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Multicriteria Analysis for Selection of Sustainable Urban Drainage Techniques and Recommendation of their Spatial Allocation for the City of Itajubá – MG

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Análise Multicritério para Seleção de Técnicas Compensatórias de Drenagem Urbana e Recomendação de sua Distribuição Espacial para a Cidade de Itajubá – MG

RESUMO
Objetivo - Este trabalho avaliou a aplicabilidade da integração de métodos de análise multicritério com ferramentas de Sistema de Informação Geográfica para identificar locais adequados para implantação de medidas de drenagem sustentável
Metodologia – Foi utilizado o método de análise multicritério Analytical Hierarquic Problem (AHP) com o software QGIS para as técnicas biorretenção, bacia de detenção, pavimento permeável, reservatório individual e telhado verde/armazenador, aplicando para um estudo de caso na cidade de Itajubá – MG.
Originalidade/relevância – Ainda há uma dificuldade por parte dos tomadores de decisão em identificar os melhores locais para implantação de técnicas de drenagem urbana sustentável, que respeitem as suas limitações técnicas e espaciais.
Resultados – Observou-se que bacias de detenção são mais adequadas para áreas periféricas e reservatório individual e telhado verde/armazenador para áreas urbanas. A biorretenção não teve grande adequação em áreas urbanas, devido à restrição de espaço. O critério de maior peso em geral foi “aporte de sólidos”, exceto para o telhado verde/armazenador, que priorizou a população residente.
Contribuições sociais e ambientais - O presente trabalho fornece uma metodologia consolidada para criação de mapas que podem ser utilizados pelos tomadores de decisão para efetuar a escolha dos locais mais propícios para a aplicação de técnicas de drenagem sustentável, contribuindo para redução de alagamentos e poluição difusa em centros urbanos.

Palavras-Chave: Drenagem sustentável. Desenvolvimento de baixo impacto. AHP.

Multicriteria Analysis for Selection of Sustainable Urban Drainage Techniques and Recommendation of their Spatial Allocation for the City of Itajubá – MG

ABSTRACT
Objective - This study evaluated the applicability of the integration of multicriteria analysis methods with Geographic Information System tools to identify suitable locations for the implementation of sustainable drainage measures.
Methodology – The multicriteria analysis method known as Analytical Hierarchical Process (AHP) was employed alongside QGIS software to evaluate bioretention, detention basins, permeable pavements, individual reservoirs, and green/storage roofs in a case study conducted in the city of Itajubá, MG.
Originality/relevance – Decision-makers continue to face challenges in identifying optimal locations for implementing sustainable urban drainage techniques that account for technical and spatial constraints, posing a persistent barrier to their widespread adoption.
Results – It was observed that detention basins are more suitable for peripheral areas and individual reservoirs and green/storage roofs systems for urban areas. Bioretention was not very suitable for urban areas, due to space restrictions. The most influential criterion overall was “solid input”, except for the green/storage roof system, which prioritized the resident population.
Social and environmental contributions - This work provides a consolidated methodology for creating maps that can be used by decision makers to choose the most suitable locations for the application of sustainable urban drainage techniques, contributing to the reduction of flooding and diffuse pollution in urban centers.

Keywords: Sustainable urban drainage. Low-impact development. AHP.

Análisis Multicriterio para la Selección de Técnicas de Drenaje Urbano Sostenible y Recomendación de su Distribución Espacial para la Ciudad de Itajubá – MG

RESUMEN
Objetivo - Este trabajo evaluó la aplicabilidad de integrar métodos de análisis multicriterio con herramientas del Sistema de Información Geográfica para identificar ubicaciones adecuadas para implementar medidas de drenaje sostenible.
Metodología – Se utilizó el método de análisis multicriterio del Analytical Hierarchical Problem (AHP) con el software QGIS para técnicas de biorretención, cuenca de detención, pavimento permeable, depósito individual y techo verde, aplicándolo a un estudio de caso en la ciudad de Itajubá – MG.

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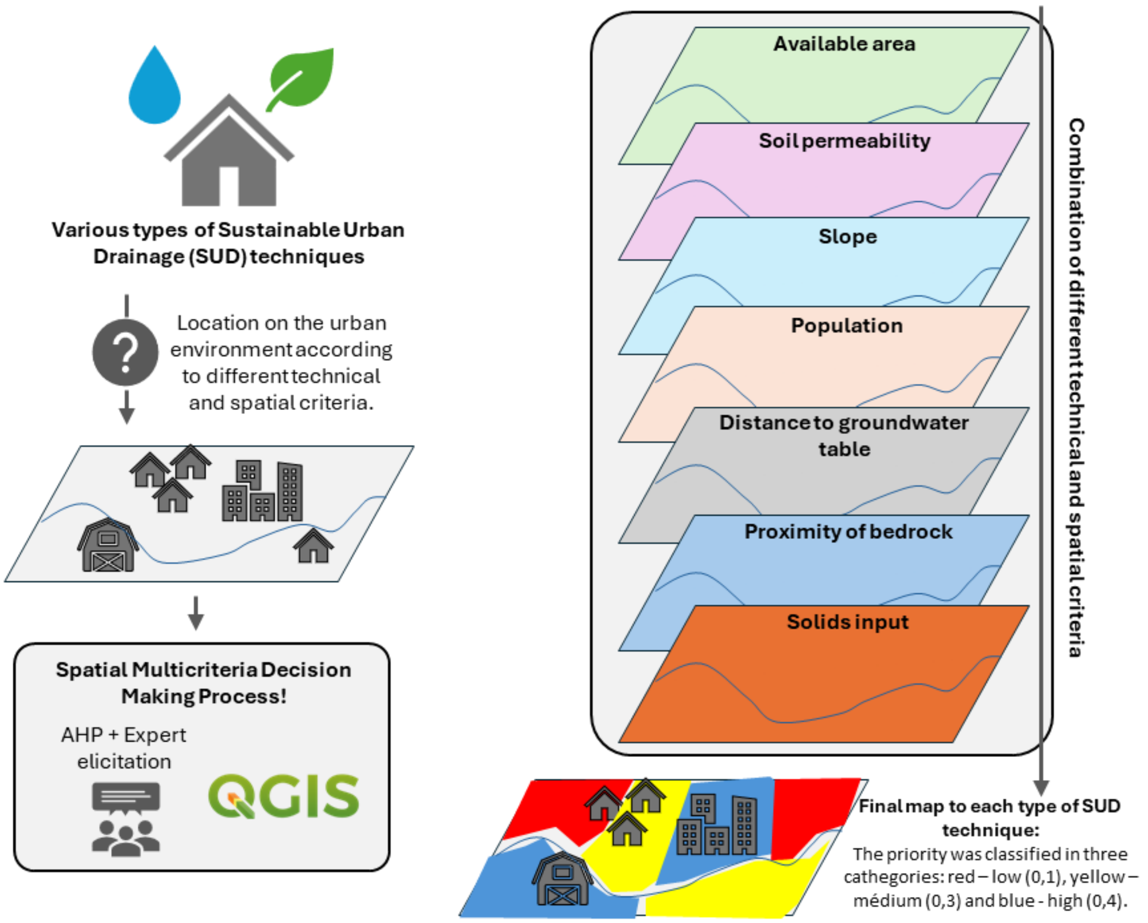
Originalidad/relevancia – Todavía existe dificultad por parte de los tomadores de decisiones para identificar los mejores lugares para implementar técnicas de drenaje urbano sostenible, que respeten sus limitaciones técnicas y espaciales, lo que sigue siendo una barrera para su aplicación a gran escala.
Resultados – Se observó que los cuenca de detención son más adecuados para áreas periféricas y los depósitos individuales y techos verdes para áreas urbanas. La biorretención no era particularmente adecuada en áreas urbanas debido a restricciones de espacio. El criterio más importante en general fue el de “insumos sólidos”, excepto para el techo verde, que priorizó a la población residente.
Contribuciones sociales y ambientales - Este trabajo proporciona una metodología consolidada para la creación de mapas que pueden ser utilizados por los tomadores de decisiones para elegir los lugares más adecuados para la aplicación de técnicas de drenaje sostenible, contribuyendo a la reducción de inundaciones y contaminación difusa en los centros urbanos.

Palabras clave: Drenaje urbano sostenible. Desarrollo de bajo impacto. AHP.

GRAPHICAL ABSTRACT



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1 INTRODUCTION

The principles of hygienism for water drainage recommended the rapid evacuation of urban areas through conduits, preferably underground, using gravity (Baptista et al., 2015). This approach made it possible to prevent diseases and improve traffic flow. Thus, classic urban drainage systems were created, which consist of micro-drainage devices that transport water from streets through gutters. When the flow capacity is exceeded, catch basins and typically buried conduits are used to direct water toward macro-drainage systems, such as open channels or galleries.. These systems may also include stormwater drains, energy dissipators, and pumping stations. However, the application of this system in isolation, combined with the ever-growing urban perimeter, is insufficient to address some of the challenges in the urban hydrological cycle, such as flooding, poor water quality caused by the runoff of diffuse pollution (Miguez et al., 2016), and may even worsen these problems due to the increased hydraulic efficiency of the catchment.

In response to the aforementioned challenges, alternative, compensatory, or Sustainable Urban Drainage (SUD) technologies were developed. These approaches aim to mitigate the effects of urbanization on hydrological resources while offering benefits for environmental preservation and quality of life. (Macedo et al., 2022; El Hatab et al., 2020). According to Baptista et al. (2015), this system is a solution to some of the problems brought by the classical system, as it considers the impacts of urbanization in a comprehensive way, using the catchment as the basis for study. Compensation is achieved by controlling the production of excess runoff due to impervious surfaces and preventing rapid downstream transfer. This can be done through combinations of technological solutions that facilitate the infiltration of rainwater and increase transit time with temporary storage.

Sustainable Urban Drainage techniques can be classified as structural or non-structural (Baptista et al., 2015; Miguez et al., 2016; Canholi, 2014). The first includes infrastructures applied to increase infiltration and evapotranspiration, detain water, and treat it. These can be categorized as large-scale basins (detention basins, bioretention), linear works (trenches, ditches, and permeable pavements), or point works (infiltration wells, green roofs, and storage units, as well as techniques adapted to specific parcels, such as individual reservoirs and small-scale bioretention) (Baptista et al., 2015). Non-structural measures are related to environmental education, rational land use, legislation, and planning (Canholi, 2014).

Regarding structural measures, there are various technical restrictions for each type of technique, limiting the locations where they can be applied within the urban area. For example, infiltration measures (such as bioretention and permeable pavements) are limited by the soil's infiltration capacity and the distance to groundwater. Linear works (such as trenches and permeable pavements) have significant limitations regarding terrain slope (Baptista et al., 2015). Therefore, a more in-depth study of existing techniques is necessary to select the most suitable one for specific application sites.

In this context, Karami et al. (2022) developed a multi-objective approach to choose the best combination of SUD systems, aiming to minimize costs, flood risk, and diffuse pollution, in association with the SWMM model. Nazari et al. (2023) combined multicriteria decision models with two hydrological models that allow for the inclusion of sustainable drainage

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measures: SWMM and SUSTAIN. However, there are currently various hydrological models to explore the different applications and objectives associated with the implementation of these techniques. The application and selection of the models can be complex, posing a challenge in the decision-making process (El Hatab et al., 2020). Therefore, simpler methodologies to facilitate the decision-making process have been developed.

Since different structural compensatory techniques can be applied within the urban territory, with each technique having its own criteria and technical constraints, the choice of which technique to apply and in which location can be understood as a multicriteria decision problem, applied to a spatial scale. Examples of multicriteria methods for this purpose have been developed in Spain and Iran for spatial allocation (Suárez-Inclán et al., 2022; Saadat Foomani & Malekmohammadi, 2020), in Colombia for maximizing ecosystem services (Uribe-Aguado et al., 2022), and in China for various complementary objectives (Yang & Zhang, 2021). It is expected that structured multicriteria analysis methodologies can be applied in conjunction with Geographic Information Systems (GIS) methods to aid in this decision-making process in a more rational, objective, and optimized manner (El Hatab, 2020; Faroozesh et al., 2022; Amoushahi et al., 2022).

Thus, the aim of this study is to evaluate the applicability of the multicriteria analysis method AHP combined with the QGIS software to identify suitable locations for the implementation of five sustainable drainage measures: bioretention; detention basin; permeable pavement; individual reservoir; and green/storage roof. For this, the municipality of Itajubá, in Minas Gerais, was used as a case study, due to its geographical characteristics of significant variations in slope, soil, and hydrology, which pose a challenge for applying sustainable urban drainage techniques.

2 METHODOLOGY

2.1 Study area

The city of Itajubá is located in the southern region of Minas Gerais, with a southern latitude and western longitude of Greenwich, respectively, 22°30'30" and 45°27'20" (PREFEITURA DE ITAJUBÁ, 2023) (Figure 1). According to the IBGE (2023), the municipality has an area of 294.8 km² and a population density of 315.7 inhabitants/km², with a population of 93,073 based on 2022 data, with approximately 91% living in urban areas (Gonçalves, 2019). The average annual rainfall is 1,897 mm, with the highest historical precipitation concentrated in January (average of 396 mm and average temperatures of 22.7 °C), and the lowest historical precipitation usually occurring in August (average of 36 mm and average temperatures of 18.7 °C) (INMET, 2021).

The drainage works in this urban basin are of great importance due to the history of flooding and inundation of the Sapucaí River in the city of Itajubá (e.g., the 2000 flood, which affected approximately 70% of the urban area of the municipality – Vianna et al., 2001; Silva and Barbosa, 2007).

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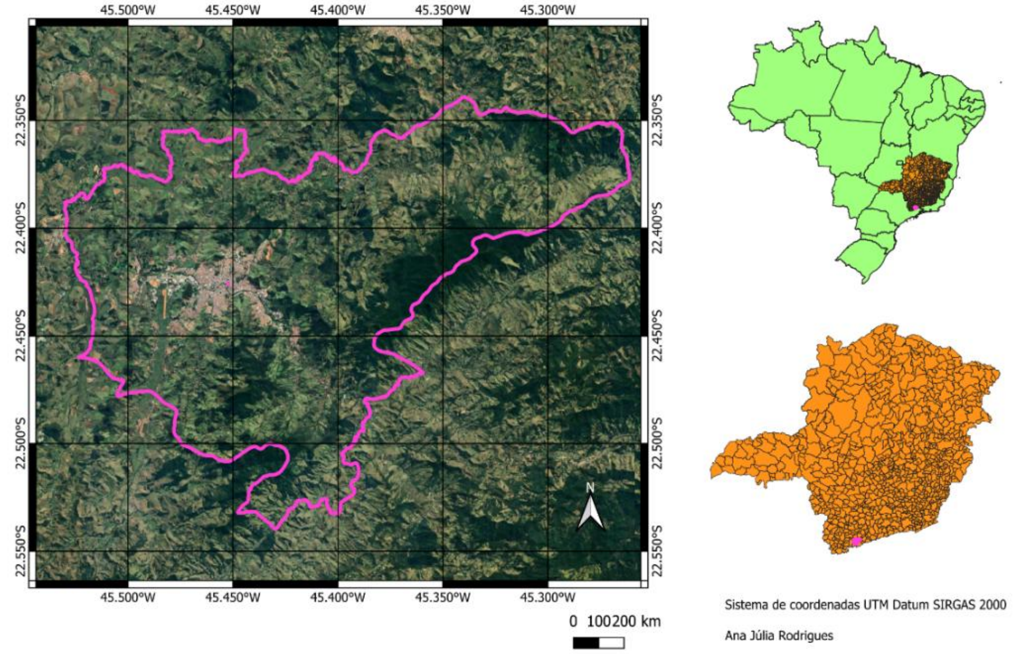
Figure 1 – Location of the Study Area, Itajubá – MG



Source: Authors

2.2 Multicriteria Decision-Making: AHP Method

Since the process of allocating different types of SUD techniques within a municipality's territory is a decision-making process that must meet multiple technical criteria, this study structured a multicriteria analysis problem using the Analytical Hierarchical Process (AHP) method integrated with GIS systems. (El Hattab, 2020; Faroozesh et al., 2022; Amoushahi et al., 2022). The AHP method has been widely used as a tool for multicriteria analysis in SUD due to its ease of implementation, such as in cases for selecting bioretention in urban subdivisions (Tameh et al., 2024) and green and blue infrastructures with better cost-benefit (Tansar et al., 2023).

Only structural SUD were evaluated, namely: bioretention, detention basins, permeable pavements, individual reservoirs, and green/storage roofs. The method was applied within the boundaries of Itajubá due to the city's history with flooding and the technical challenges it presents in terms of relief, soil types, and land use and occupation.

The hierarchical structure of the problem is presented in Figure 2. The chosen criteria were: available area, soil permeability, terrain slope, resident population, groundwater level or distance from creeks, proximity to bedrock, solid input, and land use and occupation type, with the latter being limited by the options: rooftops, sidewalks, local roads and parking lots, highways, and open areas.

To construct the pairwise comparison matrices for the criteria, an elicitation process was conducted with experts in urban drainage and hydrology. The aim of this methodological step was to list the weights to be assigned to each of the mentioned criteria and to each of the selected structural SUD technique. The questions asked to the experts are presented in Chart 1. It is worth noting the scale of weights used in this study, ranging from 1 to 5. In the original

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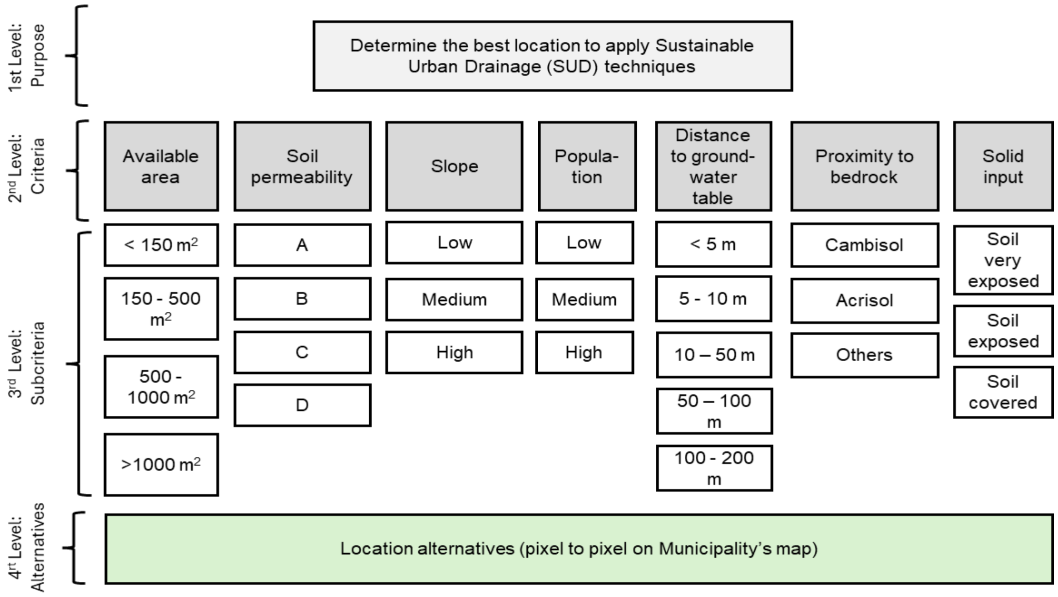
application of the method, Saaty (1991) proposes a fundamental scale with weights ranging from 1 to 9, understanding that there is a psychological limit in which humans can judge accurately a maximum of 7± 2 points. However, once the classes of the subcriteria were defined and it was observed that there was no variation beyond 5 classes, this study opted to limit the scale to a maximum of 5 to allow a better judgment by the experts.

Figure 2 – Hierarchical structure of the AHP method for selecting location alternatives for SUD techniques



Source: Authors

Chart 1 - Survey conducted with experts to define weights for the criteria outlined in the AHP method and evaluation scale

Question: What is the importance level of the following criterion for restricting the application of the respective SUD technique?	Evaluation Scale
Regarding the available surface area for applying the techniques.	Less important (can be applied in small areas) = weight 1 Very important (requires large areas) = weight 5
Regarding the permeability of the soil in the implantation area.	Less important (large soil permeability is not necessary) = weight 1 Very important (high permeability soils are necessary) = weight 5
Regarding the slope of the site in the implantation area.	Less important (not affected by high slopes) = weight 1 Very important (flat areas are necessary) = weight 5
Regarding the resident population in the implantation area.	Less important (not affected by the number of residents) = weight 1 Very important (affected by the number of residents) = weight 5
Regarding the groundwater level or the distance from watercourses in the implantation area.	Less important (not affected by water level or watercourse location/groundwater depth) = weight 1 Very important (should be located far from watercourses – areas with deeper groundwater) = weight 5
Regarding proximity to bedrock in the implantation area.	Less important (no problem being near bedrock) = weight 1 Very important (should not be near bedrock) = weight 5
Regarding the solid input in the implantation area.	Less important (no problem with solid waste accumulation) = weight 1 Very important (solid waste significantly affects performance) = weight 5

Source: Authors

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2.3 Thematic Maps of the Municipality of Itajubá

Thematic maps were created for each of the criteria listed in Figure 2, using the data presented in Chart 2. After the final definition of the relative priorities of each subcriterion, they were reclassified and combined to calculate the final priority of each alternative.

Chart 2 – Data used for evaluating each criterion and subcriterion in the AHP method

Criteria	Data used	Database	Scale	Year
Available surface area	Land use and occupation map	CBERS 04A	2x2m	2023
Soil permeability	Soil map and reclassification by hydrological group	Soil map Gonçalves (2021)	1:50,000	2021
Slope	Digital Elevation Model (DEM)	Topodata (SRTM treated)	30x30m	2020
Resident population	Total population by census sector	IBGE	Census Sector	2010
Groundwater level or distance from watercourses	DEM for basin and hydrological network delimitation	Topodata (SRTM treated)	30x30m	2020
Bedrock	Soil map and reclassification by soil type	Soil map Gonçalves (2021)	1:50,000	2021
Solid input	Land use and occupation map for exposed soil	CBERS 04A	2x2m	2023

Source: Authors

2.3.1 Soil Map

The soil map was used for the soil permeability criterion, with data sourced from the work of Gonçalves (2019). In the mentioned work, soil classes for the municipality of Itajubá were mapped based on the Soil Digital Model (SDM) using the Brazilian Soil Classification System (SiBCS), which classified soils into ten distinct categories. For this study, these classes were consolidated into four categories, grouped according to hydrological groups, based on the SCS-CN method. The correspondence of hydrological groups for each soil class was made based on the work of Genovez et al. (2005), resulting in the reclassification presented in Chart 3. It is noteworthy that no soils from group C were found.

Another criterion assessed based on the soil map was proximity to bedrock. For this, a reclassification into three categories of soils (Cambisol, Acrisol, and others) was made. Cambisol was considered to have high proximity, as they are newer soils with shallower depth; Acrisol was classified as medium proximity, as they are intermediate soils, and other soils, mainly Latossol, were classified as low proximity due to their deeper nature (Van Lier, 2010).

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Chart 3 – Reclassification of soils according to hydrological groups

Soil class	Hydrological group
Yellow Latossol (gentle relief); Red-Yellow Latossol (undulating relief); Red Latossol (flat/smooth undulating relief); Red-Yellow Latossol (gentle undulating relief)	Type A
Red-Yellow Acrisol (strong undulating relief); Red-Yellow Acrisol (undulating relief); Red Acrisol (undulating relief); Red Acrisol (strong undulating relief)	Type B
Gleissol (flat relief); Cambisol (mountainous relief)	Type D

Source: Adapted from Gonçalves (2019)

2.3.2 Slope Map

To construct the slope map, the Digital Elevation Model (DEM) obtained through the TOPODATA project created by the National Institute for Space Research (INPE, 2008) was used. The acquired DEM allows the extraction of slope information. The slope must be expressed as a percentage, according to EMBRAPA criteria (Hott et al., 2006). For each of these intervals, class values from 1 to 6 were defined, as shown in Chart 4, to facilitate visualization. After reviewing the classification, it was decided to implement a simplified classification by grouping the six classes into three categories: low, medium, and high, as described in the third column of Chart 4.

Chart 4 – Reclassification of slopes according to EMBRAPA

Class according to EMBRAPA	Initial EMBRAPA Classes	Reclassification
Flat terrain = 0 to 3%	1	3 - Low
Gently undulating = 3 to 8%	2	2 - Medium
Undulating = 8 to 20%	3	2 - Medium
Strongly undulating = 20 to 45%	4	1 - High
Mountainous = 45 to 75%	5	1 - High
Strongly mountainous > 75%	6	1 - High

Source: Hott *et al* (2006)

2.3.4 Hydrological Map

Since no data on groundwater and the depth of the groundwater table were found in open data for the city of Itajubá, the evaluation of this criteria was made considering the influence of rivers on the groundwater table based on their horizontal distance. Thus, based on the previously acquired DEM and the river data for Itajubá, as described in the dissertation by Gonçalves (2019), it was possible to analyze the influence of these rivers within a defined distance range. The river layer was used as input to create buffers with specific influence distances of 5, 10, 20, 50, 100, and 200 meters. A 300-meter buffer was included to represent values that exceed the chosen distances, allowing for a more comprehensive assessment of the interference zones between areas affected by the rivers.

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2.3.5 Resident Population Map

This map provides a detailed view of the population distribution in the municipality, revealing how different areas may impact the technical analyses performed. Using census sector data available on the IBGE (2023) website for the year 2010, the population was classified into different categories: rural areas, villages, and hamlets (assigned value 1); low-density urban areas (assigned value 2); and high-density urban areas (assigned value 3).

2.3.6 Land Use and Occupation Map and Available Total Area

The land use and occupation map was created to identify locations where each type of technique could be applied, as there are restrictions regarding where each can be located. For example, green roofs should be located on rooftops, permeable pavements on streets or walkways with reduced traffic speeds, and bioretention areas on vacant land. Therefore, a classification of land use and occupation was necessary based on the characteristics suitable for each technique. The defined classes included: low vegetation (value 1), exposed soil (value 2), streets (value 3), rooftops (value 4), forests (value 5), and water (assigned value 0 to avoid confusion with other classes, as water is not applicable for the techniques). After classification, the water class was assigned a value of 0.

The procedure used for generating the map was supervised classification. For this analysis, images from the CBERS 04A satellite, with RGB bands combined with the panchromatic (PAN) band, with a resolution of 2 meters for the area of Itajubá in 2023, were used. The chosen supervised classification method was the Orfeo Toolbox (OTB), available in QGIS. Finally, to evaluate the accuracy of the final classification data, the Kappa Index was calculated, resulting in a value of 0.9117, indicating good agreement. These maps were used to analyze solid inputs, by verifying the amount of exposed soil, and to assess the available area for each technique.

3 RESULTS AND DISCUSSIONS

The results will be presented for the thematic maps obtained for the municipality of Itajubá, the weighting survey based on expert elicitation, and finally, the final maps of the best locations for the different SUD techniques.

3.1 Thematic Maps

Based on the results from Gonçalves (2019), in Figure 3a, it is possible to identify that the following soil types in the city of Itajubá: Latossol, Acrisol, Cambisol, and Gleissol, with a predominance of Red Acrisol. These soils are typical of rugged and mountainous terrain, characteristics observable in the municipality (Figure 3b). However, the region with the highest concentration of urban areas and buildings is located in the western part of the municipality, in the floodplain areas of the Sapucaí River, where the predominant soil type is Gleissol, which is compatible with its relatively flatter terrain, as shown in the map in Figure 3b.

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Regarding the predominant land use and occupation in the municipality, the classification was carried out to determine the areas available for the implementation of the techniques. Thus, categories such as rooftops, streets, and ground vegetation were included to better discretize the urban area. Rooftop areas allow for the implementation of green roofs and lot reservoirs, street areas enable the installation of permeable pavements, and ground vegetation areas facilitate the implementation of bioretention systems and detention basins.

Note that land use and occupation in the municipality (Figure 3c) is predominantly characterized by low vegetation, rooftops, and forests. The adopted classification allowed for a clear differentiation in the more urbanized area of the municipality, providing a good level of detail for verifying the application of the techniques. Furthermore, several areas of exposed soil can be observed in the urban expansion zones (usually near areas with low vegetation and rooftops), indicating a lack of soil conservation management in the municipality's urban policy.

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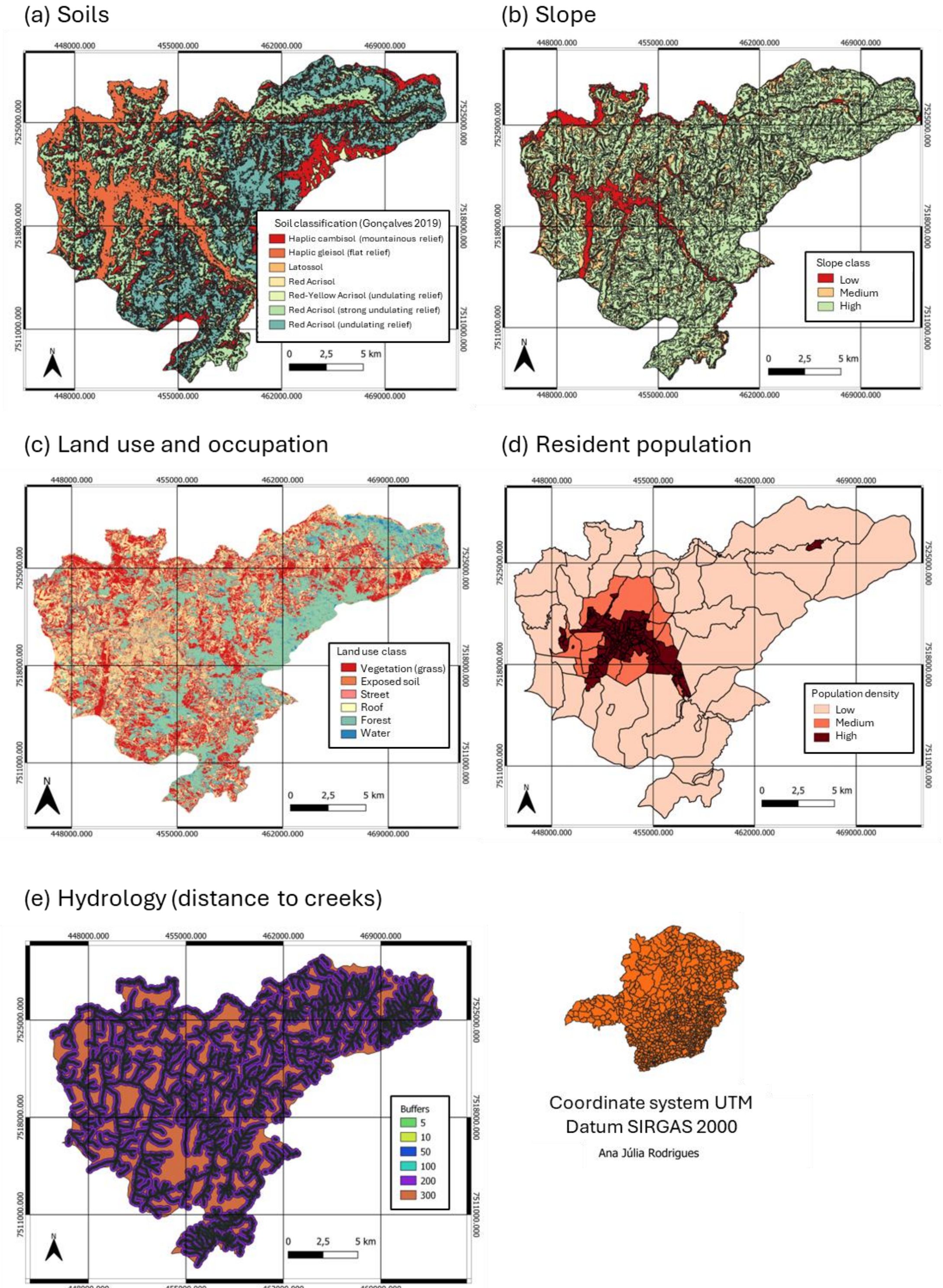
Figure 3 – Final thematic maps for each criterion listed



Source: Authors

The population (Figure 3d), an important criterion for studying occupied urban areas, is predominantly concentrated in the central region of the municipality, while the more peripheral areas exhibit a rural pattern and lower population density. It is noticeable that the highest population density is also found along the main rivers and creeks of the municipality.

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This is relevant, as over the years, several flooding events have been reported in these areas, attributed to inadequate drainage capacity (both natural and artificial) for the current volume of stormwater. This drainage insufficiency contributes to river overflows during high-water periods, impacting adjacent buildings and causing significant damage to the population (Machado et al., 2005).

Finally, in Figure 3e, the delineation of distance buffers from the rivers and creeks in the municipality is presented to allow an implicit evaluation of the distance from the groundwater table, as this information was not found in open databases for the municipality.

3.2 Weight assignment for criteria through expert elicitation

The survey conducted with researchers and experts in urban drainage and related fields received a total of 19 responses. It was possible to observe variations in the response profiles regarding the weights assigned to each criterion for each technique (Figure 4).

In general, the population criterion showed the most significant variation in the assigned weights, particularly for the techniques of bioretention, individual reservoir, and green roofs. For the latter two, population was also the criteria with the highest average weight, with values of 2.8 and 2.4, respectively. For permeable pavement and bioretention, this criterion had the lowest average weight, with values of 2.4 and 2.3, respectively. Despite the large variation in weight assignments, the average values were similar across all techniques, except for the detention basin, which had an average weight of 3.3. The detention basin stands out with a higher weight for this criterion because it can handle much larger volumes of surface runoff compared to the other techniques, making it more applicable for larger populations.

When evaluating the techniques individually, it is observed that green roofs and individual reservoirs had the lowest average values assigned for all criteria, with values all below three. This is explained by their flexibility in application and independence from physical environmental factors, such as soil permeability, proximity to bedrock, or groundwater table level, as these techniques are generally placed above the ground level.

The green roof showed an average greater than two, only for the population. The individual reservoir, on the other hand, showed higher average weights for the criteria of surface area, population, groundwater table level, and solid input. This difference from the green roofs is due to the fact that reservoirs require more surface area for construction or placement, can be buried (which means the groundwater table level may affect their placement), and require higher water quality, with fewer solids, especially if coupled with water reuse systems.

As for bioretention and permeable pavements, these were the two techniques with the highest average weights assigned for all criteria, in general. This shows the greater difficulty in applying these techniques, as they have more spatial allocation restrictions. These restrictions are mainly related to their infiltration mechanisms, meaning that areas with low soil permeability, high slope, and proximity to bedrock will have reduced efficiency, both in terms of surface runoff retention/detention and water quality improvement. Moreover, since they are infiltration-based techniques, solid input, especially fine solids, contributes to the clogging of the system, reducing its efficiency over time or requiring more frequent maintenance intervals, making them more costly. On the other hand, as these techniques are often applied on a lot

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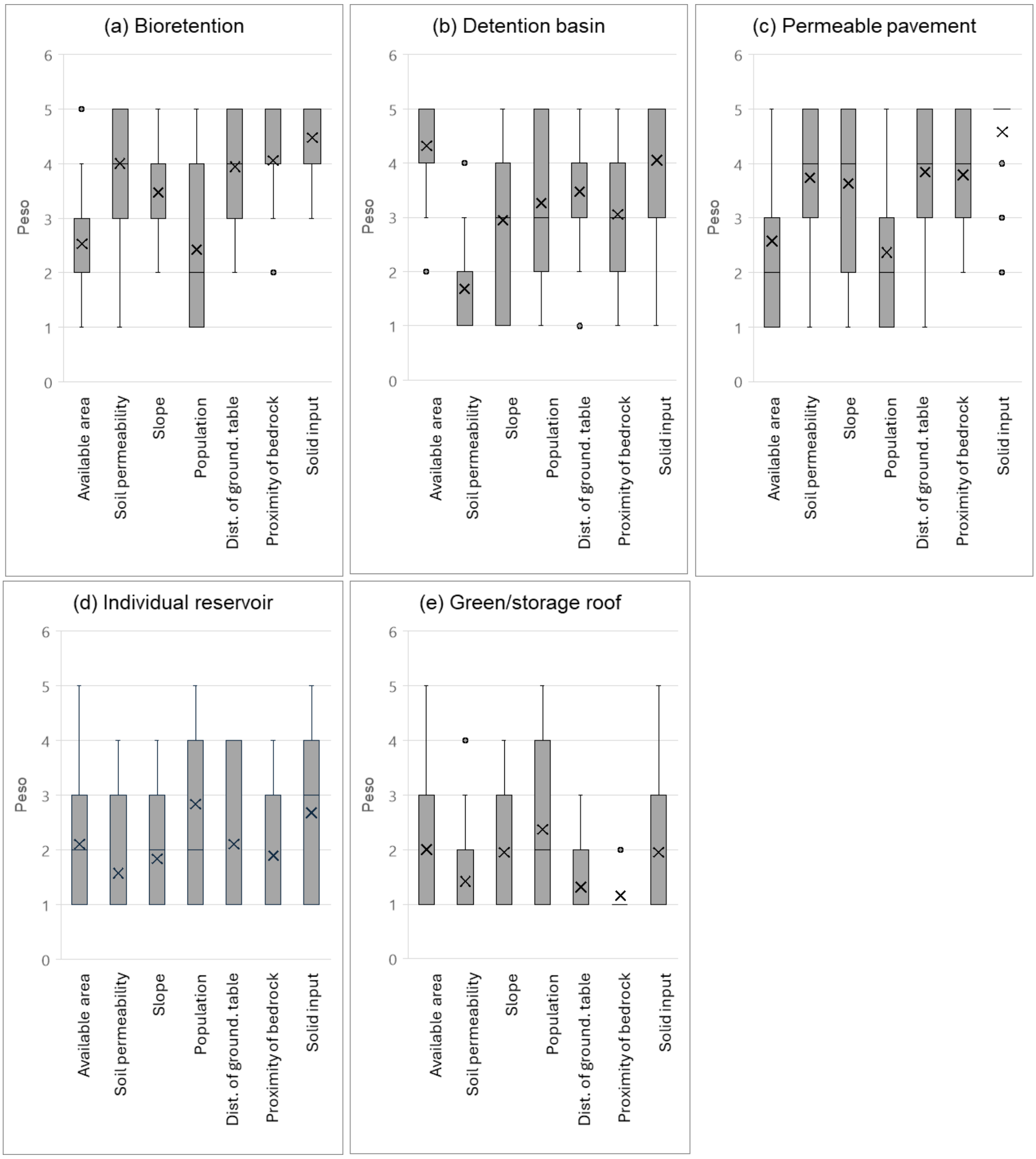
scale (source control) or street scale (by block), they do not have significant limitations regarding surface area or population.

Figure 4 – Statistical distribution of the weights obtained from experts for the different subcriteria to be used in the AHP method



Source: Authors

Finally, regarding detention basins, the main limitation is the availability of space for constructing these techniques, as they are applied on a neighborhood or basin scale. This is reflected in the higher average weights for the criteria of surface area and population. Solid input also received high average weights (the second highest for this technique), as sediments accumulate in detention basins, leading to a loss of effective volume and efficiency, requiring

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more frequent maintenance. Since detention basins do not have infiltration processes, the soil permeability criterion received a low average weight.

The variability in the weight assignments by experts reflects the different perceptions they have regarding technical limitations and, mainly, the flexibility of their applications for different conditions. Green roofs and individual reservoirs were shown to be the most flexible, while bioretention and permeable pavements were less flexible. Moreover, the assignment of average weights reflects the importance of each criterion, based on the principle of operation of each technique. Based on this, the construction of the comparison matrices for the criteria proceeded using the average weights obtained from the survey.

3.3. Best Locations for SUD Techniques in Urban Space

Based on the results of weight attribution by experts, comparison matrices were used to apply the AHP method, resulting in the best locations for the implementation of compensatory urban drainage techniques in the municipality of Itajubá. Table 1 presents the relative priorities for each technique's criteria, while Figure 5 shows the final maps indicating the most appropriate areas for the implementation of each technique, with three priority classes: red - low (0.1), yellow - medium (0.3), and blue - high (0.4). Areas marked in white on the maps indicate locations unsuitable for the assessed technique.

Figure 5 presents the final maps showing the locations for the various SUD techniques in the city of Itajubá. The solid input contribution criteria had the highest weight in the evaluation, making it a highly determining factor. In contrast, for the green roof/storage technique, the weights were equal across all criteria except for the resident population, where population density was the most influential factor. This indicates that areas with higher population density are more suitable for the implementation of this technique. This factor can be explained by the requirement for buildings to implement green roofs, as well as the limited space available in densely built-up areas for other SUD techniques.

The maps that presented the most defined locations for implementing the techniques were those for detention basins, individual reservoirs, and green roofs. The detention basin map (Figure 5a) stands out by indicating preferred locations in the peripheral areas of the municipality (peri urban and rural zones), while the maps for individual reservoirs (Figure 5d) and green roofs (Figure 5e) are more suitable for areas with higher resident population density, as expected due to the higher weight given to this criterion.

However, for the bioretention (Figure 5a) and permeable pavements (Figure 5c) techniques, the maps did not exhibit the same clear pattern. The bioretention map, specifically, is not recommended for areas of high population density, which could be related to the lower availability of free space. As for the permeable pavements, this map revealed the fewest suitable locations for implementation, as the combination of selected criteria did not highlight well-defined areas. This result can be attributed to the presence of many regions in the city of Itajubá with high solid load, steep slopes, and a shallow groundwater table, all of which are important restrictions for the application of this technique.

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Table 1 – Final Relative Priority for Each Technique's Criteria

	Available area	Soil permeabi-lity	Slope	Resident population	Ground-water table distance	Proximity to bedrock	Solid input
Bioretention	0,08	0,17	0,13	0,08	0,17	0,17	0,21
Detention basin	0,21	0,04	0,13	0,13	0,17	0,13	0,21
Permeable pavement	0,08	0,16	0,08	0,16	0,16	0,16	0,20
Individual reservoir	0,17	0,08	0,17	0,17	0,08	0,08	0,25
Green/storage roof	0,13	0,13	0,13	0,25	0,13	0,13	0,13

Source: Authors

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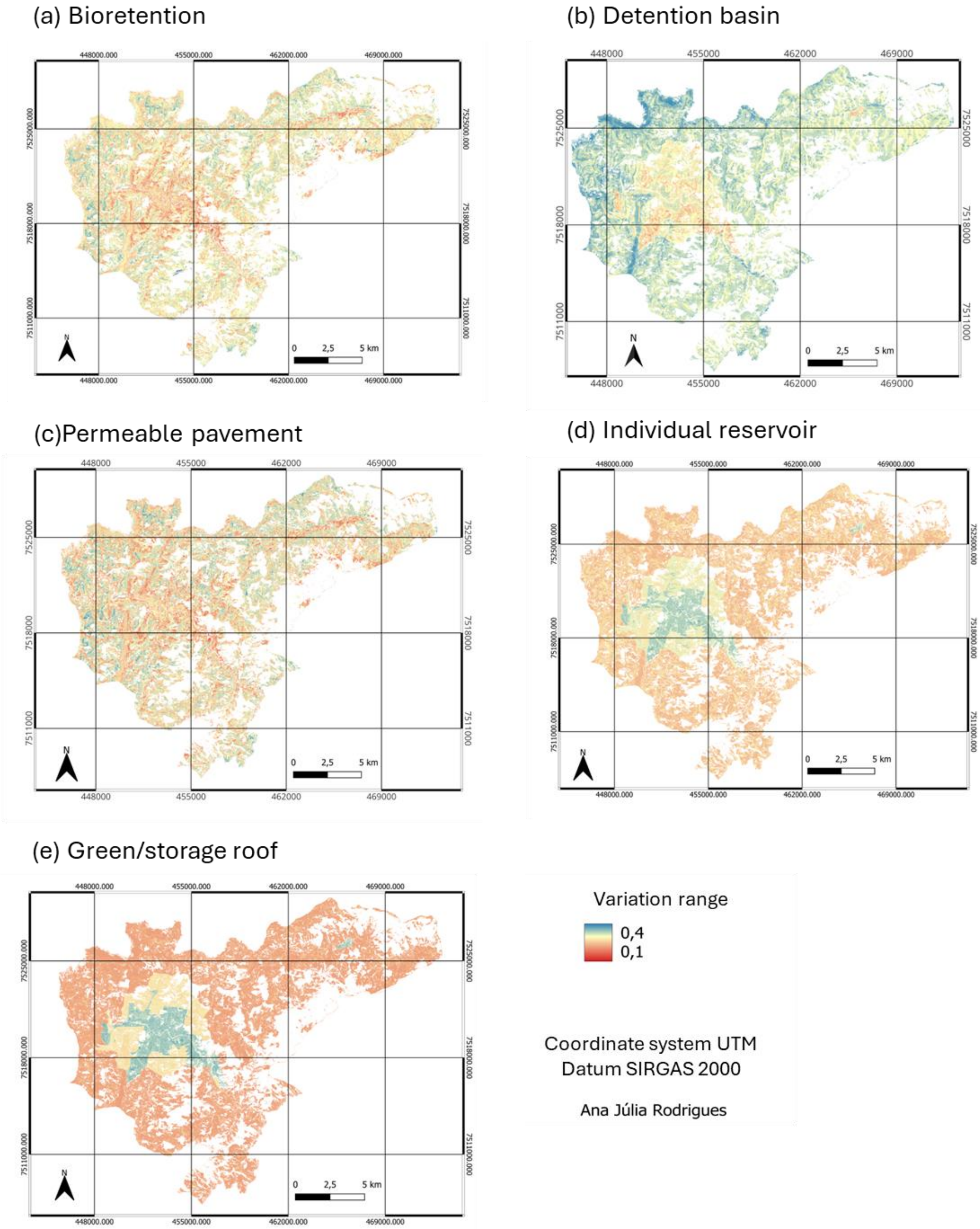
Figure 5 - Final locations maps for the various SUD techniques in the city of Itajubá



Source: Authors

For a more detailed view of the technique locations within the urban space, Figure 6 presents a zoom-in on two different areas of the city of Itajubá. Section 1 is located near the Sapucaí River in a consolidated urban area, while Section 2 is located at the top of a hill, in a new housing development, representing an area in the urban expansion zone.

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In Figure 6 – Section 1, it is observed that both green roofs and individual reservoirs can be implemented together and cover the entirety of existing buildings. These are recommended for consolidated areas with higher resident populations, as they do not have significant space restrictions and are dependent on residential contexts. For permeable pavements, despite Section 1 being a flat area, their implementation is restricted due to proximity to the river and, therefore, the shallow groundwater table, limiting infiltration capacity and their application. Thus, their implementation is suggested mainly on the pavements of blocks farther from the river. For the bioretention technique, similar limitations regarding the groundwater table and infiltration capacity are noted. However, since this technique requires more open space than permeable pavements, its application is even more limited.

For Section 2 (Figure 6), bioretention and permeable pavements are suggested for multiple locations with grassy vegetation and established streets, as the area does not present limitations regarding water infiltration. These techniques can be widely used to help retain and redirect stormwater, promoting its reintegration into the groundwater in a cleaner form. The detention basin technique also appears as a suggestion for a less urbanized, downstream area of the municipality. Lastly, green roofs do not appear as a suggestion because the land use and occupation classification did not identify significant numbers of roofs in the area, and it has a medium population density. Despite both green roofs and individual reservoirs not having many highly suitable areas in the current context (as in Section 1), it is recommended that they be considered in the construction of new buildings, incorporated from the design and construction phases.

In Section 2, being a less urbanized area, the availability of space facilitates the application of these structures in a more diverse and combined way. It is recommended that public policies be put in place to regulate urban space and promote their use in housing developments located in urban expansion zones (e.g., green property tax, drainage and stormwater management plans, urban master plan).

Finally, these maps can serve as a support tool for further analysis and urban planning studies. It is recommended that future work include hydrological modeling of different scenarios for the use of these techniques, based on locations where they can be implemented, to determine their contribution in reducing damages and losses from flooding events in the city.

This study can be integrated with other zoning efforts for sustainable drainage applications, considering more detailed soil infiltration capacity conditions when available (Failache et al., 2022). Moreover, this methodology could also be used to rehabilitate areas with poor drainage conditions in highly urbanized environments, identifying available spaces in buildings and homes when more detailed geographic data is available with higher resolution (Ji, 2023).

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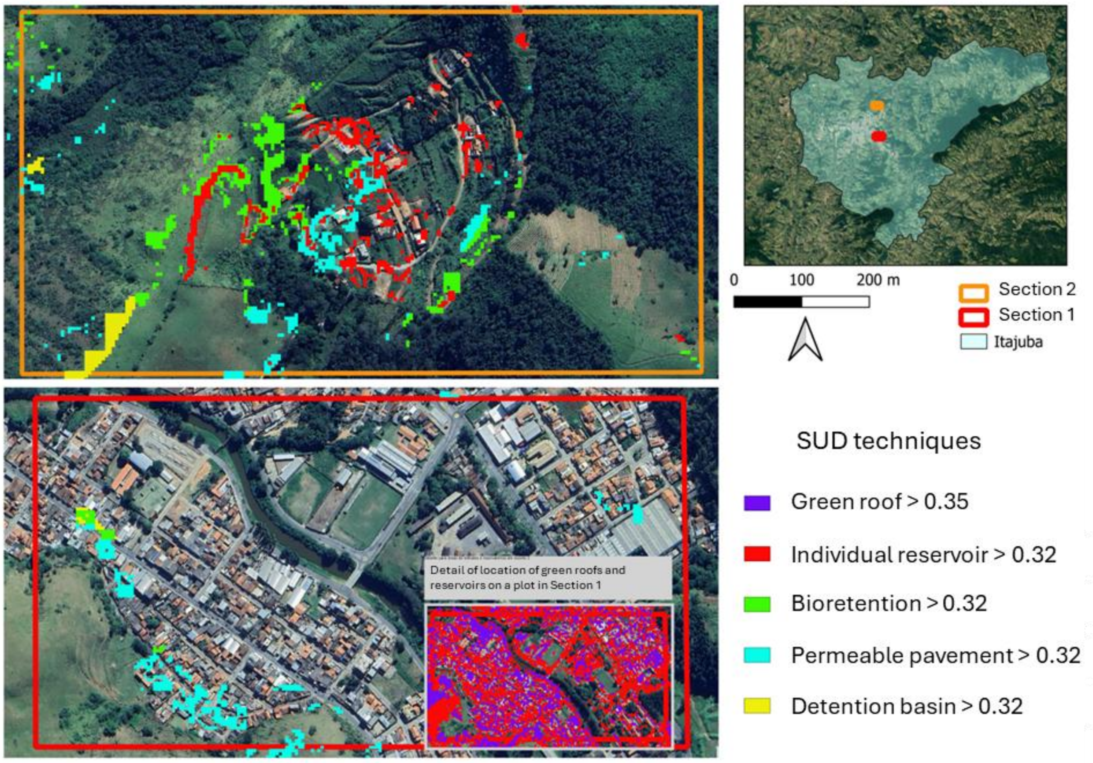
Figure 6 – Location of SUD Techniques with Higher Suitability in Two Sections of the City of Itajubá. Section 1 – Consolidated Urban Area in a Flat Location, and Section 2 – Expanding Urban Area on a Sloped Location



Source: Authors

4 CONCLUSIONS

The AHP method combined with GIS tools proved to be effective for addressing the multicriteria decision problem of locating SUD techniques in the territory of Itajubá. This work provides a set of maps that can be used by decision-makers to choose the most suitable locations for implementing these techniques.

The application of the method revealed that for bioretention and permeable pavements, no clearly defined locations for their implementation emerged, as the final map was more dispersed and indicated a higher number of unsuitable areas. On the other hand, for individual reservoirs and green roofs, as expected, the urban center with higher residential density was the most suitable location, while more peripheral areas with abundant vegetation were less suitable. Finally, the detention basin technique was more appropriate for locations farther from the urban center, particularly near the municipal boundary.

It is suggested that future work integrate these maps and methodology with hydrological basin modeling to assess the overall effect of applying these techniques in the most suitable locations, focusing on runoff volumes, peak flows, and consequently, reducing flooding and inundation in the municipality.

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DECLARAÇÕES

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DECLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, **Marina Batalini de Macedo** e **Ana Júlia Rodrigues**, declaramos que o manuscrito intitulado “**Análise Multicritério para Seleção de Técnicas Compensatórias de Drenagem Urbana e Recomendação de sua Distribuição Espacial para a Cidade de Itajubá – MG**”:

1. **Vínculos Financeiros**: Não possui/possui vínculos financeiros que possam influenciar os resultados ou interpretação do trabalho.
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