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A Multicriteria Planning Framework to Locate and Select Sustainable Urban Drainage Systems (SUDS) in Consolidated Urban Areas

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Abstract: The implementation of sustainable urban drainage systems (SUDS) is increasing due to their advantages, which transcend runoff control. As a result, it is important to find the appropriate SUDS locations to maximize the benefits for the watershed. This study develops a multiscale methodology for consolidated urban areas that allows the analysis of environmental, social, and economic aspects of SUDS implementation according to multiple objectives (i.e., runoff management, water quality improvements, and amenity generation). This methodology includes three scales: (a) citywide, (b) local, and (c) microscale. The citywide scale involves the definition of objectives through workshops with the participation of the main stakeholders, and the development of spatial analyses to identify (1) priority urban drainage sub-catchments: areas that need intervention, and (2) strategic urban drainage sub-catchments: zones with the opportunity to integrate SUDS due the presence of natural elements or future urban redevelopment plans. At a local scale, prospective areas are analyzed to establish the potential of SUDS implementation. Microscale comprises the use of the results from the previous scales to identify the best SUDS placement. In the latter scale, the SUDS types and treatment trains are selected. The methodology was applied to the city of Bogotá (Colombia) with a population of nearly seven million inhabitants living in an area of approximately 400 km^2. Results include: (a) The identification of priority urban drainage sub-catchments, where the implementation of SUDS could bring greater benefits; (b) the determination of strategic urban drainage sub-catchments considering Bogotá's future urban redevelopment plans, and green and blue-green corridors; and (c) the evaluation of SUDS suitability for public and private areas. We found that the most suitable SUDS types for public areas in Bogotá are tree boxes, cisterns, bioretention zones, green swales, extended dry detention basins, and infiltration trenches, while for private residential areas they are rain barrels, tree boxes, green roofs, and green swales.

Keywords: multiscale framework; runoff management; spatial analysis; SUDS location and selection; urban drainage planning; stormwater treatment train

1. Introduction

Increasing populations in cities and the resulting urban sprawl have been particularly marked in Latin America and the Caribbean. For example, in Colombia, the urban population has increased from 40% in 1951 to 78% in 2018 [1,2]. Unlike other countries in the region, urban growth has been concentrated in four major cities: Bogotá, Medellín, Cali, and Barranquilla [2]. As the rapid urbanization is often at the expense of the loss of valuable ecosystems and lands, serious environmental, social, and economic problems have emerged and are expected to worsen if cities fail in adopting sustainable urbanization practices. Although many concepts and definitions on sustainable urbanization have emerged, all of them refer with equal concern to environmental, governance, social, and economic sustainability [3]. In this context, sustainable urban drainage systems (SUDS) constitute an opportunity to enhance stormwater management offering multiple options for runoff control and additional benefits related with social [4], environmental [5], and economic aspects [6,7].

In the first place, SUDS reduce runoff volumes and peaks resembling the natural hydrological cycle through processes such as infiltration and detention [8–11]. Also, these systems improve the runoff quality via filtration, sedimentation, dispersion, and biological processes [10–12]. Furthermore, the presence of vegetation helps to create multifunctional spaces where runoff becomes an asset rather than a waste. As a consequence, SUDS have the potential to improve the landscape, enhance water quality, promote ecosystems connectivity, and reduce vulnerability to flooding thus helping the transition of urbanized areas to water sensitive or sponge cities [13,14].

Several types of SUDS can be implemented in public and private areas such as wet ponds, dry extended detention basins, constructed wetlands, grassed swales, bioretention zones, rain barrels, green roofs, and infiltration basins among others. Connected sets of these systems constitute stormwater treatment trains, which maximize the benefits related to runoff control. The performance of systems and trains depends on: (a) the physical, environmental and social characteristics of the emplacement; (b) the processes for runoff control, which include infiltration, detention, and conveyance; and (c) in the case of trains, the synergy between the SUDS types. For this reason, urban planning strategies involving SUDS could be developed to maximize their performance according to the watershed needs and stakeholders' perspectives. As such, a multiscale and multicriteria approach is fundamental to identifying the opportunities for SUDS implementation within a city.

Researchers have considered a variety of objectives and scales to plan for the proper location of SUDS. Objectives include runoff management, water quality improvement, and amenity generation. The most usual scales are regional, citywide, local, and microscale. Certain studies use compound indices and other GIS-based techniques to define priority areas according to hydrological and hydraulic aspects [15–19], socioeconomic and environmental aspects [17,18,20,21], and water quality issues [19]. Though, these studies have some limitations because most of the analyses correspond to the local scale and the microscale. Moreover, critical areas identified at a city scale are not used to develop specific strategies for more detailed scales. Steaming from these previous contributions in GIS applications, some other works have focused on the preferred optimal locations and configurations using benefit–cost analysis, exact optimization methodologies (e.g., linear and dynamic programming), meta-heuristics and, more recently, stochastic mixed integer linear programming that accounts for the variability of rainfall [22–27].

For example, Martin-Mikle et al. [15] defined a comprehensive methodology that includes four urban scales. However, they selected priority areas according to hydrological and hydraulic aspects only. Likewise, Garcia-Cuerva et al. [21] analyzed a watershed of 121 km^2 in North Carolina (USA) to define preferred SUDS locations and conducted a hydrological analysis of the impacts of SUDS implementation within a particular watershed sub-catchment, but they recommended areas by exclusively considering the population's socioeconomic attributes. Dagenais et al. [17] proposed a methodology in which the identification of priority zones was followed by the location of SUDS in a specific area. Nevertheless, this methodology was applied, in particular, to the local scale.

Some other studies have focused on SUDS' location assessing factors like: physical restrictions [17,28]; performance in runoff reduction, flooding mitigation, and water quality improvement [29,30]; scale, including street, neighborhood, and sub-catchment [28]; and whether the area is public or private [21,28]. The analysis conducted for the private space has generally disregarded the specific characteristics of these areas, however recent work related to permeable pavements (which can be used in a private space) considered such specific characteristics [26]. For instance, Gogate et al. [30] established alternatives for a primarily residential area, including green roofs due to the prevalence of flat roofs, but the analysis of specific spatial constraints for leaky wells and rain gardens was absent. Instead, the authors pre-selected SUDS types by evaluating the systems suitability in a developing country based on a thorough literature review and the general characteristics related to residential and commercial land use in the area. Garcia-Cuerva et al. [21] evaluated public and private space to implement bioretention cells and rainwater harvesting systems. However, in this study, the SUDS location only considered land use (i.e., commercial, residential, institutional, and vacant land) and omitted possible site-related restrictions of these systems, such as the maximum recommended slope.

Regarding SUDS selection, the definition of the best system or set of structures have comprised two main approaches: (a) performance evaluation through models to determine runoff volume reduction [30,31], and (b) multicriteria analysis considering qualitative and/or quantitative explanatory variables mainly at local scale and microscale [32,33]. The use of models can involve a high computational cost and requires detailed information that is not always available, particularly for a preliminary evaluation. Nonetheless, it is important to define recommendations and general directions for the city over the spectrum of SUDS alternatives. Therefore, multicriteria qualitative analysis is essential to conducting preliminary analyses for SUDS selection in a specific area.

Few studies have focused their attention on connected sets of SUDS or train selection. One example is the work of Charlesworth et al. [34], who defined a management train to mitigate flood events. They categorized the city area according to recommended SUDS types considering a hierarchy for stormwater control processes—giving priority to source control and infiltration. However, development of tools to select SUDS types classified under the same control process is required to define specific alternatives according to the potential benefits of each SUDS type.

In Latin America and some developing countries, the examples of SUDS prioritization are limited and usually focus on hydraulic and hydrological aspects. For example, Mora-Melià et al. [35] identified critical points for the installation of green roofs based on flooding reports in Curicó (Chile). Likewise, Gogate and Rawal [36] outlined a methodology to recognize places to conduct artificial groundwater recharge in the city of Pune (India). On the other hand, the few studies that included SUDS selection did not consider larger spatial scales (i.e., city scale). For instance, Petit-Boix et al. [37] developed a methodology that included life cycle analysis (LCA) for the selection of SUDS for an area of 0.42 km^2 in São Carlos (Brazil). In addition, Gogate et al. [30] proposed a multicriteria analysis to select strategies of SUDS implementation in a watershed (11.71 km^2) in Pune.

Analysis at city scale is fundamental for decision-making at smaller urban scales. Additionally, due to the multiple benefits from SUDS, these systems could be compared through multicriteria analysis, which include environmental, social and economic aspects, rather than only hydraulic and hydrologic criteria enhancing the common practice in several countries. Equally important is the analysis of private areas, where it is fundamental to evaluate site-specific restrictions (e.g., slope, infiltration rate, or distance to the water table). Nonetheless, there are few examples considering these aspects in the literature, which constitute gaps for the decision-making of SUDS implementation. For this reason, the present study defines a multiscale-planning framework to identify strategic and priority urban drainage sub-catchments in consolidated urban areas, and it recommends specific SUDS types and treatment trains on public and private areas. The methodology involves analyses at three scales: citywide, local scale, and microscale. At city scale, priority and strategic areas are identified according to stakeholders' interests and characteristics of the territory by means of the analysis of georeferenced information. At local scale, public and private spaces are evaluated considering slope, infiltration rate, water table, and distance to buildings. The microscale includes a process to select SUDS types and SUDS treatment trains. The city of Bogotá (Colombia) was selected as a case for the study of the application of the proposed methodology.

2. Materials and Methods

A methodology to guide SUDS implementation is proposed at three spatial scales: (1) citywide scale, (2) local scale, and (3) microscale. This approach intends to select a location and systems according to the watershed needs and stakeholders' preferences. Figure 1 describes the proposed methodology by summarizing the main activities at each step, the required information, and the expected results.

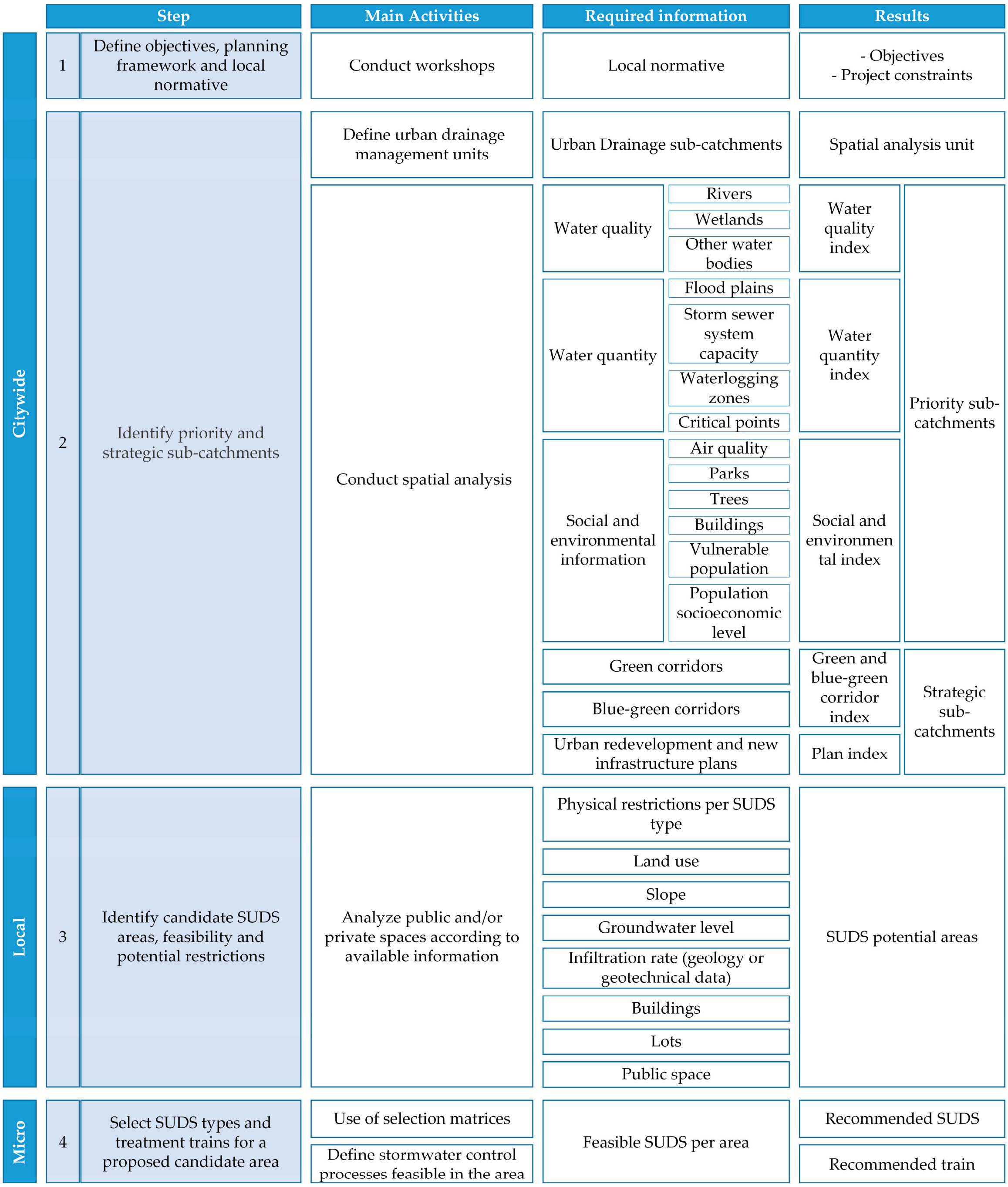


Figure 1. Multiscale methodology for sustainable urban drainage systems planning.

2.1. Citywide Scale

The main purpose of the analysis conducted at this scale was to spot urban drainage sub-catchments to address the defined citywide objectives. In this sense, two main steps are developed: (i) to define the citywide objectives using stakeholders' multicriteria perspectives, gathered by means of workshops, and (ii) to identify priority and strategic sub-catchments appraising available georeferenced information.

One important element in multicriteria decision problems is the weighting method used, which can be subjective or objective. Subjective methods base the definition of weights on preferences of the decision makers. Nevertheless, subjective weighting can have some disadvantages given that the knowledge and experience of the stakeholders may condition the results [38]. Objective weighting disregards subjective judgment and is based on mathematical procedures. Generally, the weights depend on the variability or correlation of the performance of each alternative for the evaluated criteria [38]. Both approaches are integrated into the methodology because they could generate significant differences between the territory's needs and the stakeholders' preferences in the initial phases of SUDS implementation.

2.1.1. Definition of Citywide Objectives and Their Subjective Weighting

The recognition of stakeholders' perspectives is essential when it comes to including SUDS in urban planning. Therefore, the methodology proposes workshops to identify priority aspects for different stakeholders and to improve the understanding of their vision with regards to the stormwater drainage system. The structure of the workshops is based on the soft systems methodology (SSM) developed by Checkland [39] and applied by Sánchez & Mejía [40]. This methodology deals with complex problems linked to multiple stakeholders' perceptions. For this research, the SSM involves three parts: (a) open questions about SUDS (i.e., advantages, disadvantages, components, objectives, limitations, and stakeholders' responsibilities), (b) conceptualization of the urban drainage system using a CATOWE (Customers, Actors, Transformation process, World view, Owners and Environmental constraints) analysis, and (c) closed questions about SUDS (i.e., citywide objectives, selection criteria, performance evaluation, limitations) in which the participants assign scores from zero (0) to three (3), where zero (0) means that the aspect is not applicable, one (1) that it is of low importance, two (2) moderate importance, and three (3) high importance. The delegates score objectives related to water quantity, water quality, and social aspects. The results from the workshops should be analyzed according to the existing regulations to identify shortcomings and to evaluate the stakeholders' interpretations.

2.1.2. Priority Urban Drainage Sub-Catchments

Priority urban drainage sub-catchments are areas that need an intervention due to problems related to runoff management or the characteristics of the environment. Several criteria can be analyzed to generate a qualitative index for the urban area according to three main objectives: (1) water quality improvements, (2) runoff management, and (3) amenity improvement. The relevance of these objectives depends on the stakeholders' judgment.

The analysis of the main urban water bodies guides the identification of priority urban drainage sub-catchments for water quality improvements. In this case, it is proposed to consider four commonly used water quality determinants as criteria [41]: Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorus (TP). The values of these determinants are classified as high, medium, and low, where high indicates high concentrations of nutrients, solids or organic matter. A global index is defined for the rivers and wetlands according to the highest classification considering all determinants. Finally, this index is assigned to the closest urban drainage sub-catchment.

The analysis for runoff management incorporates information about storm sewer system capacity, waterlogging zones, critical points (i.e., points with insufficient hydraulic capacity), and urban river flood plains. These variables can include qualitative and quantitative information. Hence, a standardized classification from zero (0) to one (1) is defined, where 0 refers to the absence of data, 0.25 low priority, 0.5 medium-low priority, 0.75 medium priority, and 1 high priority. To draw up a water quantity index, the highest value in any of the four criteria is selected and assigned to the urban drainage sub-catchment.

Social and environmental criteria are analyzed to identify places where amenity generation is necessary due to the presence of a vulnerable population and poor environmental conditions. The selected criteria were defined according to previous studies that developed similar indices [17,18,20]. These studies identified the vulnerable population according to age [17,18,20], education [20], income [20], housing [18], and ethnic background [17,18,20]. As for the environmental variables, the analysis considers air quality, access to parks, vegetation, and impermeable surfaces among others [18,20]. The selection of the variables depends on the available information and the city characteristics. Hence, the proposed criteria are: (a) air pollutants with highest values in accordance with the local air quality index, (b) distance to parks, (c) trees per hectare or population, (d) occupied area, (e) infant and elderly population per hectare, and (f) low socioeconomic level residential areas. Regarding the distance to parks, we calculated the ratio of the number of residential lots within a radius of 300 m from parks with an area bigger than one (1) hectare to the total residential lots per unit of analysis as proposed by Ekkel and de Vries [42].

In each case, a normalized index from zero (0) to one (1) was defined. This index is obtained by subtracting the lowest value and dividing it by the range of values of each criteria [20]. For the environmental variables, in cases where a benchmark relative to city norms or international standards exists, this value is adopted as the maximum. For the distance to parks and trees per hectare, the index is defined as one minus the index, because in such cases the maximum value represents the best condition.

The average of three objective weighting methods was used to define the social index and the prioritized urban drainage sub-catchments according to water quality improvements, runoff management, and amenity improvement: (a) Entropy Method [43], (b) Criteria Importance Through Inter-criteria Correlation (CRITIC), and (c) Principal Components and Factor Analysis [44]. For CRITIC, the method was applied according to the modifications proposed by Jahan et al. [45]. A classification was made according to the percentiles 0.25, 0.5, 0.75, and 1.

2.1.3. Strategic Urban Drainage Sub-Catchments

Strategic urban drainage sub-catchments correspond to zones with the opportunity to integrate SUDS in the city, due to the presence of natural elements or future urban infrastructure works. Two main characteristics are analyzed: (a) the presence of green and blue-green corridors; and (b) urban redevelopment and new infrastructure plans. Green corridors are defined as longitudinal green spaces that can be composed of green road dividers or parks, whereas blue-green corridors are comprised of water bodies with green areas around them. Green and blue-green corridors are considered strategic because they favor superficial drainage. Also, their identification is essential to integrate multiple public spaces using treatment trains. With respect to urban development and new infrastructure plans, these can provide an opportunity to integrate SUDS in public areas.

According to the characteristics of the green and blue-green corridors, an index is calculated for every urban drainage sub-catchment. The characteristics considered for blue-green corridors analysis include the approximated total length within the urban perimeter and the area inside the unit of analysis. In this case, the total length was used as a proxy of connectivity. Green corridors are assessed according to their width, length, area, and distance to a blue-green corridor. The connectivity is evaluated through the distance to a blue-green corridor. Also, the geometric variables allow us to determine the potential intervention area. These characteristics are normalized and added to define an index for blue-green corridors and green corridors. This is done by subtracting the minimum value and dividing the result by the range of values. In the case of the distance to a blue-green corridor, the value used corresponds to one minus the index. Lastly, the two indices are added and normalized to define a combined index for the corridors. The percentiles 0.25, 0.5, 0.75, and 1 are used to classify the values into low, medium-low, medium, and high opportunity.

The main urban redevelopment and new infrastructure plans were selected and categorized according to their stage and activity. Table 1 shows the stages and activities considered. The stages correspond to the degree of progress of the plan. For example, the reserved stage means that the plan would be included in a future project. The excluded stage refers to plans that were left out of projects, and the commissioned stage refers to plans being assigned to a project. If information about the stage is absent, the plan is assumed to be in an early stage to assign the score. The activities refer to the type of intervention to be made. For instance, adaptation corresponds to infrastructure modifications, and reconstruction to the full replacement of an existent structure. Also, the plans are graded in relation to the public elements (roads, sideways, bays, among others) that are part of them, as presented in Table 2. It is worth mentioning that Table 2 does not pretend to be exhaustive, but illustrative of the main urban elements in which SUDS can be placed. Higher scores are given to the most suitable elements for SUDS implementation.

Table 1. Scores for plan stages and activities.

Stage / Activity	In Progress	Commissioned	Excluded	Reserved	Suspended	Completed	No Data
Prefeasibility or feasibility studies	4	4	0	4	1	4	3
Studies and designs	2	3	0	4	1	1	2
Adaptation	0	0	0	3	0	0	0
Conservation	0	0	0	3	0	0	0
Construction	0	0	0	3	0	0	0
Diagnostic	0	0	0	0	0	0	0
Road improvement or maintenance (regular or occasional)	0	0	0	0	0	0	0
Reconstruction	0	0	0	3	0	0	0
Road rehabilitation	0	0	0	2	0	0	0
No data	0	0	0	0	0	0	0

Table 2. Scores for public elements.

Element	Score
Tree-lined roads	4
Sidewalk	4
Parking bay	4
Road	1
Bike trail	2
Bus station	1
Square	4
Main bus station	2
Pedestrian bridge	2
Vehicular bridge	1
Road divider	4
Ramp	2
Green areas	4
Cable car facilities	1

For each infrastructure plan, scores from zero (0) to four (4) are assigned according to Tables 1 and 2. A score of zero (0) refers to a non-relevant plan or element. A score of four (4) means that the element is part of the public space system, or the activity is pertinent, and the plan is in its early stages (e.g., prefeasibility studies in a reserved area). These scores are compared, and each plan is qualified with the lowest score between them. Later, the score of the set of plans that are inside every unit of analysis is added. A normalized index from zero (0) to one (1) is established according to the maximum score within an analysis unit. The values are classified according to the percentiles 0.25, 0.5, 0.75, and 1.

2.2. Local Scale

Public and private spaces are analyzed to determine the feasibility of twelve SUDS types: (1) grassed swales, (2) infiltration trenches, (3) permeable pavements, (4) wet ponds, (5) bioretention zones, (6) tree boxes, (7) sand filters, (8) constructed wetlands, (9) soakaways, (10) infiltration basins, (11) extended dry detention basins, and (12) rain barrels and cisterns. In addition, for private constructions the implementation of green roofs is considered. The selection of these SUDS types was based on an extensive literature review that included several design manuals and guidelines worldwide. Reviewed manuals and guidelines included six to fourteen SUDS types—excluding pre-treatment and other complementary structures—and the selected SUDS types correspond to the most commonly presented [46–68].

SUDS screening for the public space considers the type of space, site-specific restrictions, and spatial requirements. Type of space includes parks (P), squares (S), roads dividers (R), sidewalks (W), and parking lots (Pa). Site-specific restrictions comprise slope, distance to the groundwater level, infiltration rate (obtained from citywide geology or geotechnical datasets), and distance to foundations. Water storage capacity was not included as a restriction at this scale, thus it has to be considered when assessing the performance of the selected SUDS types. Spatial requirements cover minimum area, length to width ratio, and length. These requirements depend on the SUDS type and they are part of the feasibility evaluation of the ones with larger area requirements. In any case, the potential spaces must have a minimum area of 1 m^2. The considered restrictions are applied in all available public and private areas, and the specific values are presented in Table 3. Furthermore, the proximity to channels and pipes constitutes an additional criterion because it determines whether the suitable areas could be connected to the conventional drainage system. Also, some areas are discarded for the implementation of wet ponds and constructed wetlands because of their distance to channels and streams. The latter only evaluate the potential for connection, thus more detailed analyses are needed to assess the actual capacity of pipes, channels, and streams.

Table 3. Implementation constraints of sustainable urban drainage systems (SUDS).

		SUDS Type										
Parameter	**Restriction Type**	**Grassed Swales**	**Infiltration Trenches**	**Permeable Pavements**	**Wet Ponds**	**Bioretention Zones**	**Tree Boxes**	**Sand Filters**	**Constructed Wetlands**	**Soakaways**	**Infiltration Basin**	**Extended Dry Detention Basin**
Slope (%)	Maximum	10 [1]	5 [1]	5 [1]	15 [1]	10 [1]	10 [1]	5 [1]	15 [1]	15 [9]	3 [4]	15 [1]
	Minimum	1 [11]	1 [2]	0.5 [3]	-	-	-	1 [2]	1 [5]	-	0 [3]	1 [2]
Distance to groundwater level (m)	Minimum	1.5 [1]	3 [2]	3 [8]	1.3 [7]	1.8 [3]	1 [3]	1.5 [1]	1.3 [7]	1 [4]	1.2 [7]	3 [1]
Infiltration rate (mm/h)	Minimum	13 [3]	7 [7]	13 [3]	-	7 [10]	7 [10]	13 [7]	-	13 [7]	13 [7]	7 [2]
Distance to foundations (m)	Minimum	4 [9]	6 [12]	6 [12]	6 [12]	6 [12]	2 [13]	1.5 [6]	6 [12]	6 [12]	6 [12]	6 [2]
Area (m^2)	Minimum	-	-	-	150 [14]	-	-	-	1000 [7,15]	-	45	45
Length to width ratio	Minimum	-	-	-	2:1 [14]	-	-	-	3:1 [4]	-	2:1 [6]	2:1 [6]
Width (m)	Minimum	-	-	-	8 [14]	-	-	-	18	-	5	5
Length (m)	Minimum	-	-	-	20 [14]	-	-	-	56	-	9	9
Public space	Type	P R	P R	S W Pa	P R	P S R W	P S R W	P R	P R	P S R W	P R	P R
Private space	Use [16]	Re C D	Re C D	Re C D	C D	Re C D	Re C D			Re C D		Re C D

(-) No data, (P) parks, (S) squares, (R) road dividers, (W) sidewalks, (Pa) parking lots, (Re) residential use, (C) commercial use, (D) public facilities. [1] [55], [2] [60], [3] [51], [4] [49], [5] [61], [6] [50], [7] [57], [8] [69], [9] [63], [10] [70], [11] [54], [12] [65]. [13] Recommendation from the local environmental agency (Secretaría Distrital de Ambiente, SDA) (2015), [14] [53], [15] [71], [16] [72].

The first step for private spaces analysis is to identify the land uses (e.g., residential, commercial, or industrial) to be considered, followed by an evaluation of the non-occupied portion of the selected land–use category, taking into account the restrictions presented in Table 3. The analysis of green roof feasibility focuses on identifying suitable constructions. Thus, two characteristics are considered: (a) presence of flat roofs and (b) a minimum area of 200 m^2—according to recommendations from Moore et al. [73]. The suitability of rainwater barrels and cisterns as rainwater harvesting (RWH) practices for capturing and storing stormwater for later use are evaluated conforming to other criteria. For the public space, the feasibility of underground cisterns depends mainly on the approximated storage volume and the distance to a pluvial drainage pipe (i.e., pipe with diameter below 0.6 m in a radius of 20 m). An area is considered suitable for cistern installation if the storage volume is above 10 m^3. For private spaces, water demand for non-potable uses and rainwater availability determines rain barrel feasibility. In this way, if there is a potential for rainwater harvesting the private area is considered suitable for a rainwater barrel. RWH has grown over the last decades as it has potential use for drought mitigation, increased demand satisfaction, reduction of stormwater runoff volumes, and pollutant loads [74–84].

2.3. Microscale

2.3.1. Site Selection

Site selection was driven by the results at citywide and local scales. The best-case scenario is when an urban drainage sub-catchment has been defined as priority and strategic, and there is available space. In this sense, the urban drainage sub-catchment rated with the highest scores for priority and strategic criteria was evaluated. After that, according to the available space, specific areas were chosen for SUDS implementation.

2.3.2. Selection of SUDS

SUDS selection depended on their performance related to multiple aspects. Thus, a qualitative matrix was defined to compare the feasible SUDS types in an area. This matrix contains criteria related to stormwater quality improvements, stormwater volume reduction, amenity, maintenance, and costs. For each criterion, three levels are defined: high, medium, and low. In the case of quality improvement, high means over 80% pollutant load reduction, moderate indicates 30% to 80% of pollutant load reduction, and low corresponds to less than 30% of pollutant load reduction [85]. Table 4 presents the defined levels corresponding to the characteristics of the different SUDS types and information reported in the literature.

Table 4. Qualification according to efficiency in pollutant removal and relevant processes.

SUDS Type	Quality Improvement							Runoff Control		Amenity			Maintenance	Cost	
	Nutrients	Metals	Bacteria	Sediment	Oil and Grease	Trash and Debris	Filtration and Sorption	Volume Control	Maximum Discharge Control	Perception Improvement	Interference with Activities on Site	Safety risks (users)	Activities and Risk of Clogging	Capital Cost	Maintenance Cost
Grassed swale	M [1,2,3]	M [1]	L [1]	M [1,2,3]	M [1]	M [1]	L [1]	L [1]	L [1]	M	H	H	L	L [8]	L [8]
Rain barrel and cistern (RWH)	N [1]	N [1]	N [1]	N [1]	N [1]	N [1]	N [1]	M [1]	M [1]	N	L	L	L	M [8]	M [8]
Bioretention zone [b]	M [1,4,5]	H [1,3,4,5]	M [4,5]	M [4,5]	H [1]	H [1]	H [1]	M [1]	L [1]	H	H	M	M	M [8]	M [8]
Tree box [b]	M [1]	M [1]	M [a]	M [1]	H [1]	H [1]	M [1]	L [1]	L [1]	M	L	L	M	M [8]	M [8]
Extended dry detention basin [b]	L [2,3,6]	M [2]	M [2,3,6]	M [2,3]	M [2]	H	L [7]	L	M	H	M	M	M	M [8]	M [8]
Infiltration trench	M [2,3]	H [1]	H [1]	H [1]	M [1]	H [1]	H [1]	H [1]	H [1]	N	M	M	H	M [8]	M [8]
Permeable pavement [b]	L [3]	M [1]	M [1]	H [1]	H [1]	M	M [1]	H [1]	M [1]	N	L	L	M	H [8]	H [8]
Wet pond	M [2,3]	M [2,3]	M [2,3]	M [2,3]	M [2]	H [6]	L [7]	L	H	H	H	H	M	H [8]	M [8]
Sand filter [b]	M [1,3]	M [3,6]	M [1]	H [1,3]	M [1]	H [6]	H [1]	L [1]	L [1]	L	M	M	H	M [8]	H [8]
Constructed wetland	M [1,2,3,6]	M [2,3,6]	M [3]	H [1]	H [1]	H [6]	M [1]	L [1]	H [1]	H	H	H	H	H [8]	M [8]
Soakaway	L [1]	L [1]	L [1]	H [1]	L [1]	L [1]	M [1]	H [1]	M [1]	N	L	L	M	M	M
Infiltration basin	M [1,2]	H [1]	H [1]	H [1]	M [1]	H [1]	M [1]	H [1]	M [1]	H	M	M	H	M	H
Green roof	L [1]	L [1]	L [1]	L [1]	L [1]	L [1]	L [1]	H [1]	M [1]	M	L	L	M	H [8]	L [8]

(H) High, (M) medium, (L) low, (N) null. [a] Conditions equivalent to bioretention zones are assumed. [b] Performance related to quality improvement and runoff control can improve depending on the infiltration rate of the area. [1] [85], [2] [53], [3] [71], [4] [86], [5] [87], [6] [88], [7] [89], [8] [55].

2.3.3. Treatment Trains Selection

Five processes are identified to configure and select treatment trains: (a) infiltration, (b) detention, (c) rainwater harvesting, (d) conveyance, and (e) irrigation. Feasible relations and the sequential order among these processes are presented in Table 5. These relations result by dismissing unsuitable associations between processes and identifying processes that should be at the final stage. In this sense, it was considered that the runoff captured for later uses (e.g., rain water harvesting and irrigation) must be treated, and therefore they cannot be an initial process. Also, these relationships allow the formation of treatment trains with more than two components. For instance, for a three-stage treatment train, if the initial process is conveyance and this is followed by infiltration, according to Table 5, the final process can be rainwater harvesting or irrigation.

Table 5. Processes combinations.

Final Process / Initial Process	Infiltration	Detention	Conveyance	Rainwater Harvesting (RWH)	Irrigation
Infiltration			X	X	X
Detention	X		X	X	X
Conveyance	X	X		X	X
Rainwater harvesting (RWH)					
Irrigation					

Sequential order schemes between two SUDS types are summarized in Table 6. Rows correspond to the initial component of the train and columns to the second component. The processes for stormwater control are presented in pairs. The first letter of each pair indicates the process that the initial component would perform. The second letter shows the process performed by the final component. Several combinations are presented given the different processes suitable for each SUDS type. These sequences are defined by the characteristics of the evaluated SUDS types. For instance, SUDS types used in the treatment of runoff from extended areas or several sites should be at the end of the treatment train. In this sense, systems such as extended dry detention basins, wet ponds, constructed wetlands and infiltration basins are at the end of the sequential schemes [49]. The schemes allow us to conceive trains of two, three, or more stages. For example, if the first component of a three-stage train is a grassed swale that conveys the runoff to a bioretention zone, as stated in Table 6 a feasible third element is a cistern.

To calculate a score for each feasible treatment train identified, each SUDS type is rated according to its characteristics and the stormwater control processes (see Table 7). In this manner, the score of a train is the result of the information presented in Tables 4 and 7, and the recommended trains correspond to the ones with higher scores.

Table 6. Sequential schemes between SUDS types.

FINAL / INITIAL	Grassed Swale	Rain Barrel and Cistern (RWH)	Bioretention Zone	Tree Box	Extended Dry Detention Basin	Infiltration Trench	Permeable Pavement	Wet Pond	Sand Filter	Constructed Wetland	Soakaway	Infiltration Basin
Grassed swale		C.D C.R C.Ir	C.D C.I C.Ir	C.D C.I C.Ir	C.D C.I	C.I	C.I	C.D	C.D C.I	C.D C.Ir	C.D C.I	C.D C.I
Rain barrel and cistern (RWH)	D.C					D.C D.I						
Bioretention zone	I.C D.C	C.D D.R I.R D.Ir I.Ir		C.D	C.D	I.C D.C D.I	C.D D.I	C.D	C.D	C.D		C.D
Tree box	I.C D.C	D.R I.R D.Ir I.Ir	D.Ir			I.C D.C D.I	D.I					
Infiltration trench	I.C	D.R I.R C.R D.Ir I.Ir CIr	C.I C.Ir	C.I C.Ir						C.Ir	C.I	C.I
Permeable pavement		D.R I.R D.Ir I.Ir										
Sand filter	I.C	D.R D.Ir I.R I.Ir				I.C						
Soakaway		D.R I.R D.Ir I.Ir	D.Ir	D.Ir								
Green roof	D.C	D.R D.Ir	D.Ir	D.Ir		D.C D.I	D.I		D.I		D.I	

The first component indicates the process related to the row and the second component the process related to the column: (I) infiltration, (D) detention, (C) conveyance, (R) rainwater harvesting, (Ir) irrigation.

Table 7. Assigned score to the evaluated processes (from 0 to 5).

Process / SUDS Type	Infiltration	Detention	Conveyance	Rainwater Harvesting	Irrigation
Grassed swale	2	1	5	0	0
Rain barrel and cistern (RWH)	0	4	0	5	5
Bioretention zone	3	4	0	0	4
Tree box	3	4	0	0	4
Extended dry detention basin	3	5	0	1	1
Infiltration trench	5	3	3	0	0
Permeable pavement	5	3	0	0	0
Wet pond	0	5	0	0	0
Sand filter	3	4	0	0	0
Constructed wetland	0	5	0	0	3
Soakaway	5	3	0	0	0
Infiltration basin	5	5	0	0	0
Green roof	0	3	0	0	4

3. Case Study

The selected case study was the city of Bogotá (Colombia), which covers approximately 400 km^2 of urban area. The urban drainage system consists of a combined sewer system in the oldest urban areas and a separate system in the newest developments. Stormwater is discharged into four urban tributaries of the Bogotá River: Torca, Salitre, Fucha, and Tunjuelo rivers. Other natural elements in the urban drainage system include wetlands within the city limits (see Figure 2). The water utility of the city defined 485 urban drainage sub-catchments.

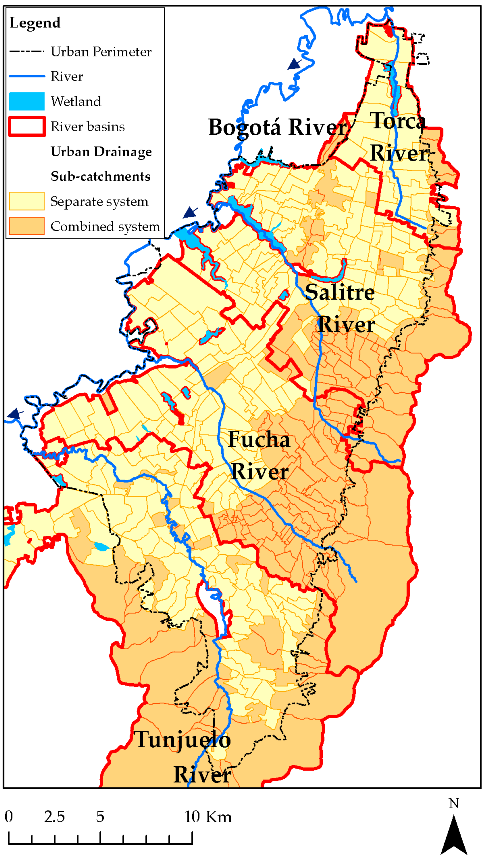


Figure 2. Main elements of the Bogotá's urban drainage system.

3.1. Citywide Information Sources

3.1.1. Water Quality Factors

Information to characterize the water quality status of urban rivers was obtained from a study conducted by Universidad de los Andes and the local environmental agency (SDA) [90]. The chosen data corresponded to the 75th percentile of measured concentrations to account for seasonal variations. A study from the water utility (EAB) and the SDA [91] was used to characterize the wetlands. The average of the reported concentration values was used.

3.1.2. Water Quantity Factors

The local planning department (SDP) classified each urban drainage sub-catchment into five levels according to their stormwater collection and transport capacity: (a) without service, (b) critical, (c) restricted, (d) moderate, and (e) high [92]. This classification was used to characterize the current urban drainage system capacity. Waterlogging zones were established according to a raster layer with different ponding areas elaborated by the local risk management institute (IDIGER). The analysis of the sewer system critical points was based on a study carried out by the local water utility (EAB) [93]. Flood plains areas were obtained from SDP data [94], which defines three risk levels: high, medium, and low.

3.1.3. Environmental and Social Factors

For the analysis of social and environmental criteria, the selected air pollutant was PM 2.5 (particulate matter with diameters that are 2.5 micrometers and smaller). The reported values in the national air quality index (ICA) and the city index (IBOCA) were assessed. These indices evidence that for most of the year, the concentrations of other air pollutants were moderate or good. Nevertheless, PM 2.5 concentrations reached an unhealthy level for sensitive groups on several occasions during 2017 [95], and more recently in early 2019. Information about PM 2.5 from the local air quality network is used [96]: 2017 time series of hourly data of 11 stations were analyzed to define the annual average for each station. If daily measures were less than 75%, data were excluded as it is set in the protocols for the city's air quality network [95]. The highest value considered for the index is 25 $\mu g/m^3$, which corresponds to the maximum allowed annual level [97].

To assess urban parks, an inventory carried out by the SDP was available. Trees per hectare were analyzed according to the tree census from the city's Botanical Garden (JBB) [98]. The occupied area within each urban plot was calculated according to the information from the city's spatial database (IDECA) [99]. The analysis of the infant (under five years) and the elderly (over sixty-five years) low-income population uses data from SISBEN (System for Identifying and Classifying Potential Beneficiaries for Social Programs in Colombia) [100]. For the identification of low-income residential areas, a classification of the city area by the SDP was considered. This classification values the characteristics of each house and its surroundings. The total area of lots rated as low or minor was calculated in every sub-catchment to conduct the analysis.

3.1.4. Strategic Urban Drainage Sub-Catchments

To identify strategic urban drainage sub-catchments, blue-green corridors and green corridors are defined from the analysis of a satellite image taken by Sentinel-2 with a resolution of 10 m per pixel. The Normalized Difference Vegetation Index (NDVI) allowed the identification of green areas considering a threshold value of 0.4. For blue-green corridors, information about channels, wetlands, ponds, rivers, riparian corridors, and preservations zones from two city databases [99,101] was used, as well as information about trees located at river rounds [98]. Regarding green corridors, the tree inventory [98] and information about the public space support the identification of linear spaces.

Renovation projects and repair works in the city were identified in the databases of the Urban Development Institute (IDU). The development plan for 2016–2020 [102] and projects supervised by the IDU [102,103] were considered. A total of 242 projects and works were evaluated including public space infrastructure, road infrastructure, and public transport infrastructure. Some of them cover various sub-catchments and comprehend different stages and elements.

3.2. Local Scale Information Sources

Public space was defined according to information from the SDP, which corresponds to georeferenced polygons of parks, squares, road dividers, sidewalks, and parking lots. Supplementary green areas were identified in an orthophoto provided by the EAB. Information about the natural and constructed drainage system was also provided by the EAB. The distance to buildings' foundations was approximated through reports by IDECA [99].

For the analysis of private space, residential use was selected because it was the predominant land-use category (i.e., approximately 40% of the city area). The analysis was conducted according to the information available for lots, uses, and buildings from IDECA [99]. Flat roofs were identified using the information available for residential use, socioeconomic level, and the number of floors in the buildings. In this sense, it was assumed that housing with more than three (3) floors had flat roofs. In addition, in low socioeconomic level areas, progressive self-constructed housing is more common, which is why these houses were presumed to have flat roofs regardless of the number of floors.

The distance to the water table and infiltration rate values were estimated from geotechnical surveys available from the geographic information system of the EAB [104]. For the distance to the groundwater level, 3384 depth measurements within the city were analyzed, whereas for the infiltration rate, the strata descriptions from 2973 geotechnical surveys were used. These descriptions were grouped into 33 classes and the permeability was defined according to: (a) the soil textural triangle from the United States Department of Agriculture (USDA); (b) the classification of Twarakavi, Šimůnek, and Schaap [105]; and (c) the saturated hydraulic conductivity estimated from the content of clay, silt, and sand.

4. Results and Discussion

4.1. Citywide Scale

4.1.1. Citywide Objectives

During 2015, workshops were held involving several stakeholders from: (a) the water utility (EAB), (b) the city environmental agency (SDA), (c) the urban development institute (IDU), (d) the risk management institute (IDIGER), and (e) researchers from public and private universities. The results were analyzed considering the local normative (Decree 528 of 2014). According to their preferences, the most important objective for implementing SUDS was stormwater quantity management. The latter was followed by storm, and thus, urban rivers water quality improvements. The objectives considered less important were the promotion of social participation, the reduction of public health risks, and reduced wrong connections in the sewer system.

These workshops allowed the identification of the main limitations for SUDS implementation in the city as a result of social, institutional, regulatory, and economic issues. Social concerns included potential negative perceptions of the communities close to SUDS projects. Institutional limitations comprised problems that resulted from the lack of interinstitutional and interdisciplinary work. Also mentioned was the lack of awareness of the role of every local institution. As regulatory limitations, the participants indicated the absence of clear policies and incentives. Technical issues were mostly associated with lack of knowledge about design, construction, operation, and maintenance of SUDS from public and private stakeholders. Additionally, the participants pointed out two economic constraints: lack of financial resources and high implementation costs.

The institutional issues were evident in the definition of the conceptual models. The stakeholders were unaware of the group of institutions involved with the design and maintenance of the city's drainage system set by local regulations. Only two of the twelve stakeholders and institutions were included in all the conceptual models that resulted from the workshops. Just one of the institutions (i.e., the SDA) mentioned entities and elements related to urban planning and recreation. On the other hand, some stakeholders evinced deficiencies in the normative, because key topics like regional interaction and cross connection issues were excluded from it.

These results are consistent with difficulties in urban stormwater management and SUDS implementation already identified in other countries. For example, Roy et al. [106] reviewed examples of stormwater management programs in Australia and the US and found technical, economical, and institutional issues. Technical issues included a lack of knowledge about the performance and requirements of the systems. Economic issues referred to a lack of information about costs. Institutional issues comprised a lack of proper regulations and interinstitutional work. Problems resulting from the absence of cooperation between institutions and regulations were also pointed out by Brown [107]. The isolated vision of stormwater management was mentioned as a problem by Dhakal and Chevalier [108]. These studies indicate the absence of improvement in this area and the negative consequences of the achievement of a sustainable system.

4.1.2. Priority Urban Drainage Sub-Catchments

Figure 3 shows the indices for water quality, water quantity, and social aspects. The priority urban drainage sub-catchments based on water quantity criteria are located mainly in the north and southwestern parts of the city. Regarding the water quality aspect, priority urban drainage sub-catchments are located mainly around the Tunjuelo, Fucha, and Salitre rivers. These results show that stormwater treatment strategies have to be implemented starting at the upper sub-catchments. According to the social index, 106 urban drainage sub-catchments were classified as a priority, which included 27% of the area. The weights for the social index that resulted from averaging the three proposed objective methods were: (a) 12% fine particulate matter levels (PM 2.5), (b) 10% distance to parks, (c) 13% trees per hectare, (d) 13% occupied area, (e) 25% low-income population under five years and over sixty years, and (f) 27% low-income residential areas. In this case, most of the urban drainage sub-catchments designed as a priority are located at the southern and southwestern parts of the city. Additional results are presented in Appendix A.

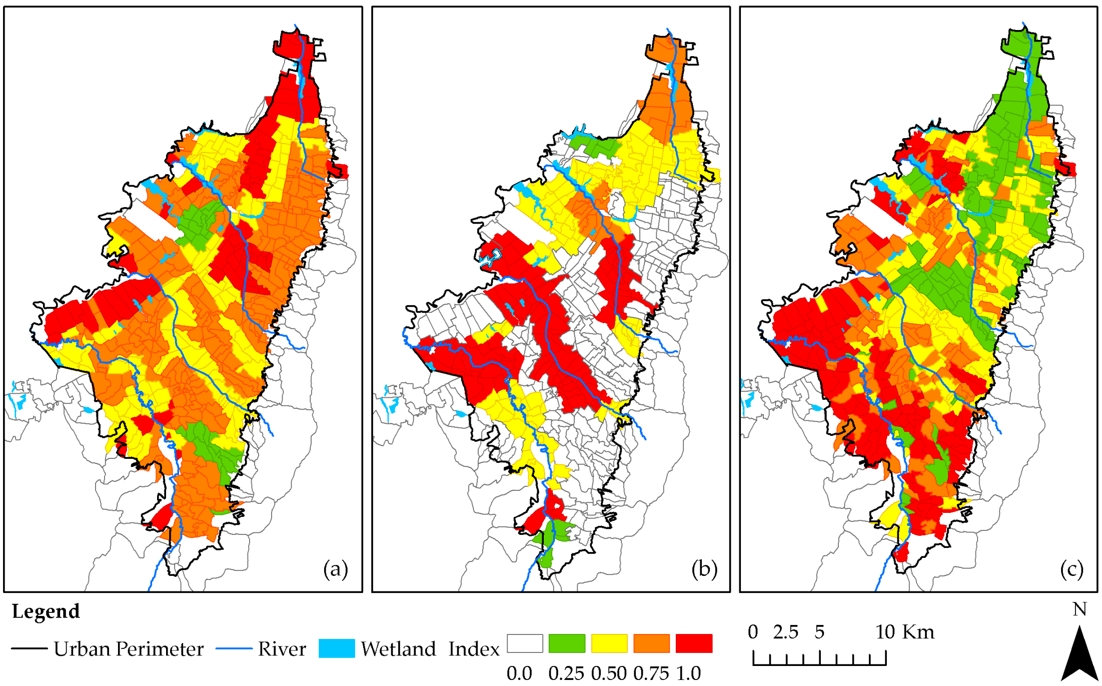


Figure 3. (**a**) Water quantity index, (**b**) water quality index, (**c**) social index.

Figure 4 presents the index that results from the analysis of water quantity, water quality, and social aspects. The results from the workshops indicate that runoff management corresponds to the stakeholders' primal concern. Subjective weights (i.e., those obtained from the workshops) were: 38% for the water quantity index, 33% for the water quality index, and 29% for the social index. Objective weights were: 27% for the water quantity index, 45% for the water quality index, and 29% for the social index. In both cases, the priority area corresponds to 29% of the analyzed area. The main difference between these two scenarios is the priority urban drainage sub-catchments along the Fucha river basin and in the north of the city. There would be more priority urban drainage sub-catchments along this river if more relevance was given to water quality. If the weight given to water quantity is higher, the north area becomes a priority. Additionally, various priority urban drainage sub-catchments are grouped in the city's southwestern part. Therefore, intervention in this part of the city is strongly recommended.

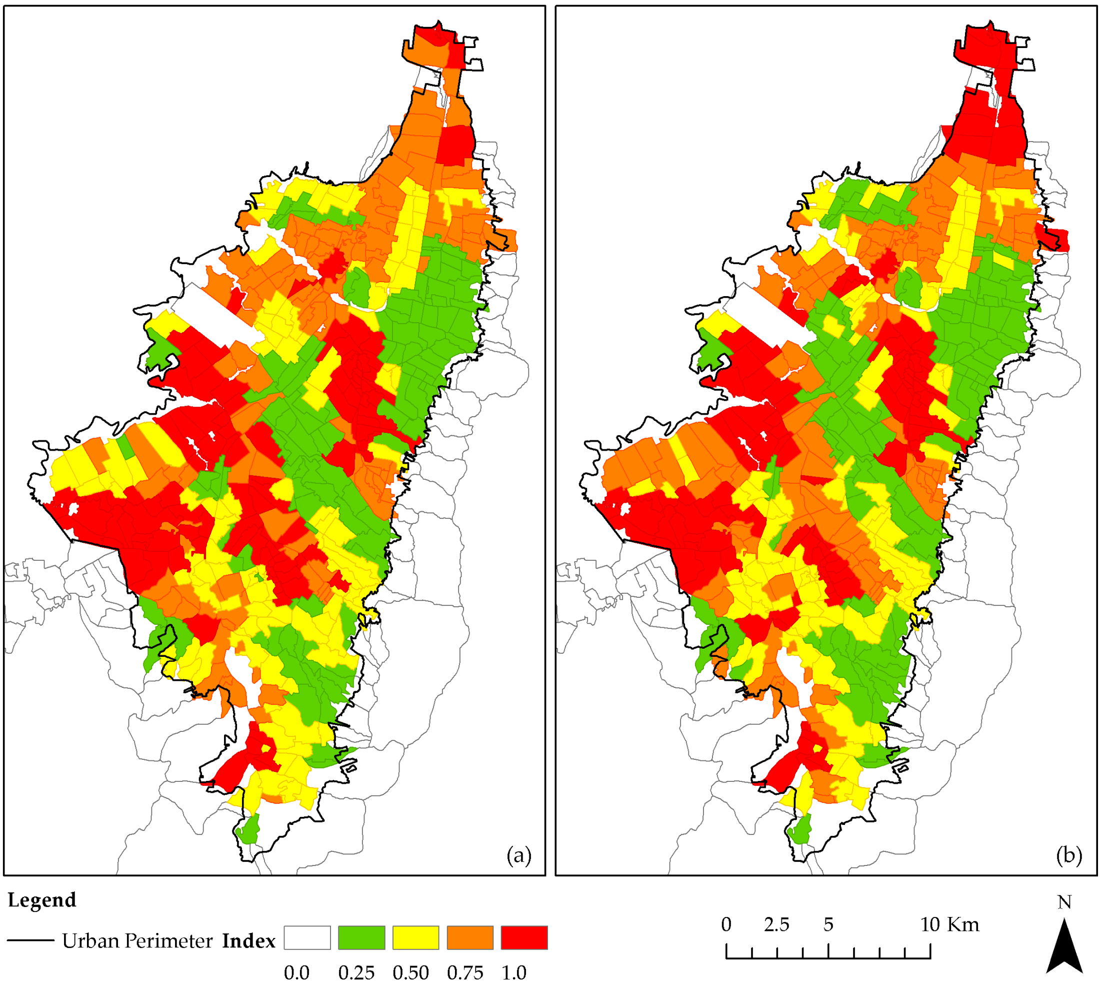


Figure 4. Priority urban drainage sub-catchments: (**a**) objective weighting, (**b**) subjective weighting.

4.1.3. Strategic Urban Drainage Sub-Catchments

The results for the analysis of corridors are summarized in Figure 5. Green corridors with a better score are located in the north of the city (Figure 5a). In particular, one corridor located along an important avenue could be an opportunity to implement SUDS. On the other hand, the main rivers of the city determine blue-green corridors. Because there are green areas adjacent to most of the Tunjuelo River, this constitutes the longest blue-green corridor. The combined index (Figure 5c) shows that there are opportunities for the joint use of the green and blue-green corridors in most of the urban drainage sub-catchments.

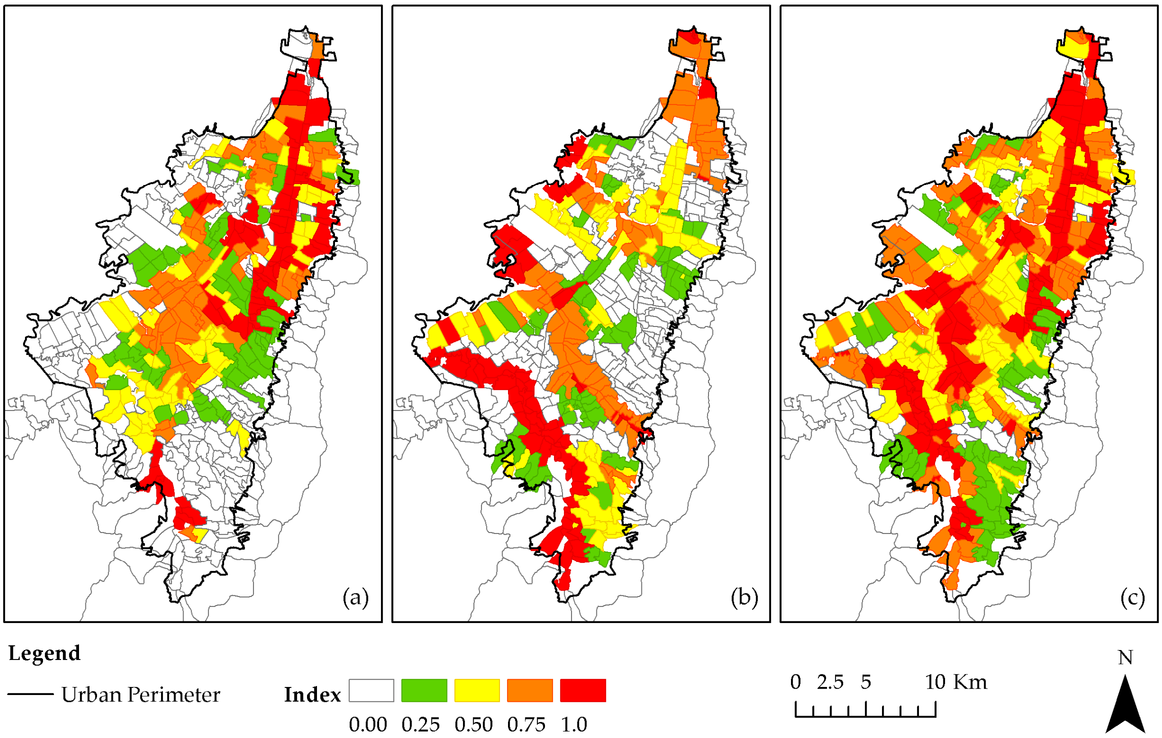


Figure 5. (**a**) Green corridor index, (**b**) blue-green corridor index, (**c**) green and blue-green corridor index.

Urban redevelopment and new infrastructure plans are distributed over the entire city area with a high potential for SUDS implementation (see Figure 6). However, there is a lower amount of these in the south of the city. Opportunities in the north of the city are road and public transport infrastructure that include the development of public space. A similar situation was identified in the western part of the city, which is also subject to projects for the construction of pedestrian networks, squares, and tree-lined roads. These designs are already in progress and may hinder the integration of SUDS. The southern part of the city has dispersed potential plans with a good score, which mainly constitute future public transport projects.

4.2. Local Scale

For public space, the most suitable SUDS type constitutes tree boxes, which could potentially be implemented in 58% of the public space (see Figures 7 and 8). This is because it can be implemented in several areas such as parks, squares, road dividers, and sidewalks. In contrast, infiltration basins have a low potential for implementation in the city area because of the area and minimum infiltration rate requirements. Hence, they are suitable for approximately 5.3% of the public area and 2.0% of the residential areas. Similarly, the area suitable for permeable pavements is limited to 3.2% of the public area and 8.1% of the residential area in this case study. Nevertheless, this system could be implemented in areas that were absent in the analysis. For example, narrow roads or low traffic roads may be suitable for this SUDS type and should be considered in future spatial evaluations as previous studies have identified the benefits out of implementing permeable pavements in different impervious areas due to their multifunctionality [23,109]. Permeable pavements have the potential to provide more hydrological and environmental benefits in comparison with traditional pavements. For example, in addition to managing stormwater through detention and infiltration, these systems help to reduce the heat island effect [110,111].

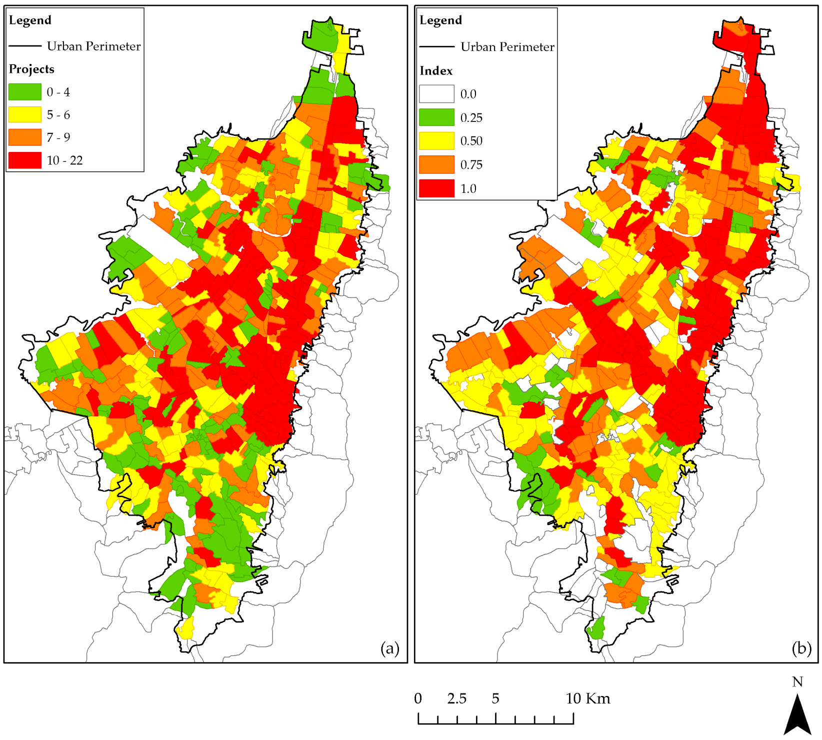


Figure 6. (**a**) Number of urban redevelopment and new infrastructure plans per urban drainage sub-catchment, (**b**) plan index.

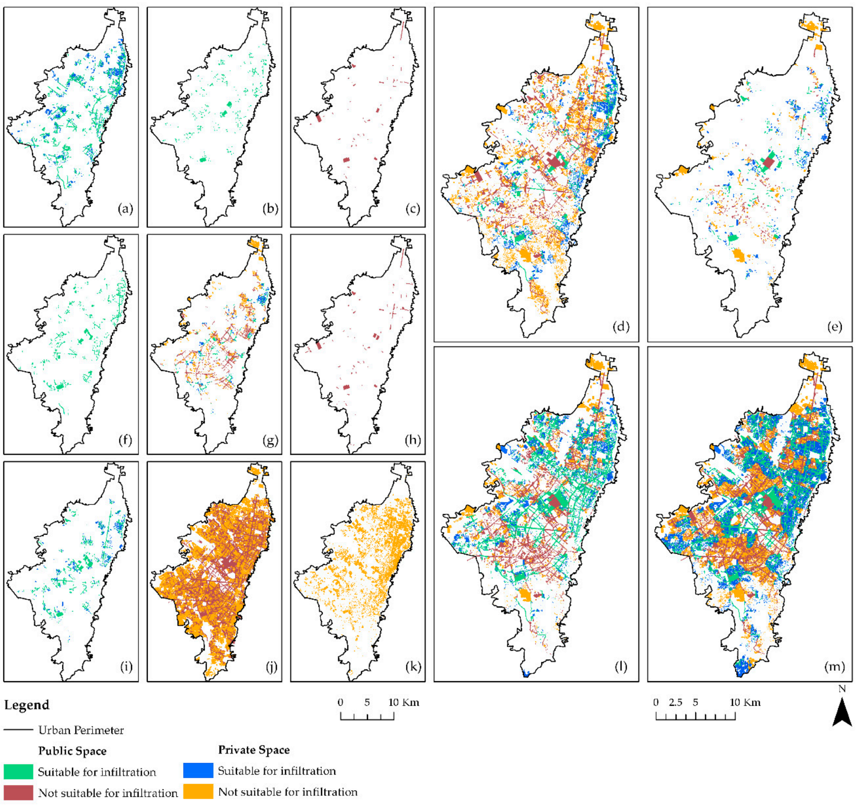


Figure 7. SUDS potential areas: (**a**) soakaways, (**b**) infiltration basins, (**c**) constructed wetlands, (**d**) grassed swales, (**e**) extended dry detention basins, (**f**) sand filters, (**g**) permeable pavements, (**h**) wet ponds, (**i**) infiltration trenches, (**j**) rain barrels and cisterns, (**k**) green roofs, (**l**) bioretention zones, and (**m**) tree boxes.

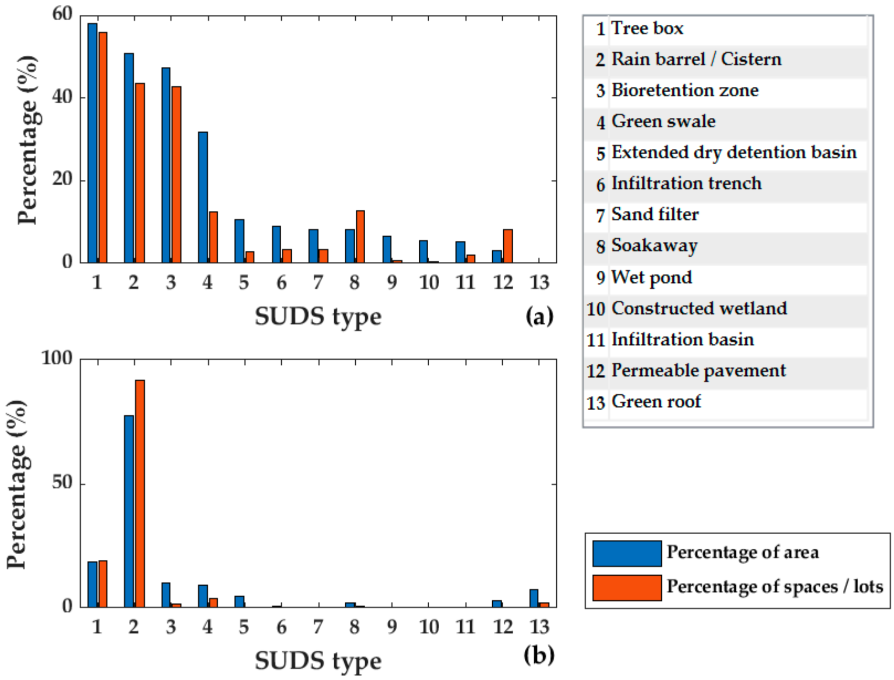


Figure 8. (**a**) Percentage of public area suitable for the evaluated SUDS types, (**b**) percentage of private residential area suitable for the evaluated SUDS types.

Figure 8 shows the percentage of the total analyzed area and the spaces suitable for the SUDS types. In this case, spaces refer to polygons of public space or lots for the private area. Wet ponds and constructed wetlands present the biggest differences between the percentage of suitable areas and spaces (see Figure 8a). Some 6.5% of the analyzed public area was found to be feasible for wet ponds, but this area corresponded to 0.6% of the number of analyzed spaces. Likewise, wetlands are suitable for 5.4% of the analyzed public area, which corresponds to 0.3% of the number of public spaces. This results from the minimum area required, limiting the implementation of this SUDS type in the southern part of the city (see Figure 7c,h). In contrast, permeable pavements are suitable in 3.2% of the public area, which is equivalent to 8.1% of the number of public spaces. There are small public spaces, mainly in the center of the city, that are feasible for this SUDS type (see Figure 7g).

Concerning private space, the most suitable SUDS type for residential use is rain barrels (see Figure 8). This is because the analysis considered flexibility in implementing this SUDS type. Nevertheless, additional restrictions related to the characteristics of the buildings could reduce the amount of suitable space. The potential area for other SUDS types is more reduced. For example, tree boxes are the second most suitable SUDS type in the residential area, but they could only be implemented in 19% of the analyzed lots. However, their implementation could bring more advantages than the rainwater barrels, particularly in terms of amenity and water quality improvement. Bioretention zones, green swales, and green roofs present notable differences between the percentage of suitable area and lots. This indicates that the opportunities for implementation concentrate in lots with large unoccupied areas.

Figure 9 presents a comparison between the suitable public and private residential areas for SUDS implementation. In each case, the value for private and public space suitability is determined according to the difference between the areas divided by the biggest area (private or public). Private residential areas have a greater potential for SUDS implementation in most of the city due to rain barrels. Figure 9a shows that 51% of the urban drainage sub-catchments have a value of over 0.80 in relation to private residential space suitability, which comprises 43% of the evaluated area. Nevertheless, other SUDS types present more benefits in terms of runoff control and amenity generation. In this sense, Figure 9b indicates that when rain barrels and cisterns are omitted, there are areas in the southwest of the city where the implementation of other kinds of SUDS is more feasible in the public space. The number of urban drainage sub-catchments with a value of suitability for private space over 0.80 changes to 14%. Figure 9c also excludes green roofs, reducing the number of urban drainage sub-catchments with that value to 11%, which corresponds to 0.26% of the evaluated area. This shows that the implementation of SUDS in private residential space needs to involve the constructed area, and the use of other types of SUDS is more feasible in public spaces. In general, public areas have a greater potential in the city center, and private residential areas in the northern and southern parts of the city.

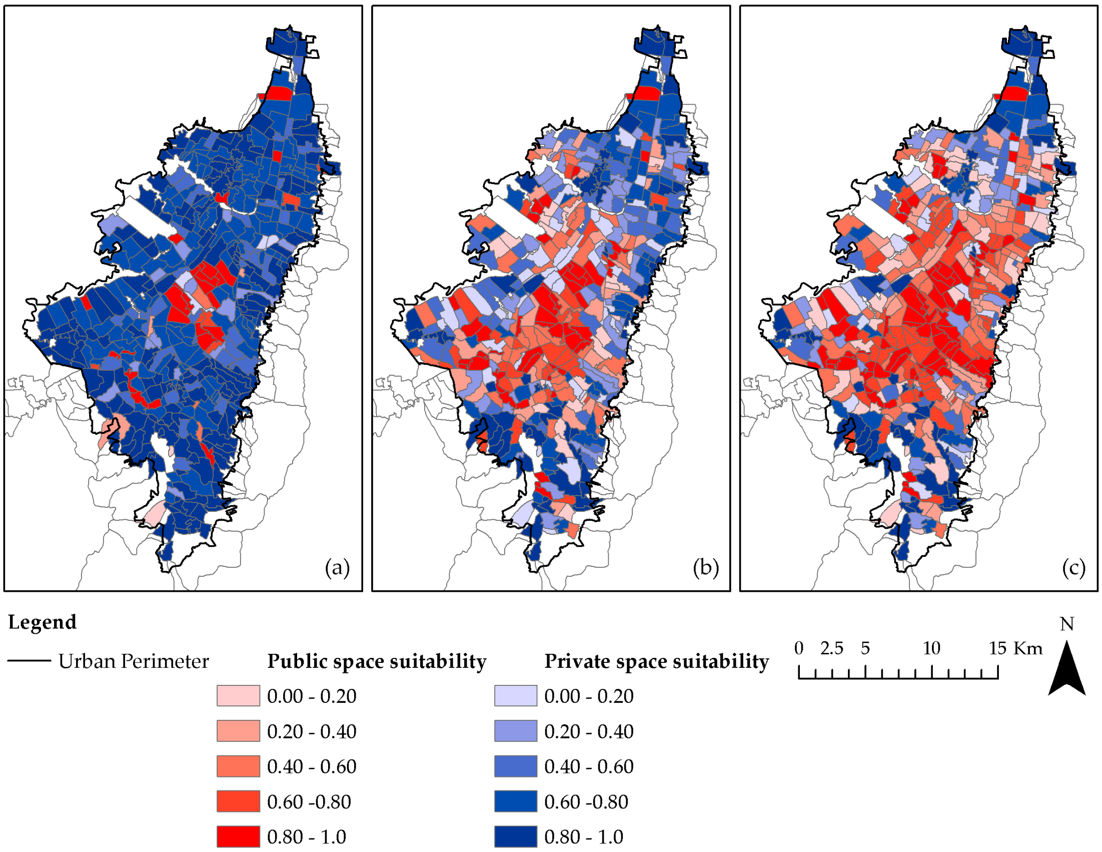


Figure 9. Public and private (residential) space comparison: (**a**) difference between total suitable area for SUDS implementation in public and private space, (**b**) difference between total suitable area for SUDS implementation in public and private space disregarding rain barrels and cisterns, (**c**) difference between total suitable area for SUDS implementation in public and private space disregarding rain barrels, cisterns, and green roofs.

4.3. Microscale

Two sites were selected to carry out the microscale analysis. The selection process included field visits to places identified in priority and strategic urban drainage sub-catchments, and from recommendations of local institutions (i.e., EAB and SDA). The first site corresponded to San Cristobal Park, in the southeast of the city (Figure 10). It is part of three urban drainage sub-catchments in the upper basin of the Fucha river. It could be a strategic area for SUDS implementation according to the analysis of green and blue-green corridors and due to its proximity to the Fucha River. The urban drainage sub-catchments in which the park is located are not prioritized, but improvements in water quantity and quality could have positive impacts downstream in prioritized urban drainage sub-catchments. The second site was a road divider located in the south of the city, referred to as the Tunal road divider. In this area, there is a future project to build a massive transport system, which constitutes an opportunity to implement SUDS. It is in an urban drainage sub-catchment where the green and blue-green corridors index is equal to one (1). Thus, even though this road divider is not in a priority urban drainage sub-catchment, it was selected for this analysis.

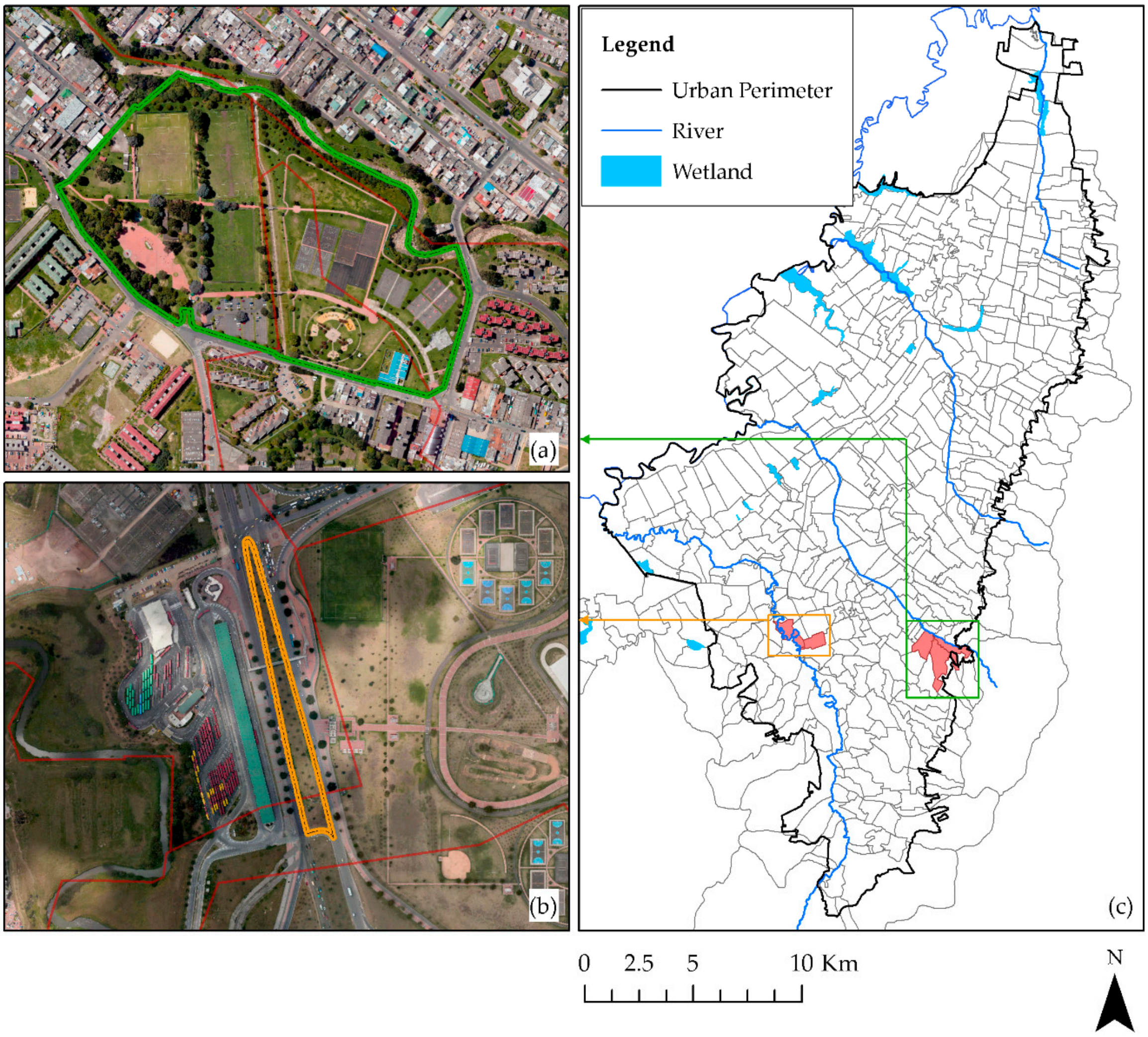
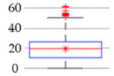
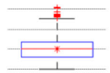
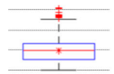
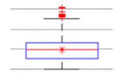
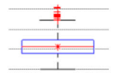
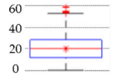
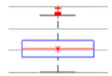
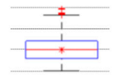
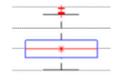
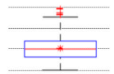
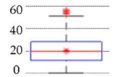
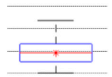
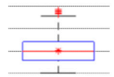
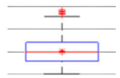
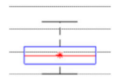
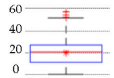
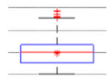
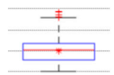
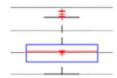
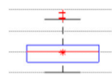
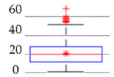
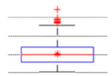
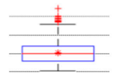
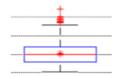
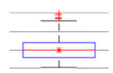


Figure 10. Selected sites: (**a**) San Cristobal Park, (**b**) the Tunal road divider, (**c**) sites location.

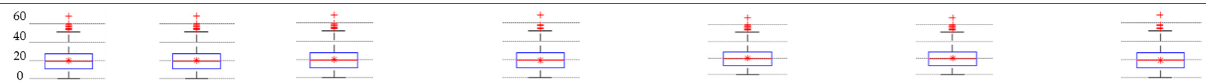
The proposed methodology for the treatment train selection was applied considering 1000 weights combination for five aspects to define a score from zero (0) to five (5) for each train. The suitable SUDS types for each selected site were determined by the spatial analysis conducted at local scale. In addition, in situ-evaluations led to the inclusion of other SUDS types. For San Cristobal Park, the processes analyzed were conveyance, detention, infiltration, and irrigation. For the Tunal road divider, the process of rainwater harvesting was included instead of irrigation, because it is possible to implement a cistern. Tables 8 and 9 present the most highly recommended two-stage treatment trains according to the suitable SUDS types in the selected areas. Each column presents the pairs of processes analyzed and the recommended treatment train. The number one (1) indicates the first element of the train and number two (2) indicates the second element of the train. If the SUDS types can be arranged into two different orders, both trains are shown. The weights considered for the most frequent trains are summarized and compared.

Table 8. Recommended treatment train for San Cristobal Park.

Processes	C–Ir	D–Ir	C–D	C–I	
Possible trains	2	1	7	5	
SUDS types	Most frequent train				
Tree box		1			
Bioretention zone	2	2		2	1
Grassed swale	1		1	1	2
Extended dry detention basin			2		
Frequency	93%	100%	100%	79%	
Higher score over 5 (most frequent train)	4.27	3.96	4.50	4.02	
Evaluated weights (%)	Most frequent train weights (%)				
Quality improvement 					
Runoff Control 					
Amenity 					
Maintenance 					
Costs 					

Processes: (I) infiltration, (D) detention, (C) conveyance, (Ir) irrigation. (1) First stage, (2) second stage.

Table 9. Recommended treatment train for the Tunal road divider.

Processes	C–R	D–R	C–D		I–R	C–I		I–D
Possible trains	2	3	11		3	10		3
SUDS types	**Most frequent train**							
Tree box								
Bioretention zone		1	1	2				1
Underground cistern	2	2			2			
Grassed swale	1		2	1	1	1	2	
Infiltration trench						2	1	2
Frequency	100%	92%	79%		100%	100%		79%
Higher score over 5 (most frequent train)	4.73	4.13	4.21		4.39	4.42		4.24
Evaluated weights (%)	**Most frequent train weights (%)**							
Quality improvement								
Runoff Control								
Amenity								
Maintenance								
Costs								

Processes: (I) infiltration, (D) detention, (C) conveyance, (R) rainwater harvesting. (1) First stage, (2) second stage.

The recommended train for San Cristobal Park varied depending on the process analyzed. If the processes are conveyance and detention, the recommended train is always composed by a grassed swale followed by an extended dry detention basin. For the processes of conveyance and infiltration, the recommended train is composed of a grassed swale and a bioretention zone in 79% of cases. In this case, according to Table 8, the set of water quantity weights are above the median, which indicates the importance of this aspect in recommending this train. Based on these results, a SUDS train composed by a grassed swale and an extended dry detention basin was designed and constructed as a pilot unit, which has been monitored for water quantity and quality performance since 2017. A similar case is presented in the Tunal road divider in the detention and conveyance analyses. For detention and infiltration, the recommended train is composed of a bioretention zone followed by an infiltration trench. According to the variation in the weights, this train selection follows the assignation of higher weights to water quality and lower weights to maintenance (see Table 9). These results indicate that stakeholders' preferences and project constraints are decisive in the best alternative. As in San Cristobal Park, a SUDS train conformed by tree boxes, infiltration trenches, and bioretention zones was designed in detail as another pilot case.

5. Conclusions

The development of a multiscale and multicriteria analysis is necessary to integrate the systems, scales, stakeholders, and benefits of SUDS. In this sense, the proposed methodology aims to promote a holistic approach for urban stormwater management. In addition, it seeks the inclusion of SUDS in citywide policies providing the tools to identify priority and strategic areas.

The city of Bogotá was selected to apply the proposed methodology, resulting in the identification of its advantages and limitations. In the first place, stakeholder participation in the early stages proved its importance in defining projects that responded to their concerns, and improved the city area. SUDS constitute a new approach to stormwater management in the city; thus, one of the advantages of the workshops is that they shed light on stakeholder misconceptions and gaps regarding SUDS implementation. For example, the most relevant aspects for stakeholders in Bogotá were still linked to the traditional view of the drainage system. Thus, activities like the workshops could provide an important pedagogic component. Additionally, they evince the need for institutional changes to involve social diversity and technical aspects in local regulations.

The identification of priority and strategic sub-catchments is fundamental to creating policies for SUDS implementation. In Bogotá, the evaluation of the areas according to water quantity, water quality, and social aspects indicates that the southwestern part of the city is an area that requires intervention. These interventions could be supported by the strategic sub-catchments, particularly by the sub-catchments identified through the analysis of corridors. The use of corridors provides an opportunity in every river basin to create connected spaces and give value to the runoff by improving environmental conditions.

The analysis of public and private areas according to physical constraints was a preliminary approximation that indicated the most suitable SUDS types conforming to the city characteristics. This analysis showed that the type of suitable area (i.e., public or private) varies in every urban drainage sub-catchment. On this account, regulations and incentives need to be oriented according to the potential areas. However, some of the constraints, such as the minimum infiltration rate, were estimated only roughly, meaning that site-specific analyses are still necessary to validate the results.

In Bogotá, the most suitable SUDS types for the public space were tree boxes, cisterns, bioretention zones, green swales, extended dry detention basins, and infiltration trenches. Regarding the private space, the SUDS types with more available space included rain barrels, tree boxes, green roofs, and green swales. According to the results, the constructed area is very important for runoff management in the private space. Moreover, SUDS implementation in the northern and southern parts of the city needs to include private areas due to the reduced amount of suitable public space.

Residential use was analyzed because it is the predominant type of use in the city. Nevertheless, the area available is fractionated into small spaces, limiting the suitability of many SUDS types, especially in city zones with smaller lot sizes. Furthermore, some SUDS types were not suitable for residential use. Therefore, it is recommended to conduct future studies in the city analyzing other city uses (i.e., institutional or commercial) to identify the ones with greater potential for SUDS implementation in every urban drainage sub catchment.

The purpose of the proposed methodology for train management is to simplify the identification of the most suitable train according to the processes and SUDS types whose implementation is feasible in a particular area. Nonetheless, the final recommendation can vary in accordance to the stakeholders' preferences. In this sense, it is fundamental to identify the most relevant aspects for them and the requirements of their emplacement.

Author Contributions: All the authors participated in the conceptualization and methodology. S.L.J.A., J.A.M., A.F.M. and J.P.Q. developed the formal analysis for the public space. J.P.Q. conducted the workshops with stakeholders. J.A.M. performed the formal analysis for the private spaces. Writing of the original draft and visualization was made by Jiménez. Supervision, writing, review, and editing was done by J.P.R., L.A.C. and M.D.-G.

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Appendix A

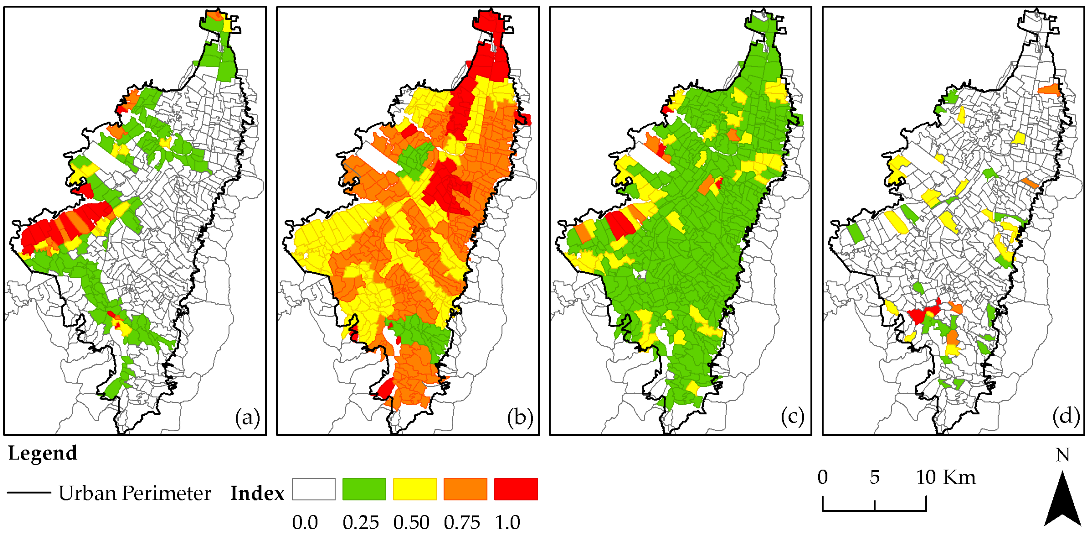

Figure A1. (**a**) Flood plains index; (**b**) storm sewer system capacity index; (**c**) ponding zones index; (**d**) critical points index.

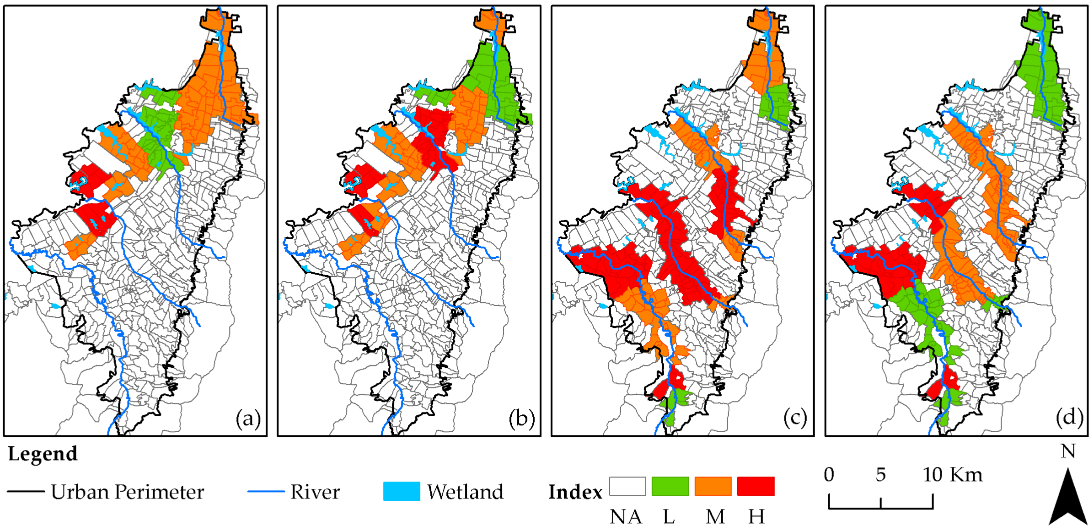

Figure A2. (**a**) Nutrient concentrations in wetlands; (**b**) TSS and BOD concentrations in wetlands; (**c**) nutrient concentrations in rivers; (**d**) TSS and BOD concentrations in rivers.

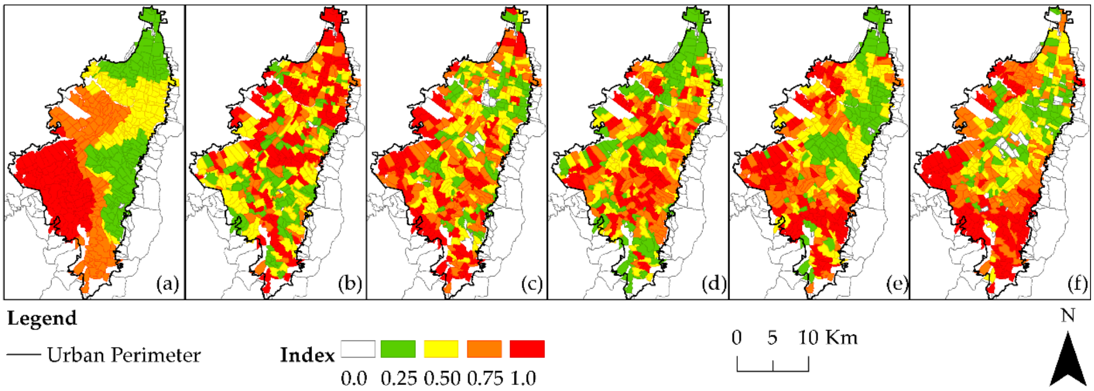

Figure A3. (**a**) Fine particulate matter levels (PM 2.5); (**b**) distance to parks; (**c**) trees per hectare; (**d**) occupied area; (**e**) population under five years and over sixty years with low economic resources; (**f**) residential areas with a low socioeconomic level.

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