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Susceptibility to flooding in climatic extremes: the role of urban morphology revealed by multicriteria analysis

A suscetibilidade às inundações em extremos climáticos: o papel da morfologia urbana revelado por análise multicriterial

Susceptibilidad a inundaciones en extremos climáticos: el papel de la morfología urbana revelado por análisis multicriterio

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Abstract

Growing urbanization, when disconnected from land use planning and associated with extreme precipitation events resulting from climate change, can lead to disasters such as floods. This article proposes the use of multicriteria analysis to produce a map of flooding susceptibility based on urban morphology metrics, with the aim of understanding how the various morphological metrics influence runoff generation. The method is applied in an urban basin with heterogeneous morphological patterns, located in the city of Campina Grande, Paraíba. The final map, validated by hydrological simulation of an extreme event, demonstrated that urban morphology metrics can be considered in the formulation of adaptation strategies to climate change.

Keywords: Hydrology; Inundation; Climate Change.

Resumo

A urbanização crescente, quando desarticulada do planejamento do uso e ocupação do solo e associada a eventos extremos de precipitação decorrentes das mudanças climáticas, pode levar a desastres como inundações e alagamentos. Este artigo propõe a utilização de análise multicriterial para produção do mapa de suscetibilidade às inundações e aos alagamentos com base em métricas de morfologia urbana, com o objetivo de compreender como as diversas métricas morfológicas influenciam a geração do escoamento. O método é aplicado em uma bacia urbana com padrões morfológicos heterogêneos, localizada na cidade de Campina Grande, Paraíba. O mapa final produzido, validado por simulação hidrológica de um evento extremo, demonstrou que as métricas da morfologia urbana podem ser consideradas na formulação das estratégias de adaptação às mudanças climáticas.

Palavras-Chave: Hidrologia; Alagamentos; Mudanças Climáticas

Resumen

La creciente urbanización, cuando se desconecta del uso de la tierra y la planificación de la ocupación y se asocia con eventos de precipitación extrema como resultado del cambio climático, puede provocar desastres como inundaciones. Este artículo propone el uso de análisis multicriterio para producir un mapa de susceptibilidad a inundaciones basado en métricas de morfología urbana, con el objetivo de comprender cómo las diversas métricas morfológicas influyen en la generación de escorrentía. El método se aplica en una cuenca urbana con patrones morfológicos heterogéneos, ubicada en la ciudad de Campina Grande, Paraíba. El mapa final producido, validado por simulación hidrológica de un evento extremo, demostró que las métricas de morfología urbana pueden ser consideradas en la formulación de estrategias de adaptación al cambio climático.

Palabras clave: Hidrología; Inundación; Cambios Climáticos.

1 Introduction

The urbanization process promotes land occupation, including within environmentally fragile areas, often disorderly and unplanned. At the same time, this process causes the dispersion and fragmentation of the urban fabric, causing discontinuities in space (of a physical or morphological nature), society (communities that adopt segregation logics), and politics (actors and devices for urban management and regulation) (Prevot-Schapira, 2001; Caldeira, 2000).

The housing sector is an essential agent in the production of urban space, setting up streets and allotments "according to the interests of the capitalists concerned, without being part of any joint plan" (Langenbusch, 1971, p. 137), thus resulting in future severe problems for the city. For these agents, the concern for integration with neighboring fabrics is not a priority, and it is often up to the state to connect the areas that have been implanted in a disconnected way, providing infrastructure and monitoring the non-urbanized interstices of clandestine occupation processes (Campos, 2008; Coelho, 2016).

This results in heterogeneous occupation processes, different construction patterns, and an increase in the impermeability of urban basins. These processes alter the hydrological functions of the landscape, which, consequently, increase the peak, the volume of flow, and the frequencies and impacts of floods (Aerts *et al*., 2014; Blöschl *et al*., 2013; Dankers *et al*., 2014). These disasters have been widely discussed and recognized as scientific issues that should be prioritized (Sarauskiene *et al*., 2015; Deng; Xu, 2018). In addition to posing threats to urban areas, they cause impacts on the environment and public health and must, therefore, be dealt with efficiently.

A typical data source for urban water management processes is flood susceptibility maps. These maps are interesting because they represent the hydrological response of the basin to precipitation events, i.e., the influence of the basin on the generation, propagation, and accumulation of runoff in such events, as well as its vulnerability. Susceptibility maps can be essential tools for formulating policies and strategies for adapting cities to climate change, both for managing areas already urbanized and for planning occupied areas. These maps are built using numerical hydrological and hydraulic simulation models. However, for many areas in cities, including informal and precarious settlements, there is a need for hydrometric data, land use data, and hydrological and hydraulic characteristics that can be used as a basis for simulations. In this context, an alternative is building these maps from information readily available in public data sets and remote sensing.

Several studies have investigated the susceptibility to flooding in river basins using hydrological metrics (Pinto *et al*., 2016; Ahmed *et al*., 2021; Azareh *et al*., 2021). However, little attention has been paid to the influence of urban morphology on susceptibility in markedly urbanized basins. Studies on the role of urban morphology on sustainable urban development have yet to consider flooding (*e.g*., Barau *et al*., 2015; Dadashpoor *et al*., 2019).

The hypothesis raised in this article is that urban morphology, described through specific metrics, can be related to flood susceptibility maps and thus inform planners and managers on how and where to intervene in urban management to mitigate the impacts of increased extreme precipitation events resulting from climate change. Specifically, the aim is to answer the following questions: How does urban morphology influence the susceptibility of urban settlements to flooding? Which morphological metrics are most influential, and in what contexts? Explaining the relationships between the morphological metrics of an urban area and the generation, propagation, and accumulation of runoff is a particularly interesting methodological challenge. This article proposes using spatial multi-criteria analysis, urban morphology, and hydrological criteria as potential flooding susceptibility determinants. Flooding scenarios are produced by hydrological-hydraulic numerical simulation to reference the spatial multi-criteria analysis. The proposed method is applied to a small urban catchment characterized by heterogeneous occupation and different morphological patterns in Campina Grande, Paraíba, Brazil.

2 Urban morphology and flooding

Urban morphology is determined by the historical and spatial contexts of consolidation, influencing the intensity of phenomena linked to urban nature (Bogo, 2020). It is also essential to highlight the interconnection between the city's social and political stage and its physical formation. Thus, different concepts and morphology methods are used to interpret better urban composition (Rego; Meneguetti, 2011; Monteiro *et al.*, 2020).

The production of urban space and its effects on urban morphology encompasses conflicts arising from the relationship between occupation and natural cycles, since the actions of social actors are strategic interactions aimed at institutionalizing and ensuring the processes of delimitation, withdrawal, and use of resources. For example, changes in soil cover due to sealing modify the hydrological cycle and generate flooding in urban areas.

3 Study Area

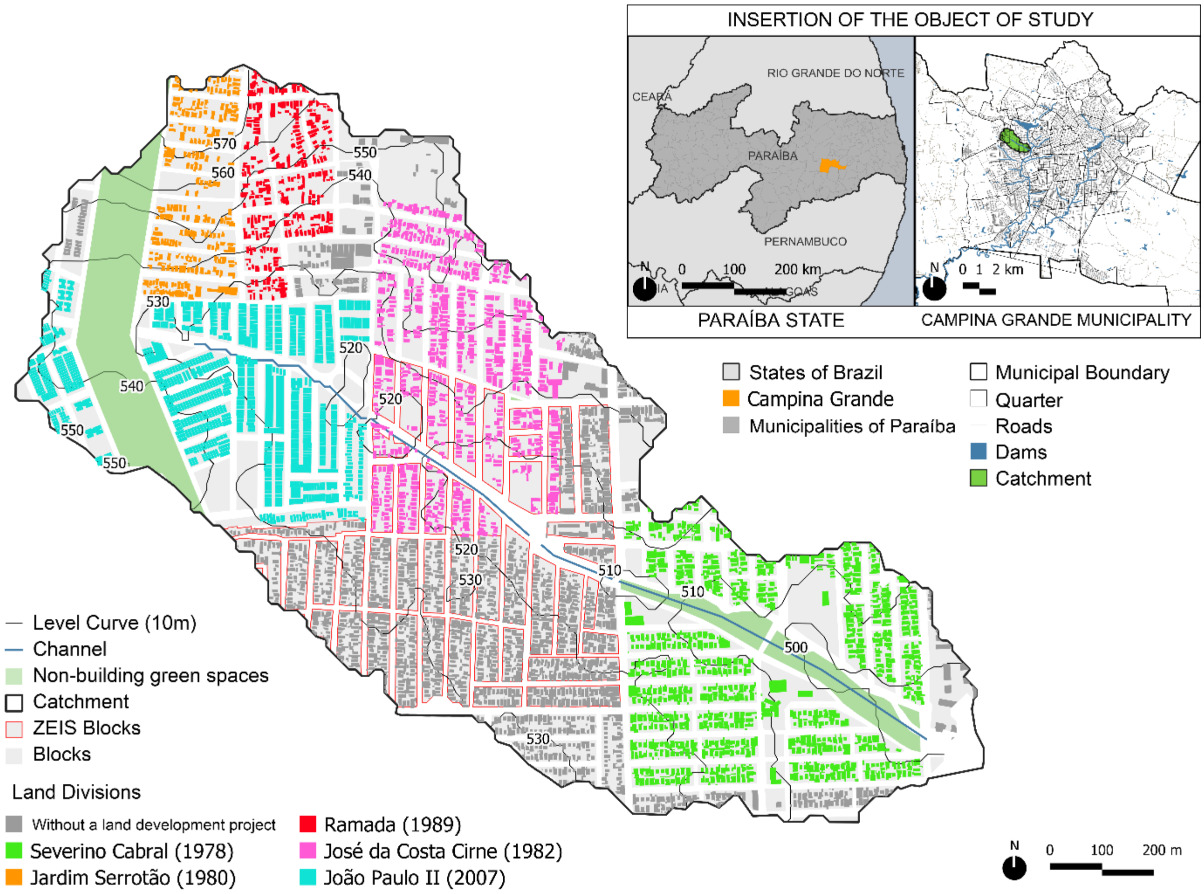
The study area consists of the Ramadinha Catchment (Figure 1) in the city of Campina Grande, Paraíba, covering 129 hectares, of which about 30% are occupied by one of the municipality's Special Zones of Social Interest (ZEIS), called Invasão Ramadinha II. In addition to social vulnerability and precarious housing, the catchment lacks infrastructure, public facilities, and presents irregular lots. Urbanization in this catchment expanded in the 1970s and 1980s through subdivisions with different income levels. Despite municipal land-use planning, which was responsible for validating land-use projects in the catchment area, the occupation has not escaped from processes of disorderly occupation through clandestinity and irregularity.

The catchment includes five formal subdivisions and an area occupied without any formal development project. In the latter, most blocks fall within the Ramadinha ZEIS polygon. The municipality recognizes this zone as precarious, as it is classified as a Type 1 ZEIS, which, according to Municipal Law No. 4806, are "areas occupied by precarious settlements of low-income populations, with the possibility of the public authorities promoting land and urban regularization, with the implementation of public facilities, including recreation and leisure, commerce and services of a local nature".

The Severino Cabral (1978) subdivision, run by the Companhia de Habitação Popular (CEHAP), is the oldest and was gradually occupied after the houses were built. This can be observed by consulting the remote sensing images made available by Google Earth. The same happens for José da Costa Cirne (1982) and the most recent João Paulo II (2007) subdivisions. In the Jardim Serrotão (1980) and Ramada (1989) subdivisions, there were occupations before the project that were adapted to the territory's restructuring. It should also be noted that, until 2010, the Jardim Serrotão (1980), Ramada (1989), and José da Costa Cirne (1982) subdivisions did not have paved streets. This intervention is only noticeable in remote sensing images after 2018, more than 20 years after the approval of these subdivisions. After the 2000s, the reduction in lot size marked real estate production, which, driven by the maximization of land use and, consequently, profit, added to the reduction in soil permeability without setbacks.

The dates assigned to the subdivision projects refer to the year the project was approved, not its occupation process. It may have occurred gradually after the subdivision or even before the project, with spontaneous buildings that adapted to the subdivision over time.

Figure 1: Location and characterization of the Ramadinha Catchment.



Source: Edited from Municipal Cartographic Database (2010)

As a result, the Ramadinha Stream's water body, behaves like a boundary that enters subdivisions with heterogeneous patterns from a socio-spatial point of view. At its eastern end, in the Severino Cabral subdivision (Figure 1), it is channeled and contained in a free space established from the limits of 15 meters of non-building area (Law No. 6766/79). Moving westwards and entering the ZEIS, the houses are more densely arranged than most neighboring subdivisions. In certain places, some houses come within 15 meters of the water body, in stretches marked by unpaved roads and a lack of infrastructure.

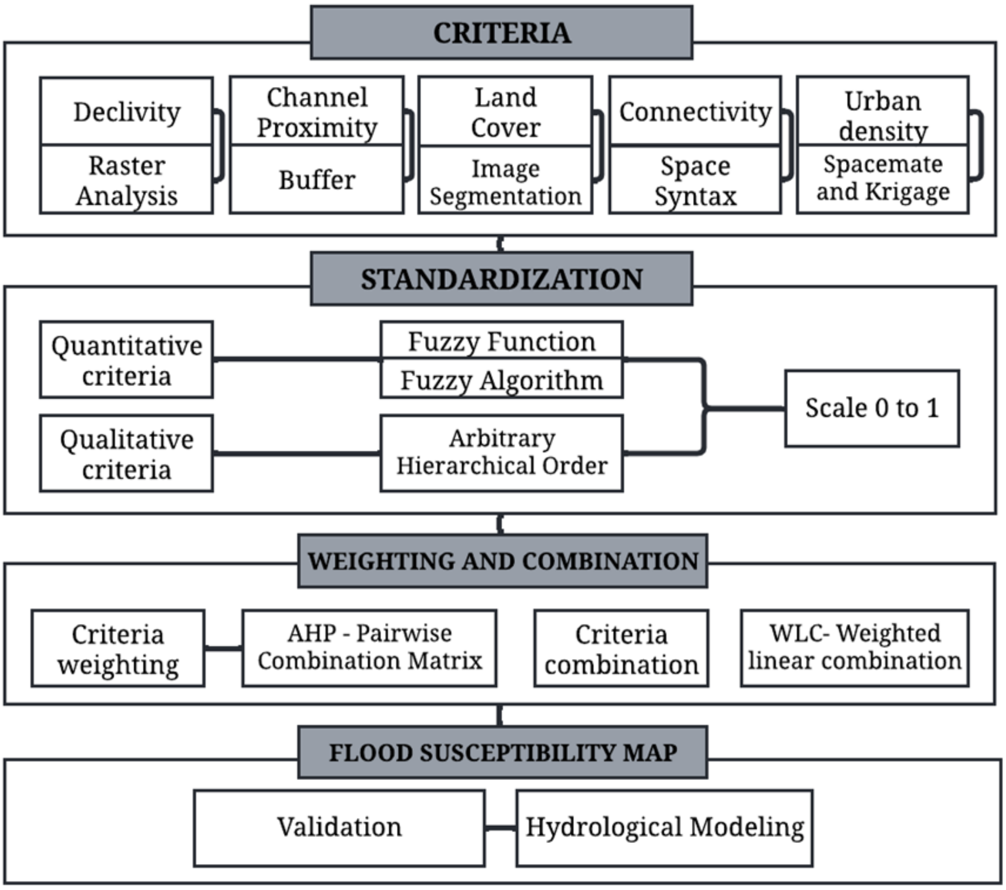
The canalization of part of the stream was the product of interventions by the Federal Program for Accelerating Growth - Urbanization of Precarious Settlements (PAC-UAP) in the region (Moraes *et al.*, 2021), however, it was never completed, especially in the

Ramadinha ZEIS area. The micro-drainage elements are mainly located downstream of the streets that cross the canal to guarantee that the water will be directed to the watercourse.

4 Methodology

The flood susceptibility map was drawn up using a multi-criteria analysis, the Analytic Hierarchy Process (AHP, Saaty, 1987), and Fuzzy Logic, with the standardization of the layers by the weighted linear combination (Figure 2). The AHP approaches the choice process hierarchically, comprising objectives, criteria, sub-criteria, and alternatives. Thus, the elements evaluated are compared in pairs to gauge the relative preference or influence according to each element at the same level, thus producing the weights that will define the ranking of the alternatives. Saaty (2008) proposes four stages to apply the AHP method in decision-making: (i) identify the research problem and establish the decision-making hierarchy; (ii) build a set of matrices to compare the data between the upper and lower levels; (iii) compare the weight definitions between the priorities obtained; and (iv) use the digital intensity scale to define the priorities. The AHP has already been used in flood susceptibility studies, but not for the same purpose as this one (*e.g.*, Nachappa *et al.*, 2020; Alves *et al.*, 2018).

Figure 2: Methodological flowchart.



4.1 Criteria

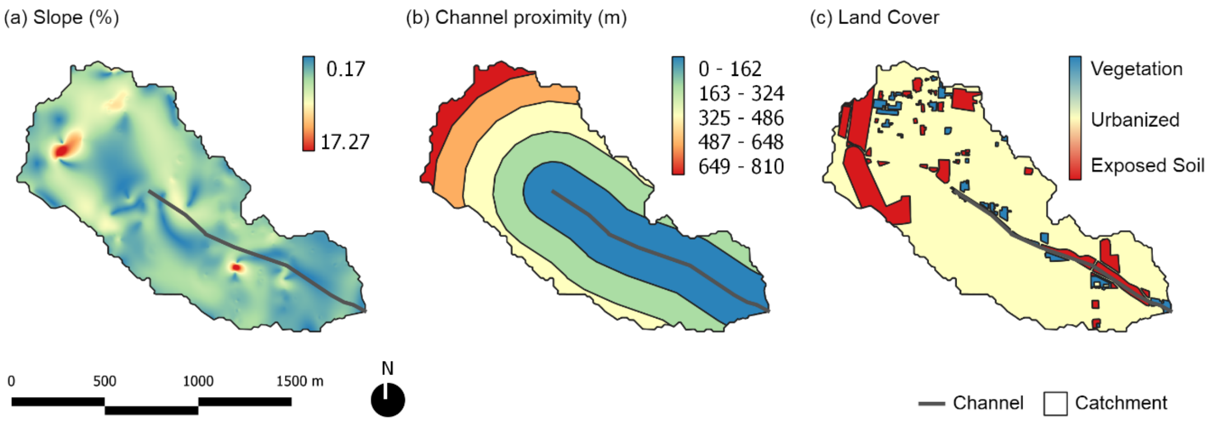
The urban morphology criteria for the multi-criteria analysis were selected based on their relevance to susceptibility to flooding. The selected criteria, with their respective descriptions, are shown in Table 1.

Table 1: Criteria used in the multi-criteria analysis.

Criteria	Relation to hydrologic function	Sources
Land slope	Slope interferes with infiltration capacity since areas with a higher slope have a lower infiltration capacity than plainer areas. As such, it directly influences the accumulation of water on the ground and is one of the main factors responsible for the occurrence and speed of surface runoff. For this reason, this criterion correlates numerically inversely with the propensity and magnitude of flooding. It is measured from the contour lines of the terrain.	Dalfi *et al*. (2013) Jalayer *et al*. (2014) Oliveira and Vieira (2009) Mendes *et al*. (2020)
Channel proximity	The proximity of urban rivers increases the susceptibility to flooding due to the overflow of the channels in flood events. Thus, in scenarios of heavy rainfall and rising water levels, overflow can occur onto adjacent land in valley rivers. This criterion does not apply to plateau rivers.	Goerl, Michel and Kobiyama (2017) Cunha *et al*. (2017) Seabra and Rocha-Leão (2019) Oliveira, Silva and Nascimento (2019)
Land cover	Land cover is associated with the hydrological cycle, linked to the roughness and permeability of the surface. In this sense, the criterion plays a significant role in the regime of surface runoff and infiltration.	Luiz and Romão (2019) Neves *et al*. (2019) Moura *et al*. (2019)
Connectivity	More connected roads receive more water upstream and therefore record higher runoff values, although they promote better distribution of flood waves.	Gil and Steinbach (2008) Esposito and Di Pinto (2014) Ahmed, Meenar and Alam (2019) Morelli and Cunha (2019)
Urban density	The increase in density leads to an increase in impermeable areas and consequent generation of runoff on the scale of analysis of an already occupied urban area.	Motta Jr. and Tucci (1984)

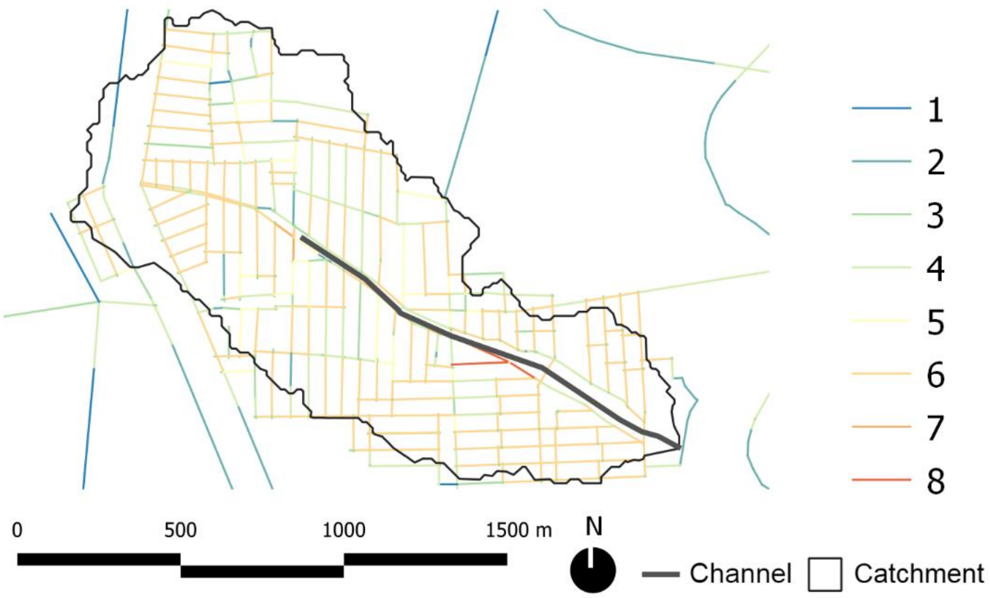
The first two criteria (slope and proximity to the channel) were obtained from the Digital Elevation Model (DEM) of the study area (Figure 3). A high-resolution image from Google Earth and Google Street View delineated the land cover map, making distinguishing the different occupation types. The slope is the difference in the level of the terrain relative to its horizontal projection. The map in Figure 3(a) shows the values found in the study area. Proximity to the channel was obtained by analysis of proximity by areas of influence, generated for 162, 324, 486, 648, and 810 meters from the banks of the water body (Figure 3b). The land cover map was created from the visual classification of objects generated by segmenting a high-resolution image (Figure 3c).

Figure 3: Hydrological criteria.



Connectivity is the number of direct connections a road has with the other roads in a network, so the greater this number, the greater its connectivity value (Rismanchian; Bell, 2011). This criterion is based on the Space Syntax Theory, which seeks to understand the relationship between spatial configuration and social behavior, especially the flow of people (Hillier and Hanson, 1984). The results can be interpreted by the gradation of colors, from red, which symbolizes high connectivity, to blue, which symbolizes low connectivity in a network (Figure 4). The measure of connectivity between roads was analyzed with the help of DepthMap software, and the results were presented in raster format.

Figure 4: Connectivity criteria.



Urban density initially requires a definition, as this term is inserted within a spectrum of different relationships, such as demographic, housing, and construction density. Thus, its absolute value cannot represent the totality of the urban form (Berghauser Pont; Haupt, 2005; Cavalcanti; Mendes; Barros Filho, 2022). In this work, the density calculated is relative to buildings, and classified based on each urban context's geographical and occupation characteristics. The method for obtaining the criterion combines various urban indices that influence building density, such as: Occupancy (GSI - Ground Space Index), Utilization (FSI - Floor Space Index) and Average Number of Floors (L - Levels).

According to Berghauser Pont and Haupt (2005), each index is not capable of representing the quality of the urban space generated, and this methodology combines the various indices. It is one of the most innovative, as it represents density not just as a metric value, but in a multivariate way.

The occupancy rate (GSI - Ground Space Index) consists of the ratio between built and unbuilt space, calculated as the ratio of the usable area (Bx) of the building over the aggregation area (Ax) of the unbuilt space used as a reference. In this indicator, only the first-floor area is considered as the usable area of the building. The Floor Space Index (FSI) considers the gross floor area of the building, i.e. the sum of the area of all the floors over the aggregation area (Ax) of the unbuilt space used as a reference. The Average Number of Floors (L - Levels) is given by the ratio between the GSI and the FSI.

The OSR (Open Space Ratio) is an indicator derived from the GSI and FSI and indicates the pressure of the built-up area on open spaces (Spaciouness). According to this indicator, the higher the verticalization (FSI), the lower the pressure. This is justified by the greater rationalization of land use due to the overlapping of slabs, resulting in a greater quantity of free (unbuilt) spaces that would probably not exist in the case of a proportional occupation in single-story buildings. The measures are summarized in Table 2.

Table 2: Density indicators

GSI	GSIx = Bx/Ax, Bx = usable area (m^2), Ax = aggregation area (m^2)
FSI	FSIx = Fx / Ax, Fx = gross floor area (m^2), Ax = aggregation area (m^2)
L	L = FSIx/GSIx
OSR	OSR = (1 – GSIx) / FSIx, dimensionless

Source: Berghauser Pont and Haupt (2005).

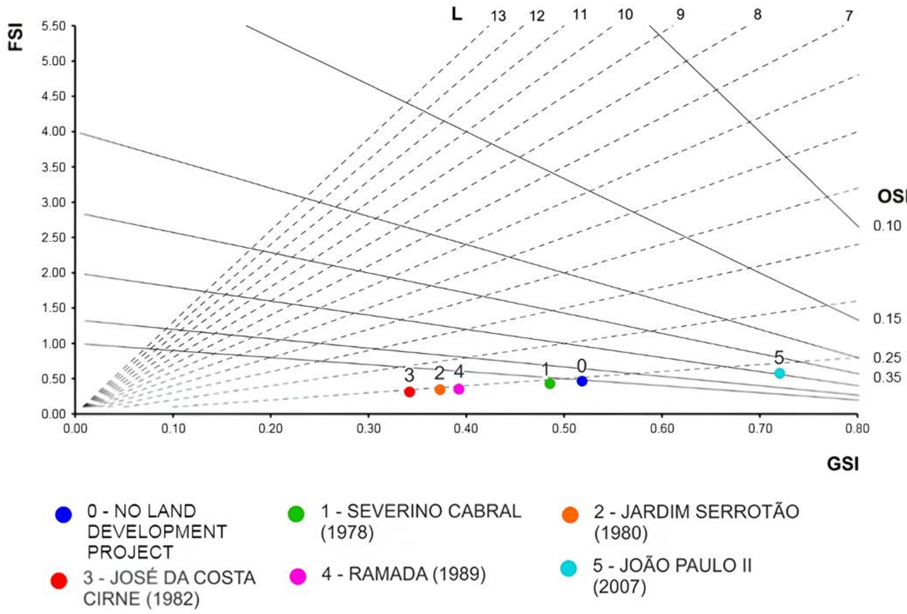
To calculate the indicators, the aggregation area was the sum of the area of the blocks of the different subdivision projects in the catchment. When discussing the results, the year in which each subdivision was built and its socio-spatial conditions were considered to analyze the differences in occupation over time.

When calculating the density of each subdivision, unoccupied blocks and non-building blocks were excluded, according to the Land Parceling Law No. 6766/79. This catchment has two non-building areas: the open space adjacent to the body of water and the other large area to the west, where a high-voltage transmission network is located.

The graph in Figure 5 shows the density indicators. These are grouped in a three-dimensional space called the Spacematrix, which, in turn, generates the Spacemate graph, made up of the two axes of the GSI and FSI indices, deriving two more indices, the Average Number of Pavements (L) and the Pressure on Open Spaces (OSR).

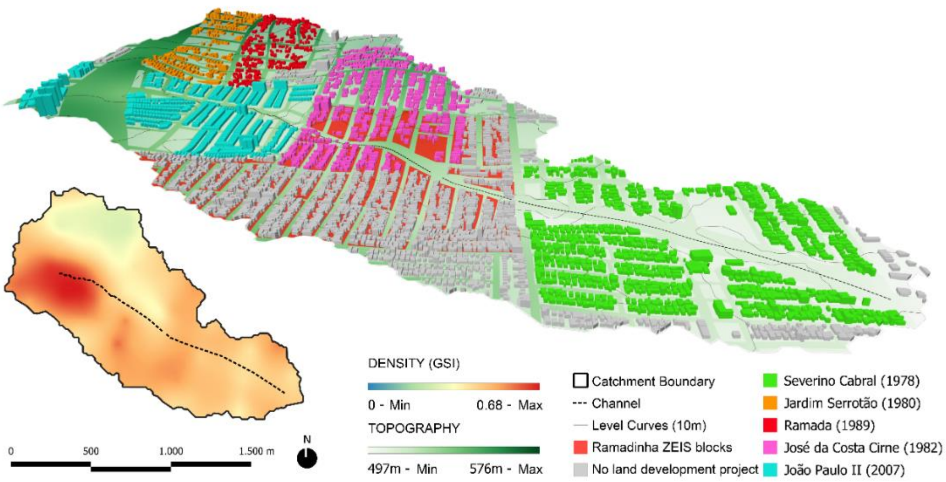
From the graph, the points showed a higher horizontal variation. Thus, the characteristic that most distinguishes the settlements in the basin is the occupancy rate (GSI), shown in Figure 6. Variations in the floor space index, average numbers of floors, and pressure on free space (OSR) are incipient. Therefore, the density analysis for this basin was based on the GSI, an independent measure that highly influences hydrological functioning (Table 1). The GSI values obtained in the density analysis were interpolated using the Kriging method, based on the prior definition of a continuous function that estimates the behavior of a variable in different directions in space, i.e., it evaluates the level of similarity of the values as they move apart (Gallardo, 2006).

Figure 5: Spatialization of the occupation patterns of subdivisions in Spacemate.



Source: Authors, based on Berghauser Pont and Haupt (2005).

Figure 6: Density criteria.



The final maps for all the criteria were generated with a two-meter pixel size for the pixel-by-pixel analysis used to overlay the layers.

4.2 Criteria standardization

Since each criterion has different scales and dimensions, standardization is required for the combination process. Thus, an arbitrary hierarchical order was applied for the qualitative land cover criterion, whereby each class is associated with a numerical value

(Table 3). The other criteria were standardized using the QGIS SAGA extension for raster calculations in the processing toolbox using the Fuzzify algorithm. This algorithm translates the grid values into a set of fuzzy members in preparation for analysis via Fuzzy Logic. The density criterion did not require standardization, as it is a dimensionless measure delimited within the required range (0 to 1); the others have their algorithm member functions described in Table 4. The maps with the standardized values of the criteria are shown in Figure 7.

Table 3: Arbitrary hierarchical order of land cover.

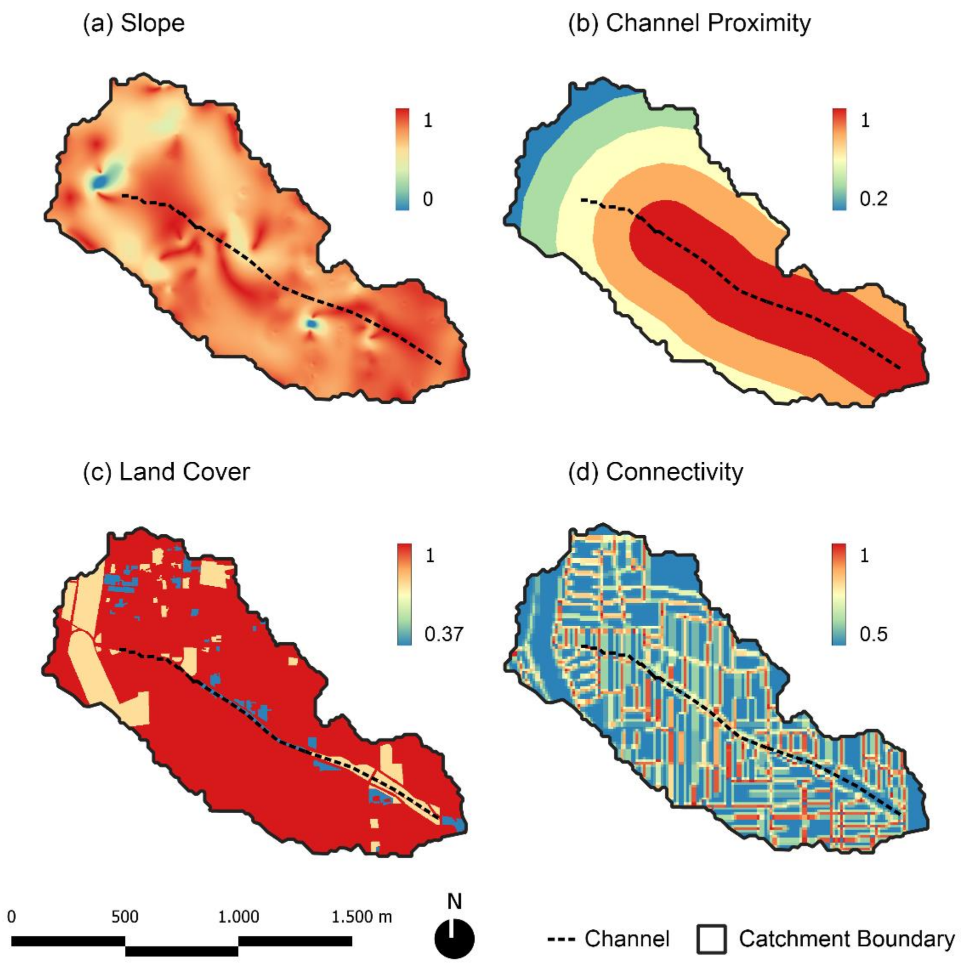
Land Cover Classes	Numerical Value
Vegetation	0.37
Exposed Soil	0.75
Urbanized	1.00

Source: Authors adapted from Falcão (2013).

Table 4: Member function used for each layer.

Criteria	Member function
Slope	Linear decreasing
Channel Proximity	Linear decreasing
Connectivity	Linear increasing

Figure 7: Standard criteria.



4.3 Comparing, weighting and combining criteria.

The comparison between pairs was made using a linear scale from 1 to 9, described in Table 5 (Saaty, 1987; Saaty, 2008).

Table 5: Pairwise comparisons in AHP.

Value	Definition	Description
1	Equal importance	Two alternatives equally contribute to the objective
3	Moderate importance	Experience and judgment slightly favor one alternative over the other
5	Strong importance	Experience and judgment strongly favor one alternative over the other
7	Very strong importance	One alternative is strongly favored over the other
9	Extreme importance	The evidence favoring one alternative over the other is of the highest possible order of affirmation
2,4,6,8	Average values	They are assigned to indicate compromise values of importance

Source: Authors adapted from Saaty (1987) and Saaty (2008).

Therefore, based on the values established in the comparison, matrix A is assembled, known as the Pairwise Comparison Matrix (PCM), with n alternatives, as shown in Equation 1. In this matrix, $\boldsymbol{a_i}$ and $\boldsymbol{a_j}$represent the criteria, and the term $\boldsymbol{a_{ij}}$ represents their pairwise comparison. It is assumed that the matrix has no inconsistencies, since $\boldsymbol{a_{ij}}$= $\boldsymbol{a_{ji}}^{-1}$ for any index.

$$A = [a_{ij}] = \begin{bmatrix} 1 & 1/a_{12} & \cdots & 1/a_{1n} \\ a_{12} & 1 & \cdots & 1/a_{2n} \\ \vdots & \vdots & 1 & \vdots \\ a_{1n} & a_{2n} & \cdots & 1 \end{bmatrix} \quad (1)$$

The *λmax* is the main eigenvalue of A, which can be obtained from Equation 2, where *w* refers to the vector of weights of the alternatives. In this way, the matrix of eigenvectors, which is the quotient of the sum of the row by the sum of the matrix elements, is multiplied by matrix A. So, the vector of eigenvalues is obtained by dividing this vector product by the eigenvectors. Next, the Consistency Index (CI) – detailed in Equation 3 – is calculated to obtain the Consistency Ratio (CR), calculated in Equation 4. The CR parameter is necessary to assess the logical consistency of the matrix, and, according to Saaty (1987), the value must be equal to or less than 0.1. This process was carried out using the QGIS raster calculator.

$$\text{A} * \text{w} = \lambda_{\text{max}} * \text{w} \quad (2)$$

$$\text{CI}= (\lambda_{\text{max}}\text{-n})/(\text{n} - 1) \quad (3)$$

$$\text{CR}= \frac{\text{CI}}{\text{RI}} \quad (4)$$

The AHP was then applied in QGIS using a Weighted Linear Combination (WLC) tool (Santos; Louzada; Eugenio, 2010). The WLC for flood susceptibility mapping is given in Equation 5.

$$WLC = \left(\sum_{i=1}^{n} W_i X_i\right) \quad (5)$$

where Wi is the relative weight derived from the AHP, of importance for layer i of the map, and Xi represents layer i of the normalized map.

Subsequently, an image was generated with attributes ranging from 0 to 1, corresponding to the lowest (0) and highest (1) values of susceptibility to flooding.

The construction of the MCP for the case consisted of determining the order of importance of the criteria. A first estimate of the weights was based on theoretical assumptions (Table 1), related studies, the judgment of researchers and further work conducted in the field of study (Santos, 2021; Machado *et al*., 2021; Alves *et al*., 2022). The weights were then adjusted using the results of the hydrological simulation of an extreme rainfall event, which generated the corresponding flooding sites in the catchment (Alves *et al*., 2022). The MCP weights were adjusted until the most susceptible locations to flooding generated by the AHP corresponded to the flooding locations from the hydrological simulation. The hydrological model used was the Stormwater Management Model (SWMM), a dynamic rainfall-runoff model for simulating surface runoff in urban basins, which uses the Curve Number method of the US Soil Conservation Service (SCS).

Finally, a sensitivity analysis was performed to understand how sensitive the susceptibility map is to each criterion. In the literature, there are some sensitivity analysis methods for the AHP, such as Monte Carlo analysis, regression or correlation methods, and the OAT ("One At a Time") method, among others (Saltelli *et al*., 2000). Some methods manipulate the weights, assigning the same weight to all the AHP criteria and/or removing some specific criteria (Moradi *et al*., 2020). The removal of the criterion, or its assignment with zero weight, is followed by a new weighting of the paired combination. In this work, the removal of criteria was applied to address two aspects: firstly, the identification of criteria that are particularly sensitive to changes in weight, and, secondly, the visualization of the dynamics of spatial change.

5 Results and discussion

The hierarchical analysis of the process resulted in a paired consistency ratio (CR) matrix equal to 0.098, considering the final adjustment of the weights aided by the hydrological modelling; therefore, there is an indication that the pairwise comparison was acceptable. The procedure resulted in a λmax of 5.43 and a CI of 0.109. The relative importance of the criteria is shown in Table 6, from which it was possible to identify which urban morphology metrics have the most significant influence on susceptibility to flooding in the catchment (Table 7).

Table 6: Pairwise comparison matrix of criteria.

Criteria	C1	C2	C3	C4	C5
C1	1	1/5	1/5	1/6	1/6
C2	5	1	1/2	1/3	1/4
C3	5	2	1	1/2	1/5
C4	6	3	2	1	1/2
C5	6	4	5	2	1

C1 (Channel Proximity); C2 (Land Cover); C3 (Slope); C4 (Proximity); e C5 (Urban Density).

Table 7: AHP weights.

Criteria	Weight
Channel proximity	0.04
Land cover	0.15
Slope	0.18
Connectivity	0.26
Urban density	0.37

The Channel Proximity criterion (C1) is less important in the comparison, as the catchment has the macro-drainage element with hydraulic capacity for rainfall with a return period of more than 100 years (Santos, 2021). Thus, susceptibility in its vicinity is reduced due to the unlikelihood of the channel overflowing, even for extreme events.

It is followed by land cover (C2), which, despite having a greater weight to C1, is still the second least important criterion, due to the uniform soil cover throughout the catchment. Even though it is a determining factor in soil surface sealing and surface runoff generation, there are no relevant changes in the pixel-by-pixel analysis, as the catchment has mostly urbanized land cover.

The slope criterion (C3) is the most important among the hydrological criteria, as higher slopes imply greater production of runoff downstream, leading into areas such as the confluence of watercourses, drains, or streets, which favor the occurrence of flooding. It, therefore, weighs 0.18 within the combination, since the catchment has locations with the most significant changes in slope.

The connectivity criterion (C4) is important because the drainage in the catchment is primarily superficial, with flow over the streets (Alves *et al*., 2022). Even though the area has differences in the occupation of subdivisions and different forms of occupation, its roads are connected. Thus, the more connected roads receive a larger flood wave and carry it downstream, resulting in a weight of 0.26 for the criterion.

The urban density criterion (C5) is the most important since it reflects the blocks' imperviousness, based on the occupation rate of the built environment, considering that the occupation process alters the morphology of the catchment and the natural water cycle. It is interesting to note that the criteria of land cover and urban density would have similar roles in characterizing the influence of the production of space on hydrology and the accumulation of water in the catchment. However, as expressed in this hierarchical analysis, the density criterion is more sensitive and can better discriminate between flooding and inundation processes locally. It is, therefore, the criterion that best responds to changes caused by the occupation and has a weight of 0.37.

The AHP weights were used to produce the map, whose scores ranged from 0.25 to 0.78, with higher values indicating greater susceptibility to flooding. Based on these scores, some catchment parts were classified as highly susceptible (Figure 8). In addition, according to the proposed methodology, the average susceptibility values for each subdivision were calculated from the raster's zonal statistics, classified, and prioritized, in terms of their susceptibility to flooding (Figure 8; Table 8).

Figure 8: Map of susceptibility to flooding in the Ramadinha Catchment.

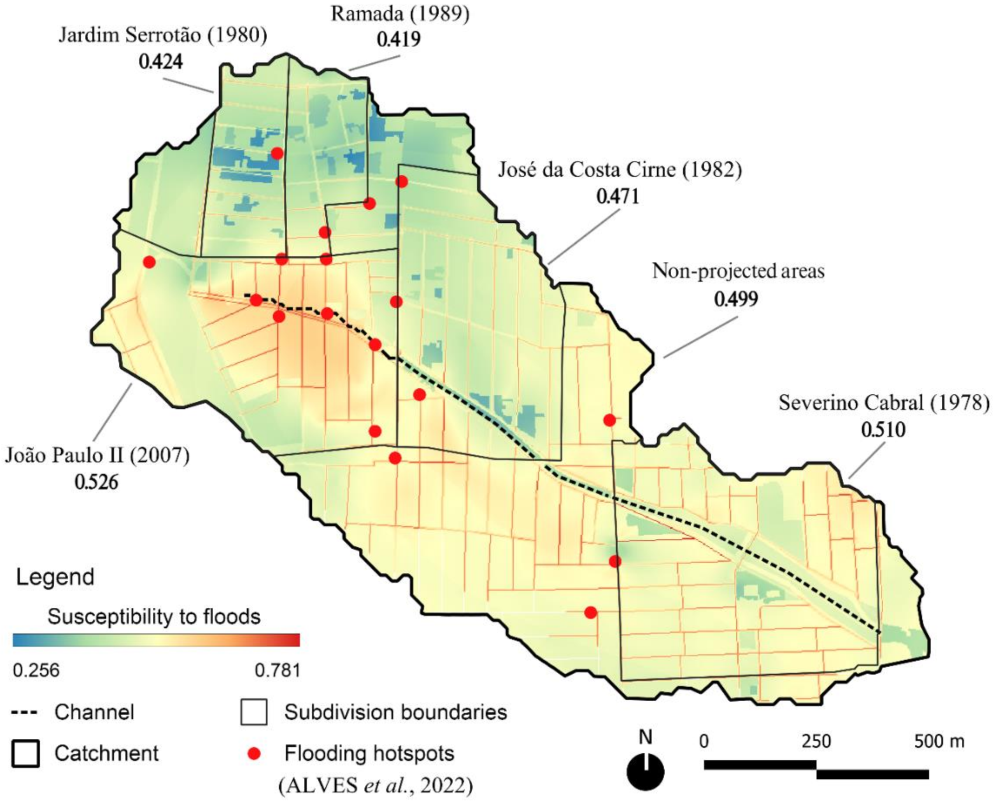


Table 8: Susceptibility of subdivisions to flooding.

Subdivisions	Susceptibility (average value)
No land development project	0.499
Severino Cabral	0.510
Jardim Serrotão	0.424
Ramada	0.419
José da Costa Cirne	0.471
João Paulo II	0.526

From the map, it can be deduced that the areas with the higher susceptibility probability are delimited by streets, which is explained by the fact that rainwater is conveyed superficially without micro-drainage elements. In this way, the streets with the most significant connections produce most runoff. Even though this morphological condition contributes significantly to the propagation of runoff, it is socially required, as the lack of connected roads is still one of the disadvantages experienced in precarious settlements on the banks of water bodies (Hatipoglu; Mahmut, 2020), both as public spaces and as accessibility routes. It is, therefore, necessary to invest in measures to mitigate flooding at these connections, such as implementing upstream infiltration areas and/or micro-drainage infrastructure at these road intersections.

In addition to connectivity, other morphological metrics are important in analyzing the succession of flooding in the catchment, such as the direction of the roads to the channel, which is evident in the Ramada and Jardim Serrotão subdivisions and the no-project zones, especially at the intersection with the ZEIS. In addition, the irregular layout in these areas and the lack of paving and support for drainage elements make it difficult to control the generation and propagation of runoff.

The density analysis revealed that the Jardim Serrotão, José da Costa Cirne and Ramada subdivisions have lower occupancy rates (0.37, 0.34 and 0.39, respectively). These areas have larger blocks, with more irregular roads and small buildings, which are sometimes interspersed with unoccupied land and sometimes have large streets, creating large unoccupied spaces in the center of the blocks. These factors reduce the susceptibility to flooding in these areas, justifying the lower average values (Table 8).

The Severino Cabral subdivision, as it was one of the first to be built and has a flatter terrain, has a higher occupancy rate (0.49). The blocks without a development project, mainly in the Ramadinha ZEIS, have an even higher occupancy rate (0.52). In addition, there is a rotation in the layout of the blocks, mostly arranged perpendicular to the creek, which, due to the topographical particularities, favors a greater number of roads with a greater slope, a fact also found in the José da Costa Cirne and João Paulo II subdivisions, linked to the more significant runoff downstream.

The João Paulo II subdivision has a high land occupation rate (0.72); the buildings constructed there meet current real estate market standards for housing aimed at the lower and lower-middle income classes. To maximize profits, developers opt for an occupation that maximizes the number of housing units, which tend to be small (rarely more than 70 m^2 of built area) and have little architectural diversity. The resulting scenario consists of streets marked by a constant housing typology. This occupation justifies the high average susceptibility value (Table 8). The main consequences of this new form of occupation are a low adherence to the minimum setbacks established in the Municipal Construction Code (Law 5410/13), which recommends side setbacks that are not always enforced, and the minimum front setbacks (4 meters) almost always give way to garages and high walls. This pattern is recurrent throughout the urban perimeter: increasingly inactive interfaces concerning public open spaces.

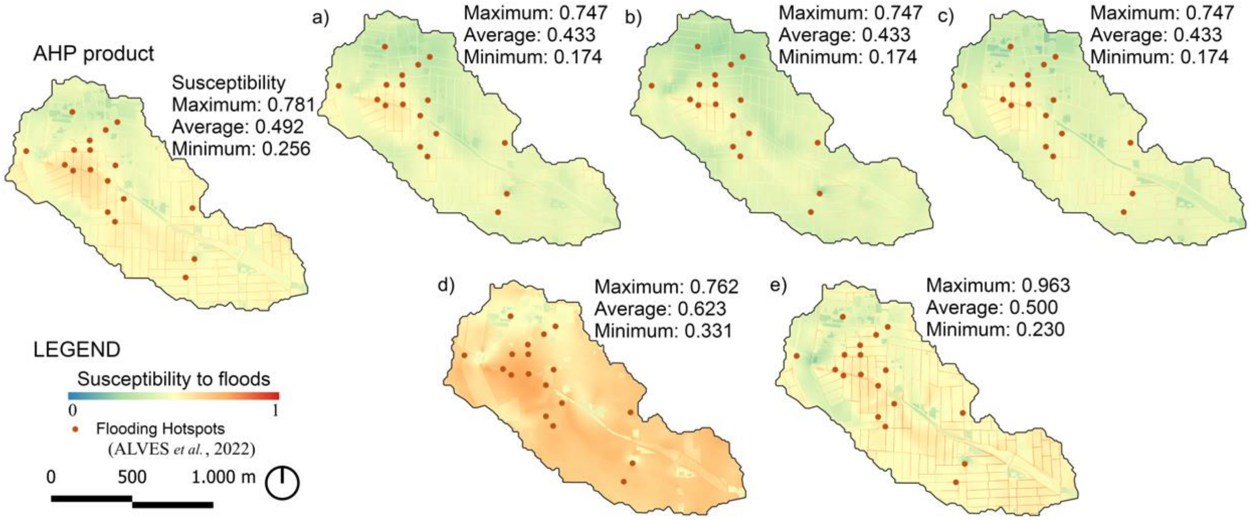
This shows how different urbanization projects influence susceptibility to flooding in different ways, especially in a catchment with heterogeneous subdivisions occupation (spontaneous and planned) and a tendency towards a "patchwork" city of diverse urban microcosms. Therefore, not only these projects, but also the resulting morphology should be analyzed. As a comparative example, the Severino Cabral and João Paulo II subdivisions showed gradual occupation after the housing was built but had different susceptibilities and incidences of flooding due to the differences in their morphological metrics.

In addition to this analysis, the macro-drainage channel is not enough, per se, to solve these problems throughout the catchment, as the most susceptible areas are far from this macro-drainage element, meaning that the drainage project was not produced according to morphological standards, thus favoring vulnerabilities in the locality.

Despite the results highlighted, as this method performs inference based on pixel-by-pixel analysis, some limitations can interfere with the results, such as the calculation not considering the area upstream of the pixel where the runoff is generated.

In conclusion, the sensitivity analysis for each criterion (Figure 9) shows that the system is more sensitive to changes in the connectivity criterion due to the configuration of the surface drainage system and density, which restricts the occupation of plots, with significant changes in the final susceptibility results.

Figure 9: Sensitivity analysis of criteria.



Criteria removed: a) Channel proximity b) Land cover c) Slope d) Connectivity e) Density.

6 Conclusion

The conceptual and empirical consistency of the map of susceptibility to flooding demonstrated that the methodology could incorporate factors relevant to assessing drainage in these urban forms, complementing other qualitative and theoretical studies on the subject. A significant contribution was the inclusion of urban morphology metrics in hydrological investigations, demonstrating how the process of producing space influences the disasters that strike urban settlements. It, therefore, adds a new discussion to studies investigating susceptibility to flooding, disregarding urban occupation and the shape of the built space.

In the catchment studied, the most relevant metrics, in this order, were urban density, connectivity, slope, land cover, and channel proximity. The multi-criteria analysis also revealed the impacts of the various morphological patterns in the catchments. The case study demonstrates how considering morphological metrics can help formulate urban planning and management strategies to adapt to the extremes expected in a future climate, including being robust to the uncertainties of climate change projections. Applying the same methodology to catchments with other morphological patterns could generate a database for generalization.

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