A Multi-Criteria Analysis (MCA) for optimizing Nature-Based Solution allocation in climate-resilient urban planning – A Brazilian study case

Une analyse multicritère (AMC) pour optimiser l'allocation de solutions fondées sur la nature dans la planification urbaine résiliente au climat – Une étude de cas brésilienne

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RÉSUMÉ

Cette étude développe une Analyse Multi-Critères (AMC) basée sur les SIG (Systèmes d'Information Géographique) capable d'intégrer six critères socio-environnementaux — tels que le ruissellement des eaux pluviales, la vulnérabilité sociale et la régulation thermique — afin de soutenir l'allocation équitable des Solutions Basées sur la Nature (SBN). Appliquée à une ville brésilienne de taille moyenne, l'approche démontre comment les outils d'aide à la décision spatiale peuvent révéler des décalages critiques entre la demande et l'offre de services écosystémiques dans les centres urbains denses. L'analyse identifie des zones avec une forte imperméabilisation des sols (CN > 90 dans 44 % du territoire) et des îlots de chaleur urbains intenses, qui coïncident avec un déficit sévère d'espaces verts (0,39 %). Pour répondre à ces problèmes, l'étude recommande de prioriser les SBN intégrées au bâti dans les quartiers densément construits, améliorant ainsi la résilience climatique et promouvant l'équité sociale grâce à une planification axée sur les données.

ABSTRACT

This study develops a GIS-based Multi-Criteria Analysis (MCA) capable of integrating six socio-environmental criteria—such as stormwater runoff, social vulnerability, and thermal regulation—to support the equitable allocation of Nature-Based Solutions (NBS). Applied to a medium-sized Brazilian city, the approach demonstrates how spatial decision-support tools can reveal critical mismatches between ecosystem service demand and supply in dense urban centers. The analysis identifies areas with high soil sealing (CN > 90 in 44% of the territory) and intense Urban Heat Islands, which coincide with a severe deficit of green spaces (0.39%). To address these issues, the study recommends prioritizing building-integrated NBS in densely built districts, thereby enhancing climate resilience and promoting social equity through data-driven planning.

KEYWORDS

Analytic Hierarchy Process (AHP), Ecosystem Services, Geographic Information Systems (GIS), Social Vulnerability, Urban Heat Island

1 INTRODUCTION

Urban areas worldwide are facing complex socio-environment challenges driven by rapid urbanization and climate change. The replacement of natural land cover with impervious surfaces has exacerbated issues such as urban heat island (UHI), increased surface runoff, and habitat fragmentation. In this context Nature-Based Solutions (NBS) – including green roofs, permeable pavements, and urban forests – have emerged as essential strategies for enhancing urban resilience (Apud et al., 2020; Sarabi et al., 2022). NBS provides multifunctional benefits, ranging from stormwater regulation and thermal comfort to social cohesion and biodiversity enhancement.

However, the implementation of NBS is often opportunistic rather than strategic, frequently prioritizing a single benefit (e.g., flood control, thermal regulation, etc) while neglecting others (Meerow; Newell, 2017). To maximize the provision of ecosystem services, urban planning requires integrated approaches that can evaluate trade-offs and identify optimal locations for intervention (Haase et al., 2014). Multi-Criteria Analysis (MCA) offers a robust decision-support framework for this purpose, allowing the integration of diverse spatial, environmental, and social variables (Bousquet et al., 2023; Goodspeed et al., 2022).

This study presents a spatial decision-support methodology applied to the city of Santa Maria, Rio Grande do Sul (Brazil). Located in a transition zone between the Atlantic Forest and Pampa biomes, Santa Maria faces significant climate risks, including intense rainfall events and heatwaves. These vulnerabilities were starkly highlighted during the extreme weather event that occurred in 2024, when unprecedented rainfall and widespread flooding exposed critical weaknesses in the city's drainage infrastructure and urban resilience (Collischonn et al., 2025). The objective of this research is to develop and apply an MCA framework to identify priority areas for NBS implementation, reconciling conflicting urban objectives such as flood mitigation, social equity, thermal regulation and climate adaptation.

2 METHODOLOGY

2.1 Study Area

This study proposes a GIS-based Multi-Criteria Analysis (MCA) to optimize Nature-Based Solutions (NBS) allocation in Santa Maria, Brazil. Situated in the Atlantic Forest-Pampa transition zone, the city faces a humid subtropical climate characterized by sharp seasonal contrasts, with winters dropping below freezing and summers frequently exceeding 30ºC (Ouriques., 2023).

Previous local studies have already confirmed the necessity and adaptability of NBS, particularly green roofs (Pimentel et al., 2023; Pimentel; Tassi, 2024)., green façades (Fensterseifer et al., 2022) in mitigating these specific thermal extremes By segmenting socio-environmental data at the census tract level, the framework integrates six criteria, such as stormwater runoff and social vulnerability, to identify priority intervention.

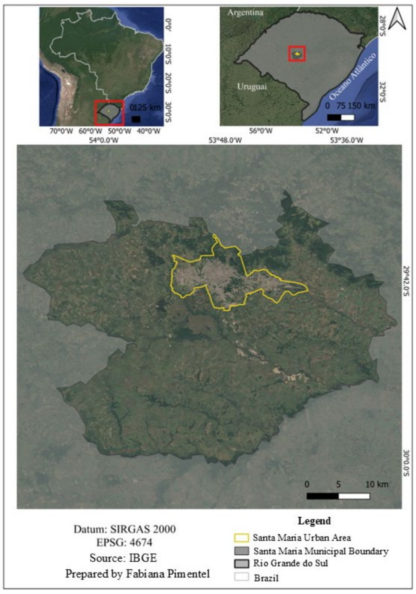


Figure 1 – Study area localization

2.2 Multi-Criteria Analysis Framework

The methodological approach involves a Geographic Information System (GIS)-based multi-criteria Analysis. The software QGIS version 3.28.13 was used to analyze the data. The framework is structured in four stages: (i) Criteria selection; (ii) Indicator definition and data acquisition; (iii) Normalization and weighting using the Analytic Hierarchy Process (AHP); and (iv) Spatial overlay and suitability mapping.

Six key criteria were selected to address the city's specific socio-environmental challenges:

i. **Stormwater Management:** To identify areas with high runoff potential, assessed using the *Curve Number* (CN) derived from MapBiomas land cover and pedological data (MapBiomas, 2023).

ii. **Social Vulnerability:** To prioritize interventions in at-risk communities, measured by the *Social Vulnerability Index* (SoVI) based on census data for residents under 5 and over 60 years old.

iii. **Social Cohesion:** To improve equitable access to green spaces, analyzed via proximity to public parks.

iv. **Temperature Regulation:** To mitigate Urban Heat Islands effects, utilizing *Land Surface Temperature* (LST) from Landsat imagery complemented by NDBI and NDVI indices

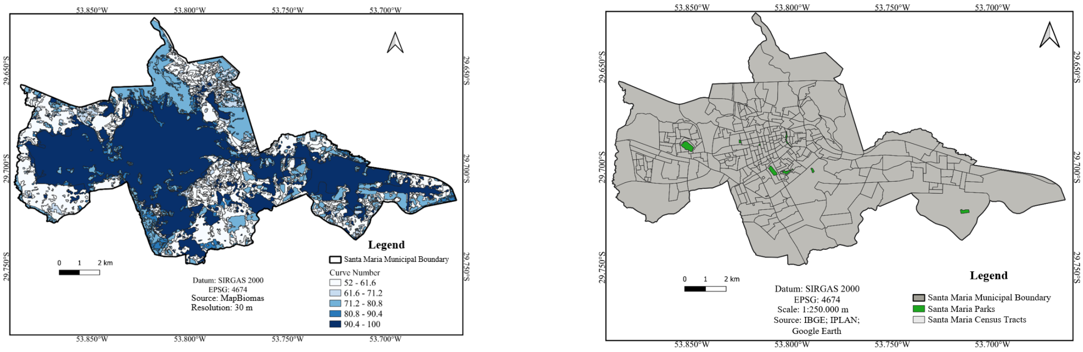
v. **Ecological Connectivity**: To reduce habitat fragmentation, evaluated through landscape metrics using the LecoS plugin

vi. **Air Pollution:** To buffer the impacts of vehicular emissions, estimated by the percentage of area within 200-meter buffers along major traffic arteries

Following the individual analysis of the six criteria, a normalization procedure was applied to standardize all distinct metrics to a common scale ranging from 0 to 100. To determine the relative importance of each variable, the Analytic Hierarchy Process (AHP) was employed. Through pairwise comparison matrices, specific weights were derived for each criterion, reflecting their priority within the local urban context. Subsequently, the normalized spatial layers were weighted and overlaid to generate a single composite value for each census tract. This integration allows for the ranking and identification of priority sectors for Nature-Based Solutions intervention based on their cumulative socio-environmental needs.

3 PRELIMINARY RESULTS AND DISCUSSION

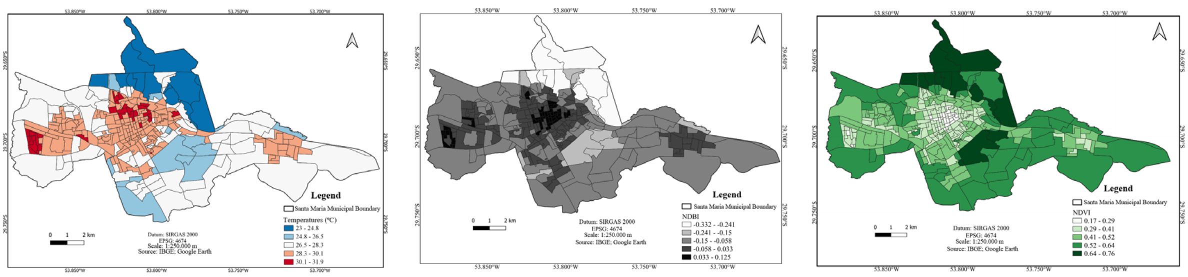
The spatial analysis of the Curve Number (CN), presented in Figure 2a, revealed critical levels of soil sealing. Approximately 44% of the urban area presented CN values above 90, indicating high impermeability and significant runoff generation potential. These areas are concentrated in the city center and in the neighborhood around it. In these areas the replacement of natural cover by concrete has drastically reduced the infiltration capacity of soil. The peripheral areas maintained CN values (52 – 61), reflecting a better hydrological conditions and performance face high amounts of precipitation. This physical condition is aggravated by a severe deficit in social cohesion infrastructure: public parks cover only 0.39% of the urban territory (~0.5 km²), as shown in Figure 2b. This result indicates that most of the population do not have immediate access to recreational green infrastructure.



(a) (b)

Figure 2 – Spatial distribution of (a) Curve Number and (b) Public parks locations in Santa Maria

The deficit of public parks correlates directly with thermal behavior of the city. The LST maps (Figure 3a) highlight distinct Urban Heat Islands (UHI) in the city center. The city center, highly built, presents temperatures up to 8ºC higher than vegetated areas. The NDBI values (Figure 3b) confirm this correlation between build density and thermal stress. Oppositely, areas with higher NDVI (Figure 3c), indicating preservation of vegetation, showed lower surface temperatures, reinforcing the cooling potential of vegetation.



(a) (b) (c)

Figure 3 – (a): LTS; (b) NDBI; (c) NDVI values

As can be seen in Figure 3a, Santa Maria core presents a few urban heat islands, with temperatures up to 31.9ºC, in contrast to peripheral zones where temperatures drop to approximately 23ºC. This thermal gradient is spatially consistent with the NDBI values (ranging from 0.033 to 0.125), which indicates dense impervious surfaces. Conversely, these same central sectors exhibit the lowest NDVI values (0.17 – 0.29), confirming that the lack of vegetation combined with high urbanization density is the primary driver of thermal stress in the city center.

4 CONCLUSION

This study highlights that the complexity of urban climate challenges necessitates the joint consideration of socio-environmental criteria to optimize resource allocation. As this research is currently under development, the spatial mapping for Social Vulnerability, Ecological Connectivity and Air Pollution will be finalized and integrated into the methodological framework. In future stages, the specific layers will be spatially overlaid with the physical indicators (stormwater and thermal regulation) already analyzed. This integration will produce a final definitive map that identifies and ranks the specific census tracts considered priority for the allocation of Nature-Based Solutions, ensuring a targeted and evidence-based approach to enhancing urban resilience in Santa Maria.

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