warned of the upcoming El Niño and the unusually high ocean surface temperatures months before the onset of the drought[60–62]. Still, decisive reactions from the government only came in response to the surge of news reporting the death of hundreds of dolphins and tons of fish[13] after rivers levels dropped to historic lows, as well as media coverage on the isolation of communities. Emergency efforts focused on food provision and cash payments for families, as well as a planned river dredging effort to make navigation viable at specific river stretches[11,12]. Although important, these actions are not enough to address the immense challenges posed by ongoing droughts in the Amazon.

Large-scale assessments like this study, in conjunction with local case studies[63], are fundamental for mapping hotspots of vulnerability and evaluating the specific types and magnitude of impacts felt by the local population, providing essential information for policy design. Our research reveals that the majority of non-Indigenous localities and Indigenous villages prone to isolation during severe droughts are clustered in Amazonas state, although other states have also reported serious drought impacts. Such spatially explicit information may assist in prioritizing efforts and resources in areas with the greatest number of exposed communities.

Regarding accessibility for rural villagers, some local politicians claim that road building is the solution to prevent the isolation of communities during droughts. However, roads in the Amazon are a primary driver of deforestation and forest degradation, as demonstrated by an extensive literature[64–69]. Large-scale deforestation promotes wildfires and leads to changes in the hydrological cycle that could further alter rainfall regimes in the Amazon, aggravating droughts by increasing the number of water deficit days during the dry season[70–74]. Moreover, deforestation and forest degradation accelerate erosion processes[75], increasing siltation in rivers, which can further reduce river channels, produce more sandbanks, and hence negatively affect navigation. Finally, road building and paving without proper planning and mitigation measures frequently lead to economic losses and social impacts on local communities[69].

Conventional emphasis on single or direct impacts is not enough to design effective policies to cope with and adapt to hydrological droughts in the Amazon. Our study highlights several processes where cascading impacts from droughts can unfold, exacerbating vulnerability of remote rural communities by affecting several interconnected aspects of their livelihoods. Robust policy design to promote mitigation of and adaptation to droughts will benefit from a thorough understanding of these compounding and cascading impacts, their interactions[33], the affected economic sectors, and their multidimensional effects on the quality of life of remote communities. In this regard, further studies integrating the effects of hydrological droughts, heatwaves, forest fires, and agricultural droughts will be critical to inform appropriate responses.

While addressing the consequences of droughts in the Amazon is not simple, efforts towards long-term mitigation and adaptation planning might benefit from an inter-sectorial dialogue that includes civil society and support from robust science. To that end, a transdisciplinary approach that combines insights derived from natural and social sciences—as well as traditional knowledge from Amazonian communities and local perceptions of environmental change—may be the most efficient and socially just way to tackle this complex issue. When designing public policies to address extreme droughts, local knowledge is fundamental for understanding how extreme events affect communities[76,77], as well as identifying potential solutions and opportunities for adaptation[78]. Current practices by these communities can serve as a starting point for ground-based strategies to increase resilience and reduce vulnerability. Only through community consultation and involvement can policies be effectively tailored to avoid common systemic failures that are typical of top-down approaches applied with a limited understanding of local conditions[49].

This study is limited to the Brazilian part of the Amazon basin, but further studies including all Amazonian countries could provide a valuable basin-wide perspective and may reveal geographical differences in the impacts felt across the region (e.g., the Andean Amazon, and the savannas of the Moxos plains). Hydrological droughts might play out differently for local communities from these diverse environments and a broad understanding of these differences is important to inform decision-making and identify effective strategies to reduce local vulnerability. Moreover, adaptation policies should consider the interconnectedness of this transboundary river system, which likely requires cross-national approaches that span all Amazonian countries. Finally, spatially distributed vulnerability assessments that include both current conditions and future scenarios are vital inputs to drought early-warning systems, which can support governments in more efficiently directing emergency actions.

Methods

We combined three approaches to understand the impact of extreme droughts on communities located in the Brazilian part of the Amazon basin whose boundaries are defined according to the Brazilian Water Agency[79]. First, we assessed the dependence of local populations on inland water transport by analysing the spatial distribution of human settlements and their relative distance to major water bodies and roads. Second, we analysed digital media outlets and screened for news articles reporting the impacts of droughts on local populations. We extracted statements that reflected impacts on the local population and categorised them. Finally, we mapped these statements to nearby river gauges, which we then used to analyse the historical time series of river levels and quantify the low-water thresholds associated with local drought impacts over the historical period.

Access to water bodies and roads

We analysed the shortest straight distance from non-Indigenous localities and Indigenous villages to the nearest major water body during high- and low-water seasons. Here, we define major water bodies as floodable areas, mapped at 1-km spatial resolution, as estimated through two raster maps of the minimum and maximum inundation extents in the Amazon[80]. We then compared them with the shortest distance to roads (paved or unpaved) based on a combination of road datasets from the "Sistema Nacional de Aviação" (SNV) for official roads as of 2020[81], and the "Centro de Sensoriamento Remoto" (CSR/UFMG)[82] and IMAZON[83] for unofficial roads as of 2016 and 2012, respectively. Two datasets were used to map human settlements: non-Indigenous localities (including remote rural settlements, villages, and cities) derived from "Bases Cartográficas Contínuas" from the "Instituto Brasileiro de Geografia e Estatística" (IBGE) as of 2021[36] and Indigenous villages from the "Fundação Nacional dos Povos Indígenas", updated in 2020[37]. After selecting only point locations occurring inside the Amazon basin, we converted the inundation (raster) maps into point data layers where each point represents the centre of a given pixel, with data values indicating the number of models that agree with the mapped wetland extent. We then used the "v.distance" function from GRASS in QGIS 3.28.6 to calculate the "minimum distance to the nearest feature". From this data, we calculated basic statistics for straight-line distances, considering the agreement of at least 2 models for the maximum inundation map and 1 model for the minimum inundation map. As the inundation map excluded some portions of the low Amazon basin, 101 settlements were left out. For these points, the procedure to calculate the nearest distance to water bodies was different. We merged two datasets: hydrography from HydroRIVERS[84], and water surface from the "Instituto Nacional de Pesquisa Espacial"[85]. After that, we used the same "v.distance" tool to calculate the nearest distance to water bodies. While we are aware that this procedure makes it impossible to differentiate low- and high-water seasons for these points, the approach allowed us to maintain those settlements in the study rather than exclude them (see Supplementary Note 1).

Digital media outlets

Data collection of articles from digital media outlets was performed using the Google Search engine. To collect the results, we employed the software platform Apify (https://apify.com/), which collects the URLs returned by specific queries into the Google Search engine. We set the scraper to return the first 100 search results for the query "amazônia seca navegabilidade" (amazon, drought, navigability) and "amazônia seca isoladas" (amazon, drought, isolated). Probably due to pagination issues, the scraper ended up collecting a little more than 100 URLs for each query: 113 for the first one (performed on 30 July 2020) and 117 for the second one (performed on 2 September 2020). A third data collection was performed on 27 January 2021 to consider only news from 2020. In total, the search returned 80 additional URLs for the query "amazônia seca navegabilidade" and 84 for the query "amazônia seca isoladas".

News articles collected from digital media outlets were listed in a spreadsheet and manually processed following these steps: (i) verification of each web link; (ii) manual screening and reading; (iii) application of exclusion criteria; (iv) identification of basic metadata—including year, month, and location of the event; (v) extraction of statements mentioning impacts to communities; (vi) categorisation of reported impacts; (vii) identification of the affected river and associated basin; (viii) identification of administrative boundaries; and (ix) identification of the closest river gauging stations via "Hidroweb"[86]. When a single digital media article included more than one statement of impact, we treated them separately.

We adopted the following exclusion criteria: media articles related to books, dissertations, theses, and scientific papers; news about ongoing research; news that did not specify year and/or location; news without information on drought impacts; corrupted links; reports without data on water levels and/or navigation issues related to droughts; repeated entries. If the news piece mentioned the municipality or the river segment/sub-basin, we considered the location sufficient for inclusion. Pieces with a larger scope and no specific location information were discarded.

We produced two final tables with the digital media statements: one where each statement corresponds to a unique entry (i.e., one line in the table) and another where each line corresponds to a unique combination of statement and location. That is, we added an extra line in the database and replicated information about the entry every time the same entry was related to more than one location (Supplementary Data 1). This latter approach was used to produce maps indicating the spatial distribution of impacted locations.

We adopted a categorisation scheme based on the economic activities/services affected by droughts, including the following 15 categories: passenger transportation, load transportation, fuel supply, water supply, food supply, medicine supply, energy access, agriculture, healthcare, education, hunting, fishing, postal services, immunisation and pest control, leisure.

Hydrological analysis

To evaluate the drought events occurring from 2000 to 2020, we overlapped the map of municipalities and basins; locations of the news accounts of annual droughts impacts (Fig. 3); and a map of the Brazilian river gauging stations network[86]. We then selected the gauging stations indicated in this overlap and neighbouring regions to take a closer look at river levels during high-impact drought events from 2000-2020. After excluding 10 gauging stations under the direct influence of large hydropower dams (Santo Antônio, Jirau, Belo Monte, Balbina) (see Supplementary Note 2), we extracted the complete time series of water level for each remaining station. We then filtered out gauging stations with time series shorter than 15 hydrological years and eliminated years with data gaps greater than 10% per month, leaving a final dataset of 90 stations whose records we analysed. The time series for each station varied in length—that is, although our analysis started in the hydrological year of 1978, not all stations began collecting data that year and several were deactivated after some time. Based on our selection criteria, the maximum number of gauging stations with available data was reached in 2005–2006 ($n = 83$), while the minimum was in 1978–1979 ($n = 39$) (see Supplementary Data 2). As a reference for low water levels, we identified the lowest water level that is exceeded 80% of the time (P80) over the complete time series available for each gauging station. We then counted the number of days in each hydrological year (from 2000 to 2021) that water levels reached values below this long-term P80 (see Supplementary Data 3). We computed this and developed Fig. 4 using R and a data visualisation design adapted from the work of Cédric Scherer[87].

Limitations of this study

Spatiotemporal assessments of the societal impacts of climate change are inherently challenging, given the need to combine data from various sources, each with its own limitations and uncertainties. This is particularly challenging in data-scarce regions, including the large and complex river system of the Amazon basin. Our study faced limitations on several fronts. First, assessing distances to navigable water bodies proved arduous due to the extreme flood pulse dynamics of the central Amazon river-floodplain, as well as limitations on the availability of accurate modelling of hydrology and mapping of flooded areas with high-resolution sensors. To address this, we opted to use the nearest distance as a proxy, relying on the best available intercomparison map of inundation extent[80], despite uncertainties and constraints on spatial resolution. Second, assessing the distance to roads in the Amazon is equally complex due to the scarcity of reliable, updated information on roads, particularly unpaved or unofficial ones. Here we opted to merge the available datasets to partially overcome this difficulty. We recognise that this approach may generate errors such as duplicate vector lines or overlaps and have tried our best to minimise these issues where possible (see Supplementary Note 1).

Third, the time series of river stages (water levels) for Amazon gauging stations have frequent data gaps, which may impair our analysis of water level duration curves. In this study, we adopted a conservative approach, considering only more complete series, which limited the number of stations available for analysis (see Supplementary Note 2). Finally, the use of media articles enables assessments of the spatiotemporal distribution of impacts and offers opportunities for inter-sectoral impact analysis in a data-scarce region[28]. However, it also brings its own challenges. In media articles, statements from affected individuals are selected and presented in a manner suitable for journalistic purposes, often leaving out much useful information that could serve research. Moreover, the absence of news articles does not necessarily imply an absence of impacts but rather reflects the unique conditions, timing, and interest of the media in covering specific regions or events. Lastly, the use of web scraping has some shortcomings since it limits the volume of searched articles and may not identify all relevant articles.

Data availability

The data that support the findings are publicly available in "CORA.Repositori de Dades de Recerca" at https://doi.org/10.34810/data1390. These data include water level records, data summary of river gauging stations, content analysis of media articles and selected statements as well as their corresponding sources. All data used in this study were derived from content that was free of charge at the time of collection (either from official governmental sources, publications and articles without paywalls, or from non-profit organisations). Sources are available in the links provided in Supplementary Table 1 in this document, and Supplementary Data 1 (via the repository link above).

Code availability

The R code used to process the hydrological data in this paper is available in "CORA.Repositori de Dades de Recerca" at https://doi.org/10.34810/data1390.

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Author contributions
Santos de Lima L.: research design, conceptual framing, literature review, data collection, data analysis, writing. Silva F.E.: research design, data collection, development of analysis tools, data analysis. Anastácio P.R., Kolanski, M.M.P., Pereira, A.C.P., Menezes, M.S.R.: literature review, data collection, data analysis. Cunha E.L.T.P: data collection, data analysis, language editing. Macedo, M.N.: conceptual framing, literature review, data analysis, writing, language editing.

Competing interests
The authors declare no competing interests.

Inclusion and ethics statement
This study has been designed and conducted through a collaboration between a Spanish-Catalan university, a Brazilian university, and a U.S.-based research centre. The research team is led and co-led by Brazilian women, and it gathers researchers from various career stages following a proactive effort to highlight the merits of early career female researchers from the Global South.

Additional information

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Correspondence and requests for materials should be addressed to Letícia Santos de Lima.

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