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Exploring the Relationship between Urbanization, Floods and Green Infrastructures: A Study in The Nado Stream Watershed, Belo Horizonte, Brazil.

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A B S T R A C T
Urban floods are significant hydrological phenomena that impact both physical and social systems. This study explores the relationship between land use and cover dynamics and flood occurrences within Nado stream watershed (Belo Horizonte, Brazil), aiming to identify potential areas for green infrastructure implementation. The research uses geospatial analysis techniques and remote sensing, to examine how urbanization and landscape changes influence flood risk. The methodology includes analyzing land cover changes over time, urbanization trends, flood susceptibility mapping, environmental health and social vulnerability indices. By integrating these datasets, the study identifies priority areas for green infrastructure, such as rain gardens and linear parks, as effective flood mitigation strategies. It highlights the importance of nature-based solutions and sustainable drainage systems in enhancing urban resilience. The results reveal evolving land use patterns, the concentration of urbanization around water bodies, and the negative impact of vegetation loss on flood risk. The analysis identifies high-susceptibility areas, particularly in heavily urbanized zones, and underscores the intersections between urbanization trends, flood risk, and social vulnerability. The study emphasizes the need for strategic interventions to bolster urban resilience, providing valuable insights for flood management and green infrastructure planning decision-making. It underscores the urgency of implementing nature-based solutions to address increasing flood risks amid urban expansion and climate change.
Key-words: Urban Floods. Remote Sensing. Land Use and Land Cover Dynamics. LID infrastructures.

Explorando a Relação entre Urbanização, Inundações e Infraestruturas Verdes: Um Estudo na Bacia do Córrego do Nado, Belo Horizonte, Brasil.

R E S U M O
Inundações urbanas são fenômenos hidrológicos significativos que impactam os sistemas físicos e sociais. Este estudo explora a relação entre a dinâmica de uso e cobertura do solo e a ocorrência de inundações na bacia do Córrego do Nado (Belo Horizonte, Brasil), com o objetivo de identificar áreas potenciais para a implementação de infraestruturas verdes. A pesquisa utiliza técnicas de análise geoespacial e sensoriamento remoto para examinar como a urbanização e as mudanças na paisagem influenciam o risco de inundações. A metodologia inclui a análise das mudanças na cobertura do solo, tendências de urbanização, mapeamento da suscetibilidade a inundações e índices de saúde ambiental e vulnerabilidade social. Integrando esses conjuntos de dados, o estudo identifica áreas prioritárias para infraestrutura verde, como jardins de chuva e parques lineares, como estratégias eficazes para mitigação de inundações. Destaca a importância de soluções baseadas na natureza para aprimorar a resiliência urbana. Os resultados revelam padrões evolutivos de uso do solo, a concentração da urbanização ao redor de corpos d'água e o impacto negativo da perda de vegetação no risco de inundações. A análise identifica áreas com alta suscetibilidade, particularmente em zonas altamente urbanizadas, e sublinha as interseções entre tendências de urbanização, risco de inundações e vulnerabilidade. O estudo enfatiza a necessidade de intervenções estratégicas para fortalecer a resiliência urbana, fornecendo insights valiosos para a tomada de decisões relacionadas ao gerenciamento de inundações. Ressalta a urgência de implementar soluções baseadas na natureza para enfrentar os riscos de inundações diante da expansão urbana e das mudanças climáticas.
Palavras-Chave: Inundações Urbanas. Sensoriamento Remoto. Dinâmica do Uso e Cobertura da terra. Infaestruturas LID.

Introduction

Urban floods are hydrological phenomena that connect physical and social systems, resulting in severe impacts such as loss of life, property damage, transportation infrastructure damage, proliferation of disease vectors, and disease spread, thus affecting the overall socio-economic dynamics (Raza et al., 2023.). These floods are closely related to the spatio-temporal dynamics of land use and occupation (Viero et al., 2019). Although floods are perceived as disasters when they negatively impact communities (Macedo et al., 2022), they are natural and temporary processes associated with the characteristics of the hydrometeorological system. Floods occur when the drainage and infiltration capacities are lower than the instantaneous flow in the water body, causing water to overflow onto the seasonal bank (Sohn et al., 2020). However, their effects are intensified by higher degrees of urbanization, occupation of floodplains, soil impermeabilization, and channelization of water bodies (Viero et al., 2019).

To analyze the spatial distribution of flood phenomena, developing dynamic, spatially explicit models and tracking changes in land use and cover is essential. This involves using geographic information system (GIS) tools (Al-Faisal et al., 2018), environmental modeling (Peredo et al., 2022), optical remote sensing image processing (Farhadi and Najafadeh, 2021; Goffi et al., 2020; Güvel et al., 2022), and synthetic aperture radar (SAR) (Kageyama et al., 2022). In the context of methodologies that integrate geospatial data and geoprocessing, multicriterial analysis is a methodological approach based on weighting parameters that identify the best decisions for problem resolution or response to a specific demand. This methodology is widely used in geosciences across various contexts (Macedo et al., 2018; Caldas et al., 2019), especially due to its integration with GIS using spatial statistical techniques.

There is an explicit relationship between land use and cover and the occurrence and impact of floods. In urban environments, the characteristics of natural hydrological systems are altered due to urbanization processes. In Belo Horizonte, these changes are particularly evident due to the impacts of soil impermeabilization (Rosa et al., 2020). Thus, this study's analysis encompasses the relationship between the city's urban planning policies and the spatialization of flood processes. The possibilities of rethinking land use through nature-based solutions, such as urban river rehabilitation and green infrastructure implementation associated with Sustainable Urban Drainage Systems (SUDS) (Morais et al., 2021), appear promising.

Green infrastructures are innovative methods designed within the context of resilient cities to integrate the urban landscape with ecological urbanism conditions. Grabowski et al. (2022) highlight various definitions of green infrastructures, considering their different functions and benefits (ecological, economic, and technological) and their different types (e.g., rain gardens, green roofs, riparian or linear parks, and bioretention cells). In this study's context, rain gardens are urban drainage systems established as nature-based solutions that serve as landscaping strategies and natural compositions in urban environments. These compensatory techniques aim to increase soil water infiltration and reduce surface runoff, particularly on a micro-drainage scale (Belo Horizonte, 2016). These solutions counter traditional drainage systems, prioritizing rapid water flow and overlooking various water cycle processes, particularly infiltration and percolation. In considering the natural form of the hydrological cycle, bioretention systems are designed to compensate for changes in the natural micro-drainage hydrological course due to urbanization (Catimay, 2019). Moreover, linear parks are strategies to reduce the occupation of risk areas in floodplains, as they are installed around urban water bodies and fit within nature-based solutions and sustainable drainage systems. Linear parks can be implemented in larger public areas, potentially reducing peak flow and surface runoff (Morais, 2022).

In Belo Horizonte, flood-related impacts are frequent and linked to land management, both anthropogenic factors—such as changes in the city's urban space and drainage techniques that disregard rivers' physical nature—and the city's physical-natural conditions, such as its rugged and undulating terrain and climatic variables (Morais, 2022). These characteristics have led to recurring flood events, particularly in areas intensively occupied and urbanized in the last 50 years, including the Pampulha and Venda Nova regions (Belo Horizonte, 2020). In these areas, accelerated urbanization has impacted the hydrological dynamics, creating recurrent flood points in streams covered by paved streets, such as the intersection of Sebastião de Brito Avenue with Cristiano Machado Avenue (Pampulha stream), Vilarinho Avenue (Vilarinho stream), Dr. Álvaro Camargos Street (Nado stream), and Camões street (Borges stream).

The Belo Horizonte Municipal Government

has worked over the past 30 years to implement public policies to make the city more resilient to flood events (Belo Horizonte, 2014). Among these measures are structural solutions for implementing drainage infrastructure and using sustainable green technologies, particularly linear parks and, more recently, rain gardens. There is also a strong emphasis on non-structural measures, such as establishing and strengthening urban water management policies through the Belo Horizonte Drainage Plan (Belo Horizonte, 2014; Morais, 2022). In this context, this study aimed to investigate the potential of green infrastructure, such as rain gardens and linear parks, on flood events control by examining the relationship between urbanization, flood susceptibility, and population vulnerability in a densely urbanized watershed in Belo Horizonte, Brazil.

Methodology

Study Area

The study area comprises the Nado stream watershed, located in the Pampulha and Venda Nova regions within the municipality of Belo Horizonte, the Minas Gerais state capital and its primary economic hub. The Nado Stream watershed covers an area of 12.39 km², representing 3.8% of Belo Horizonte's territory and approximately 130,000 people (IBGE, 2021) (Figure 1). Urban development primarily occurred in headwater areas and floodplains, increasing flood risks near the Nado stream banks (Belo Horizonte, 2020).

The Nado stream watershed's hydrology is shaped by infiltration and runoff conditions, with a dendritic drainage pattern influenced by the Belo Horizonte Granite-gneiss complex. Productive infiltration zones recharge the local aquifer. However, urbanization has led to frequent floods and environmental damage. Rapid expansion since the 1950s has reduced recharge areas, increasing water flow and discharge rates in flood-prone regions (Lopes et al., 2003; Belo Horizonte, 2020).

The accelerated urbanization after the 1950s reduced recharge areas in the watershed, consequently increasing water flow accumulation in critical areas. This has led to elevated discharge rates in regions that frequently flood (Lopes et al., 2003).

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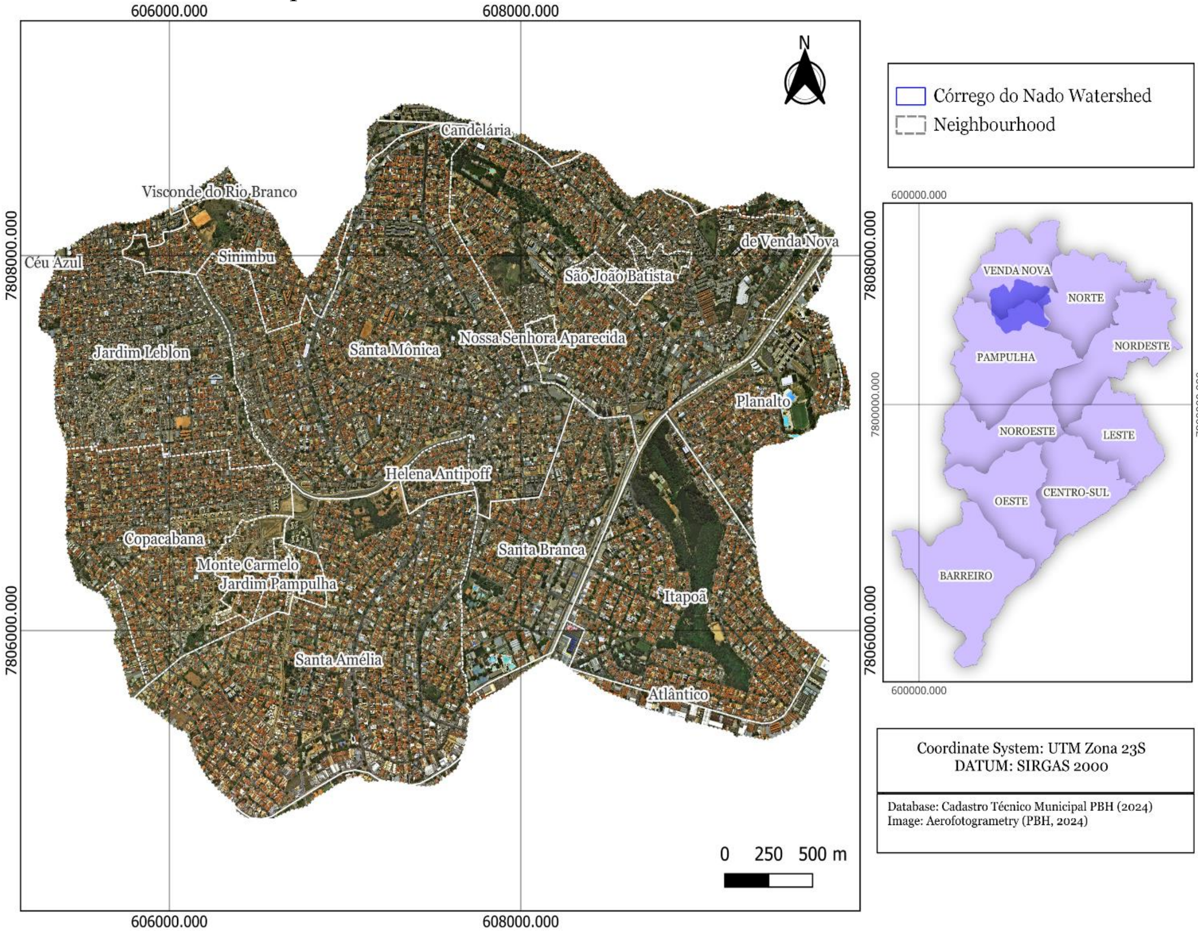

Figure 1: Study area and neighborhood boundaries.

Methodological procedures

We utilized a methodology divided into four stages to identify priority areas for green infrastructure installation (Figure 2).

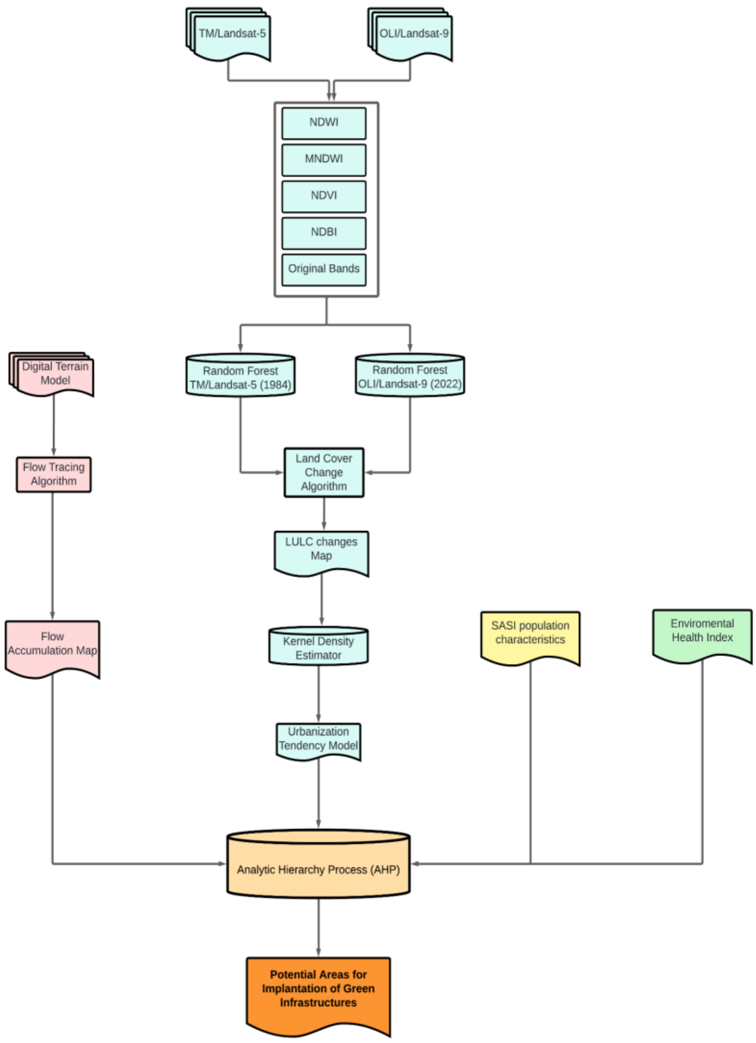

Figure 2: Methodological procedures flow.

Analysis of Land Use and Land Cover Changes and Urbanization Spatial Trends

For the analysis of land use and land cover changes in the Nado stream watershed, we selected Landsat satellite images of June 1984 and September 2022 (Thematic Mapper - TM and Operational Land Imager - OLI sensors, respectively). These images are Level 2, meaning they underwent preprocessing with atmospheric correction and geometric registration, and the data is presented in surface reflectance (ρ). Due to the medium spatial resolution of the sensors (i.e., 30m), we used four spectral indices to extract land use and cover information: MNDWI - *Modified Normalized Difference Water Index;* NDWI (*Normalized Difference Water Index*); NDVI (Normalized Difference Vegetation Index); NDBI (*Normalized Difference Build-Up Index*) (Equations 1, 2, 3, and 4).

$$MNDWI = \frac{G-SWIR1}{G+SWIR1} \quad (1)$$

$$NDWI = \frac{G-NIR}{G+NIR} \quad (2)$$

$$NDVI = \frac{R-NIR}{R+NIR} \quad (3)$$

$$NDBI = \frac{SWIR1-NIR}{SWIR1+NIR} \quad (4)$$

Where: G represents the green band (spectral response between approximately 0.51µm and 0.60µm); R represents the red band (spectral response between approximately 0.63µm and 0.68µm); NIR represents the near-infrared band (spectral response between approximately 0.80µm and 0.89µm); SWIR1 represents the shortwave infrared band (spectral response between approximately 1.56µm and 1.71µm).

The objectives of the MNDWI and NDWI are to enhance the detection of water bodies, while the NDVI is used for vegetation mapping (Jensen et al., 2009. The NDBI differentiates between more densely and less densely urbanized areas and can be used to map urban growth and densification (Zha et al., 2001).

To identify land use and cover changes between 1984 and 2022, we classified the scenes from these two dates using an image cube that incorporated the original spectral bands (i.e., blue, green, red, near-infrared, and shortwave infrared) added with the generated indices. We performed pixel-based classification using the Random Forest algorithm (Breiman, 2001). We collected training samples from representative points of land use and cover classes.

To analyze the spatial trend of urbanization, we characterized land use and land cover changes between 1984 and 2022 using a transition matrix between the maps generated for the two periods. We executed this step using the Land Cover Change algorithm in the Semi-Automatic Classification Plugin in QGis software (Congedo, 2021). The matrix represented anthropized areas (transitions from natural to urbanized areas) and restored areas (from urbanized to natural areas). We converted these data from matrix to vector format. We then integrated the vector data to create a spatial trend model using the Kernel density estimator. The Kernel density estimator establishes a probability density function based on a sample data set following a Gaussian distribution (Bierens, 1987). We used parameters of 100 meters for the radius—which defines the aggregation distance for each attribute—and the Epanechnikov kernel shape, which provides smoother densities and reduces the possibility of overestimation (Epanechnikov, 1969).

Flood Susceptibility Analysis

We conducted the flood susceptibility analysis using the Flow Tracing accumulation model in the SAGA-GIS software (Conrad et al., 2015). This algorithm tracks the theoretical flow of runoff from each cell in the Digital Terrain Model (DTM) until the flow leaves the corresponding cell in the DTM or ends at the outlet, generating points of water accumulation in specific cells. This method follows the principles of the physical system model for energy flow proposed by Fairfield and Leymarie (1991). We generated the DTM from a LiDAR point cloud obtained through an aerial photogrammetric survey conducted by the Computer and Information Company of the Municipality of Belo Horizonte, which is available in its database. We processed the point cloud using TIN interpolation via Delaunay triangulation, producing a final product with a spatial resolution of 5 meters.

Environmental Health Index

Belo Horizonte (2020) developed the Environmental Health Index (EHI) to quantify the coverage of sanitation-related services within the municipality, as represented by Equation 5. In this study, the EHI was employed to characterize the environmental health of sub-basins, highlighting sanitation as a key factor influencing environmental vulnerability.

$$EHI = I_{ab} \times 0.05 + I_{es} \times 0.35 + I_{rs} \times 0.20 + I_{dr} \times 0.40 \quad (5)$$

Where: I_{ab} is the Water Supply Index; I_{es} is the Sanitary Sewage Index; I_{rs} is the Solid Waste Index; I_{dr} is the Urban Drainage Index.

Social Vulnerability

Special Areas of Social Interest (SASI) are designated areas within the municipality government that are used to establish housing for low-income individuals, existing communities, or new housing projects. We used these areas to identify regions with populations potentially more vulnerable to flood events and to understand the expansion of access to green infrastructure as a mitigation measure through the development of greater socio-ecological resilience.

Potential Areas for Green Infrastructure Implementation through Multicriteria Analysis

We identified potential areas for green infrastructure implementation by considering the elements modeled, processed, and analyzed in the previous sections as four factors: (1) Spatial trend of urbanization; (2) Susceptible to flood events; (3) Environmental Health Index (EHI); Population living in Special Areas of Social Interest (SASI).

We conducted the study using a multicriteria analysis, calculating weights and evidence with the Analytic Hierarchy Process (AHP). This method establishes patterns and accurately assigns values to compare different elements (Saaty, 1990). We linked the criteria for selecting potential areas to the role of green infrastructure in reducing peak flow, surface runoff, and rainwater retention to mitigate the impacts of floods (Morais, 2022). We aggregated variables associated with disaster risk (vulnerability, susceptibility, and risk) to interpret areas where implementation would reduce the impact of flood events.

Factors weight

Considering the established factors, we normalized them using scores based on Table 1. We scaled all modeled variables between 0 and 1, where 1 represents the maximum need for green infrastructure and 0 represents the minimum need.

Table 1: Normalization criteria for the need for green infrastructure.

Factor	Rating			
	1	0.75	0.50	0
Spatial trend of urbanization (influence area)	< 100 m	100-200 m	200-300 m	> 300 m
Susceptible to flood events (number of pixels)	> 700000	466667- 700000	233333-466667	< 233333
Environmental Health Index (index value)	< 0.500	0.5-0.7	0.7-0.95	> 0.95
Special Areas of Social Interest (population)	> 3000	1000-3000	1-1000	0

The Analytic Hierarchy Process (AHP) method involves pairwise comparison of factors, assigning a weight to each relationship, which allows for the organization of each variable according to a hierarchy. We organized the factors in a matrix and assessed the relative importance of each factor in relation to the others. When one factor (A) is more important than another factor (B), it receives a score of x, and correspondingly, factor (B) receives a reciprocal score of 1/x (Table 2). The final weight is the sum of the relative importance of each factor, with the total sum of these weights equal to 1 (Table 3).

Table 2. Importance Level of Relationships Between Factors

Degree of importance	Definition
1	Equal importance of two factors
3	Weak importance of an element in comparison to the other
5	Strong importance of an element in comparison to the other
7	Certified importance of an element in comparison to the other
9	Absolute importance of an element in comparison to the other
2, 6, 4, 8	Intermediate values between two assessments
½, ⅓, ¼, ⅕, ⅙…	Reciprocal values of the previous factors

Source: Saaty, 1990

To verify the consistency of the judgment matrix (for example, if A is more important than B, and B is more important than C, then C cannot be more important than A), we used the consistency ratio (CR; Equation 6).

$$CR = \frac{CI}{RI} \quad (6)$$

Where: RI is the value assigned based on the size of the matrix, as defined by Saaty (1990), and CI (Equation 7).

$$CI = (\frac{\lambda max - n}{1 - n}) \quad (7)$$

Table 3: Relative weights of the factors.–

Factor	(1)	(2)	(3)	(4)	Weights
(1) Spatial trend of urbanization	-	1/5	1/5	2	0.094
(2) Susceptible to flood events	5	-	1	7	0.425
(3) Environmental Health Index	5	1	-	7	0.425
(4) Special Areas of Social Interest	1/2	1/7	1/7	-	0.056

Where: λmax is the largest or principal eigenvalue of the matrix, and n is the order of the matrix. A consistency ratio (CR) of 0.10 or less indicates that the relationships within the matrix are consistent (Saaty, 1990).

Areas for green infrastructure implementation were identified based on the multicriteria analysis results, prioritizing locations around the existing road network in the study area.

Results

Land Use and Land Cover Changes and Spatial Urbanization Trends

In 1984, the basin already displayed significant urbanization (Figure 3). Based on the NDBI index, this classification identified two levels of urbanization: high-density urban areas and low-density urban areas. The analysis showed that 1984 urbanization was concentrated around Fazenda Lagoa do Nado Natural Park in the southeast and near Avenida Vilarinho in the northeast. Natural areas characterized by arboreal vegetation were still present, particularly around the streams. By 2022, urban areas had expanded throughout the basin, leaving only a few natural areas (vegetation and water) primarily concentrated around the park (Figure 4). Sankey Diagram (Figure 5) shows some of the changes in LULC.

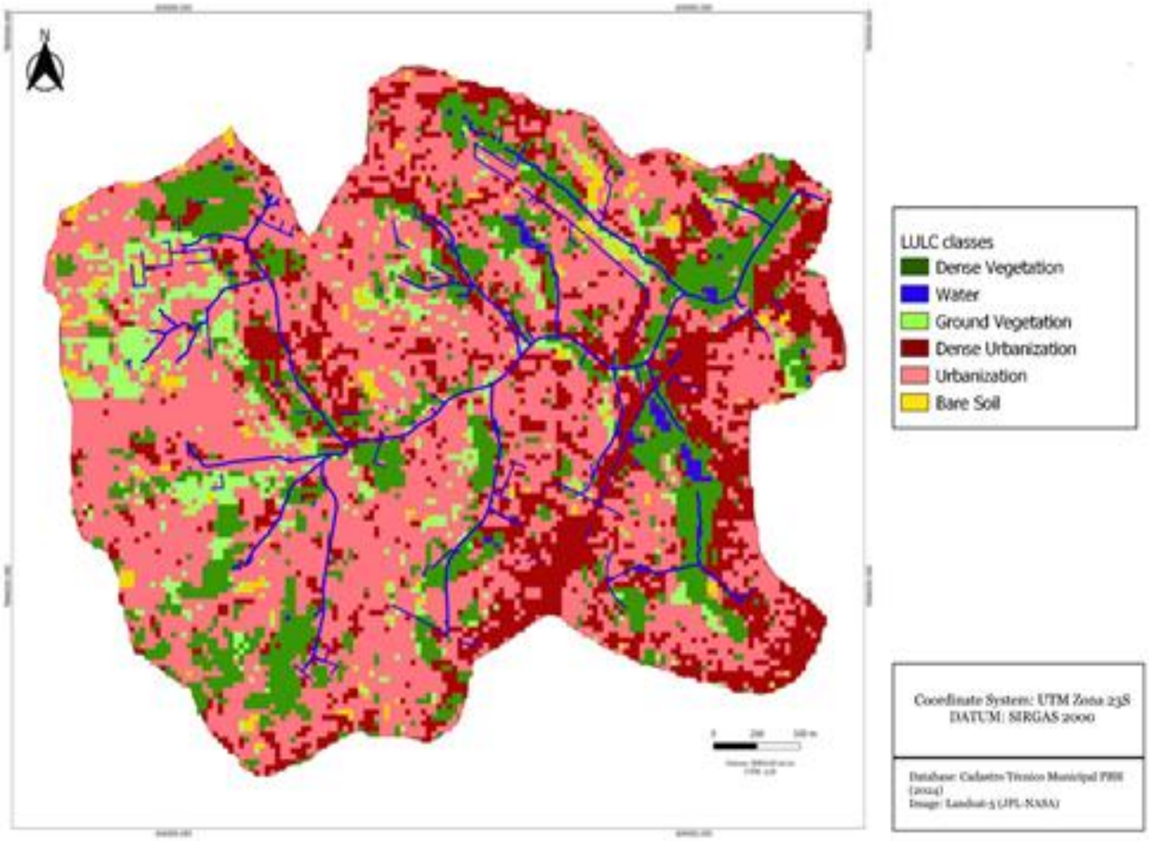

Figure 3. Land use and cover classification of the Nado stream watershed in 1984.

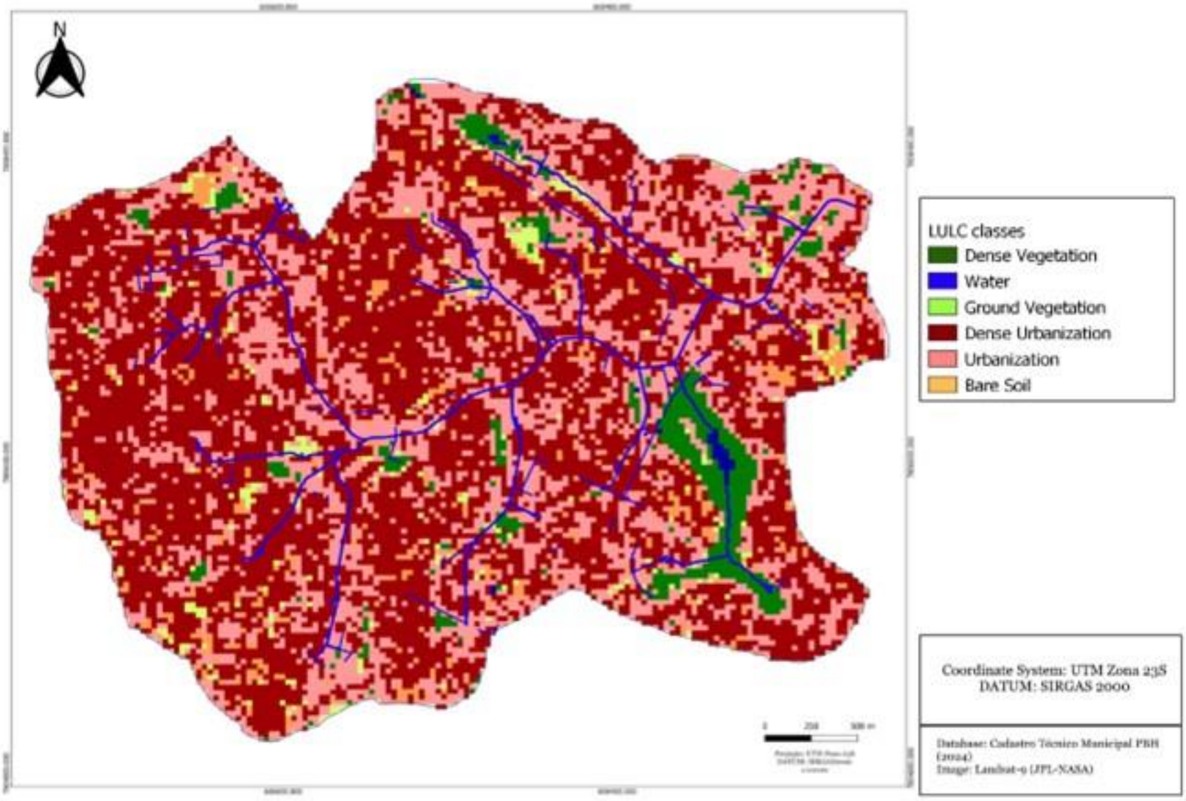

Figure 4. Land use and cover classification of the Nado stream watershed in 2022.

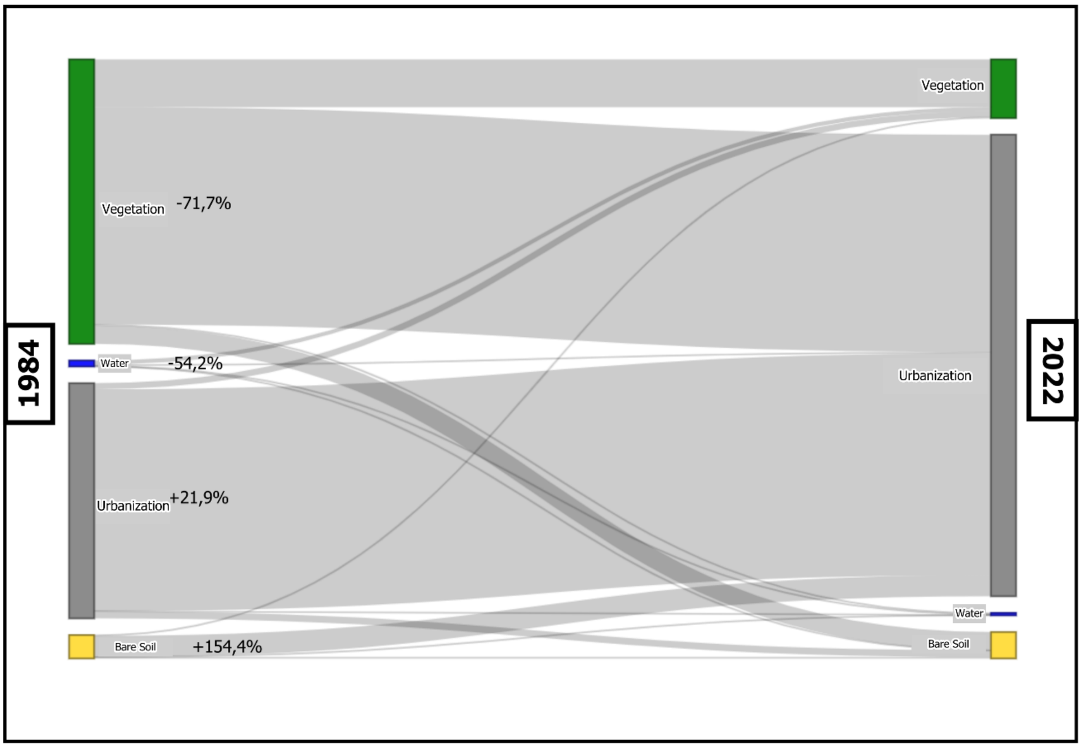

Figure 5: Sankey diagram showing changes in land use and cover in the Nado watershed between 1984 and 20

Spatial Trend of Changes from Natural Areas to Urbanized Areas

The analysis produced a cartographic product highlighting temporal land use and cover changes. Using a clustering approach, the spatial trend model identified which natural areas transitioned to anthropized areas and where these changes are most likely to occur (Figure 6). The matrix shows that anthropized or urbanized areas are spread throughout the watershed, with higher concentrations in the northeast, southwest, and northwest and lower concentrations in the southeast (Figure 7). Notably, the southeast region includes more areas designated as restored, a pattern likely linked to the official establishment of Fazenda Lagoa do Nado natural park in 1994 and the subsequent implementation of "nature-based solutions."

Flood Susceptibility

Flood susceptibility areas were mapped using the flow accumulation tracking algorithm (Figure 8), which closely aligns with the drainage network. Analysis of flow accumulation on roads reveals that certain regions exhibit higher accumulation, especially in the western part of the basin and in highly urbanized areas. These areas frequently experience flooding.

Environmental Health Index

The environmental health analysis (Figure 9) utilized the index mapped by Belo Horizonte (2020), assigning a uniform environmental health score to each sub-basin. Despite variations in sanitation across different neighborhoods and streets within each sub-basin, the Environmental Health Index (EHI) was used for methodological consistency. Sub-basins in the south and Pampulha region exhibit higher EHIs, indicating lower environmental vulnerability and better access to services. In contrast, the largest sub-basin, 4140211, which has the highest population, shows a significantly lower EHI compared to the other sub-basins.

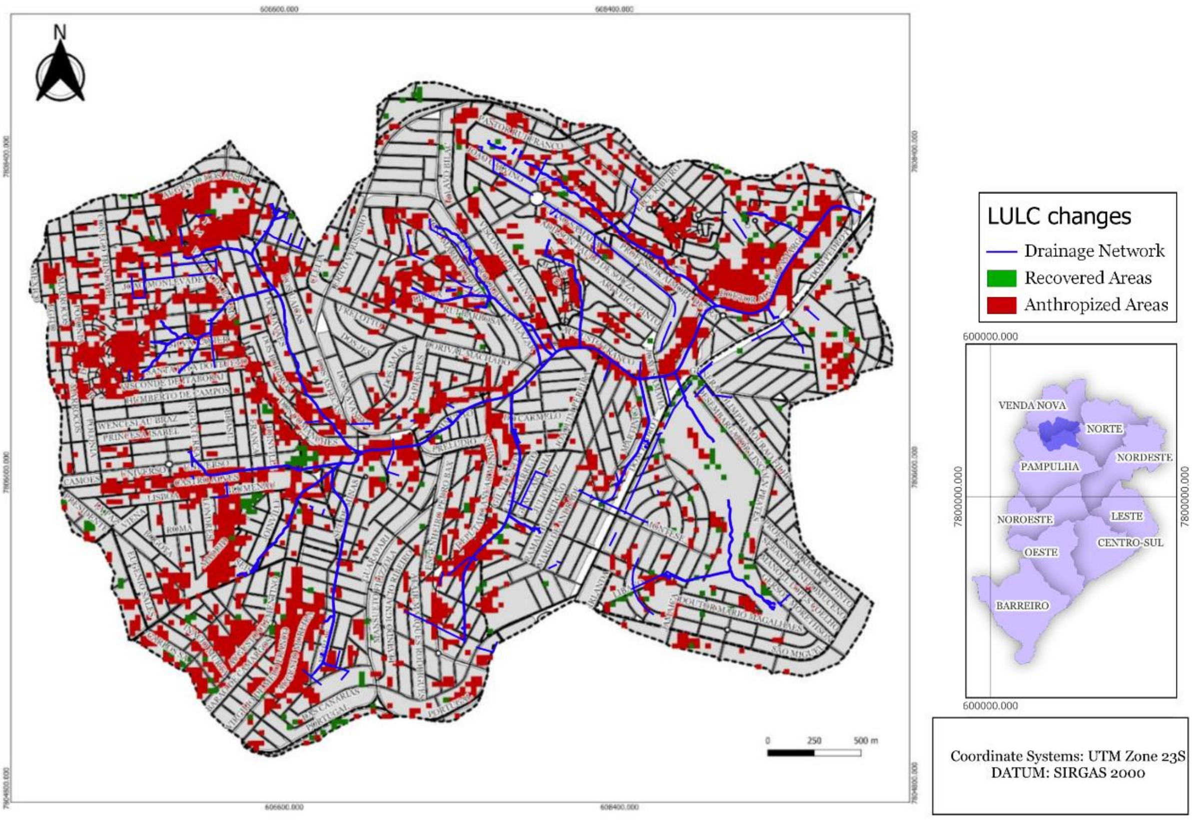

Figure 6: Land use and cover changes between anthropized and recovered areas.

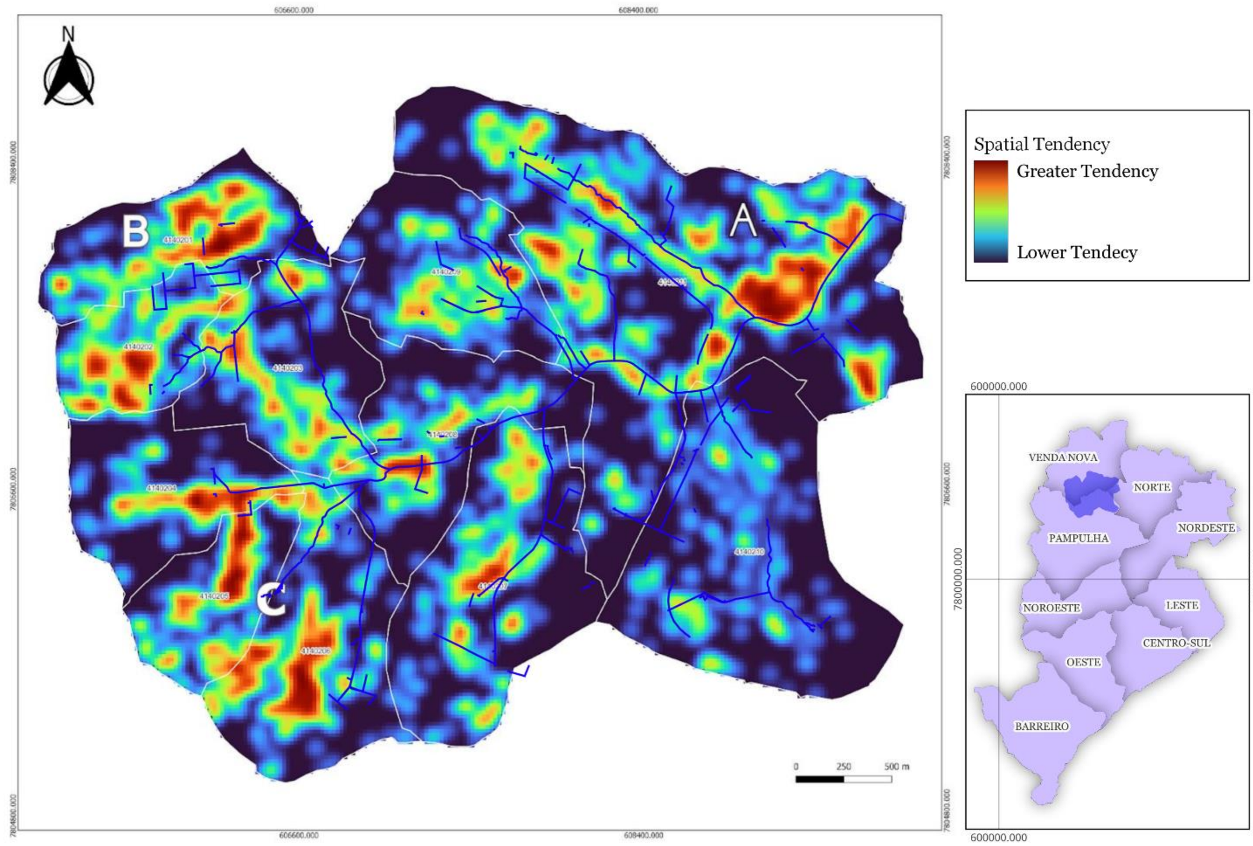

Figure 7: Urbanization spatial tendency model.

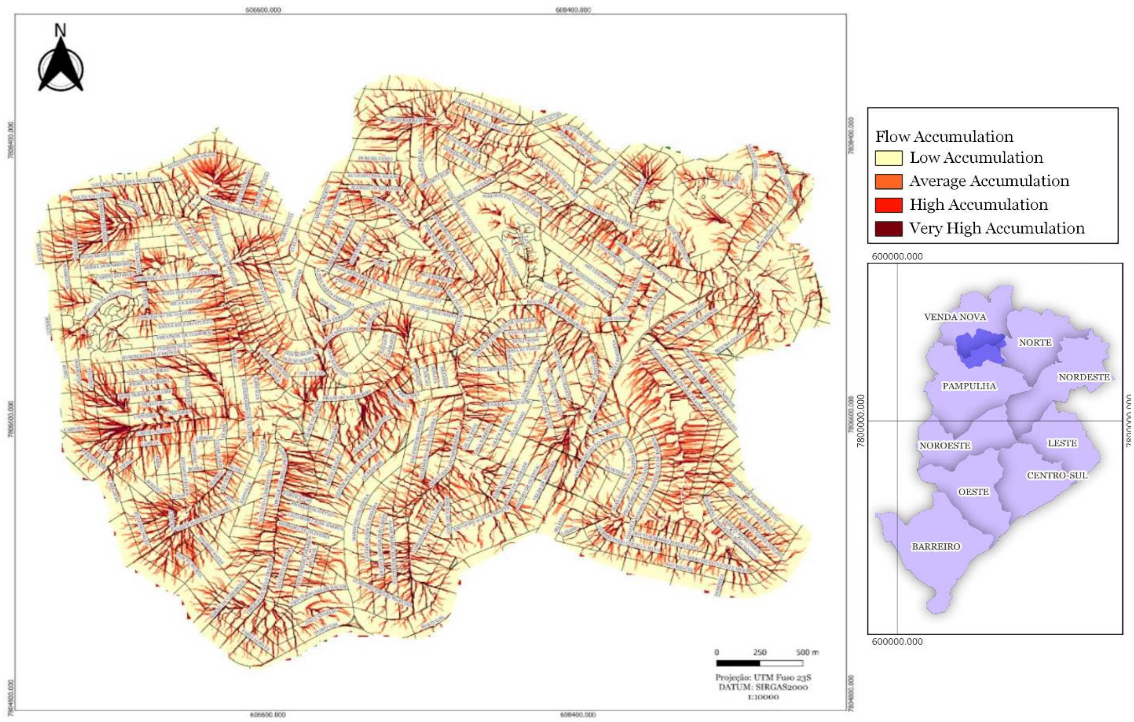

Figure 8: Susceptibility areas by flow accumulation model

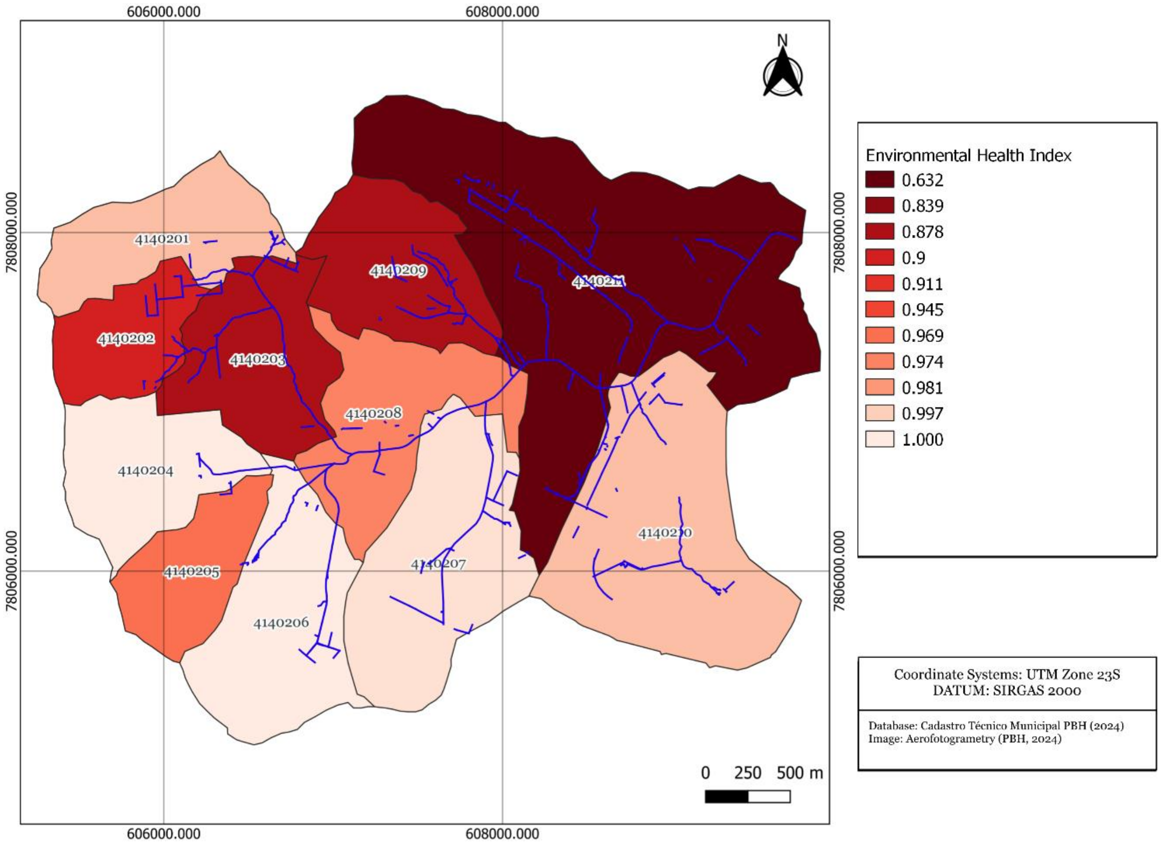

Figure 9: Environmental Health Index for Sub-basin

Population in Social Vulnerability Areas

We assessed vulnerability by examining the total population in Special Areas of Social Interest (SASI) within each sub-basin (Figure 10). Sub-basins 4140203, 4140204, and 4140208 contain overlapping communities, so the same population count was applied to all three. Most of the SASI population is concentrated in the northern and northwestern parts of the Nado stream watershed. In contrast, sub-basins 4140206, 4140207, and 4140210 in the southern part lack SASI areas, with a higher middle-class population indicating potentially lower vulnerability to flood processes, though these regions remain susceptible.

Potential Areas for Green Infrastructure Implementation Using Multicriteria Analysis

We used the values provided by AHP to identify potential areas for green infrastructure implementation (see Table 3). A map algebra operation applied these weights to all attributes, producing weighted scores ranging from 0 to 1. This resulted in a map indicating potential areas for rain gardens and linear park implementation around the existing road network, categorized into very low, low, medium, and high potential (Figure 10). Based on their implementation potential, the map in Figure 11 shows the most suitable areas.

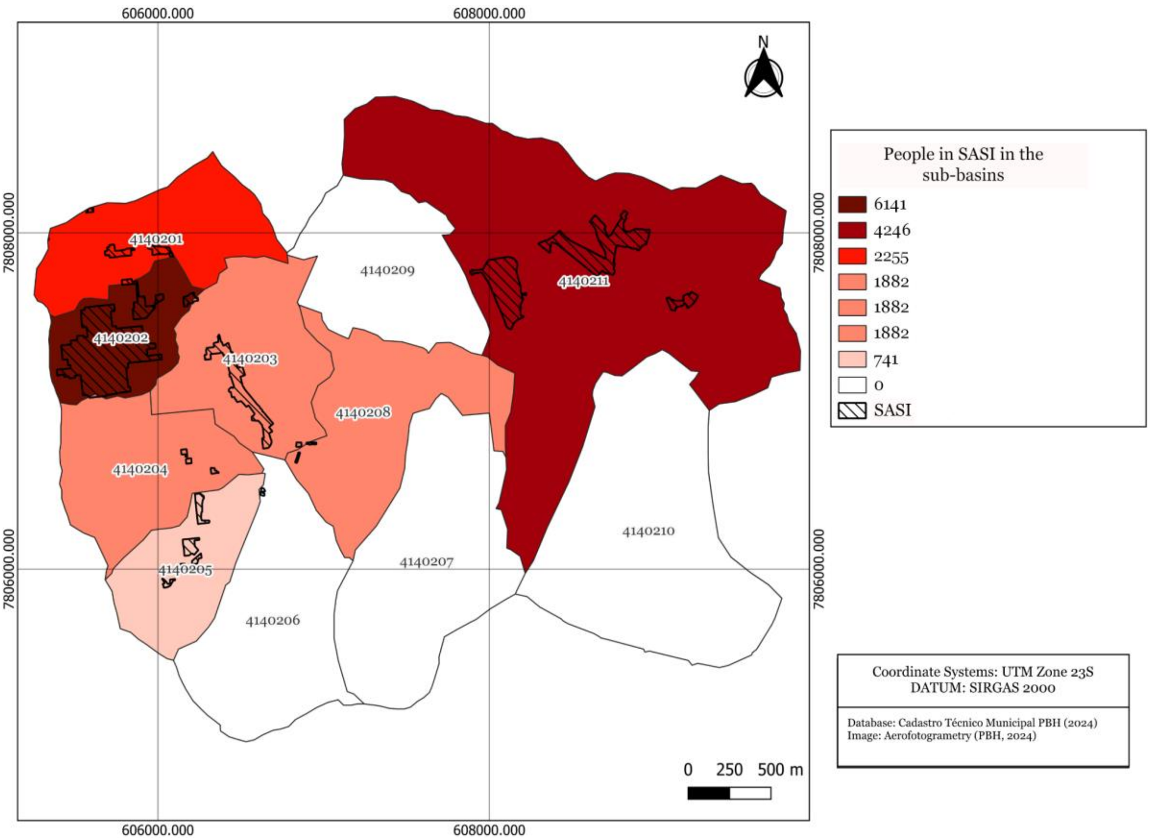

Figure 10: Population living in Special Areas of Social Interest

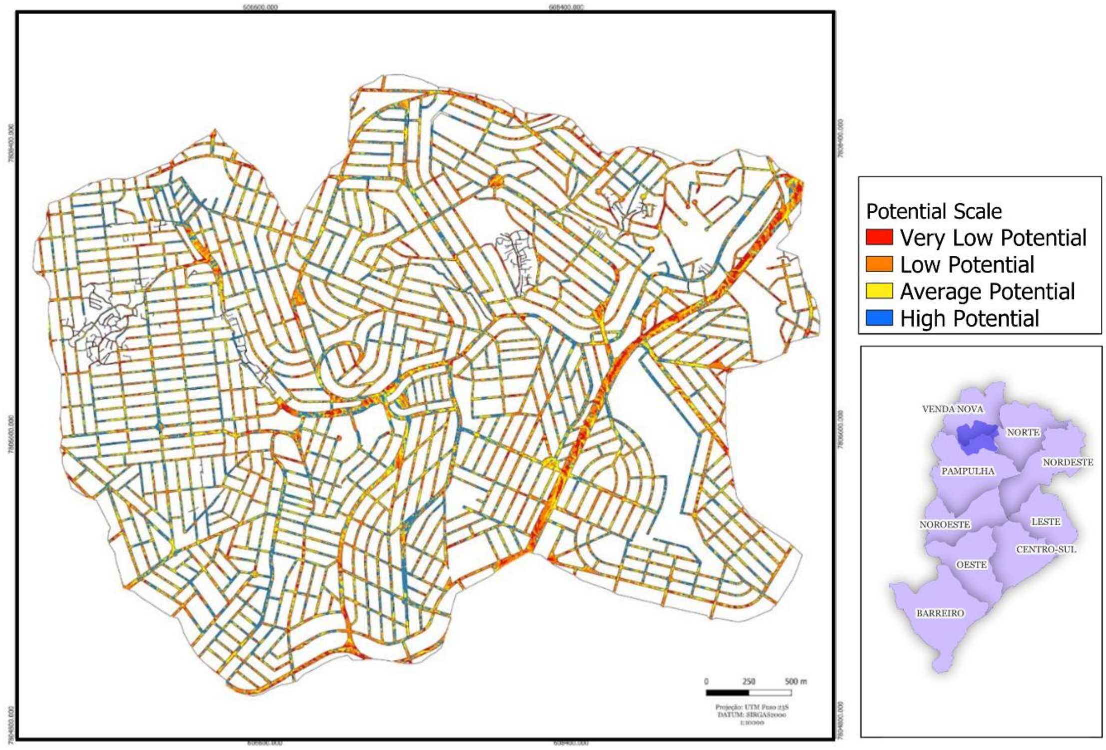

Figure 10: Potential Areas for Implementation of Green Infrastructures

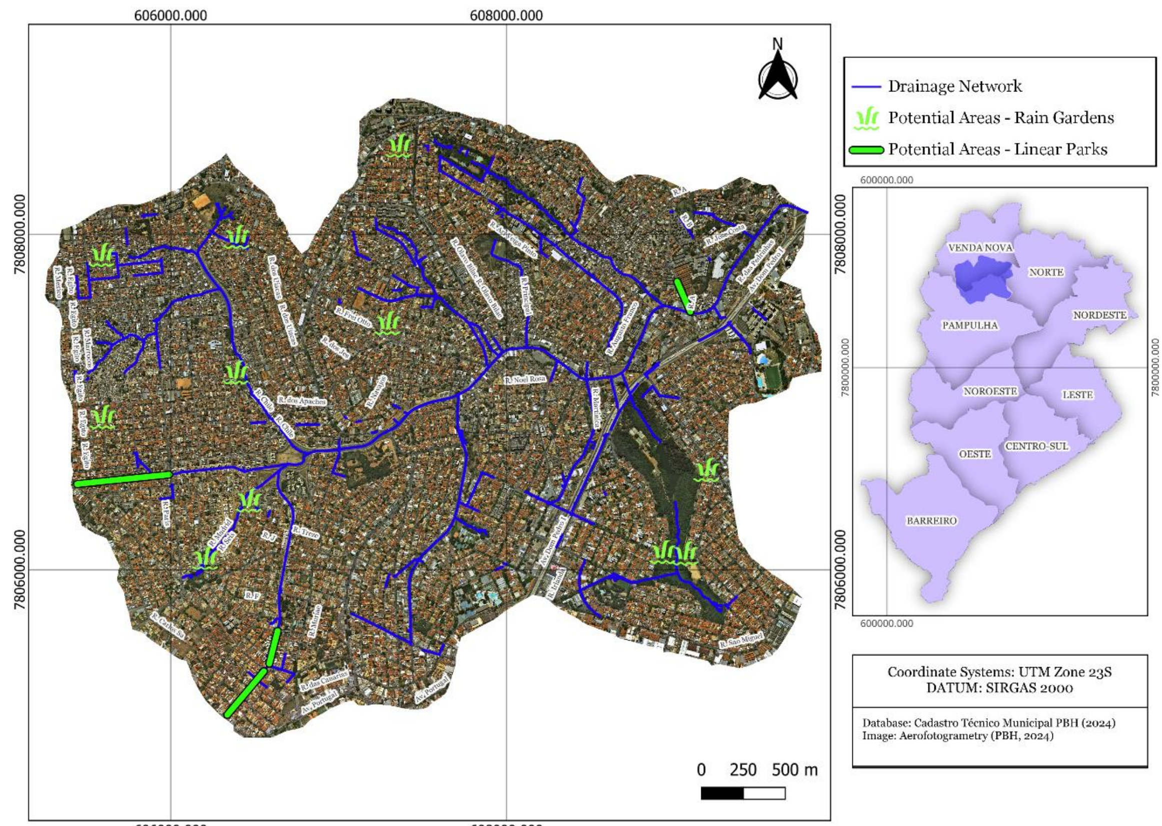

Figure 11: Streets selected as a potential for the implementation of green infrastructures

Discussion

The study identifies potential areas for implementing green infrastructure, such as rain gardens and linear parks, based on the greatest need for urbanization and local population requirements. This mapping allows for prioritizing investments by focusing on socio-environmental returns and aligning with sustainable urban development goals, particularly "city leading climate action," "cities and nature integrated," and "urban waters for life" (Brasil, 2021).

Linear parks are important green infrastructures, providing ecosystem services such as flood control, nutrient cycling, sediment control, cultural services, recreation, and mental health benefits (Macedo et al., 2022). Notably, the Nado stream watershed recently received 62 rain gardens, most in sub-basins 4140207 and 4140210 (Belo Horizonte, 2023). Markedly, in the latter, the areas selected for garden implementation aligned with those proposed in this study, as they exhibited significant hydrological flow accumulation.

Similarly, in sub-basin 4140207, areas with more rain garden implementations correspond to locations near one of the proposed linear parks in this study. Future implementation studies should consider social and environmental vulnerability as relevant factors for planning.

The hydrological study identified areas of flow accumulation and flood susceptibility. These areas generally follow the drainage network trend. Still, some, like most of Avenida Doutor Álvaro Camargos—especially its northeastern part near Avenida Vilarinho—and Rua Camões, a frequently flooded street, are particularly vulnerable. The basin's southeastern, northern, and northwestern regions showed more areas with low susceptibility, but high and low susceptibility points exist throughout the basin. This pattern is linked to the geomorphological structure of the digital terrain model, with the highest accumulation in the basin's channels and lower accumulation in the interfluves.

Flood maps, supported by the drainage master plan and established within the Drenurbs program, are essential tools for urban water management and foundational for disaster risk reduction actions in the municipality (Belo Horizonte, 2019). Geotechnologies enhance area characterization through land use and cover mapping, spatially explicit modeling, and statistical data integration (Macedo & Lima, 2022). However, more mapping studies are needed in densely urbanized basins like the Nado stream watershed, where risks concentrate around watercourses, and land use and floodplain occupation exacerbate flood events (Paul and Meyer, 2008).

Future studies should consider using distributed hydrological models or terrain descriptors, such as HAND (Rennó et al., 2008), which generally yield good results. We conducted the multicriteria analysis for green infrastructure implementation with a limited number of variables and in a more straightforward manner. Incorporating new relevant variables and more accurate criteria modeling would yield more comprehensive results. Additionally, future work should survey the population's perception, especially in Special Areas of Social Interest, regarding the potential implementation of these infrastructures.

Conclusions

The study conducted in the Nado stream watershed examined the relationship between urban floods, land use, and green infrastructure implementation as a solution to mitigate these events' impacts. Located in Belo Horizonte, the watershed exhibits a hydrological pattern affected by unplanned urbanization, resulting in recurrent floods and environmental damage. Analyzing flood susceptibility, environmental health, and social vulnerability was essential to identify priority areas for green infrastructure. The methodology, including the Analytic Hierarchy Process (AHP), enabled the careful selection of areas most suitable for interventions to reduce peak flow and retain stormwater.

The proposal for rain gardens in areas with hydrological flow accumulation proved to be an effective flood management strategy. In contrast, the multi-temporal land use analysis helped us understand the region's urbanization evolution. Integrated and sustainable approaches are crucial for addressing urban flood challenges, considering environmental, social, and infrastructural aspects. This study provides valuable insights for urban and environmental management, highlighting the relevance of green infrastructure as part of resilient and adaptive city solutions.

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