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Multi-Criteria Decision Analysis Inputs for Planning the Implementation of Nature-based Solutions in Urban Contexts

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Abstract

Water Sensitive Urban Design (WSUD) and Nature-based Solutions (NbS) constitute an alternative approach for managing water and ecosystems that need to be integrated with local regulations. In this context, effective knowledge transfer is essential to include NbS guidelines derived from quantitative analysis in planning tools. Hence, this research proposes a methodology that assesses the needs and opportunities for providing ecosystem services at a site in order to generate NbS recommendations focused on stormwater management. The methodology has two parts (i.e., spatial analysis and landscape design) and the city and local planning unit scales. Also, it evaluates three analysis units to tie urban and NbS planning: 20*20 m cell, Local Climate Subzones (LCSZ), and Local Climate Zones (LCZ). The first part identifies priorities and opportunities —by calculating two indices that weigh multiple criteria related to ecosystem services— NbS types, processes, and area percentages for stormwater management. The second part tests the usefulness of these spatial and numerical outcomes to support NbS landscape design. The methodology is implemented in the city of Bogotá (Colombia). Results show LCSZ's potential as a planning unit for the case study conditions to identify intervention zones and devise replicable strategies. Also, area percentages constituted a guide to integrating various NbS types into the design and recognizing insufficient coverage for stormwater management.

Keywords: water-sensitive urban design; landscape multi-functionality; landscape architecture; ecological planning

Citation

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Insumos a partir de análisis multicriterio para la implementación de Soluciones basadas en la Naturaleza en contextos urbanos

Resumen

El diseño urbano sensible al agua y las Soluciones basadas en la Naturaleza (SbN) constituyen una aproximación alternativa para el manejo del agua y los ecosistemas que requiere integración con la normativa local. En este contexto, es esencial la transferencia efectiva del conocimiento para incluir lineamientos de las SbN derivados de análisis cuantitativo en herramientas de planeación. Por lo tanto, se propone una metodología que evalúa las necesidades y oportunidades de proveer servicios ecosistémicos en un lugar con el objetivo de generar recomendaciones sobre SbN para el manejo de la escorrentía. Esta metodología comprende dos partes (i.e., análisis espacial y diseño del paisaje) y las escalas de ciudad y unidad de planeación local. Asimismo, evalúa tres unidades de análisis para enlazar la planeación urbana y de SbN: celda de 20*20 m, Subzona Climática Urbana (SZCU), y Zona Climática Urbana (ZCU). La primera parte identifica áreas de prioridad y oportunidad mediante el cálculo de dos índices a través de la ponderación de múltiples criterios relacionados con servicios ecosistémicos, así como tipos de SbN, procesos y porcentajes de área para el manejo del agua pluvial. La segunda parte prueba la utilidad de los resultados espaciales y numéricos para apoyar el diseño paisajístico. La metodología es implementada en la ciudad de Bogotá (Colombia). Para el caso de estudio, los resultados evidencian el potencial de las SZCU como unidad de planeación para identificar zonas de intervención y diseñar estrategias reproducibles. A su vez, los porcentajes de área constituyen una guía para integrar varios tipos de SbN en el diseño y reconocer si la cobertura es insuficiente para el manejo del agua pluvial.

Palabras clave: diseño urbano sensible al agua; multifuncionalidad del paisaje; paisajismo; planeación ecológica

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1. Introduction

Cities are complex ecosystems that integrate social, ecological, economic, physical, and political systems with interdependent multi-scale matter and energy cycles (Wolfram, 2016). Also, given cities' population concentration, the resource use model can reduce or accentuate long-term detrimental environmental effects (Rees and Wackernagel, 2008; Wong and Brown, 2009). Water management is essential in terms of this issue, which conventionally manages water fluxes—such as drinking water, wastewater, and stormwater—as separate systems (Wong and Brown, 2009). This approach has affected sustainability by classifying each water flux as waste or resource. For instance, classifying stormwater as waste limits its management to capturing, conveying, and discharging, which increases risks and negative repercussions and reduces its potential benefits (Butler et al., 2018). Considering that stormwater needs to be handled as a resource in order to increase urban sustainability (ibid.), various alternatives have arisen that aim to achieve sustainable water management, with similar scopes and goals for multiple urban scales (Fletcher et al., 2015).

Urban water has a clear relationship with ecosystem services addressed by emerging concepts. Specifically, Water Sensitive Urban Design (WSUD) proposes a holistic approach focused on the connection between determining factors of the cities' ecological footprint and biodiversity (Wong and Brown, 2009). The suggested practice for urban design has three pillars: cities as water supply catchments, cities providing ecosystem services, and cities comprising water-sensitive communities (ibid.). This constitutes an ideal that optimizes water resources and structures' livability and well-being through governance and awareness of ecosystem services. Within the WSUD approach, the Nature-based Solutions (NbS) concept becomes relevant. NbS is an umbrella term that includes ecosystem management concepts (e.g., ecological engineering, green-blue infrastructure, natural infrastructure, ecosystem approach, and ecosystem services), integrating elements for sustainable water management (Somarakis et al., 2019). Sustainable systems for stormwater control correspond to a particular type of NbS related to the design and management of new ecosystems (Eggermont et al., 2015).

Precedents such as WSUD and NbS constitute a conceptual basis for transitioning to more sustainable regimes to manage urban water and ecosystems. However, multiple technical, institutional, and resource barriers have been detected in the current paradigm shift (Brown, 2005; Keeley et al., 2013). Also, most of the available NbS frameworks do not embody the urban planning role in successful NbS implementation (Wickenberg et al., 2021). Therefore, overpowering the traditional system inertia means addressing the specific requirements in the planning, design, and implementation stages to transform these new principles into urban water management practices and spaces.

To this end, coordinating different fields of knowledge is essential to integrate the goals of each area of expertise. In this context, architects have a primary role in merging technical, environmental, and sociocultural elements to produce sustainable solutions and coordinate multiple stakeholders (Backhaus et al., 2012; Kwak et al., 2021). In fact, McHarg (1981) formulated a methodology for ecological planning by taking socio-ecological factors into account to determine a place's capabilities, opportunities, and constraints to establish future development alternatives. Hence, the framework implicitly recognizes ecosystem services to analyze land use suitability (McHarg, 1992).

Nevertheless, cooperation between disciplines, including architecture and engineering, has persistent obstacles. For example, Backhaus et al. (2012) held a workshop with landscape architects to devise stormwater management options in a specific area. They identified design challenges such as suitable dimensioning, water quality considerations related to the source, integration of biodiversity goals, effective synergy achievement between stormwater management and other uses, and understanding hydrological dynamics. Likewise, Kwak et al. (2021) determined three types of gaps in integrating quantitative modeling results and architectonic practice: perception, scale, and knowledge. These gaps control the preferred solution, impede multi-scale approaches, and affect interdisciplinary work.

Therefore, to attain the WSUD goals and achieve the attributes of effective multifunctionality, establishing a common language between practitioners is paramount. The approach should include identifying urban areas' needs and the potential to increase benefits using pre-existing characteristics. Also, the design process should integrate multi-scale objectives given the priorities and opportunities outlined.

Consequently, this study proposes a methodology to support water-sensitive urban renewal design by generating information compatible with planning regulations. NbS recommendations are established considering site priorities and opportunities regarding the provision of ecosystem services. The proposed method is based on the Local Climate Zones (LCZ) classification (Stewart and Oke, 2012) and the framework developed by Uribe-Aguado et al. (2022) and aims to be a flexible tool to support decisions regarding different types of interventions in an urban area, considering the planning and design stages. The city of Bogotá (Colombia) was used as a case study for the methodology implementation, including a detailed design of an urban renewal area.

2. Literature Review

2.1 NbS, Ecosystem Services, and Urban Planning

Ecosystem services have been considered part of urban planning even before the term became more mainstream. For instance, McHarg (1981) developed a human ecological planning method by recognizing the interactions between people and the environment to identify the best uses for a territory. McHarg's methodology starts with a baseline by assessing relevant natural resource factors (e.g., hydrology, soils, vegetation, and population) depending on the study area (McHarg, 1992). Next, the methodology proposes a suitability analysis for prospective land uses by classifying the initial information with a value system. Each factor is mapped and superposed to generate suitability maps for each land use. Finally, the maps are combined, grouping complementary activities and excluding competitive ones (ibid.). In this sense, land use planning integrates restrictions and opportunities derived from a region's preexisting dynamics, enforcing actions like conservation practices to reduce risks posed by natural disasters.

The link between NbS and ecosystem services (Somarakis et al., 2019) has led to several approaches for NbS planning in urban contexts. These approaches resemble the basic principles outlined by McHarg (1981), in which territorial dynamics, framed as ecosystem services, were evaluated to support decision-making. For example, Liu et al. (2022) integrated five ecosystem services and NbS principles to formulate a framework to limit urban expansion. The methodology assessed primary ecosystem conditions and subsequently defined and evaluated scenarios. Likewise, to integrate NbS into metropolitan-scale planning at Seville (Spain), Santiago Ramos and Hurtado Rodríguez (2021) developed a multifunctionality index for the metropolitan open space by assessing the provision of seven ecosystem services. This framework identified the importance of the preexisting land-use planning concepts for developing NbS implementation schemes. Nin et al. (2016) applied a methodology for land-use planning in a basin by considering multiple attributes regarding erosion control, food production, and the prevention of floods, eutrophication, and exotic plant invasion. As a result, areas with high ecosystem services provision were identified to guide the expansion of preexisting uses. These methods recognize NbS and ecosystem services demands for sustainable urban planning. Nevertheless, their application depends on understanding the variation in ecosystem services' relevance due to context and scale.

Regarding NbS for stormwater management, research is currently transitioning from valuing hydrological and hydraulic benefits to integrating more ecosystem services. However, explicitly linking ecosystem services to these NbS types can create a complex issue arising with the formulation of objectives (Lu and Wang, 2021), which should embody the multiple advantages and requirements of the NbS. Nevertheless, the often ambiguous objectives impede NbS adoption by discouraging investor and stakeholder incorporation (ibid.). Thus, integrating multiple criteria in NbS planning is necessary to ensure decisions are made by evaluating synergies and trade-offs (Chang et al., 2021; Vail Castro, 2022).

One prevalent approach to NbS planning is devising urban indices, mostly following GIS-based Multi-Criteria Decision Analysis (MCDA) methodologies. This technique systemically prioritizes areas and place systems, in accordance with predefined goals and site constrictions (Lu and Wang, 2021), and combines qualitative and quantitative information (Langemeyer et al., 2020). GIS-MCDA studies for NbS implementation usually include socio-ecological (Heckert and Rosan, 2016; Meerow and Newell, 2017; Pacetti et al., 2022) and hydrological or hydraulic (Pacetti et al., 2022) factors and, in some cases, relate explicitly to ecosystem services (Chang et al., 2021; Kuller et al., 2019; Langemeyer et al., 2020; Lourdes et al., 2022; Venter et al., 2021). According to Meenar (2019), the results of this type of analysis can support design by allowing information sharing, providing basic geographic and expert information, and integrating outputs from various stakeholders.

Regarding Colombia, Jiménez Ariza et al. (2019) developed a multi-scale framework for Sustainable Urban Drainage Systems (SUDS) implementation in consolidated urban areas, integrating a three-scale analysis. The methodology assessed water quality and quantity aspects as well as socio-environmental concerns, employing urban drainage sub-catchments as an analysis unit for recognizing priority and opportunity areas for SUDS adoption. Also, Uribe-Aguado et al. (2022) proposed a framework for urban projects considering ecosystem services with more potential to be provided by SUDS. The framework incorporated work done by Jiménez Ariza et al. (2019) and Torres et al. (2020), the latter being a methodology to optimize SUDS selection and location. Hence, the results included SUDS allocation considering ecosystem services needs in an area and the available space. The case studies included distinct urban project types (i.e., renewal and development) in different planning stages. Figueroa (2020) formulated a seven-stage guide to support NbS implementation in Colombia by identifying and prioritizing strategic urban zones and maximizing NbS interventions to improve resilience, life quality, and ecosystem health. This methodology proposes an appraisal of available areas, different urban sector needs, and NbS requirements.

2.2 NbS Design

The approaches to support NbS landscape and architectonic design vary according to the NbS type to integrate multi-functionality. Vasiliev and Greenwood (2022) formulated a multi-scale framework based on landscape ecology principles to implement trees, carbon sinks, and large parks to provide multiple services to achieve carbon storage and promote biodiversity. The researchers identified design principles like promoting landscape diversity within and between habitat patches, considering connectivity, and integrating NbS into the context. Regarding NbS for stormwater management, Romnée et al. (2015) developed a methodology considering different urban spatial typologies and providing typical configurations for NbS implementation given the space type. They contemplated indicators for the landscape and urban fabric and the private and public character of the available space to suggest possible interventions.

Therefore, the methodology focuses on offering information to support NbS selection rather than establishing a unique solution. Also, the CIRIA SuDS manual (Woods Ballard et al., 2015) identifies various design considerations given the four main objectives for Sustainable Drainage Systems implementation (i.e., water quantity, water quality, amenity, and biodiversity). Consistent with the objectives established in the manual, Mak et al. (2017) provided non-expert methods to include multiple services in NbS for stormwater management. They proposed two methodologies to consider biodiversity and amenity services in SUDS retrofit site selection and design decisions.

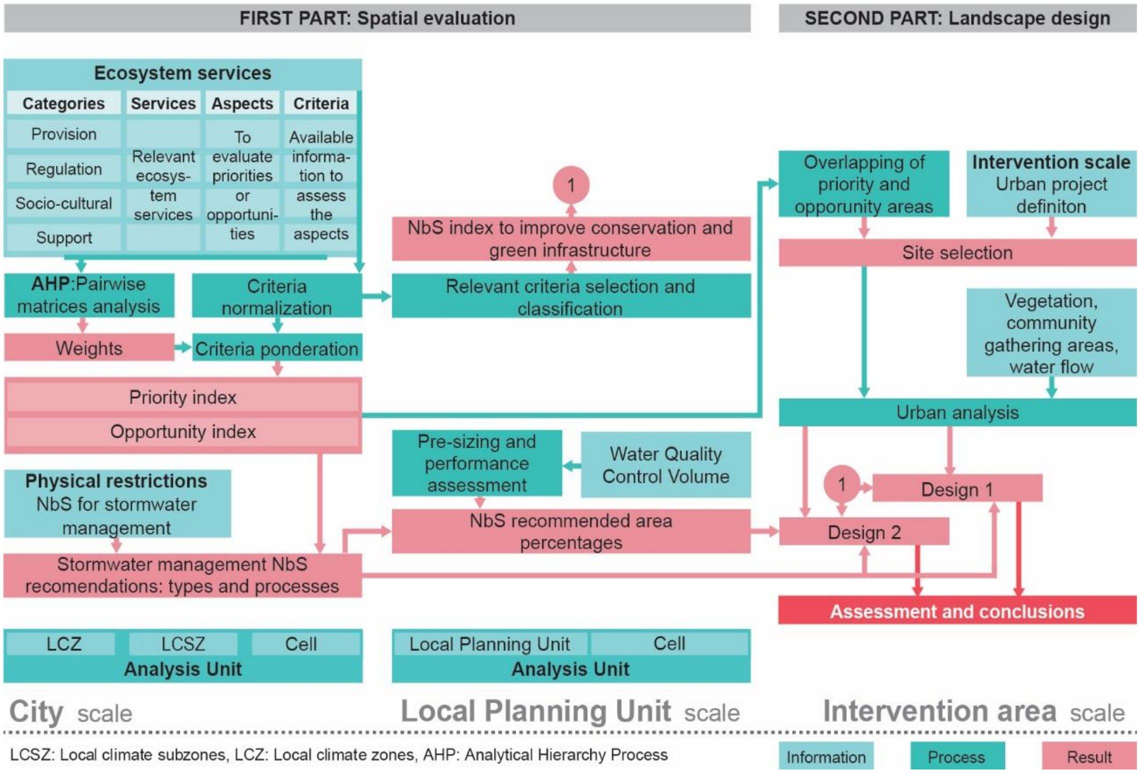
Effective NbS design depends on collaborative and interdisciplinary techniques (King et al., 2022; Matos Silva, 2020). King et al. (2022) highlighted the increased ability to integrate complex information in NbS designs, given results from the “Engineering with Nature” initiative, which combined landscape architecture, applied science, and engineering. Also, precedents of multifunctional strategies in public spaces with structures resembling NbS show the need for multidisciplinary practices in the design of public spaces (Matos Silva, 2020). For instance, Potsdamer Platz in Berlin (Germany) addresses the treatment and use of stormwater in a series of urban pools. Thus, the project manages stormwater while achieving temperature regulation and aesthetical functions (ibid.).

3. Methodology

The two-part methodology corresponds to spatial evaluation and landscape design by integrating analyzes at two different scales: city and local planning units. Figure 1 summarizes the methodology. The first part results in baseline information to support NbS selection and design. At the city scale, LCZ and Local Climate Subzones (LCSZ) are defined using a 20*20 m size cell as the initial analysis unit. This unit allows administrative boundaries to be surpassed (Chang et al., 2021) and LCZ and LCSZ to be integrated with other assessments. Next, priorities and opportunities indices are calculated considering the ecosystem services potentially supported by NbS for stormwater management.

Each index corresponds to a composite score according to the weighting of criteria normalized from zero (0) to one (1). Also, physical restrictions for NbS for stormwater management are assessed to provide recommendations for NbS implementation. At the local planning unit level, suggestions for NbS are outlined for stormwater management areas.

Figure 1. **Methodology to define the baseline information for NbS selection and design and develop two design tests**



Source: Elaborated by authors.

Additionally, indices are established for three NbS for conservation and green infrastructure improvement. These results constituted the basis for the two design tests used as a research technique (Prominski, 2019), where the architects complement their usual approach (i.e., site analysis, identification of intervention areas, and landscape proposal) considering WSUD principles and recommendations for NbS implementation.

3.1 City Scale

First, the LCZ are outlined, which constitutes the basis of the framework to obtain adaptable results for similar urban conditions. The methodology to determine the LCZ was formulated by Álvarez Lucero et al. (2020) with the dual purpose of characterizing the urban area and supporting tree cover selection. It is based on the methods proposed by Lee et al. (2019) and Stewart and Oke (2012). The LCZ are outlined by defining spatial clusters with significant variables to predict the maximum multiannual temperature. The variables considered correspond to the following categories: climate, pollution, topography, land use, land cover, urban form, and locational characteristics (i.e., distance to transport infrastructure and natural waterbodies) (Lee et al., 2019; Stewart and Oke, 2012). LCZ are subdivided into LCSZ using the precipitation characteristics and the cluster analysis method (Lyra et al., 2014).

Next, priority and opportunity indices assess the needs of ecosystem services and their potential to be supported in the urban area. The ecosystem services included those identified by Uribe-Aguado et al. (2022). Habitat for species is also analyzed given its relevance in a Water Sensitive Urban Design framework, considering The Economics of Ecosystems and Biodiversity (TEEB) classification (TEEB, 2010). Table 1 summarizes the evaluated services and proposed aspects. Priorities correspond to requirements and issues due to the urban dynamics (e.g., territory occupation, constructed space characteristics, or population groups). Opportunities are features intrinsic to the territory or urban dynamics that could favor the provision of ecosystem services and urban spaces with potential for improvement.

The identification of priorities and opportunities constitutes a multi-attribute problem in terms of decision-making because criteria weighting can impact the conclusions made (Meerow and Newell, 2017). Hence, the methodology incorporates the Analytical Hierarchical Process (AHP) (Saaty, 1990) to translate the perspectives of various professionals into subjective weights for adding multiple criteria. Two hierarchical structures are defined—one for the priority index and the other for the opportunity index. Regardless of the objective, the hierarchical levels are the same. So, the second level of the hierarchical structure corresponds to the ecosystem service categories, which are analyzed according to the relevant third-level ecosystem services. For each service, one or more aspects are delineated according to whether priorities or opportunities are being evaluated. The final level of the hierarchy corresponds to the criteria to assess the aspects. The components of the structure are summarized in Table 1. To determine the weights for the categories, ecosystem services, aspects, and criteria, pairwise matrices are constructed for each level and evaluated according to the Saaty Scale (ibid.). The analysis of the pairwise matrices uses the R package “ahpsurvey” version 0.4.1., computing the weights with the Dominant Eigenvalues method (ibid., 2003). The expert opinion appraisal involves a two-part interview: 1) the interviewer’s description of the ecosystem services, aspects, and criteria; and 2) a consultation about the comparative importance of each one in the analyzed context.

The criteria are normalized (Heckert and Rosan, 2016; Uribe-Aguado et al., 2022) and aggregated according to specific weights to obtain the priority and opportunity indices per cell. For example, to calculate a priority value for the provision category, the normalized NDVI values, average precipitation and potential evapotranspiration ratio in the dry months, and well density is aggregated according to the relative importance given to the criteria and aspects by the experts.

To obtain a global priority index, all the criteria must be added according to the determined weight for the priority criteria, which add up to one and depend on the comparative importance given to the categories, ecosystem services, aspects, and criteria. To determine a value for the LCSZ and LCZ, the 75th percentile of the cells’ indices value is used. This statistic is selected to increase the differentiation of each zone and subzone and identify issues and opportunities that are not equally distributed along the evaluated area.

Table 1. **Aspects and suggested criteria for the analysis of ecosystem services to determine priorities and opportunities**

Category	Service	Priority			Opportunity		
		Aspect	Criteria	Unit	Aspect	Criteria	Unit
Provision	Fresh water	Irrigation water needs[10]	NDVI	Index	Recharge areas[1]	Potential recharge areas	Qualitative score
			Average precipitation and potential evapotranspiration ratio in dry months	mm/mm	Runoff quality[7,10]	Distance to main roads	m
		Use of underground water	Well density	#/km2		Distance to land uses that may restrict infiltration	m
Regulation	Water regulation	Runoff quantity problems[1,2,3,8]	Flood threats	Threat level	Runoff quantity control[3,5,8]	Infiltration rate	mm/h
			River dike breach threats	Threat level		Public area	m2
			Torrential floods threats	Threat level		Private available area	m2
			Waterlogging zones	Threat level		Relationship between the public area and the elevation in the micro-basin	m2*m/m
			Storm sewer system capacity	Threat level		Slope	%
						Runoff management index	Index/km^2
	Water treatment	Runoff water quality[1,8]	Rivers water quality	Index	Runoff quality control[6,8]	Potential of increasing vegetation in public areas (considering the NDVI)	Index
			Wetlands water quality	Index		Distance to wetlands	m
						Reduction of combined and sanitary sewer overflows index	Index/km^2
	Microclimate regulation	Urban Heat Island[1,3,4]	Land surface temperature	°C	Microclimate regulation[8]	Potential of increasing vegetation in public areas (considering the NDVI)	Index
	Global climate regulation	Carbon sequestration[8]	Tree density	#/tree	Carbon sequestration[8]		
	Air quality regulation	Air quality[3,4,5,8]	PM 2.5	μg/m^3	Air pollutants capture[8]		
		Population vulnerability[5,8]	People from zero to four years and older than 65 years[9]	#/ha			
Sociocultural	Aesthetic value	Public space access[4,5,8]	Residential access deficit[10]	%	Enhance amenity[8]	Public space type	Index
			Working places distance	m			
		Population needs (socioeconomic)[4,5,8]	Multidimensional Poverty Index	Index			
	Educational value	Population needs (density)[8]	Population density	pop/ha	Potential public[7,8]	Interest sites and public space index	Index
Support	Habitat for species	Green areas connectivity[3,4]	Distance and surfaces between the elements of the main ecological structure	Index	Preexisting habitats	Distance to wetlands	m
		Waterbodies state	Rivers' water quality	Index		Distance to zones with high tree density*	m
			Wetlands' water quality	Index	Renaturation potential	Canalization type	Index
			Length of canalization of lotic natural water bodies	m/m			
		Natural wetlands state	Average rate of sealing of natural areas	-			

*Considers quantity and height

Source: Elaborated by authors based on: [1]Dagenais *et al.* (2017), [2]La Rosa and Pappalardo (2020), [3]*Chang et al.* (2021), [4]Meerow and Newell (2017), [5]Heckert and Rosan (2016), [6]Charlesworth *et al.* (2016), [7]Garcia-Cuerva *et al.* (2018), [8]Uribe-Aguado *et al.* (2022), [9]Given previous studies and available information (Dagenais *et al.*, 2017; Heckert and Rosan, 2016; Meerow and Newell, 2017), [10]Jiménez Ariza *et al.* (2019).

Chosen criteria depend on a city's available information. Hence, proxies are used if there are data limitations. The suggested criteria presented in Table 1 are related to the case study. Enhancing amenity potential considers the type of public space by assigning a score to each area according to the possibility of implementing systems with vegetation or a permanent water pool. For the educative value, the potential public is estimated with the public space type in areas with a maximum distance of 150 m to areas with uses that can increase pedestrian traffic (Garcia-Cuerva et al., 2018). These areas may correspond to commercial establishments, public transport nodes, areas for recreation, health establishments, religious and cultural places, and service buildings. A score is also assigned to the public space considering its possible uses (walk, stand, or sit) and the type of related activities (necessary or optional) given the definitions stated by Gehl and Svarre (2013).

NbS recommendations for stormwater management are derived from the evaluation of eleven types: green swale, infiltration trench, permeable pavement, wet pond, bioretention zone, tree pit, sand filter, constructed wetland, infiltration basin, dry extended detention basin, and filter trench. NbS implementation feasibility is determined in the cells by assessing their physical characteristics: slope, distance to the water table, infiltration rate, available area, and distance to waterbodies (Jiménez Ariza *et al.*, 2019).

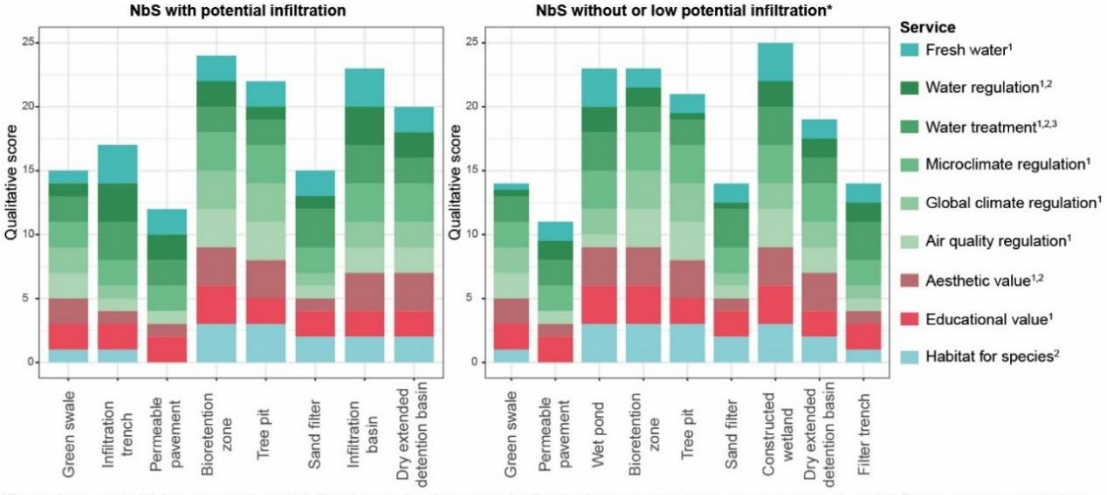
Since development and renewal processes can change the area available for NbS implementation, the public or private nature of the cells' area is not assessed, and only main roads and waterbodies are considered unavailable spaces. Distance to roads is evaluated in some NbS types according to the possible limitations in long-term operation in areas with high sediment content (Pittner and Allerton, 2010).

The evaluation integrates a feasibility score considering recommended values to avoid excluding areas that nearly fulfill the requirements and recognize zones with better conditions for NbS implementation. For instance, the maximum recommended site slope includes values from 0% to 15%, depending on the NbS type; however, the required slopes for stormwater management NbS are usually below 6%. In this sense, steeper terrains will demand strategies like check dams to adjust to each type's operative requirements (Strecker *et al.*, 2010; Urban Drainage and Flood Control District, 2010). According to a cell's characteristics, a score from one (1) to three (3) is assigned for each evaluated restriction. The feasibility score corresponds to the average score for the relevant restrictions. The feasibility score is zero if one applicable restriction is outside the recommended values.

Recommendations per cell, LCSZ, and LCZ are established based on the potential benefits and feasibility of implementation. First, a priority and opportunity score is defined for each NbS type in each cell, considering the calculated indices and the NbS type's potential to contribute to ecosystem service provision—similar to Uribe-Aguado *et al.* (2022). The analysis involves a qualitative score presented in Figure 2. An average score from zero (0) to three (3) is calculated by adding the feasibility results with priority and opportunity scores.

Subsequently, the NbS are filtered by identifying possible impediments to implementing them in the same cell (see Figure 3) and selecting the types with a higher score if simultaneous usage could be limited by NbS area requirements or by having similar characteristics and functions. The outcome is a list of NbS for each cell. Next, the score and number of NbS are used to select up to six NbS types for each LCZ and LCSZ. The selected NbS helps identify the processes for stormwater management (i.e., detention, retention, conveyance, and infiltration) in the cells (See Figure 4), considering their characteristics and information provided in the literature (Woods Ballard *et al.*, 2015).

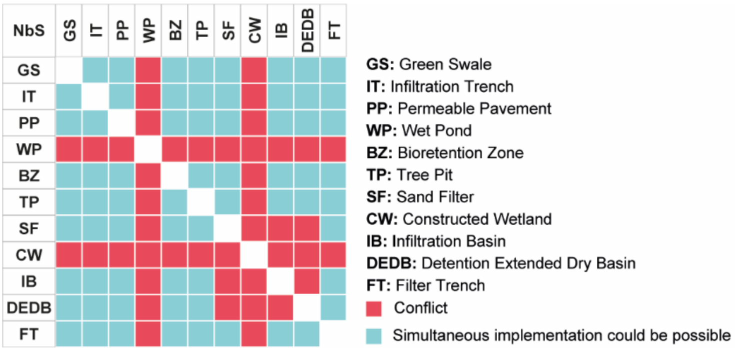
Figure 2. **Qualitative scores for the analysis of provision of ecosystem services in NbS for stormwater management**



*Even when certain NbS types could permit infiltration on site, this can be ineffective for managing the stormwater due to the soil infiltration rate (a rate higher than 7 mm/h is recommended for managing runoff in several NbS types)[1].

Source: Elaborated by authors according to [1]Uribe-Aguado *et al.* (2022), [2]Woods Ballard *et al.* (2015), [3]Clary *et al.* (2020).

Figure 3. **Conflicts for simultaneous implementation – evaluated cells**

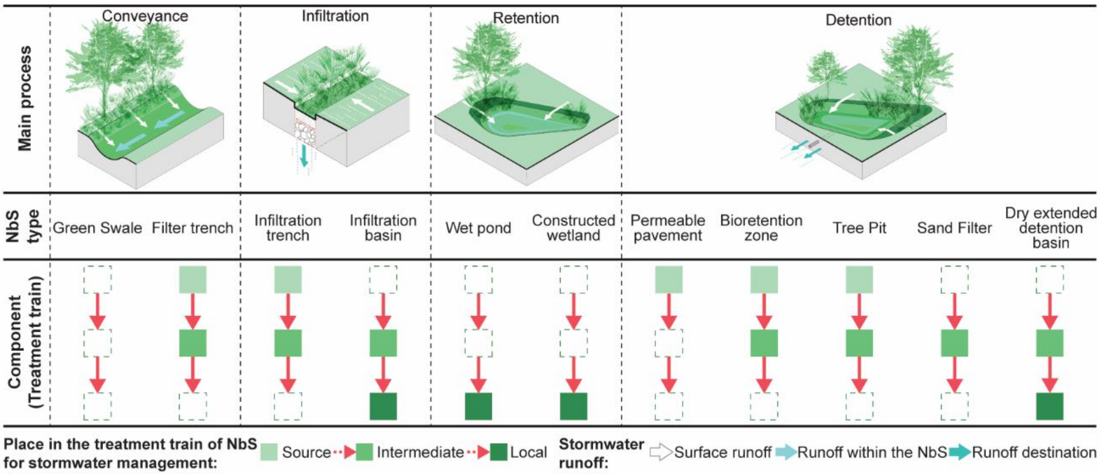


NbS	GS	IT	PP	WP	BZ	TP	SF	CW	IB	DEDB	FT
GS		🟦	🟦	🟥	🟦	🟦	🟦	🟥	🟦	🟦	🟦
IT	🟦		🟦	🟥	🟦	🟦	🟦	🟥	🟦	🟦	🟦
PP	🟦	🟦		🟥	🟦	🟦	🟦	🟥	🟦	🟦	🟦
WP	🟥	🟥	🟥		🟥	🟥	🟥	🟥	🟥	🟥	🟥
BZ	🟦	🟦	🟦	🟥		🟦	🟦	🟥	🟦	🟦	🟦
TP	🟦	🟦	🟦	🟥	🟦		🟦	🟥	🟦	🟦	🟦
SF	🟦	🟦	🟦	🟥	🟦	🟦		🟥	🟥	🟥	🟦
CW	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥
IB	🟦	🟦	🟦	🟥	🟦	🟦	🟥	🟥		🟥	🟦
DEDB	🟦	🟦	🟦	🟥	🟦	🟦	🟥	🟥	🟥		🟦
FT	🟦	🟦	🟦	🟥	🟦	🟦	🟦	🟥	🟦	🟦	

GS: Green Swale
IT: Infiltration Trench
PP: Permeable Pavement
WP: Wet Pond
BZ: Bioretention Zone
TP: Tree Pit
SF: Sand Filter
CW: Constructed Wetland
IB: Infiltration Basin
DEDB: Detention Extended Dry Basin
FT: Filter Trench
🟥 Conflict
🟦 Simultaneous implementation could be possible

Source: Elaborated by authors.

Figure 4. **Processes and place in the treatment train of NbS for stormwater management**



Source: Elaborated by authors.

3.2 Local Planning Units

Previously characterized criteria help determine indices of floodplain reconnection, waterbody renaturation, and urban carbon sinks. The result is an index from zero (0) to five (5) for these NbS. Firstly, each criterion is classified from one (1) to four (4) according to the quantiles for values higher than zero. This classification is used to determine a priority and opportunity value for NbS implementation by taking the highest class for the criterion being considered. Next, a global score is established according to Table 2. Lastly, an average value is calculated for each local planning unit. For floodplain reconnection requirements, the priority criteria include those related to runoff quantity problems regarding fluvial issues, and the opportunity criteria for aspects related to renaturation potential. Priority analysis for waterbody renaturation includes criteria related to runoff quantity problems, and the state of waterbodies and natural wetlands. To evaluate opportunities, renaturation potential is assessed. Regarding urban carbon sinks, priorities include areas with less potential carbon sequestration. Opportunities evaluate available public space and the potential for improving carbon sequestration by increasing vegetation.

Table 2. **Matrix to determine the index for conservation and green infrastructure according to priority and opportunity classification**

Index for conservation and green infrastructure					
Opportunity	Priority				
	0	1	2	3	4
0	0	1	2	3	4
1	0	2	2	4	4
2	0	2	3	4	4
3	0	3	3	4	5
4	0	3	4	5	5

Source: Elaborated by authors.

Area percentage recommendations for NbS consider uncertainty due to possible variations in the NbS scheme. This uncertainty includes the preferred types and the potential implementation of NbS sequences or treatment trains. Hence, a three-part process is formulated: 1) pre-sizing for various NbS configurations; 2) hydrological balance for each configuration; and 3) results evaluation. The pre-sizing is based on the water quality capture volume (WQCV) and assumed features for each NbS type. The WQCV is the optimal volume from frequent storm events, which, through capture and treatment, will lead to water quality improvement (Urban Drainage and Flood Control District, 2010). In this case, WQCV estimation considers the local planning unit's average runoff coefficient and precipitation depth.

The area percentages for the three stages of a simplified treatment train are defined considering NbS suitability for each stage (Figure 4). It is assumed that the first stage (source control) receives the runoff and drains to the second stage (intermediate control), which drains to the third stage (local control). Therefore, pre-sizing for NbS at the second and third stages considers losses by infiltration. These assumptions support the creation of various configurations with different NbS options in each cell. For each configuration, a drainage area is assigned to the NbS to calculate the corresponding surface area, taking into account storage and freeboard depth. If the space for NbS is limited, at least the area of the NbS's first stage should be pursued.

A hydrological balance follows the pre-sizing to determine losses by infiltration and evapotranspiration. This balance considers the site characteristics (i.e., daily precipitation, daily evaporation, and infiltration rate) and each NbS. The hydrological balance, conducted for all NbS types, adapts the methodology developed by Pitt et al. (2008) for bioretention systems (Jiménez Ariza, 2017). Each configuration is analyzed by the capture runoff volume, losses by infiltration and evapotranspiration, and average area with additional water requirements. Water requirements result from considering a minimum acceptable level of 50% for the permanent pool in constructed wetlands and wet ponds as well as the wilting point for NbS with vegetation. Of the configurations with better performance (in the 75th percentile), 25% are used to provide recommended ranges for designing each component. This value is selected to cover different options with a performance above the median. The recommendations are simplified to provide maximum, mid, and minimum suggested values from the 25th, 50th, and 75th percentiles of the selected configurations.

Research through design was used as a methodological approach for: 1) identifying which kind and format of information is more effective for designers when implementing NbS in an urban context; and 2) providing planning inputs for local regulations. According to Prominski (2019), research through design is a valid method for transferring specific design strategies to a "general validity and broader impact." Two design tests are performed with different information sets. A first design test starts with the processes for stormwater management (See Figure 4) and types of NbS recommendations. Another design test is done with the percentage of the implementation area of the recommended NbS in addition to the first design's information set.

For the design test, a specific site is selected based on a qualitative location and urban analysis of areas where the highest priority and opportunity indices overlap. The intervention scale is defined according to the urban project definition provided by Solà-Morales Rubió (1987). Therefore, the implementation aims for the following: 1) a project with a possible medium-term execution time; 2) a community and public sector collaboration; 3) a variety of users and uses; 4) a positive impact beyond the intervention area; and 5) a prioritization of the city over the intervention object (Solà-Morales Rubió, 1987).

A design team proposes an urban design renewal project that mainly transforms public space. The team uses the Water Sensitive Design framework and previous findings from NbS projects implemented in consolidated urban areas as conceptual bases for the design (De Urbanisten and Deltares, 2016; Wong and Brown, 2009). Therefore, current area conditions regarding vegetation, community gathering areas, and water flow are mapped to identify the project structure. Electrical and data infrastructure is not studied due to time constraints and information availability.

The location, size, and composition of tree patches are studied to identify opportunities for ecological connectivity. Location and size are evaluated based on a mapping exercise (Corner, 2011). Patch composition is assessed based on native and exotic species. Location, size, and species provide fundamental information for promoting the natural richness of and connectivity between patches (Forman, 2014).

Current cultural and social buildings are mapped to identify community gathering areas. Buildings inside the project's perimeter and 500 m around are located. These types of buildings—dedicated to serving the community—are strategic areas for the didactic and educational components of NbS.

Stormwater management is studied based on storm drain sewer information provided by the city's water utility company. The information includes collectors and their flow direction. This information provides a basic idea of where the possible water surplus resulting from the proposed NbS would go.

4. Case Study

Bogotá (Colombia), with an urban area of approximately 380 km^2 (Alcaldía Mayor de Bogotá, 2021) and a population of 7,181,469 (DANE, 2022), was used as a case study for methodology implementation. It encompasses four main rivers and 17 recognized wetlands (Alcaldía Mayor de Bogotá, 2021). The city is characterized by socio-spatial inequalities and a conflicted relationship with waterbodies (Gallini *et al.*, 2014; Mayorga Henao and Ortiz Véliz, 2020). In this sense, NbS constitutes an opportunity to improve the city dwellers' quality of life and promote more equitable access to ecosystem services. Additionally, Bogotá is proposing a new planning unit, called Local Planning Unit (LPU). Its effective integration with stormwater management could pose an opportunity to improve NbS implementation. Table 3 summarizes the main information sources.

Table 3. **Case study information sources**

Scale	Information	Main source
City scale	Climatic characteristics[1,2,3]	National institute of hydrology, meteorology, and environmental studies City's water utility Environmental agencies – city and regional
	Natural resources quality and state	Environmental agencies – city and regional City's botanical garden
	Private and public space	City's agency for urban planning and development City's agency for recreation City's agency for economic development.
	City drainage	City's water utility
	Land use	City's spatial data institution City's urban planning agency
	Population characteristics	National Administrative Department of Statistics
	Possible outcomes of NbS implementation	Torres *et al.* (2021)
	City's NDVI	Torres Cajiao (2019). Estimated with 20 satellite images from Sentinel 2 with a resolution of 10 * 10 m.
	City's soil characteristics	Universidad de los Andes; Centro de Investigaciones en Ingeniería Ambiental (CIIA) (2017); Pontificia Universidad Javeriana (2018).
Local Planning Unit	WQCV	Precipitation Depth: Universidad de los Andes; Centro de Investigaciones en Ingeniería Ambiental (CIIA) (2017) City's NDVI: Torres Cajiao (2019). Using a threshold value of 0.1 to qualify an area as permeable.
	Hydrological balance	Precipitation and evaporation from the weather station "INEM Kennedy" for 2010-2012 and 2015 (periods with high, low, and average precipitation).
	Composition of vegetation patches	City's botanical garden Aerial photographs
	Communal services and building's uses and location	City's spatial data institution
	Stormwater drainage system	City's water utility

[1] Dry months were characterized (i.e., December, January, & February) (Álvarez Lucero *et al.*, 2020), [2] Temperature: 1991-2018 (22 stations), [3] Precipitation: 1981-2018. Source: Elaborated by authors.

5. Results

5.1 *City Scale*

Six LCZ and 18 LCSZ resulted from considering eight variables with a significant relationship with the average maximum temperature for the analyzed period: elevation, residential use, tree canopy, NDVI, built density, water table, distance to main roads, and distance from transport stations. For each LCZ, cells were categorized into three LSCZs based on the magnitude of annual precipitation. For instance, LSCZ 1.1 has the highest precipitation, followed by LSCZ 1.2 and LCSZ 1.3. This enumeration is consistent within every LCZ.

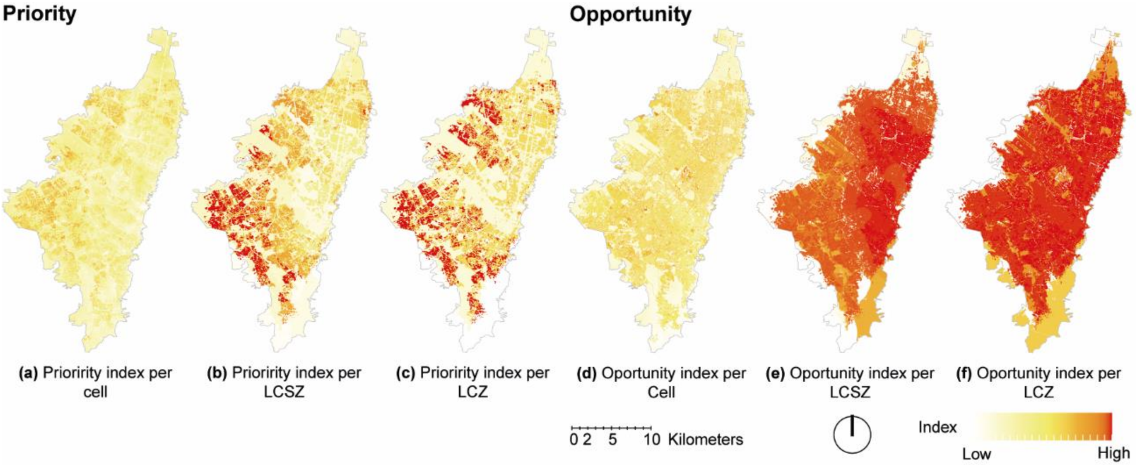
The results show spatial differences in the urban area regarding land use and the built environment. LCZ 1 constitutes a zone of particular interest for NbS needs, given its residential use, high building density, and low presence of vegetation. LCZ 2 presents a similar residential proportion to LCZ 1 but has a higher NDVI and lower building density, with more potential space for NbS implementation. LCZ 3 corresponds to areas closer to main roads, where linear and smaller NbS may be more convenient for stormwater management. Land use in LCZ 4 could make it less relevant for providing sociocultural services; however, that characteristic, along with the low density, can provide opportunities for support and regulation. LCZ 5 could facilitate sociocultural services given the residential use and low building density. However, some limitations result from its distance to main roads and transport stations. Similarly, the location of LCZ 6—high-altitude zones far from transport stations—could constrain interventions to a local impact.

The average weights used to aggregate the criteria resulted from interviewing three experts with various trajectories regarding NbS: two architects—including an author—that work in landscape design, and one environmental engineer with experience in NbS research. The experts' availability limited the sample. If possible, conducting more interviews is preferable to better capture diverse viewpoints. The main observed differences corresponded to the importance given to each ecosystem service category. For instance, for one of the architects, sociocultural services were less meaningful in assessing priorities and opportunities. However, for the other architect, these were decisive in priority determination. Only one of the architects did not give importance to regulation services in the priority analysis.

Regarding priority criteria, the criteria with a greater weight included population density, distance, and surfaces between the main ecological structure elements, and well density. The least relevant criteria for the participants included the length of canalization of lotic natural water bodies and river dike breach threats. The most influential criterion in opportunity assessment was the potential to increase vegetation in public areas. Also, some participants found having an audience relevant (i.e., interest sites and public space index). Participants gave less importance to slope and available private and public space because they saw the possibility of adapting the areas for NbS implementation.

Figure 5 presents the priority and opportunity index established by cell, LCSZ, and LCZ. In this figure, the aggregation per LCSZ seems to conserve the differences observed in the cell analysis. In general, the west part of the city appears to be prioritized under the different analysis units. LCZ 1 presents higher priority values, with the highest value seen for LCSZ 1.3. This area possesses large values for population-related criteria (e.g., population density, people from zero to four years and older than 65, and residential access deficit to parks), PM 2.5, and the precipitation and potential evapotranspiration ratio. LCSZ 1.3 includes a considerable portion in a risk area for fluvial issues. The analysis of opportunities, summarized in Figure 5, resulted in similar values for various LCZ and LCSZ. However, perimeter areas have a lower index value due to the lower average presence of public space. LCZ 1, 2, and 3 have similar high opportunity values, and LCSZ 2.1, 3.1, and 4.1 present more opportunities. Specifically, LCSZ 2.1 and 3.1 have more possibilities for improving public space surfaces. LCSZ 4.1 has more availability in zones to intervene (public and private), and public space has more potential for implementing NbS that contributes directly to amenity generation.

Figure 5. **Priority and opportunity indices by cell, LCSZ, and LCZ**

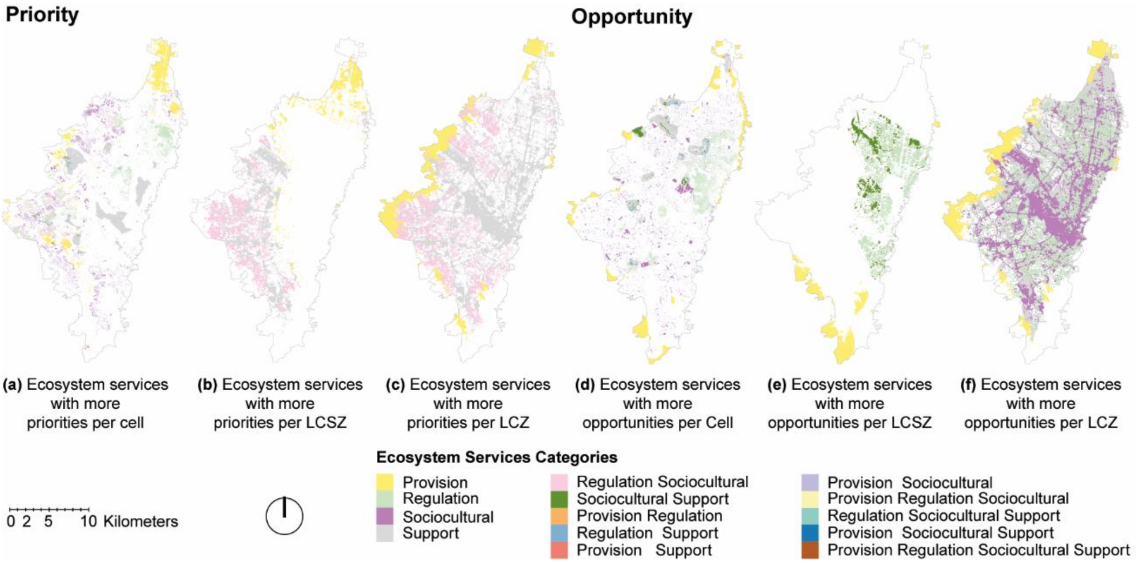


Source: Elaborated by authors.

Figure 6 summarizes the indices result for the ecosystem services categories by presenting the highest value for the LCSZ and LCZ and the values in the 95th percentile for the cells. This figure shows multiple requirements for various categories of ecosystem services in the southwest part of the city. This observation remains once the index is aggregated to LCSZ. Regarding opportunities, the potential to support sociocultural services is scattered within the urban area. However, the northeast of the city has multiple opportunities. Therefore, LCSZs in the region show higher opportunity values for regulation, sociocultural, and support ecosystem services related to a presence of large parks and wetlands.

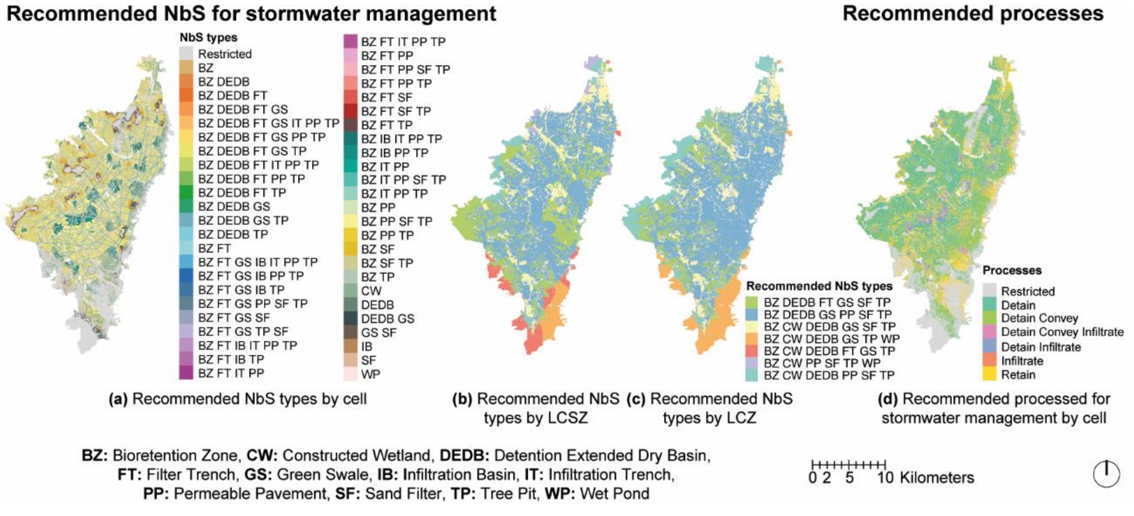
NbS requirements for stormwater management in terms of feasibility, infiltration, and distance to water table restrict systems like infiltration trench and infiltration basin. These systems are potentially applicable in less than 10% of the city area. The condition of a base flow limits wet ponds and constructed wetlands, but several zones have potential feasibility (i.e., around 23% for wet ponds). Bioretention zones, tree pits, and sand filters have a more extensive implementation potential across the city area, which is more than 60%.

Figure 6. **Ecosystem services with more priorities and opportunities per ecosystem service category by cell, LCSZ, and LCZ**



Source: Elaborated by authors.

Figure 7. **Recommended NbS per cell, LCSZ, and LCZ, and processes for stormwater management per cell**



BZ: Bioretention Zone, **CW:** Constructed Wetland, **DEDB:** Detention Extended Dry Basin, **FT:** Filter Trench, **GS:** Green Swale, **IB:** Infiltration Basin, **IT:** Infiltration Trench, **PP:** Permeable Pavement, **SF:** Sand Filter, **TP:** Tree Pit, **WP:** Wet Pond

Source: Elaborated by authors.

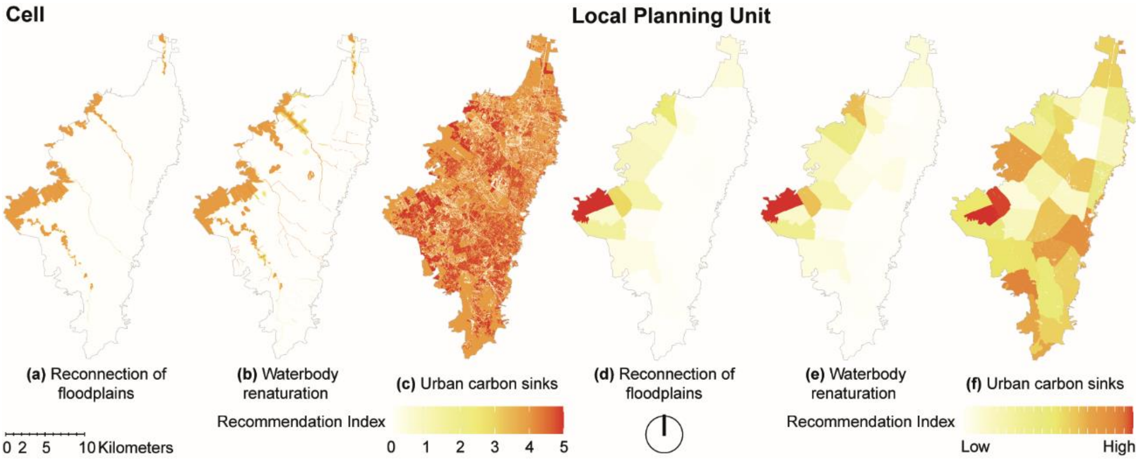
Figure 7 summarizes NbS recommendations supplied to the design team. Figure 7a illustrates a set of NbS types under the developed methodology. Both, Figure 7b, and c, summarize the recommendations by LCSZ and LCSZ. LCSZ presents a wider set of groups of NbS types, where bioretention zones are usually part of the recommendations. Wet ponds are recommended in peripheral areas in the southern part of the city. Infiltration NbS types are not part of any group due to the reduced potential space, mainly because of these two requirements: infiltration rate and distance to the water table. Figure 7d displays the stormwater treatment processes, showing a prevailing potential for detention and conveyance processes across the city. Thus, some central and peripheral areas are strategic for retention and infiltration.

5.2 Local Planning Units

Figure 8 presents the NbS recommendations for conservation and green infrastructure for the cells and LPU. The highest values for implementing reconnection of floodplains and waterbody renaturation are concentrated in the western margin of the city. Regarding urban carbon sinks, the southern and eastern parts of the city present the highest index values. In this zone, three LPUs could be of interest for implementing the three considered NbS.

The LPU Patio Bonito was selected for the design exercise since it is located where more overlapping areas for opportunity and priority occur. Additionally, it has a network of historic artificial drainage channels built in response to persistent flooding events. The area is below the Bogotá River level, resulting in a high threat of flooding (IDIGER, 2018). In 2011, as a consequence of the La Niña phenomenon and sediment accumulation in the Bogotá River, flooding affected several people in the Calandaima and Patio Bonito neighborhoods and negatively impacted public infrastructure (ibid.). Therefore, improving the area's resilience to extreme climate events could be beneficial.

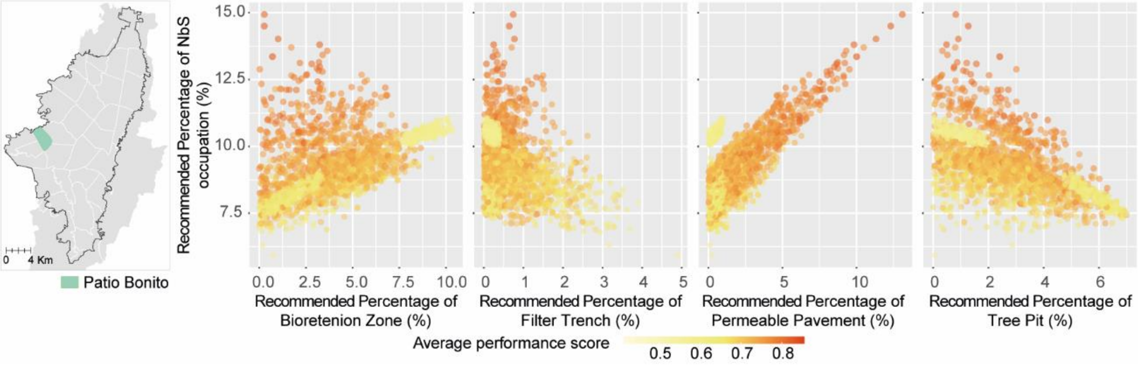
Figure 8. **NbS for conservation and green infrastructure recommendations by cell and Local Planning Unit**



Source: Elaborated by authors.

Size recommendations were established for the LPU in Patio Bonito by assessing 2,000 configurations for three stages to manage stormwater and multiple NbS types. All configurations considered aimed to represent different combinations of NbS implementation, but this number was limited by the time required to evaluate each scenario. Figure 9 shows the results for the first stage (i.e., source treatment) of the 2,000 configurations, which is the first condition to manage the WQCV. This figure represents variability between the expected performance and the recommended area percentage of a specific NbS type due to other components' characteristics. The information provided to the design team aspired to replicate the application of this information available at the LPU for specific projects. In this sense, the percentages were adjusted using the NbS proportion for stormwater management in the intervention area and the LPU. This adjustment implied the exclusion of NbS types that were not feasible in the area, such as permeable pavements, constructed wetlands, and wet ponds.

Figure 9. **Recommended percentage of area for the first component (source treatment) of NbS for stormwater treatment, and average performance score for the LPU “Patio Bonito”**



Source: Elaborated by authors.

Within the LPU, an area of 41.3 ha was selected, considering the existence of diverse urban typologies around a channel. Diverse typologies were considered because they increase the possibilities of open space transformation. The site corresponds with the neighborhoods of Calandaima and Patio Bonito, which are separated by the Calle 38 Sur Channel. Calandaima has structured green space and a reticular layout. Conversely, Patio Bonito is dense and compact with a small amount of permeable or vegetated area.

Following the proposed methodology, seven vegetation species were found as the most suitable species for ecological connectivity. These species are part of the ten most common species in the study area and the vegetation recommended by Bogotá’s Botanical Garden (Álvarez Lucero *et al.*, 2020). Therefore, the design proposes to increase the number of patches containing primarily: *Tecoma stans* (Yellow Bells), *Schinus molle* (False Pepper), *Eugenia myrtifolia* (Eugenia), *Callistemon viminalis* (Weeping Bottlebrush), *Hibiscus rosa-sinensis* (Chinese Hibiscus) and *Sambucus nigra* (Black Elder).

Inside the 41.3 ha, there are two schools, one technical school, five communal centers, and one kindergarten. Within 500 m of the intervention perimeter, there is a sports center, two technical institutes, two schools, one base care center, and three communal centers. The area surrounding these buildings and the roads that connect them are possible community gathering areas. Therefore, these areas are considered hotspots for NbS implementation.

One of the major schools (Cafam Bellavista) is selected to host future events and interventions to foster the relationship between design and the community. This school is in a cluster of communal services and has some open space available for NbS implementation. According to Krajnović, M. et al, 2023, multipurpose school outdoor spaces that are shared with a community benefit both the students and the city by improving children educational process and urban services.

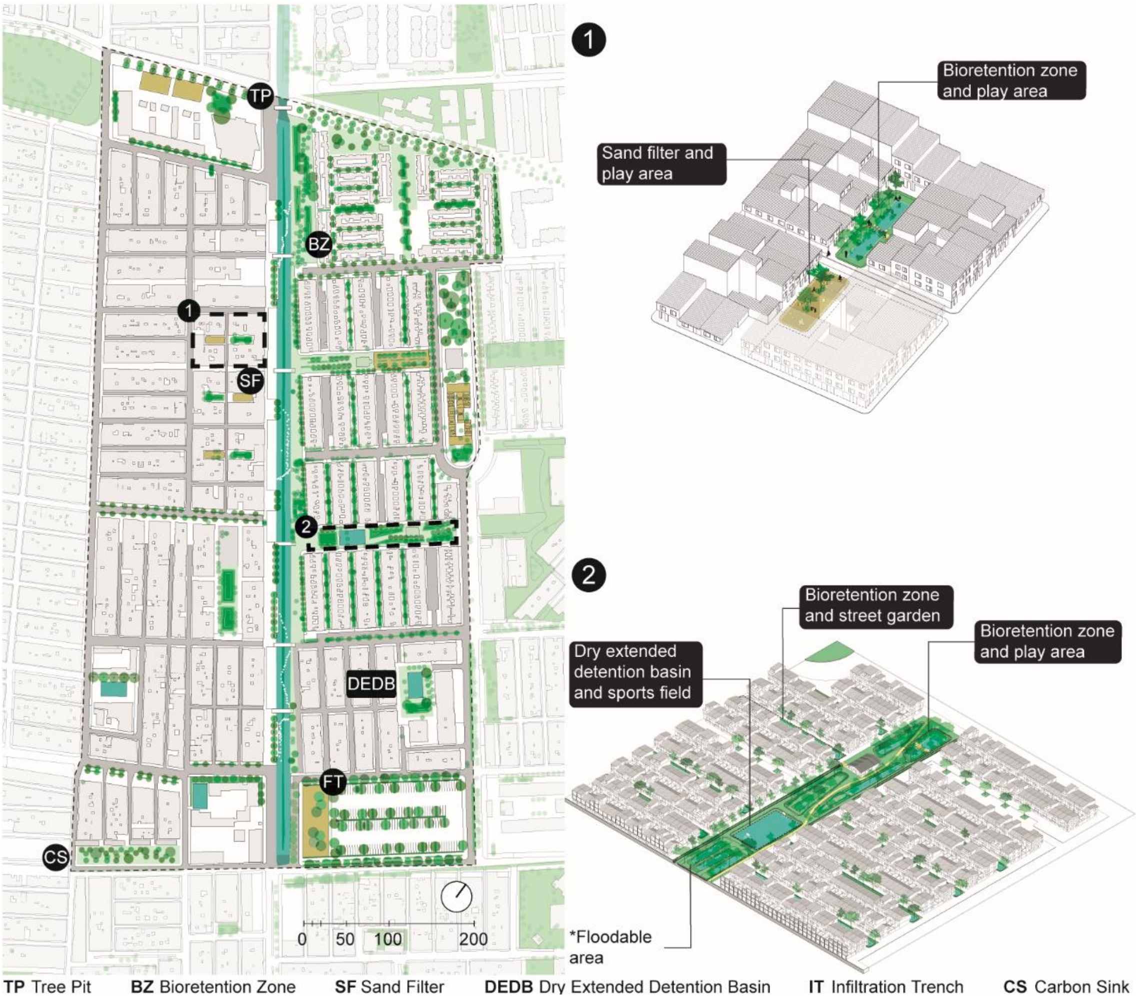
The area has a separate drainage system from the Calle 38 Sur channel that conveys the collected runoff. This channel flows into an interceptor channel within a sub-basin of 26 km^2 that directly discharges to the Bogotá River. The intervention area is situated at a midpoint of the Calle 38 Sur channel, where collected runoff in some upstream areas flows towards the southeast margin. A small part, close to the southwest margin, drains to an underground collector that discharges directly to the interceptor channel. Various zones have superficial drainage elements that could be an opportunity to intercept and manage the runoff before it enters the underground system.

Design results are presented in Figure 10 and Figure 11. Design 1 uses a reticular composition to guide the public space design to adapt to the scarce available space. The linear geometry varies according to NbS technical requirements while helping create a greener urban landscape. The project aims to establish a place where vegetation and green areas dominate the landscape perception.

Streets, basketball courts, playgrounds, and parking lots are transformed into multipurpose areas where water management and ecological connectivity are added as functions. Current pedestrian streets include bioretention zones and tree pits. Some on-street parking is replaced with tree pits. Basketball courts are transformed into dry extended detention basins surrounded by infiltration trenches and gardens. Sand filters are proposed as playgrounds.

Tree pits replace some parking spots in a large parking area. Filter trenches are also added to the parking area's perimeter. Additionally, the parking lot area is reduced to give way to a bioretention zone, sand filters, and tree pits. This area is also used as a playground.

Figure 10. **Design 1**



Source: Elaborated by authors.

The channel maintains its original geometry with some modifications on its banks. The adjacent topography is altered to create a corrugated space to retain water in bioretention zones and dry extended detention basins. Banks permit access to the waterbed, where it is possible to walk on top of a stone pathway.

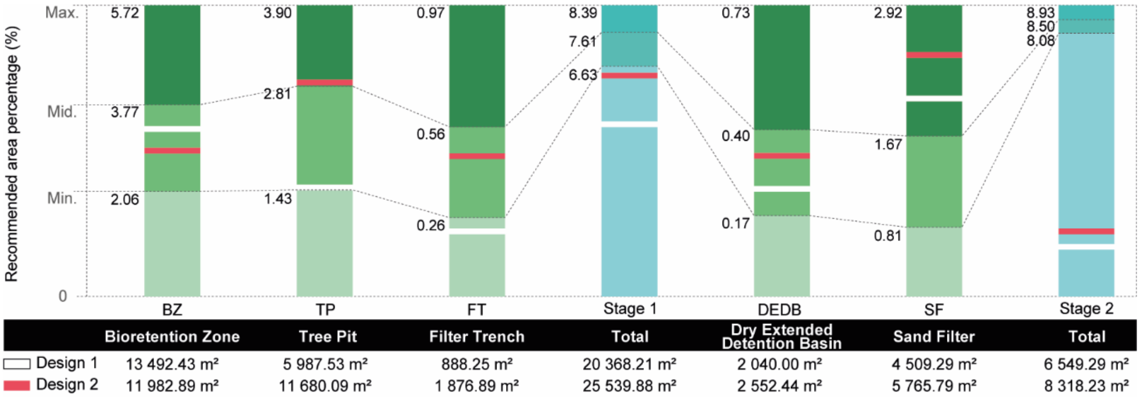
Design 2 modifies the previous proposal to achieve the required percentages. In this case, private spaces are included. Therefore, open spaces found at the Cafam Bellavista school and a gated residential complex are transformed into multifunctional areas with bioretention zones, sand filters, and dry extended detention basins. The channel's design is also transformed to include additional sand filters, infiltration trenches, and tree pits.

Figure 11. **Design 2**

Source: Elaborated by authors.

Figure 12 summarizes the coverage of each NbS type for the two designs, with lower values for Design 1. NbS coverage in Design 1 corresponds to 74.9% of the minimum suggested NbS use for Stage 1 and 19.8% for Stage 2. Regarding the percentages per NbS type, most areas are above the minimum. Nonetheless, filter trenches corresponded to 82.3% of the minimum recommended area for this NbS type, and tree pits are only 2% above the minimum. Hence, Design 1 may be sub-estimating the required area for frequent precipitation events. Also, bioretention zones constitute more than half of the extent for NbS. Tree pits follow this NbS type, with 22.2% of the NbS area. In Design 2, the coverage for Stage 1 NbS is 93.9% and 25.1% for Stage 2. This design fulfilled the minimum area for each NbS type and changed the area distribution. Specifically, the designers gave similar areas to bioretention zones and tree pits—around 35% of the space allocated for stormwater management. So, Design 2 provides more space for NbS and does not lean on one specific NbS type.

Figure 12. **Area percentages for Design 1 and Design 2 compared to recommendations**



	Bioretention Zone	Tree Pit	Filter Trench	Total	Dry Extended Detention Basin	Sand Filter	Total
☐ Design 1	13 492.43 m²	5 987.53 m²	888.25 m²	20 368.21 m²	2 040.00 m²	4 509.29 m²	6 549.29 m²
🟥 Design 2	11 982.89 m²	11 680.09 m²	1 876.89 m²	25 539.88 m²	2 552.44 m²	5 765.79 m²	8 318.23 m²

Source: Elaborated by authors.

Both designs leave room for flexibility, aiming to achieve a “high acceptance, high influence” community engagement (Everett *et al.*, 2021). The design stage presented is only a schematic design that could serve as a conversation starting point with a possible future approach to the community. According to Everett *et al* (2021), a flexible design is the key to achieving effective community engagement.

6. Discussion

6.1 NbS for Conservation and Green Infrastructure

The results showed the suitability of the LCSZ as a planning unit to support decision-making for NbS implementation. Using LCSZ has the potential to help identify strategic areas, integrate multi-scale issues, and aid in formulating potentially replicable NbS interventions. Firstly, in the case study, the aggregation of the priority index from cell to LCSZ draws similar conclusions about the city requirements (see Figure 5 and Figure 6), which can guide the selection of intervention areas based on the priority level. In the opportunity analysis, the highest values for the indices at the LCSZ level for each ecosystem service category allow for the differentiation of areas that comparatively have more potential to improve the provision of ecosystem services in specific categories (see Figure 6). Finally, recommended NbS types by LCSZ constitute a guide for implementing sustainable stormwater management that integrates ecosystem services priorities and opportunities. LCSZ is preferred over LCZ because of the increased variety of the recommended types.

Additionally, results regarding priorities and opportunities reinforce the idea of prevalent spatial inequalities and the need for NbS to be strategically placed to enhance this condition. As shown in Figure 6, the city’s southwest area is a convergence point of various issues, and NbS implementation could improve multiple ecosystem services in these zones. Nonetheless, higher opportunities regarding sociocultural, support, and regulation categories are in the northern part of the city. In this regard, the indices can contribute to spatial equity by engaging multiple stakeholders and capturing diverse issues (Heckert and Rosan, 2016; Venter *et al.*, 2021), making weighting a determining factor. Therefore, subjective weights and ecosystem service category inclusion for priorities and opportunities assessments sought to integrate different viewpoints to perform a multicriteria analysis. However, new iterations over the importance assigned to the criteria and aspects could favor the methodology’s capabilities.

One of the suggested methodology’s limitations is not fully integrating changes in land use, which conflicts with its potential for urban planning. Several authors have recognized the relationship between urban planning and NbS planning (Kuller *et al.*, 2019; Lourdes *et al.*, 2022), but current methodologies and frameworks usually treat them as two different processes. In this context, the approach presented by McHarg (1992) sets a precedent for joining urban and NbS planning together through ecological urban planning, where the territory provides urban planning information through the intrinsic value of non-developed land. The developed methodology embodied a first step to translating this approach to the context of urban renewal in the traditional development scenario. Nevertheless, future work should encompass expected land use changes and non-urbanized areas.

The presented methodology allows for identifying criteria in other cities aiming to implement NbS for stormwater management. Similarly, the characterized criteria can be useful for private practitioners interested in supporting information about the benefits of NbS implementation and its impact on ecosystem services. In this sense, the results can contribute to the availability of the knowledge required to achieve systematical implementation of NbS (Keeley *et al.*, 2013).

6.2 NbS Design

Due to the reformative nature of the expected interventions and uncertainty related to zoning in this type of project, information regarding the specific allocation of NbS was not part of the inputs. Cartographic information (see Figure 7) comprised suitable NbS and processes for stormwater management without establishing a scheme for NbS implementation. However, areas with feasible NbS did not always overlap with the available space. Therefore, the designers localized the NbS according to the public space and used the information provided on recommended types and processes for stormwater management as a list. As a result, Design 1 presented an unbalanced distribution of NbS because public space was unequally present in the study area. Also, the design team minimized changes in land use to reduce the need for demolitions and relocations. Nonetheless, the architects' use of the information to support their feasibility analysis for the appropriated NbS according to the available space improved their design proposal. For example, they added an urban carbon sink after analyzing conservation and green infrastructure development options (see Figure 8).

To allow a more flexible design process, a range of percentages was provided instead of a unique value. Thus, the area percentages aimed to contribute to the initial stages of the design process by establishing storage needs for stormwater management in an LPU. As a result, the architects could assess their proposed scheme without being constrained to a unique solution. In Design 2, the use of these values showed an initial sub-estimation of the required area in Design 1. Also, the percentages promoted the inclusion of diverse NbS types, initially disregarded in favor of the preferred solutions (i.e., bioretention zones). These results show that this information addresses knowledge gaps and leads to a more varied and site pertinent solution, which is congruent with resilience attributes (Palazzo, 2019). This observation is consistent with the results of Kwak *et al.* (2021), who concluded on the role of scientific evidence in producing more resilient designs. However, a quantitative analysis of the project performance is missing to be certain of the impact that area percentages will have.

Although the provision of percentages aimed to involve hydrological aspects, these numbers constitute an approximation and have some constraints resulting from the selected analysis unit. Namely, better results are expected from an intervention closer to the analysis unit because the assessment of average characteristics supports the recommendations. For instance, feasible NbS types may vary between the analysis unit and the intervention zone. In the case study, permeable pavements were not viable, which added to the low available areas and determined a lower percentage of potential NbS implementation.

As a result, the NbS areas in Design 2 were below the recommendations for the first stage. Also, even when the total designated area for stormwater management (i.e., Stages 1 and 2) would most likely allow the treatment of the WQCV for the area, multistage treatment would not be possible for most of the runoff volume. In this sense, stormwater control with the considered NbS types could benefit from major urban renewal interventions to achieve the recommended areas. Alternatively, strategies for built spaces, such as green roofs, could be an option.

However, private space interventions could offer limited ecosystem services and be constrained by the local population's preferences. For example, 96 people were surveyed in surrounding neighborhoods, and 49% of those surveyed indicated that they preferred not to install alternative measures for stormwater management in their residences. Their reasons included a substantial amount of tenants, lack of space, and concerns about the time and monetary resources involved (Ortega, 2022).

This study proposed and evaluated an interdisciplinary framework integrating architectural design and engineering analysis. The design procedure focused on identifying preferences and possible improvements regarding the kind and format of the provided information. Firstly, data from recommended stormwater management processes was more suitable for the initial proposal by explaining the possible goals for stormwater management in a simplified manner. Hence, recommendations in terms of processes have the potential to construct a common language linking stormwater management and landscape design without inhibiting the creative process to preconceptions regarding the characteristics of each NbS type. In addition, as suggested by the landscape architect, the information on surface area percentages was complemented with the proportion of each NbS type to the total surface area with NbS for stormwater management. Subsequent work should evaluate the possibility of these percentages as a more effective way to provide the information per NbS type.

Future work should consider that different NbS types may require broader interdisciplinary work, including other professionals such as biologists, ecologists, and social scientists (BenDor *et al.*, 2018; Fryd *et al.*, 2010). Also, concerns regarding stormwater sources were secondary in the design process. For instance, interpreting the area percentages resulted in a challenge because Stages 2 and 3 were difficult to assign before identifying drainage areas for a particular NbS. That highlighted the need for more specific guidelines at this scale to influence the design process by including hydrological aspects.

WQCV analysis guided size recommendations, which allows for the management of frequent precipitation events, but needs to be complemented with stormwater quantity management goals. In a typical hydraulic and hydrological design process, additional depth will be provided for storage or safe control of less frequent events, considering the area requirements and NbS characteristics. Nevertheless, handling extreme precipitation events could require an additional area omitted in the recommendations. This approach is congruent with a multi-scale paradigm for stormwater management, where the aggregated effect of attenuation processes will contribute to a reduction in the need to control large flows by managing runoff on site (Woods Ballard *et al.*, 2015). Even when concerns regarding managing extreme events are frequent among stakeholders (S. M. Charlesworth and Booth, 2016; Jiménez Ariza *et al.*, 2019), these can conflict with establishing multi-functional spaces because large volumes and flows can create safety risks (Echols and Pennypacker, 2008). In this sense, the methodology aims to recognize the importance of different management scales for stormwater, which coincides with pursuing multiple benefits. However, supplementary planning recommendations could integrate suggestions for water quantity control on large scales, given watershed dynamics in the implementation of NbS for stormwater management.

7. Conclusions

This research developed a two-part methodology for identifying information type and format more suitable for including NbS in local planning. The steps aimed to materialize WSUD principles by translating multi-scale concerns to NbS recommendations for architects and landscape designers. The outcomes included determining that the LCSZ is an adequate planning unit for the case study, appraising the feasibility of supporting design through general recommendations, and identifying other requirements for more effective integration of NbS in planning. In this sense, quantitative goals for area occupation constitute a valuable input for designers to assign adequate space to NbS for stormwater treatment. Nonetheless, applying this type of parameters requires architectonic and landscape design methodologies to be complemented with holistic notions like WSUD.

The results of the first part showed that managing stormwater allowed us to address the WSUD pillars. Firstly, stormwater constitutes a resource that can increase amenity by enhancing public space conditions. Also, the analysis is based on ecosystem services' potential provision of NbS for stormwater management, establishing priorities and opportunities from the potential benefits of these systems. Finally, there is potential for community engagement in the different stages of the methodology and final NbS adoption, given the presence of sociocultural aspects in the analysis as an ecosystem services category.

This research constitutes a first step in coordinating engineers and architects in NbS for stormwater management with the creation of resources to support NbS planning and design. The approach proved to be useful, but it has some limitations. Mainly, it is necessary to explicitly integrate land-use changes, community concerns and preferences, and other water fluxes to manage the multiple urban water resources. Therefore, further methodology development would improve the link between NbS and urban spaces through planning processes.

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Authorship

First author: Design of the methodology, research, data analysis, writing and draft review. Second author: Research, data analysis and draft review. Third author: Research, methodology and draft review. Fourth author: Conceptualization of the research, spatial design, writing and draft review.

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