Development of a multiscale methodology for sustainable urban drainage systems planning. Case study: Bogotá, Colombia

Développement d'une méthodologie multi-échelle pour la planification de systèmes de drainage urbain durables. Étude de cas: Bogotá, Colombie

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RÉSUMÉ

L'expansion des zones urbanisées et la densification des villes ont accru la fréquence des inondations et causé la dégradation des eaux réceptrices du fait de la modification du cycle hydrologique naturel. En outre, la gestion des eaux urbaines s'est plutôt concentrée sur l'évacuation aussi rapide que possible des eaux de ruissellement, ce qui augmente les effets négatifs du processus d'urbanisation. Une approche alternative pour la gestion des eaux urbaines a été développée, qui propose l'utilisation de systèmes de drainage urbains durables (SUDS) afin de prévenir et atténuer ces effets. Le succès des SUDS dépend de l'interprétation correcte des besoins et des possibilités d'une zone particulière. Cet article présente une méthodologie qui guide la planification de SUDS, en suivant une approche multi-échelle. Elle comprend trois échelles : (1) l'échelle de la ville, (2) l'échelle locale et (3) la micro-échelle. La méthodologie a été appliquée à la ville de Bogotá (Colombie) et a permis d'identifier des zones prioritaires, en fonction des objectifs locaux spécifiques (gestion des eaux de ruissellement et amélioration de la qualité de l'eau), où une intervention urgente est nécessaire. De plus, d'autres espaces publics où différents types de SUDS pourraient être mis en place, ont été identifiés.

ABSTRACT

Expansion of urbanized areas and densification of cities have increase the frequency of flooding events and degradation of receiving water bodies as a result of changes in the natural hydrological cycle. Besides, traditional urban water management has focused in evacuating the runoff as quickly as possible, increasing the negative effects of the urbanization process. An alternative approach for the management of urban waters is the use of sustainable urban drainage systems (SUDS) to prevent and mitigate these effects. The success of SUDS depends on the correct interpretation of the needs and opportunities of a particular area. In this article, a methodology is proposed that guides the planning of SUDS based on a multi-scale approach. This methodology includes three scales: (1) citywide, (2) local and (3) microscale. The methodology was applied in the city of Bogotá (Colombia) allowing the identification of priority areas, in accordance to specific local objectives (i.e. runoff management and water quality improvements), where an urgent intervention is needed. As a result, public areas were identified where different SUDS could be implemented.

KEYWORDS

Multiscale framework, runoff management, spatial analysis, SUDS, urban drainage planning

1 INTRODUCTION

Nowadays, the accelerated population growth in urban areas is increasingly more unsustainable, especially in those cities that do not have strong urban planning mechanisms and effective programs of expansion control. The elevated concentration of people in limited areas causes a strong pressure on the environment dynamics. For instance, the natural hydrologic balance of urbanized basins changes due to the reduction of the pervious natural soils, which in turn, increases the amount of runoff generated in the basin (Ahiablame et al., 2012; Dietz, 2007). Therefore, complex networks of drainage systems have been designed with the main objective of collecting stormwater as quickly as possible and discharging it to nearby waterbodies following the philosophy of “flush and forget”. This approach of treating stormwater as a waste is discouraged, because the management of urban water does not bring benefits to the city and instead imposes many urban challenges (Ahiablame et al., 2012). For that reason, in recent years it has been proposed a more sustainable view for urban drainage systems: Sustainable Urban Drainage Systems (SUDS) (also known as Best Management Practices – BMPs, Stormwater Green Infrastructure – SGI, or Stormwater Control Measures - SCMs).

SUDS are an innovative alternative for urban drainage management, complementary to conventional systems. These systems include a wide range of typologies promoting water retention, detention, and infiltration at different areal scales, from source to regional control. This approach, besides managing stormwater volumes and peaks, has the potential of improving water quality, increase the landscape and urbanism, and even re-naturalize concrete-lined channels, among other benefits (Woods-Ballard et al., 2007). In this context, urban water is considered as a resource that needs to be managed instead of a waste that must be disposed. However, the advantages of SUDS is still unknown in many developing countries. Therefore, protocols and guidelines to implement them have to be developed (Perales et al., 2012). This paper proposes a multiscale methodology for implementation of SUDS in highly urbanized cities, and presents the results for the city of Bogotá (Colombia).

2 METHODS AND RESULTS

The proposed methodology involves analyses at three scales: (1) citywide, (2) local and (3) microscale. The citywide scale focuses on strengthen the links among stakeholders at the regional level (e.g. local authorities, public water utilities and academia), in order to identify effective measures, promoters and limitations of SUDS implementation (Perales et al., 2012). Figure 2 shows the proposed methodology.

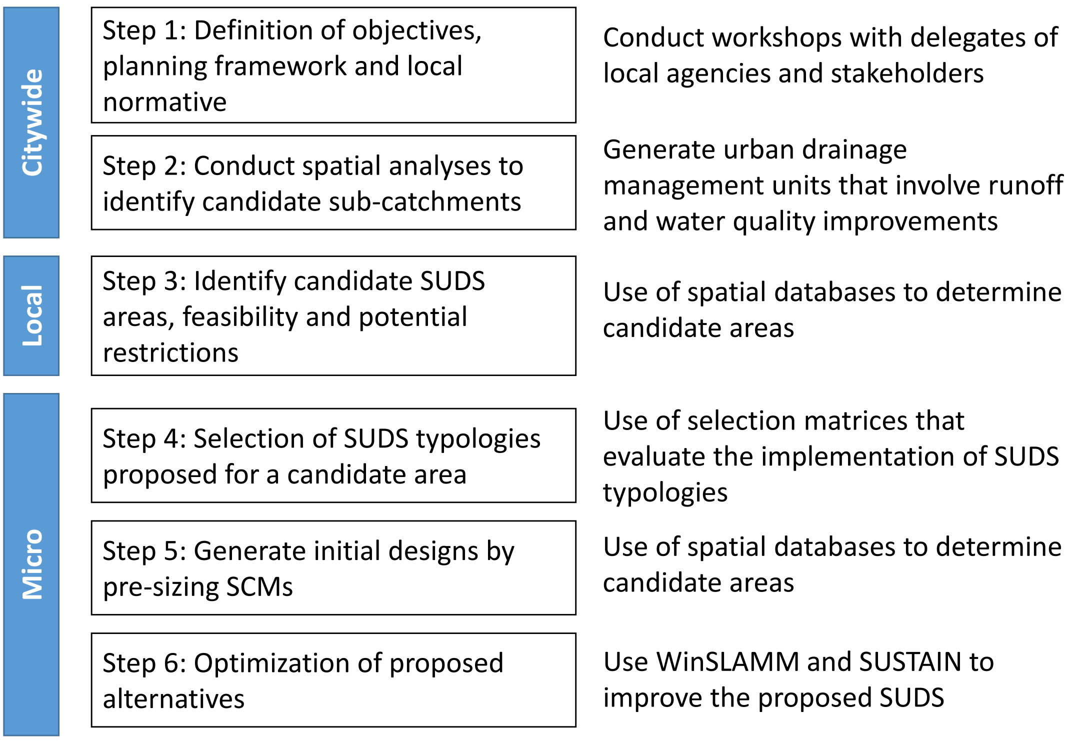

Figure 1. Multiscale methodology for sustainable urban drainage systems planning.

Thus, the first step of the methodology is the determination of an operative framework that integrates normative, institutional and planning aspects. This is accomplished through the definition of SUDS implementation objectives considering perspectives and interests of stakeholders by the design of surveys and workshops. Furthermore, this step includes the identification of a planning framework, the consideration of the local normative, and the recognition of the project restrictions, which are fundamental for the execution of the project according to limitations towards it (e.g. budget, available time and scope). The second step is to conduct spatial analyses that identify candidate sub-catchments according to the defined objectives (e.g. runoff management, water quality improvements, amenity, urban restoration and re-naturalization/preservation of natural values). Steps one and two create a framework for the citywide scale and provide normative, institutional, and management elements to the remaining scales.

Analyses at the local scale examine SUDS feasibility in an intermediate level (e.g. prioritized sub-catchments or local planning units) taking into account design guidelines, and recommended technical aspects. These analyses define the best locations for SUDS implementation. Therefore, the methodology uses spatial databases to determine available areas where different types of SUDS could be implemented. In addition, it considers spatial and operative restrictions of SUDS typologies as well as available public city areas. Hence, the third step is to identify the potential areas (e.g. squares, road dividers, private spaces, parks, walkways, commercial and industrial zones) and evaluate their feasibility and potential using factors such as land use, longitudinal slope, water table depth and infiltration rates. A quantittative evaluation decides possible typologies to implement at potential areas by considering the restrictions shown below.

Table 1. Implementation constraints of SUDS

		Typology										
Parameter	**Restriction type**	**Grassed swales**	**Infiltration trenches**	**Porous 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	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	Minimum	13[3]	7[7]	13[3]	-	7[10]	7[10]	13[7]	-	13[7]	13[7]	7[2]
Distance to foundations	Minimum	4[9]	6[12]	6[12]	6[12]	6[12]	2[13]	1.5[6]	6[12]	6[12]	6[12]	6[2]

(-) No data, (1) Geosyntec consultants, 2010, (2) Riverside County Flood Control and Water Conservation District, 2011, (3) City of Edmonton, 2011, (4) Woods-Ballard et al., 2007, (5) City of Santa Rosa, 2011, (6) Urban Drainage and Flood Control District, 2010, (7) Center for Watershed Protection, 2000, (8) Clean Water Services, 2009, (9) Toronto and Region Conservation Authority, 2010, (10) Departament of Defense - USA, 2010, (11) City of Los Angeles, 2011, (12) Virginia Departament of Transportation, 2013, (13) Recommendation from Secretaría de Ambiente de Bogotá, 2015.

Finally, the microscale involves the implementation of SUDS in a specific area. Thus, the fourth step involves the selection of the most suitable SUDS typologies or treatment trains proposed for a candidate area. This is driven by the use of selection matrices that evaluate the implementation of different SUDS typologies through qualitative criteria. The aspects included for this evaluation are relations with the activities within the area, constructive considerations, adaptability, amenity, safety, stormwater quality improvement, stormwater volume reduction, and functionality as part of a treatment train. Scores are defined for every aspect and these are added in order to establish a total score for every SUDS typology in order to select the most appropriate ones. Once step four has been completed, the fifth step is to generate initial designs by pre-sizing stormwater controls measures (SCMs) according to site-specific drainage and hydrological conditions, and soil characteristics. The last step corresponds to the optimization of proposed alternatives by using computer models that evaluate multiple configurations and calculate removal efficiency (e.g. WinSLAMM and SUSTAIN), and a qualitative criteria for evaluation and improvement (e.g. amenity, maintenance requirements, environmental and social affairs).

The proposed multiscale methodology, was applied as a case study in the city of Bogotá, Colombia. Bogotá is an urban area of 400 km^2 and a population of 7’800,000 inhabitants (a mean density of 260 inhabitants per hectare). Average public space per capita is around 3.93 m^2 and the public green area per capita is approximately 6.3 m^2 (Departamento Administrativo de la Defensoría del Espacio Público website, 2016). The surface water drainage system of the city consists of a combined sewer system in the oldest urban areas, whereas the newest developments have been constructed using separate sewer systems, and where, unfortunately, cross connection problems exist. The sewerage system involves the discharge of gray water (portions without treatment) into four urban rivers tributaries of the Bogotá River: Torca, Salitre, Fucha and Tunjuelo. A relevant feature of the city's urban drainage system is the presence of natural wetlands and lakes within the city limits.

According to the proposed methodology, the first step is to define the objectives, regulatory framework and restrictions. The main objectives were identified after five workshops with delegates from different local institutions and other stakeholders. The workshops included the participation of delegates from the water and sewer utility (Empresa de Acueducto y Alcantarillado de Bogotá), the city environmental agency (Secretaría de Medio Ambiente), the city urban planning and development agency (Instituto de Desarrollo Urbano), and researchers from public and private universities. During the workshops, the Soft Systems Methodology (SSM) was applied with the CATWOE framework to define relevant systems and conceptual models. Delegates were asked to quantify the following objectives ranked from 1 to 4 (being 4 the most relevant): runoff control, minimize degradation of receiving water bodies, mitigate climate change effects, reduce public health risks, reduce contamination from wrong connections and improve social benefits. As a result of the workshops, the two objectives with the highest punctuation were to improve runoff control and to diminish degradation of receiving water bodies. The regulatory framework that supported these objectives is the Decree 528 of 2014.

During the second step of the proposed methodology, there were identified candidate areas where the implementation of SUDS would meet the two objectives identified in the previous step. A spatial database was created with data that included the location of public spaces (parks, sidewalks, road dividers, and plazas), buildings, land use, protected areas, rivers, drainage systems, flooding risk maps and quality of receiving water bodies. Spatial analyses were conducted using areal planning units known as UGAs (urban drainage management units, defined by the water and sewer utility). As a result of the spatial analyses, 179 (out of 485) UGAs were identified as those with higher benefits (runoff control and water quality) by SUDS implementation. Figure 2 shows the ranking of UGAs, where areas in red indicate preferred areas for SUDS implementation. During the third step, databases of water table depth, precipitation, infiltration rate, topography, and distance to building foundations were used to assess the available effective area in each UGA, considering the restrictions for each SUDS typology and the type of public space available for construction. Consequently, maps were generated with the available area for twelve typologies (i.e. wet ponds, dry extended detention basins, constructed wetlands, grassed swales, bioretention zones, porous pavements, soakways, infiltration trenches, tree pits, storage tanks, filter strips and infiltration basins). Figure 3 shows the results for spatial analysis applied to bioretention zones.

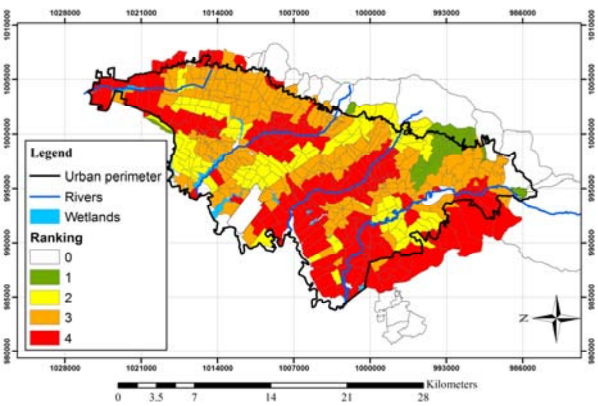

Figure 2. Classification of UGAs for implementation of SUDS according to the objectives defined.

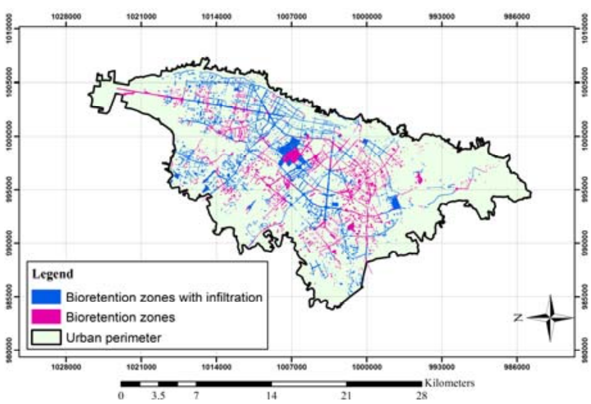

Figure 3. Classification of public space for implementation of bioretention zones.

The resulting maps for each typology in public spaces of the city indicate that the typologies more suitable for the city of Bogotá are tree pits, storage tanks, bioretention zones, swales, extended dry detention basins and infiltration trenches. As a result, a final layer was derived by a geographical spatial analysis, which contains all the information of possible typologies to be implemented in effective areas of the city. An example of these results is shown in Figure 4, where every public space has a pie diagram that provides information about the typologies that could be implemented. To validate this work, two sites with pilot SUDS have been proposed by the water utility and the environmental agency for constructing and monitoring. The San Cristóbal Metropolitan Park in Bogotá has been chosen in this article to describe the procedure at microscale. The park is located upward from several priority UGAs, it has an area of 13.42 ha and the potential area for intervention is 0.55 ha. According to the proposed methodology, the feasible typologies to be constructed in this site are tree pits, swales, dry detention basins and bioretention zones (see Figure 4).

The following is the selection of the most appropriate SUDS for the park. This was developed through a comparative analysis of the feasible typologies, according to different aspects outlined above, with the objective of evaluating their performance based on specific site conditions. The analysis, summarized in Table 2, indicated that a coupled grassed swale and extended dry detention basin is an appropriate treatment train for the park and some neighborhood areas.

Table 2. Matrix score of the feasible typologies at the San Cristobal Park

Typologies / **Aspects**	**Description**	**Extended dry detention basin**	**Tree boxes**	**Bioretenion zones**	**Grassed swales**
Construction	The construction aspects are feasible for the site	3	3	3	3
Site activities	It encourages the activities for which the site is conceived	3	1	1	2
Safety for users	It does not represent a risk to site users	1	3	3	1
Site adaptability	The site conditions are suitable for the general characteristics of the typology	3	1	1	2
Stormwater quality improvement	Promotes a high removal of pollutants from retain/detain stormwater	2	2	3	2
Stormwater volume reduction	It has a high capacity to reduce stormwater volume or peak flow attenuation	3	1	2	2
Amenity	Greatly improve the amenity of the site through its landscape value	3	2	3	2
Functionality as part of a treatment train	It is very suitable as pretreatment and / or conveyance structure	1	2	2	3
Total score		19	15	18	17

These two types of SUDS were designed following the adaptation of two international guidelines, corresponding to those established by the Urban Drainage and Flood Control District of Denver and the Department of Water of Western Australia. For the extended dry detention basin, the overall dimensions defined are a superficial area of 0.09 ha and a storage volume of 195 m^3. On the other hand, the grassed swale has a length of 70 m and a superficial top width of 4 m. Additionally, it was carried out a parallel work with the community of the area through focal groups, social cartography, informative talks and participative workshops. This allowed to involve the community in the design process of the treatment train. Figure 5 shows this treatment train located at the north part of the park, where a grass swale receives direct runoff from the park and surrounding areas that flows to the extended dry basin and subsequently to a nearby channel that discharges to the Fucha River. At the time of this publication, this project is still being developed, so the next stage of the proposed methodology (optimization) is not included.

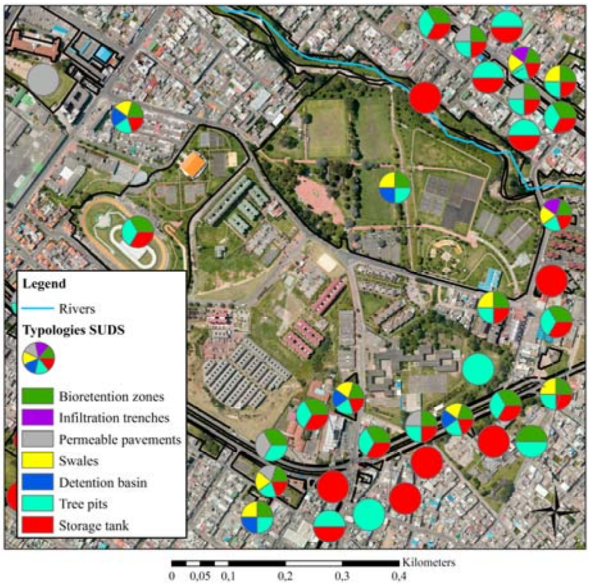

Figure 4. Recommended typologies for the area of San Cristóbal in Bogotá.

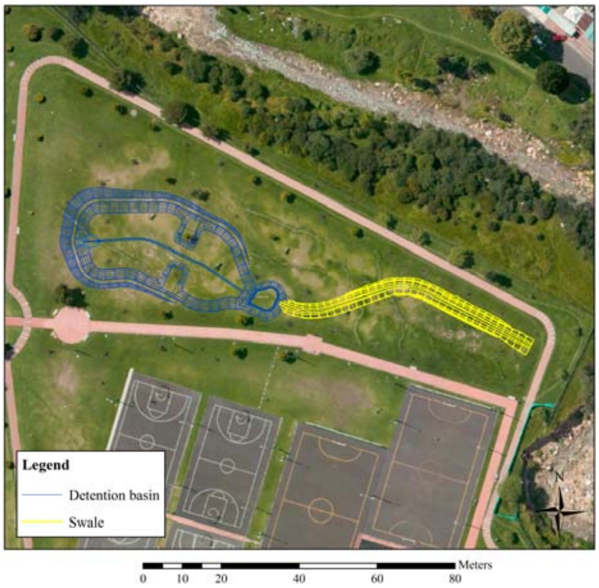

Figure 5. SUDS treatment train for the San Cristóbal Metropolitan Park in Bogotá

3 CONCLUSIONS

The proposed multiscale methodology presented here represents a complete scheme for urban drainage planning. The procedure encourages the selection of SUDS as an alternative to traditional urban drainage conventional systems and allows the evaluation and feasibility of this type of systems in specific locations. The application of SUDS is usually limited due to uncertainty related to their planning, design and operation, and therefore the methodology presented here can be a useful tool that promotes their application in highly urbanized cities with major challenges associated to the runoff management like Bogotá. Thereby, through the multiscale approach and local physical and hydrological conditions it was possible to identify the most appropriate typologies of SUDS for Bogotá. This case study included the participation of various stakeholders, so their comments and recommendations were explicitly integrated as part of the proposed procedures. The definition of objectives, planning framework, and local normative generated by local agencies, stakeholders, and members of the academia facilitated the development of rules and permits that promoted the implementation of SUDS within the city limits.

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