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To cite this article: Daniel A Maciel *et al* 2024 *Environ. Res. Lett.* **19** 124034

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
13 May 2024

REVISED
2 October 2024

ACCEPTED FOR PUBLICATION
23 October 2024

PUBLISHED
13 November 2024

LETTER

Sentinel-1 data reveals unprecedented reduction of open water extent due to 2023-2024 drought in the central Amazon basin

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Keywords: droughts, synthetic aperture radar, Amazon floodplain, remote sensing

Abstract

In 2023, an intense drought impacted the Amazon basin triggered by climate change and a strong El Niño event, with the Negro River reaching its lowest water level in 120 years. However, the spatiotemporal open water extent (OWE) during this drought remains unclear. This study comprehensively evaluates OWE variability in the central Amazon using Sentinel-1 synthetic aperture radar (SAR) data since 2017. Monthly OWE masks were generated through an empirical threshold classification with accuracy >95%. Overall, the central Amazon experienced a reduction of ~8% in OWE in the 2023 dry season months (November and December) when compared to monthly-average. However, reductions of up to 80% in OWE were observed in several specific lakes. Our analysis underscores the unprecedented severity of the 2023/2024 drought on rivers and floodplains. Utilizing SAR remote sensing technologies, this study emphasizes the urgent need for proactive conservation measures to safeguard the Amazon's ecological integrity amid escalating environmental challenges. Monthly water masks from January/2017 to September/2024 are available here: https://doi.org/10.5281/zenodo.12751783.

1. Introduction

The Amazon basin, the largest tropical forest basin in the world, represents one of the most important freshwater environments, exporting about 15% of the world's freshwater discharge to the ocean and containing the highest biodiversity on Earth (Castello *et al* 2013, Junk 2013). It provides ecosystem services preservation, carbon stock, community livelihood and well-being, transportation, and food supply (Junk 2013, Tomasella *et al* 2013). However, anthropogenic pressures, such as climate change, dam constructions, illegal gold mining, deforestation, and fires are threatening the basin (Nobre *et al* 2016). One impact of these disturbances is the intensification of extreme drought and flood events, which directly affects freshwater environments, including changes in water quality, floodplain nutrient supply, and fish population (Castello *et al* 2013, Fassoni-Andrade *et al* 2021). Extreme events have been increasing in the Amazon with severe growth in the occurrence of flood events in the last 20 years when compared to the 1920–2000 period (Barichivich *et al* 2018). In addition, Marengo and Espinoza (2016) suggested that drought would intensify throughout the 21st century, with an increase in high temperatures, and in the length of the dry season (Fu *et al* 2013).

In 2023, climate change and a strong El Niño event (Espinoza *et al* 2024) triggered an unprecedented record-breaking drought in the Amazon, imposing severe life risks and economic losses for more than

30 million people who live in the region (Clarke *et al* 2024). The Negro River presented the lowest value in more than 120 years (since measurements started) (Rodrigues 2023, Toreti *et al* 2023). Similarly, Óbidos station, located in the Lower Amazon region (closer to Santarém, Pará), reached in October 2023 the lowest value since 1968 (ANA 2024). As rivers are the primary water source for the floodplain lakes, the drought had an extraordinary impact on these ecosystems. The Tefé and Coari lakes (affluents of the Solimões River) recorded the deaths of more than 250 river dolphins related to the temperature increase and water level reduction between September and October 2023 (Rodrigues 2024). The droughts in the Amazon had a significant impact on fluvial transportation in cities and isolated communities. This made navigation impossible in certain areas by increasing the distance to the waterways (Santos De Lima *et al* 2024). As a result, access to food, healthcare, schools, and other basic services were affected. Therefore, mapping the water surface extent is essential to understanding drought and flood patterns and their impacts on ecological processes, carbon cycle, and natural hazards management.

The recent advances in satellite remote sensing technologies offer many complementary alternatives for open water extent (OWE) mapping throughout the Amazon (Fleischmann *et al* 2022, Enguehard *et al* 2023). Although optical data has been used to map OWE (Pekel *et al* 2016), the use of such data is challenging in Amazon due to the high cloud cover, mainly during the high-water season (Martins *et al* 2018), which prevents gathering information on OWE variability at high time frequency. To overcome this issue, synthetic aperture radar (SAR) data has been used to generate OWE maps for at least 30 years in Amazon (Hess *et al* 2015, Fleischmann *et al* 2022). SAR active sensors operate in a wavelength that can penetrate the clouds, producing reliable images regardless of weather conditions. Methods used for OWE mapping include thresholds (e.g. Otsu, fixed thresholds) (Liang and Liu 2020, Pereira *et al* 2023a) to more advanced techniques, such as Machine Learning (Wagner *et al* 2024). Despite being used for more than 30 years, the applications of SAR in the Amazon for OWE generation were usually limited to a specific time (Chapman *et al* 2015, Hess *et al* 2015, Rosenqvist *et al* 2020) or to time series at specific basins (Pereira *et al* 2023a, 2023b, Wagner *et al* 2024). The lack of systematic monitoring of Amazon OWE areas using SAR data was connected to the limited availability of freely access remote sensing images and the high computing costs for large-scale processing of SAR data. Before the launch of Sentinel-1A in 2014, most SAR sensors were not freely available to the public. The Sentinel-1 is a European sensor (launched by European Space Agency, ESA), equipped with a C-Band SAR sensor. First with limited coverage around Earth, it started continuously monitoring of Earth with a 12 day temporal resolution in 2017. In addition, the recent advent of cloud computing platforms aligned with the availability of pre-processed SAR data enabled large-scale processing and time-series retrieval using these sensors (Fleischmann *et al* 2022).

Despite that, a systematic monitoring system for water extent in the basin still lack. Then, we are still unable to fully understand the extension of the 2023 drought in the aquatic environments of the Amazon. In this study, we comprehensively analyzed the spatiotemporal (2017–2024) dynamics of the OWE areas within the Amazon basin, emphasizing the noteworthy 2023/2024 drought events. Using seven years of freely available Sentinel-1 SAR data (2017–2024), we processed more than 1500 images to create monthly OWE masks for the central Amazon. With this dataset, we observed the spatiotemporal changes in water extent during the period. In this way, we studied how water coverage changed over time and sought to understand the impact of the 2023 drought on water extent in the central Amazon.

2. Material and methods

2.1. Study area

This study provided a spatiotemporal analysis of the OWE in the central Amazon (figure 1) using Sentinel-1 SAR data. This region encompasses the most important rivers and floodplains of the basin (i.e. Amazon, Solimões, Negro, Madeira, and Tapajós rivers). These rivers and their floodplains are subjected to a high variability in flood regimes (Melack and Coe 2021). The drought peak in the western regions occurs generally between October and November, whereas in the lower Amazon region, the eastern portion, the drought peak occurs between November and December (Junk *et al* 2010). There is considerable variability in water quality and river sinuosity along the Amazon River's upstream, middle, and downstream reaches. Lakes in abandoned river meanders (i.e. oxbow lakes) dominate the upstream region, whereas the central area has *Ria* and shallow lakes. In this study, we analyzed the OWE in two different ways: first, mosaics were created for the central Amazon region (figure 1) and time-series were calculated for all the study area. Then, we manually drew boundaries of six lakes that are representative of their location (i.e. location in relation to the basin, such as in the upstream, central, and downstream reaches). Coari, Piorini, Manacapuru, and Cabaliana Lakes are tributaries of the Solimões River. However, they are in different sub-basins, representing different flood patterns. Negro River reach was selected to account for OWE changes in the Negro River Basin; Canaçari Lake accounts for changes in the medium reaches of the Amazon and Curuai Lake accounts for changes

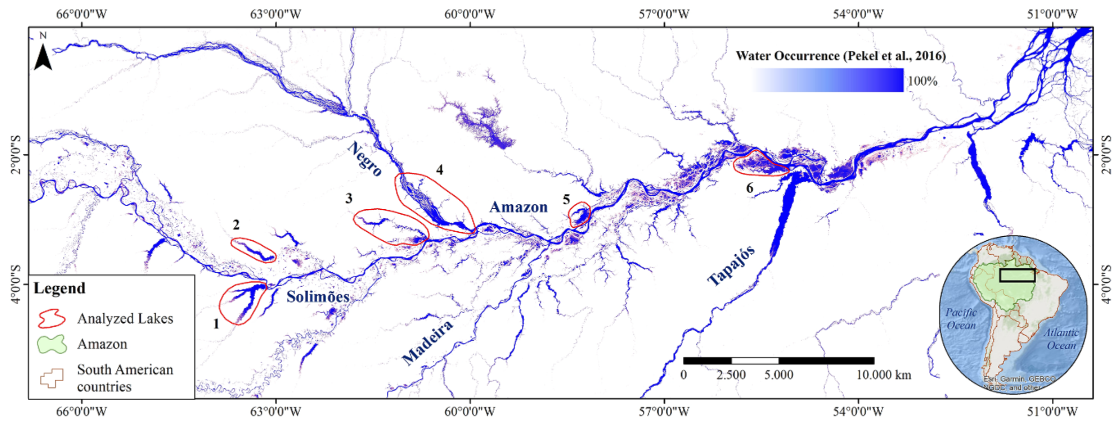

Figure 1. Study area—Central Amazon Region. Colored circles refer to the lakes were time-series where detailed in figure 3, section 3.2. Locations 1–6: (1) Coari Lake; (2) Piorini Lake; (3) Manacapuru and Cabaliana Lakes; (4) Negro River; (5) Canaçari Lake; (6) Curuai Lake.

in OWE in the downstream reaches of the Amazon Basin.

2.2. Dataset used

2.2.1. Sentinel-1 SAR data

The classification of the OWE utilizing Sentinel-1 images was based on an empirical threshold method, based on the Vertical–Horizontal (VH) polarization. The first step involved selecting Sentinel-1 data available on the Google Earth Engine (GEE) platform. We used the preprocessed Level-1 ground range detected (GRD) scenes, provided as backscattering coefficients in decibels (dB), ortho-corrected, and with a 10 m spatial resolution. The preprocessing steps included applying orbit files, removing thermal noise, radiometric calibration, terrain correction, and converting the data to dB using log scaling. Further details are available in the Sentinel-1 Toolbox (https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1). and in Vanderhoof *et al* (2023). The Sentinel-1 GRD data format has been used in several other studies to map open water areas around large-scale locations (DeVries *et al* 2020, Vanderhoof *et al* 2023). Although launched in 2014, Sentinel-1 images between 2014 and 2016 did not have global coverage and were collected only at specific locations. Therefore, these years were excluded from the analysis. On average, 220 images for each Sentinel-1 tile were available for the time-series analysis (a total of ~2800 images).

As Sentinel-1 has a C-Band sensor, it lacks dossel penetration and is not able to distinguish between flooded forests and non-flooded forests—as it requires longer wavelengths. However, as the main aim of this study is assessing the OWE during the low water season, most of the water beneath the flooded forest has already dried up. Therefore, estimations of OWE are reasonable for the drought characterization. Utilizing data available on the GEE platform, we developed the OWE masks for the Amazon region spanning the period from January 2017 to September 2024.

2.2.2. Validation samples

The algorithm validation was based on collecting 96 000 samples over the central Amazon between 2017 and 2021. The collection of the validation samples was based on the Pekel *et al* (2016) monthly water masks over the Amazon Region. The Pekel's water masks are generated using cloud-free Landsat data and are one of the most used satellite water products. The Pekel's occurrence maps provided a reliable baseline for identifying water areas and excluding outliers (e.g. soil, shadows, etc) as it is based on a ~40 years' time-series of Landsat data (1985–2021). In addition, the usefulness of the Pekel's mask for data labelling of water areas was recently demonstrated by Mayer *et al* (2021). For the water and non-water samples collection, for each month between 2017 and 2021, we randomly generated stratified 2000 points (i.e. 1000 for water and 1000 for non-water) to validate the threshold classification method. After that, we compared the validation samples with the classified image for each of these months and calculated validation metrics. More details are available in section 2.3.3.

2.3. SAR classification method

2.3.1. Model development

To generate the water masks, we selected a threshold of −23 dB based on VH polarization (i.e. values lower than −23 dB were classified as water areas) (equation (1)). The threshold selection was based on an analysis of a one-year time series (2022–2023) within the Curuai Floodplain in the Lower Amazon Reach (figure 1) (Pegolo 2024). One year was selected to capture the hydrological variability (i.e. all seasons) along the study area. We selected this region because it can be considered a representative part of the Amazon floodplain lakes, with a high variability in the water level along the hydrological year (Bourgoin et al 2007), and presenting different land use and land cover classes (Renó et al 2011). For the threshold creation, we downloaded all the Sentinel-1 images available (34) for 2022 in the VH polarization. After that, we extract the values of all pixels in each image and calculated the mixed histogram (i.e. one histogram for all images together). From this histogram, we calculated the threshold with the higher intra-class variance by using the Otsu thresholding method (Otsu 1979) (i.e. better separability). This calculation resulted in the value of −22.58 dB, which was rounded to −23 dB.

$$\begin{aligned} &\mathrm{VH} \leqslant -23\ \mathrm{dB}; \mathrm{Class} = \ \mathrm{Water} \\ &\mathrm{VH} \geqslant 23\ \mathrm{dB}; \mathrm{Class} = \ \mathrm{Non-Water}. \end{aligned} \tag{1}$$

2.3.2. Mosaic creation

We created monthly water mask mosaics for the time-series analysis of OWE (e.g. a mosaic for January 2018). This process entailed generating a mosaic for the central Amazon for each month (January–December) spanning January 2017–September 2024. Some of the acquisitions between 2017–2024 failed or were unavailable in the GEE for mosaic creation, causing a reduction in water areas. Therefore, these months were excluded in the evaluation of time-series and water areas (6 dates, 7% of the total). For the mosaic creation, we selected the minimum dB value of each pixel at each month (∼2–3 images per month), because water targets typically exhibit low backscattering values. Subsequently, water masks were derived for each month based on the −23 dB VH threshold defined in section 2.3.1. We refined the accuracy by masking misclassified areas outside the possible water regions by using the Pekel et al (2016) water occurrence maps by removing pixels with water-probability lower than 5% (i.e. pixels classified as water in less than 5% of Landsat images used in Pekel's). Then, following outliers' removal, the time series of surface water extent was analyzed in the entire study area (i.e. the central Amazon) and for the selected lakes, as illustrated in figure 1.

2.3.3. Model validation

The validation of the water mask mosaics was carried out using the validation samples collected using the Pekel et al (2016) water mask as a reference, as described in section 2.2.2. The validation metrics calculated to assess model accuracy were the overall accuracy (OA), user's and producer's accuracies, as well as the omission and commission errors (Fisher et al 2016). These metrics allowed us to validate the model performance against a well-established dataset.

3. Results

3.1. Algorithm validation

For the threshold method validation, we used 96 000 samples collected between 2017–2021 with the Pekel's water mask as a reference. The OA presented high values (96.81%), indicating the high agreement between the classified water mask versus Pekel's reference. When we look at the confusion matrix, we can see that there are more false negatives (water classified as non-water) than false positives (non-water classified as water). Omission and commission errors for water class were 6.02% and 5.70%, respectively. User and Producer accuracies were higher than 94% for both classes, indicating a high agreement in the model results.

3.2. Time-series evaluation

The analysis using Sentinel-1 SAR data allowed us to understand spatiotemporal patterns of OWE in the central Amazon. Time-series analysis between 2017 and 2024 showed that the months with the lowest OWE are November and December (see red lines in figure 2). In contrast, the month with the highest OWE accounted for June and July, which is in accordance with water level variation in this region (Fleischmann et al 2023). Since 2017, two years had values higher than the average ± standard deviation (2019–2020 and 2021–2022), in accordance with extreme flood events reported recently (Espinoza et al 2024). In relation to drought events, only the 2023–2024 drought presented values below the average ± standard deviation.

Regarding the temporal variability, in November and December 2023 the OWE was the lowest considering the analyzed time-series. In addition, after reaching the lowest values in November/December 2023, the OWE continued to be lower than the average ± standard deviation until September 2024, indicating that the impacts of drought are still visible in 2024, and even worse. In comparison, September/2023 had an OWE of 55 414 km^2 and the OWE for September/2024 was 51 775 km^2 (a reduction of 3639 km^2), indicating that the 2024 year would be worse than the record-breaking 2023 drought.

A reduction of 9.72% (4458 km^2) was observed for December 2023 and a reduction of 7.18% (3324 km^2) was observed for November 2023 when comparing monthly data with average monthly data (i.e. OWE for November 2023 vs averaged value for November). In November 2020 (the 3rd lowest OWE area between 2017–2024), the reduction compared with average November OWE was 4.7% (2345 km^2). This demonstrates that the 2023 drought presented values up to 2000 km^2 higher in dry areas than 2020 (e.g. 4458 km^2 for December 2023 vs 2345 km^2 for November 2020). In addition, when compared to

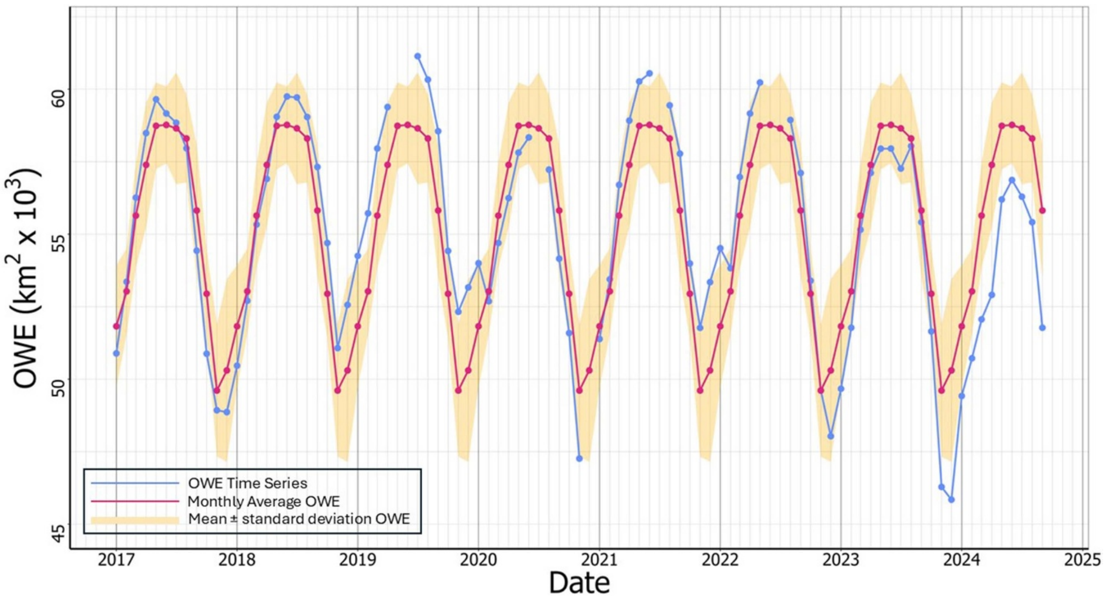

Figure 2. Time-series of OWE areas in the study area between January/2017 and September/2024. Blue lines refer to the time-series of open water areas, red lines refer to the monthly average, and shaded beige refers to the mean ± standard deviation of the monthly average.

mean OWE time-series, December 2023 presented an OWE reduction of 16.7%, or 9195.95 km^2 (an area equivalent to 3 times Paris urban area). When the maximum water extent was compared, the reduction was 25.01% (15 293.41 km^2). In addition to the water area mapping in drought periods, the OWE also showed the flood years in Amazon, such as the 2019–2020 and 2020–2021 extreme flood events (Espinoza *et al* 2022).

We observed a distinctive drought pattern between the western and eastern regions of the Amazon (figure 3), due to the high size of the basin (Marengo and Espinoza 2016). The western region, upstream of the Madeira and Amazon rivers confluence (figures 3(a)–(d)), experienced the lowest values in November 2023. In contrast, for the remaining areas, (i.e. the eastern region), lowest values were reached in December 2023 (figures 3(e) and (f). This time-series exemplifies the selected locations' temporal patterns that typifies the Amazon basin flood regime. Piorini Lake (figure 3(b)), located in a tributary of the Solimões River, had the highest relative reduction (79.74%) in the OWE compared to the average November values (∼200 km^2 of reduction). In another Solimões River tributary, Coari Lake, the water area in November 2023 (figure 3(b)) was nearly 300 km^2 below the average values for November (a reduction of 50.06%). The Manacapuru and Caballana lakes also presented a high reduction in OWE for November 2023 compared to the average November values (64.23% reduction, ∼300 km^2; figure 3(c)). In the segment of the Negro River evaluated here, there was a decrease of about 400 km^2 in November 2023 compared to the average values for that month (20.38% of reduction in the water surface; figure 3(d)). Moving downstream the Amazon basin, Canaçari Lake exhibited a decrease of 200 km^2 compared to the December average (71.48% of reduction; figure 3(e)), while Curuai Lake experienced a substantial decline of approximately 500 km^2 compared to the typical values for that month in the lake (40.28% of reduction; figure 3(f)).

3.3. Spatiotemporal analysis of 2023 drought

In addition to the 2023 drought, we selected another significant drought event that occurred in the 2020–2021 hydrological year for a comparative spatiotemporal analysis (figure 4). This event marked the second worst drought event (i.e. comparing the hydrological years) since the start of continuous monitoring with Sentinel-1 over the Amazon (as illustrated in figure 2). Notably, the extent of dry areas during the 2023 drought surpassed that of November 2020, as shown in our time-series analysis. These critical months experienced a substantial reduction in water surface areas and experienced the transformation of numerous expansive floodplains and reservoirs into partially or entirely dry areas (figure 4). The impacts on the Solimões River and its tributaries were profound, evidenced by a significant decrease in water levels during the 2023 drought compared to the 2020 dry season and the peak water area observed in 2021. A previous study documented that 2023 recorded below-average rainfall in the headwaters of the Solimões, Purus, and Juruá Rivers, contributing to the extraordinary reduction in water areas observed

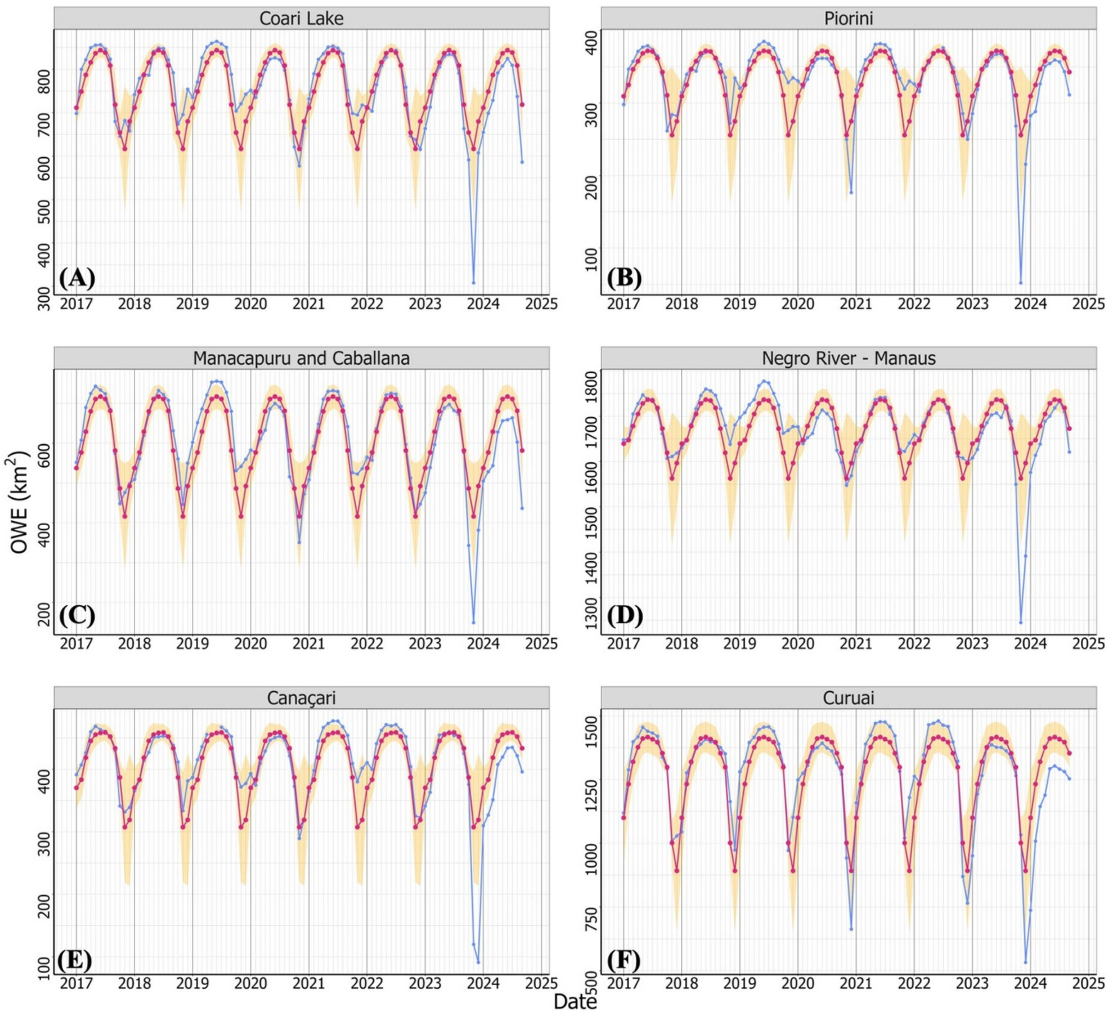

Figure 3. Time-series of OWE between January/2017 and September/2024 in the analyzed lakes (Red circles in figure 1). Blue lines refer to the time-series of open water areas, red lines refer to the monthly average, and shaded beige refers to the mean ± standard deviation of the monthly average.

in November 2023 within that region (Toreti *et al* 2023).

Furthermore, despite belonging to a different sub-basin, the Negro River was also influenced by the reduction in rainfall and above-average temperatures, resulting in a decrease in OWE compared to the average mean water area (Toreti *et al* 2023). This extreme event presents a significant threat to the entire region, since the Negro River at Manaus Station reached the lowest water level in 120 years. Due to the inundation patterns and the vast dimensions of the basin, the drought conditions that started upstream in November 2023 were observed downstream in December 2023 (in the lower Amazon). A larger drought area in 2023 than in 2020 was observed for the two regions, as illustrated in figure 4.

4. Discussions

Our spatiotemporal analysis utilizing Sentinel-1 SAR data unveiled the extent of the 2023–2024 drought on OWE dynamics in the Amazon Basin. Although simple, our proposed VH polarization threshold method performed well for the study area, based on up to 100 000 validation samples collected along the central Amazonia. The model's performance was higher than 95%, indicating a high accuracy in creating water masks. The performance of our model was similar to other complex machine learning algorithms applied in other environments. For example, Vanderhoof *et al* (2023) used a Gradient Boost machine learning method to map open water areas in the United States and

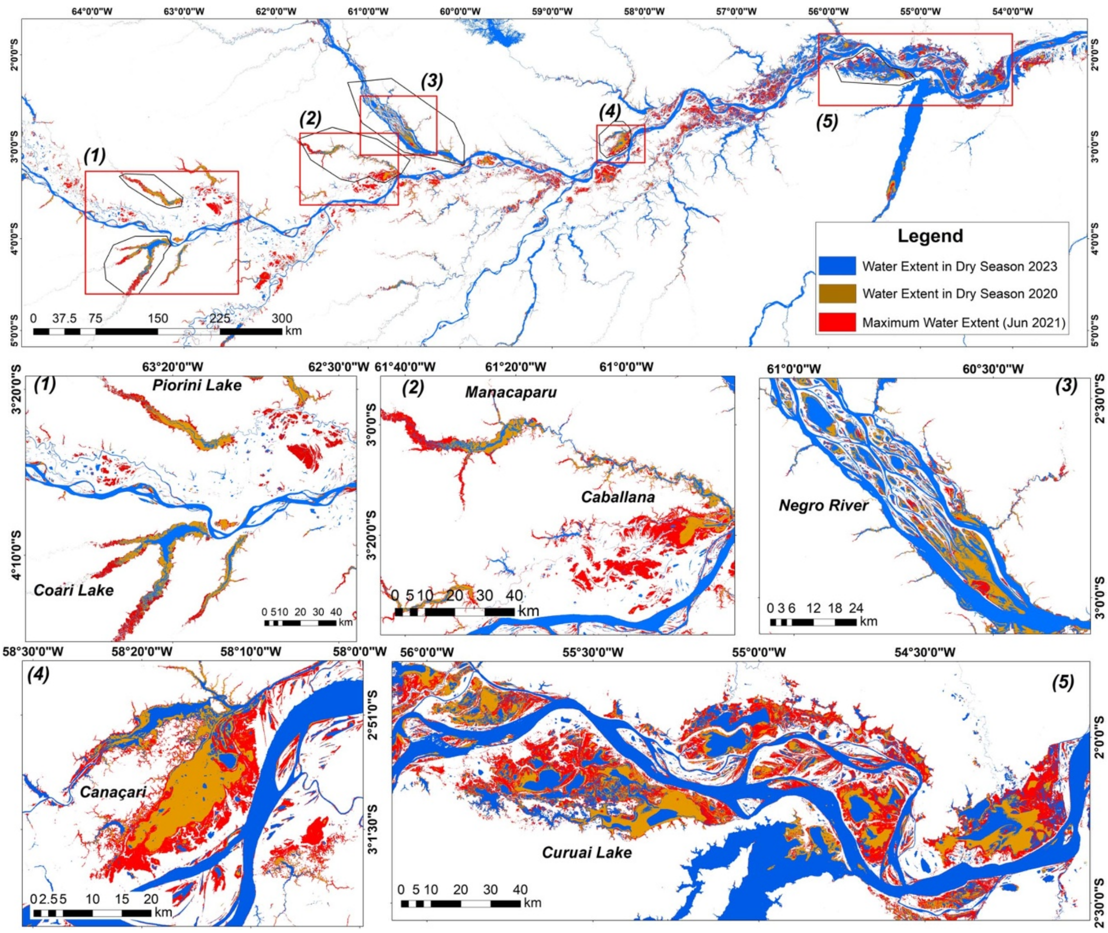

Figure 4. OWE in different locations in the central Amazon, considering the two worst droughts recorded in the Amazon region in the last years (2020 and 2023), and the 2021 extreme flood.

Table 1. Confusion matrix for predicted vs reference (Pekel's Water Mask) classification.

	Sample reference				
Prediction	Non-water	Water	Total	User accuracy	Commission error
Non-water	47 827	2,892	50 719	94%	6%
Water	173	45 108	45 281	99.9%	0%
Total	48 000	48 000	96 000	Overall accuracy	96%
Producer accuracy	99.9%	94%			
Omission error	0%	6.02%			

obtained omission/commission errors of 3.1% and 0.6%. Using Deep Learning techniques, Mayer *et al* (2021) found an overall accuracy of ∼93% for OWE in Cambodia.

These accuracies highlight the usefulness of the threshold approach, aligned with an evaluation of several Sentinel-1 images to create the histogram used for the threshold derivation. In addition, as being a simple method that does not require high computational power such as deep learning methods (Wagner *et al* 2024), our proposed approach could be used in applications (i.e. a smartphone app) for near-real-time OWE monitoring throughout Amazon. Although the high accuracy observed, we point out some limitations of this approach, which are mainly connected to an underestimation of water areas (see table 1). This underestimation could be connected to weather-related conditions, such as strong clouds (i.e. thunderstorms) and wind-induced waves (Benninga *et al* 2019), that increases the SAR backscattering by changing surface roughness and atmospheric conditions. Another observed limitation was the lack of Sentinel-1 images at some dates, due to changes in the imaging plans related to the failure of Sentinel-1B in December 2021 (Woodhouse 2022).

The 2023–2024 drought, which was triggered by the above-average temperatures and a reduction in precipitation due to a strong El Niño year (Espinoza *et al* 2024), reduced by more than 8% the OWE area in the central Amazon when compared to the average

OWE for November and December. These months emerged as the epicenter of severe droughts, surpassing monthly average water areas across the central Amazon (a reduction in 4458 km^2 for December 2023 compared to the average December OWE). According to Espinoza *et al* (2024), temperature anomalies in 2023 were the highest since 1980 for August, September and October (1.8 °C, 2.2 °C, and 2.7 °C higher, respectively). The reduction in OWE during the 2023 drought exceeded the severity of previous events, including the 2020 drought. Furthermore, our comparative analysis highlighted the transition of previously flooded areas into dry zones during the 2023 drought, highlighting a substantial difference in both percentage and area (up to 80%). Extensive floodplains, reservoirs, and tributaries of the Solimões River, such as Piorini (79.74% reduction in OWE) and Coari (50.06% reduction in OWE) Lakes, and the Manacapuru River mouth (64.23% reduction in OWE), were observed partially or almost dry during this period. In the lower Amazon region, Curuai Lake presented a reduction of 40.28% in the OWE compared to December average values.

It is important to note that the reduction in the OWE has not yet recovered, as the 2024 year is still presenting below average OWE (∼4500 km^2 for September/2024 compared to average September). The below average ± standard deviation should be treated as a warning, as the Amazon region is not yet at the peak of the dry season (November/December) and the OWE could be lower than the observed in 2023. An indication of this is that Lake Coari, the most upstream lake assessed, already has an OWE for 11 September 2024% lower than 2023 (∼77 km^2). It was demonstrated that memory effects can carry over seasonal anomalies from one season to another in the Amazon, increasing the time needed to recover to OWE average values (Tomasella *et al* 2008, Pfeffer *et al* 2014). Moreover, below average precipitation in the Amazon region were reported for the first months of 2024 (Senna *et al* 2024), increasing the impacts of the drought and reducing the availability of water.

This reduction in OWE poses a significant threat to Amazon ecosystems. Life within these ecosystems heavily depends on water for sustaining populations, diverse fauna, and rich flora (Junk *et al* 2010, Householder *et al* 2024). One notable impact of the anthropogenic pressures faced by the Amazon basin is observed in the increase frequency of extreme flood and drought events (Marengo and Espinoza 2016, Barichivich *et al* 2018, Garcia *et al* 2018, Espinoza *et al* 2022). The impacts of drought extend beyond freshwater ecosystems and biodiversity. In Amazon floodplains, Householder *et al* (2024) showed that one-sixth of the Amazon trees are ecologically specialized in floodplain habitats, demonstrating the importance of these freshwater environments for biodiversity conservation. The droughts's impact on forest environments was recently demonstrated by Lapola *et al* (2023), in which the authors showed that drought events could be the dominant cause of carbon emissions associated with forest degradation in future scenarios. The rise in extreme drought events also increases the risk of drought-induced forest fires. Aragão *et al* (2018) observed a 36% increase in fire incidence during the 2015 Amazon drought compared to the previous 12 years. Similarly, during the 2023 drought, fire events increased by 32% in October compared to the October historical mean from 1998 to 2023 (INPE 2024). These threats could push the Amazon Forest past its tipping point (Lovejoy and Nobre 2018).

Furthermore, extreme drought events are connected to fish death events, which affects food supply and income to the local population (Hurd *et al* 2016). The increase in fish deaths due to these extreme drought events are a threat for the local Amazon population, as recent studies are demonstrating a reduction in the fish stock in Amazon lakes in a consequence of overfishing pressures (Pereira *et al* 2023a). Drought events on the Amazon also affect people's everyday life, mainly in riverine communities, as it reduces or stops river transportation, that are essential for people access school, healthcare services, as well as essential goods such as food, fuel and medicine (Santos De Lima *et al* 2024). Therefore, understanding how drought affects freshwater ecosystems and its availability, as well as deciphering past flood and drought patterns in the basin, are crucial for predicting and mitigating future challenges (Flores *et al* 2024, Householder *et al* 2024).

5. Conclusions

Using Sentinel-1 SAR data, we were able to develop a threshold model to map the OWE in the central Amazon Basin. The results presented accuracy higher than 95%, indicating the high performance of the proposed algorithm. We observed that the reduction in OWE was of ∼8% for the 2023 dry season when compared to average dry season OWE's areas. In specific locations, this reduction was up to 80%, such as Piorini Lake. These findings underscore the intricate impacts of the 2023 drought on water resources across the Amazon Basin, revealing not only a reduction in water surface areas but also the transformation of previously inundated regions into dry landscapes. We also highlight that following the projections, the dry season of 2024 (November/December) would surpass the record-breaking values of 2023, as we observed below average values of OWE for all months of 2024. As the dry season progresses, water masks can be viewed in this app: https://daniel-maciel.projects.earthengine.app/view/water-mask-amazon. Understanding the OWE spatiotemporal variability is vital for informing targeted conservation strategies and underscores the urgency of addressing the escalating threats to the Amazon's water dynamics. In addition, it is essential to understand spatiotemporal patterns of drought and flood events to provide information for the development of disaster risk reduction strategies, aiming to mitigate possible environmental and socio-economic impacts. As we face these ecological challenges, this study presents insights into the broader discourse on water-related issues, urging collective efforts to preserve the environmental integrity of the Amazon Basin. By employing SAR remote sensing technologies and cloud computing platforms like GEE, our study contributes to the large-scale spatiotemporal OWE monitoring in the Amazon, facilitating a deeper understanding of complex ecosystems and informing urgent conservation strategies. As we confront an era of environmental challenges, scientific endeavors and policy decisions must converge to safeguard the invaluable ecological heritage of the Amazon.

Data availability statement

All the codes used to generate the water masks are freely available in the Google Earth Engine code editor: https://code.earthengine.google.com/40be03256402ffe4e326c9fb5b7a3149. An application to visualize the water masks is also available: https://daniel-maciel.projects.earthengine.app/view/water-mask-amazon.

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11187955. Data will be available from 13 December 2024.

Acknowledgment

This research is funded through the 2017-2018 Belmont Forum and BiodivERsA joint call for research proposals, under the BiodivScen ERANet COFUND programme, and with the funding organizations French National Research Agency (ANR), São Paulo Research Foundation and National Science Foundation (NSF), the Research Council of Norway and the German Federal Ministry of Education and Research (BMBF). This study was also funded by São Paulo Research Foundation (Process: 2023/13904-7 and 2018/12083-1) and in part by the Coordenação Nacional de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)—Finance Code 001. Alice Fassoni-Andrade is partially supported by the NASA-CNES SWOT Science Team project SAMBA. Authors thank the anonymous reviewers for they careful evaluation of the previous version of the manuscript.

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References

ANA 2024 Hidroweb: hydrological information system (available at: http://hidroweb.ana.gov.br)

Aragão L E O C *et al* 2018 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions *Nat. Commun.* **9** 536

Barichivich J, Gloor E, Peylin P, Brienen R J W, Schöngart J, Espinoza J C and Pattnayak K C 2018 Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation *Sci. Adv.* **4** eaat8785

Benninga H J F, van der Velde R and Su Z 2019 Impacts of radiometric uncertainty and weather-related surface conditions on soil moisture retrievals with Sentinel-1 *Remote Sens.* **11** 2025

Bourgoin L M, Bonnet M P, Martinez J-M-M, Kosuth P, Cochonneau G, Moreira-Turcq P, Guyot J L, Vauchel P, Filizola N and Seyler P 2007 Temporal dynamics of water and sediment exchanges between the Curuaí floodplain and the Amazon River, Brazil *J. Hydrol.* **335** 140–56

Castello L, Mcgrath D G, Hess L L, Coe M T, Lefebvre P A, Petry P, Macedo M N, Renó V F and Arantes C C 2013 The vulnerability of Amazon freshwater ecosystems *Conserv. Lett.* **6** 217–29

Chapman B, McDonald K, Shimada M, Rosenqvist A, Schroeder R and Hess L 2015 Mapping regional inundation with spaceborne L-band SAR *Remote Sens.* **7** 5440–70

Clarke B *et al* 2024 *Climate change, not El Niño, main driver of exceptional drought in highly vulnerable Amazon River Basin* (Grantham Institute for Climate Change) p 143

DeVries B, Huang C, Armston J, Huang W, Jones J W and Lang M W 2020 Rapid and robust monitoring of flood events using Sentinel-1 and landsat data on the google Earth engine *Remote Sens. Environ.* **240** 111664

Enguehard P, Frappart F, Zeiger P, Blarel F, Satgé F and Bonnet M P 2023 Contribution of automatically generated radar altimetry water levels from unsupervised classification to study hydrological connectivity within Amazon floodplains *J. Hydrol.* **47** 101397

Espinoza J-C, Carlos Jimenez J, Marengo J A, Schongart J, Ronchail J, Lavado-Casimiro W, Vitor J and Ribeiro M 2024 The new record of drought and warmth in the Amazon in 2023 related to regional and global climatic features *Sci. Rep.* **14** 1–12

Espinoza J-C, Marengo J A, Schongart J and Jimenez J C 2022 The new historical flood of 2021 in the Amazon River compared to major floods of the 21st century: atmospheric features in the context of the intensification of floods *Weather Clim. Extremes* **35** 100406

Fassoni-Andrade A C *et al* 2021 Amazon hydrology from space: scientific advances and future challenges *Rev. Geophys.* **59** 1–97
Fisher A, Flood N and Danaher T 2016 Comparing Landsat water index methods for automated water classification in eastern Australia *Remote Sens. Environ.* **175** 167–82
Fleischmann A S *et al* 2022 How much inundation occurs in the Amazon River basin? *Remote Sens. Environ.* **278** 113099
Fleischmann A S *et al* 2023 Increased floodplain inundation in the Amazon since 1980 *Environ. Res. Lett.* **18** 034024
Flores B M *et al* 2024 Critical transitions in the Amazon forest system *Nature* **626** 555–64
Fu R *et al* 2013 Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection *Proc. Natl Acad. Sci. USA* **110** 18110–5
Garcia B N, Libonati R and Nunes A M B 2018 Extreme drought events over the amazon basin: the perspective from the reconstruction of South American hydroclimate *Water* **10** 1594
Hess L L, Melack J M, Affonso A G, Barbosa C C F, Gastil-Buhl M and Novo E M 2015 Wetlands of the lowland Amazon Basin: extent, vegetative cover, and dual-season inundated area as mapped with JERS-1 synthetic aperture radar *Wetlands* **35** 745–56
Householder J E *et al* 2024 One sixth of Amazonian tree diversity is dependent on river floodplains *Nat. Ecol. Evol.* **8** 901–911
Hurd L E, Sousa R G C, Siqueira-Souza F K, Cooper G J, Kahn J R and Freitas C E C 2016 Amazon floodplain fish communities: habitat connectivity and conservation in a rapidly deteriorating environment *Biol. Conserv.* **195** 118–27
INPE 2024 Banco de Dados de queimadas (available at: www.Inpe.Br/Queimadas/Bdqueimadas)
Junk W J 2013 *The Central Amazon Floodplain: Ecology of a Pulsing System* vol 126 (Springer Science & Business Media)
Junk W J, Piedade M T F, Wittmann F, Schöngart J and Parolin P 2010 *Amazonian Floodplain Forests: Ecophysiology, Biodiversity and Sustainable Management* vol 210 (Ecological Studies)
Lapola D M *et al* 2023 The drivers and impacts of Amazon forest degradation *Science* **379** eabp8622
Liang J and Liu D 2020 A local thresholding approach to flood water delineation using Sentinel-1 SAR imagery *ISPRS J. Photogramm. Remote Sens.* **159** 53–62
Lovejoy T E and Nobre C 2018 Amazon tipping point *Sci. Adv.* **4** eaat2340
Marengo J A A and Espinoza J C C 2016 Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts *Int. J. Climatol.* **36** 1033–50
Martins V S, Novo E M L M, Lyapustin A, Aragão L E O C, Freitas S R and Barbosa C C F 2018 Seasonal and interannual assessment of cloud cover and atmospheric constituents across the Amazon (2000–2015): insights for remote sensing and climate analysis *ISPRS J. Photogramm. Remote Sens.* **145** 309–27
Mayer T *et al* 2021 Deep learning approach for Sentinel-1 surface water mapping leveraging google Earth engine *ISPRS Open J. Photogramm. Remote Sens.* **2** 100005
Melack J M and Coe M 2021 Amazon floodplain hydrology and implications for aquatic conservation *Aquat. Conserv.* **31** 1029–40
Nobre C A, Sampaio G, Borma L S, Castilla-Rubio J C, Silva J S and Cardoso M 2016 Land-use and climate change risks in the amazon and the need of a novel sustainable development paradigm *Proc. Natl Acad. Sci. USA* **113** 10759–68
Otsu N 1979 A tlreshold selection method from gray-level histogram *IEEE Trans. Syst. Man Cybern. Syst.* **9** 62–66
Pegolo F L 2024 Avaliação de métodos de limiarização de imagens Sentinel-1 para o mapeamento de superfícies de águas abertas de lagos de várzea do baixo Rio Amazonas (Instituto Nacional de Pesquisas Espaciais (INPE)) (available at: http://urlib.net/ibi/8JMKD3MGP3W34T/4AK8DNE)
Pekel J F, Cottam A, Gorelick N and Belward A S 2016 High-resolution mapping of global surface water and its long-term changes *Nature* **540** 418–22
Pereira D V, Mereles M D A, de Matos O F, Lopes G C D S, da Conceição K G and Freitas C E D C 2023a Vulnerability to overfishing of fish stocks in the Amazon Basin *Fish. Res.* **265** 106740
Pereira A C P, Paule-Bonnet M, Frappart F, Marie-Louise L, Enguehard P, Catry T and Paiva R 2023b Flood extent and volume changes analysis in curuai floodplain using remote sensing xxv simpósio brasileiro de recursos hidrícos flood extent and volume changes analysis in curuai floodplain using remote sensing *XXV SBRH—Simpósio Brasileiro de Recursos Hídricos* (available at: https://hal.science/hal-04382083)
Pfeffer J, Seyler F, Bonnet M P, Calmant S, Frappart F, Papa F, Paiva R C D, Satgé F and Silva J S D 2014 Low-water maps of the groundwater table in the central Amazon by satellite altimetry *Geophys. Res. Lett.* **41** 1981–7
Renó V F, Novo E M L D M, Suemitsu C, Rennó C D and Silva T S F 2011 Assessment of deforestation in the lower Amazon floodplain using historical Landsat MSS/TM imagery *Remote Sens. Environ.* **115** 3446–56
Rodrigues M 2023 The Amazon's record-setting drought: how bad will it be? *Nature* **623** 675–6
Rodrigues M 2024 *Eos* (https://doi.org/10.1029/2024EO240078) (Accessed 15 August 2024)
Rosenqvist J, Rosenqvist A, Jensen K and McDonald K 2020 Mapping of maximum and minimum inundation extents in the amazon basin 2014–2017 with ALOS-2 PALSAR-2 scan SAR time-series data *Remote Sens.* **12** 1326
Santos De Lima L, Silva F E O E, Dorio Anastácio P R, Kolanski M M D P, Pires Pereira A C, Menezes M S R, Cunha E L T P and Macedo M N 2024 Severe droughts reduce river navigability and isolate communities in the Brazilian Amazon *Commun. Earth Environ.* **5** 1–12
Senna R C, Carvalho L R R and Arcos A N 2024 Climate monitoring bulletin for the major river basins vol 2 pp 17 (available at: https://repositorio.inpa.gov.br/handle/1/40437)
Tomasella J, Hodnett M G, Cuartas L A, Nobre A D, Waterloo M J and Oliveira S M 2008 The water balance of an Amazonian micro-catchment: the effect of interannual variability of rainfall on hydrological behaviour *Hydrol. Process.* **22** 2133–47
Tomasella J, Pinho P F, Borma L S, Marengo J A, Nobre C A, Bittencourt O R F O, Prado M C R, Rodriguez D A and Cuartas L A 2013 The droughts of 1997 and 2005 in Amazonia: floodplain hydrology and its potential ecological and human impacts *Clim. Change* **116** 723–46
Toreti A *et al* 2023 *Drought in the Amazon basin—November 2023* (Publications Office of the European Union) (https://doi.org/10.2760/756827)
Vanderhoof M K, Alexander L, Christensen J, Solvik K, Nieuwlandt P and Sagehorn M 2023 High-frequency time series comparison of Sentinel-1 and Sentinel-2 satellites for mapping open and vegetated water across the United States (2017–2021) *Remote Sens. Environ.* **288** 113498
Wagner F H, Favrichon S, Dalagnol R, Hirye M C M, Mullissa A and Saatchi S 2024 The Amazon's 2023 drought: sentinel-1 reveals extreme rio negro river contraction *Remote Sens.* **16** 1056
Woodhouse I 2022 The impact of the Sentinel-1B failure and looking forward to Sentinel-1C | blog | Earth blox (available at: www.earthblox.io/blog/the-impact-of-the-sentinel-1b-failure-and-looking-forward-to-sentinel-1c)