

## GIS-RS-based methodology for Multipurpose SuDS Planning with Machine-Learning Integration in Complex Urban Environments.

Méthodologie fondée sur les SIG-TD pour la planification multiobjectifs des SuDS avec intégration d'algorithmes d'apprentissage automatique dans des environnements urbains complexes.

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### RÉSUMÉ

Les Systèmes Urbains de Drainage Durable (SuDS) sont devenus des solutions clés pour relever les défis liés à l'expansion urbaine rapide et à l'augmentation de l'imperméabilisation des surfaces urbaines. Cependant, des limites persistent concernant les outils intégrés permettant de sélectionner des groupes de SuDS adaptés aux besoins spécifiques des grandes villes. Cette étude présente une méthodologie fondée sur les Systèmes d'Information Géographique et la Télédétection (SIG–TD) combinée à une analyse multicritère adaptative pour évaluer l'applicabilité des SuDS en contexte urbain. Bogotá a été utilisée comme étude de cas, ce qui a permis d'identifier des zones prioritaires pour la mise en œuvre de différents groupes de SuDS selon des objectifs fonctionnels tels que le contrôle des inondations, la régulation thermique, la sécurité routière, la santé publique, les aménités urbaines, l'esthétique urbaine, la réponse d'urgence, la collecte des eaux pluviales et le soutien à la biodiversité. Les résultats montrent une grande variété de configurations potentielles et mettent en évidence la capacité des SuDS à générer des bénéfices environnementaux, sociaux et économiques dans des environnements urbains complexes. Enfin, ce travail pose les bases d'un Système d'Aide à la Décision (SAD) enrichi d'outils spatiaux et d'algorithmes d'apprentissage automatique non supervisé — notamment K-means et HDBSCAN — permettant une optimisation agile, reproductible et évolutive de la sélection et de la priorisation des SuDS.

### ABSTRACT

Urban Sustainable Drainage Systems (SuDS) have become key solutions to address the challenges associated with rapid urban expansion and the increasing imperviousness of urban surfaces. However, limitations persist regarding integrated tools that allow for selecting SuDS groups adapted to the specific needs of large cities. This study presents a methodology based on Geographic Information Systems and Remote Sensing (GIS–RS) combined with adaptive multicriteria analysis to evaluate the applicability of SuDS in urban contexts. Bogotá was used as a case study, enabling the identification of priority areas for implementing different SuDS groups according to functional purposes such as flood control, thermal regulation, traffic safety, water-related disease control, urban amenities, urban aesthetics, fire response capacity, stormwater harvesting, and biodiversity support. The results show a wide variety of potential configurations and highlight the ability of SuDS to generate environmental, social, and economic benefits in complex urban environments. Finally, this work lays the foundations for a Decision Support System (DSS) enhanced with spatial tools and unsupervised machine-learning algorithms —including K-means and HDBSCAN— that enable agile, reproducible, and scalable optimization of SuDS selection and prioritization.

### KEYWORDS

Sustainable Drainage Systems (SuDS), GIS–RS Modelling, Multipurpose Planning, Machine-Learning.

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## 1 INTRODUCTION

Cities are facing increasing pressures associated with rapid urban expansion and soil imperviousness, processes that intensify runoff, raise land surface temperatures, and deteriorate the functionality of existing infrastructure. By 2030, nearly 5 billion people are expected to live in urban areas, increasing pressure on the built environment and the hydrological cycle (Chapman & Hall, 2022). Recent studies report thermal increases greater than 6 °C and more than 80% growth in runoff in urbanized areas (Falah et al., 2024; Ongaga et al., 2024).

Climate change exacerbates these effects by increasing the frequency and intensity of extreme events (Tootoonchi et al., 2022; Weynants et al., 2024). In Bogotá, for 2021–2040, precipitation increases of 10–20% and temperature increases of 0.5–1 °C are projected under different SSP scenarios (IDEAM, 2024), intensifying risks of flooding, urban heat, and environmental degradation.

Green Infrastructure (GI) offers mitigation and adaptation alternatives by providing ecosystem services such as thermal regulation, ecological support and runoff management (Sokolova et al., 2024). Sustainable Drainage Systems (SuDS) stand out within GI because they combine infiltration, retention and additional environmental benefits (Ossa-Moreno et al., 2017). However, their implementation at the urban scale remains limited due to the lack of methodologies that integrate their multipurpose.

This study proposes a GIS–RS–based methodology that integrates nine functional purposes and nineteen SuDS typologies. This approach establishes the foundations for a robust Decision Support System (DSS), supported by unsupervised algorithms —K-means and HDBSCAN— to automate functional classification and spatial prioritization.

## 2 METHODOLOGY

The methodology integrates high-resolution spatial analysis using GIS and Remote Sensing, together with spatial and urban criteria filters, and prioritization techniques, to identify feasible SuDS implementation zones in Bogotá under a multipurpose approach. The process is structured into five stages.

First, nine functional purposes were identified through the analysis of more than 190 geospatial layers (ponding hazard, urban heat islands, traffic accidents, ecological corridors, fire events, public facilities, among others). These layers were standardized between 0–1 and combined to generate purpose-specific criticality maps, where pixels with the highest demand were grouped into clusters and classified by size using percentiles.

In the second stage, nineteen SuDS typologies were evaluated considering four spatial feasibility criteria: minimum installation area, optimal slope range (derived from the 2014 DEM), minimum groundwater depth, and urban compatibility (sidewalks, medians, roads, green areas or buildings). The intersection between criticality and feasibility produced feasible zones for each typology and purpose, expressed as manageable surface area (km<sup>2</sup>).

Subsequently, a Multicriteria Decision Analysis (MCDA) was applied to compare the feasible typologies within each purpose, using investment (CAPEX), operation and maintenance (OPEX), functional efficiency and benefit–cost ratio as criteria. The MCDA enabled a comparative ranking of typologies according to their relative performance, complementing the spatial analysis of compatibility and extent.

In the fourth stage, dominant typologies were identified for each purpose by integrating two metrics: (i) the percentage of total manageable area assigned to each SuDS option, and (ii) its relative performance in the MCDA. This allowed the characterization of multipurpose configurations at the urban scale and the identification of typologies with the greatest replicability and multifunctional potential.

Finally, the resulting spatial structure enabled the integration of unsupervised algorithms —K-means and HDBSCAN— to explore latent patterns, identify zones with functionally similar behaviors, and advance toward an adaptive, reproducible and scalable Decision Support System (DSS).

## 3 RESULTS AND DISCUSSION

The spatial analysis enabled the quantification of potential implementation areas for the nine evaluated urban purposes. The results reveal contrasting patterns: some purposes show a clear dominance of a single SuDS typology, while others exhibit more balanced distributions.

For flood control, the potential area reaches 68.85 km<sup>2</sup> (see Figure 1), of which constructed wetlands account for

97.5 %, confirming that large-scale retention solutions represent the most viable strategy in Bogotá (see Figure 2). For the other purposes, figures are not shown due to space limitations, but all the results will be illustrated during the conference. For thermal regulation, the largest potential areas correspond to green roofs and green façades, each representing around 24 % of the total; together with green gutters (24.4 %), these three typologies comprise nearly 72 % of the available potential to mitigate urban heat island effects. In traffic accident reduction, green gutters account for 33.6% of the feasible area, followed by permeable pavements (10.6%). The remaining typologies contribute similarly (7–9%), reflecting the need for small-scale linear interventions. For water-related diseases, the four evaluated typologies each contribute 25%, due to physical–urban constraints that limit spatial differentiation. The biodiversity support purpose exhibits a more diversified distribution : green roofs contribute 31.6%, followed by green gutters (15.1%), bioretention zones (11.3%), rain gardens (11.3%) and wetlands (9.6%), highlighting the key role of distributed vegetated typologies. For urban amenity and heritage, green roofs and green façades concentrate more than 80% of the potential, reflecting their viability on consolidated building structures. For fire response, storage-based solutions dominate more than 95% of the feasible area (cisterns 47.3%, rainwater harvesting systems 33.7%, and storage tanks 14.9%). In rainwater harvesting, four typologies represent 94% of the potential: storage tanks (24.7%), cisterns (24.3%), wet ponds (23.9%) and green roofs (21.5%). Finally, for architectural enhancement, green roofs concentrate more than 98% of the feasible area.

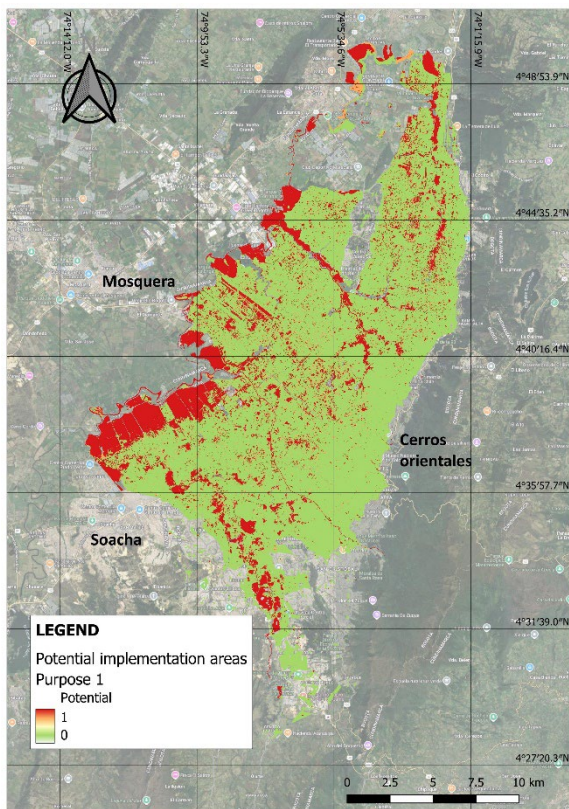


Figure 1. Purpose 1. Potential implementation areas

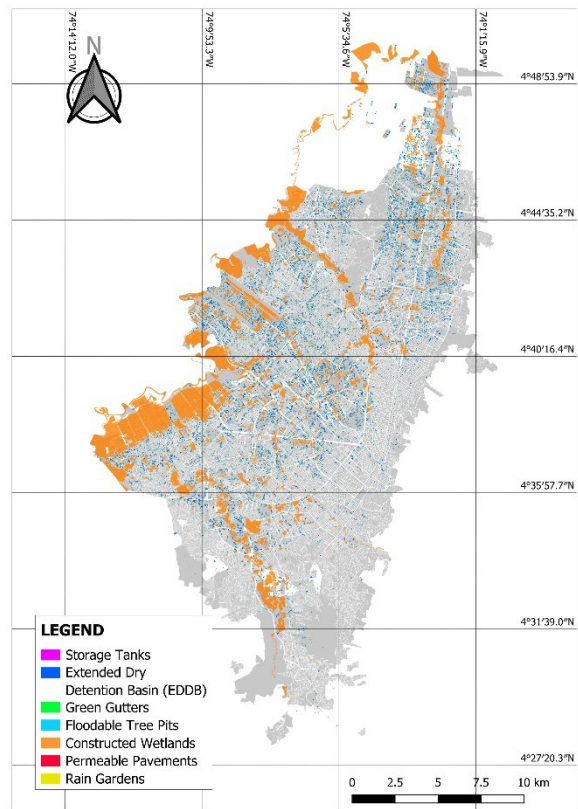


Figure 2. Purpose 1. Potential SuDS

Taken together, several multifunctional typologies are identified —rain gardens, bioretention zones, green roofs, green gutters and storage tanks— which consistently appear among the highest-scoring alternatives across multiple purposes. This pattern suggests their relevance as structuring elements for integrated SuDS strategies in Bogotá and reinforces the need for spatially differentiated planning according to purpose and urban morphology. To complement these findings, the clustering analysis performed with HDBSCAN was validated using Cramér’s V, revealing consistent associations between the spatial clusters and the functional purposes of the evaluated typologies. Constructed wetlands, green gutters and EDDB exhibited the strongest relationships, each surpassing a value of 0.30. These results confirm that the clustering outputs reflect meaningful spatial organization rather than random variability, thereby strengthening the analytical robustness of the methodology and supporting its applicability for SuDS selection and prioritization in complex urban environments.

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## 4 CONCLUSIONS

The multipurpose spatial analysis made it possible to identify differentiated patterns in the implementation capacity of SuDS in Bogotá. The solutions with the greatest functional dominance—wetlands for flood control (97.5% of the potential area), green roofs and green façades for thermal regulation and urban amenity (>80%), and storage-based systems for fire response (>95%)—show that certain typologies are structurally better suited to address specific urban challenges.

The identification of typologies that recur across several purposes, such as rain gardens, bioretention zones, green gutters and green roofs, demonstrates their value as multifunctional solutions capable of providing simultaneous benefits across multiple environmental and urban dimensions. These results suggest that SuDS planning strategies should integrate these typologies as foundational elements for flexible and robust configurations.

Finally, the spatial data structure generated enables the integration of unsupervised algorithms such as K-means and HDBSCAN, which can automate the delineation of functional zones and the prioritization of areas with greater multipurpose compatibility. This represents a significant step toward an adaptive DSS for SuDS planning in complex urban environments, particularly in large cities such as Bogotá.

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