Spatial Modeling of Flood-Prone Areas Through Multi-Criteria Analysis Applied to a Brazilian Municipality

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Abstract: This study applied a spatial multi-criteria analysis (MCA) integrated with Geographic Information Systems (GIS) to identify flood risk areas in Sorocaba, Brazil. The variables—slope, elevation, flow accumulation, soil susceptibility, and land use and land cover (LULC)—were standardized, reclassified into vulnerability levels, and integrated using the categories very low, low, moderate, and high, resulting in a flood risk map. Additionally, a spatial overlap analysis between LULC classes was performed to identify occupation patterns in risk areas. The areas classified as high and moderate risk are concentrated in low-altitude regions, characterized by high environmental susceptibility and intense anthropogenic occupation, especially along the Sorocaba River and its tributaries. In contrast, very low-risk zones are located in forested or silvicultural areas, associated with higher altitudes and greater infiltration capacity. The spatial overlap between risk and land use revealed that non-vegetated surfaces (38.0%) and pasture/agriculture areas (58.6%) predominate in the highest-risk zones, indicating low infiltration and increased surface runoff. These results demonstrate that flood vulnerability arises from the interaction between geomorphological and anthropogenic factors, reinforcing that land cover changes and environmental degradation intensify hydrological events. The proposed model proved efficient, transparent, and replicable, providing technical support for territorial planning, disaster risk management, and the formulation of preventive public policies.

Keywords: Multi-criteria analysis, Environmental susceptibility, Geomorphological variables, Socioeconomic variables, Territorial planning, Urban flooding.

1. INTRODUCTION

Floods are among the most recurrent and devastating natural disasters worldwide, affecting millions of people each year and causing significant economic, social, and environmental losses [1-4]. The increasing frequency and intensity of these events have been widely associated with global climate change and unplanned urban expansion, which amplify soil impermeabilization and overload drainage systems [5, 6]. The Sixth Assessment Report of the IPCC highlights that the rise in extreme precipitation and hydrological variability intensifies the occurrence of both pluvial and fluvial floods in different regions, particularly in densely urbanized areas [1]. Similarly, the Global Assessment Report on Disaster Risk Reduction (GAR2022) indicates that the impacts of floods are exacerbated by social vulnerability and inadequate territorial planning [2].

In the technical-scientific domain, the combination of Geographic Information System (GIS) techniques and Multi-Criteria Decision-Making (MCDM) analysis has been consolidated as a practical methodology for mapping flood risk areas [7-12]. This integration enables a more robust spatial assessment by considering both geomorphological conditions—such as slope, elevation, flow accumulation, and environmental susceptibility—and anthropogenic factors—such as land use and land cover (LULC), population density, and urbanization patterns [9, 10].

In the Brazilian context, the application of multi-criteria methodologies within a GIS environment has proven effective for identifying flood-prone areas at different spatial scales [9-11]. In tropical basins, the integration of topographic and anthropogenic variables has revealed consistent spatial risk patterns, supporting urban planning and environmental management efforts [9, 13]. In urban areas, similar approaches have been employed to analyze vulnerabilities associated with soil impermeabilization and irregular occupation of floodplains, as observed in studies conducted in Ananindeua (Pará) [11] and in southern Brazil [10]. However, there is still a shortage of research that integrates multiple dimensions of risk—physical, geomorphological, environmental, and socioeconomic—at the municipal scale, particularly in medium-sized cities, where rapid urbanization poses specific challenges for drainage and LULC management.

The municipality of Sorocaba (São Paulo State), located in the Metropolitan Region of Sorocaba, represents an emblematic case of intense urban growth and recurrent flooding events [14, 15]. The expansion of impervious surfaces, encroachment on river margins, and pressure on drainage systems contribute to frequent flooding across different sectors of the city [15, 16]. Recent data indicate that between

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41 % and 50 % of the municipal area presents some degree of flood risk, especially in low-lying and central regions [17]. Furthermore, Sorocaba's Master Plan for Physical and Territorial Development highlights the need to improve spatial diagnostics of vulnerabilities related to urban drainage and land use [15]. These factors justify the adoption of integrated approaches that combine geomorphological and socioeconomic variables, enabling the identification of spatial risk patterns and supporting preventive public-policy design.

In this context, the present study aims to develop an integrated flood risk analysis model for the municipality of Sorocaba (São Paulo State), using a multi-criteria approach within a GIS environment. The proposed model integrates geomorphological variables (slope, elevation, and flow accumulation), environmental variables (environmental susceptibility), and socioeconomic variables (LULC) to map and classify areas with different levels of vulnerability. The results are expected to contribute to the formulation of urban and environmental planning strategies aimed at mitigating flood risk and strengthening urban resilience in the face of climate change.

2. MATERIALS AND METHODS

2.1. Study Area

The municipality of Sorocaba is located in the south-central region of the state of São Paulo, within the Metropolitan Region of Sorocaba (Figure **1**). The total territorial area is approximately 449.9 km², with altitudes ranging from 531 m to 830 m. The municipality has predominantly undulating terrain and a humid tropical climate, characterized by a rainy season in summer and a dry season in winter. The main watercourse is the Sorocaba River, a tributary of the Tietê River, which crosses urbanized areas and has a history of periodic overflows [14, 15, 18]. These geomorphological and hydrological conditions, combined with intense urban expansion and soil impermeabilization, make Sorocaba a representative case for studying flood risk in medium-sized Brazilian cities [16, 17].

2.2. Database and Variables

The construction of the integrated model was based on the selection of variables recognized in the literature as determinants of hydrological behavior and geomorphological dynamics in urban areas susceptible to flooding. The variables were selected following a systemic approach, considering the interaction among physical, environmental, and anthropogenic factors in modulating flood risk [7-11, 19-21]. This integration allows for a spatially explicit representation of surface runoff, infiltration, and water accumulation processes, as well as the vulnerability conditions derived from land occupation.

Topographic and hydrological data were obtained from the NASADEM Digital Elevation Model (DEM) with a spatial resolution of 30 m, available on the NASA Earthdata platform. From this model, the variables

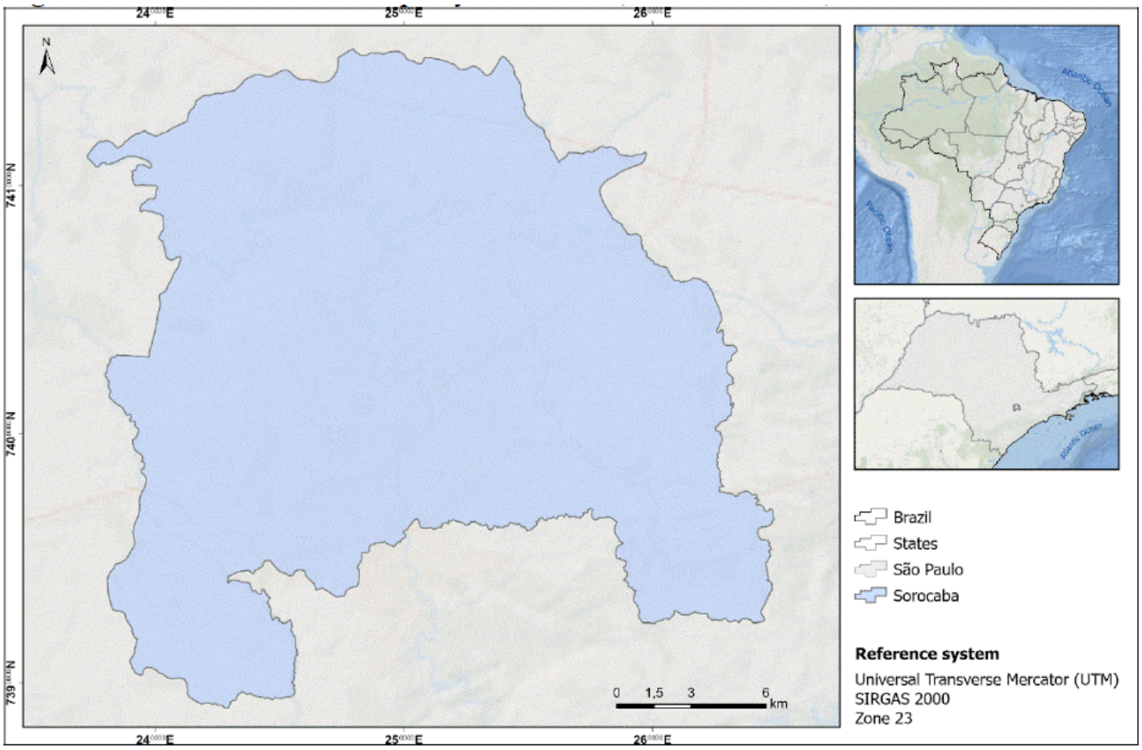


Figure 1: Location of the municipality of Sorocaba, São Paulo State, Brazil.

slope, elevation, and flow accumulation were derived and processed in the ArcMap 10.8 environment. The environmental susceptibility variable was extracted from the *Atlas de Suscetibilidades dos Solos do Estado de São Paulo* [22], which synthesizes attributes such as erodibility, erosivity, mass movement, waterlogging, karst subsidence, and flood risk—factors that condition surface stability and the hydrodynamic behavior of the soil [2, 11]. The LULC variable was obtained from MapBiomas Collection 9, representing land cover classes at a 30 m spatial resolution [23]. All datasets underwent a spatial standardization process, including reprojection to the SIRGAS 2000 / UTM Zone 23S coordinate system and clipping to the municipal boundary provided by IBGE.

2.3. Integration of Variables and Multi-Criteria Modeling of Flood Risk

The integration of variables in the spatial model was carried out through a multi-criteria analysis within the GIS environment, using the Weighted Overlay tool in ArcMap 10.8. This method is based on the weighted combination of reclassified variables on a standard vulnerability scale, allowing for a spatial synthesis of risk according to the relative influence of each factor [24-26]. The reclassification of the parameters was performed into four ordinal classes—very low, low, moderate, and high vulnerability—ensuring comparability among variables that initially possess distinct natures and units, while standardizing value ranges as shown in Table **1**.

The definition of reclassification ranges followed geomorphological and hydrological criteria supported by the literature, in which lower slope and elevation values correspond to zones with a higher propensity for water accumulation, while areas with high flow accumulation represent natural convergence regions of surface runoff [9,10]. The environmental susceptibility variable, derived from soil vulnerability mapping, expresses the intrinsic capacity of the physical environment to resist or yield to erosive processes, waterlogging, or hydric saturation [2, 11]. Land use and land cover were interpreted as indicators of surface impermeabilization, with urban and non-vegetated classes associated with the highest risk levels [22].

The assignment of weights to the variables was primarily supported by a literature review and by relative-importance criteria commonly adopted in MCA flood modeling studies [7-11, 19-21, 27]. However, the weighting scheme was also informed by the internal behavior of the variables within the study area. Environmental susceptibility received the highest weight (37%) because preliminary inspection of the dataset revealed that areas historically affected by flooding in Sorocaba coincide with zones mapped as having high soil fragility, mass-movement potential, and hydric saturation tendencies [15].

Additionally, the assignment of weights was supported by a qualitative sensitivity verification, in which alternative combinations of weights for each variable were tested to observe potential shifts in the spatial distribution of risk classes. These exploratory tests indicated that the final risk map was stable with respect to moderate perturbations in the weighting scheme, with high-risk areas remaining consistently located in the same geomorphological sectors.

The processing was executed according to the operational principles of the Weighted Overlay tool, which requires standardization of the layers in raster format and scale correspondence among all variables. Each reclassified value was multiplied by the weight assigned to the respective variable, and the results were integrated according to Equation 1.

$$R_i = \sum_{n=1}^{5} \left(W_n \times X_{n,i} \right) \quad (1)$$

Where:

R_i: Flood risk index for cell i;

W_n: Weight of variable n;

$X_{n,i}$: Standardized value corresponding to variable n in cell i.

The output is a continuous raster with a 30 m spatial resolution, representing the spatial gradient of flood

Table 1: Classes and Variable Values Contributing to Flood Risk in the Municipality of Sorocaba. The Weights Correspond to the Relative Weighting of each Variable in the Multi-criteria Analysis, Following [19-21, 27]

Variable	Weight (%)	Very low	Low	Moderate	High
Slope (°)	21	> 15	8-15	4-8	0-4
Elevation (m)	8	> 662	592–662	560–592	531–560
Flow accumulation	9	0–1,600	1,601–5,500	5,501–18,000	> 18,000
Environmental susceptibility	37	Very low	Moderate	High	Very high
LULC	25	Forest	Planted forest	Agriculture, pasture, and mosaic of uses	Non-vegetated areas

risk. This approach enabled the combination of factors of different natures into a single analytical surface, classified into four risk categories: very low, low, moderate, and high.

2.4 Spatial Analysis of Risk and Correlation with LULC

To understand the spatial relationship between flood risk and LULC, an overlay analysis was performed between the final flood risk map and the MapBiomas (Collection 9) LULC layer. This technique enabled the identification of the percentage distribution of LULC categories within each risk class, quantifying the proportion of forested, agricultural, silvicultural, urban, and non-vegetated areas across zones with different susceptibility levels. This procedure allowed the assessment of land occupation patterns in vulnerable areas, highlighting how urbanization and anthropogenic transformations influence the spatial distribution of risk.

The spatial coherence of the model was qualitatively evaluated by comparing the high-risk areas with historical flood records provided by Sorocaba's Civil Defense and with information from the *Plano Diretor de Desenvolvimento Físico Territorial* [15, 16].

3. RESULTS

3.1. Spatial Behavior of Variables and Susceptibility Areas

The classification of variables allowed the identification of distinct spatial patterns of flood vulnerability within the municipality of Sorocaba (Figure **2**). The analyses of slope, elevation, and flow accumulation (Figure **2A**–**C**) highlight the strong influence of terrain morphology on the redistribution of surface runoff. Areas with low slopes (< 4°) and altimetric levels below 560 m are mainly concentrated in the central and northern portions of the municipality, coinciding with fluvial plains and densely urbanized zones.

The environmental susceptibility variable (Figure **2D**) exhibited wide spatial variation, highlighting areas of high and very high vulnerability along the banks of the Sorocaba River and its tributaries. LULC data (Figure **2E**) revealed that urbanized and non-vegetated zones predominate precisely in these low-elevation areas.

The weighted combination of these variables through the multi-criteria analysis resulted in the final flood-risk map (Figure **3**). The model showed that high- and moderate-risk classes are mainly concentrated in

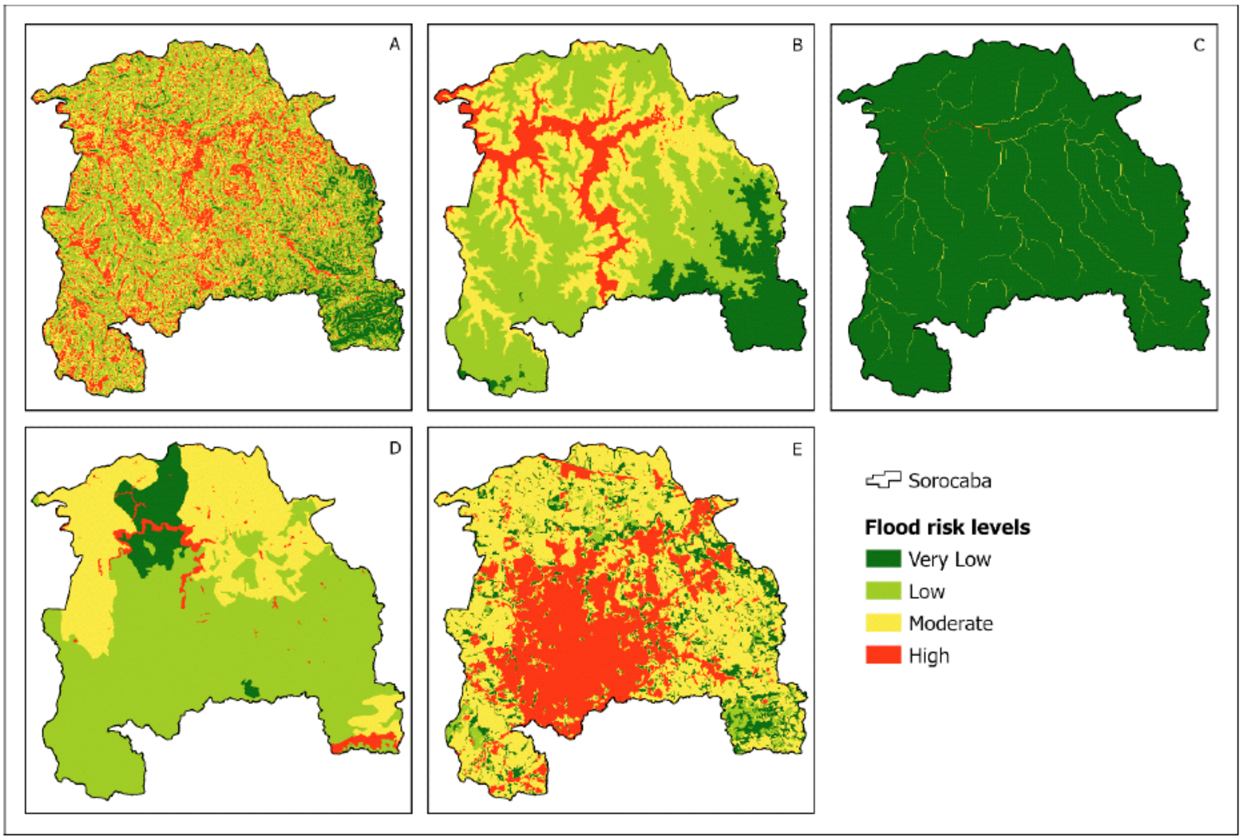


Figure 2: Spatial distribution of geomorphological, environmental and socioeconomic variables used for flood risk mapping. *(**A**) Slope, (**B**) Elevation, (**C**) Flow accumulation, (**D**) Environmental susceptibility, and (**E**) LULC*

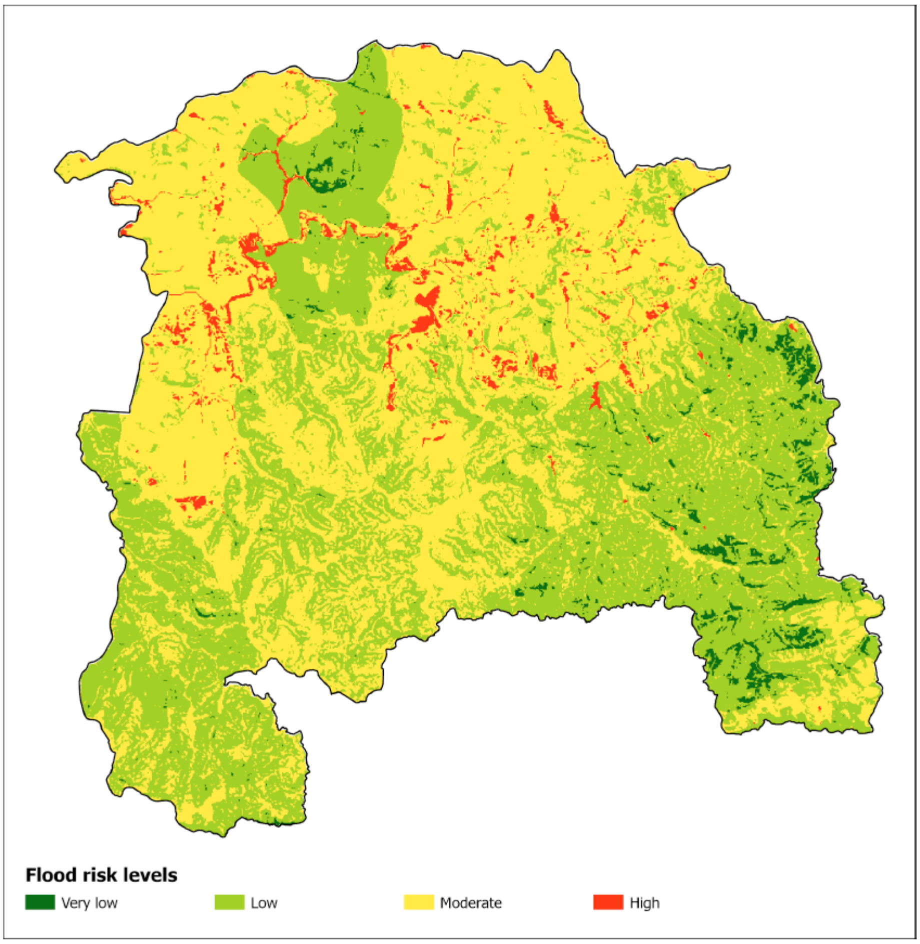
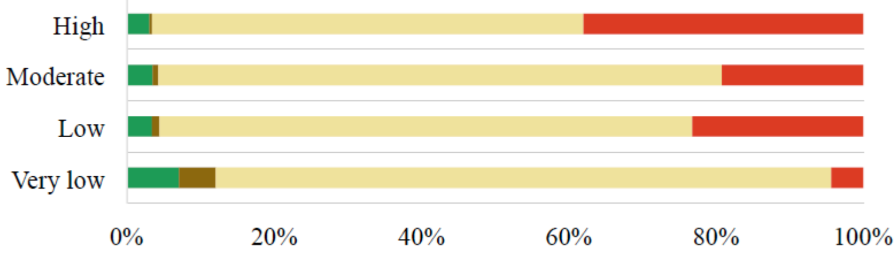


Figure 3: Spatial distribution of flood risk in the municipality of Sorocaba.

the central-northern sectors and along the main course of the Sorocaba River, where low altitude, high environmental susceptibility, and intense surface impermeabilization coincide. Very-low- and low-risk classes occur predominantly in the eastern, western, and northern portions of the municipality, associated with higher altitudes, forest cover, and lower urban density.

3.2. Relationship between Land use and Land Cover and Risk Classes

The overlay between the flood risk map and the LULC layer enabled the evaluation of the distribution of LULC categories within each susceptibility class (Figure **4**). The results show that areas classified as high risk are predominantly occupied by non-vegetated



	Very low	Low	Moderate	High
Forest	7.06%	3.43%	3.47%	3.04%
Forest Plantation	4.94%	0.99%	0.74%	0.35%
Pasture/Agriculture	83.61%	72.30%	76.61%	58.60%
Non vegetated area	4.39%	23.28%	19.19%	38.00%

Figure 4: LULC map for each susceptibility class.

surfaces (38.00%) and by pastures, agricultural lands, and mixed-use mosaics (58.60%), reflecting a landscape characterized by intense anthropogenic modification and reduced infiltration capacity. Agricultural and mosaic categories maintain a significant presence across all risk classes, indicating a diffuse and heterogeneous land occupation pattern at the municipal scale.

In the very low-risk areas, forest formations (7.06%) and silvicultural zones (4.94%) predominate, confirming the role of vegetation cover in regulating surface runoff and mitigating hydrological risk. This spatial pattern suggests an inverse relationship between vegetation cover and flood vulnerability.

The distribution of land use and land cover classes within each risk category highlights the overlap between urbanized zones and the most susceptible areas, reinforcing the importance of integrating anthropogenic variables into spatial risk assessment models.

4. DISCUSSION

The geomorphological and socioeconomic variables analyzed in the context of flood risk in Sorocaba reveal spatially differentiated vulnerability across the municipality. Although slope influences runoff generation, our results show that flood-prone zones are primarily controlled by low-lying areas where surface flow converges and saturates the soil. However, the results indicate that floods do not necessarily occur in the steepest regions but instead concentrate in shallow-slope convergence zones characterized by persistent surface saturation [19, 27, 28]. This pattern aligns with international analyses showing that flood incidence in urban basins is often governed more by topographic convergence and drainage position than by slope magnitude alone [1, 7]. Similar behavior has been reported in hydrological modeling of rapidly urbanizing catchments [5, 9].

According to [22], regions with high environmental susceptibility present soils more prone to erosive processes, mass movements, and siltation, which worsen drainage obstruction and increase flood risk in fluvial corridors where sediment accumulation and channel instability coincide. This behavior is also reported by [20], who observed a greater risk in areas where natural vulnerability combines with inadequate land use. Global assessments similarly emphasize that risk emerges from the interaction between environmental fragility and LULC pressure [1, 2].

Comparison with [19, 20, 27] shows that many studies use precipitation as the primary explanatory variable for flood risk. Although this climatic approach is valid, such studies often fail to integrate variables related to soil properties, such as the environmental susceptibility employed here, which limits the representation of infiltration potential and surface instability. In this regard, the present study aligns with [21], who incorporated pedological attributes in flood risk mapping for the Buzău River (Romania), and with [7], who combined machine learning and multi-criteria analysis (MCA) to enhance mapping accuracy. Unlike these studies, our findings show that even without precipitation data, local geomorphology and LULC explain spatial risk patterns effectively, suggesting that long-term landscape structure may outweigh short-term hydroclimatic variability in medium-sized tropical cities.

The analysis of LULC distribution across risk areas revealed spatial patterns not addressed by [19-21, 27]. High-risk areas are predominantly composed of non-vegetated surfaces and pasture/agriculture/mixed-use mosaics, reflecting landscapes with reduced infiltration capacity and accelerated runoff generation. These results reinforce the relationship between soil impermeabilization and increased hydrological risk [29]. Similarly, national studies have shown that the suppression of native vegetation, combined with erosive processes and siltation, intensifies hydrological disasters [11, 30-32]. Internationally, similar patterns emerge in rapidly urbanizing regions, where soil exposure and land conversion amplify runoff regardless of rainfall volume [8].

In the very low-risk areas, forests and silvicultural zones predominate, indicating the buffering role of vegetation in stabilizing surface conditions and enhancing infiltration. This mitigating role of vegetation is supported by [5, 6, 31, 33] and emphasized in global reports [1, 2].

A relevant aspect is the relatively uniform distribution of pasture/agriculture classes across all risk categories. This indicates that their contribution to risk is mediated primarily by geomorphological context rather than land use alone [30]. However, when the presence of these classes coincides with high environmental susceptibility or proximity to river channels, the risk increases significantly, reinforcing that flood risk is a product of the interaction between hazard, vulnerability, and exposure [22, 34]. This interpretation aligns with the conceptual frameworks of IPCC and UNDRR, which emphasize that these components act synergistically rather than independently [1, 2].

CONCLUSION

The integrated MCA-GIS approach allowed the identification of areas most susceptible to flooding in Sorocaba, demonstrating that the combination of geomorphological, environmental, and socioeconomic variables significantly increases vulnerability—particularly in low-elevation zones and areas near water bodies. The model proved efficient and replicable, providing technical support for territorial planning and the formulation of public policies aimed at flood prevention and mitigation.

Despite its applicability, the model is subject to limitations inherent to MCA, including the dependence on the quality and spatial resolution of datasets, the static nature of the variables considered, and the subjectivity associated with weighting schemes. Additionally, the lack of dynamic hydrological variables such as precipitation intensity or temporal runoff restricts the ability to capture short-term flood events.

Future research could incorporate socio-spatial indicators of exposure and adaptive capacity to expand the model's potential for comprehensive risk assessments. Evaluating temporal changes in land cover and climate projections would further strengthen the predictive utility of this framework.

CONFLICT OF INTEREST STATEMENT

The Authors declare that there are no relevant financial or non-financial competing interests to report.

AUTHORS' CONTRIBUTION

Nícholas de Paula Nicomedes was responsible for the conceptualization, methodology, formal analysis, data curation and processing, model development, figure preparation, manuscript writing, and final revision. Liliane Moreira Nery contributed to data acquisition, validation, and theoretical support in the conceptual framework of the study. Gabriela Gomes collaborated on the literature review and manuscript organization. Darllan Collins da Cunha e Silva supervised the research, provided scientific guidance, and performed the critical review of the manuscript.

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