Geotemas, Pau dos Ferros, RN, Brasil
ISSN: 2236-255X, v. 16, 2026.

ASSESSMENT OF FLOOD HAZARD ALONG A STRETCH OF THE ALMADA RIVER IN THE URBAN AREA OF ITAJUÍPE, BAHIA

Avaliação Do Perigo À Inundação Em Trecho Do Rio Almada No Núcleo Urbano Do Município De Itajuípe-Ba

Evaluación del riesgo de inundación a lo largo de un tramo del río Almada en el área urbana de Itajuípe, Bahía

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Article History
Received: 27 march, 2026
Accepted: 07 july, 2026
Published: 14 august, 2026

ABSTRACT

O The municipality of Itajuípe, Bahia, was hit by a major flood in 2021 that left more than 60% of its urban center submerged, isolating its population and interrupting the supply of water, basic resources, services, and communication. Despite recurring floods, its municipal seat lacks flood hazard mapping. Therefore, the objective of this work is to map the flood hazard distribution of the Almada River in its urban stretch within the municipality of Itajuípe, using the HAND (Height Above Nearest Drainage) model. The methodology employed includes processing historical data from its river gauging station; geomorphological characterization of the urban center; and the identification and classification of its susceptibility through terrain modeling using the HAND Model. As a result, this study identified three historical flood events in the hydrological data, occurring in 1945, 1981, and 2021, with a maximum supported flow of 150 m³/s and an overflow level of 500 cm in the main channel. The geomorphological study of the area revealed that Itajuípe is located in a valley bottom area with altitudes and slopes that favor the occurrence of floods and inundations. Finally, the hazard mapping generated by the HAND model proved to be a functional tool for delineating floodable and inundable areas in the urban center of Itajuípe, generating five classes of susceptibility to flooding and inundations, highlighting that the very high-risk and high-risk areas correspond to almost half of the study area.

Keywords: Hand Model; Hydrology; Hazard; Susceptibility; Floods.

https://doi.org/10.33237/2236-255X.2026.7919

RESUMO

O município de Itajuípe-Bahia foi atingido por uma grande inundação em 2021 que deixou mais de 60% do seu núcleo urbano submerso, isolando a sua população e interrompendo o abastecimento de água, insumos básicos, serviços e comunicação. Mesmo com inundações recorrentes, a sua sede municipal não possui mapeamento do perigo de inundação. Portanto, o objetivo deste trabalho é mapear áreas com perigo de inundação do Rio Almada em seu trecho urbano no município de Itajuípe, por meio da aplicação do HAND Model (*Height Above Nearest Drainage*). Para sua execução tem-se como método o processamento das séries históricas da sua estação fluviométrica; caracterização geomorfológica do núcleo urbano; e, a identificação e classificação de sua susceptibilidade com a modelagem do terreno por meio do HAND Model. Como resultado, o presente trabalho identificou nos dados hidrológicos três eventos históricos de inundações ocorridos em 1945, 1981 e 2021, a vazão máxima suportada de 150 m³/s e a cota de extravasamento de 500 cm do canal principal. O estudo geomorfológico da área revelou que Itajuípe está em uma área de fundo de vale com altitudes e declividades do relevo que favorecem a ocorrência de inundações e alagamentos. Por fim, o mapeamento do perigo gerado pelo HAND Model se mostrou uma ferramenta funcional para a delimitação de áreas inundáveis e alagáveis no núcleo urbano de Itajuípe, gerando cinco classes de suscetibilidade a inundação e alagamentos destacando-se que as áreas de muito alto risco e alto risco correspondem a quase metade da área de estudo.

Palavras-chave: HAND Model; Hidrologia; Perigo; Suscetibilidade; Inundações.

RESUMEN

El municipio de Itajuípe, Bahía, sufrió una gran inundación en 2021 que dejó sumergido más del 60% de su centro urbano, aislando a su población e interrumpiendo el suministro de agua, recursos básicos, servicios y comunicaciones. A pesar de las inundaciones recurrentes, su cabecera municipal carece de un mapeo de riesgo de inundación. Por lo tanto, el objetivo de este trabajo es mapear la distribución del riesgo de inundación del río Almada en su tramo urbano dentro del municipio de Itajuípe, utilizando el modelo HAND (Height Above Nearest Drainage). La metodología empleada incluye el procesamiento de datos históricos de su estación de aforo; la caracterización geomorfológica del centro urbano; y la identificación y clasificación de su susceptibilidad mediante el modelado del terreno utilizando el modelo HAND. Como resultado, este estudio identificó tres eventos históricos de inundación en los datos hidrológicos, ocurridos en 1945, 1981 y 2021, con un caudal máximo soportado de 150 m³/s y un nivel de desbordamiento de 500 cm en el cauce principal. El estudio geomorfológico de la zona reveló que Itajuípe se ubica en el fondo de un valle con altitudes y pendientes que favorecen la ocurrencia de inundaciones. Finalmente, el mapeo de riesgos generado por el modelo HAND demostró ser una herramienta funcional para delimitar las áreas inundables en el centro urbano de Itajuípe, generando cinco clases de susceptibilidad a inundaciones. Se observó que las áreas de muy alto riesgo y alto riesgo corresponden a casi la mitad del área de estudio.

Palabras clave: Modelo de mano; Hidrología; Peligro; Susceptibilidad; Inundaciones.

1 INTRODUCTION

Floods are natural phenomena with significant impacts that occur within river basins as a consequence of their physical and environmental characteristics. They are inherently uncontrollable and unavoidable processes, occurring naturally at global, regional, and local scales depending on flood regimes and the magnitude of hydrological events. The complexity of the numerous factors acting within these environments, which vary spatially and temporally, often makes monitoring their dynamics and interpreting their processes a multidisciplinary challenge (Alves et al., 2020).

In urban environments, the intrinsic characteristics of the physical landscape, combined with intense and concentrated rainfall events typical of flood seasons, together with rapid urbanization and unplanned land occupation, contribute to the intensification of flooding and urban waterlogging, frequently culminating in severe natural disasters (Kobiyama et al., 2010).

Accordingly, efforts aimed at preventing and mitigating flood impacts are closely aligned with the United Nations 2030 Agenda for Sustainable Development, particularly when they result from cooperation among governments, the private sector, and civil society. According to the United Nations (2025), the 2030 Agenda represents a global commitment to achieving goals and targets that promote a more sustainable, resilient, peaceful, and environmentally balanced planet. Within this framework, flood management is directly related to several Sustainable Development Goals (SDGs), notably SDG 1 – No Poverty; SDG 3 – Good Health and Well-being; SDG 6 – Clean Water and Sanitation; SDG 11 – Sustainable Cities and Communities; SDG 13 – Climate Action; and SDG 15 – Life on Land (United Nations, 2025).

Given their magnitude and the extensive socioeconomic damage they cause, floods are among the principal natural hazards monitored by the Emergency Events Database (EM-DAT), established in 1988 through collaboration between the Centre for Research on the Epidemiology of Disasters (CRED) and the World Health Organization (WHO). According to EM-DAT, floods rank among the most frequent natural hazards worldwide (CRED, 2025). In Brazil, 207 flood events were recorded between 2000 and 2022, placing the country among the most affected nations in South America and among those with the highest number of reported flood occurrences worldwide (CRED, 2019).

Within the Brazilian context, the state of Bahia has been repeatedly affected by intense and prolonged rainfall events that trigger flash floods and riverine flooding, particularly in its southern and far southern regions. According to the Natural Disaster Surveillance System (Vigidesastres), coordinated by the Strategic Health Surveillance Information Center (CIEVS, 2022), the most recent major flood events occurred in 2021 and 2022, resulting in states of public calamity, casualties, substantial social losses, and extensive damage to urban infrastructure amounting to tens of millions of Brazilian reais.

Located within the Eastern River Basin (Bacia do Leste) in southern Bahia, the municipality of Itajuípe, with an estimated population of approximately 18,781 inhabitants, stands out because its urban area was severely affected by the floods of 2021 as well as by the flash floods and urban flooding recorded in 2022 (CIEVS, 2022). According to information released by the municipal government, approximately 60% of the urban area was affected, isolating the local population and making the municipality dependent on goods and services supplied by neighboring cities. Despite this history, the municipality lacks historical flood delineation maps and flood hazard assessments for its urban area. Nevertheless, residents' reports indicate the occurrence of at least four major historical flood events (SNIS, 2022).

Consistent with this scenario, the National Sanitation Information System (SNIS), in its *Diagnosis of Urban Stormwater Drainage and Management (DMAPU)* (2022), reports that more than half of Brazilian municipalities lack flood risk mapping. Most of these municipalities are characterized by small populations (up to 20,000 inhabitants) and by the absence of effective flood risk management strategies.

The present study aims to map flood hazard areas along the urban reach of the Almada River in the municipality of Itajuípe through the application of the Height Above Nearest Drainage (HAND) model. Specifically, the study seeks to: (i) analyze the study area with respect to terrain characteristics that either favor or restrict the occurrence of flooding and urban waterlogging; (ii) investigate the hydrological behavior of the Almada River using secondary data and a consolidated cartographic database; and (iii) identify and map flood- and waterlogging-prone areas within the urban center of Itajuípe through the application of the HAND model.

The municipality of Itajuípe fits the profile described by the SNIS (2022), both as a small-sized municipality and as one presenting several constraints that hinder flood risk management and decision-making. These constraints include the absence of detailed planialtimetric mapping, the lack of flood hazard mapping, and unplanned urban expansion associated with the municipality's physical and natural characteristics, as highlighted by Graciosa and Mendiondo (2007), Manz (2021), and Oliveira et al. (2018).

Therefore, these limitations constitute critical barriers to effective planning and the implementation of strategies for flood risk reduction. Such challenges can be addressed through comprehensive flood hazard mapping and the delineation of flood-prone and waterlogging-prone areas, thereby providing essential information to support urban planning, disaster risk reduction, and public policy decision-making.

2 Floods and Their Management in Small Urban Settlements

Therefore, beyond the material damage and financial losses imposed on affected populations, effective decision-making requires the adoption of appropriate flood risk management strategies. Graciosa and Mendiondo (2007) describe flood risk management as comprising four interrelated phases: prevention, response, recovery, and mitigation. According to Manz (2021), these phases should be understood and implemented within an integrated management framework. Consequently, small municipalities should begin with a comprehensive understanding and diagnosis of the phenomenon through flood risk mapping and flood hazard identification, thereby providing a scientific basis for the development of effective management plans. Between 1990 and 2015, flood events recorded in Brazil accounted for approximately 25% of all flood disasters worldwide, highlighting the national relevance of this issue (Silva Júnior et al., 2022).

Understanding the exposure of urban settlements to flooding requires first defining the concepts of hazard, vulnerability, and risk. Flood hazard refers to the physical and environmental conditions that naturally predispose an area to flooding. In areas with an intrinsic susceptibility to natural hazards, anthropogenic activities and urban expansion tend to intensify the effects of these hazards (Farias et al., 2024).

Vulnerability is associated with the occupation of naturally flood-prone areas by populations living in settlements characterized by inadequate or deficient infrastructure, thereby creating conditions of social insecurity. Once both hazard and vulnerability have been identified, it becomes possible to assess potential damage. In the context of flooding, damage is determined by the magnitude of the event, including the delineation of inundated areas, flood depth, and flood extent (Hora & Gomes, 2009).

Finally, flood risk results from the interaction among hazard, vulnerability, and potential damage. Risk therefore reflects the combined influence of physical and natural characteristics, social conditions, and the adverse impacts associated with flood occurrence. Consequently, flood risk mapping represents a fundamental step in diagnosing flood-prone areas and provides essential support for strategic territorial planning and effective flood risk management (Dias, Júnior, & Pimentel, 2015).

Regarding flood hazards, Alves (2018) emphasizes that flood occurrence is associated with rainfall intensity, terrain morphology, geological substrate characteristics, and the presence or absence of vegetation cover. In general, flood hazard is primarily related to the spatial extent of inundation and to hydraulic characteristics such as flood depth and flow velocity (Fernandez et al., 2015).

According to Farias et al. (2024), flood hazard can be spatially represented through cartographic products derived from hydrological, hydraulic, and terrain-surface modeling. When supported by appropriate datasets, these models simulate the transformation of rainfall into surface runoff, enabling the delineation of flood extent as well as the estimation of flood depth and flow velocity within inundated areas.

Within this context, one of the most widely adopted terrain-based approaches for flood prediction is the Height Above Nearest Drainage (HAND) model, developed by Nobre et al. (2015) under the coordination of Cuartas et al. (2012). The HAND model has been extensively applied because of its operational simplicity, computational efficiency, and reliable performance, as demonstrated by Mengue et al. (2016), Goerl et al. (2017), Speckhann (2015), Dantas and Canil (2017), Milanesi, Quadros and Lahm (2017), Conceição and Simões (2021), the Institute for Technological Research (IPT) (2023), Pinheiro (2024), and Mantovani et al. (2025).

The HAND model was originally developed to normalize digital topographic datasets by correcting errors associated with artificial depressions in Digital Elevation Models (DEMs). The method calculates the relative elevation of each terrain cell with respect to its nearest drainage channel, allowing the identification of areas that are potentially susceptible to flooding. Its application is highly versatile, ranging from large river basins to regions with limited hydrological data, and it has been widely employed in urban planning, flood hazard mapping, and natural disaster management (Rennó et al., 2008; Nobre et al., 2011b; Momo et al., 2016).

Because of its efficiency and rapid implementation, the HAND model has become an important tool for terrain mapping and the classification of hydrologically homogeneous units. In predictive flood hazard assessment, the model generates drainage-normalized vector contours that represent potential flood hazard zones. Consequently, it provides an efficient and reliable approach for the rapid identification of areas susceptible to riverine flooding and urban waterlogging (Nobre et al., 2015).

3 MATERIALS AND METHODS

3.1 Study Area

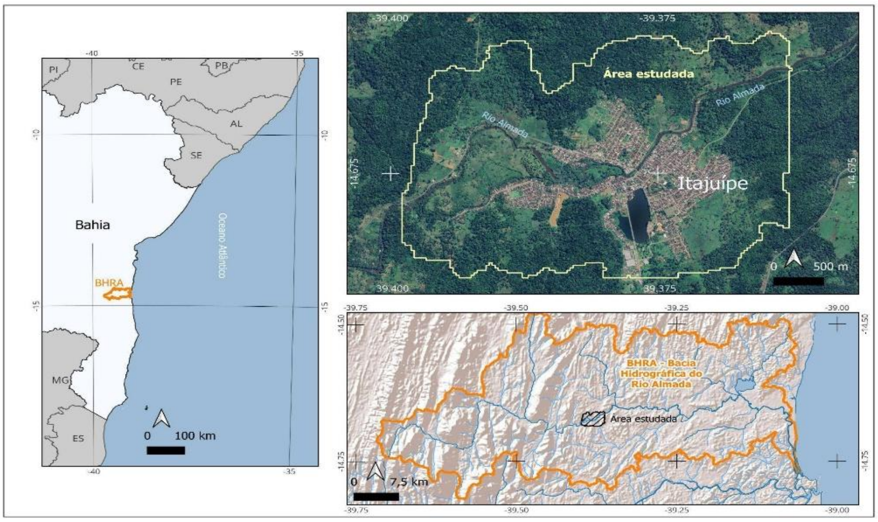
The study area comprises a 9.72 km² polygon encompassing the urban center of the municipality of Itajuípe, Bahia State, Brazil, located approximately 419 km from Salvador, the state capital. According to the Brazilian Institute of Geography and Statistics (IBGE, 2022), Itajuípe has a population of 18,781 inhabitants and a total territorial area of 270.75 km². The municipality is predominantly urban, with 14,724 inhabitants (78%) residing in the urban area and 4,057 inhabitants (22%) in rural areas. The entire municipality is located within the Almada River Basin (ARB) (Figure 1).

The Almada River Basin is part of the Eastern Atlantic Hydrographic Region and covers approximately 1,570 km². Of this total area, approximately 23% consists of pasturelands, exposed soils, and urbanized areas; 18% corresponds to remnants of the Atlantic Forest and mangrove ecosystems; 54% is occupied by the traditional cabruca agroforestry system (shade-grown cocoa plantations); and 3.9% is covered by water bodies and wetlands (Gomes, 2013).

The Almada River originates in the mountainous region of the municipality of Almadina and flows approximately 138 km before discharging into the Atlantic Ocean in the northern portion of the municipality of Ilhéus, Bahia. Its principal right-bank tributaries include the Braço River, Boqueirão Stream, and Sete Voltas Stream, whereas its principal left-bank tributaries comprise the São José River, Jussara Stream, and Braço Norte Stream. The municipality of Itajuípe is located along the main channel of the Almada River within its middle reach (Figure 01).

The regional climate is classified as Tropical Rainforest Climate (Af) according to the Köppen classification, with an average annual precipitation of approximately 1,780 mm and a mean annual temperature of 22.9 °C (Bahia, 2001). The basin's drainage network exhibits an average drainage density of approximately 1.56 km km^{-2}, characterized by a trellis drainage pattern in its western sector and a predominantly dendritic drainage pattern throughout the remainder of the basin.

Figure 01 - Study area: urban reach of the municipality of Itajuípe, Bahia, Brazil.



Source: Authors (2026).

3.2 Methodology

To achieve the proposed objectives, the methodological framework began with activities aimed at understanding flood processes within the study area through the analysis of terrain attributes, including elevation and slope, together with an assessment of the hydrological behavior of the Almada River.

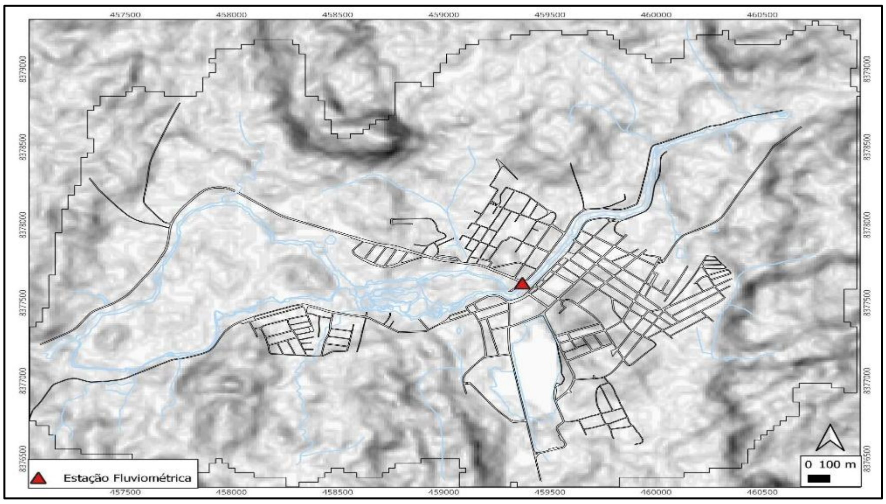
Terrain analysis was performed using a Digital Elevation Model (DEM) processed within a Geographic Information System (GIS) environment. This study employed DEM data derived from the Copernicus GLO-30 remote sensing mission, specifically the FABDEM (Forest And Buildings removed Copernicus Digital Elevation Model) dataset developed by Hawker et al. (2022), with a spatial resolution of 30 m. The dataset was freely accessed through the LF Tools plugin for QGIS (Figure 2).

The FABDEM dataset provides near-global coverage and is specifically designed to remove vegetation and buildings from the original Copernicus DEM, thereby producing a terrain representation that more accurately reflects the bare-earth surface. Consequently, it offers greater accuracy than conventional elevation datasets, such as the Shuttle Radar Topography Mission (SRTM) DEM, particularly for applications requiring realistic terrain representation, including flood modeling. Raster processing was performed using QGIS version 3.30, allowing the extraction of the study area from the original dataset.

Elevation and slope maps were generated by applying raster analysis tools available in QGIS directly to the DEM.

Hydrological analyses were conducted using both secondary and primary datasets. Secondary information was obtained from previous studies carried out within the basin (in press), whereas primary data consisted of historical discharge and stage records collected at the Itajuípe streamflow gauging station (Station Code 5305000), operated by the Brazilian National Water and Basic Sanitation Agency (ANA). The gauging station is located at the bridge crossing in the central district of the municipality and its records were processed using the Hidroweb platform and Hidro 1.4 software (Figure 02).

Figure 02 - Digital Elevation Model (DEM) derived from the FABDEM dataset and location of the Itajuípe streamflow gauging station.



Source: Authors (2026).

Hydrological data available through the Hidroweb platform (ANA, 2024) were processed using Hidro 1.4 (ANA, 2001) and SisCAH 1.0 (Sousa et al., 2009) to obtain monthly mean discharges, annual mean discharges, and maximum streamflow values from the historical series. A comprehensive analysis of the hydrological characteristics of the gauging station and their implications for flood dynamics in the study area is presented by Araújo and Gomes (in press).

The second stage of the methodology focused on flood hazard (susceptibility) mapping through the application of the Height Above Nearest Drainage (HAND) model, originally developed by Cuartas et al. (2012) and further refined by Nobre et al. (2011a, 2015). The HAND model estimates the relative elevation of each terrain cell with respect to its nearest drainage channel, enabling its application across both large river basins and regions with limited hydrological information. Owing to these characteristics, the model has become an important tool for urban planning, flood hazard mapping, and disaster risk management (Rennó et al., 2008; Nobre et al., 2011b; Momo et al., 2016).

The HAND model was considered particularly appropriate for this study because the municipality of Itajuípe lacks high-resolution cartographic data, substantially limiting the application of conventional hydrological and hydraulic models. In contrast, the HAND algorithm, developed by the Brazilian National Institute for Space Research (INPE), requires relatively few input datasets while providing reliable flood hazard assessments.

Using the 30-m-resolution DEM derived from freely available radar data, the HAND raster was generated for the urban area. It should be noted that the level of detail represented by the DEM directly influences the accuracy of terrain characterization and, consequently, flood modeling results. Although the spatial resolution may limit the representation of fine-scale topographic features, the HAND model proved effective in delineating flood-prone areas when validated against historical records of flood events in Itajuípe.

Nevertheless, studies requiring greater spatial precision and more detailed flood characterization depend on higher-resolution cartographic datasets. Although the HAND model successfully identified flood hazard levels and delineated flood-prone and waterlogging-prone areas, it does not simulate flood hydraulics under varying discharge and rainfall scenarios. Consequently, it is insufficient for assessing flood depth, flood extent, potential damage, social vulnerability, and overall flood risk, which require physically based hydrodynamic modeling approaches.

The resulting HAND raster was exported and subsequently reclassified in QGIS into flood hazard classes representing flood susceptibility within the urban area of Itajuípe. The adopted classification scheme consisted of the following classes: Very High: 0–1 m, High: 1–2 m, Moderate: 2–5 m, Low: 5–10 m, Very Low: >10 m.

4 RESULTS AND DISCUSSION

4.1 Terrain Characteristics and Hydrological Behavior of the Study Area and Their Contribution to Understanding Flood Events

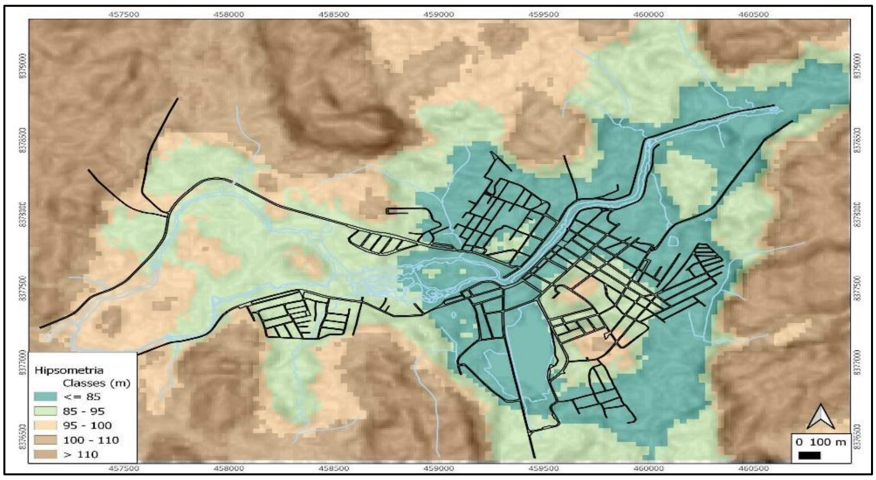
The analysis of the study area's terrain, represented by its elevation and slope characteristics, provides essential information for understanding the landscape's natural predisposition to either convey or accumulate surface water during flood events. Elevation values range from 79.8 to 158.7 m, with the lowest elevations corresponding to the Almada River channel at the downstream limit of the study area. Conversely, the highest elevations occur on the hills located in the northern portion of the study area.

The hypsometric map (Figure 3) indicates that the lowest elevations correspond to the fluvial valleys occupied by the Almada River and its local drainage network, where the urban center of Itajuípe is also predominantly established. Most of the municipal headquarters developed on terrain below the 85 m elevation, except for two elevated sectors located in the Centro and Nova Itajuípe neighborhoods. As illustrated in Figure 3, the 85 m contour delineates a topographic depression relative to the surrounding higher terrain, naturally favoring the concentration and temporary storage of surface runoff within the urban area.

The slope analysis (Figure 04) revealed terrain gradients ranging from 0° to 33.8°, indicating relatively low topographic variability throughout the municipality. The steepest slopes are associated with hillside environments, whereas the gentlest slopes occur within low-lying terrain and valley bottoms.

Within the urban area, terrain slopes generally vary between 1.7° and 4.6°. These gentle gradients naturally reduce the kinetic energy of surface runoff, decreasing flow velocity and promoting water accumulation during high-flow events. Areas with slopes ranging from 4.6° to 24.2° correspond primarily to elevated terrain surrounding the Sacred Heart of Jesus Church, which has historically served as an emergency shelter during major flood events because of its topographically favorable location.

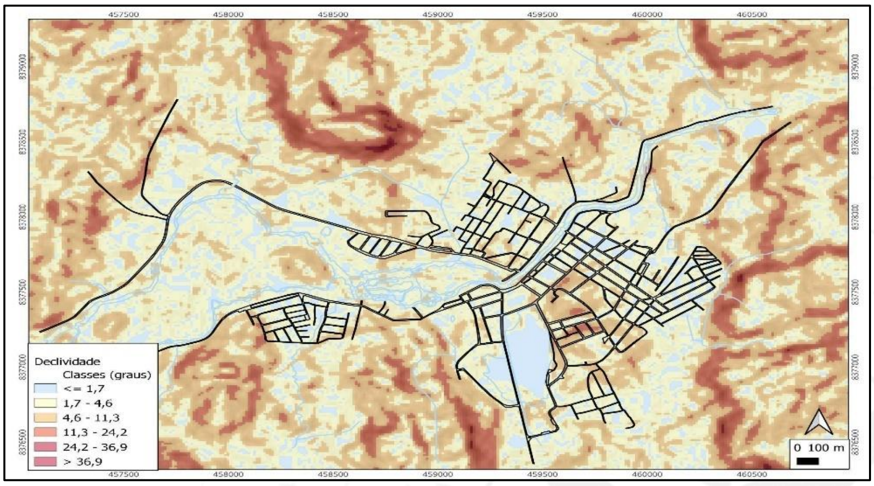
Figure 03 - Hypsometric classes of the study area.



Source: Authors (2026).

According to the terrain classification proposed by Embrapa (1979), which defines flat relief as areas with slopes equal to or less than 4.6°, Figure 04 demonstrates that these nearly level surfaces are predominantly distributed along the main channel of the Almada River and its adjacent floodplain. Consequently, the low-gradient terrain of the urban center substantially reduces runoff velocity, increasing water retention and favoring flood occurrence during periods of high river discharge.

Figure 04 - Slope classes of the study area.



Source: Authors (2026).

Regarding the hydrological behavior of the Almada River, analysis of records from the Itajuípe streamflow gauging station indicates an annual mean discharge of 8.34 $m^3 s^{-1}$.

The period extending from November to April exhibits the highest monthly mean discharges, with November averaging 10.4 m³ s⁻¹ and December reaching 13.8 m³ s⁻¹. In contrast, the months from May through October present the lowest average flows, with September recording the minimum monthly mean discharge (5.25 m³ s⁻¹).

A similar seasonal pattern is observed for the monthly maximum discharges. November (42.7 m³ s⁻¹) and December (47.6 m³ s⁻¹) consistently present the highest peak-flow averages. Historically, December concentrates the most severe flood events, indicating that this month presents the highest probability of flooding within the study area.

Conversely, monthly minimum discharges indicate that January (1.83 m³ s⁻¹) and October (1.84 m³ s⁻¹) correspond to the periods of lowest streamflow in the Almada River.

Analysis of annual mean discharge over the 79-year observation period shows that 43 years presented below-average discharge conditions, whereas 36 years were wetter than the long-term annual mean of 8.34 m³ s⁻¹.

Regarding historical flood identification, peak discharges exceeding 150 m³ s⁻¹ were considered extreme flow events capable of producing urban flooding due to substantial increases in river stage and flood depth.

Among the most significant years identified in the historical record are 1945, 1947, 1980, 1981, 2014, and 2021, with documented urban flood events occurring primarily in 1947 and 1981. On 30 November 1947, the Almada River reached a discharge of 267 m³ s⁻¹, approximately 32 times greater than the long-term annual mean discharge of 8.34 m³ s⁻¹, demonstrating the exceptional magnitude and destructive potential of this flood event.

Concerning the 2021 flood, hydrological data available through the Hidroweb database indicate that the Almada River experienced two major discharge peaks during December 2021. The first occurred on 10 December 2021, reaching 151.4 m³ s⁻¹, which substantially increased river stage. The second occurred on 24 December 2021, with a discharge of 153.2 m³ s⁻¹, ultimately causing channel overflow. The maximum recorded water level (604 cm) was reached on 26 December 2021, although the corresponding discharge was not measured because the gauging station ceased discharge recording above this level. Measurements resumed only on 28 December 2021, when river stage had decreased to 400 cm, corresponding to a discharge of 153 m³ s⁻¹, indicating that discharge measurements become unavailable once the river stage exceeds approximately 400 cm.

Historical stage records further indicate that the long-term mean discharge (8.34 m³ s⁻¹) corresponds to a water level of approximately 74 cm above the riverbed. As discharge increases, progressively higher river stages are observed. The most significant historical flood events include: 1947: water level of 567 cm and discharge of 267 m³ s⁻¹; 1981: water level of 507 cm and discharge of 226 m³ s⁻¹; 2021: maximum recorded water level of 604 cm, associated with discharge exceeding 153.2 m³ s⁻¹.

At the gauging station cross-section, the Almada River channel is confined by retaining walls extending up to the 500 cm stage. Consequently, channel overflow within the urban area occurs whenever river stage exceeds this threshold, as documented during the flood events of 1947, 1981, and 2021. This overflow stage corresponds to an elevation of approximately 82.62 m above mean sea level.

The spatial distribution of the estimated elevations representing the channel overflow threshold (83 m) is illustrated in Figure 5. Based on field evidence and hydrological analysis, the flood event of 2021 is estimated to have reached an elevation of approximately 84 m, corresponding to nearly 2 m above the channel overflow elevation. Table 1 summarizes the principal hydrological characteristics derived from the historical streamflow series recorded at the Itajuípe gauging station.

Table 01. Hydrological characteristics of the Almada River derived from historical streamflow records

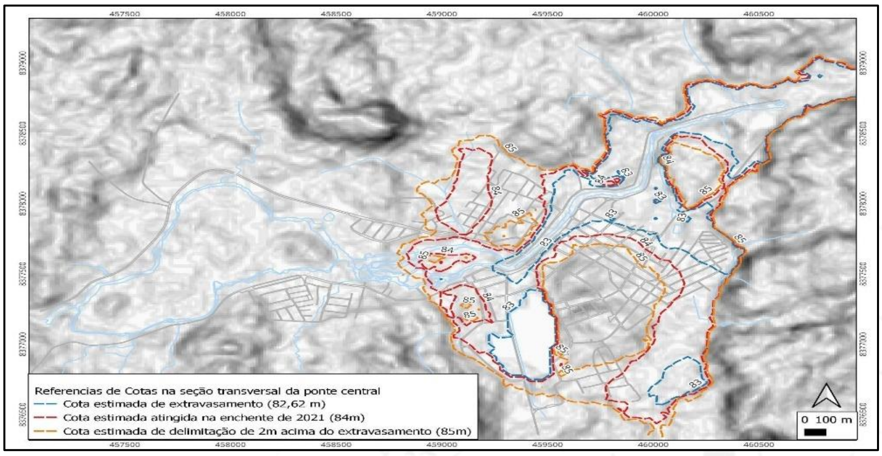
Annual mean discharge	Highest monthly mean discharges	Lowest monthly mean discharges	Monthly maximum discharge averages	Monthly minimum discharge averages	Highest recorded discharge	Historical flood events
8,34 m³ · s⁻¹	November (10,4 m³ · s⁻¹) and December (13,8 m³ · s⁻¹)	May-October; September minimum (5,25 m³ · s⁻¹).	November (42,7 m³ · s⁻¹) and December (47,6 m³ · s⁻¹)	January (1,83 m³ · s⁻¹) and October (1,84 m³ · s⁻¹)	267 m³ s⁻¹ (30 November 1947)	**1947:** 567 cm, 267 m³ s⁻¹; **1981:** 507 cm, 226 m³ s⁻¹;

	2021: 604 cm, >153.2 $m^3 s^{-1}$

Source: Authors.

Once the river stage exceeds the 83 m elevation, floodwaters tend to occupy the floodplain bordering the main channel through the central urban area before expanding toward broader downstream areas. The 84 m elevation, associated with the maximum water level reached during the 2021 flood, extends across the city's low-relief sectors while surrounding the elevated hills located in the downtown area. Under these conditions, hydraulic connectivity may occur between Humberto Badaró Lagoon and the main channel of the Almada River. The 85 m contour, in turn, delineates the geomorphological depression occupied by the urban center and defines the maximum area likely to be affected during extreme flood events.

Figure 05 - Estimated elevation thresholds associated with the cross-section at the central bridge within the study area



Source: Authors (2026).

Finally, the historical streamflow records provide valuable insights into the long-term hydrological behavior of the Almada River by identifying periods for which consistent and reliable measurements are available. These records make it possible to recognize long-term trends in flood and drought occurrence, compare years characterized by extreme discharges, and identify critical periods associated with historical flood events.

As emphasized by Farias and Gomes (2023), the analysis of minimum, mean, and maximum discharges is fundamental for understanding and monitoring water resources, supporting sustainable water management, and improving decision-making during extreme hydrological events. Such analyses provide essential scientific information for developing effective flood prevention and mitigation strategies.

4.2 Application of the HAND Model in the Study Area

The spatial distribution of flood hazard classes derived from the application of the Height Above Nearest Drainage (HAND) Model provides a comprehensive assessment of flood hazard within the study area through the delineation of flood-prone and waterlogging-prone areas. As shown in Figure 6, the resulting flood hazard map classifies the terrain into five susceptibility classes: Very High, High, Moderate, Low, and Very Low flood susceptibility.

The HAND values represent the relative elevation of each terrain cell with respect to the nearest drainage channel. Consequently, the Very High susceptibility class comprises areas located up to 1 m above the elevation of the nearest drainage channel, representing the sectors most prone to riverine flooding and urban waterlogging. Conversely, areas classified as Low flood susceptibility are situated between 5 and 10 m above the nearest drainage channels and are expected to be affected only during historical floods or extreme flood events of exceptional magnitude. Of the total 9.72 km² encompassed by the study area, 1.29 km² were classified as Very High susceptibility, 0.81 km² as High, 1.96 km² as Moderate, 1.68 km² as Low, and 4.02 km² as Very Low flood susceptibility.

These flood susceptibility classes encompass virtually the entire urban area of Itajuípe, extending across almost all neighborhoods (Figures 6 and 7). Urban development has occurred predominantly along the banks of the Almada River and over low-lying floodplain areas. Combined with the area's gentle slopes and topographic characteristics, this occupation pattern substantially increases flood vulnerability.

Urban occupation along the banks of the Almada River (Figure 6) represents a significant source of flood hazard, since these sectors are predominantly classified as exhibiting Very High flood susceptibility. In this context, land-use planning constitutes a strategic instrument for integrated flood risk management. According to Ashley et al. (2005) and Tucci (2012), territorial planning combined with urban drainage management represents one of the principal pillars of modern integrated flood management. Therefore, effective flood management should focus not only on stormwater control but also on the spatial distribution of flood risk and population exposure (UNDRR, 2022).

Consequently, comprehensive flood risk management must extend beyond emergency response to encompass actions undertaken before, during, and after flood events. Urban expansion along the Almada River has generated not only environmental impacts on the fluvial system but also increased social vulnerability within the municipality.

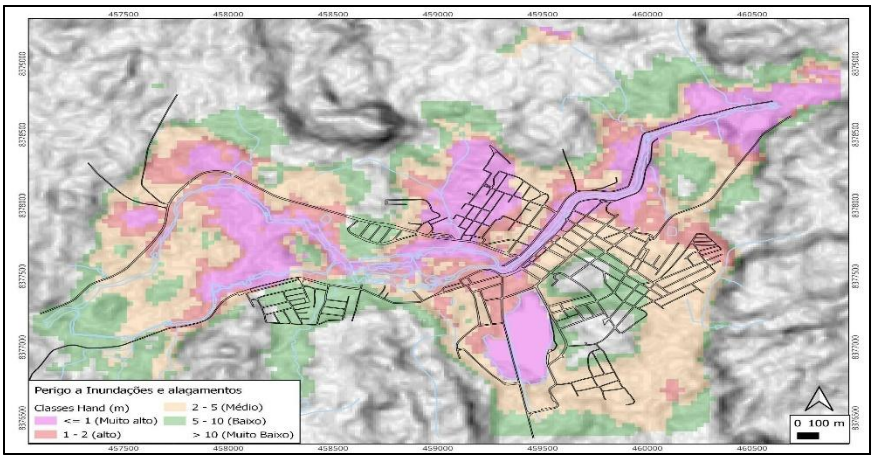
Furthermore, the absence of essential planning instruments—including the Municipal Master Plan, Urban Zoning Plan, Environmental Zoning Plan, Municipal Disaster Risk Reduction Plan, geotechnical and hydrological maps, and flood hazard mapping—has contributed to increased urban exposure to flood hazards in Itajuípe (Tucci, 2012).

The absence of official flood hazard mapping (SNIS, 2022), together with the lack of detailed topographic datasets despite the municipality's documented history of flooding, considerably limits evidence-based decision-making. Flood hazard mapping constitutes a fundamental component of disaster risk management because it provides the diagnostic basis for territorial planning. Such information enables urban expansion to be directed toward safer areas, restricts occupation of floodplains and alluvial valleys, and supports the implementation of environmental and urban planning policies (Dias, Júnior, & Pimentel, 2015). Satellite imagery presented in Figure 7 clearly illustrates the disorderly urban expansion occurring immediately adjacent to the riverbanks without any relocation or risk reduction measures.

The delineation of flood-prone areas defines the maximum spatial extent potentially affected by flooding. Accordingly, Figure 7 presents four flood-depth classes (Very High, High, Moderate, and Low). Flood depth provides an indication of the sectors where floodwaters are expected to reach the greatest depths and consequently where flood hazard and potential damage to the population are highest (Hora & Gomes, 2009).

The Very High and High susceptibility classes extend continuously along the Almada River and expand well beyond the riverbanks. Notably, the Very High susceptibility zone occupies more than half of the Nova Itajuípe neighborhood, whereas the High susceptibility class is primarily associated with Humberto Badaró Lagoon, extending toward adjacent residential areas.

Figure 06 – Distribution of flood susceptibility classes within the urban area of Itajuípe, Bahia, Brazil.

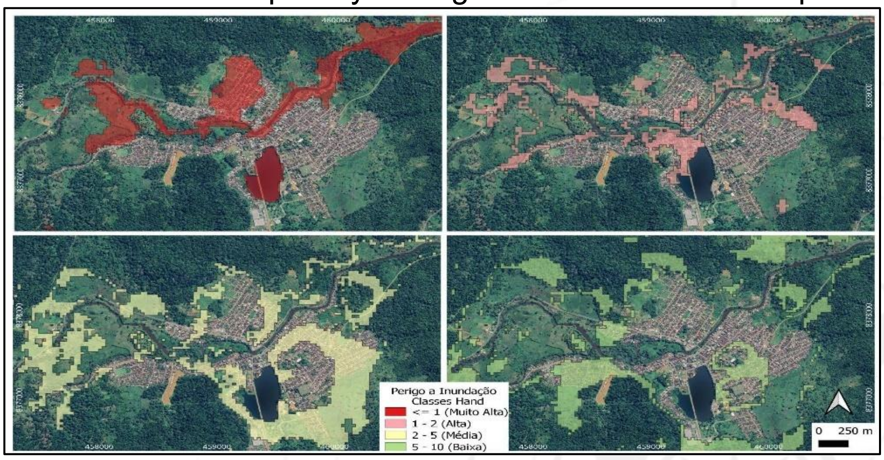


Source: Authors (2026).

During major flood events, the natural drainage network crossing the urban area intensifies flood impacts and increases disaster severity. As observed during the 2021 flood, several neighborhoods became isolated because roads and bridges were submerged, interrupting ground transportation.

The Nova Itajuípe neighborhood, located on the left bank of the Almada River, lies partially within areas classified as High and Very High flood susceptibility, although some sectors occupy locally elevated terrain. According to residents' testimonies, floodwater depths reached approximately 1.80 m, submerging numerous houses, causing substantial material losses, and displacing many residents.

Figure 07 – Flood susceptibility zoning based on four flood-depth classes.



Source: Authors (2026).

The highest topographic sectors remained among the few locations not reached by floodwaters, particularly the municipal commercial district known locally as the "Feirinha". In this area, water accumulation appears to result predominantly from urban waterlogging rather than riverine flooding, most likely associated with obstruction and insufficient capacity of the stormwater drainage and sewerage systems.

It is important to emphasize that flooding within the urban area of Itajuípe is not always directly associated with overflow of the Almada River. Topographic highs act as natural barriers that restrict floodwater propagation. Consequently, water accumulation observed in some neighborhoods is primarily associated with localized urban waterlogging resulting from deficiencies in the stormwater drainage network.

Hydrological analyses based on validated streamflow records from the Itajuípe gauging station indicated that channel overflow occurs when river stage reaches approximately 500 cm. Following extraction of the urban cross-sectional terrain profile from the HAND raster, the modeled results were consistent with hydrological observations, indicating that floodwaters reach elevations approximately 5 m above the river channel during major flood events.

The pixelation observed in the resulting maps reflects the limited availability of high-resolution topographic information for the urban area, particularly the absence of detailed planialtimetric datasets. This limitation is consistent with observations by Oliveira et al. (2018) regarding data scarcity in small municipalities. Nevertheless, Hu and Demir (2021) demonstrated that the HAND Model is particularly suitable for data-scarce environments. In the present study, the model successfully identified and delineated areas classified as having Very High flood susceptibility.

Regarding areas classified as Very High susceptibility, Bitar et al. (2014) demonstrated that the vertical distance from the nearest drainage channel is inversely related to groundwater depth. Small vertical distances indicate shallow groundwater tables, resulting in permanently saturated soils, whereas greater vertical distances indicate deeper groundwater levels and improved natural drainage conditions.

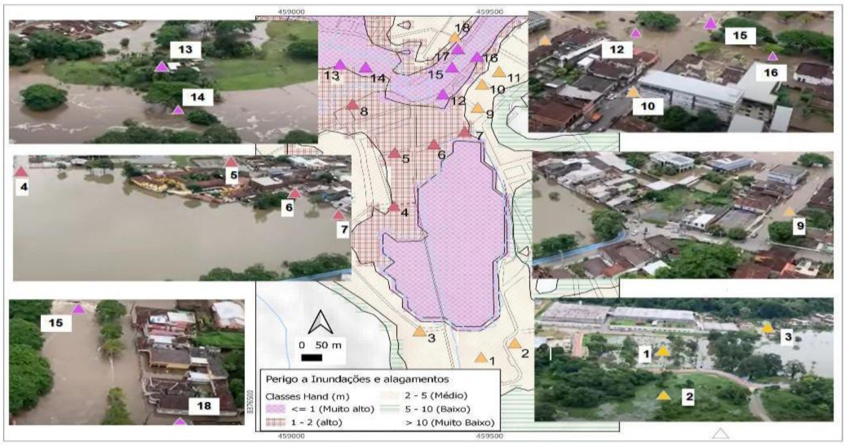
Accordingly, the study area is inferred to possess a shallow groundwater table, producing naturally saturated soils that reduce infiltration capacity and increase both the intensity and duration of flooding and urban waterlogging during high-flow periods.

Model validation followed the methodology proposed by Brouwer et al. (2017). The HAND-derived flood hazard map was validated using field surveys conducted in 2024, including residents' testimonies, aerial photographs, and videos acquired during the extreme rainfall and flood event of 26 December 2021 (Figure 8). These aerial records, publicly available on the YouTube platform, enabled direct comparison between the modeled flood hazard classes and the actual flood extent observed during the event.

To validate the model results, Figure 8 overlays the HAND-derived flood hazard classes with aerial images documenting flooding and urban waterlogging in the Centro and Humberto Badaró Lagoon neighborhoods following the December 2021 flood. Beyond the predictive capability of GIS-based flood mapping, this comparison visually demonstrates the magnitude of the disaster, which inundated approximately 60% of the urban area, isolated the municipality from neighboring cities, and required emergency assistance by air.

The flood susceptibility classes produced by the HAND Model—ranging from Very High to Very Low—provide essential information for flood risk management before, during, and after flood events. According to Pereira (2024), of the 9.72 km² study area, 1.29 km² correspond to the Very High susceptibility class, 0.81 km² to the High class, and 1.96 km² to the Moderate class, indicating that nearly half of the urban area presents moderate to very high flood susceptibility. These zones are concentrated primarily within the Nova Itajuípe, Centro, and Beira Rio neighborhoods, exposing their inhabitants to substantial flood-related losses and damages.

Figure 08 – Overlay of HAND-derived flood hazard classes with aerial imagery of the December 2021 flood event in Itajuípe.



Source: Authors (2026).

Flooding and urban waterlogging within the Centro neighborhood significantly restrict residents' access to goods and essential services because this district concentrates most commercial activities and public facilities. According to residents' reports, flood depths reached approximately 1.80 m near the Almada River bridge, while Humberto Badaró Lagoon also exceeded its natural boundaries. Both areas correspond to zones classified as exhibiting Very High and High flood susceptibility.

Flood susceptibility mapping constitutes an essential decision-support tool because it provides a comprehensive understanding of the spatial extent and potential impacts of flood events. As highlighted by Júnior (2024), such information supports the development of mitigation and emergency response strategies through the integration of structural and non-structural flood management measures.

For the delineation of flood-prone and waterlogging-prone areas based on their natural physical determinants, the HAND Model proved to be an efficient approach for the urban area of Itajuípe, where topographic information is scarce. Nevertheless, according to Falcetta (2023), comprehensive analyses of flood behavior require high-resolution Digital Terrain Models (DTMs) with approximately 5-m spatial resolution, allowing future hydrological and hydraulic modeling capable of converting rainfall events into flood-frequency scenarios and estimating the hydraulic conveyance capacity of river channels.

The flood event that affected the urban area of Itajuípe in 2021, causing extensive social and economic damage, occurred predominantly within the Very High, High, and Moderate susceptibility classes identified by the HAND Model, as evidenced by the flood extent presented in Figure 7 and the post-event aerial imagery shown in Figure 8.

Based on the historical hydrological behavior of the Almada River, flood events of similar magnitude may recur whenever river stage approaches 604 cm and discharge exceeds 153.2 $m^3\ s^{-1}$. Under these conditions, areas classified as Very High flood susceptibility are expected to be inundated first because of their direct proximity to the Almada River.

Finally, social justice represents a critical dimension of flood risk management. In Brazil, economically vulnerable populations are disproportionately compelled to occupy flood-prone areas because of housing shortages, real estate speculation, socio-spatial inequality, and persistent deficiencies in public housing policies (Maricato, 2015).

Consequently, flood risk is not distributed uniformly among social groups. Social vulnerability is therefore a determining factor influencing the magnitude of the social and economic losses associated with flood disasters (Valencio, 2014).

5 CONCLUSIONS

The results of this study demonstrate that the urban area of Itajuípe is characterized by a valley-bottom geomorphological setting that naturally favors riverine flooding. The extensive low-lying and gently sloping terrain bordering the Almada River creates favorable conditions for flood occurrence. Terrain analyses based on hypsometric and slope mapping indicate that these geomorphological characteristics reduce surface runoff velocity, thereby promoting water accumulation within low-lying areas adjacent to the main river channel.

In the context of riverine flooding, the presence of a streamflow gauging station located along the Almada River within the urban area of Itajuípe represents an important source of hydrological information, providing valuable insights into the river's behavior during flood events. Nevertheless, the availability of higher-resolution planialtimetric data would substantially improve the application of hydrological and hydraulic models, enabling more reliable flood scenario simulations and supporting the definition of both structural and non-structural flood mitigation measures.

The application of the Height Above Nearest Drainage (HAND) model for flood hazard mapping demonstrated that, despite the limitations imposed by the absence of detailed topographic datasets, the method constitutes an effective alternative for data-scarce environments. Its relatively low data requirements allowed the identification and delineation of flood-prone areas as well as the classification of flood hazard within the urban area of Itajuípe. Furthermore, the modeled flood hazard map was successfully validated through field surveys, residents' testimonies, and photographic and audiovisual records documenting historical flood events, demonstrating the model's suitability for supporting flood hazard assessment in small municipalities.

The analyses also revealed that several neighborhoods experience localized urban waterlogging unrelated to overflow of the Almada River. These events are primarily associated with deficiencies in the municipal stormwater drainage and sewerage systems, highlighting the need for improvements in drainage infrastructure, routine maintenance, and continuous system monitoring.

Finally, effective flood risk management requires recognition that flooding constitutes a recurrent hydrological process rather than an exceptional event. Understanding both the hydrodynamic behavior of flood recurrence and the spatial distribution of flood hazard is fundamental for developing effective disaster risk reduction strategies. This objective depends on coordinated actions among different levels of government, sustained investments in preventive and mitigation measures, and the establishment of an official municipal flood database capable of preserving historical records and supporting future scientific research. Such initiatives would strengthen the reconstruction of historical flood events, improve understanding of local flood dynamics, and provide a robust scientific basis for urban planning, disaster preparedness, and climate adaptation policies.

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