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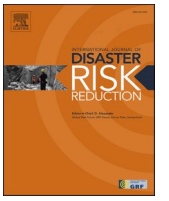

Attributing the 2021 Juruá River Floods to climate change: Evidence, impacts, and adaptation in the Brazilian Amazon

Renata Pacheco Quevedo [a,b,*], Alex Ovando [c], Bianca Nunes Calado [d], Gisleine Cunha-Zeri [e], Larissa Antunes da Silva [c], Queren-Hapuque Rodrigues de Luna [f], Janaína Cassiano dos Santos [c,g], Rafael Cesario Abreu [h], Wan Ting Katty Huang [i], Pedro Noronha [j], Henrique Leão [c,g], Luiz Felipe Goulart Fiscina [b], Rafaela Quintella Veiga [k,l], Débora Joana Dutra [c,g], Ylza Marluce Silva de Lima [f], Edvan de Meneses [m,n], Marcos Timóteo Rodrigues de Sousa [b], Marcos Massao Futai [b], Fraser C. Lott [i], Sihan Li [o], Rafael Luiz [c], Sarah Sparrow [h], Liana Oighenstein Anderson [c]

[a] *ENGAGE Research Group, Department of Geography and Regional Research, University of Vienna, Vienna, 1010, Austria*
[b] *Department of Structural and Geotechnical Engineering, Polytechnic School of the University of São Paulo, São Paulo, 05508010, São Paulo, Brazil*
[c] *National Centre for Monitoring and Early Warning of Natural Disaster (CEMADEN), São José dos Campos, 12247016, São Paulo, Brazil*
[d] *Earth System Science Postgraduate Course, Earth System Science Center, National Institute for Space Research (INPE), São José dos Campos, 12227010, São Paulo, Brazil*
[e] *National Institute for Space Research (INPE), São José Dos Campos, 12227010, São Paulo, Brazil*
[f] *Integrated Center for Geoprocessing and Environmental Monitoring of the Acre State Secretariat for the Environment, Rio Branco, 69900160, Acre, Brazil*
[g] *Remote Sensing Postgraduate Course, Earth Observation and Geoinformatics Division, National Institute for Space Research (INPE), São José dos Campos, 12227010, São Paulo, Brazil*
[h] *Oxford e-Research Centre, Engineering Science, University of Oxford, Oxford, OX13QG, United Kingdom*
[i] *Met Office Hadley Centre, Exeter, United Kingdom*
[j] *Defesa Civil do Estado do Acre, Rio Branco, 69901097, Acre, Brazil*
[k] *Programa de Pós-Graduação em Geografia, Department of Geography, Institute of Geosciences (iGeo), Federal University of Rio de Janeiro, Rua Athos da Silveira Ramos, 274, Cidade Universitária, Rio de Janeiro, 21941901, Brazil*
[l] *Department of Geography, Indiana University Bloomington, Bloomington, 47405, Indiana, United States of America*
[m] *Secretaria de Saúde do Estado do Acre, Rio Branco, 69900064, Acre, Brazil*
[n] *Federal Institute of Science and Technology of Amazonas, São Gabriel da Cachoeira campus, Amazonas, Brazil*
[o] *School of Geography and Planning, University of Sheffield, United Kingdom*

* Corresponding author. ENGAGE Research Group, Department of Geography and Regional Research, University of Vienna, Vienna, 1010, Austria.
E-mail addresses: renata.quevedo@univie.ac.at (R.P. Quevedo), alex.ovando@cemaden.gov.br (A. Ovando), bianca.calado@inpe.br (B.N. Calado), gisleine.zeri@inpe.br (G. Cunha-Zeri), antunesla86@gmail.com (L. Antunes da Silva), querenluna@gmail.com (Q.-H.R. Luna), jana.cassiano@gmail.com (J. Cassiano dos Santos), rafael.deabreu@oerc.ox.ac.uk (R.C. Abreu), katty.huang@metoffice.gov.uk (W.T.K. Huang), studionoronha@yahoo.com (P. Noronha), henri.leaos@gmail.com (H. Leão), luizfiscina@usp.br (L.F.G. Fiscina), raquin@iu.edu (R.Q. Veiga), debora.dutra@cemaden.gov.br (D.J. Dutra), y.marluce@gmail.com (Y.M.S. Lima), edvan.ferreira@ifam.edu.br (E. Meneses), marcostrsousa@usp.br (M.T.R. Sousa), futai@usp.br (M.M. Futai), fraser.lott@metoffice.gov.uk (F.C. Lott), sihan.li@sheffield.ac.uk (S. Li), rafael.luiz@cemaden.gov.br (R. Luiz), liana.anderson@gmail.com (L.O. Anderson).

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ABSTRACT

An extreme rainfall event caused historic floods in the western Brazilian Amazon in 2021, with significant socio-economic impacts. Since global climate change is amplifying the frequency and severity of such extreme events, our objective was to assess the extent to which this disaster can be attributed to anthropogenic climate change. To achieve this goal, we used CHIRPS data for observational validation of the HadGEM3-A model, which was employed for the attribution analysis, assessed land cover areas directly affected by the floods, and analysed the socioeconomic impacts. The results revealed a positive precipitation anomaly, with rainfall from December to March reaching 48 % above the average (1,329 mm). This extreme event is 153 % more likely to occur in the context of current human-induced climate change than in a natural scenario, with the return period reduced from 107 to 42 years. Furthermore, we found that the Attributable Risk Fraction (FAR) was 61 %, i.e., the likelihood of such an event occurring can be attributed to anthropogenic influence on climate. Despite FAR limitations, we estimated that the proportion of climate change-attributable damages amounts to nearly US$10 million and affects over 43,000 individuals directly, likely underestimated. Our findings emphasise the urgent need for global climate action. Nationally, multi-sector data collection and climate integration into disaster risk reduction planning are essential for societal adaptation. Public management must include climate change in territorial planning, as environmental preservation and income redistribution can mitigate flood impacts, which tend to be increasingly frequent, as our findings show.

1. Introduction

Greenhouse gas emissions derived from human activities are causing global mean surface temperatures to rise, with the decade from 2010 to 2019 presenting the highest average annual emissions [1]. Warming trends continue to increase, with the year 2023 considered (until now) the warmest year since the start of records (1850), reaching 1.18 °C above the 20th-century average temperature [2]. The changes in thermodynamic (heat and moisture) and dynamic (atmospheric and oceanic motion) processes are intensifying temperature increases and extreme weather event occurrences [3,4]. Because of this, global climate change is currently one of the main socio-environmental issues [5].

In addition to the increased frequency of extreme weather events, some studies have found changes in seasonal and diurnal rainfall cycles [6,7], resulting in more droughts and heavy rainfalls [4] with consequent flood occurrences. According to the spatial heterogeneity of climate changes [8,9], some zones can present an increase in precipitation, such as the high latitudes in the Northern Hemisphere, while other zones suffer a growth in rainfall variance, as in the case of Equatorial regions [10].

Rainfall in the Amazon region has a seasonal cycle that causes droughts and floods throughout the year [11]. The precipitation and river discharge have been increasing, especially during the wet season [12], amplifying the difference between maximum and minimum flows [13]. In addition, some future projection models have predicted scenarios of longer dry seasons in the eastern Amazon and increased precipitation in the Western Amazon [14].

Although droughts and floods are common phenomena in this region, it is estimated that the event severity has increased along with the frequency of extreme events [15,16]. Hydrological extreme events represented 95 % and 79 % of the total number of disasters from 2000 to 2015 in Acre and Amazonas states, respectively [17], being the second type of disaster in Brazil with higher socioeconomic losses. The 2009 and 2012 events, which reached especially the Amazonas state in the Brazilian Amazon, were characterised as ‘once in a century’ at the time [11]. The 2009 flood was considered the third worst inundation, following the 1953 and 1976 events [18]. Moreover, the 2012 and 2015 floods reached Acre state [19], causing much socioeconomic damage [20,21]. In addition, many major floods have been recorded since the beginning of the records at the Acre River (1971) [22].

Western Amazon is experiencing more extreme events [23] and is expected to face even more in the future [24,25]. Among the affected areas, the Juruá River Basin, which covers part of Acre and Amazonas states, suffered recurrent extreme rainfall events with subsequent floods. Specifically in this basin, there has been an increasing trend in extreme flood event occurrences over the last 40 years, with emphasis on the flood events that occurred from 2013 to 2015, and in 2021 [26]. For example, the Cruzeiro do Sul municipality, northern Acre state, recorded 21 extreme events between 1987 and 2023 [24], with nearly 33 thousand inhabitants hit by the 2021 flood [27]. Also, in 2021, the Juruá River reached 16.46 m in Eirunepé municipality, where the warning level is 14.05 m, reaching urban and rural areas [28].

Silva et al. [24] showed that around 85 flood events were recorded in Acre state between 1987 and 2023, with the western part, especially the Cruzeiro do Sul municipality (Juruá River Basin), being the most affected area. Between November 2014 and April 2015, 14 floods were recorded on the Tarauacá River, in the Juruá basin [29]. The 2019 flood was considered the greatest inundation at the Juruá River at that time; however, Silva et al. [30] calculated the flooded area in Eirunepé municipality and found that the 2021 flood was 35 % greater than the 2019 flood. The floods in February 2021 caused much damage, with 10 municipalities in Acre decreeing Emergency Situation, including the Tarauacá municipality [29].

The apparent increase in extreme event frequency and intensity raises the question of the role of anthropogenic climate change in heavy rainfall and subsequent flood occurrences [31,32]. Attribution studies can help to understand and quantify how much of the probability of an extreme event occurring has been altered by climate change, and how much can be attributed to it [33,34]. Through

the comparison between the current climate scenario with climate model simulations that consider no anthropogenic greenhouse gas emissions, we can estimate the impact of climate change on extreme event occurrence [35,36].

Attribution analyses have previously been applied to study extreme events associated with heavy rainfalls [37–39] and their consequent landslides [40,41] and floods [42–44]. Furthermore, some studies simulate future scenarios for extreme events considering the climate change projections [45]. This type of analysis can guide local managers in disaster risk reduction (DRR) policies and territorial planning, as underestimating possible damage can result in a lack of preparation for the real magnitude of the extreme event.

In this sense, the main aim of this study was to evaluate how much of the extreme precipitation event, such as the one responsible for the floods in the Juruá River Basin in 2021, can be attributed to climate change. Furthermore, we aimed to estimate the socio-economic impacts related to these floods, in addition to discussing their relationship with global warming and recommending policy approaches for adaptation in the region.

2. Study area

The Juruá River Basin is located in the western part of the Amazon Region, covering an area of approximately 220,000 km^2, with 93.5 % of the basin in Brazilian territory and the remainder 6.5 % in Peru (Fig. 1). The altitude varies from ~40 m downstream, where the confluence between Juruá and Solimões rivers occurs, to ~453 m upstream, with 141 km^2 (0.06 %) reaching higher altitudes of up to 703 m. The Juruá River flows from Acre state to Amazonas state, where it flows into the Solimões River, in a Southwest-Northeast direction, with a length of 3283 km [46].

According to Köppen's climate classification, the Juruá River Basin presents a tropical rainforest climate without a dry season (Af), i.e., the driest month presents at least 60 mm [47]. The precipitation varies throughout the year, with dry (April to September) and rainy (October to March) seasons well-defined, reaching an annual rainfall between 2200 mm and 3100 mm [48]. In Western Amazonia, the peak of rainfall in the wet season occurs between December and February, which can correspond to river discharge peaks months after the rain (nearly 3–4 months on the Amazon main stem) [11,49]. These characteristics promote the seasonal occurrence of floods, with the floodable area varying spatially and temporally throughout the Amazon River basin, with the maximum inundated area being estimated at 599,700 ± 81,800 km^2 [50].

Although this variability in floodable area is a natural hydrological aspect in the Amazon Region, the flood intensity and frequency have been increasing [15]. The population exposure to climatic extremes, together with socioeconomic vulnerabilities and limited adaptive capacity, has been increasing poverty, health and food insecurity in the region [51,52]. The Juruá River Basin covers completely or partially 22 municipalities (Supplementary material 1), with more than 300 thousand inhabitants [53], concentrating riverside communities along the Juruá River floodplain [54] that are highly dependent on water dynamics for economic activities [55].

3. Data acquisition

3.1. Precipitation and streamflow data

The fluvial (river stage and streamflow data) and pluvial information obtained by the National Water Resources Information System (SNIRH),[1] made available by Brazil's National Water and Sanitation Agency (ANA). In addition, rainfall and temperature data come from the National Institute of Meteorology (INMET)[2] and Brazil's National Centre for Monitoring and Early Warning of Natural Disasters (CEMADEN).[3] We considered 19 and 18 gauges distributed over the study area for fluvial and rainfall analysis, respectively (Supplementary material 1).

The Juruá River Basin is sparse and limitedly covered by the observational rainfall network, therefore, we included a gridded rainfall dataset in our analysis. Specifically, we use the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset, developed by the United States Geological Survey (USGS) in collaboration with the Climate Hazards Center (CHC) at the University of California, Santa Barbara [56]. The CHIRPS dataset integrates precipitation estimates obtained through interpolation between data from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) [57] and ground-based rain gauges [58].

With a spatial resolution of 0.05° (approximately 5 km), CHIRPS covers a quasi-global extent from 50°S to 50°N and offers a historical record dating back to 1981 [56]. Moreover, CHIRPS provides data at various temporal resolutions, including daily, monthly, and annual estimations, and has been shown to accurately capture the seasonal fluctuations of rainfall in the Amazon region [59–62]. Therefore, the CHIRPS dataset was used to: i) represent the precipitation data, ii) validate the climate model, and iii) carry out the attribution analysis. The climatology considered for CHIRPS data covered the period between 1981 and 2013 [37], used to validate the HadGEM3-A model.

3.2. Climate model

The attribution analysis was conducted using the Hadley Centre Global Environmental Model version 3-A (HadGEM3-A)

[1] www.snirh.gov.br/hidroweb/download.
[2] portal.inmet.gov.br/servicos/bdmep-dados-hist%C3 %B3ricos.
[3] www.gov.br/cemaden/pt-br.

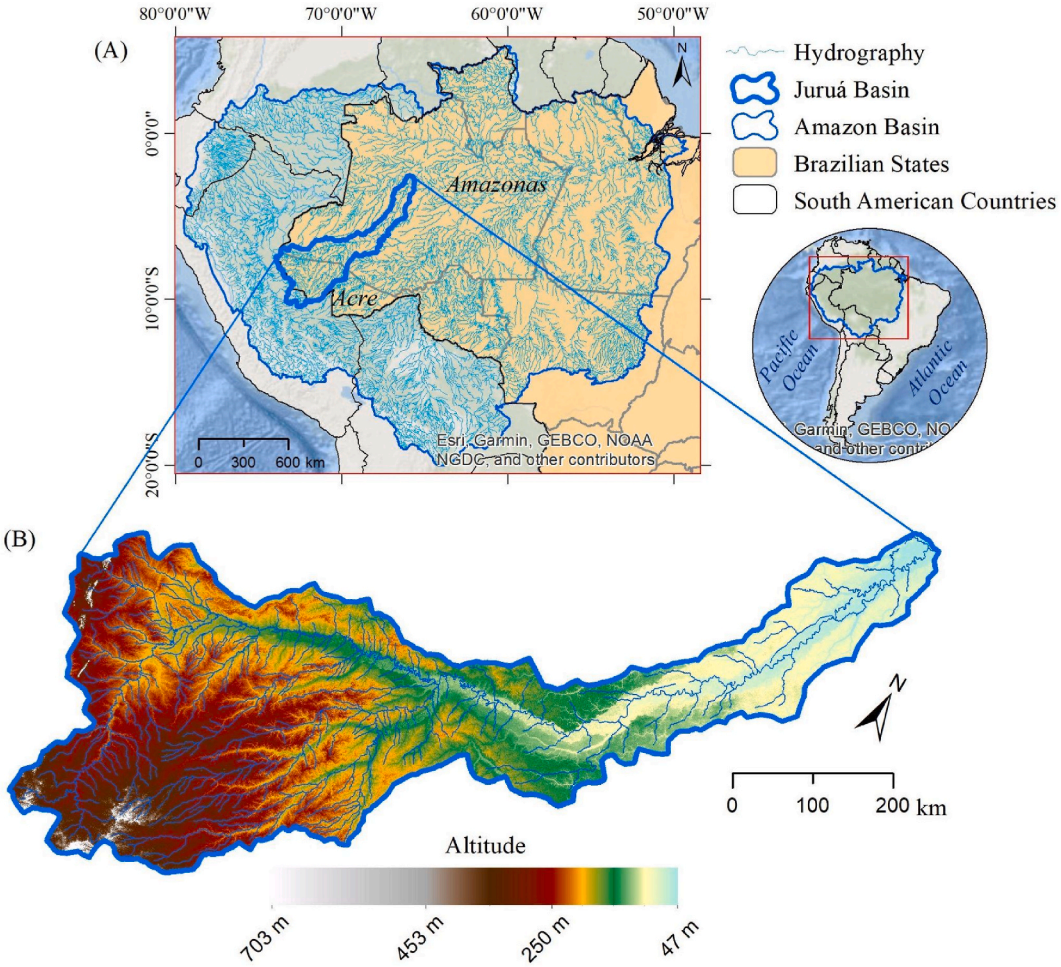


Fig. 1. The Juruá River Basin is presented according to its location in the Amazon Basin (A), in South America. The basin covers two Brazilian states, namely Acre and Amazonas. Most river sources are located in Acre state, with an altitude of around 400 m, with the Juruá River mouth located in Amazonas state, approximately at 50 m (B).

(Ciavarella. 2018). Although different climate models can be used for attribution analysis [63], HadGEM3-A is an optimised version of HadGEM3 [64], conceived specifically to facilitate attribution studies of climate extreme events [65]. The HadGEM3-A has a higher resolution compared to previous versions; it is run at an N216 horizontal resolution, with 85 vertical levels (50 tropospheric and 35 stratospheric (Ciavarella. 2018).

HadGEM3-A simulations included two scenarios: i) a natural scenario (NAT) that considers only natural forcings; and ii) the climate change scenario (ALL), which considers both anthropogenic and natural forcings [66]. In the NAT scenario, the considered natural forcings include solar irradiance variability and volcanic activity expressed as latitudinal variation of stratospheric aerosol. On the other hand, the ALL scenario covers the same natural forcings of the NAT in addition to the greenhouse gases (GHGs), ozone concentrations, and land use changes [67,68]. Since HadGEM3-A is an atmosphere-only model, it uses prescribed sea ice concentrations and sea surface temperature as boundary conditions. In the ALL scenario, these metrics are taken from observed values, while for the NAT scenario, changes due to anthropogenic influence are removed using the CMIP5 multi-model mean [65,67]. We used 525 ensemble members per scenario setup to capture internal variability, which allows for the quantification of the event probability under each climate scenario. The historical data from both scenarios (NAT and ALL) are available from 1960. For this study, we considered the period between 1981 and 2013 to validate with observational CHIRPS data.

3.3. Flood extent and land use and land cover

To identify the land use and land cover (LULC) areas potentially affected by the 2021 flood, we used the Maximum Water Extent (MWE) data extracted from the Global Surface Water Explorer [69] from the Joint Research Centre Data Catalogue (JRC). In addition, we delimited flood susceptible areas considering a 100-year return period to simulate the maximum potential flood-affected area through the Fathom Global Flood Model (FGFM) data. The FGFM is a high-resolution global flood extent map (3 arcsec or 90 m),

generated by using regionalised flood frequency to generate return period and hydrographs, being propagated through a two-dimensional hydraulic model [70]. The MWE was merged with the FGFM to ensure a more suitable flood area estimation. After obtaining the flood surface, we used the LULC data from collection 8 of the MapBiomas project [71] to estimate LULC class areas hit by floods. The LULC classification from MapBiomas covers the entire Brazilian territory since 1985, with a 30m spatial resolution.

3.4. Socioeconomic impacts database

The socioeconomic impact database was compiled using data from Brazil's Integrated Disaster Information System (S2ID) and disaster response records provided by Civil Defence. Managed by the National Secretariat for Civil Defence (SEDEC), the S2ID aims to improve data quality and transparency for disaster risk management. This system integrates disaster reports from municipalities and states across Brazil during the Emergency Situation or the State of Public Calamity. According to Brazil's National Law 14,750 of 2023 [72], an Emergency Situation is defined as an abnormal situation causing damage and losses that partially compromise the response capacity of public authorities, requiring support from other entities of the Federation. On the other hand, a State of Public Calamity refers to an abnormal situation with severe damage and losses that significantly impair the response capacity of public authorities, making it possible to overcome the situation only with substantial assistance from other entities of the Federation.

Therefore, the decrees are available in the S2ID platform, including the Disaster Information Form (FIDE), which documents the magnitude of the disaster, filled out by Civil Defence authorities [73]. This form details types of disasters, dates, times, human and material losses, and economic impacts. The analysed FIDEs were obtained from Municipal and State Civil Defence Coordinators, containing information on affected populations, households, and infrastructure damage, accessible only to Civil Defence and the Ministry of Regional Development. Specifically, we accessed FIDE annexes from Acre State municipalities, situated within the upstream area of the basin, through the State Civil Defence.

4. Methodology

4.1. Attribution of the extreme rainfall event

The event definition was based on the Juruá River Basin limits and, due to the precipitation patterns in the region, we considered four-month accumulated rainfall [74]. The extreme rainfall event studied spans the period between December 2020 and March 2021, after which the accumulated precipitation resulted in floods in July 2021. The delayed flood process is related to the natural runoff process in a river basin as large as the Amazon [11,49]. The CHIRPS data were selected as the observational data to define the extreme precipitation threshold used in the attribution analysis. After being consolidated in both spatial and temporal resolutions, HadGEM3-A data were validated against CHIRPS for model bias.

The validation process involved comparing the two datasets (CHIRPS and HadGEM3-A) over a climatological reference period from 1981 to 2013. Based on the event characterisation, four-month (December to March) rainfall accumulations were calculated for each corresponding year within the specified timeframe for each dataset, and the spatial average was obtained for each member. Normalised precipitation was then calculated by dividing each accumulated rainfall by the dataset's climatological mean of the four-month accumulations over the reference period. These were compared between CHIRPS and HadGEM3-A to determine the model bias.

The attribution analysis was conducted by first quantifying how extreme the precipitation event was relative to the climatology. This was then used as a threshold with which we assess the probability of a similar or more extreme event happening under different modelled scenarios. To establish the precipitation threshold value, we considered the normalised precipitation for the event based on the CHIRPS data. That is, the ratio between the accumulated precipitation during the event (December 2020 to March 2021) and the historical mean precipitation value (climatological period from December to March):

$$th = \frac{CHe}{CHc}$$

where th is the precipitation threshold value, CHe represents the accumulated precipitation value during the event (December 2020 to March 2021) from the CHIRPS dataset, and CHc represents the historical mean of the accumulated precipitation value during December and March, according to the climatology from CHIRPS data.

Similar normalised precipitation for the event (December 2020 to March 2021 accumulation divided by the climatological mean of December to March accumulations) was also calculated for each ensemble member of HadGEM3-A. A normal distribution function was fitted separately to all ensembles of the ALL scenario and those of the NAT scenario, and the probability of exceeding the normalised precipitation threshold (th) was then determined for each scenario. With this, we estimated whether there was a higher probability of exceeding this threshold in the ALL scenario in contrast with the NAT scenario. We calculated the Probability Ratio (PR) as follows:

$$PR = \frac{P_{ALL}}{P_{NAT}}$$

where PR is the Probability Ratio, P_{ALL} represents the probability of the distribution exceeding the threshold (th) of the extreme event occurring in the ALL scenario, and P_{NAT} represents the probability of the distribution exceeding the threshold in the NAT scenario.

The PR significance was evaluated by conducting 10,000 bootstrap samples with a replacement for P_{ALL} and P_{NAT} to build a PR distribution. The 95 % confidence interval was then derived using the 2.5th ($PR_{0.025}$) and 97.5th ($PR_{0.975}$) percentiles of the PR

distribution, considering a normal distribution. $PR_{0.025}$ (the lower bound of the confidence interval) above 1.0 denotes a significant increase in the likelihood of the extreme event in the ALL scenario compared to the NAT scenario. Since both ALL and NAT are conditioned on observed sea surface temperature and sea ice concentration, the PR calculated in this study is more closely tied to the actual conditions of the observed event. In other words, we are answering the question: how has the probability of an event of this magnitude changed under conditions similar to those of 2020–2021?

Furthermore, we based our attribution analysis on the risk-based approach [75], which employs the concept of Fraction of Attributable Risk (FAR) [76]. FAR indicates the fractional contribution of anthropogenic climate to the extreme event [77], i.e., how much the frequency of such an extreme event, or a bigger one, was changed by human-induced climate change [78]. In this way, we can use it to estimate the proportion of damage caused by anthropogenic climate change, serving as a measure that allows us to evaluate the contribution of human-induced forcing [36,37,74,75,79–81]. FAR is calculated as follows:

$$FAR = 1 - \left(\frac{1}{PR}\right)$$

4.2. LULC impacted by 2021 floods

The MWE was obtained from the Global Surface Water Explorer [69] in raster format, which represents the maximum extent of detected water over the 1984–2015 period. This water extent data was generated using three million Landsat satellite images [82] in a 30m spatial resolution. Therefore, the MWE was computed considering water detections during the analysed period (32 years), which estimated permanent and seasonal water surface, taking into account valid observations. Since the 2021 flood event was historic in a large part of the Juruá basin, the MWE mask was considered to map the potential flood-affected areas. The water mask was used in binary representation, in which flooded areas were represented by one and non-flooded areas were assigned with the number zero. Furthermore, to ensure that the maximum flood-susceptible areas were fully considered in our analysis, we merged the maximum flood limits in both the MWE and the Fathom Global Flood Model (FGFM).

Subsequently, we generated a 300 m buffer around the floodable surface to better understand the LULC class pattern in the region. To consider the effects of flooding in the expanded area, we used the least cost method [83], which calculates the distance cost, i.e., the least effort to move over a region (in this case, flooding in the floodplain). After that, using data from the MapBiomas, we extracted the LULC information for the areas affected by the flood in 2021. We calculated the affected area (in km^2) of each LULC class per municipality.

4.3. Socioeconomic impact estimation

Data related to human damage were grouped as follows: i) injured and sick, and ii) displaced and homeless. Injured refers to people who were hurt during the disaster event and require medical attention, and sick is related to people who developed pathological processes as a direct result of the effects of the disaster. Displaced refers to people who temporarily left their homes during the disaster, while homeless include, in addition to homeless people, who had their homes completely destroyed by the extreme event and require shelters or temporary housing [84].

Material damage is related to damage to housing and public infrastructures, such as health and education facilities, service providers, facilities for community use, and the amount spent on works due to the extreme event occurrence. Public losses involve expenses with medical assistance (public health and emergency medical care), sewage systems (rainwater sewage and sanitary sewage system), urban cleaning, and water and electricity supply. Private losses are composed of economic losses caused by the extreme event occurrence and reported by industry, agriculture, livestock, services, and commerce.

All the impact information was contained in tables (S2ID, 2024), which were processed, corrected, compared with other databases, and updated in collaboration with a Civil Defence officer. The analysis sought to identify the percentage of the population affected by floods in relation to the total number of inhabitants per municipality [53]. For that, we considered the total inhabitants per municipality available in the Census, which is made available by the Brazilian Institute of Geography and Statistics (IBGE), the official database at the national level [53]. This analysis aimed to detect the impacts suffered by each municipality, mostly covering the urban and peri-urban regions, due to the floods that occurred in the Juruá River Basin in 2021, including reported economic damages related to material damage, and public and private losses.

Furthermore, to understand the magnitude of the 2021 floods, we compared the impacts of this event with previous recorded flood disasters. The S2ID has had a disaster database since 2013, based on emergency and calamity decrees, i.e., when there is at least one fatality. Consequently, some municipalities presented no historical official disaster data record related to floods, as in the case of Marechal Thaumaturgo. Other municipalities, such as Feijó, Jordão, and Porto Walter have no other flood record before the 2021 floods [73]. For the municipalities with previous flood disaster records, we estimated the 2021 impacts in comparison to the historical data.

Many studies are also applying the FAR metric to estimate the fraction of observed socioeconomic impacts and attribute it to anthropogenic climate change [37,41]. In this approach, the authors consider that the contribution of anthropogenic climate change to extreme event occurrence is replicable for the attributable fraction of impacts [85]. Although we recognise that the nonlinear relationships between meteorological variables and impacts may prevent FAR from fully capturing the true effects of anthropogenic climate change [78], we emphasise that FAR remains a valuable metric for preliminary estimates [86]. Particularly, when the connection between the meteorological variables and impacts is difficult to model or the observation data availability is limited [87],

as in our study. Therefore, in this study, we will extend the FAR metric for socio-economic impact analysis and present the limitations in the discussion section.

5. Results

5.1. Extreme rainfall event

The precipitation event occurred throughout the Juruá River Basin, mainly in the upstream municipalities, increasing river levels and causing flooding all over the basin. The rain gauge record analysis showed that the four-month accumulated rainfall, from December 2020 to March 2021, was above the average accumulated precipitation for this period over 18 rain gauges. Furthermore, the precipitation anomaly analysis, using CHIRPS data for both 2021 and the validation period, indicated that the upstream area of the basin witnessed a substantial surplus of rainfall during 2021, reaching 48 % above the average rainfall from December to March. Conversely, the downstream section of the basin presented a shortfall in precipitation compared to the historical average (Fig. 2).

Streamflow data for the hydrological year 2020–2021 provides insights into the dynamics of the Juruá, Envira, and Tarauacá rivers, shedding light on both the magnitude and timing of the observed events. Within the upper and middle reaches of the basin, the streamflow patterns exhibit a distinctive multipeak flood wave characteristic, suggesting a rapid response to precipitation inputs. On the other hand, downstream areas display smoother hydrographs, often indicating a single pronounced flood pulse, as exemplified by the Eirunepé gauge, situated furthest downstream. Across all locations, the flood event spans from December 2020, marking the onset of the flood process, through March 2021, where the recession curve becomes discernible. Notably, in many instances, the observed streamflow surpasses the 95th percentile values, particularly evident in the middle and lower reaches of the basin, reflecting the anomalies depicted in Fig. 2.

5.2. Attribution analysis

5.2.1. Model validation

The HadGEM3-A model underwent validation against observational CHIRPS rainfall data spanning the climatological period from

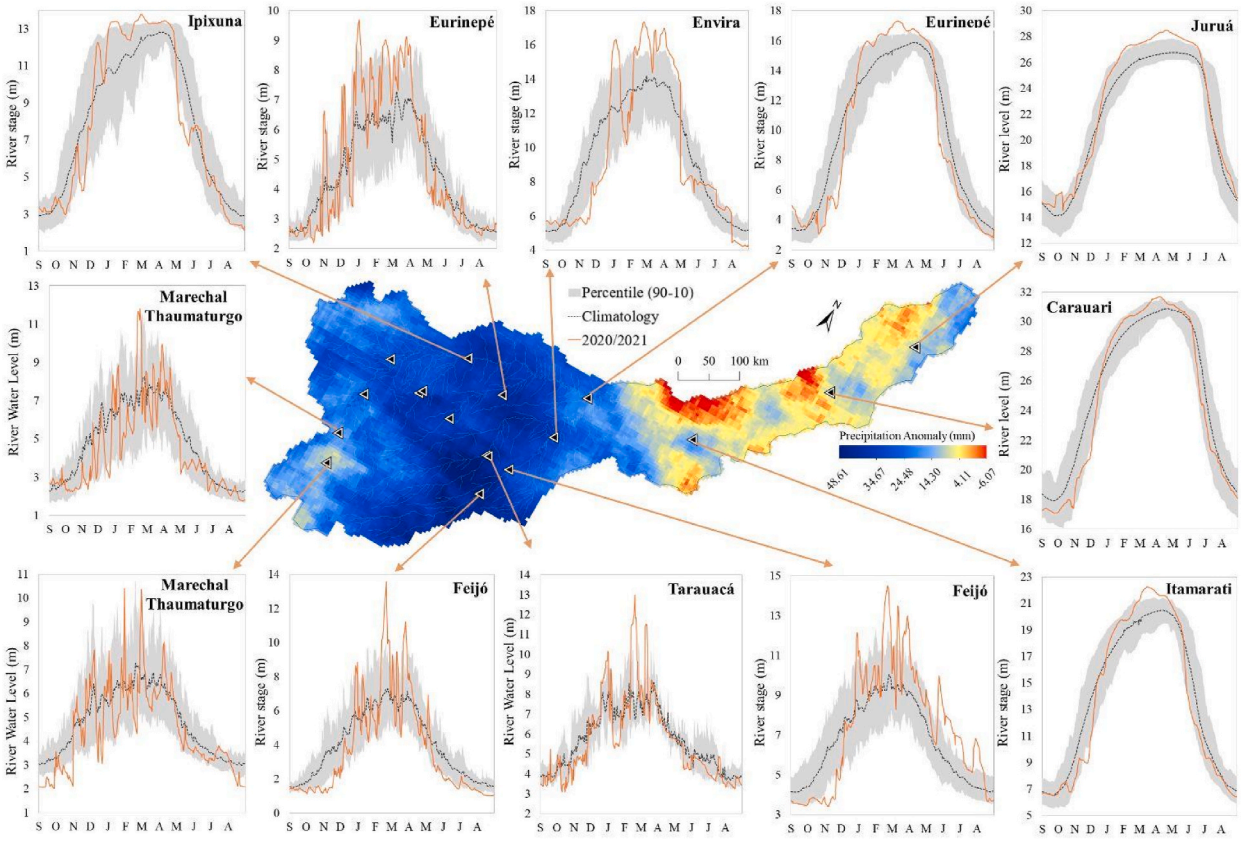


Fig. 2. Precipitation anomaly recorded during the analysed period (December 2020 to April 2021) in the Juruá River Basin. The triangles represent the gauge locations, with some of their historical river water level (light grey), the historical average (black line), and the river water level during the extreme precipitation event (orange line) shown in the subpanels.

1981 to 2013. The correlation coefficient ($r = 0.63$) indicates a positive linear relationship between observed and modelled values, while the Mean Absolute Error (MAE) of approximately 245 mm highlights notable differences in magnitude. Further statistical analysis, assuming a normal distribution, revealed distinct characteristics between CHIRPS and HadGEM3-A. Although both datasets have been normalised to a mean (location) of 1.0, CHIRPS exhibits a lower median (0.9978) than HadGEM3-A (1.0070), suggesting a slightly left-shifted distribution in observed data. Concerning scale parameters, CHIRPS showed lower variability, with a standard deviation of 0.0754 and interquartile range (IQR) of 0.0768, compared to HadGEM3-A's 0.0797 and 0.1075, respectively. Despite a slight rightward bias in the modelled data, the fitted normal distributions exhibited significant overlap (Fig. 3), affirming the suitability of the HadGEM3-A model for attribution analysis.

5.2.2. Event attribution

We compared ALL and NAT scenario simulations to evaluate the differences between the ensemble distributions (Fig. 4). The ALL scenario presents a distribution slightly shifted to the right-hand side compared to the NAT scenario, which suggests an increased probability of higher or extreme precipitation events. The event threshold was 1329 mm according to CHIRPS data (1.20 in the normalised precipitation), which shows that the studied event is indeed extreme since it is located at the right tail of both distributions. In this sense, the differences between the scenarios mean that the rainfall event is more extreme in the NAT scenario than in the ALL scenario, that is, less likely to occur in an environment without anthropogenic climate change.

The PR presented a value of 2.53 [1.45, 4.65] (Table 1), suggesting that anthropogenic climate change has increased the probability of occurrence of an event of this magnitude, or greater, by more than twice. Furthermore, the estimation of the return period showed that in an ALL scenario, the studied extreme event now occurs once every 42 years. The same event was estimated to occur once every approximately 107 years in a NAT scenario. In addition, we estimated that 61 % (FAR = 0.61) of the likelihood of the event occurring can be attributed to anthropogenic influence on the climate.

5.3. Socioeconomic impacts

5.3.1. LULC dynamics

The Juruá River Basin is composed of eight LULC classes: i) forest formation, ii) savanna formation, iii) floodable forest, iv) wetland, v) grassland, vi) pasture, vii) urban area, and viii) river, lake and ocean (Fig. 5). Among them, forest formation is the predominant class, covering almost the entire Juruá River Basin with nearly 200,000 km^2 (93 % of the total area). Pastures and urban areas are highly concentrated along roads, especially the BR-364 highway, and rivers, being the most economically affected by floods. Considering the potential flood-affected area, approximately 21,000 km^2 (9.34 %) were flooded in the Juruá River Basin during the 2021 floods (Fig. 5). The forest cover was the most affected LULC class (in total area) by the 2021 floods, due to its predominance. However, although the other LULC classes were not as widespread in the study area, it is estimated that around 30 % of the urban area and 20 % of the total pasture area were affected by the increase in river levels.

It was estimated that around 25 km^2 (almost 40 %) of the total urban area in the Juruá River Basin was affected by the floods. From the 25 km^2 impacted urban area, 23 % corresponds to Cruzeiro do Sul city, followed by the cities of Eirunepé (11 %) and Tarauacá (10.7 %) (Fig. 6A). When considering pasture areas, nearly 1150 km^2 out of a total of approximately 5700 km^2 were affected by the floods, i.e. 20 % of the pasture in the study area. Among the most affected municipalities are Feijó, Tarauacá, and Cruzeiro do Sul, with more than 100 km^2 affected in each of them (Fig. 6B).

5.3.2. Affected population

The 2021 floods directly affected more than 43,000 and 28,000 people in the assessed Acre and Amazonas states' municipalities, respectively [73]. In addition, the total number of indirectly affected people (e.g., people who were isolated or without access to

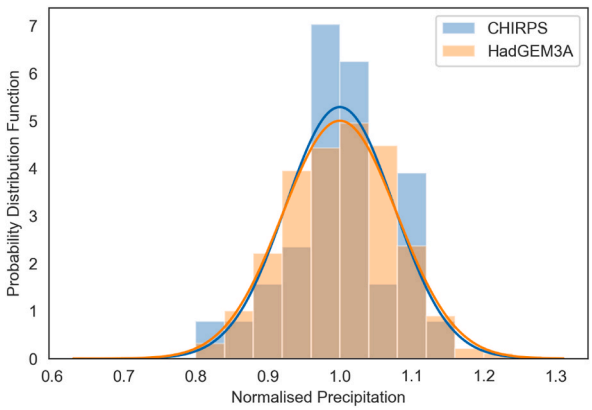


Fig. 3. Validation of the HadGEM3-A data with the observed data from CHIRPS for the climatological period from 1981 to 2013. The solid line represents the fitted normal distributions.

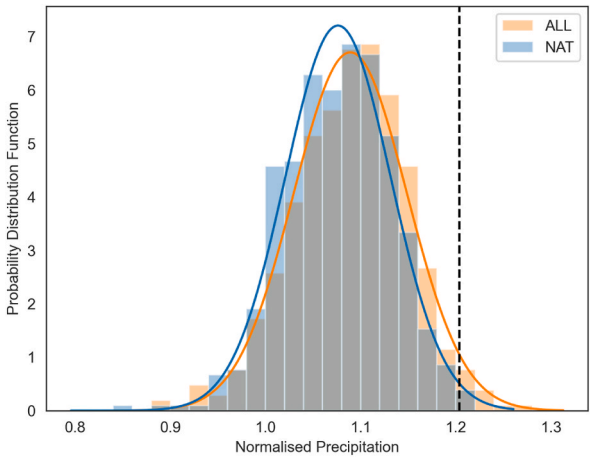


Fig. 4. Histogram with the distributions for the analysed period (between December 2020 and March 2021) for NAT and ALL scenario ensembles. The threshold for the analysed extreme event is presented in the black dashed line.

Table 1
Attribution metrics for the extreme precipitation event in the Juruá River Basin based on NAT and ALL scenarios. The 95 % confidence interval (CI) was obtained by the 2.5th and 97.5th percentiles using 1000 bootstrap samples.

Metric	CHIRPS Estimate [95 %CI]
Event threshold (normalised precipitation)	1.20
Probability Ratio (PR)	2.53 [1.45, 4.65]
Fraction of Attributable Risk (FAR)	0.61 [0.31, 0.79]
Natural Scenario (NAT) Return Period (years)	106.54 [73.08, 174.56]
Climate Change Scenario (ALL) Return Period (years)	42.07 [30.86, 60.93]

drinking water or food due to the disaster) reached more than 97,000 in Acre and over 25,000 in Amazonas [73]. The Juruá River Basin region was severely impacted, with the river's levels exceeding historic levels. Consequently, many municipalities located in the Juruá River Basin decreed a State of Emergency due to loss and damage caused by the floods (Fig. 7). Among them, Cruzeiro do Sul and Tarauacá recorded one death each due to the flood event [88], while Atalaia do Norte recorded three casualties [73].

In Jordão, all inhabitants (100 %) were affected by the floods (Table 2) (additional information is provided in section 6.2). Other greatly affected municipalities in Acre state include Cruzeiro do Sul, with more than 20 % of the population affected by the floods, followed by Mâncio Lima (12.46 %) and Rodrigues Alves (11.71 %). In addition to the floods, a landslide blocked the BR-364 highway, isolating the cities of Manoel Urbano, Feijó, Tarauacá, Cruzeiro do Sul, Rodrigues Alves, and Mâncio Lima, which worsened the situation in these municipalities [88].

In official records, the total affected population by the 2021 floods accounted for 334 injured, 5916 sick, 12,092 homeless, and 46,538 displaced. In Itamarati, almost 50 % of the inhabitants were affected by the floods, of which 37 % (3000 people) were left homeless. A similar situation occurred in Jutaí, with more than 40 % of its population affected, followed by Atalaia do Norte (29.16 %) and Uarini (21.44 %). In Envira, the Tarauacá River reached the historic mark of 17.20 m (the alert level is 14.90 m), flooding part of the city. Consequently, 14 % of the population was affected, with the displacement of 12 % (1056 displaced people; 977 homeless) to temporary (public or private) shelters [28]. Cruzeiro do Sul had the highest number of displaced people (15,808), followed by Jordão (7,199) and Jutaí (6061). The municipality with the highest number of homeless people was Itamarati with 3000 people, followed by Jordão (2,246) and Atalaia do Norte (1,826). All these municipalities have decreed a Situation of Emergency or Public Calamity.

5.3.3. Economic losses

The 2021 floods also caused material and environmental damage, and interruption of energy, food, and drinking water supplies in the period following the floods. Furthermore, many farmers and riversiders suffered losses regarding their production in both Acre [88] and Amazonas states. Moreover, the population faced traffic interruptions and a rise in cases of waterborne diseases [29]. For example, as stated by the municipal environment department of Ipixuna, Amazonas state, the floods contributed to the contamination of approximately 50 % of agricultural soil used for farmers' subsistence [89].

The impacts in the Juruá River Basin region caused by the February 2021 floods generated many economic losses, both public and private. Losses were divided into three categories in this analysis: Private Losses (Commerce and Service, Agriculture and Livestock, and Industry), Public Losses (Water supply, Urban cleaning, Sewage system, and Health Care), and Material Damage (Public infrastructure and Dwellings) (Table 2). The Private Losses recorded the largest monetary losses, US$ 8.8 million, followed by Material Damage with US$ 6.2 million, and Public Losses with US$ 1.6 million.

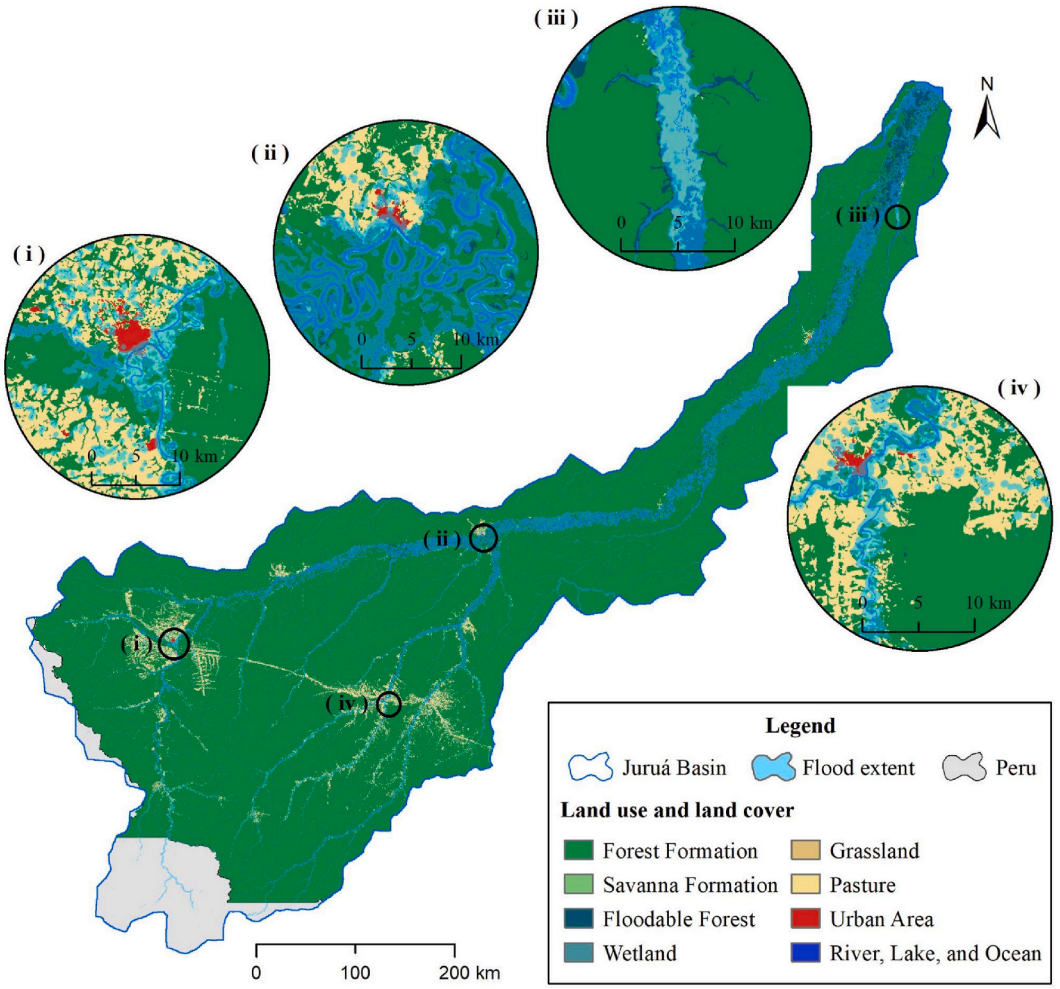


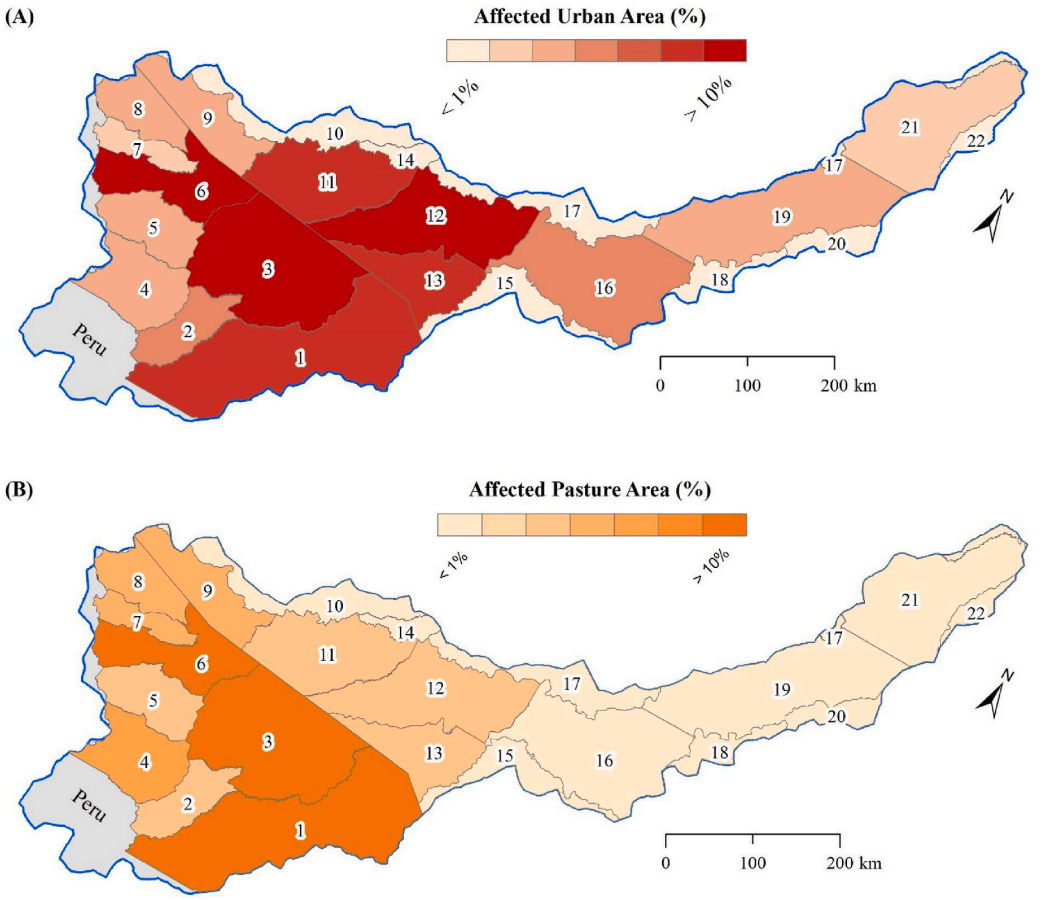
Fig. 5. The existing LULC in 2021 in the Juruá River Basin is presented with the flood extent overlay. The zoom areas highlight the LULC class more affected by the floods, highlighting the affected urban and pasture areas in Cruzeiro do Sul (i), Eirunepé (ii), and Tarauacá (iv), and affected pasture areas in Juruá (iii).

Regarding the economic impacts in Acre and Amazonas states in private losses, agriculture and livestock were the most affected sectors, with the largest losses ever recorded in the analysed municipalities, a total of US$ 8.6 million. The greatest damages reported in the Agriculture and Livestock category were in the Amazonas state. Eirunepé municipality reported losses only in agriculture and livestock, presenting the greatest losses in this category among the municipalities, US$ 2.3 million, followed by Envira, with US$ 1.1 million.

Acre state recorded a total of US$ 5.6 million, and Amazonas state recorded US$ 11.1 million in material losses (Table 3). More specifically, Tarauacá municipality presented the greatest losses, with a total of US$ 2.6 million, distributed in all categories. In sequence, Eirunepé and Feijó recorded US$ 2 million each in monetary losses; however, these municipalities had no record of public losses in health and private losses in commerce and services. Jordão and Ipixuna had no records of any material damage, although 100 % of Jordão's population was affected by the floods; Cruzeiro do Sul recorded losses only in housing (dwellings).

5.3.4. Event magnitude and attributable impacts to anthropogenic climate change

Among the total affected people recorded since 2013 in Cruzeiro do Sul municipality (Acre state), 60 % were affected in 2021. Similarly, most of the impacted people in the historical records in Rodrigues Alves (85 %) and Tarauacá (48 %), both in Acre state, were accounted for in 2021. In the Amazonas state, considering all the flood disaster records since 2013, Jutaí and Atalaia do Norte municipalities had the greatest number of affected people during the 2021 floods, accounting for 56 % and 53 %, respectively. In other municipalities, the proportion of affected people by the 2021 floods varied between 5 % and 30 % of the total recorded. Specifically, Benjamin Constant municipality had no record of human or material damage in 2021. The predominance of flood impacts from 2013 being highly concentrated in 2021 shows us the magnitude of this extreme flood event. Although these records allow us to dimension the 2021 floods, we highlight that our analysis considered only the last decade, due to the available data in the region (S2ID presents



Municipalities					
1. Feijó	5. Porto Walter	9. Guajará	13. Envira	17. Jutaí	21. Juruá
2. Jordão	6. Cruzeiro do Sul	10. Atalaia do Norte	14. Benjamin Constant	18. Tapauá	22. Uarini
3. Tarauacá	7. Rodrigues Alves	11. Ipixuna	15. Pauini	19. Carauari	
4. Marechal Thaumaturgo	8. Mâncio Lima	12. Eirunepé	16. Itamarati	20. Tefé	

Fig. 6. The estimation of urban and pasture areas affected by the 2021 floods. The percentage of total affected urban (A) and pasture area (B) by municipality, considering the total urban and pasture areas in the Juruá River Basin.

records from 2013, as cited above).

Finally, according to the event attribution analysis, we found that 61 % (FAR = 0.61) of the likelihood of such an extreme event occurring was attributable to anthropogenic climate change. Therefore, extending this analysis to flood impacts, nearly US$ 10.1 [5.1, 13.1] million of the total losses caused by the 2021 floods could be attributable to human-induced climate change. It is estimated that among the economic impacts verified in agriculture and livestock (more than US$ 6 million), approximately US$ 3.7 [1.8, 4.7] million would be attributed to anthropogenic influence on climate. Public losses were estimated to be more than US$ 7 million, of which US$ 4.3 [2.1, 5.5] million could be attributable to anthropogenically induced changes in climate. In addition, the most economically affected municipality, Sena Madureira, witnessed US$ 7.4 million in losses, of which US$ 4.5 [2.2, 5.8] million are attributable to the human effects on climate. Finally, Porto Acre and Envira presented approximately US$ 854 [434, 1106] thousand and US$ 671 [341, 869] thousand, respectively, of losses attributable to anthropogenic climate change.

6. Discussions

6.1. Extreme events in a changing climate

The consideration of extreme climate events according to the classic extreme event theory, in which the probability of such kind of event occurring is a constant, does not fit in a continuously greenhouse-influenced world [90]. A warming climate is leading us to more

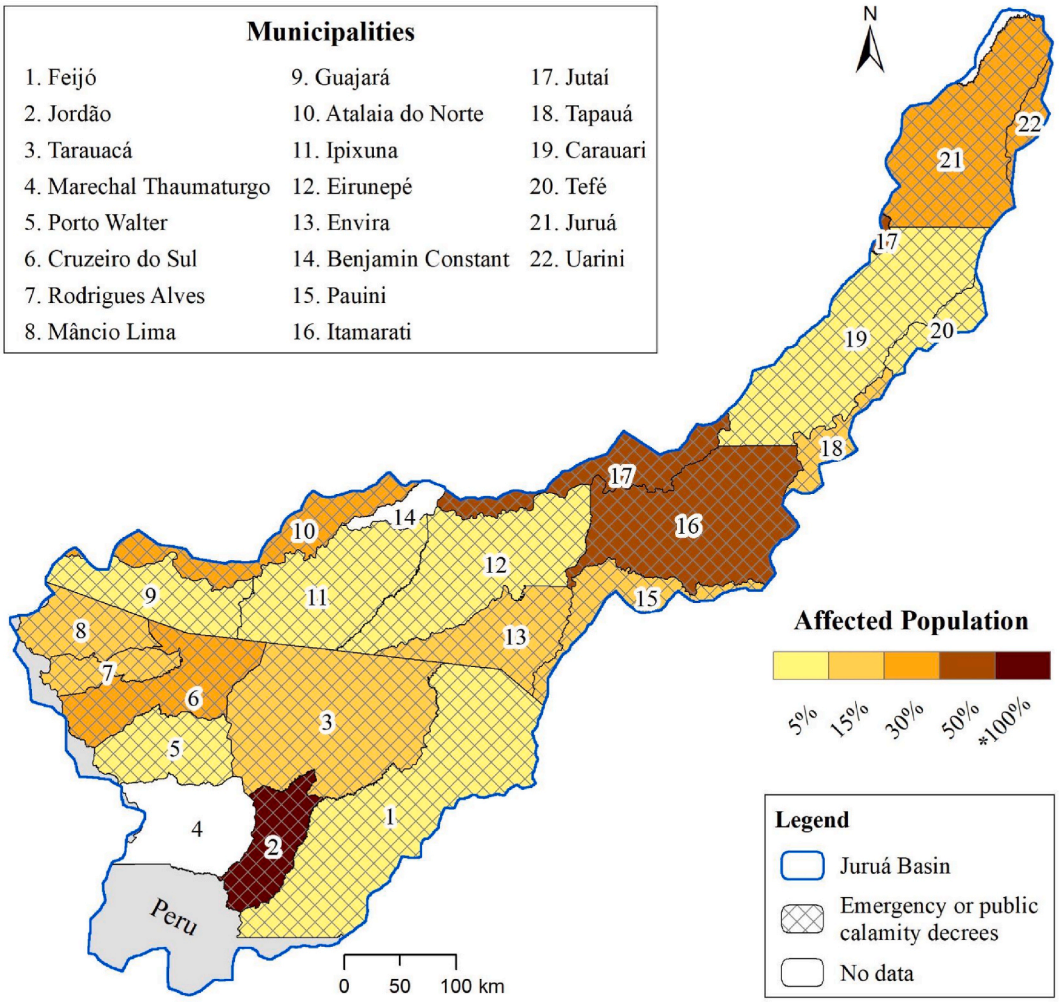


Fig. 7. Percentage of people affected by floods in each municipality of the Juruá River Basin. No data was obtained for the Marechal Thaumaturgo and Benjamin Constant municipalities. Jordão municipality presents a particular case, in which the municipal data estimates more population than national estimates (for details, please see section 6.2 in the discussions).

frequent extreme climate events, such as heavy rainfall and floods, with geographical variability [91]. Multiple global and regional studies have underscored the escalating frequency and expectation of flood events attributable to climate change [5,35,42,92].

Specifically, research conducted for Brazil has pinpointed the states of Rio Grande do Sul, Santa Catarina, and Acre as particularly vulnerable regions to significant socio-economic consequences from potential flood events under various global warming scenarios [93]. Although the Acre and Amazonas states, specifically the Juruá River Basin region, frequently experience flooding [94,95], this phenomenon has occurred with a higher frequency and magnitude. In fact, the upstream area of the Juruá River Basin presents a positive precipitation trend [96], which could result in more extreme floods in the coming years.

Corroborating with this, here we showed that the precipitation event that caused floods in the Juruá River Basin in 2021 is 2.53 times as likely, or 153 % more likely, to occur due to anthropogenic climate change. In a natural climate scenario, such extreme events are likely to occur once in 107 years; however, in our current changed climate, their return period is 42 years. In addition, 61 % of the likelihood of such an extreme event occurring is attributable to climate change. We also presented an extension of this evaluation to account for socio-economic impacts.

Another indication of changes in climate can be found in Dubreuil et al. [97], in which the authors defined annual climate types, based on temperature and precipitation for Brazil, and analysed their variation between 1964 and 2015. The results showed changes in the average Köppen's type in 17 % of the analysed stations, including a variation in the Juruá River Basin. In the Southeastern part of the Juruá basin, i.e., Tarauacá and Envira tributaries, the Af (warm climate without dry season) became Am (warm monsoon climate), which indicates a greater presence of drought season, compensated by periods of intense precipitation, as seen in the analysed period.

The current climate emergency highlights the importance of understanding the effects of climate change on the occurrence of hazardous events and their impacts on society. At the time of conducting this study, extreme events had already been documented in Acre and Rio Grande do Sul [98] states. This emphasises the pivotal importance of such studies and their relevance in informing public

Table 2
Human damage caused by the 2021 floods by municipality, according to the four analysis classes: displaced, homeless, sick, and injured people.

		Municipality	Human Damage				Directly Affected Population	
			Displaced	Homeless	Sick	Injured	Total number	% of total population
Acre	1	Feijó	120	367	0	0	487	1.51 %
	2	Jordão[a]	7199	2246	0	0	9445	109.47 %
	3	Tarauacá[b]	974	831	50	0	1855	5.22 %
	4	Marechal Thaumaturgo	–	–	–	–	–	–
	5	Porto Walter	200	55	0	0	255	2.78 %
	6	Cruzeiro do Sul[b]	15,808	876	0	0	16,684	21.27 %
	7	Rodrigues Alves	1542	136	0	0	1678	11.71 %
	8	Mâncio Lima	1900	0	0	0	1900	12.46 %
Total (Acre)			**27,743**	**4511**	**50**	**0**	**32,304**	**3.89 %**
Amazonas	9	Guajará	270	27	0	0	297	2.11 %
	10	Atalaia do Norte[b]	2561	1826	20	10	4417	29.16 %
	11	Ipixuna	415	0	0	0	415	1.87 %
	12	Eirunepé	86	178	708	0	972	3.17 %
	13	Envira	1056	977	250	50	2333	14.29 %
	14	Benjamin Constant	–	–	–	–	–	–
	15	Pauini	865	992	4	8	1869	10.30 %
	16	Itamarati	1000	3000	0	0	4000	49.75 %
	17	Jutaí	6061	20	1700	24	7805	43.45 %
	18	Tapauá	1328	−0	820	145	2293	12.02 %
	19	Carauari	732	50	145	62	989	3.85 %
	20	Tefé	1446	52	1336	24	2858	4.65 %
	21	Juruá	1050	255	470	0	1775	16.40 %
	22	Uarini	1925	204	413	11	2553	21.44 %
Total (Amazonas)			**18,795**	**7581**	**5866**	**334**	**32,576**	**0.83 %**
Total (Juruá River Basin)			**46,538**	**12,092**	**5916**	**334**	**64,880**	**13.54 %**

[a] Jordão presented more affected population than the official estimation of inhabitants in the municipality. This case is discussed in section 6.2.
[b] Municipalities that recorded fatalities.

authorities and society at large about the pressing need to mitigate the escalating risks exacerbated by climate change.

6.2. *Socioeconomic impact records: the effects of data underestimation*

Loss estimation supports important decisions carried out by decision-makers on disaster preparedness, mitigation and adaptation policies, providing a sense of urgency and need [99]. In addition, reliable disaster impact data can aid in the projection of future costs of climate change [100]. Therefore, to ensure the high quality and consistency of disaster loss estimates, the data must be collected, verified, and managed by specialised professionals [101]. However, many challenges are faced when reporting disaster loss estimation, such as inconsistencies in the reports, methodological difficulties, missing data, and double counting of casualties and damages [101, 102], and transnational compatible datasets, since climatological driven disaster events cover large areas. Each of these challenges presents different limitations and implications for organisation structures, governance and communication, response and adaptation strategic planning.

In Brazil, the official disaster loss estimation is done during the hazardous event, which enables the affected municipalities to receive financial aid from the national government [20]. Nevertheless, due to the nature of the disaster and the logistical difficulty of carrying out this survey in time, much human and material damage ended up being underestimated [103]. An example of underestimated data is the exact survey of human and material damage outside urban centres and peri-urban areas, but especially difficult in traditional and indigenous people's territories due to the difficulty of access and communication during the disaster. Many villages do not have human, technical and infrastructural means for registering, documenting, and communicating impacts. In addition to the difficult access to remote communities of the Amazon, Civil Defence actions during the disasters are limited according to the impact extent and number of people needing support [104], usually with all resources used for the areas with higher concentration of urban population, such as the capital city of the municipalities.

Moreover, disagreement in the population database could make the real estimation of affected people difficult. For instance, the affected population in Jordão reached 109.5 % of the municipality's population. This occurred because officially the municipality had an estimated 8628 residents in 2021 [105]; however, the Civil Defence from Acre estimated that 9445 people were impacted by the 2021 floods (2246 homeless and 7199 displaced) [106]. Although the municipality identified a higher number of inhabitants, we considered data from the Census [53] because it is the official population database at the national scale.

Another piece of data that ends up being left out of official surveys is post-event health expenditure, whether on hospitalisations, treatment of illnesses resulting from the flood [107], or mental illnesses, such as anxiety, depression, and panic syndrome [108]. Then, the number of people requiring health care assistance can be much higher than injured and sick people (more than 6 thousand in our case study) [109]. The sudden increase in cases requiring urgent care enhances the local population's vulnerability and impacts the municipality's public economy [22]. Therefore, it is essential to adopt analytical approaches to estimate more realistic human and economic damages to develop medium- and long-term plans capable of more effectively dealing with the challenges of climate change.

Table 3
Economic impact by municipality: 2021 flood losses in Acre and Amazon states.

		Municipality	Public Losses (US$)				Private Losses (US$)			Material Damage (US$)		Total by municipality (US$)
			Health Care	Sewage System	Urban Cleaning	Water Supply	Agriculture/ Livestock	Commerce/ Service	Industry	Public Infrastructure	Dwellings	
Acre	1	Feijó	–	186,220	93,110	93,110	279,330	–	–	3724	1,396,648	**2,052,142**
	2	Jordão	–	–	–	–	–	–	–	–	–	**-**
	3	Tarauacá	18,622	93,110	9311	37,244	176,909	186,220	9311	1,927,374	223,464	**2,681,564**
	4	Marechal Thaumaturgo	–	–	–	–	–	–	–	–	–	**-**
	5	Porto Walter	–	–	1862	14,898	93,110	–	–	132,775	5959	**248,603**
	6	Cruzeiro do Sul	–	–	–	–	–	–	–	–	9125	**9125**
	7	Rodrigues Alves	37,244	40,968	9311	5587	48,045	17,691	–	178,771	116,015	**453,631**
	8	Mâncio Lima	–	–	–	–	167,598	–	–	–	–	**167,598**
Total (Acre)			**55,886**	**320,298**	**113,594**	**150,839**	**764,992**	**203,911**	**9311**	**2,242,644**	**1,751,211**	**5,612,663**
Amazonas	9	Guajará	130,604	–	–	32,775	305,438	–	–	–	–	**468,817**
	10	Atalaia do Norte	9311	–	–	–	2218	–	–	161,172	38,083	**210,784**
	11	Ipixuna	–	–	–	–	–	–	–	–	–	**-**
	12	Eirunepé	–	–	–	–	2,389,849	–	–	–	–	**2,389,849**
	13	Envira	64,908	13,635	–	14,872	1,186,739	–	–	50,279	55,866	**1,386,299**
	14	Benjamin Constant	–	–	–	–	–	–	–	–	–	**-**
	15	Pauini	12,104	–	–	–	477,654	–	–	52,142	45,555	**588,454**
	16	Itamarati	151,755	–	–	–	975,135	–	–	171,951	11,546	**1,310,387**
	17	Jutaí	38,175	–	–	–	260,708	–	–	27,933	–	**326,816**
	18	Tapauá	68,382	–	22,346	36,127	53,631	–	–	28,389	390,764	**599,639**
	19	Carauari	294,457	–	–	–	255,121	–	–	47,859	20,484	**617,920**
	20	Tefé	–	–	–	–	919,739	–	–	324,259	150,056	**1,394,054**
	21	Juruá	72,995	–	–	–	345,754	–	–	180,633	283,799	**883,181**
	22	Uarini	37,751	–	–	–	698,184	–	–	193,883	20,901	**950,720**
Total (Amazonas)			**880,442**	**13,635**	**22,346**	**83,774**	**7,870,170**	**-**	**-**	**1,238,500**	**1,017,054**	**11,126,920**
Total (Juruá River Basin)			**936,308**	**333,933**	**135,940**	**234,613**	**8,635,162**	**203,911**	**9311**	**3,481,144**	**2,768,265**	**16,739,583**

The population in the Juruá River Basin is mainly composed of traditional communities and the riverside population. The original communities usually depend on subsistence small-scale agriculture, family plantations, hunting, and fishing [110], while the riverside and urban population are dependent on agriculture carried out on the riverbanks. Therefore, the floods economically affect these populations and, in addition, threaten their food security [95]. This effect was verified in the Juruá River Basin, in which agriculture and livestock represented the main economic losses during the 2021 floods (Table 2). In brief, the increase in frequency and magnitude of flood events affecting this region requires a combination of governmental, non-governmental, and organised civil society efforts [111].

6.3. Policy Approaches for adaptation and disaster risk reduction

Based on this comprehensive assessment of the available data on socioeconomic impacts and climate-related challenges faced, several policy approaches and strategies can be recommended to enhance climate change adaptation, disaster preparedness, and disaster risk reduction in the Juruá River Basin. Although here we explore recommendations for floods, most of them are also adequate for extreme droughts, like the 2023/24 drought experienced by most of the Amazonian population [16]. By implementing these measures, policymakers can better protect vulnerable populations, reduce economic losses, and build resilience to future climate-related disasters in the Juruá River Basin and similar regions worldwide:

a) **Early Warning Systems (EWS)**: Effective EWS significantly reduce disaster impacts by issuing timely warnings to communities and authorities, enabling proactive evacuation and preparedness measures [112]. Given the increasing frequency of floods in the Juruá River Basin, it is necessary to enhance EWS, including (i) investments in modern meteorological infrastructure, such as weather radar and satellite monitoring, (ii) establishment of reliable communication channels and languages to remote communities for disseminating alerts, and (iii) conduct regular drills and training for emergency response teams and local population.
b) **Community-based DRR:** Engaging local communities (i.e., indigenous and riverside populations) in DRR strategies can significantly improve their effectiveness [113]. This involves raising awareness about flood (droughts) risks, enhancing community resilience through livelihood diversification away from flood-prone areas, and providing training in early response actions, among other measures.
c) **Improved LULC planning and infrastructure resilience**: LULC planning has a key role in reducing vulnerability to climate change and improving DRR management [114,115]. Strategies include integrating climate projections into LULC planning regulations, avoiding construction in flood-prone areas, promoting resilient infrastructure design, and adopting nature-based solutions [116], such as reforestation, agroforestry, and wetland restoration.
d) **Policy integration**: Strengthening coordination among governmental and non-governmental agencies, community organisations, schools, and research institutions is crucial for effective DRR management. Implementing comprehensive policies that integrate DRR with climate change adaptation strategies ensures a holistic approach to managing multi-risks [117,118]. For instance, aligning LULC planning regulations with flood and drought hazard forecasts and integrating climate change scenarios into development plans can reduce impacts.
e) **Data Improvement and Standardisation**: Robust data collection supports evidence-based decision-making in DRR, providing reliable information for allocating resources and implementing effective response measures [100]. Establishing standardised protocols for data collection, verification, and reporting, as well as investing in technologies that facilitate real-time data sharing among stakeholders and strengthen the capacity of local authorities to collect and manage data effectively, can improve the accuracy of impact assessments.
f) **Financial Mechanisms and Insurance Coverage**: Develop and promote economic mechanisms to provide financial support for recovery and reconstruction, such as disaster insurance and risk transfer. Ensuring that vulnerable populations have access to affordable insurance coverage against climate-related risks is essential to provide financial security, incentivise proactive DRR management, support economic stability, and promote societal resilience, among other benefits [119].
g) **Communication of event attribution results to policymakers and laypeople:** Understanding the effects of climate change is essential for effective adaptation and mitigation measures to be implemented. According to Zanocco et al. [120], confidence that climate change has influenced extreme events varies depending on several factors, such as the type of event, level of education, and political affiliation. One challenge is that scientific communication is not always effective. This is partly due to the use of different scientific approaches for event attribution, which may lead to different results. Moreover, the prevailing perception that such events are natural and historically recurrent contributes to a sense of inevitability, reinforcing the notion that little can be done to address them. In this regard, McClure et al. [121] suggested adopting a clearer narrative that emphasises the multifactorial nature of these phenomena, highlighting that part of them is related to the increasing concentration of greenhouse gases in the atmosphere. They further underscore that actions can be taken to reduce these emissions and, consequently, mitigate their influence on extreme events.

6.4. Limitations and recommendations

Some limitations were identified during this study regarding data acquisition, such as the sparse coverage of ground-based rain gauge networks in the Juruá River Basin [62] and the inconsistent maintenance of the existing ones. For example, when considering stations with the lowest number of gaps in the National Water and Sanitation Agency (ANA) database, Cordeiro and Blanco [59] found historical rainfall data for only 164 stations across the entire Brazilian Amazon (5,217,423 km^2). The difficulty of having widespread

rain gauges in the Amazon forest region is understandable, due to logistical access and the huge presence of high tree canopy. Therefore, we analysed existing ground-based rainfall data and complemented it with remote sensing data, i.e., the CHIRPS, which satisfactorily represents the rainfall seasonality in the region [59,62].

Secondly, while the HadGEM3-A model has demonstrated its capability to simulate extreme precipitation events [37,97,122], we acknowledge that the use of a single model may introduce dependencies on its performance [123]. Furthermore, although Monerie et al. [124] suggest that higher model resolution improves the representation of convective systems in South America, we highlight that limitations are related to potential uncertainties and data biases in climate modelling parameterisations [41].

Moreover, the large extent of the Juruá River Basin (approximately 220,000 km^2), associated with frequent cloud cover, made it difficult to map the exact extent of the floods between December 2020 and March 2021. Because of that, we considered the two flood extent data, namely the Maximum Water Extent (MWE) [69,82] and the Fathom Global Flood Model (FGFM) [70]. Despite this, small-scale family agriculture [125] may have been missed in the LULC damage assessment due to image (un)availability and constraints with spatial resolution.

In addition, the way data is recorded for the S2ID system also presents some limitations. In the case of sudden onset disasters, the Civil Defence agents have a period of up to 10 days from the start of the extreme event to register, fill, and update the data on the S2ID system [126]. For gradual disasters, the deadline is 10 days from the declaration of the State of Emergency or Public Calamity (when death is recorded) [126]. Therefore, the data is normally filled out while the disaster is still ongoing, and before such information is finalised, which can only occur after the re-establishment of activities, with usually a very limited number of agents covering all the necessary tasks.

This limitation can be noted in some municipalities of Acre state that declared a State of Emergency through S2ID. For instance, the FIDE used in S2ID presented only one death, which occurred in Cruzeiro do Sul; however, the response document presented a second fatality, registered in Tarauacá [127,128]. Other data also showed disagreement between the databases, such as sick people (50 people in S2ID, 57 people in the response files); homelessness, with 1499 people recorded in the S2ID and a total of 4511 people estimated in the response files; and 18,850 displaced people recorded in the S2ID, but 25,000 in the response files [127–136]. Therefore, as the response file is a restricted document, studies using only FIDE data through S2ID may underestimate the impact of past disasters.

A last drawback to highlight is the extended use of the Fraction of Attributable Risk (FAR) to estimate the attributable socioeconomic impacts of climate change [85]. As we emphasised in section 4.3, FAR can be not totally effective in capturing the effects of anthropogenic climate change and the impacts of an extreme event. This occurs due to the non-linear relationship between climate variables and social and economic characteristics of impacts [78]. However, FAR continues to be a valuable metric to indicate the dimension of anthropogenically induced changes in climate and some consequences arising from this [37,41].

While highlighted as limitations to be aware of, these drawbacks did not undermine the validity of our study findings but demonstrate that impacts are underestimated. For possible improvements for future studies, we recommend the installation of new rain gauges urgently and the frequent maintenance of the existing ones. This can support monitoring the territory, improving early warning platforms, and generating baselines for tracking climate change. In academia, it would allow new studies on precipitation variability in the Amazon region, as well as improve rainfall satellite data validation. Moreover, identifying small-scale subsistence agriculture-affected areas by this event but not recorded as such could provide valuable information to better prepare response plans to attend to these vulnerable populations. Finally, the availability of official response documents will facilitate a more suitable estimation of damages and therefore DRR proposals that are more in line with reality.

7. Conclusions

The present study aimed to assess how much of the extreme precipitation that caused floods in 2021 in the Juruá River Basin, Brazilian Amazon, and their impacts, can be attributed to human-induced climate change. The extreme rainfall event over the Juruá River Basin between December 2020 and March 2021 recorded an accumulated value of 1329.37 mm, according to CHIRPS data. During this event, the upstream area reached 48 % above the average rainfall from December to March. We estimated that 61 % (FAR = 0.61) of the likelihood of such an extreme event occurring can be attributed to anthropogenic influence on the climate, being currently 153 % more likely to occur in the current climate compared to a world without anthropogenic climate change. The return period reduced from 107 years to 42 years with climate change, highlighting the increase in frequency. Due to the magnitude of the 2021 floods, more than 71,000 people were directly affected, over 123,000 people were indirectly affected, and approximately US$ 16,6 million were estimated in losses. When extending the FAR analysis to the impacts, we considered nearly US$ 10.1 million and more than 43,000 directly affected people (over 75,000 if considered indirectly affected people) attributable to climate change (although FAR is a valuable metric, we highlighted the limitations of this approach). Our findings can support policymakers on disaster mitigation strategies and inform the general public about climate change and the related future extreme events, emphasising the urgency of considering climate change scenarios to improve disaster risk reduction policies.

CRediT authorship contribution statement

Renata Pacheco Quevedo: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Alex Ovando:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Bianca Nunes Calado:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Gisleine Cunha-Zeri:** Writing – original draft, Investigation. **Larissa Antunes da Silva:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Queren-Hapuque Rodrigues de Luna:** Writing – original draft, Methodology,

Investigation. **Janaína Cassiano dos Santos:** Writing – review & editing, Methodology. **Rafael Cesario Abreu:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Wan Ting Katty Huang:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Pedro Noronha:** Writing – original draft. **Henrique Leão:** Writing – review & editing, Methodology. **Luiz Felipe Goulart Fiscina:** Writing – review & editing, Validation, Methodology, Investigation. **Rafaela Quintella Veiga:** Writing – review & editing. **Débora Joana Dutra:** Writing – review & editing. **Ylza Marluce Silva de Lima:** Writing – review & editing. **Edvan de Meneses:** Writing – review & editing. **Marcos Timóteo Rodrigues de Sousa:** Writing – review & editing. **Marcos Massao Futai:** Writing – review & editing, Funding acquisition. **Fraser C. Lott:** Writing – review & editing, Supervision, Resources, Methodology, Data curation, Conceptualization. **Sihan Li:** Writing – review & editing, Methodology. **Rafael Luiz:** Writing – review & editing, Methodology. **Sarah Sparrow:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Liana Oighenstein Anderson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sarah Sparrow reports financial support and travel were provided by Newton Fund. Bianca Nunes Calado reports financial support was provided by Coordination of Higher Education Personnel Improvement. Marcos Massao Futai reports financial support was provided by Vale. Renata Pacheco Quevedo reports financial support and travel were provided by Vale. Liana Oighenstein Anderson reports financial support was provided by State of Sao Paulo Research Foundation. Liana Oighenstein Anderson reports financial support was provided by National Council for Scientific and Technological Development. Liana Oighenstein Anderson reports financial support was provided by Newton Fund. Fraser C. Lott reports financial support and travel were provided by Newton Fund. Wan Ting Katty Huang reports financial support and travel were provided by Newton Fund. Rafael Cesario Abreu reports financial support and travel were provided by Newton Fund. Luiz Felipe Goulart Fiscina reports financial support and travel were provided by Vale. Marcos T. R. Sousa reports financial support and travel were provided by Vale. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105530.

Data availability

Data will be made available on request.

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