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Amazon severe drought in 2023 triggered surface water loss

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Abstract

The Amazon underwent a severe austral springtime drought attributed to the onset of El Niño in 2023 and the warmer North Atlantic, Indian, and North Pacific Oceans. The Amazon rivers, lakes, small streams, wetlands, and reservoirs quickly lowered their water level below historical records due to decreased rainfall and warmth in the region. Based on satellite imagery, this study presents the first estimate of the water loss extent in the 4.2 million km^2 of the Brazilian Amazon biome (∼62% of the Amazon total biome) in 2023. We estimated the loss of 3.3 million hectares of surface water relative to 2022, with an overall accuracy of 92%. The surface water losses were concentrated in the states of Amazonas (59.4%) and Pará (25.5), adding up to 2.8 million hectares. The warmer and drier climate in the region affected the main rivers in the Amazon. Among them, the Solimões, Negro, Purus, Acre, and Branco suffered extreme drops in their levels in some regions, resulting in a high negative impact on the aquatic biodiversity, yet estimated only in local areas. A total of 1.14 million hectares of surface water loss (i.e. 35%) was detected within protected areas territories, affecting extractivist, indegenous, African-Brazilian, and fishing and traditional communities. Proximity analysis revealed that 75% of the 2023 surface water loss was within 25 km of small towns, 48% and 65.8% at 50 km from indigenous villages and urban areas, respectively. Our results reinforce people's vulnerability to climate change, anticipating a plausible adverse impact scenario in the Amazon region and urging solutions to adaptation and mitigation. Therefore, an integrated monitoring system based on climate and water dynamics from satellite and ground stations is necessary to improve understanding of the problem for timing response of climatic change negative impacts.

1. Introduction

The mainstream media responded with alarming coverage of the 2023 surface water loss impacts on communities and biodiversity (Kelly and Spring 2023), pointing out the worst decline in the Amazon River water level in over a century (Espinoza *et al* 2024). According to the Brazilian Geological Survey, the level of the Madeira River in Porto Velho was the minimum observed in the 56 year of measurements. On October 26, the Negro river recorded the lowest level in 121 years since measurements began (12.61 m) (ANA (Brazilian national water and basic sanitation) 2024). Several rivers across the Amazon Basin also recorded levels lower than the historical normal, with five stations recording the minimum values and another nine stations recording values lower of extreme drought or drought thresholds (Espinoza *et al* 2024).

The drought and warmth, followed by the lowering of several rivers, streams, lakes, and reservoir levels, caused the Amazonas government to decree a state of emergency in 95% of its municipalities, where more than 500 thousand people were affected, and communities were isolated. The Amazon's drought also isolated and affected people's welfare (Santos de Lima *et al* 2023). Other negative impacts have been detected outside the Amazon region, in central South America, due to the dangerous combination of dry-warm conditions reflecting in wildfires and smoke pollution and effects on regional ecosystems (Marengo *et al* 2024). The drought also negatively affected the economy and welfare. Agriculture and smallholder farming losses, powerlines had to be cut off, and fluvial transportation was disrupted (Kelly and Spring 2023). The water loss and the increase in water temperature of shallow isolated lakes are suggested to cause the death of aquatic biodiversity in the Amazon. Local organizations have reported that 250 Amazon River dolphins died in the Tefé (155, 10% of the estimated population) and Coari (98) lakes in the Amazonas state (Marmontel *et al* 2024). Finally, as a previous study has shown (Gatti *et al* 2021), low precipitation and warmth can lead to tree mortality in the Amazon, releasing more carbon dioxide into the atmosphere.

As shown above, several studies have been conducted to estimate the negative impact of the 2023 severe drought in the Amazon. Yet, there is no estimate of the extent of surface water loss associated with this event. Therefore, the objective of this study is to present the first estimate of the extent of the surface water loss in the 4.2 million km^2 of the Brazilian Amazon biome ($\sim$62% of the Amazon total biome) in 2023 using Sentinel 1 and 2, and Landsat imagery. The surface water loss map allowed us to identify surrounding human settlements, indigenous villages, cities, and protected areas (PAs) affected by the 2023 drought. We also discuss the link between climate change and deforestation and the need to alleviate the adverse impacts of likely future droughts.

2. Methods

2.1. Study area and hydrological data

Encompassing the boundaries of eight South American countries, the Amazon biome possesses the largest tropical rainforest in the world. Its ecological roles are essential to maintaining the global climate's balance, the planet's rich biodiversity, South America's hydrological cycle (Davidson *et al* 2012), and the Amazonian people's ancestral home (Couto-Silva *et al* 2023). Our study area focused on 4.2 million km^2 of the Brazilian Amazon biome, encompassing $\sim$62% of the Pan-Amazon extension (figure 1). Compared to Brazilian territory, the Amazon biome makes up 49.5% of the country.

Figure 1 also shows the Hydro-Telemetry stations managed by the Brazilian National Water Agency and Basic Sanitation (ANA (Brazilian national water and basic sanitation) 2024). We used eight streamflow stations (figure 1) to acquire river-level data, considering consistency in the time-series dataset and avoiding failed, no-data, or out-of-operation stations. The data were analyzed with descriptive statistics to compare the minimum water level in 2022 (without El Niño influence) and 2023 (with El Niño influence) and to correlate with surface water loss estimates from satellite data.

2.2. Satellite image processing

We used Sentinel-1 and Sentinel-2 images to detect surface water in 2022 and 2023. We selected 4171 Sentinel 1 scenes and 22 353 Sentinel 2 in 2022 and for 2023, 4147 and 24 882, respectively. Our analysis involved comparing the monthly median mosaics of these two types of satellite data to identify and map the loss and gain in surface water in 2023 relative to the previous year. We mapped with Sentinel-2 surface water at the sub-pixel scale using spectral mixing analysis (SMA) (Souza Jr *et al* 2005) to estimate the abundance or proportion, within a pixel, of the purer spectral response (i.e. endmembers) of green vegetation, non-photosynthetic vegetation, soil, shade, and cloud. The Sentinel-2 visible, near, and mid-infrared spectral bands were selected to apply the SMA model.

The result of SMA is a set of compositional bands of the spectral endmembers modeled with an estimation of their abundance. Water behaves as a dark object in the Sentinel-2 images (i.e. low reflectance) and, therefore, has a high percentage of Shade endmember within the pixel. Edges of lakes, rivers, and wetlands form mixed water (i.e. high Shade) with vegetation and soil in the pixel. Therefore, the SMA model allows water to be detected in complex environments with mixed soil and vegetation (Souza *et al* 2019). The pixel compositional images from SMA were inputs to fuzzy logic empirical rules to calculate a water membership index ranging from 0 (low water membership) to 1 (high water membership) (figure 2). This SMA technique has already been successfully applied to Landsat imagery for detecting water surface loss in complex environments such as floodplains and flooded fields, described in detail elsewhere, including the accuracy assessment protocol for mapping surface water (Souza *et al* 2019). Code implementation of the

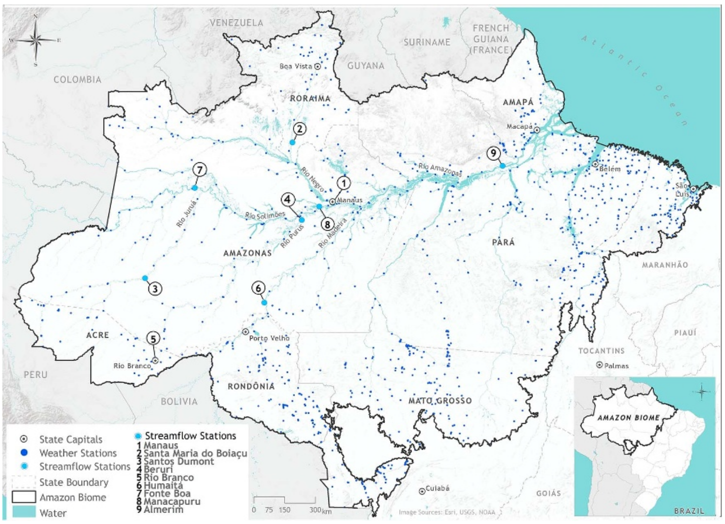

Figure 1. Brazilian Amazon biome and location of streamflow stations used to assess water levels of the main rivers affected by the 2023 drought. The Hydro Telemetry streamflow data can be assessed at this link.

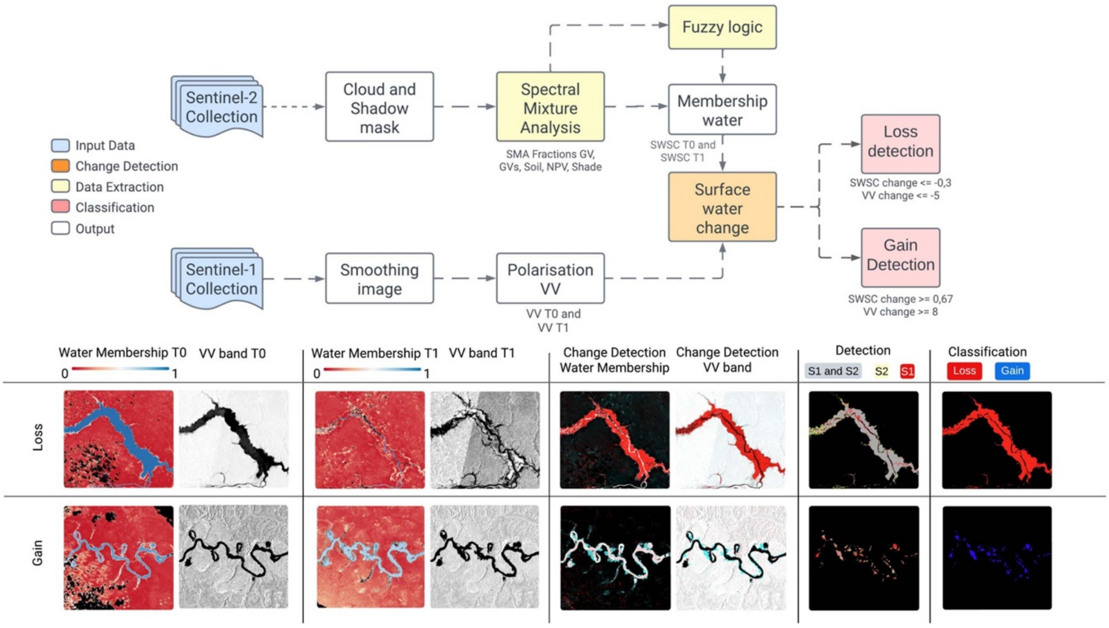

Figure 2. Remote sensing workflow to detect surface water change between 2022 and 2023 (i.e. loss and gain) using Sentinel-1 and Sentinel-2 satellite imagery and examples of surface water change detected with both sensors.

SMA model in Google Earth Engine (GEE) is also available (Souza *et al* 2024). We have also used data from the Hydro-Telemetry stream stations (figure 1) to assess the estimates of surface water loss relative to river level.

Because clouds block sentinel-2 optical data, we also used Sentine-1 imagery to get ground observation to detect surface water change under cloudy conditions. We processed Sentinel-1 VV Polarization bands in the same period analyzed with Sentinel-2, i.e. 2022 ($t0$) and 2023 ($t1$), using monthly mosaics and then performed the change detection analysis. Next, we applied an empirical calibration to detect surface water loss and gain and no surface water change. Areas with Sentinel-1 change $\leqslant -5$ dB and Sentinel-2 $\leqslant -0.3$ were classified as surface water loss. Surface water gain thresholds were Sentinel-1 change $\geqslant 8$ dB and Sentinel-2 $\geqslant 0.67$. With visual interpretation, we removed the false positive change detection at the estuary of the Amazon region because sediment concentration lowered the Sentinel-1 and Sentinel-2 change signals. Figure 2 summarizes the methodological steps described above. We generated the reference data to estimate the change detection accuracy using 1200 stratified random samples and PlanetScope imagery.

Table 1. Ancillary data used in the surface water loss spatial analysis.

Data Layers	Source	Year	Access
Small towns	IBGE	2021	link
Indigenous villages	FUNAI	2022	link
African-Brazilian Quilombo	INCRA	2022	link
Urban	MapBiomas	2022	link
Conservation unit	CNUC	2023	link

Supplementary material (SM) provides a detailed accuracy assessment protocol for detecting surface water changes between 2022 and 2022.

2.3. Surface water loss spatial analysis

We conducted several spatial analyzes combining the 2022–2023 surface water loss maps. The ancillary data used in the spatial analyzes are presented in table 1. We used the Brazilian Institute of Geography and Statistics (IBGE) small town maps, Indigenous villages, and urban area maps to estimate the extent of water surface loss from these territories in 2022–2023. To do this, we first calculated a distance map for each type of territory. The spatial analysis was carried out in GEE using the distance function to create distances of 1 km from the territory maps (table 1). Then, we cross-tabulated the distance maps with the total surface water loss mapped in 2022–2023 to estimate the correlation of water loss with distance from these locations.

Next, we intersected our 2022–2023 water surface loss map with the Amazon municipalities from the IBGE database (table 1). Again, we used the GEE to estimate the extent of surface water loss in each municipality. Finally, we conducted the same spatial analysis applied to municipalities to assess surface water loss in PAs (i.e. direct and indirect use of Conservation Units (UC) and Indigenous Lands, and African-Brazilian Quilombos in the Amazon. We compiled the databases of UCs from CNUC, indigenous lands, and Quilombos from INCRA (table 1).

3. Results

The total surface water loss in 2023, relative to the same period in 2022, reached 3.3 million hectares (figure 3). The overall accuracy in detecting surface water in this period was 92%, with 83% and 71% of producer's and user's accuracy for water loss, respectively (SM table 3 and SM figure 4; more details are available in the SM section 1). The state of Amazonas, in the western Amazon, lost 1.96 million hectares (59.4%) of surface water, followed by Pará (841.2 thousand hectares; 25.5%) and Roraima (333.2 thousand hectares; 10.1%). The remaining six states of the Brazilian Amazon lost 5.0% of surface water (i.e. 166.7 thousand hectares). Eighty percent of the surface water loss (i.e. 2.74 million hectares) occurred in 34 municipalities. Amazonas state had 22 municipalities (51%; 1.70 million hectares of surface water loss), with five in the top ten ranking of surface water loss. In Amazonas state, Barcelos was the municipality most affected with 401.4 thousand hectares of surface water loss, i.e. 12.1% of the total surface water loss in 2023 in the Amazon biome. Pará state had four municipalities in the top ten surface water loss ranking (757.2 thousand hectares; 23%), concentrating in its northwestern region. The municipality of Caracaraí (215.1 thousand hectares) in Roraima state was the top two in the surface water loss ranking, mainly affecting the *várzea* wetlands.

The geography of the municipalities highlights the region affected by surface water loss in 2023, which concentrated mainly along the Amazon and Negro rivers, in the center north portion of Brazil's Amazon biome, mainly in the Amazonas and Pará state. However, the surface water loss also reached out to the mouth of the Amazon River on the Atlantic coast (figures 3 and 4). Figure 4(A) highlights the location of the municipalities most affected by surface water loss (i.e. >5000 hectares). However, the drought and warmth affected the Brazilian Amazon biome entirely to some extent, resulting in some degree of surface water loss. For example, municipalities in Pará, located at the Marajó Island at the mouth of the Amazon River, also registered a loss of surface water in 2023 (figure 4(A)).

We also assessed the impact of surface water loss PAs, which include Indigenous Land and sustainable and direct and indirect use PAs called UC (figure 4(B)). A total of 1.14 million hectares of surface water loss (i.e. 35%) was detected within PA territories. Most surface water loss happened in CUs of direct use where traditional communities live, reaching 810 thousand hectares, 24% of the total surface water loss in 2003. Indigenous Land lost 116 thousand hectares of surface water loss (3.5%), and indirect use CUs lost 189 thousand hectares (5.7%). The African-Brazilian Quilombo areas lost 27.7 thousand hectares (<1%) of surface water loss, a conservative estimate since several Quilombos are not officially demarcated (Smikle 2023).

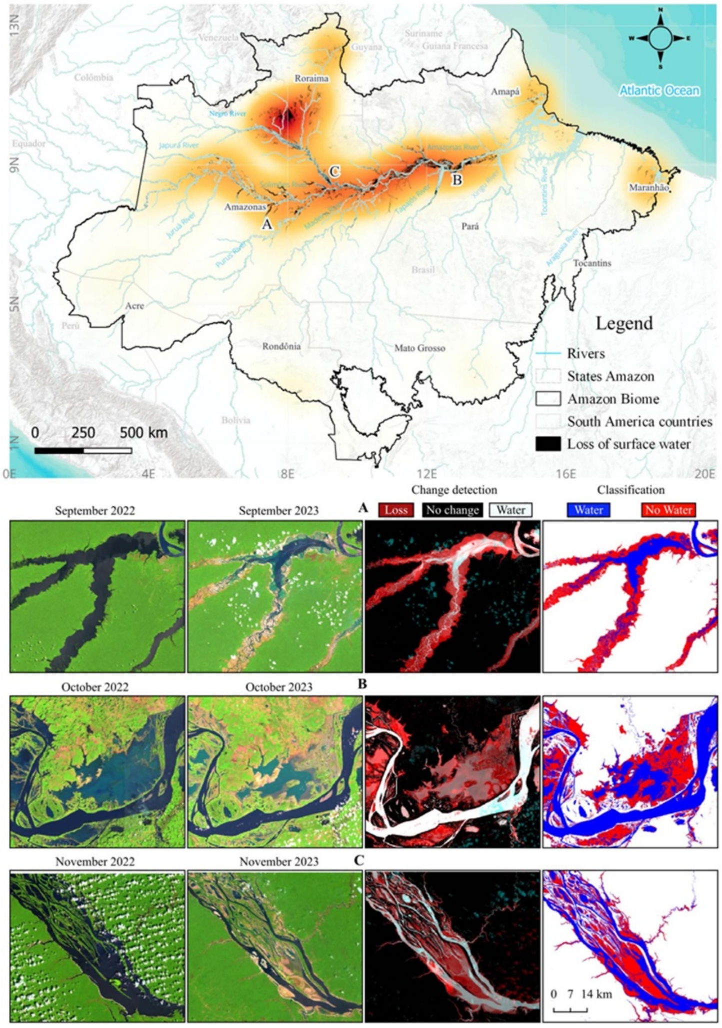

Figure 3. The extent of water loss in the Brazilian Amazon in 2023 relative to the same period in 2022. The heat colors on the map indicate the concentration of surface water loss (yellow: lower, red: higher). The panel images show examples of surface water loss as detected in Sentinel-2 imagery, the temporal change of water membership, and the surface water loss.

The top 10 TIs most affected by the 2023 drought were in Roraima and Amazonas, with six losing more than 5000 hectares of surface water (figure 4(B)). In Roraima State, the Raposa Terra do Sol and São Marcos were the TIs most affected, losing 27.4 thousand hectares of surface water. These most affected TIs concentrate along the Amazon and Negro rivers. Amazonas ($n = 4$) and Roraima ($n = 3$) also had the majority of UCs most affected by surface water loss in 2023 in the top 10 rank. Of these, nine were UCs of direct use, meaning they were established to support river and forest communities. Pará and Maranhão had two and one UCs in the top 10 rank, respectively. The African-Brazilian Quilombo areas in this rank were in Pará ($n = 9$), with the Alto Trombetas II losing almost 13 000 hectares of surface water (figure 4(B)).

Additionally, we assessed the extent of surface water loss at a distance from indigenous villages, urban areas, and small towns (figures 4(C) and (D)). Our proximity analysis revealed that 75% of the surface water loss in 2023 was within 25 km of small towns, 41% from urban areas, and 29% from indigenous villages, respectively (figures 4(C) and (D)). These results highlight the vulnerability of isolating people due to water loss.

4. Discussion

What could explain the quick surface water loss in the Amazon region? The Amazon has experienced a severe austral springtime drought caused by various factors, including the onset of a strong El Niño (Lian *et al* 2023) in April 2023 and the warmer North Atlantic, Indian, and North Pacific Oceans.

This means an increase in temperatures as part of the global warming trend that acts together with El Niño in 2023, classified as Eastern Pacific El Niño (Cai *et al* 2020), resulting in drought and unprecedented heat waves due to warmer winter and spring in 2023, 2 °C–5 °C warmer. These are signals of El Niño in

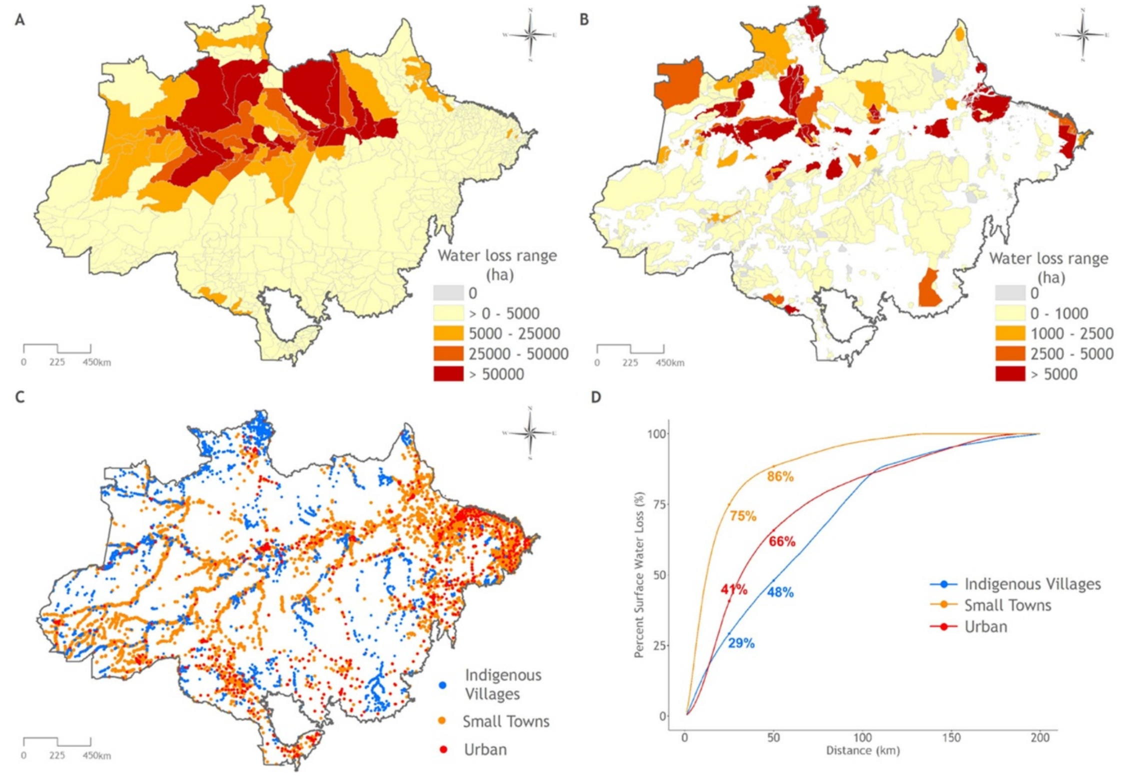

Figure 4. Geography of municipalities (A) and protected areas (B) affected by surface water loss in 2023. Panel (C) shows the location of the of Indigeneous villages, small towns and urban areas potentially affected by the 2023 drought and (D) the correlation of surface water loss relative to these locations.

2023. Among the expected impacts are dry conditions in central western and northern Amazonia and northeast Brazil during austral summer and fall in 2024. Drought has also been observed in west Amazon countries during the winter and spring of 2023, with low rainfall since the end of winter and pre-rainy seasons in spring, respectively, over the Peruvian and western and north-central Amazonia in August and September. In October 2023, the basin recorded below-average rainfall in the Peruvian and Bolivian Amazonia and northwest and southwest Brazilian Amazonia in the headwaters of the Solimões, Purus, Juruá, and Madeira River basins (figure 5).

The warmer and drier climate in 2023 (figure 5) affected the main rivers in the Amazon; among them, the Solimões, Negro, Purus, Acre, and Branco suffered extreme drops in their levels in some regions (figures 1 and 3). They just dried up, with the highest concentration of surface water loss as detected in satellite images reported here (figure 3).

Analysis of the curves representing the minimum monthly river levels for 2022 and 2023 obtained from Hydro-Telemetry stations (figures 6(A) and (B)) showed that the highest levels recorded occur between May and June, except the Juruá, Madeira and Amazonas hydrological ground stations. On the other hand, we observed that during the period analyzed, the lowest water levels of these rivers occurred between September and October, corroborating with the lowest precipitation period (figure 5).

Due to the adverse effects of El Niño 2023–2024 on the precipitation regime in the Amazon basin, the monthly water levels showed a steep slope in the river recession curve, especially between June and October (figure 6(B)), confirming the magnitude of the climatic event. Compared to 2022, river levels fell sharply in 2023, especially the Negro, Purus, and Solimões rivers.

The difference between the minimum monthly levels showed that all the rivers monitored did not recover their levels from 2022 to December 2023 (figure 6(C)) as a result of the low rainfall caused by the combined effects of El Niño and the above-normal warming of the Atlantic Ocean on the Brazilian coast. The most drastic water level reduction was observed in the Negro, followed by the Solimões, Purus, and Branco rivers, which correlated with the months and areas with the greatest extent of surface water losses (figures 3, 4 and 6(C) and (D)).

Regarding the percentage reductions and minimum levels recorded in 2023, the following stand out: the Branco fiver in Rorainópolis/RR (average reduction of 43.3%, with a minimum level of 3.38 m); the Solimões in Manacapuru/AM (average decrease of 40.8%, with a minimum level of 3.06 m); the Purus in Beruri/AM

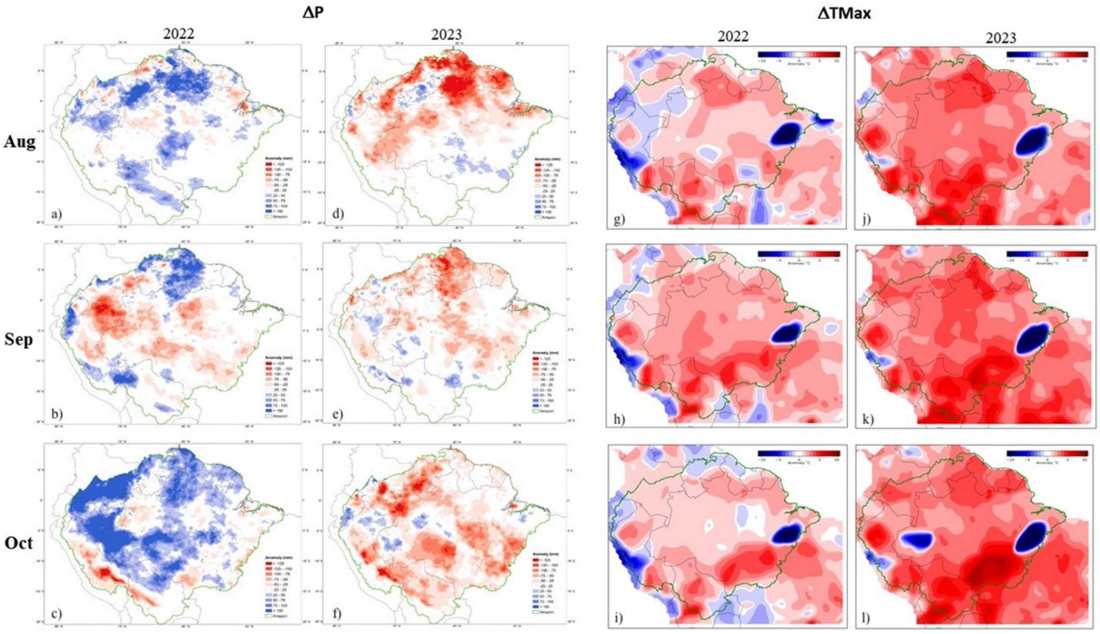

Figure 5. Changes in precipitation (DP in mm/month) on the Amazon region for August, September, and October of 2023 (a)–(c) as compared to 2022 (d)–(f) and in maximum temperature (DTMax in oC) for September of 2023 (g)–(i) as compared to 2022 (j), (f), (l). Month precipitation is from CHIRPS (Funk *et al* 2015). Maximum temperature anomalies are from the daily CPC19 0.5° X 0.5° lat/lon data. Both data sets come from a CPC Global Unified Temperature data dataset provided by NOAA PSL, Boulder, Colorado, USA, accessible at htps://psl.noaa.gov.

(average reduction of 33.8%, with a minimum level of 4.02 m); the Amazonas in Almeirim/PA (average decrease of 27, 9%, with a minimum level of 1.43 m); Negro in Manaus/AM (average reduction of 20.4%, with a minimum level of 12.61 m); Juruá in Itamarati/AM (average decrease of 19.7%, with a minimum level of 5.02 m); Solimões in Fonte Boa/AM (average reduction of 16.8%, with a minimum level of 8.63 m); and Madeira in Humaitá/AM (average decrease of 10.3%, with a minimum level of 8.10 m) (figure 6(C)).

Figure 6(D) shows the time series of surface water between 1985 and 2023 per month from the MapBiomas Water initiative, with the dark blue line depicting the estimation in 2023 (presented in this study). That year, surface water dropped from August to November and increased in December. Compared with the previous years (i.e. 1985–2022), from January to July 2023, surface water was above or close to the average surface water (orange line) and dropped to the lowest surface water extent from October to December registered in this time series. This indicated that it was the lowest surface water detected over the time series.

Surface water loss between 2022 and 2023 was also highly correlated with river level in 2023 (i.e. R^2 ranging from -0.89 to -0.72) except for the Branco River, which showed a lower one ($R^2 = -0.46$; figure 7). These results implied that the lowest the river level, the highest the surface water loss, demonstrating the robustness of this study's surface water loss estimates.

This study used the same SMA model applied to Landsat imagery (Souza *et al* 2019) surface water mapping, also used in the MapBiomas Water time series, which obtained a user accuracy of 96%. By comparing the surface water detection with Landsat and Sentinel-2, we observed a high agreement among the yearly mapping consistent with the time series results (figure 6(D)). However, the Sentinel-2 revealed more spatial detail of surface water (e.g. narrow streams and small lakes). Sentinel-1 could not detect surface water in a mixed environment of water, soil, and grassland vegetation but showed similar results with Landsat and Sentinel-2 in open surface water. The time series presented in figure 6(D) allowed us to estimate monthly surface water change between 1985 and 2002 relative to 2023 (SM figure 5). We identified two temporal patterns of surface water loss in the time series. First, between 1985 and 2000, surface loss in 2023 was higher in most years and months, much higher than relative to 2022. Between 2001 and 2022, surface water change was more pronounced in October through December, with surface gain decreasing from January to September (SM figure 5). A further detailed spatially explicit analysis is required to estimate the total extent of surface change in this time series data set. Still, the results showed that the surface loss in 2023 was much higher when compared to years with more surface water in the Amazon biome (see SM figure 6 for annual surface water extent between 1985 and 2023). Therefore, the surface water loss between 2022 and 2023 is conservative since 2022 was a yearly water gain. Defining a reference period for assessing surface water loss is also required and will require further studies.

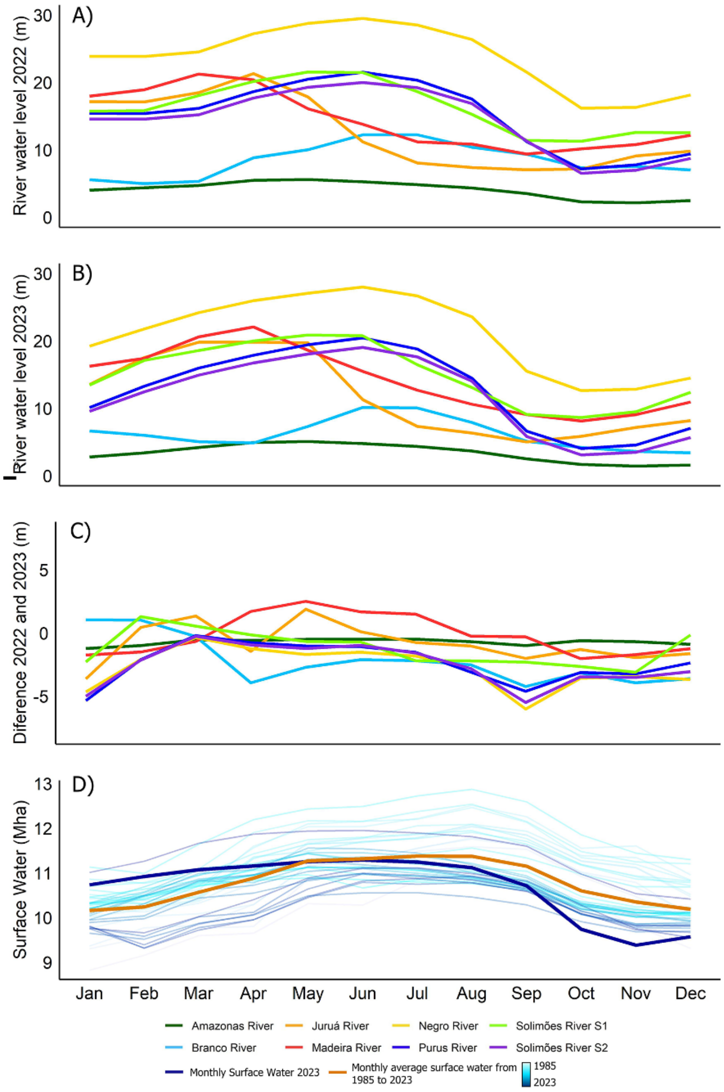

Figure 6. Monthly minimal water levels of the main rivers affected by the 2023 drought in the Brazilian Amazon biome. River level in 2022 is shown in panel (A), 2023 in (B), and the change in water level in 2023 relative to 2022 in (C). Panel (D) shows surface water detection over 1985 (light blue) and 2023 (dark blue) and the average surface water over this period. The Rio Branco station was not included due to missing data.

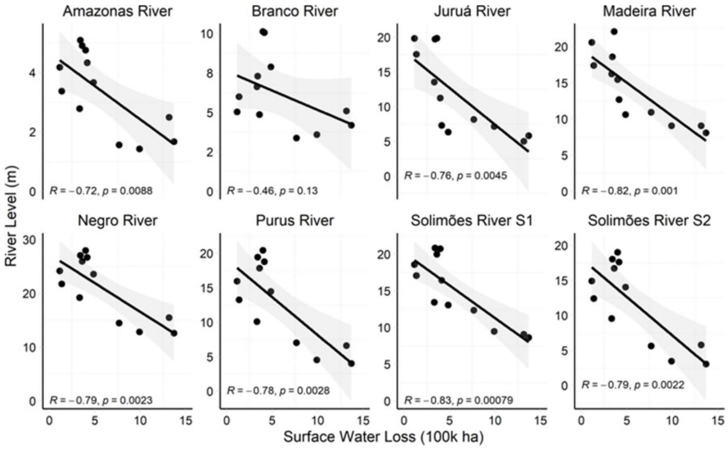

Figure 7. Correlation of river level against surface water in 2023 as measured monthly. The points mean monthly measurements of the month.

Our estimates of surface water loss also showed a high correlation of river level measured from hydro telemetry streamflow data (figure 1). Therefore, our surface water loss estimate for the Brazilian Amazon in 2023 provides reliable information to understand the negative impact of this and possible future droughts, supporting adaptation and mitigation plans.

5. Conclusion

The surface water loss in the Brazilian Amazon presented in this study is one of the indicators of the negative impact of the ongoing severe drought. Considering the combined warming of the Amazon due to deforestation and climate change (Alves de Oliveira *et al* 2021), the overall negative effect on people, tree mortality, aquatic biodiversity, and water loss has not yet been assessed. The solution to the crisis imposed by the 2023 severe drought and warming of the Amazon includes zero deforestation, forest restoration at a larger scale, and measures to control and reduce the fire risk and protect the aquatic biodiversity. Rapid response to help people affected and adaptation measures must also be prioritized. As the drought may continue in 2024 (Lian *et al* 2023), an integrated monitoring system must be implemented, including climate and water dynamics from satellite and ground stations, as demonstrated in this study, including social and biodiversity indicators. Such a monitoring system is necessary to rapidly assess the negative impact and respond to future severe droughts, which are likely more frequent and intense. Analyzing the drought's impact on surface water types (i.e. artificial and natural) is also necessary, especially for water consumption and hydropower production. We propose measuring surface water loss in closed-canopy forests as a future improvement since our methods only capture open and mixed water with vegetation and soil. Mitigation and adaptation measures must also be carried out to support the indigenous and vulnerable people living along the riverbanks. Governments must also include the overall economic, social, and biodiversity losses in their accountability. Growing empirical evidence of climatological and hydrological changes in Amazonia has been reported (Boulton *et al* 2022, Bochow and Boers 2023), and past droughts in the Amazon basin have been partially linked to El Niño. In the past 40 years, the dry season in eastern Amazonia has intensified, and increasing deforestation appears to contribute to ecosystem stress, a rise in the frequency of fires, and an increase in carbon emissions (Gatti *et al* 2021). However, the connection between deforestation, forest degradation, fires, global warming, and climate change in the Amazonian region remains an open problem (Rodrigues 2023).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://code.earthengine.google.com/00d5771c9855ff67c7b4385aa7a39731.

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