



Continuous Quantity and Quality Modeling for Assessing the Effect of SUDS: Application on a Conceptual Urban Drainage Basin

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Abstract

The development of computational tools based on urban drainage models is fundamental for the correct selection of SUDS. The present study proposes a systematic approach based on continuous modeling on USEPA SWMM. The objective was to select the most suitable Sustainable Urban Drainage Systems (SUDS) by evaluating several aspects related to their design and configuration. The proposed methodology was applied to a conceptual watershed with meteorological information from Santander, Spain. The analysis of SUDS design parameters showed that only the surface variables showed a sensitivity of $\approx 20\%$ for berm height and vegetation volume. The optimal configuration for the case study was a SUDS train consisting of green roofs, permeable pavements, vegetated swales and rain gardens, with 1% of the total subcatchment area cover, one structure, and a semi-aggregated spatial distribution. The methodology proved efficient but also highly dependent on the case study parameters and the meteorological conditions. The SUDS proved to have different efficiencies (30%—90%) in reducing the total runoff volume, the peak flow, and the pollutant loads depending on the region where the conceptual watershed was modeled. The methodology proved to be efficient for studying the combinations and interconnection of seven different typologies, as well as the effect of SUDS configuration, design and distribution on their performance.

Highlights

- Most of the SUDS design parameters were found to be low-sensitive.
- The optimal SUDS configuration found was a train formed by GR, PP, VS, and RG.
- SUDS performance varies widely depending on the region and variables assessed.

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1 Introduction

Urban water management has become a priority to resolve runoff quantity and quality problems caused by urbanization. In recent years, different countries (e.g., China, Iran, Australia) have implemented national and/or regional urban runoff management policies (Srishantha and Rathnayake 2017). In these, they promote the restoration of hydraulic and hydrological conditions prior to urbanization. These goals are achieved by implementing green infrastructure and enhancing rainwater infiltration, storage, and evapotranspiration (Stovin 2010). Sustainable Urban Drainage Systems (SUDS) are also called Low Impact Development (LID), Green Infrastructure (GI), Best Management Practices (BMP), or Water Urban Sensitive Design (WSUD). Mentioned runoff control techniques aim to solve water quality and quantity problems caused by urbanization (Li et al. 2016; Perales-Mompalmer et al. 2015). The SUDS are proposed to reduce the dimensions and costs of traditional sewerage systems (grey infrastructure) by using structures that complement the traditional paradigm of water management in cities (Sharma et al. 2016).

Furthermore, SUDS have become relevant to mitigate climate change and urbanization effects (Xu et al. 2020). Typologies such as infiltration trenches, green roofs, permeable pavements, storage tanks, detention basins, constructed wetlands and bioretention zones have been studied in terms of their quantity, quality, and amenity performance (Wang et al. 2019; Galarza-Molina et al. 2015). One of the research topics has been the inclusion of these structures in urban drainage models; nowadays programs such as USEPA SWMM (Rossman 2010b), MUSIC (eWater 2020), Mike Urban (DHI 2008) allow this possibility.

When working with models, one of the critical factors is the correct definition of the build-up and wash-off parameters for water quality. Since 1998, some authors (Tsihrintzis and Hamid 1998) made efforts to report values of these parameters in calibrated models. Authors such as Temprano et al. (2006), Hossain et al. (2012), Marek and Blazej (2018), Modugno et al. (2015), Chen and Adams (2007) and Wicke et al. (2012) calibrated urban drainage models, reporting the performance and values achieved in their calibrations. Furthermore, Leutnant et al. (2018), and Baffaut and Delleur (1990) proposed novel model calibration methodologies that included water quality modules. At the same time, Chow et al. (2012) and Hood et al. (2007) began to make isolated efforts to report values for calibrated models in poorly studied areas, such as tropical and desertic regions.

Regarding SUDS modeling, the first authors to address the subject were Li et al. (2016), Tobio et al. (2015), Rosa et al. (2015), Jia et al. (2012), Rossman (2010a), Kourtis et al. (2018), and Gulbaz and Kazezyilmaz-Alhan (2018). Initially, they reported simplified models, focused on small study areas, which included SUDS performances and calibration procedures for certain, but limited, SUDS typologies (mainly GR, BC and PP). Furthermore, research interest began to expand its thematic focus. Baek et al. (2020), Kourtis et al. (2021), and Sarminingsih et al. (2019) began to investigate the potential of SUDS to mitigate the effect of climate change, and Kourtis et al. (2020) focused on the flood risk reduction. Zhang et al. (2019) and Tu and Smith (2018) included groundwater interaction modules within their models. At the same time, studies such as Macro et al. (2019) and Zhu et al. (2019) proposed the development of tools for the inclusion of hydrological-hydraulic models in decision-making processes with SUDS. Bai et al. (2018) emphasized

the importance of including different combinations of SUDS typologies within the models. Likewise, Cipolla et al. (2016) is one of the few studies that has reported SUDS models with long-term continuous temporal resolution. Furthermore, Hamouz and Muthanna (2019) made isolated efforts to study SUDS under poorly studied climatic and hydrometeorological conditions, but a rigorous study on this issue is still needed.

Although the previous, and some other case studies have successfully implemented and validated SUDS urban models (e.g., Kong et al. 2017; Maftuhah et al. 2018; Rujner et al. 2018; Garbanzos and Maniquiz-Redillas 2022; Arjenaki et al. 2021; Ma et al. 2022), there are still gaps regarding modeling technicalities and aspects that have not been addressed so far, such as trains modeling, continuous-long term modeling, effect of temporal and spatial scale, or performance of different typologies. Previous studies have highlighted the importance of systematically studying the sensitivity of the models to specific SUDS design parameters. Leimgruber et al. (2018) and Peng et al. (2021) addressed this issue for three different typologies (green roofs, infiltration trenches and bioretention cells), but there is still a need to include different parameters and typologies. Furthermore, previous studies have identified the current need to fully comprehend the effect of specific aspects on SUDS performance, such as the spatial distribution (Guo et al. 2019), temporal scales (Bai et al. 2018), SUDS trains (Beltran et al. 2019), and water quality (Baek et al. 2020). However, these studies only apply to the specific case studies and have not proposed a standardized methodology to address some of the previously mentioned gaps. Furthermore, these studies have only implemented event-based modeling, and have excluded capturing the long-term performances of SUDS using continuous rainfall databases from different regions. Concerning this last aspect, studies such as Goncalves et al. (2018) and Andrés-Doménech et al. (2018) have made isolated efforts to study the performance of SUDS in tropical and Mediterranean regions, but there is still a need to identify the potential of SUDS for key regions such as these two.

To address these issues, the present study proposes a novel methodology based on continuous long-term modeling to analyze and select seven different SUDS typologies systematically. In the process, the effect of the following SUDS aspects will be analyzed for seven different typologies: 1) design parameters; 2) area; 3) number of structures; 4) spatial distribution; and 5) combinations and trains. The methodology is applied to a case study based on a conceptual watershed with meteorological information from Santander, Spain. To address the lack of information for tropical and semi-arid regions, rainfall databases from these regions were used for the selected SUDS configuration to assess the effect of meteorological information on their performance.

2 Materials and Methods

2.1 SWMM Conceptual Model

As this study was based on a conceptual watershed, no calibration-validation procedure was performed, and all parameters of the model were defined based on previous studies (Tu and Smith 2018; Rosa et al. 2015; Modugno et al. 2015; Li et al. 2016; Hos-sain et al. 2012; Hood et al. 2007; Chow et al. 2012; Chen and Adams 2007; Temprano et al. 2006) and the recommendations of the user manual by USEPA SWMM (Rossman 2010b). The watershed (Figure 1) developed consisted of a rectangular area of 80 ha, distributed in 8 equal subcatchments (A1—A8). Subcatchments A5 to A8 discharged

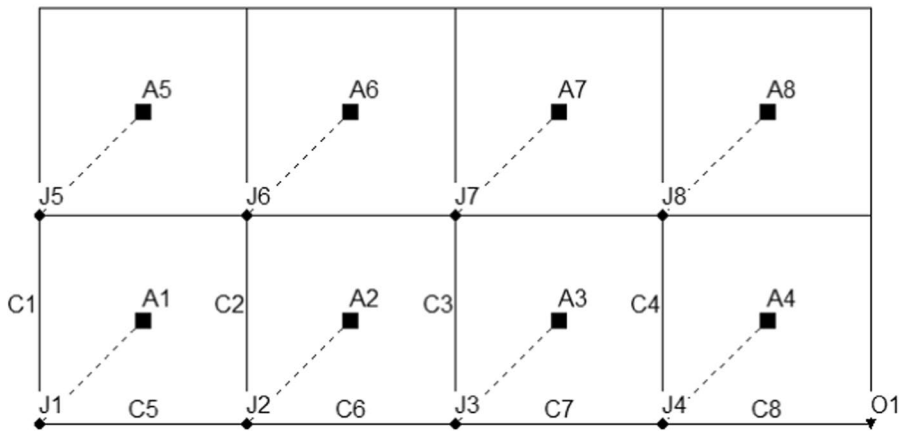
RG1


Fig. 1 Conceptual watershed developed on USEPA SWMM for the case study

to nodes J5 to J8 respectively, and runoff was transported to nodes J1 to J4 through conduits C1 to C4. At the same time, subcatchments A1 to A4 discharged to nodes J1 to J4, and runoff was then transported using pipes C5 to C8; the final outlet node was O1. All conduits of the sewer system consisted of pipelines dimensioned using the rational method. For this matter, the return period was fixed as 20 years, and the concentration time was averaged as the maximum transport time in the watershed. The IDF curves were gathered and used for all regions with available information. All conduits were circular, and the maximum capacity allowed was fixed as 0.85.

Based on the SWMM user manual recommendations, the mean slope defined for the watershed was 1%, the impervious coverage was 50%, and the storage depths were 2.45 mm and 7.62 mm for impervious and pervious areas, respectively. The surface roughness values were defined as 0.01 and 0.1 s/m^{1/3} for impervious and pervious areas, respectively, and the fraction of impervious areas without depression storage was set as 50%.

The routing and infiltration methods were the dynamic wave and the curve number, respectively. Following the recommendations given by Rossman (2010b), the routing time step was 30 s, and the curve numbers were calculated by interpolation for the different impermeability coverages. The rainfall database used was from Santander, Spain, and had a total length of 10 years, with temporal resolutions of 10 min. The basic statistics for the rainfall characteristics are presented in Table 1. The evaporation was modeled using mean multiannual averages for the different regions.

For the water quality modeling, the exponential function was selected to simulate the pollutant build-up and wash-off. The parameters used (Table 2) were defined using as reference 17 previous studies (Table 3) which had previously reported parameters for calibrated models. These articles were selected because they had conditions similar to those of the case study. Build up (B) was calculated as $B = C_1(1 - e^{-C_2})$, where C_1 was the maximum build up, and C_2 the constant. Washoff (W) was calculated as $W = C_1 q^{C_2} B$, where C_1 was the coefficient, C_2 the exponent, and q the runoff rate.

Table 1 Mean, Min, Max and Std for main indicators of rainfall characteristics for Santander, Spain

Variable	Mean	Standard deviation	Min	Max
Annual rainfall depth (mm)	1108	-	-	-
Number of annual rainfall events (#)	210	-	-	-
Mean intensity (mm/h)	1.54	2.4	0.1	57.6
Maximum intensity 10 min (mm/h)	5.34	7.0	0.6	78.0
Antecedent dry period (days)	1.72	3.0	0.0	65.2
Duration (min)	5.13	7.93	0.16	450.8

Table 2 SWMM parameters used for water quality modeling

Pollutant	Parameter	Selected value
TSS	Max. Build Up (C_1)	71.06
	Constant	0.74
	Coefficient	4.03
	Exponent	2.45
TP	Max. Build Up	0.04
	Constant	0.16
	Coefficient	1.95
	Exponent	2.05
TN	Max. Build Up	0.15
	Constant	2.02
	Coefficient	25.22
	Exponent	3.96

Table 3 Reference values used for defining the water quality parameters

#	Article	#	Article
1	Baffaut and Delleur (1990)	10	Modugno et al. (2015)
2	Barco et al. (2004)	11	Qin et al. (2013)
3	Chen and Adams (2007)	12	Tu and Smith (2018)
4	Chow et al. (2012)	13	Temprano et al. (2006)
5	Gülbaz and Kazezyılmaz-Alhan (2018)	14	Tobio et al. (2015)
6	Hood et al. (2007)	15	Tsihrintzis and Hamid (1998)
7	Hossain et al. (2012)	16	Wicke et al. (2012)
8	Leutnant et al. (2018)	17	Marek and Blazej (2018)
9	Li et al. (2016)		

2.2 Methodological Framework and Scenario Analysis

The methodological approach proposed for SUDS selections consisted of five stages (Fig. 2). The first stage consisted of defining the optimum values of the design parameters of the typologies. Subsequently, the area of each structure was determined. The third stage consisted of defining the number of structures in which the fixed area would be allocated.

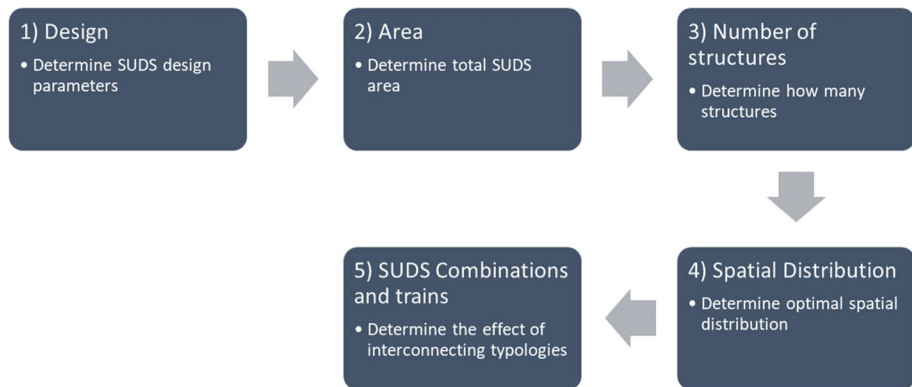


Fig. 2 The proposed five-stage methodological framework. Each stage consists of an individual analysis that yields decisions regarding SUDS configuration and design

The next step was defining the spatial distribution of the SUDS typologies. Finally, the optimal combination of structures and the possibility of interconnecting the SUDS structures with each other (trains) were assessed. Sections 2.2.1 to 2.2.6 describe the methodology and the scenarios defined at each stage. Furthermore, Table 4 summarizes the scenarios that were defined at each step.

2.2.1 Design Parameters

The typologies assessed in the analysis were bioretention cells, rain gardens, green roofs, infiltration trenches, permeable pavements, rain barrels, and vegetated swales. Based on previous studies (Table 5), the minimum and maximum reported values for each parameter are known (Table 6). The groups of the parameters are presented using the same categories that USEPA SWMM uses.

The minimum and maximum values for each parameter are defined as the ranges for the sensitivity analysis. As the ranges for each typology differed, it was decided to generate independent sets of scenarios for each typology. For computational and processing reasons,

Table 4 Variables assessed, options and decisions made at each step (green)

Area (%)	Structures	Distribution	Combination	Trains
0.1	1	Distributed	Yes	GR-PP-IT-BC
0.2	2			GR-PP-VS-BC
0.3	3			
0.4	4			GR-PP-IT-RG
0.5	5	Semi-Distributed	No	
0.6	6			GR-PP-VS-RG
0.7	7			
0.8	8	Aggregated		GR-PP-IT-RB
0.9	9			
1.0	10			GR-PP-VS-RB

Table 5 Articles referenced for defining the SUDS design parameters ranges

#	Article	#	Article
1	Baek et al. (2020)	6	Jia et al. (2012)
2	Bai et al. (2018)	7	Rosa et al. (2015)
3	Zhang et al. (2018)	8	Rossmann (2010a) 2010
4	Cipolla et al. (2016)	9	Sarminingsih et al. (2019)
5	Gulbaz and Kazezyilmaz-Alhan (2018)	10	Zhu et al. (2019)

five scenarios were developed for each typology, consisting of progressive changes in the design parameters, keeping the rest of the parameters fixed in the model.

2.2.2 Area and Number of Structures

The second stage of the analysis consists of assessing the effect of the total area of the SUDS. Based on previous recommendations (Table 5), the ranges for the analysis were fixed as 0.1%—1% of SUDS areas, with respect to the total watershed. Subsequently, twenty different scenarios were developed for each typology, which consisted of progressive increases in the SUDS total area.

Furthermore, the effect of modifying the number of fixed SUDS distributed area was assessed. For this purpose, ten scenarios were generated for each typology. Each scenario distributed the total SUDS area in one, and up to ten structures.

2.2.3 Spatial Distribution

To define the effect of the spatial distribution on SUDS performances, four different scenarios with different spatial configurations were developed (Figure 3). Distribution one (D1) had a total of eight SUDS structures evenly distributed on the subcatchments; from D2—D4, the spatial distribution was progressively centralized.

2.2.4 Combination of Typologies and Trains

In this stage, the effect of combining different typologies in the same catchment was assessed. The urban drainage guide by Butler et al. (2018) was utilized to propose logical combinations for the structures. The suggested stages/processes and the recommended typologies for each stage (Fig. 4) were used. Furthermore, two basic criteria were established for proposing the combinations in which: (a) each scenario included all stages of the drainage process, and (b) each scenario included one, and only one typology for each process.

Following these criteria, all possible combinations were reached, leading to an independent scenario for each combination (Table 7). Also, two control scenarios (not mixing typologies) were proposed.

The same combinations from Table 7 represented SUDS trains in the watershed. For this matter, it was necessary to manage each SUDS typology as independent subcatchments, that were subsequently connected. By these means, one for each combination of typologies, resulting in six scenarios.

Table 6 SUDS minimum and maximum design parameters reported in the literature

Variable	Units	Bioretention cell		Green roof		Rain garden		Infiltration trench		Permeable pavement		Rain barrel		Vegetated swale	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Surface															
Berm Height	mm	3	300	10	500	150	1000	0	300	0	25			1	400
Vegetation Volume	mm	0.05	0.8	0.1	0.2	0	0.2	0	-	0	0			0	0.1
n Manning	mm	0.03	0.3	0.05	0.13	0.1	0.12	0.24	-	0.01	0.05			0.13	0.24
Slope	%	0.1	3	0.3	2	0	2	1	-	0.5	4			0.8	1.3
Soil															
Thickness	mm	100	800	30	300	500	1200			150	200				
Porosity	%	0.45	0.65	0.4	4	0.3	0.5			0.35	0.5				
Field Capacity	%	0.1	0.35	0.11	4	0.11	0.2			0.1	0.1				
Wilting Point	%	0.05	0.15	0.05	4	0.05	0.2			0.02	0.024				
Conductivity	mm/h	12	300	25	72	2.2	500			100	130				
Conductivity Slope	-	5	10	5	15	10	32.2								
Suction Head	mm/h	15	115	20	110	24.6	50								
Storage															
Thickness	mm	10	380					500	600	10	750	800	914		
Void Ratio	%	0.3	0.8			0.41	0.75	0.75	-	0.3	0.78				
Seepage Rate	mm/h	0	80			2.2	200	24	-	0	600				
Bottom Area (RB)	m2											0.31	0.58		
Clogging Factor	-	0	0			0	0			0	0				
Drain															
Flow Coefficient*	-	0	3.33					0.69	-	0.15	1	0.68	294		
Flow Exponent	-	0.5	2.1					0.5	-	0.5	1.6	0.5	0.5		
Offset	mm	0	150					0	150	0	150	0	150		
Drain Delay (RB)	h											5.8	6		

Table 6 (continued)

Variable	Units	Bioretention cell		Green roof		Rain garden		Infiltration trench		Permeable pavement		Rain barrel		Vegetated swale	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Surface															
Pavement															
Thickness	mm									50	150				
Void Ratio	%									0.13	0.7				
Impervious Surface Fraction	%									0	0.3				
Permeability	mm/h									50	3000				
Drainage Mat															
Thickness	mm	10			75										
Void Fraction	%	0.43			3										
n Manning	mm	0.03			3										

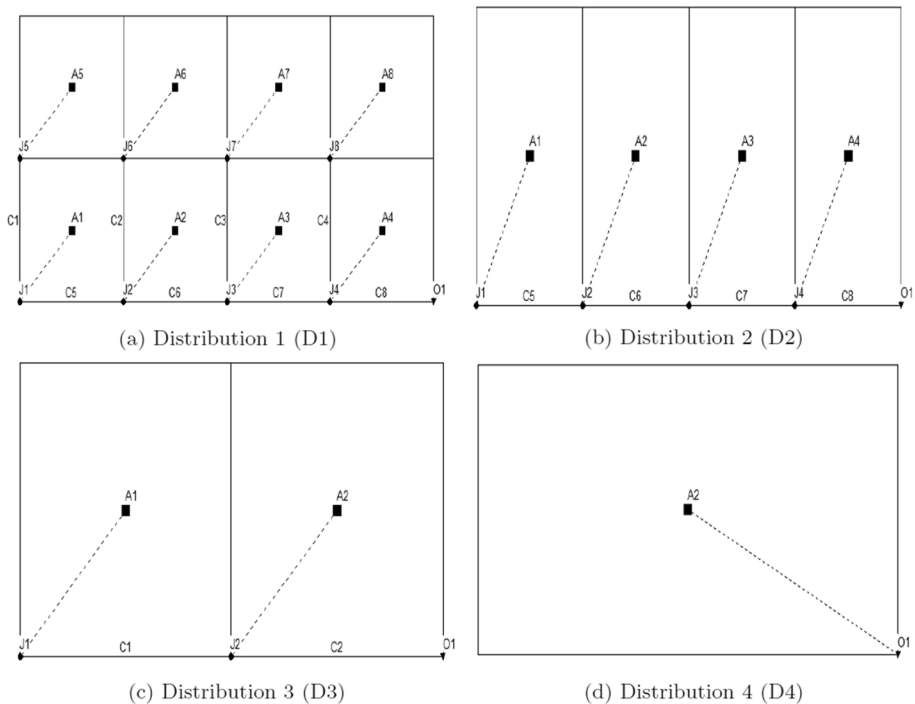


Fig. 3 SWMM model configuration for spatial distributions D1 (distributed) to D4 (Aggregated)

2.3 Sensitivity Analysis

The metrics used to assess the performance of SUDS were total runoff volume, peak flow, maximum flows (average of the top 50 flows), and pollutant loads (total suspended solids, total phosphorus and total nitrogen). The reduction was calculated for all the scenarios by comparing the values with the base scenario (no SUDS implementation). In all cases, the water quantity and quality measures were made at the outfall (O1) of the watershed, after modeling the ten-years rainfall database.

The sensitivity analysis consisted on a One at a Time (OAT) approach (Fig. 5); different Global Sensitivity Analysis methods were tested but failed to be implemented due to the computational cost involved in these approaches (considering that each model consisted on a ten-years continuous data-base). Thus, a model was developed for each scenario defined in Section 2.2. Subsequently, the effect of these scenarios on the performance metrics was analyzed. To summarize the results, sensitivity graphs for the performance variables were developed. Furthermore, the absolute changes in these metrics were calculated as the percentage with respect to the base scenario and a color-coded matrix was developed.

2.4 Decision Making

For each of the stages presented in Figure 2, and based on the results of the sensitivity analysis, a decision regarding SUDS design and configuration was made at each step. To

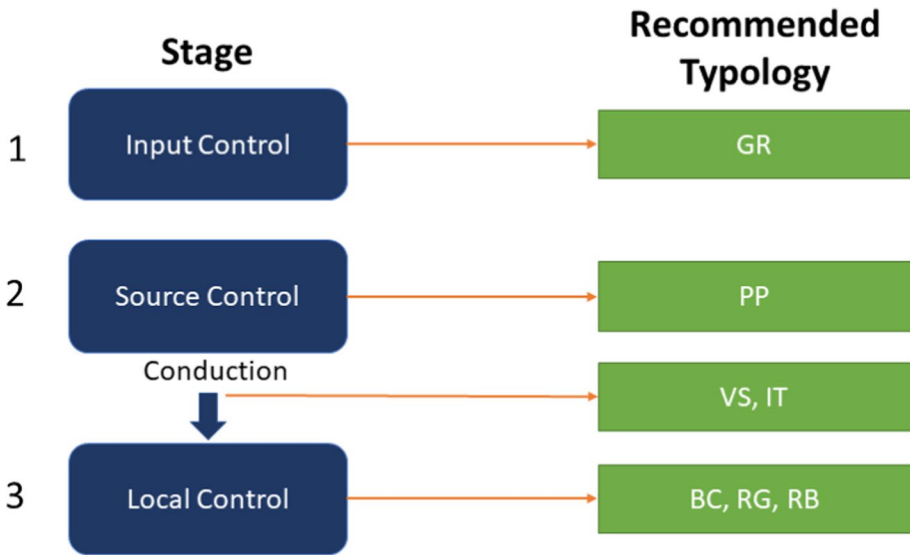


Fig. 4 SUDS trains design process. Blue boxes refer to the drainage-control stages suggested. Orange arrows refer to the typologies recommended (green boxes) for each stage. Adapted from Butler et al. (2018)

Table 7 SUDS combinations selected for green roofs (GR), permeable pavements (PP), infiltration trenches (IT), bioretention cells (BC), vegetated swales (VS), rain gardens (RG), and rain barrels (RB)

#	Input control	Source control	Conduction	Local control
1	Control (GR)			
2	GR	PP	IT	BC
3	GR	PP	VS	BC
4	GR	PP	IT	RG
5	GR	PP	VS	RG
6	GR	PP	IT	RB
7	GR	PP	VS	RB
8	Control (RG)			

avoid bias in the decision-making process, each decision was based on the sensitivity levels, and the performances found during the analysis.

Specifically for the design parameters analysis, the data distribution was processed by defining the values of each quartile. Subsequently, two different levels of sensitivity were defined. The low sensitivity level was assigned to those values below quartile 2; for these values, the minimum value for the parameter was selected. Furthermore, the values above quartile 2 were assigned as high sensitivity, and a manual parameter selection was made. For the rest of the stages of the analysis, the best-performed scenarios were selected.

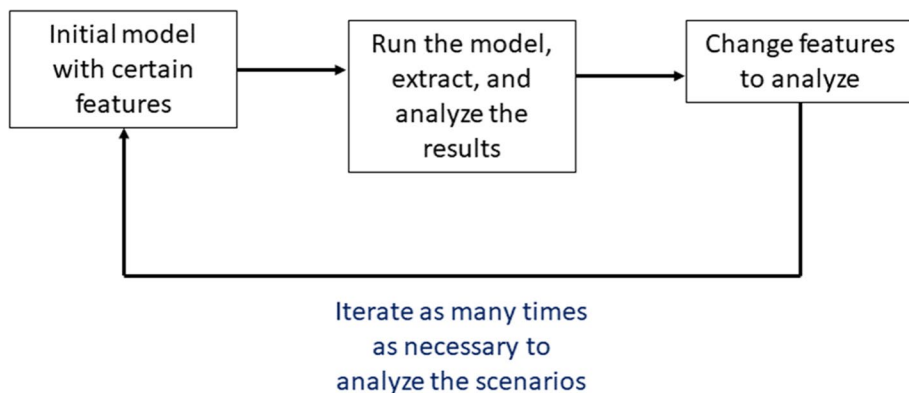


Fig. 5 Step-By-Step methodological framework proposed for the sensitivity analysis

2.5 Effect of Rainfall Regime

Finally, the SUDS scheme selected from the previous analysis was evaluated with different rainfall regimes to quantify the effect of this variable on SUDS performance. 23 continuous rainfall and evaporation (mean multi-annual averages) databases from cities in Colombia and Spain were used to develop the models. They were all developed using the same conceptual watershed described in section 2.1, and the results for total runoff, peak flow, and pollutants reductions were compared.

3 Results and Discussion

3.1 Overall Performances

In order to graphically summarize the performances (reduction percentages) found for the different metrics in the seven typologies, Table 8 presents a summary of the values found. The analysis for the total runoff volume reductions (10%–30%) identified similar performances for the RG, BC, and PP as those reported in previous studies (Arjenaki et al. 2021; Garbanzos and Maniquiz-Redillas 2022; Jato-Espino et al. 2016; Bai et al. 2018), but somewhat limited for the rest of the typologies (<5%). At the same time, the decrease in pollutant (TSS, NT, and TP) loads was high for all the typologies (>90%). Regarding the peak flow, a similar capacity was evidenced for the BC, GR, RG, IT, and PP, with reductions of 20%–30%. Simultaneously, the reduction for the maximum flows did not show the same behavior, with no reductions or even slight increments (IT and VS).

3.2 Design Parameter Analysis

Table 9 presents the sensitivity (expressed as % of change with respect to the base scenario) for each parameter included in the analysis. In addition, the design parameters of

Table 8 Color-coded average reductions found for the four performance metrics (runoff volume, peak and extreme flows and pollutant loads reductions) for the seven typologies analyzed. The color scale is presented at the bottom of the table. Typologies included are green roofs (GR), permeable pavements (PP), infiltration trenches (IT), bioretention cells (BC), vegetated swales (VS), rain gardens (RG), and rain barrels (RB)

Average Reductions (%)		
Volume	BC	
	GR	
	RG	
	IT	
	PP	
	VS	
	RB	
Peak Flow	BC	
	GR	
	RG	
	IT	
	PP	
	VS	
	RB	
Extreme Flows	BC	
	GR	
	RG	
	IT	
	PP	
	VS	
	RB	
Pollutant Loads	BC	
	GR	
	RG	
	IT	
	PP	
	VS	
	RB	

0
25
50
75
100

SUDS included in the analysis are presented. The novel aspect of the results presented consists mainly in the inclusion of 7 typologies. For each typology, the sensitivity to the

Table 9 Color-coded sensitivity found for the four performance metrics (runoff volume, peak and extreme flows and pollutant loads reductions) for the five design parameters analyzed. The color scale is presented at the bottom of the table. Typologies included are green roofs (GR), permeable pavements (PP), infiltration trenches (IT), bioretention cells (BC), vegetated swales (VS), rain gardens (RG), and rain barrels (RB)

		Berm Height	Vegetation Volume	Soil Depth	Storage Depth	Drainage offset
Volume	BC					
	GR					
	RG					
	IT					
	PP					
	VS					
	RB					
Peak Flow	BC					
	GR					
	RG					
	IT					
	PP					
	VS					
	RB					
Extreme Flows	BC					
	GR					
	RG					
	IT					
	PP					
	VS					
	RB					
Pollutant Loads	BC					
	GR					
	RG					
	IT					
	PP					
	VS					
	RB					
60	50	40	30	20	10	0

different performance metrics is presented independently. In general terms, the predominance of the red and yellow colors in Table 9 allowed to identify the low sensitivity found for most of the parameters. Only some specific sensitivities reported values above 40%. These latest cases will be discussed in Sections. 3.2.1—3.2.4.

3.2.1 Surface Variables

According to the procedure described in section 2.4, the berm height sensitivity found for the volume reduction and peak flow was low, with no more than 5% variations for all typologies. However, when analyzing the pollutant loads, results showed a clear positive correlation, with increases of 10%—50% in the reductions. This confirms that berm height is a relevant parameter by allowing higher levels of surface ponding and promoting settlement and filtering of pollutants (Bastien et al. 2010; Charlesworth et al. 2003; Napier et al. 2009).

The sensitivity for the vegetation volume presented variations of 0%–60%. In the case of the total runoff reduction, the BC started with reductions of 20% and decreased as the vegetation cover increased. Simultaneously, the RG presented constant reduction values (25%) with low sensitivity for the design parameter. Both the GR and the VS (including modifying their vegetation cover) showed ineffective strategies to reduce the total volumes, with constant values of 0% reduction. Previous studies (Leimgruber et al. 2018) had identified the low sensitivity of this parameter when assessing the performance of the structures. Therefore, it is highly recommendable for future work to further investigate the performance of the structure.

The metrics of pollutants load and peak flow presented similar results. In all cases, the sensitivity yielded for the vegetation coverage was low, as reported by Leimgruber et al. (2018). The net changes were small (0% — 10%). Therefore, it is suggested that the percentage of surface vegetation cover does not directly influence the runoff quality and quantity. However, it is considered that the greatest potential of the vegetation cover of SUDS regards the aesthetic and landscape dimension. Monberg et al. (2018) highlighted that it is recommended to focus on these aspects when defining the percentage and type of vegetation cover.

3.2.2 Soil Parameters

The sensitivity found for the depth of the soil layer was low for peak and maximum flows and runoff volume (<5% in most cases). Only the mean duration and volume of runoff events presented a 10% increment due to increased soil depth for the BC.

Results for pollutants loads were different. In this case, the variable sensitivity was high for BC, GR, and PP, with increases of up to 10% in reducing contaminants when increasing the soil depth. This fact can be explained by the fact as the total volume of soil increases, the adsorption and filtering processes of contaminants are favored (Schlüter and Jefferies 2005). For the rest of the performance metrics, the depth of the soil did not show significant repercussions on the functioning of the structures, confirming the conclusions made by Leimgruber et al. (2018).

3.2.3 Storage and Drainage Parameters

The analysis for the storage variables was also made for the height of this layer. Overall, the analysis yielded low levels of sensitivity (<3%). This was the first analysis that included the RB. However, the sensitivity of the parameter and the global reductions of this structure, behaves similarly to the rest of the typologies. In this case, only the BC presented increases of 30% in the mean average duration of runoff events while the storage layer increased.

A possible reason why the storage height of the structures was not a relevant parameter is that most of the relevant phenomena that intervene in the long-term modification of the patterns of runoff quality and quantity (seepage, infiltration, evapotranspiration, etc.) are not directly related to this parameter (Charlesworth et al. 2012).

In this case, the offset of the drainage orifice was analyzed, and the results obtained are similar to the previous sections: low sensitivity levels, with less than 2% variations with changes in the offset between 0–150 mm. These results indicate that this parameter might not clearly influence the structures' long-term performance.

Table 10 Design parameters values selected and sensitivity levels. Low level (green, < 10%) and high level (orange 10%—50%)

Variable	Units	BC	GR	RG	IT	PP	RB	VS
Surface								
Berm Height	mm	300	120	150	0	0		100
Vegetation Volume	%	0.4	0.1	0				0
Soil								
Thickness	mm	100	30	500		150		
Storage								
Thickness	mm	10		200	500	10	800	
Drain								
Offset	mm	0			0	0	0	

3.2.4 Parameters Re-definition

The design parameters were re-defined depending on their sensitivity levels, and results from this process are presented in Table 10. Four parameters presented a high sensitivity level (orange), in which a manual selection of the value of the parameters was made. This balances the performance and the constructive facilities of the structure. The rest of the parameters presented a low level of sensitivity (green), which is why the lowest values for the parameters were assigned. The rest of the parameters were fixed as the average values from those reported in the studies in Table 6.

3.3 Distribution and Disposition Analysis

3.3.1 Area

The analysis of the area indicates that the sensitivity in the performance metrics for changes in the area was high for SUDS. For the specific cases of total runoff volume, maximum flow, and pollutants loads, the performances of SUDS increased in values (20%—50%). As a general fact, the performance of the structures improved when the area of the SUDS was higher; the above occurred indistinctly for all typologies.

The SUDS area value was chosen based on two criteria; considering that 1% area offered a fair balance between performance and implementation complexity and following the design guidelines (Strecker et al. 2010; Till and Torres 2004; Valley 2010; Woods-Ballard et al. 2007).

3.3.2 Number of Structures

Results showed low sensitivity for most of the analyzed parameters. The variation in the performance of the SUDS when modifying the number of structures was practically imperceptible. The two highest sensitivities observed were 25% variations (for GR and VS). In both cases, the best-performed scenario was the one-structure (pollutant reductions of 75%, in comparison with reductions of 50% for the rest scenarios). Due to this, this was the chosen scenario.

3.3.3 Spatial Distribution

This analysis allowed to identify the sensitivity changes of the performance metrics in response to the spatial distribution of SUDS. The variations were minimal for the total runoff volume and pollutant loads depending on the spatial distributions. However, for the peak flow, there were higher differences. Therefore, to guarantee that the spatial distribution selected was the one that maximized its performance, additional analyses were performed for this variable.

The results for the peak flow analysis in the seven typologies were assessed (Figure 6). In all cases, D4 was the distribution that best-performed. However, it was discarded due to its lack of real-life implementation (no pipelines or additional runoff transport infrastructure). Subsequently, depending on the typology, D2 and D3 had better performances than D1. Previous authors had already highlighted the importance of having decentralized managing strategies to improve the performance of SUDS (Guo et al. 2019). Therefore, giving priority to IT, RB, and VS, and also to ease the applicability in real cases (less complex and expensive sewage systems), D3 was chosen as the spatial distribution for SUDS. Overall, it was concluded that because the SUDS modify the hydraulic and hydrological patterns of the catchment, their spatial distribution will be a determining variable in these modifications, and for this reason it is essential to define adequately what is the best distribution, as also stated by other authors (Tedoldi et al. 2017; Joshi et al. 2021; Fenner 2017).

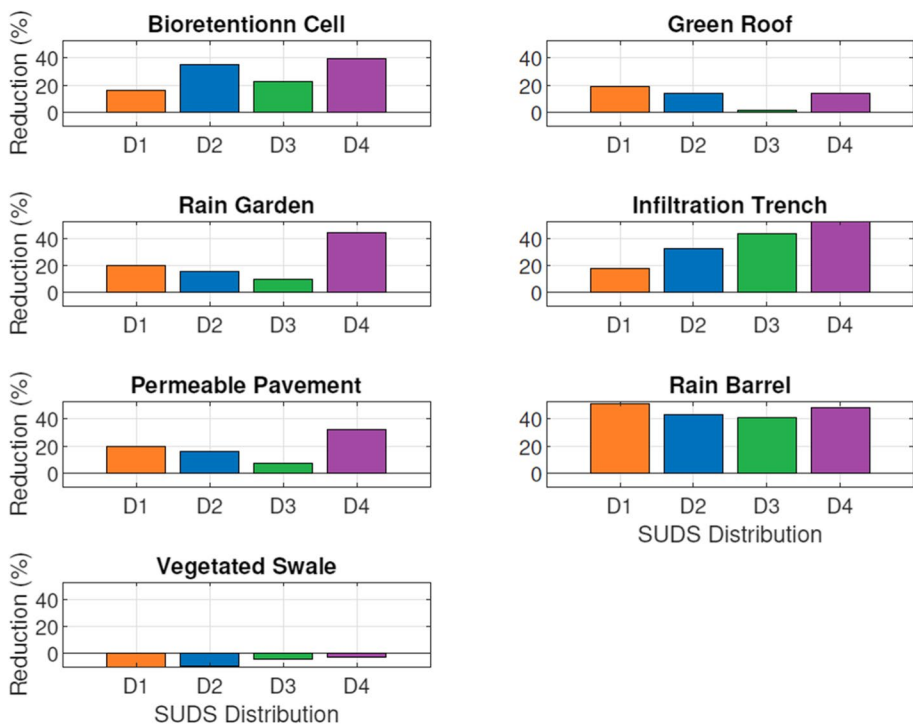


Fig. 6 Peak flow reduction (%) for spatial distributions D1, D2, D3 and D4. Starting from D1, the spatial distributions are distributed, and progressively centralized

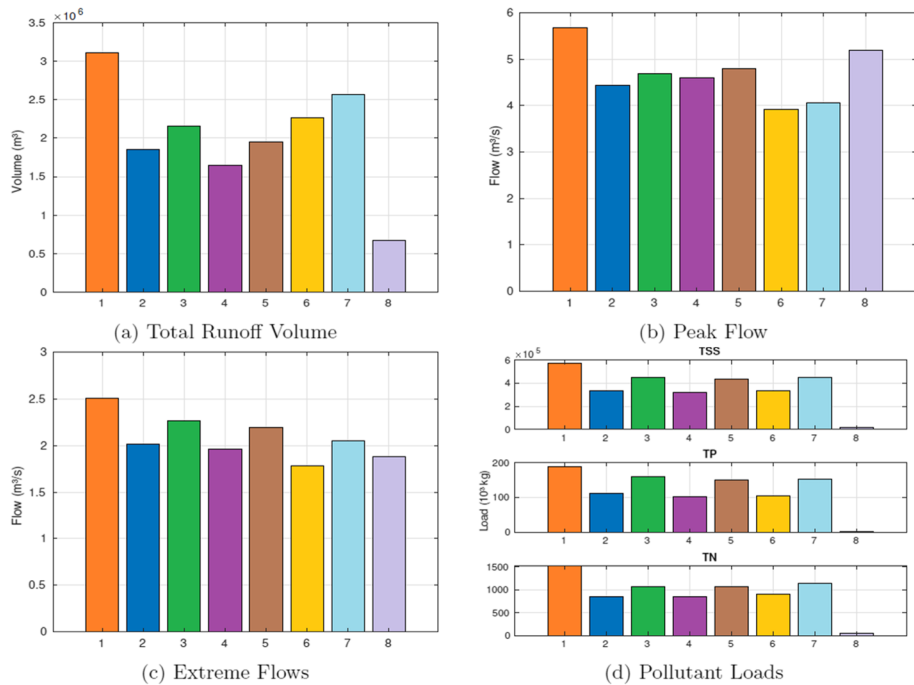


Fig. 7 Total Runoff Volume, Peak and Maximum Flows and Pollutants Loads for 8 possible combinations of SUDS typologies

3.3.4 Combination of Typologies

Results for total runoff volume, peak and maximum flows, and pollutants loads are presented in Figure 7. For the total volume of runoff (Figure 7a) and the pollutant loads (Figure 7d), it is shown that in none of the combined cases (scenarios 2—7) results are higher than the best control scenario (Scenario 8), nor worse than the worst control scenario (Scenario 1). However, results for the peak flow (Figure 7b) and the extreme flows (Figure 7c) did show a tendency to improve performance for the combined scenarios. In both cases, scenarios, 6 and 7 showed the best performance (expressed as the lowest flow). In addition, the local control strategy was the RB, which suggests that this typology has a strong effect on reducing peak flows.

Generally, this analysis allowed to identify that it is particularly important to clearly define the objective variable (volume, peak flow, or contaminant load). In addition, from that definition, determine which combination is the most appropriate, considering that in some cases combining typologies might not be the most appropriate.

3.3.5 SUDS Trains

Figure 8 presents the results with and without SUDS trains (blue and green bars), and the percentage of reduction implied by including the trains (red dots).

Results yielded that the performances for the interconnected structures improved substantially. Furthermore, for the total volume of runoff (Figure 8a), the fact of including

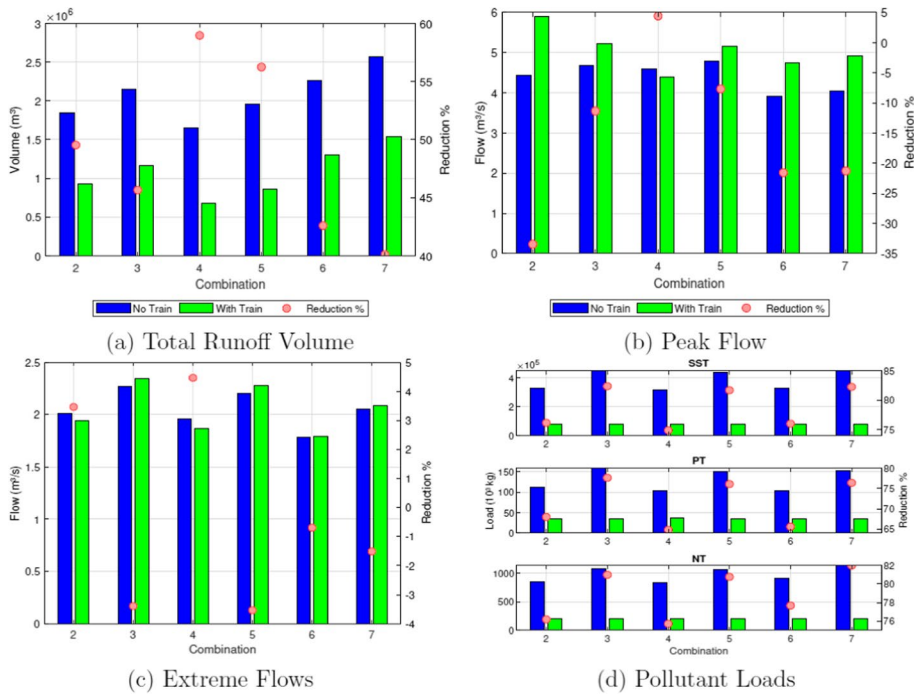


Fig. 8 Total Runoff Volume, Peak and Maximum Flows and Pollutant Loads for combinations with and without SUDS trains

SUDS trains causes the reduction of the total volume of runoff to increase significantly (40%—60%), and similarly for the pollutant loads (65%—85%). Overall, suggestions made by Beltran et al. (2019) were confirmed, highlighting the importance of structured methodologies to include SUDS trains in the models, as their potential for improving SUDS performances is high.

For this specific case, and because the positive effect of trains over runoff volume and pollutants loads was comparatively higher than the negative effects over the peak flows, it was decided to prioritize the first two variables, and for this, it was decided to continue using SUDS trains. Based on the results, combination five was the best option and was selected for the subsequent analysis.

3.3.6 Optimal SUDS Scheme Definition

To summarize the decision-making procedure followed, Table 11 presents each of the stages of the analysis, along with the possibilities in each stage and the decision made (in green).

It is worth clarifying that this configuration was selected for this specific case study. Although it cannot be guaranteed that it applies to other case studies, this selection methodology can be recommended as applicable and extrapolated to other cases. Because the results can be highly variable, and also because of the variability of possible decisions

Table 11 Variables assessed, options and decisions made at each step (green)

Area	Structures	Distribution	Combination	Trains
0.1	1	Distributed	Yes	GR-PP-IT-BC
0.2	2			GR-PP-VS-BC
0.3	3			
0.4	4	Semi-Distributed		GR-PP-IT-RG
0.5	5			
0.6	6	Semi-Aggregated	No	GR-PP-VS-RG
0.7	7			
0.8	8	Aggregated		GR-PP-IT-RB
0.9	9			
1	10			GR-PP-VS-RB

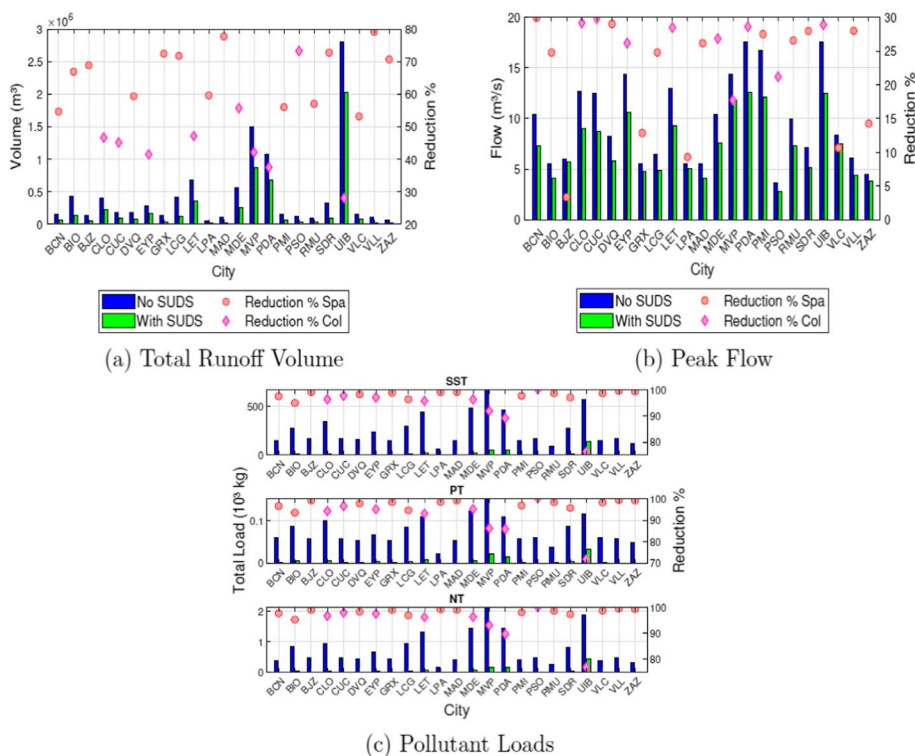


Fig. 9 Total Runoff Volume, Peak Flow and Pollutants Loads with and without SUDS trains for 23 different Colombian and Spanish Cities. The main Y-axis represents the performance metrics for the model with SUDS (blue) and without SUDS (green). The secondary Y-axis represents the percentage of reduction due to the presence of SUDS in each case. Results are differentiated between rainfall information from Colombian (Col) and Spanish (Spa) cities, with rounded red indicators for the first group and pink quadrangle indicators for the second. The International Air Transport Association (IATA) code was used to represent the cities

based on the specific objectives, it is recommended to apply this methodology to each specific case study.

3.4 Effect of Rainfall Regime on SUDS Performance

Figure 9 summarizes the main results for the effect of rainfall regimes. The analysis for the total runoff volume (Figure 9a) identified high variability in the efficiency of reduction, with overall values varying between 30%–80%. Except for Pasto (PSO), the scenarios with the lowest reduction percentages were from Colombia, with values between 30%–55%. At the same time, scenarios from Spanish cities showed higher reduction rates (above 60%). Similar trends were previously reported by authors that worked in Mediterranean and tropical areas (Andrés-Doménech et al. 2018; Goncalves et al. 2018).

Based on the above, it is suggested that SUDS might have high variability in their efficiency and effectiveness depending on the region; for tropical regions with more intense rainfall regimes, the SUDS effectiveness decreases, while for regions with more prolonged but less intense rainfall events, the effectiveness of these structures increases considerably, as previously identified by Zhang et al. (2019).

Analyzing the inner-region variability, a similar trend was identified. For example, in the case of Colombia, in cities with large rainfall events, such as Inirida (PDA), Quibdó (UIB) and Mitú (MVP), SUDS efficiency was lower than for the rest of the cities. The same happened for Spanish scenarios, showing that the variability in performance rates is also observed at the regional (inner-country) level.

The analysis for the peak flow (Figure 9b) allowed to identify reductions between 5% and 30%. A similar (but inverse) variability was observed regarding the global and inner-region analysis. This means that in this case, the potential of the SUDS to reduce peak flows is greater for cities with more intense rainfall regimes (Colombian cities), and gradually decreases for cities with more stable rainfall regimes (Spanish cities). However, in this case, the dispersion between the different performances was less perceptible than that of those observed in Figure 9a.

Finally, Figure 9c allowed to identify that for the contaminant loads, the variability, both regional and inner-regional, decreased significantly. Colombian cities such as Inirida (PDA), Quibdo (UIB) and Mitu (MVP), which are those with the highest annual rainfall, had lower rates of reduction, but in this case, the differences were less than 5% or 10% within the cities. Overall, the pollutant reductions were between 90% and 99%. Data suggests that SUDS have a high potential to reduce pollutants, and this potential does not depend directly on the rainfall regimes.

Considering that the selection methodology was applied to the city of Santander (SDR), it could be confirmed that the results obtained from the methodology proposed were satisfactory since the performance of SUDS was good for this city. At the same time, this confirms the need to apply the proposed methodology to each case study, since SUDS did not perform equally with all the different rainfall regimes analyzed.

4 Conclusions

A novel modeling-based methodology was proposed to assess and study SUDS performance in a systematic manner. The combinations and interconnection of typologies was successfully studied, as well as the effect of SUDS configuration, design and distribution

on its performance. The study was successfully implemented using long-term modeling with rainfall information from different and unstudied regions. The five-step methodology is expected to be replicable for different case studies, in order to contribute in the development of SUDS-tools based on models that will ultimately assist the decision-making process for urban drainage projects involving SUDS.

The analysis for the design parameters identified the low sensitivity levels for most of the parameters. Generally, the surface parameters (berm height and vegetation cover) had a slightly higher sensitivity (maximum 50%). In contrast, the soil, storage, and drainage parameters presented lower levels of sensitivity (many times imperceptible). The low sensitivity levels found might be due to the high amount of SUDS parameters. This study analyzed the most relevant parameters during the design process. However, variables related to the nature of the construction materials and the study site (hydraulic conductivity of the substrate, soil porosity, field capacity, surface roughness, etc.) may be highly relevant in the process. In this case, it was considered that these variables are fixed and dependent on external factors, which are not easily defined by the designer of the structures, and for this reason, they were excluded from the analysis. Furthermore, for future studies, it is highly recommended to assess the crossed-effect of changing more than one parameter at a time, in order to evaluate the high complexity of the parameters involved in the models.

Additionally, it is highly likely that aspects related to the nature and conception of the model also mediate the results found. For example, the modeling time scale can be fundamental to the results. In this study, the objective was to evaluate the effect of SUDS in the long term, and for this reason, it was decided to do continuous modeling of a ten years database. However, it is highly likely that if the database is shorter or even modeling by event is done, the results will be different. Thus, it is particularly important to define beforehand the objective of the study, to select the most appropriate time scale for the model.

Regarding the effect of the distribution and configurations of SUDS, the variables that proved to be of greater relevance were the area, as well as the spatial distribution, and the presence of trains. For the area, the performance of SUDS increased with their total area, and the percentage selected (with respect to the total area) was 1%; concerning the spatial distribution, the semi-aggregated option proved to be the most efficient, specifically for managing peak flows. Finally, SUDS trains proved to have high efficiency in managing the total runoff volume and the reduction of pollutants.

The dependent result on the performance metrics (including the desired goals) highlights the importance of clearly defining them. For this study, all the metrics were included. However, for future exercises, the modeler needs to define the main performance variable and the desired objectives for this variable. Additionally, aspects such as the economic, construction, maintenance, social or landscape dimensions might be highly relevant and should be included in future studies.

For the specific case of Santander, Spain, it was found that the optimal configuration of SUDS included a 1% area of SUDS concerning the total catchment area, with a semi-aggregated spatial distribution, combining and interconnecting the following typologies: GR-PP-VS-RG.

Finally, the analysis of the effect of rainfall regimes showed variability in the performance of the SUDS for the different scenarios evaluated. The fact that the results were satisfactory for the city of Santander indicates that the proposed methodology was adequate. Still, it also reaffirms the urgent need to apply this methodology to each case study. The optimal SUDS configuration obtained by applying this methodology will

likely be different depending on the city. For future work, it is recommended to perform structured analyses including more regions to find regional, national, or even continental patterns, regarding how certain typologies or configurations adapt more easily to certain contexts. It is also essential to include the economic dimension in the decision-making process and the possibility to mediate and negotiate among multiple stakeholders in the decision-making process. In the latter, it is proposed as future work to automate, through a software tool, the methodology exposed in this study, to facilitate the decision-making process.

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Data Availability Datasets and material used to develop this research are available to readers, upon request to the corresponding author.

Declarations

Competing Interests Authors declare they have no financial or competing interests of any kind.

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