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Research article

When rainfall meets tides: flood hazards in an Amazonian Metropolis

Milena Andrade[1,2,*], Giovanni Silva[2], Ewerton Souza[1] and Giordani Sodré[2]

[1] Instituto Ciberespacial, Universidade Federal Rural da Amazônia, Av. Presidente Tancredo Neves, n.2501, Belém, Pará, 66077-830, Brasil

[2] Instituto de Geociências, Universidade Federal do Pará, Pós-Graduação em Gestão de Riscos e Desastres Naturais na Amazônia, Av. Tucunduba, S/N—Universitário, Belém, Pará, 66075-110, Brasil

* **Correspondence:** Email: milena.andrade@ufra.edu.br; Tel: +55 091 3205 4435.

Abstract: Urban estuarine areas are exposed to flooding caused by heavy rain and tidal processes in cities lacking adequate infrastructure. Our aim of this paper was to analyze the relationship between precipitation intensity, tidal dynamics, and flooding occurrence in Belém (Pará, Brazil), located in Guajará Bay. Flood-related losses and damage have occurred throughout the city, especially in central consolidated and peripheral areas. The materials and methods included data collected from weather stations (1961–2020) of the National Institute of Meteorology and remote sensing data (1990–2023) from the Climate Hazards Group InfraRed Precipitation with Station dataset. Tide data (2006–2020) were obtained from the Brazilian Navy website, and damage information was collected from news reports, scientific articles, and official databases covering the period from 1987 to 2020. The locations mentioned in these reports were georeferenced and mapped. The results showed that in 1961 and 1990, the months with the highest precipitation were February and March, while during the period from 1991 to 2020, the rainiest months shifted to March and April. Extremely intense rainfall led to flooding-related damage in all city districts. A total of 51 news reports detailing the damage caused by flooding related to excessive rainfall and tides were identified, of which 24 occurred under extremely intense conditions. The highest tides were recorded in 2010, reaching 3.9m, and in 2014, 2015, and 2019, the tides reached 3.8 m at noon. In exposed and vulnerable areas, combined rainfall and high tides are the major causes of flooding, according to analysis of coincidences. The most common damages included loss of furniture and household appliances, interruptions to urban mobility, urban infrastructure damage, and the temporary isolation of residents. The linkages between rain and tides may contribute to risk management and alert purposes.

Keywords: adaptation; Belém; hazards impacts; public policy; tidal effects; COP30

1. Introduction

Estuarine coastal cities are particularly vulnerable to floods caused by rapid urbanization, extreme events, and tidal process [1]. Rapid urbanization has altered the surface land cover from natural to impermeable materials, and urban drainage systems often struggle to keep up with the demands of expanding infrastructure [1]. Therefore, flood-scenarios has intensified globally with extreme climatic events [2,3].

Extreme events are defined when the value of a variable exceeds or falls well below an established threshold [2,4,5]. For the rain, the analysis of these extreme events can be based on the volume or intensity of precipitation. Moreover, strong (between 10 and 50 mm/h) and violent (more than 50 mm/h) rainfall events considerably impact the environment and human society [6]. The Brazilian National Institute of Meteorology (INMET) considers rainfall events between 30 and 60 mm/h or 50 and 100 mm/day as “dangerous”; precipitation events exceeding 60 mm/h or above 100 mm/day are considered “seriously dangerous” and trigger a red alert [7]. The Brazilian government uses these rainfall thresholds to send out alerts warning states and municipalities for risk response. Risk is defined as the potential loss of life, injury, or damage to assets that may occur to a system, society, or community in a specific period, determined probabilistically based on a combination of exposure, threat, and vulnerability (R = Exposure x Hazard x Vulnerability) [8].

In low-lying coastal cities, mitigating flooding risks also depends on the structure to deal with the combined effects of strong rain, tidal levels, and the efficiency of the urban drainage system [9]. Researchers worldwide have simulated flood-risk dynamics at the coast using historical and field data [10], conducted probabilistic and deterministic simulations [11], and have analyzed the hydrological and hydrodynamics urban flood model [1].

In Brazil, a regional study on coastal flooding entailed sea level-rise scenarios [12]. Regarding the Amazon region, researchers present the relation between extreme daily rainfall and temperature [13], and climatology pattern dynamics [14]. Additionally, there are advances in estuarine hydrodynamics studies on the Amazonia coastal and inland environments [15]. However, when it comes to cities, there is a lack of comprehension regarding how and where rain patterns and high tides influence floods on a local district scale.

In Amazon cities, there are few stations for rain and tidal continuous monitoring, which decreases the precision and the prediction of flood events on a proper scale for city prevention and risk-response. Despite this, intense precipitation events cause disruptions related to flooding, the loss of material goods, and health problems in medium Amazonian cities [16,17] and metropolitan areas such as Belém (Pará) [18,19].

Flooding in Belém has always been a problem due to urban expansion choices made in past centuries involving landfilling and draining of water bodies [20]. Thus, hydrological disasters in Belém tend to increase due to changes in maximum precipitation amounts annually [13], relations with tides [19], and permanent challenges with water supply, sanitation, waste management, and adequate storm drainage [20,21]. The most vulnerable areas are in occupied areas along the channel banks, with construction materials ranging from wood to high-end materials. Autonomous adaptative capacity play a main role with private structural modifications [22], as the government invests in macro drainage projects [23].

The combination of high seasonal precipitation, elevated tides, and vulnerable urban areas at riverside neighborhood's in Belém increases the risk of flooding. As such, we aim to analyze the relationship between precipitation intensity, tidal dynamics, and flooding occurrence in Belém (Pará, Brazil), located in Guajará Bay. Our results may provide technical data for public policies regarding decisions on risk and disaster management.

2. Materials and methods

2.1. Study area

Belém is located in an equatorial zone along the shores of Guajará Bay and the Guamá River, with an area of 1,059.458 km² and a population of 1,303,403 [24]. The political–administrative division of the territory encompasses administrative districts, namely, Belém (ADBEL), Benguí (ADBEN), Entroncamento (ADENT), Guamá (ADGUA), Icoaraci (ADICO), Mosqueiro (ADMOS), Outeiro (ADOUT), and Sacramenta (ADSAC) (Figure 1).

The land use and cover include agriculture, airports, bare soil, beaches, built-up areas, grassland, roads, mining, primary vegetation, secondary vegetation, urban vegetation, and water bodies with and without sediment [25]. Forest fragments are classified as Terra Firme and Várzea forests, which are under the dense ombrophilous forest subtype [26]. The urban Belém area covers 150 km² [27] on the continental land (excluding the island areas that are occupied).

The city elevation varies little, with a maximum height of 50 m; approximately 74.31% of the city is below 15 m. The terrain is predominantly flat, with slopes ranging from 0 to 5%, corresponding to a maximum inclination of approximately 2.33°. These conditions describe three types of relief: floodplain (≤4 m), dissected plateau (4 to 14 m), and plateau (≥14 m). In general, these formations have been shaped and reshaped by fluvial and marine dynamics, causing the highly susceptibility of Belém to flooding in its lower-lying areas [28].

The region has a humid tropical climate characterized by abundant rainfall throughout the year, with the rainiest period occurring between December and May, and a drier period from June to November [29]. The average temperature is 26.4 °C, with unstable air, and the average air humidity is 84%. The average annual rainfall is 3,000–4,000 mm [7].

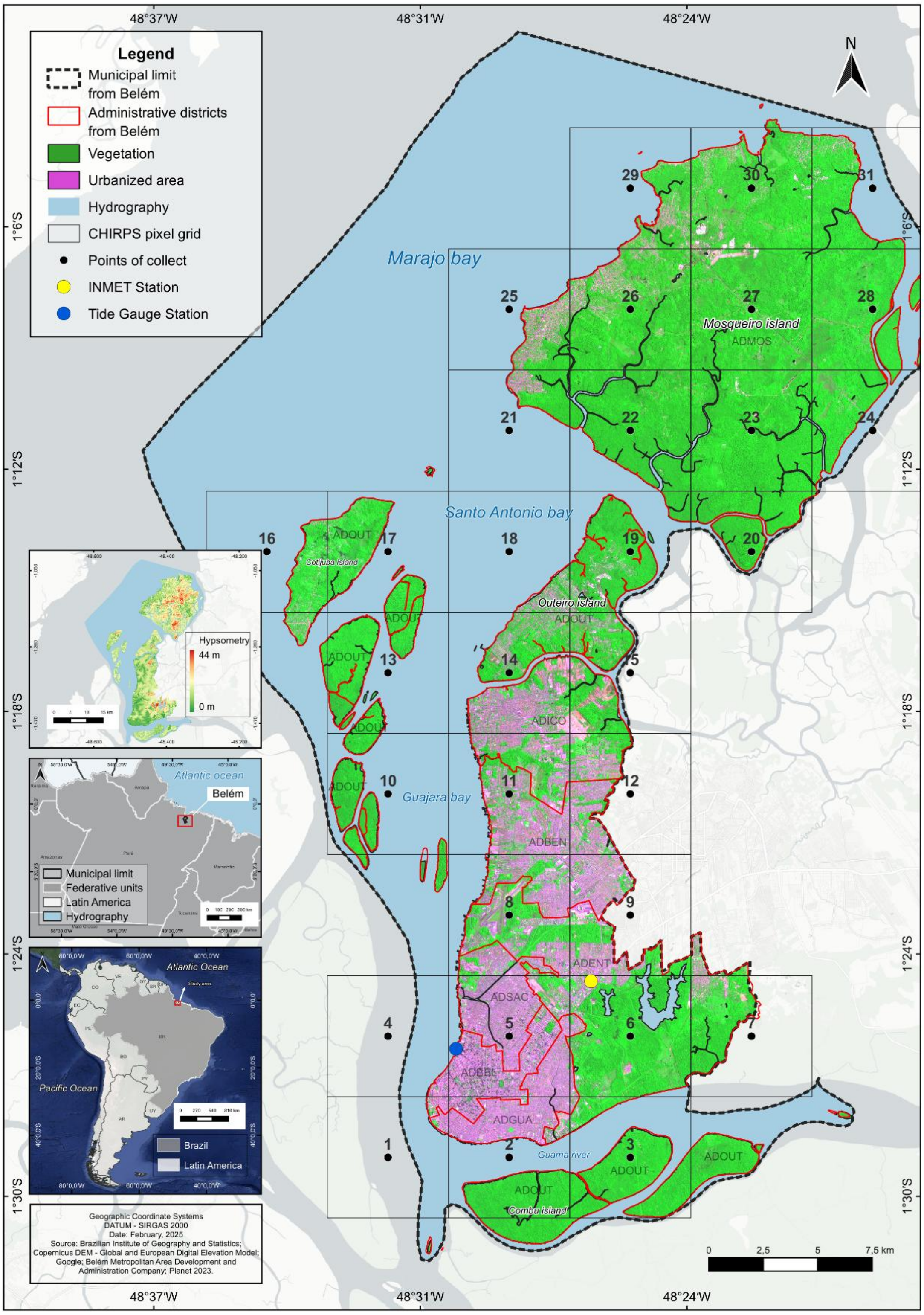

Figure 1. Location of Belém showing the division of administrative districts, the location of the INMET weather station, CHIRPS grid (31 points for information extraction), and detailed topography.

2.2. Flooding in Belém

In Belém, the flooding process is understood as a hydrological process of overflowing water from drainage channels to adjacent areas due to a temporary rise in water level caused by intense rainfall and high tide phenomena. Studies on urban floods in Belém point out the change forest cover to artificialization of the basin-total watershed, and the unplanned settlements increase flood impacts [30,31]. Risk areas are characterized by exposed buildings and roads, with social vulnerability during variable water levels due floods. Occupations are therefore affected by inefficient drainage infrastructure and soil impermeability [30,32].

The city has a historical drainage intervention with artificial channels, accelerating flood peaks in lower areas, which creates higher impacts in poor residential neighborhoods [20]. Flooding, whether seasonal, periodic, or exceptional, is enhanced by deficiencies in basic sanitation, land occupation, and technically critical and irregular landfills, and is exacerbated by the poverty of the residents [33]. Thus, in urbanized areas, flooding types in Belém occur on rainy days and during low tide, affecting neighborhoods with inefficient drainage systems (Figure 2A); when high tides and extreme rain occur simultaneously, and soil is waterlogged or impermeable, causing water to reach the surface from channels and precipitation (Figure 2B); or on sunny days in channels with inefficient infrastructure during high tides in low topographic areas (Figure 2C).

2.3. Precipitation data analysis

We first separated the precipitation data from the INMET station (https://bdmep.inmet.gov.br/) (Figure 1) into two climatological periods, 1961–1990 and 1991–2020, to analyze the changes in precipitation patterns. These periods were chosen to evaluate each 30-year climate period and analyze whether there has been a variation in the precipitation pattern. Second, we used remote sensing data to obtain the spatial pattern of precipitation within the Belém municipality. The weather station data were used to validate the information obtained with remote sensing because the weather station data could not be used to detect spatial variations [34].

The methodology for analyzing monthly precipitation consisted of extracting the 34 years of precipitation data from January 1, 1990 to December 31, 2023 (CHIRPS), for 31 sites in the study area (Figure 1). The CHIRPS data were organized into daily precipitation accumulations and are presented as grid points (three-dimensional matrix: latitude, longitude, and time). The selected points followed the fixed 5 km resolution spatial grid of the dataset. This database is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/netcdf/p05/. Additional details on the methodology used to construct these data can be found in [35].

In this study, in addition to CHIRPS, data from the National Institute of Meteorology (INMET) Meteorological Station were used for hourly data collection. It is important to highlight that all intense precipitation events classified by CHIRPS were also identified in the INMET station observations, corroborating its representativeness. However, we did not focus on validating CHIRPS, but rather on its combined application with urbanization and tide data. Therefore, it was assumed that validation had been successfully performed by other researchers, such as those in [36], demonstrating the efficiency and applicability of this dataset for the Belém region.

Finally, the data were analyzed to determine the variability in the monthly and quarterly precipitation as well as the number of daily occurrences of extreme rain events. The pattern established by the researchers in [29] was used to define the precipitation intervals in Belém (Table 1). This classification was defined based on the identification of a precipitation threshold associated with the occurrence of urban- flooding problems in the city of Belém.

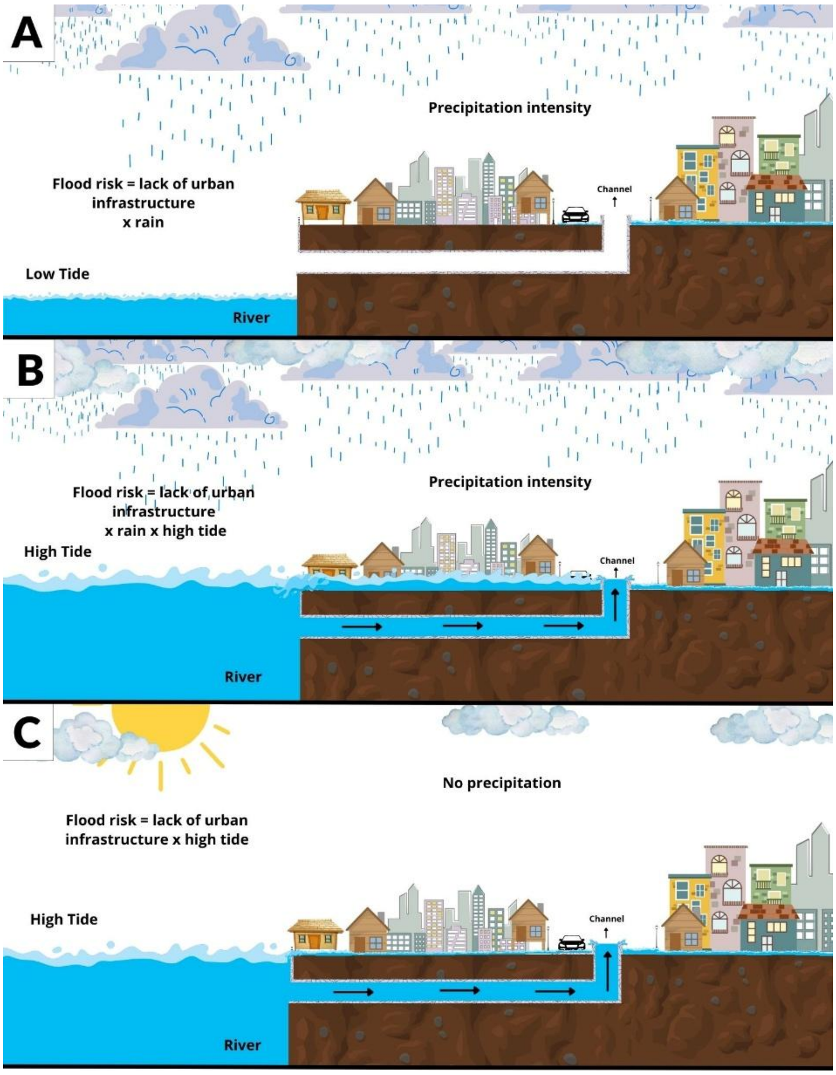

Figure 2. Types of flooding in Belém in urbanized and occupied areas near channels regarding precipitation and tide events.

Table 1. Classification of precipitation by intensity. Source: Adapted from [29]

Precipitation/day	Classification
25–33 mm	Intense
33,1–48 mm	Very Intense
>48 mm	Extremely Intense

The validation of the daily precipitation series from CHIRPS (1990–2023) was performed using the INMET station located in the study area as a reference. A Pearson linear correlation was performed, and the detection rates for the thresholds were ≥ 25 mm, ≥ 33 mm, and ≥ 48 mm. The INMET station data used were subjected to the standard quality control procedures provided by the institute, including verification of temporal consistency, removal of duplicate records, and checking for missing values. As no significant gaps were identified in the daily series, there was no need to apply additional gap-filling methods.

2.4. Data on the influence of precipitation and tides

The impacts of precipitation events were identified using secondary data from published scientific papers and news articles from digital and print newspapers available at the public library. The printed media were accessed at the Tancredo Neves Public Library in Belém. The precipitation data in the news articles were verified using data from automatic and conventional weather stations according to the total daily precipitation levels (in millimeters) available at INMET (https://tempo.inmet.gov.br/TabelaEstacoes/A001). The report-data was cross-checked with official data from the Brazilian Integrated Disaster Information System (S2ID).

The results of the tide data analysis on the days the reports recorded impacts were cross-checked with data from the Hydrography Center of the Brazilian Navy (CHM) at https://www.marinha.mil.br/chm/. The data collection corresponded to the tide gauge station at Belém Port (Figure 1). The publicly available data started in 2006; the information was marked as "no data available" for years before this. Basic statistics maximum, minimum, and median were calculated for the 2006–2020 period.

The information was organized into a timeline to include the following details: Temporal data, including nature, location, and impact of the threat, and source. The impact was analyzed based on the location and description of the impacts, with the identified points georeferenced in Q.GIS 3.10.

Finally, to validate the report-data, an analysis for coincidences was conducted for simultaneous high tide events and precipitation (rainfall from the current day and previous day) between 2006 and 2020 using official data from CHM e INMET. The height of the highest tide (above or equal to 3 meters) was compared with the accumulated rainfall from the previous day and the current day based on intensity classifications as thresholds, as provided in [29].

3. Results

The historical precipitation data for Belém showed that the rainfall patterns changed over the 60-year period. The distribution of precipitation throughout the year changed, and the rainfall amount slightly increased, according to precipitation data. The rainfall over five months (from January to May) accounted for 10% or more of the annual precipitation in 1961–1990; this number of months dropped to four (January to April) in 1991–2020 (Figure 3).

The data were subdivided into two 30-year climatological periods (1961–1990 and 1991–2020). The months with the most rainfall were February and March, whereas the driest months were October and November during the first climatological period. The rainiest months in the second period were March and April, whereas the driest months were August and September.

We noted substantial changes in the total precipitation volume over time. The average accumulated precipitation volumes for the rainiest month (March) were 406 and 513 mm during the first and second periods, respectively.

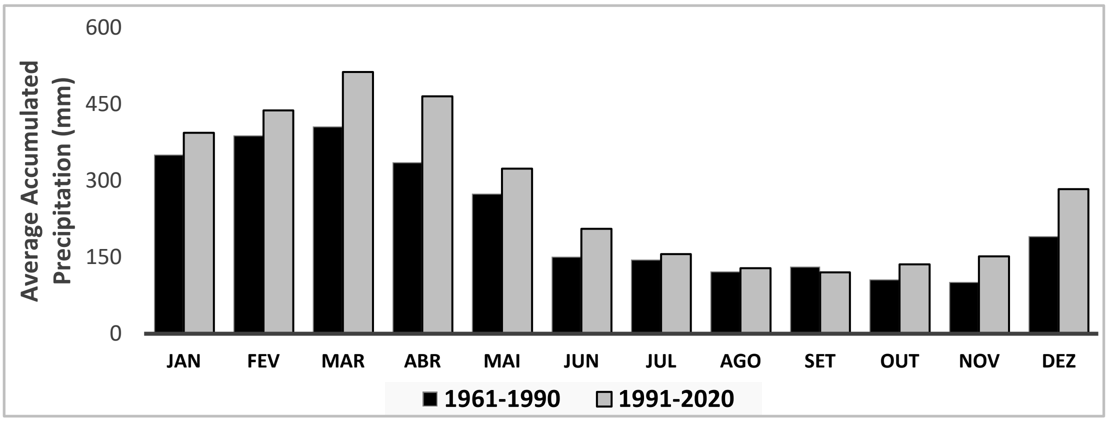

Figure 3. Climatic variability in Belém from 1961 to 2020, divided into two periods: 1961–1990 and 1991–2020. Source: Conventional INMET Weather station.

Five months accounted for most of the precipitation from 1961 to 1990, indicating a more evenly distributed precipitation pattern throughout the year than in the second period, 1991–2020, where heavy rainfall concentrated in only four months (Table 2). March was the rainiest month for both periods.

The months from 1961 to 1990 with the highest percentage of accumulated precipitation were February (14.4%) and March (15%). The patterns of the precipitation in the months with the highest accumulation from 1991 to 2020 shifted. April had the second highest volume of precipitation (14%), and the percent of the total annual accumulated precipitation increased in March to 15.5%.

Table 2. Percentage of monthly average accumulated precipitation. Months accounting for > 10% of the annual total precipitation are highlighted in bold.

MONTH	1961–1990 (%)	1991–2020 (%)
JAN	13,0	11,9
FEV	14,4	13,2
MAR	15,0	15,5
APR	12,4	14,0
MAI	10,2	9,8
JUN	5,6	6,2
JUL	5,4	4,7
AUG	4,5	3,9
SET	4,9	3,6
OUT	3,9	4,1
NOV	3,7	4,6
DEC	7,1	8,6

3.1. Characterization of current precipitation (1990–2023)

The period beginning in the 1990s was marked by changes in precipitation patterns, increases in precipitation volume, and a higher concentration of rainfall over a shorter period. We assessed whether these changes uniformly occurred across Belém or if certain areas were more or less affected to understand these variations.

We found two distinct periods of monthly precipitation patterns in Belém: A rainy period from December to May and a less rainy period occurring between June and November. The rainy period was defined as months with rainfall above or equal to the monthly average over the year, whereas the less rainy period was defined as months with precipitation lower than the average. March was generally the rainiest month, with an average of 508 mm, whereas September was the driest month, with an average of 124 mm.

The results of the analysis of the quarterly and semiannual precipitation showed that the rainiest quarter was January to March, which accounted for 40% of the annual precipitation volume. July to September was the driest quarter, with 13% of the annual precipitation falling during these months. The first half of the year was notably wetter, with 70% of the annual precipitation falling during this period (Table 3).

Table 3. Quarterly and semiannual precipitation Accumulation.

Quarterly	**Accumulation (mm)**	**% Precipitation**
JFM	1316	40
AMJ	994	30
JAS	418	13
OND	574	17
Semianual	**Accumulation (mm)**	**% Precipitation**
1sem	2311	70
2sem	992	30

We observed a well-defined pattern in the spatial variation in the quarterly accumulated precipitation data (Figure 4) between the rainier and drier quarters. The accumulated precipitation was highest in the first quarter (January, February, and March) over all of Belém, ranging from 1141 mm in more urbanized areas to 1157 mm on Mosqueiro Island, which had a lower population density. Spatial precipitation variability was observed in most periods, with the exception of the second quarter (April, May, and June), where accumulated precipitation was higher in the northern regions of Mosqueiro Island, Outeiro Island, and Cotijuba; average accumulations varied between 914 and 953 mm, than in the more urbanized parts of the municipality, where the precipitation ranged from 864 to 894 mm.

The highest accumulated precipitation (more than 400 m) in the third (July, August, and September) and fourth (October, November, and December) quarters occurred over the more urbanized area of Belém. The precipitation was approximately 300 mm per quarter on Cotijuba Island and in Mosqueiro.

The peak patterns of the rainy and drier periods in the first and third quarters, respectively, were similar between the points; the rainfall spatially varied more in the second and fourth quarters, which represented the transition periods between rainy/drier and drier/rainy periods, respectively (Figure 4). The pattern in the fourth quarter was the opposite of that in the second quarter: The accumulated precipitation was higher in the more central/urbanized regions and lower in the Mosqueiro region.

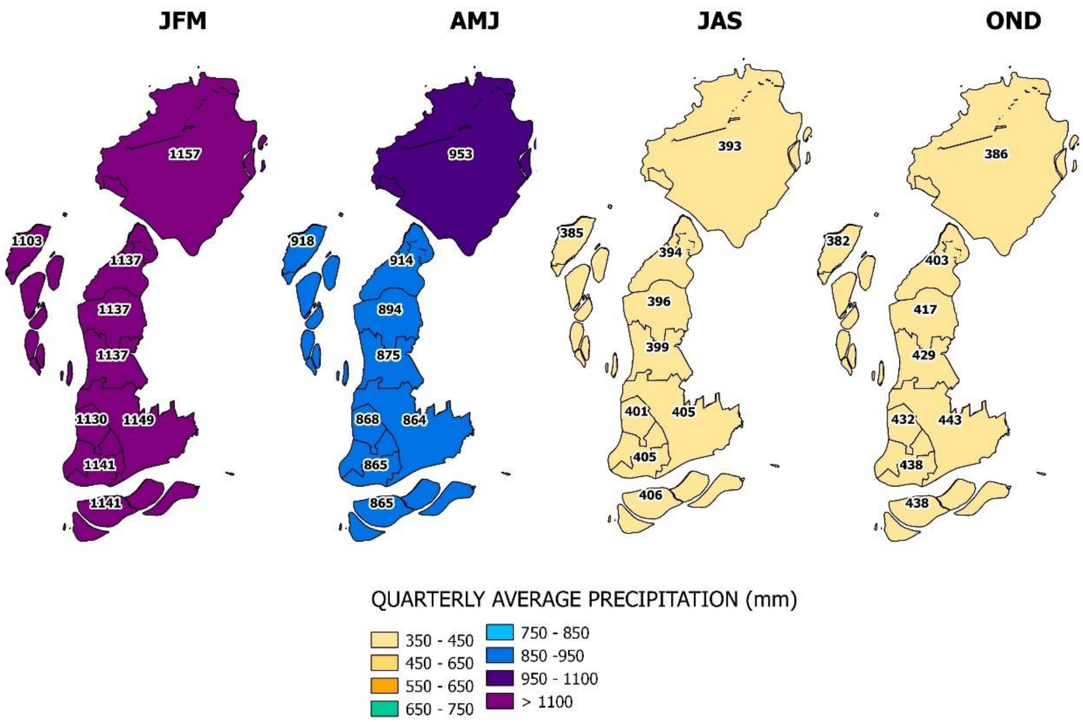

Figure 4. Spatial distribution of quarterly accumulated precipitation in Belém municipality, based on CHIRPS data (1990–2023). The values represent total precipitation (mm) for each quarter.

3.2. Extremely intense events

Precipitation had to be classified based on its potential impact to identify extreme events that affected the municipality of Belém every year. Extremely intense values (>48 mm/day indicated potential damage related to flooding and inundation.

The results of the spatiotemporal analysis of the extremely intense precipitation events showed that the more urbanized areas of Belém (DAGUA, DABEL, and DASAC) and DAMOS experienced 32 and 35 episodes of extremely intense events in the first quarter, respectively. The number of extremely intense rainfall events was lower in the second than in the first quarter, with an average of one to two events in the more urbanized areas and between five and seven events in the Ilha de Cotijuba and Mosqueiro regions (Figure 5).

The occurrence of intense precipitation was lowest in the third quarter, with an average of one to two events throughout the municipality. The number of extreme rainfall events increased in the fourth quarter, with averages ranging from five to six events.

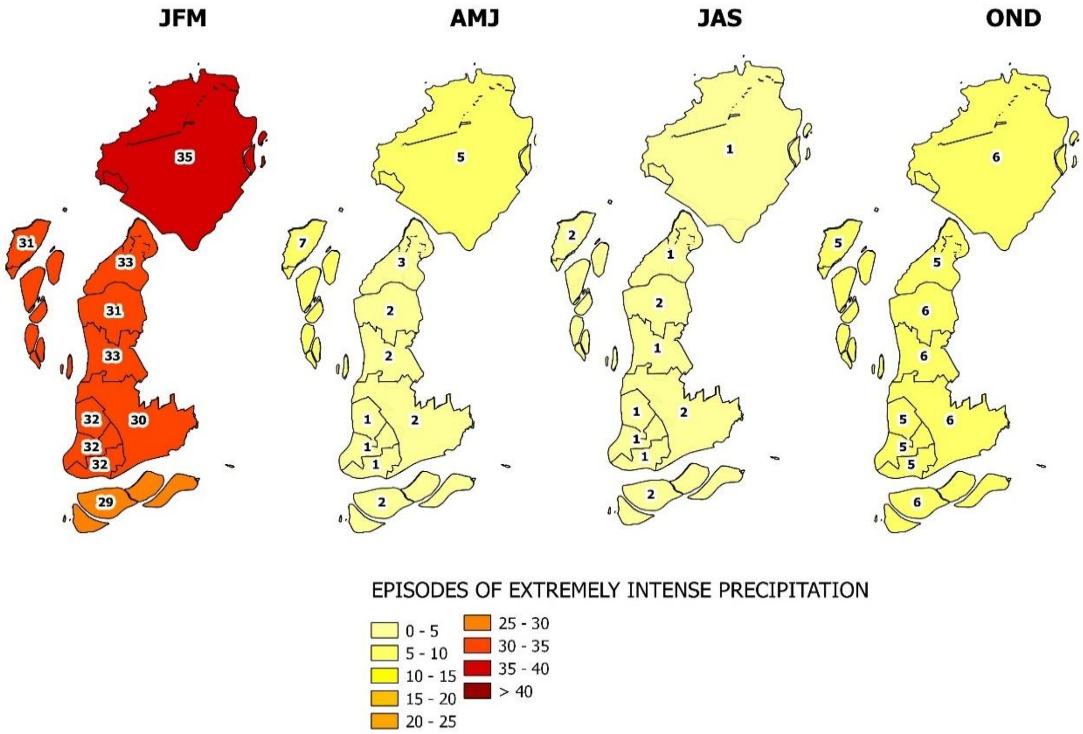

Figure 5. Spatial distribution of the frequency of extremely intense precipitation events (>48 mm/day) in Belém municipality, based on CHIRPS data (1990–2023). The values represent the number of events per quarter.

The results indicated that extremely intense precipitation events occurred between 30 and 40 times across Belém in the first quarter. The frequency of extremely intense rain events in the second quarter ranged from 0 to 24 events, with the highest frequency occurring in the northern municipality, particularly in Ilha de Mosqueiro. The frequency of intense precipitation events was the lowest in the third quarter, and was evenly distributed across the city. The frequency of these events increased in the fourth quarter, with the largest increase occurring in Mosqueiro.

In summary, Ilha de Mosqueiro had the highest frequency of intense rainfall events, with the northwestern island being the most affected in the wettest (first) quarter and the transitional (second and fourth) quarters. The most intense precipitation almost exclusively occurred in January, February, and March, primarily in the more urbanized areas.

The annual average number of extremely intense precipitation events in the first quarter was 30. Ilha de Mosqueiro had the highest number of these events, except for the third quarter, where the low event frequency indicated that the few events that occurred over the 34-year period were distributed evenly across the municipality.

Table 4 highlights over 1000 episodes of intense precipitation occurred in the first quarter over the 34-year period, with 500 events recorded in February. In contrast, only 5 of these events were recorded in July during this period.

Table 4. Total number of extremely intense precipitation events over 34-year period (1990–2023).

	Total quarterly	***Quarterly average 34 years***
JFM	1066	31
AMJ	145	4
JAS	49	1
OND	208	6
	Total month	**Média month avarage 34 years**
JAN	334	10
FEB	500	15
MAR	232	7
APR	85	3
MAY	38	1
JUN	22	1
JUL	5	0
AUG	8	0
SEP	36	1
OCT	11	0
NOV	33	1
DEC	164	5

The linear correlation between the datasets was r = 0.41, indicating moderate consistency between the products and performance comparable to other assessments in tropical regions strongly influenced by localized convection. The event detection rates based on the operational thresholds (≥25, ≥33, and ≥48 mm) indicated that CHIRPS exhibited moderate detection for light to moderate rainfall, but had reduced capability in identifying extreme events. For the 25 mm, 33 mm, and 48 mm thresholds, the detection rates were 18.3%, 10.5%, and 3.9%, respectively, demonstrating that underestimation tended to increase with event magnitude.

Despite these limitations, the use of CHIRPS proved essential for the spatial characterization of rainfall. Even with a systematic underestimation bias, the dates of critical events were correctly identified, enabling temporal alignment between intense rainfall and high tide conditions. Moreover, given the limited observational coverage in many Amazonian municipalities, CHIRPS provided superior spatial granularity, which was particularly useful for distinguishing rainfall patterns across the districts of Belém. Seasonal analysis showed that CHIRPS adequately reproduced the annual precipitation cycle, with maxima during the summer and minima during the winter, although it displayed systematic underestimation across all seasons, especially in spring and during the main rainy period.

3.3. Flood impacts due to precipitation and tide

A total of 51 news reports describing precipitation events that impacted Belém were identified, and all districts in the study area were affected by flooding. Of these, 24 reports were related to extremely intense precipitation (>48 mm/day), 11 to very intense events (33.1 48 mm/day), and 6 to intense events (25–33 mm/day). The remaining 10 records were related to precipitation values below 25 mm/day (Table 5). In total, 183 flooding points were identified, as there were records with more than one location indicated in the reports (Table 5 and Figure 6).

A total of 29 locations with damages due to flood when tide was equal or over 3m for precipitation over 48mm/day were registered. With these conditions in ADGUA, 14 events were registered; for example, there were damages in the Quintino, Timbó, and José Leal Martins channels (Figure 6; G, C, and B channels). ADBEL registered 8 flooding points, emphasizing the Armas Reduto and Doca channels (Figure 6; I and J channels in detail). In ADSAC, 4 points were registered. Moreover, in the channels of Pirajá and Galo, multiple-compounded impacts due to flooding of houses, buildings, and streets were registered (Figure 6; K and L channels in detail). In ADENT, the 3 floodings' register were far from channels, highlighting inefficient drainage infrastructure.

ADSAC, ADBEN, ADBEL, and ADGUA registered impacts related to flooding, clogged drainage systems, damaged furniture, and overflow of the 14 de Março Street channel and the Timbó channel between 1987 and 1999. All six districts were mentioned in journalistic reports regarding these events between 2000 and 2009, with a mention of the overflow of the Mata Fome Stream (ADBEN), Vileta Canal, 14 de Março Street Canal (ADBEL), and Pariquis Street Canal (ADGUA). This period was characterized by extremely intense precipitation, particularly in March and April.

The next decade starting in 2010 contained 52% of the total number of flood impact records in all six districts. Precipitation above 55 mm/day was recorded in 2013, 2015, 2016, 2019, and 2020. The highest value was recorded in 2020, with 12 h of rain and a rainfall volume of 144.4 mm/day in March. A maximum high tide of 3.4 m was recorded in 2020, and the neighborhoods in the ADBEL, ADGUA, and ADENT districts were severely affected by channel overflows, power outages, and interruptions to urban mobility. However, a tide gauge station registered 3.9 m as the highest value on March 2nd, 2010. The 3.8 m height was recorded in 2006, 2007, and 2011, while minimum values below 0 m were registered in 2007, 2014, 2015, 2016, 2017, and 2020.

The coincidence of rainfall and high tides caused the channels to overflow, even when rainfall was not intense. Reports of flooding damage were also noted in 2009, 2011, 2013, 2014, 2015, 2018, and 2019 when precipitation was below the intense threshold (<25 mm/day). The likely cause of the damage was the interaction between low precipitation during high-tide periods. For example, the high tide reached 3.8 meters at 12:17 PM in March 2019, flooding the Ver-o-Peso Market (ADBEL) and the surrounding streets and shops. Therefore, flooding in Belém was possible even with little rain under these high-tide conditions. Moreover, despite the high number of registered incidents in the media for damages, the official S2ID data reported only registrations in the official system for the years 1999, 2013, 2018, and 2020.

The most common impacts of the combination of precipitation and tides were related to i) property damage, such as flooded houses and damaged and lost furniture; ii) interruptions to urban transit and car accidents; iii) channel overflow; iv) urban infrastructure damage, including electrical systems, drainage capacity, trees falling, and waste accumulation; and v) the isolation of residents during flooding periods (Figure 7).

Table 5. Impacts of flooding based on precipitation and tides in Belém between 1987 and 2020 (purple—extremely intense rain, orange—intense rain, yellow—intense rain). Source: [Supplementary—Further Reading 1–35].

Date	Precip (mm)	Rain Class	Tide (m)	Tide ≥ 3 m	Administrative District	Notes
1987–03–27	71,8	Extremely Intense	-	-	DASAC	1
1991–02–28	48,2	Extremely Intense	-	-	DABEL	1
1998–04–28	126,8	Extremely Intense	-	-	DAGUA	1
1998–06–19	37,2	Very Intense	-	-	DASAC; DABEN	2
1999–05–12	69,5	Extremely Intense	-	-	DAGUA	3
1999–12–29	117,4	Extremely Intense	-	-	DABEL	3
2000–01–06	53	Extremely Intense	-	-	DASAC; DABEN	4
2000–04–16	133,7	Extremely Intense	-	-	DAICO; DAGUA; DABEL; DAENT; DABEN	4
2000–04–18	118,7	Extremely Intense	-	-	DAGUA	4
2000–05–10	56,5	Extremely Intense	-	-	DASAC; DAGUA	4
2001–03–10	31,8	Intense	-	-	DABEL	1
2001–03–14	28,4	Intense	-	-	DABEL; DASAC	5
2003–12–14	53,2	Extremely Intense	-	-	DAGUA	6
2005–03–30	60,7	Extremely Intense	-	-	DABEL; DAGUA; DASAC	7
2005–04–25	200,8	Extremely Intense	-	-	DABEL; DASAC; DAGUA;	7
2005–04–25	183,3	Extremely Intense	-	-	DASAC	1
2006–01–10	29,6	Intense	-	-	DABEL	8
2006–03–30	84	Extremely Intense	-	-	DAGUA; DABEL	8
2006–04–21	96,7	Extremely Intense	-	-	DAENT; DAGUA	8
2006–09–14	44,6	Very Intense	-	-	DAGUA	8
2007–02–15	64,4	Extremely Intense	-	-	DAGUA; DABEL	9
2007–12–03	73,7	Extremely Intense	-	-	DAGUA	1
2009–04–01	53,6	Extremely Intense	-	-	DAGUA	1
2009–12–04	22,6	<25 mm	-	-	DAGUA	1
2010–10–13	45,6	Very Intense	3,2	Yes	DAGUA	10
2011–01–18	24,9	<25 mm	3,3	Yes	DABEL	11
2011–04–14	15,6	<25 mm	3	Yes	Metropolitan Region of Belém	12
2011–05–16	19,8	<25 mm	3,5	Yes	DAGUA	13
2012–07–08	29,4	Intense	3,3	Yes	DABEL	14
2012–12–31	25	Intense	3,2	Yes	DASAC	15
2013–01–07	20,4	<25 mm	3,2	Yes	DABEL	16
2013–04–06	44,6	Very Intense	3,2	Yes	DABEL	17
2013–05–03	34	Very Intense	3	Yes	DAENT	18
2013–11–06	55,2	Extremely Intense	3,4	Yes	DAGUA	19
2013–11–06	55,2	Extremely Intense	3,4	Yes	DAGUA; DASAC	19

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Date	Precip (mm)	Rain Class	Tide (m)	Tide ≥ 3 m	Administrative District	Notes
2014–03–03	33,7	Very Intense	3,8	Yes	DABEL	20
2014–04–02	46,6	Very Intense	3,5	Yes	DASAC; DABEL	21
2014–12–16	19,8	<25 mm	2,7	No	DAGUA; DAENT	22
2015–04–14	63,2	Extremely Intense	3,3	Yes	DAGUA; DABEL; DASAC; DAENT	23
2015–04–19	18,4	<25 mm	3,8	Yes	DAGUA; DABEL;	24
2016–06–17	68,4	Extremely Intense	3	Yes	DABEL; DAENT	25
2016–11–30	36,7	Very Intense	3,3	Yes	DAGUA	26
2017–02–13	39,8	Very Intense	3,4	Yes	DABEL; DAGUA; DABEN	27
2017–03–07	26	Intense	3	Yes	DABEL;	28
2017–12–28	34,2	Very Intense	3	Yes	DAENT; DAICO	29
2018–12–01	19,4	<25 mm	3	Yes	DABEL	30
2019–02–26	56,4	Extremely Intense	2,9	No	DAGUA	31
2019–03–19	48	Very Intense	3,6	Yes	DAGUA; DABEL; DAENT	32
2019–03–22	21,4	<25 mm	3,8	Yes	DABEL;	33
2020–03–07	144,4	Extremely Intense	3,4	Yes	DABEL; DAGUA; DAENT	34
2020–05–21	65	Extremely Intense	3,3	Yes	DAGUA; DABEL	35

The validation with the analysis of coincidences involving high-tides and rainfall from the current day and previous day revealed 27 occurrences from tides equal or over 3 m. Co-occurrence with precipitation intensity from the day were 16; considering 48h precipitation accumulation, there were 23 co-occurrences distributed across years and hydrometeorological configurations (Table 6).

Of the total events considering rainfall exceeding 48 mm/day and over 3 m tides, 40% were classified as Extremely Intense, indicating that approximately one-third of rain–tide interactions occurred under extreme precipitation conditions, with high potential to generate hydrological and urban impacts. An additional 14.8% were categorized as Very Intense (33.1–48 mm/day), while 29.6% fell within the Intense range (25–33 mm/day). These results indicated that more than 54% of the coincidences (combining Very Intense and Extremely Intense) were concentrated within high-risk rainfall categories. Considering precipitation from the current day, 33% were Extremely Intense, 14.8 were Very Intense, and 11% were Intense, coinciding with 3m or higher tides.

The occurrence of extreme events was distributed across several years, notably 2007, 2009, 2011, 2013, 2016, and 2020, periods in which rainfall above 50 mm was recorded on the same day as elevated tide levels (typically between 3.2 m and 3.8 m). These episodes represented typical compound-risk situations in which surface runoff intensified by rainfall coincidences with reduced natural and urban drainage capacity due to tide-induced backwater effects. Many of these events occurred during the early morning or early nighttime hours when tidal peaks were commonly observed along the Amazon coastal sector, further increasing the likelihood of overflow in urban basins.

Moreover, analysis of the previous day's accumulated rainfall showed that, in several cases classified as Extremely Intense, significant precipitation had occurred during the preceding 24 hours, promoting soil saturation and amplifying hydrological risk. Episodes such as those in 2006, 2007, 2009, 2013, and 2020 exhibited 24-h and 48-h totals exceeding 80–100 mm, characterizing cycles of persistent precipitation combined with elevated tides.

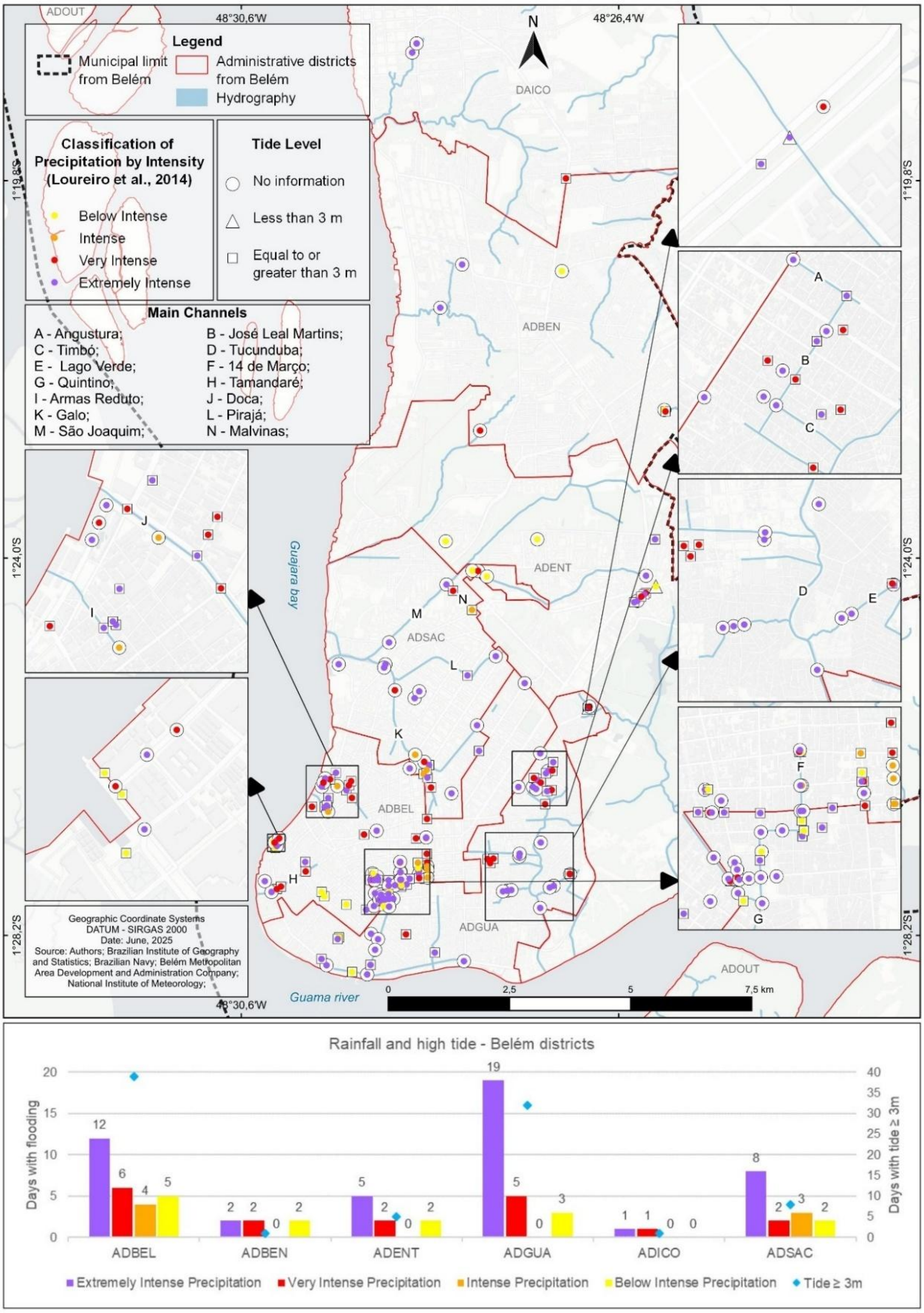

Figure 6. Flood points identified in detail for recurrent major channels affected, and the graphic statistical relation between records of precipitation, high tides (≥3 m), and flood damage report.

The analysis shown in the coincidence table indicated that: 1) High-risk events predominated among rain–tide coincidences at vulnerable areas; 2) extreme rainfall accounted for most critical situations; and 3) the interaction among intense rainfall, pre-saturated and asphaltic soils, and peak tide levels was decisive in triggering flooding and urban inundation. Therefore, the observed pattern reinforces the compound nature of the hazard, underscoring the need for models that simultaneously consider both variables.

Figure 7. Flood-related impacts of heavy rains and tide in Belém: a) Report from O Liberal (2007) with the headline "Tide expected to reach 3.8m today"; b) submerged capital after a 20-minute storm, printed report in O Liberal (2007); c) houses on Travessa Rui Barbosa near Rua dos Pariquis were flooded (Photo: Ingrid Bico/G); and d) 14 de Março Canal overflowed (Photo: Jorge Sauma/G1 PA).

4. Discussion

The results show the increase in rainfall volume and the reduced number of months receiving it. This fact increases the likelihood of an intense precipitation event, especially in March (which accounted for the highest percentage of the total annual precipitation). The researchers in [37] confirm these results, as they found March to be the month with the highest rain concentration (1967–2016) and they emphasize that the La Niña phenomenon had the highest average precipitation of 315 mm in year 2013.

Table 6. Coincidence analysis from high tides and precipitation intensity from 2006–2020.

Date	Hour Tide	Tide (m)	Accumulated from the previous day (mm)	Accumulated from the day (mm)	Precipitation intensity From the day	Accumulated from 48h (mm)	Precipitation intensity 48 h (mm)
March 30th, 2006	11:56	3,8	35	84	Extremely Intense	119	Extremely Intense
September, 14, 2006	03:23	3	0,5	44,6	Very Intense	45,1	Very Intense
February, 15, 2007	22:02	3,2	0,2	64,4	Extremely Intense	64,6	Extremely Intense
April 01st, 2009	15:23	3,3	50,5	53,6	Extremely Intense	104,1	Extremely Intense
December, 04th, 2009	00:08	3,3	13,4	57,6	Extremely Intense	71	Extremely Intense
October 13th, 2010	02:28	3,1	20	45,6	Very Intense	65,6	Extremely Intense
January 18th, 2011	22:26	3,2	0,7	24,9	-	25,6	Intense
April 14th, 2011	20:30	3,2	5,1	82,4	Extremely Intense	87,5	Extremely Intense
May 16th, 2011	10:09	3,4	7,1	49,2	Extremely Intense	56,3	Extremely Intense
July 08th, 2012	14:21	3,1	13,6	12,8	-	26,4	Intense
December 31th, 2012	00:39	3,3	14,8	12,2	-	27	Intense
January 07th, 2013	19:09	3,1	0	10,4	-	10,4	-
April 06th, 2013	20:49	3,2	0	30,4	Intense	30,4	Intense
May 03th, 2013	18:15	3	10,4	0	-	10,4	-
November 06th, 2013	00:47	3,4	24,2	56,5	Extremely Intense	80,7	Extremely Intense
April 02th, 2014	13:08	3,5	17,8	38,3	Very Intense	56,1	Extremely Intense
April 14th, 2015	19:58	3,1	0,4	24	-	24,4	-
June 17th, 2016	09:30	3,2	0	27,5	Intense	27,5	Intense

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Date	Hour Tide	Tide (m)	Accumulated from the previous day (mm)	Accumulated from the day (mm)	Precipitation intensity From the day	Accumulated from 48h (mm)	Precipitation intensity 48 h (mm)
November 30th, 2016	11:58	3,1	0	36,7	Very Intense	36,7	Very Intense
February 13th, 2017	00:38	3,4	38,4	19,7	-	58,1	Extremely Intense
March 07th, 2017	19:15	3	3	26	Intense	29	Intense
December 28th, 2017	19:00	3,1	0,9	9,4	-	10,3	-
December 01st, 2018	18:53	3	38,6	1,6	-	40,2	Very Intense
March 19th, 2019	22:28	3,5	6,2	21,4	-	27,6	Intense
March 22th, 2019	00:09	3,7	27	3,1	-	30,1	Intense
March 07th, 2020	22:00	3,3	0	60,5	Extremely Intense	60,5	Extremely Intense
May 21th, 2020	10:51	3,3	39,4	54,7	Extremely Intense	94,1	Extremely Intense

Climate change may be related to urban areas by increasing the air temperature in Belém [38], providing modifications in rain patterns. The decadal average precipitation in Belém shows an increasing trend, with precipitation values observed across all decades exceeding 2,000 mm [39].

Rainfall events above 63 mm were considered extreme events between 1967 and 2016, with the average precipitation showing an increasing trend over five decades (1976, 1986, 1996, 2006, and 2016) [37]. Our results confirm 84 mm of rain and a 3.8 m tide in March 2006 and verify extremely intense rainfall in February 2007, April 2009, December 2009, April 2011, May 2011, November 2013, and March 2020. However, most impacts related to flooding occur between December and March in Belém, which is the wettest summer period (southern autumn) [40] and when the drainage system is highly impacted, redistributing and mitigating surface water inundation and flooding risks [41]. This scenario is similar to other estuarine cities with a low-lying coast, high occupation, and rapid drainage peak system fullness [1].

Analyzing the annual maxima precipitation and peaks over average monthly accumulated precipitation values help stakeholders construct extreme rainfall thresholds. Additionally, analyses associated with high tide level series alerts could be communicated to the population. The values should be monitored for years once estuarine areas present complex dynamics with the tidal coastal process and interface with the hydrological cycle from watersheds [15]. Therefore, a backflow through drainage pipe channels, triggered by high external water levels at outlets, significantly increases the risk of inundation [42].

In Belém, precipitation alone did not cause damage, despite the large rainfall volumes, because flood risk areas involve the interplay of various indicators of threats with vulnerabilities in certain areas [43]. Vulnerability has been measured in large cities in the Amazon estuary by considering exposure indicators (locations and people in at-risk areas), socioeconomic status, and civil infrastructure conditions in terms of the availability and quality of sanitation services and housing structures [21,44]. Approximately 37,000 to 988,000 people live in highly vulnerable conditions in these areas [21].

Vulnerable conditions have historically been created in Belém through the occupational dynamics of the city. The governmental measures to adapt to flood prioritize macro drainage projects that create an ongoing cycle of removing and relocating families, contributing to further irregular occupations in risk areas [23]. The spatial heterogeneity of risk is directly linked to the historical urbanization process because of the city development dynamics. The central area (ADBEL) was built on higher, sanitized land occupied by wealthier families, whereas the surrounding lowlands and floodplains (ADGUA and ADSAC) were locations for poorer families [18,45].

In addition to extremely intense precipitation events, physical indicators related to urban occupation, such as road conditions, canal types, occupation density, and housing construction patterns, must also be considered, all of which contribute to risk in flood-prone areas [30]. The ADGUA, ADSEC, and ADBEL districts are the most densely populated in Belém and have experienced reductions in vegetation over time, impacting ecosystem services [46]. Regarding land use and cover changes, the conversion of green spaces into urbanized areas has raised concerns, as the surface temperature has increased to 31 °C, which could lead to the formation of heat islands and microclimates in urban Belém areas [47–49].

Belém was built with the systematic occupation of the lowest areas, which were filled in, and sanitation plans were implemented [45]. The occupation of the lowlands and the urban occupation patterns in Belém have been documented in the literature as a model of urban fragmentation, the transformation of riverbank spaces, and the occupation of the inner areas of Belém [50,45].

Peripherical areas are more susceptible to flooding owing to the effects of precipitation and tides on topographical factors [18]. Our results show that even in the absence of extremely intense precipitation (>48 mm/day), flood damage is possible, especially if the highest tides occur just after midday, with values larger than or equal to 3 m in the first quarter. Our findings indicate ADGUA, ADBEL, and ADENT as the areas affected by flooding near the canals under these conditions.

The researchers in [19] found that flooded areas in Belém-PA can experience flooding under minimum precipitation values, provided that the tide height is 0.64 m and if the rain intensity reaches at least 30 mm/h. However, some areas in the city also flood solely due to the effects of high tides exceeding 3.4 m under rain-free conditions [40,19]. This is because the areas with an elevation below 4 m are fluviomarine floodplains, but these have been filled in and urbanized. The occurrence of flooding is favored when the precipitation index is approximately 3000 mm/year, especially during the wet season [32,51].

Adaptation measures have been described in the literature to mitigate flooding risk. Generic measures (water supply, sanitation, waste management, and adequate storm drainage) and specific measures (individual, community, and political actions for flood mitigation) are insufficient in Belém [21]. The generic adaptation measures are not enough in lowland areas. Individual adaptation measures have been implemented in the city but without professional technical assistance or external finance. These measures are linked to structural (e.g., second floor, elevating individual property levels, and improving buildings) and nonstructural (e.g., removable water gates in properties) modifications along channels [22]. Even tough studies indicate flood issues in Belém, when it comes to the local scale, the city lacks an alert system to advance protection and preparation issues.

5. Conclusions

This paper advances rain and tidal effects on flood analyses using historical records and geospatial methods. The rainiest month is March, and the Quintino Channel and the surrounding area are the most affected by floods in ADGUA. Despite the ancient issues with inundation, the city lacks a platform to monitor continuous flood events and change patterns that can be reached with structural and non-structural measures. Floods in the city occur in three ways: When there is high-tide and intense or extremely intense rain events; high-tide and no rain; and low-tide and extremely intense rain. Recurring flood events and extensive damage will continue until Belém reduce vulnerable and exposed areas and implement alert thresholds for use by Civil Defense actions. It is worth noting that there is an elevated number of affected locations for high-tide and extremely intense rain scenarios. The floods' location depends on vulnerable places and a lack of efficient infrastructure and are mostly above a 4 m topography area. It would be important to expand the network of tide measurement stations for prevention purposes. Furthermore, the relationship between flooding, precipitation, and tides needs to be further understood and monitored on the mainland and islands so that appropriate prevention, preparation, response, and reconstruction actions can be established for Belém for urban planning and wider risk management.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare they do not have any conflict of interest in the creation of this article.

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Supplementary

Further Reading

Source from news report from Figure 3:

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