Susceptibility to floods using multicriteria decision geospatial analysis in the Lower Amazon

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1. Manuscript

1.1 Introduction

Extreme rainfall events in certain locations can put the communities living in their surroundings at risk. Risk is understood as the possibility of damage, potential losses, or expected losses (deaths, physically injured individuals, destroyed and damaged buildings, local environmental dynamic alterations, etc.). Disaster risk refers to the probability of significant social, economic, material, or environmental damage resulting from adverse events, whether natural or induced by human action, affecting vulnerable ecosystems and populations (BRASIL, 2024).
Although regions located in floodplain areas commonly experience seasonal floods, the natural susceptibility to such events puts the population at risk, as extreme rains are also recurrent in the Amazon, and associated floods can have negative impacts if they reach urban areas (Towner et al., 2021). Therefore, knowing the most susceptible points to flooding in a region containing urban centers is crucial for managers and for providing warning information to the population (Farias; Mendonça, 2019). Geotechnologies have emerged to contribute to the prevention of this issue through flood mapping (Selvam; Jabamalai, 2023). Thus, the objective of this study was to analyze the susceptibility to flooding in the urban area of the municipality of Santarém-PA.

2. Material and Methods

2.1 Study of Area

The study area is the urban zone located in the municipality of Santarém-PA, in the Paraense West (Eastern Amazon), where it has an urbanized area of approximately 95 km^2 (IBGE, 2024). The urban zone concentrates on the banks of the confluence of the Amazon and Tapajós rivers.
Although the region is dominated by large natural areas such as forests, riparian vegetation, and flooded areas (floodplains), these landscapes are also marked by transformations related to anthropogenic activities, such as agro-pastoral zones and urbanization expansion (MapBiomas, 2024). The climate of the region is classified as equatorial and very hot (Novais; Machado, 2023), with a rainy season (Jan-Jun) and a less rainy season (Jul-Dec) well defined, with an average annual precipitation of 2,000 mm and average minimum and maximum air temperatures of 22°C and 31°C respectively (INMET, 2024). The region is dominated by latosols, soils that have porous characteristics that favor infiltration and reduce surface runoff.

2.2 Methodological Procedures

The data acquisition process for this study began with locating Alos Palsar satellite imagery through the Alaska Satellite Facility (ASF) platform, accessible at [https://search.asf.alaska.edu/]. The search parameters included the following: sensor type "Alos Palsar," with a 12.5-meter resolution acquired by the sensor on December 29, 2009, and a geographic area restricted to the Municipality of Santarém. Once the relevant data sets for the study area were identified, only the Digital Elevation Model (DEM) data in .dem format were downloaded. This required registration on the ASF platform and acceptance of terms of use. The downloaded DEM data, with a spatial reference code (SRC) of EPSG:32721 - WGS 84 / UTM zone 21S, were processed to ensure compatibility with GIS software, providing high-resolution elevation data to support the analysis of flood susceptibility in Santarém.
Using the DEM data from Alos Palsar, a series of key indicators were derived to assess flood susceptibility. The software utilized for this task was QGIS long-term release version 3.34.6, incorporating both native tools and the WhiteBox tools toolbox. Before deriving indicators, the .dem file was corrected with the FillDepressions tool to ensure a smooth and accurate elevation model. The derived indicators included Slope, Topographic Wetness Index (TWI), Topographic Position Index (TPI), and Flow Accumulation (FA). Slope measures the angle of terrain inclination, indicating areas prone to rapid water flow or accumulation. TWI represents the terrain's tendency to retain moisture, while TPI indicates a location's position within the landscape, such as ridges or valleys. FA, derived from the DEM, identifies areas where water is likely to accumulate. These indicators were based on the foundational DEM layer and additional flood conditioning factors derived from both literature review and available data.
For generating the Normalized Difference Vegetation Index (NDVI) raster, Sentinel-2 SR Harmonized data were selected with less than 5% cloud cover for the months of June through September 2023, corresponding to the summer season in the Amazon. The data were clipped to the study area and processed using the Google Earth Engine platform, applying a function to mask cloud cover. The resulting output was an NDVI raster for the study area, with a spatial resolution of 10 meters. This high-resolution NDVI raster served as an important input for the analysis of flood susceptibility in the Santarém region.
Another parameter used was the Modified Fourier Index (IFM) based on precipitation (Mohtar; Yahaya; Ahmad, 2015), for which data from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS, 2024) were used. The Curve Number (CN) indicates the amount of precipitation water that infiltrates into the soil (Lee; Ling; Yusop, 2023).
To analyze flood susceptibility, a multicriteria decision-making approach using GIS was applied, specifically the Analytic

Hierarchy Process (AHP), where consultations were conducted with experts for each variable considered to assign weights indicating the degree of influence favoring flooding (França et al., 2022). The AHP process involved constructing and normalizing a comparison matrix (pairwise), as well as calculating the weights and consistency of decisions.

3. Main Body of Text

The IMF (232.4 mm-268.2 mm) indicated values classified as Very High (IMF > 160), where in the urban core region there are the highest rainfall volumes. Towner et al. (2021) warned that under the influence of climatic extremes, flooding events are recurrent in the Amazon. Furthermore, higher CN values were observed in the urban mosaic, medium in pasture zones, and lower in forest areas. The local NDVI indicates green areas surrounding the red patches that indicate the concentrated urban zone along the riverbanks. Such information suggests that alterations of the natural landscape by anthropogenic activities, especially the urbanization process, alter the regional water flow.

The land surface of the urban zone of Santarém is characterized by higher slope in the central part and lower slope as it approaches the riverbank. Although there is a predominance of low slope, several points of high FA values were detected distributed in the study region, which means that there is accumulated water originating from higher terrain and influenced by points of high slope, contributing to the increase in water velocity towards lower areas. However, the TPI showed that the region is dominated by low-lying terrain. The TWI indicated high values for some areas within and around the urban zone, especially near the river.

Almost all variables have potentially high areas that favor flooding, except for the TPI. The comparison matrix indicated that NDVI and CN are the parameters that contribute the most to increasing susceptibility to flooding.

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