Evaluation of the sustainable urban drainage systems in a small town. Case study Paipa, Boyacá, Colombia

Evaluación de los sistemas urbanos de drenaje sostenible en una pequeña ciudad. Tudio de caso Paipa, Boyacá, Colombia

Avaliação de sistemas de drenagem urbana sustentáveis em uma cidade pequena. Estudo de caso: Paipa, Boyacá, Colômbia

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Abstract

Introduction: The current article evaluates the use of SUDS to manage rainwater within the urban area of the municipality of Paipa, research developed at the Pedagogical and Technological University of Colombia in 2020.

Methods: The researchers conducted a literature review about SUDS based on the available information regarding the city's soils, urbanism, hydrology, and sewage system. In addition, in-situ visits took place throughout the study to identify potential areas for implementation, as well as the analysis of alternatives with different SUDS at a pre-feasibility level, taking into account as the most relevant aspects the technical and economic components, and comparing those alternatives with the sewerage renovation project in a sector of the urban center using the EPA SWMM 5.1 software.

Results: The study showed the sewage transition process from a combined system to a separate system and the existence of potential places for the implementation of SUDS, which can bring benefits to the design and functioning of the municipal sewer system.

Conclusions: It was found that, in this case, SUDS cannot replace conventional sewage systems; however, they can be considered a complement to achieve more integral rainwater management and control.

Originality: The study provides a comprehensive perspective on the viability and potential benefits of SUDS implementation in the local context, contributing to a growing body of literature.

Limitation: The economic analysis estimated an increase in the total cost of the project. Future research could address these limitations through a broader scope and more detailed financial considerations.

Keywords: Sustainable Urban Drainage Systems, sewer, runoff, floods, hydrological cycle, drainage.

Resumen

Introducción: El presente artículo evalúa el uso de los SUDS para el manejo de aguas lluvias dentro del área urbana del municipio de Paipa, investigación desarrollada en la Universidad Pedagógica y Tecnológica de Colombia en el año 2020.

Métodos: Los investigadores realizaron una revisión bibliográfica sobre los SUDS, apoyados en la información disponible de suelos, urbanismo, hidrología y sistema de alcantarillado. Se realizaron visitas in situ a lo largo del estudio para identificar áreas potenciales de implementación, y se analizaron alternativas con diferentes SUDS a nivel de prefactibilidad, tomando en cuenta como aspectos más relevantes el componente técnico y económico, y comparando las alternativas con el proyecto de renovación del alcantarillado en un sector del centro urbano utilizando el software SWMM 5.1 de la EPA.

Resultados: El estudio mostró el proceso de transición del alcantarillado de un sistema combinado a un sistema separado y la existencia de lugares potenciales para la implementación de SUDS, aportando beneficios al diseño y funcionamiento del sistema de alcantarillado.

Conclusiones: Se encontró que los SUDS no pueden sustituir los sistemas convencionales de alcantarillado; sin embargo, pueden considerarse como un complemento para lograr un manejo y control más integral de las aguas pluviales.

Originalidad: El estudio proporciona una perspectiva integral sobre la viabilidad y los beneficios potenciales de la implementación de SUDS en el contexto local, contribuyendo a un creciente cuerpo de literatura.

Limitaciones: El análisis económico estimó un aumento del costo total del proyecto. Futuras investigaciones podrían abordar estas limitaciones mediante un ámbito de aplicación más amplio y consideraciones financieras más detalladas.

Palabras clave: Sistemas urbanos de drenaje sostenible, alcantarillado, escorrentía, inundaciones, ciclo hidrológico, drenaje.

Resumo

Introdução: Este artigo avalia o uso de Sistemas Urbanos de Drenagem Sustentável (SUDS) para o gerenciamento de águas pluviais na área urbana do município de Paipa. Esta pesquisa foi realizada na Universidade Pedagógica e Tecnológica da Colômbia em 2020.

Métodos: Os pesquisadores realizaram uma revisão bibliográfica sobre SUDS, apoiada por informações disponíveis sobre solos, planejamento urbano, hidrologia e sistemas de esgoto. Visitas de campo foram realizadas ao longo do estudo para identificar áreas potenciais de implementação, e alternativas com diferentes SUDS foram analisadas em nível de pré-viabilidade. Os aspectos mais relevantes considerados foram os componentes técnico e econômico, e as alternativas foram comparadas com o projeto de renovação da rede de esgoto em um setor do centro urbano utilizando o software SWMM 5.1 da EPA.

Resultados: O estudo mostrou o processo de transição da rede de esgoto de um sistema combinado para um sistema separado e a existência de locais potenciais para a implementação de SUDS, contribuindo com benefícios para o projeto e operação do sistema de esgoto.

Conclusões: Constatou-se que os SUDS não podem substituir os sistemas de esgoto convencionais; No entanto, podem ser considerados um complemento para alcançar uma gestão e um controle mais abrangentes das águas pluviais.

Originalidade: O estudo fornece uma perspectiva abrangente sobre a viabilidade e os benefícios potenciais da implementação de SUDS no contexto local, contribuindo para um crescente corpo de literatura sobre o assunto.

Limitações: A análise econômica estimou um aumento no custo total do projeto. Pesquisas futuras poderiam abordar essas limitações por meio de um escopo mais amplo e considerações financeiras mais detalhadas.

Palavras-chave: Sistemas de drenagem urbana sustentável, esgoto, escoamento superficial, inundação, ciclo hidrológico, drenagem.

1. INTRODUCTION

Urban drainage is understood as the management of rainwater in a given area of the city, which implies designing structures capable of transporting it from one point to another toward the receiving source, avoiding impacts on the safety and development of communities. For this purpose, Conventional Sewerage Systems are used, allowing the capture, transport, and discharge of collected water, thus facilitating its prompt evacuation during a rain event. However, in designing these systems, some important factors are considered, such as the drainage areas, the continuous development and waterproofing processes in urban zones, as well as variations in the duration and intensity of rainfall events, which make them insufficient to guarantee the total evacuation of runoff, leading, among other consequences, to the collapse of sewerage networks and flooding [1].

Similarly, the natural water cycle involves processes such as interception of water by plants, soil infiltration, surface accumulations, surface and subsurface runoff, evapotranspiration, and evaporation, where the latter closes the cycle by returning the water to the atmosphere. However, in cities, the cycle is modified and reduced since natural surfaces are replaced by impermeable ones, which leads to high percentages of precipitation turning into runoff, with certain rain events concentrating rapidly in an area and causing large flows in a short period of time [2].

Therefore, these problems result from both natural events (heavy rainfall and topographical features) and anthropogenic factors such as planned and unplanned urban development, where flood control structures used to protect communities are, in most cases, non-existent or insufficient. This increases the vulnerability of the area when its capacity is exceeded due to extreme weather events or higher-than-expected quantities of water to be captured [3].

Bearing this in mind, in order to improve urban drainage, there are non-conventional alternatives aligned with sustainable development, such as Sustainable Drainage Systems (SuDS) [4], Best Management Practices (BMPs) [5], Low Impact Developments (LIDs) [6], and, commonly for Spanish speakers, *Sistemas Urbanos de Drenaje Sostenible* (SUDS) [7]. Thus, in the present study, to refer to these alternatives, the terminology of Sustainable Urban Drainage Systems (SUDS) is adopted and defined as structures that allow the management of rainwater in urban areas by integrating hydrological, environmental, and social aspects, maintaining control as close as possible to the site where it falls, and reducing the amount of runoff and pollutants entering conventional drainage systems [8].

In addition, these systems propose more efficient management of rainwater, considering it as one more resource for reuse, thus helping to minimize water scarcity in certain areas and periods of the year [9]. Similarly, the implementation of SUDS opens new possibilities regarding the configuration of a city's sewage system since, in certain areas, drainage managed by these systems may be reused or directed entirely to natural watercourses and may not require rainwater drainage. However, given the current difficulties that this represents, efforts are focused primarily on reducing the discharge of rainwater to conventional systems, making it possible to consider sewerage networks with smaller and/or less extensive dimensions [10].

Currently, information on sustainable drainage can be found in databases and online documents. In Colombia, the Ministry of Environment and Sustainable Development, which is responsible for defining environmental regulations, established in [11] the National Climate Change Policy, where strategic actions are indicated to make urban and rural development low in carbon and climate-resilient.

In that sense, regarding the management of aqueducts and sewerage in the municipalities, the Ministry of Housing, City and Territory —which, among other responsibilities, is in charge of directing projects in the field of human housing and drinking water in Colombia— regulates [12] the technical requirements to be fulfilled by Sustainable Urban Drainage Systems in runoff management. Along the same lines, the regulatory entity for the operation of aqueduct and sewerage systems (EAAB-ESP) of Bogotá D.C. has, in recent years, issued regulations and studies on the implementation and design of SUDS according to its conditions. However, for the rest of the country's municipalities, these systems—evaluated under their local environments and characteristics—still need to be articulated and studied in detail.

Accordingly, the municipality of Paipa, Boyacá, Colombia, has not been exempt from the processes described above. The main characteristic of its current sewerage system is the high percentage of combined operation (rainwater and sewage using the same conduit), which causes problems in evacuating all runoff in the urban area during certain rainfall events, mainly due to limitations in the network's hydraulic capacity, changes in rainfall patterns, and land use [13].

Faced with this situation, since 2012, the municipal administration has invested in redesigning the sewerage master plans. In recent years, it has made progress toward separating the system's functioning and optimizing it through the construction of sanitary and rainwater collectors. Nevertheless, during infrequent rainfall events, problems with flooding and waterlogging persist due to the accumulation of rainwater in the city, such as those recorded in 2016 [14] and 2017 [15].

Consequently, this situation suggests that the current drainage systems do not operate optimally. Therefore, SUDS represent a new approach to address these problems and generate improvements in the management of rainwater. In this study, the use of SUDS for rainwater management in the urban area of the city and their performance compared with the commonly used Conventional Sewerage Systems is evaluated. For this purpose, the researchers described the characteristics of the existing sewerage network in the municipality, conducted an analysis of alternatives with SUDS at a pre-feasibility level—considering the technical and economic components as the most relevant aspects—and compared three alternatives selected under the SUDS model with the separated sewerage system in a specific area of the municipality.

2. MATERIAL AND METHODS

The following stages were included in the development of the work:

2.1 Bibliographic compilation of SUDS

As part of this stage, different sources of information were consulted to conceptualize the topic under study. Academic databases (SciELO, Dialnet, EBSCOhost, among others), specialized documents, reference books on urban drainage, and various texts retrieved from websites were reviewed.

For this study, and based on the characteristics of the municipality, the guidelines proposed in [16] by the EAAB-ESP were adopted, as well as those proposed in [17] by the Universidad de los Andes, which present different SUDS typologies that are better adapted to the conditions of Bogotá D.C. Given the urbanistic and climatological similarities with the study area, these guidelines allowed the proposed analyses and scopes to be developed. Consequently, the following systems described in these documents were evaluated as alternatives:

1. Dry extended detention basin
2. Storage tank or rain barrel
3. Bioretention zone or bioretention cell
4. Tree box filters
5. Vegetative swale
6. Infiltration trench
7. Permeable pavement

2.2 Data review and characteristics of the municipality of Paipa

As a starting point, the municipality of Paipa is located at 2,525 meters above sea level in the Sogamoso Valley, in the central-eastern part of Colombia, on the northwestern side of the department of Boyacá (Fig. 1). It covers a total area of 30,952 hectares, and its urban area is approximately 330 hectares.

The predominant geological formations in the study area correspond to alluvial deposits and compositions of clay and sand, which, depending on the zone, have low capacities for infiltration processes and phreatic levels of one, three, or even four meters above ground level [18].

In terms of territorial space, this municipality has approximately 20,000 inhabitants distributed across 19 neighborhoods, most of which are undergoing continuous urban consolidation, with built-up areas showing high percentages of impermeability. Furthermore, the longitudinal slopes in the municipality are highly variable, with some sectors having slopes of less than 1% and others greater than 10%.

Accordingly, the reference framework adopted for the study corresponds to the urban area of the municipality. The information used was obtained from websites and from studies carried out by the administrative entity responsible for Paipa's water and sewerage services. Likewise, given the area covered and the level of analysis proposed, no field measurements of variables were taken; however, the available information was sufficient for the proposed pre-feasibility analysis.

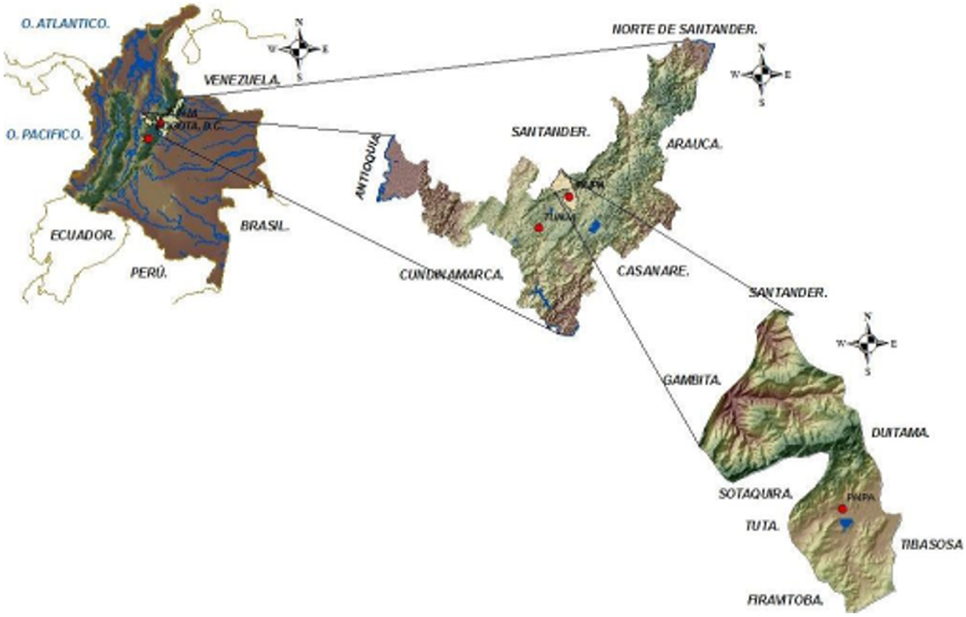


Fig. 1. Geographic location of the municipality of Paipa, Boyacá, Colombia.
Source: own work

2.3 Field visits and selection of potential areas

Throughout the investigation three on-site recognition visits were made, which covered the area of study and analyzed the following aspects; drainage and runoff evacuation problems, land uses, available urban spaces, as well as intervention projects for the renewal of the sewerage system. A total of nine sites in specific conditions to study were defined (Fig. 2) and in each one of them, related to the criteria and values proposed in the reference documents for the implementation of SUDS. In addition, aspects as soil infiltration rate, longitudinal slope, phreatic level, and distance of the system from the foundations of neighboring structures were evaluated, those allowed a selection of alternatives with SUDS taking into account the conditions of the area.

Fig. 2. Sites identified for analysis of alternatives with SUDS 1) Park in "District Villa Jardín", 2) Green area available in "District Villa Jardín", 3) Available lots, road separators and roof area in "District Villa Panorama", 4) Green areas and parks in " District El Bosque", 5) Green area in "District Centro", 6) Pedestrian platform area on "District Centro", 7) Green areas and road dividers in "District Centro", 8) Green areas in "District Villa Vianey" and 9) Road dividers on "District Sausalito".

2.4 Analysis of alternatives

2.4.1 Technical aspects of alternatives with SUDS

For the design of each system, the methodologies proposed in the adopted reference documents were followed, along with a hydrological calculation and a preliminary sizing of the structure. The design variables were defined according to the site conditions evaluated. As part of the hydrological design, the methodologies implemented in Colombia for rainfall–runoff models were applied, using available hydrological information from the city [19] and consulting data from climatological monitoring stations located in the municipality.

2.4.2 Economic aspects of alternatives

For the economic evaluation, construction activities were proposed according to each typology, calculating their respective quantities of work and using unit prices established by local regulations in Colombia [20], thereby obtaining a general budget for construction activities in accordance with the level of the study.

2.4.3 Comparison of alternatives

In this phase, a sector was selected among all those analyzed, corresponding to one known as "Villa Panorama" (see Fig. 2 Z3). Currently, it has a combined drainage system, for which a renewal project is planned, including the construction of a collector for rainwater management in the area. This sector was chosen because sufficient information was available to study and compare alternatives.

In addition, the EPA SWMM version 5.1 software was used for the comparison, since its hydrological component includes tools for editing eight LID controls ("Bioretention Cell, Rain Garden, Green Roof, Infiltration Trench, Permeable Trench, Rain Barrel, Rooftop Disconnection, Vegetative Swale") that correspond to the SUDS typologies considered in terms of geometry and structural layer information obtained from the design. Likewise, the software allows the representation of the physical model of the sewerage network, based on hydraulic principles and models with different calculation methodologies for uniform and non-uniform flow conditions. Moreover, it meets the minimum requirements stipulated by Colombian regulations for the verification of sewerage network software.

3. RESULTS

The results obtained in the study are presented in detail below.

3.1 Comparison of alternatives

As a first aspect, three watercourses are present in the study area (see Fig. 3): the Chicamocha River (flowing east–west), and the Rosal and Valencí Creeks (both flowing north–south). These watercourses, at certain points along their routes, receive rainwater and wastewater discharges collected by the drainage network, which, together with some specific discharges in open areas, generate environmental impacts and problems related to water quality and management within the city.

Regarding the evaluated variables for each site, the main finding was that the rate of soil infiltration limited the selection of SUDS in certain areas due to its low values (between 1.27 mm/h and 7.62 mm/h), as well as the proximity to surrounding structures (between 2 m and 6 m). Therefore, the coating of the structures with geotextiles and the addition of drainage elements were defined so that the volumes of water stored and/or transported by each system are returned to the sewerage system in the area, thus restricting these processes and minimizing the effects of flow and water accumulation in the surrounding zones.

In addition, the urban consolidation of the city causes high volumes of water to become runoff during rainfall events, which are conveyed into sewerage networks with varying operational conditions—some of which have been in service for more than 30 years. Currently, approximately 66% of the system operates as a combined type.

Similarly, with the renovation of the sewerage system underway, progress in network separation is evident. Regarding the rainwater component, approximately 25% of the projected collectors are in operation, mainly in the higher areas of the municipality, whereas a significant percentage of areas still need to be addressed. Due to the conditions described above, these zones are susceptible to flooding and network collapse, primarily because of hydraulic deficiencies in the existing networks, low-slope conditions (<1%), clogging of inspection wells and drains, and the age of some components, which makes them operate at their capacity limits and require construction adjustments to comply with the minimum parameters established by Colombian regulations.

3.2 Analysis of alternatives with SUDS

As described, SUDS-based alternatives were proposed to manage runoff volumes and improve drainage conditions. For this purpose, and according to the selected system and the characteristics of the area, hydrological parameters were used to calculate volumes from rainfall depths (tree box filters, bioretention areas, infiltration trenches, and permeable pavements), flows associated with a return period (dry extended detention basins and vegetative swales), and flow balance (storage tanks). Together with the sizing equations developed in previous studies and the defined drainage areas, these calculations made it possible to determine the storage capacity of each system.

Table 1 shows the main results obtained from the sizing of the structures (drainage area and management capacity per alternative) and their corresponding construction cost, according to the calculated quantities of work.

Table 1. Main results of the analysis of alternatives -

Alternative		**Drainage area (ha)**	**System capacity (m³)**	**Total costs (TRM US)**
1	1: One Bioretention area	0.242	42	5490
	2: 12 Tree box filters	0.258	44.88	6800
2	1: One Bioretention area	0.799	120	15530
	2: One Dry extended dry drainage basin	1.143	175.7	12010
3	1: One Bioretention area and one Storage tank	0.678	105	17035
	2: One Vegetative swale and 36 Tree box filters	0.741	105.1	13600
	3: Inclusion 1 and 2 separately	1.419	1 y 2	30900
4	1: One Bioretention area	0.694	120	15530
	2: 12 Tree box filters	0.501	85.68	5460
5	1: One Bioretention área	0.311	69	3160
	2:9 Tree box filters	0.144	33.66	9415
6	1:22 Tree box filters	0.309	44.88	6235
7	1: One Bioretention área	0.257	45	5875
	2: 8 Tree box filters	0.143	35.9	6335
	3: One Vegetative swale	0.257	23.4	5095
8	1: One Bioretention área	0.294	45	5875
	2: One Vegetative swale	0.501	31.2	6885
9	1:10 Tree box filters	0.128	21.76	3815

Source: own work

Table 1 indicates that the tree box filters and the bioretention areas are the systems that present better conditions for implementation in several areas of the municipality. The other systems, such as the dry extended detention basin, the vegetative swale, and the storage tanks, can also be implemented but in a more selective way. Likewise, given the evaluated *in situ* conditions, the geological characteristics, and the space limitations found, soil infiltration processes are restricted. Therefore, alternatives with infiltration ditches and permeable pavements did not present optimal conditions to be considered for this case study.

Additionally, the storage capacities, with regard to water quality control, show that the systems considered for the municipality allow the capture of approximately 20 m³ to 210 m³, which makes it possible to integrate processes of capture, retention, attenuation, and transport in the management of rainwater within the municipality through the action of SUDS. Initially, this helps the operation of sewerage systems during rainfall events by reducing the drainage areas to be captured instantly by the pipelines and minimizing the risk of rapid water accumulation in a short period of time.

It is also evident that systems such as the dry extended detention basin have a higher capacity for managing water volumes but require a larger construction area. In urbanized areas such as Paipa, the potential spaces for their implementation are small or located in areas where their impact is limited. In contrast, the tree box filters and bioretention areas have a lower management capacity but can be implemented in different parts of the city (sidewalks, road dividers, etc.), allowing for more areas to be intervened, albeit with smaller managed volumes than the former. This demonstrates some current limitations that may arise when changing rainwater management approaches and highlights the need to consider more robust or combined systems (treatment trains) to achieve more comprehensive water management and greater control of runoff.

Regarding the costs, there is a direct relationship between the areas to be intervened and the type and number of structures in each alternative. Therefore, no standard price per structure was obtained, as separate considerations must be made for each area when defining structure size, required materials, input structures, pre-treatment structures, and output structures.

Finally, the results show that SUDS, under the described conditions, present a viable option for managing runoff volumes in urban areas. They represent an additional component to complement sewerage networks and support changes in city planning and management. As can also be found in [21]–[31], sustainable drainage structures make it possible to use and adapt different spaces (green areas, parks, road dividers, etc.) to ensure optimal sewerage system operation, thereby minimizing risks to the population and local authorities.

3.3 Comparison of aspects

Regarding the comparison of alternatives in the “Villa Panorama” sector using the EPA-SWMM software, four scenarios were modeled with the projected rainwater collector for the area, as described below:

- **Scenario 1 (E1):** Projected initial rainwater collector (L = 631.5 m) composed of 12 sections with diameters of 700 mm, 900 mm, and 1,200 mm.
- **Scenario 2 (E2):** Projected initial rainwater collector (L = 631.5 m) including a bioretention zone and a storage tank.
- **Scenario 3 (E3):** Projected initial rainwater collector (L = 631.5 m) with the inclusion of 36 floodable basins and one green gutter.
- **Scenario 4 (E4):** Projected initial rainwater collector (L = 631.5 m) with the inclusion of alternatives 1 and 2.

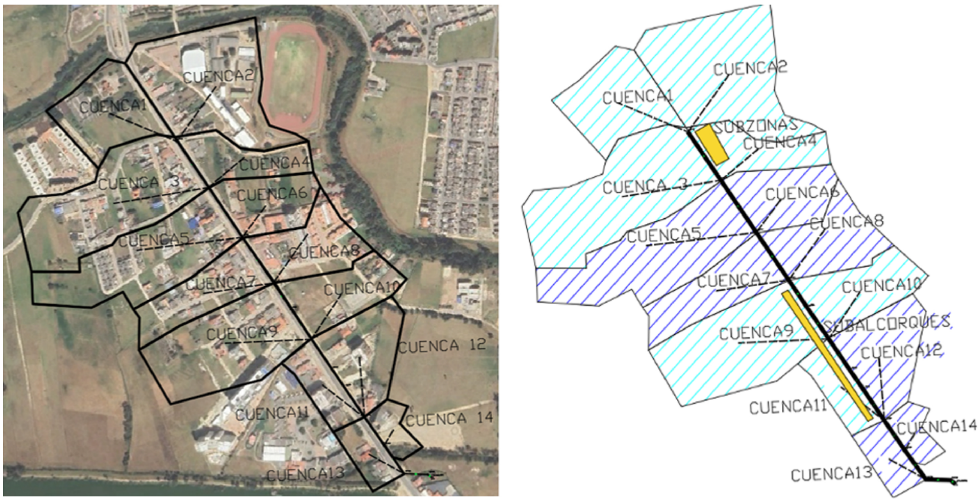
In each proposed scenario, the pipelines collect a total of 20.9 hectares of drainage distributed across 14 sub-catchments (Fig. 3).

For the rain gauges, the return periods established by current Colombian regulations for sewerage design were considered, taking into account the drainage area captured and the rainfall duration recommended in manuals for urban drainage structures. The evaluated rainfall events are as follows:

- **Event 1:** Return period of 10 years and duration of 15 minutes.
- **Event 2:** Return period of 10 years and duration of 180 minutes.

Accordingly, the Intensity–Duration–Frequency (IDF) curves were generated as indicated in [32], and, following [33], the hyetographs for the considered events were constructed using the "Alternate Block Method." These events correspond to the values used for calculating the design volumes and flows for each structure, which were derived from the analysis of maximum 24-hour precipitation data for the municipality. The results show representative rainfall depths for the area of 20.84 mm. Therefore, the simulations evaluate the behavior of the systems under events equal to and greater than those considered in the designs.

Consequently, the main results obtained from the modeling are described below.



(a) (b)

Fig. 3. (a) Rainwater collector modeling and (b) View of alternatives with SUDS in EPA SWMM.

Source: own work

3.3.1. Results at the Outfall Node

As a first aspect, it is shown the results at the outlet of the modeled rainwater collector where in figure 4 the output hydrograph is presented graphically for event 2, and in table 2 is a summary of parameters selected for comparison at the outlet of the network for both events.

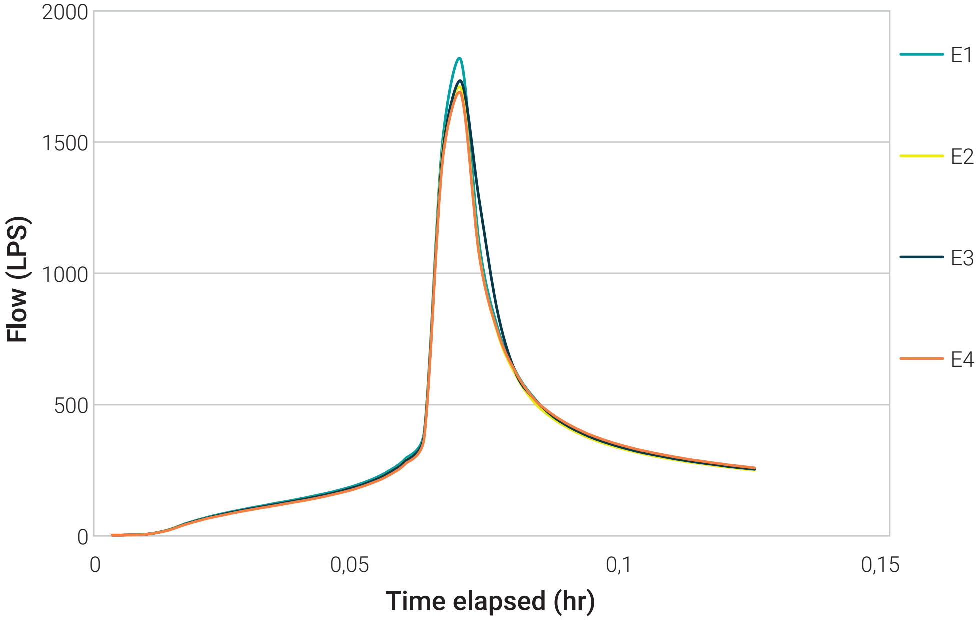


Fig. 4. Link Conduit 12 Flow (LPS) Event 2
Source: own work

Table 2. Outfall node for different scenarios and Events

OUTFALL NODE RESULT										
Esc.	Event 1					Event 2				
	Average Flow	Max. Flow	Total, Volume	Reduction Peak	Reduction Volume	Average Flow	Max. Flow	Total, Volume	Reduction Peak	Reduction Volume
	LPS	LPS	10^6 ltrs	%	%	LPS	LPS	10^6 ltrs	%	%
1	519.93	2249.9	1.37	-	-	467.31	2132.9	3.79	-	-
2	522.76	2153.4	1.32	4.29	3.71	454.49	2102.7	3.69	1.42	2.51
3	504.83	2195	1.34	2.44	2.48	472.86	2099.7	3.8	1.56	0
4	509.34	2098.1	1.29	6.75	5.83	455.12	2059	3.7	3.46	2.22

Source: own work

With the above, in table 2 it is found that the total volumes of water and maximum flows delivered by the system are reduced as the SUDS alternatives are integrated into the network, and in figure 4 a reduction of the peak of the outflow hydrograph for event 2 is observed but the time in which this occurs is not postponed, due to the fact that the software has not simulated the conditions of the outflow drainage which the control of the runoff evacuation that the SUDS alternatives have throughout the simulation is not reflected, but still the results show percentages decreases between 1.4% and 7% for the maximum flow and approximately a maximum of 6% in the reduction of the volume delivered, which indicates the protection that can be given to the drainage system in its operation for low and high intensity rain events.

3.3.2. Runoff results

Regarding the results in the surface water circulation for each of the 14 subcatchments considered in the zone, table 3 shows the main results and figure 5 shows the millimeters of total rainfall in relation to the amount of runoff generated in each area.

Table 3. Runoff results in analysis subcatchments

RUNOFF RESULTS IN SUBCATCHMENTS								
Esc.	Event 1				Event 2			
	Total, Precip	Average Runoff	Peak Runoff	Average Runoff Coeff	Total, Precip	Average Runoff	Peak Runoff	Average Runoff Coeff
	mm	mm	LPS		Mm	mm	LPS	
1	19.95	7.55	170.54	0.38	46.44	21.06	167.95	0.45
2	19.95	6.98	153.67	0.35	46.44	19.88	151.7	0.43
3	19.95	7.23	154.79	0.36	46.44	21.26	165.83	0.46
4	19.95	6.61	140.67	0.33	46.44	20.07	139.88	0.43

Source: Elaborated by author

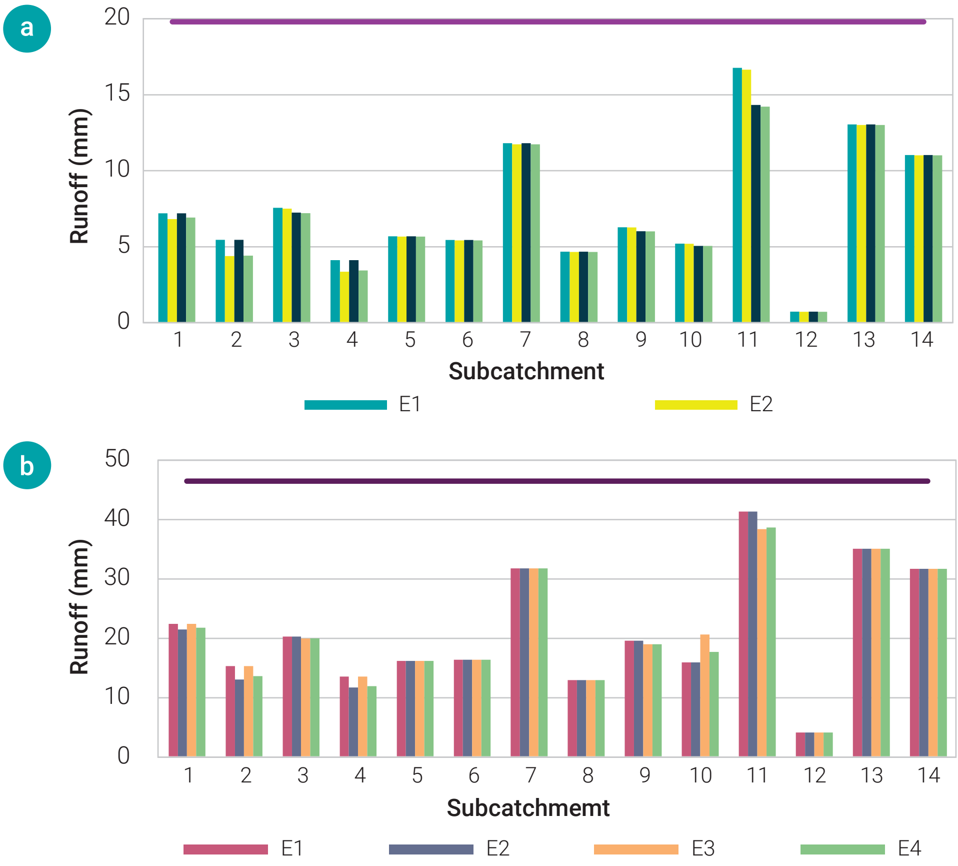


Fig. 5. Runoff graphical results in analysis subcatchments for (a) Event 1 and (b) Event 2.
Source: own work

Accordingly, Figure 5 shows that in sub-basins 1, 2, 3, 4, 9, 10 and 11, where some of the alternatives with SUDS are included (see Figure 3.b), there is an impact on the runoff values to be managed by the network.

Likewise, the low reduction values found are explained by the characteristics of the zone, given that, the expected runoff in several areas does not exceed half of the total precipitation of the event, which evidences a high percentage of permeability in each one of them by pastures (See figure 3.a), also by the type and quantity of SUDS considered from the analysis of alternatives whose designs do not provide high volumes of management for the zone.

Finally, parameters such as average runoff, peak runoff, and runoff coefficients show a better performance in the alternative of scenario 4, since all SUDS typologies are included, which influences 50% of the sub-basins analyzed in the sector, providing a high reduction in area 11 where the largest volumes to be managed are found. In this way, it is evident that the impact of the SUDS on the quantity of water increases as these are implemented on a large scale and integrated with the sewerage network in a specific area.

3.3.3. Results in the pipelines of the network

Concerning the water flow conditions through the network pipelines, the summary of the results for each of the 12 sections that make up the collector is shown. As a first measure, Figure 6 shows the maximum speed found in each one of the pipelines.

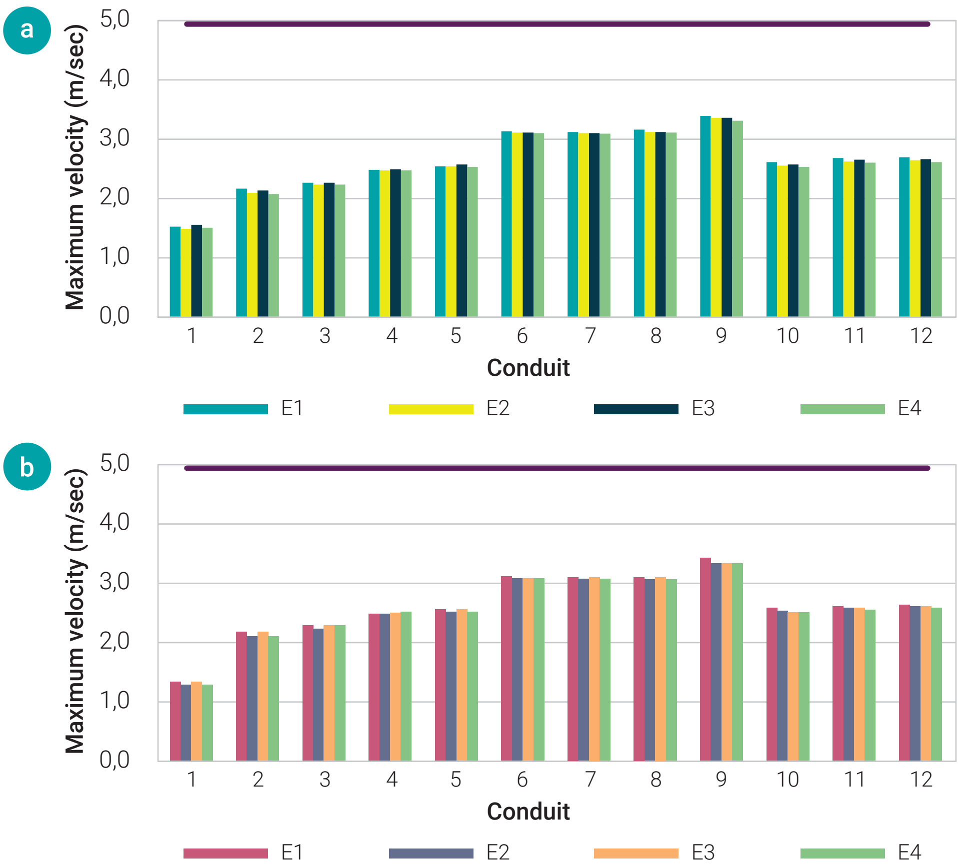


Fig. 6. Results maximum velocity (m/sec) in conduit for: (a) Event 1 and (b) Event 2.
Source: own work

From the above, it is observed that the network does not exceed the maximum speed allowed in the current Colombian regulations (V < 5 m/s). Likewise, with the inclusion of the different alternatives with SUDS, a certain impact is achieved regarding the reduction of this parameter in several sections of the system, including the ones that present the highest speed compared to the initial scenario (E1). The reduction of the maximum speed is not considered within the main objectives of SUDS use, however, it shows that it allows a more paused evacuation of the captured runoff, being adequate to avoid phenomena in pipelines such as abrasion due to high speeds. Figure 7 shows the relationship between the maximum flow and the flow allowed (Max/full flow) in each of the collectors that make up the network.

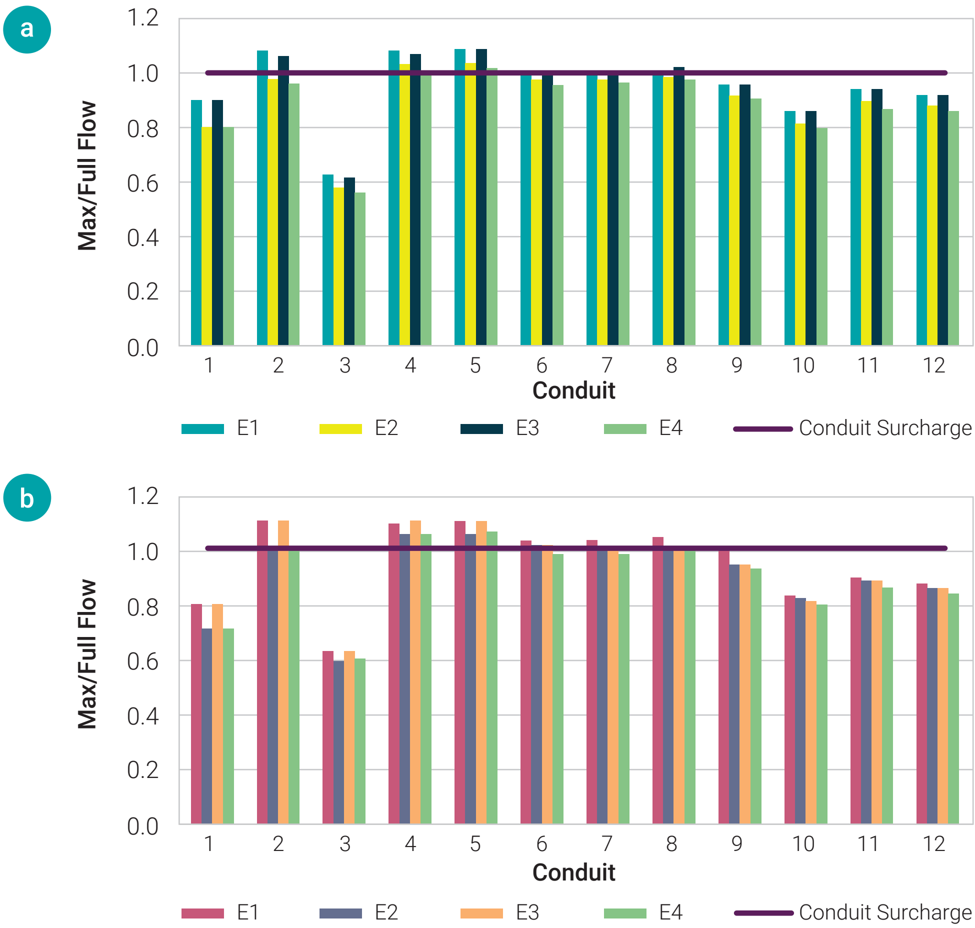


Fig. 7. Results of Conduit surcharge (Max/Full Flow) for (a) Event 1 and (b) Event 2.
Source: own work

As observed in Figure 7, several sections exceed the recommended maximum (< 1), mainly conduits 2, 4 and 5. Although this excess is not significant, it indicates an overload in the system but it must be considered the conditions in which it was presented since according to that exposed in [21] if the value of 1 is not exceeded it does not imply that the system has not been overloaded. Thus, the flow used is the average flow for the entire system which indicates the possibility of overload in those sections that reach extreme values during the simulation. In the same way, it is observed that as the alternatives with SUDS are included, an improvement in this aspect is achieved for the whole network, evidencing more benefits for its implementation.

Finally, Figure 8 shows the relationship between the maximum measured depth and the allowed depth (Max/full depth) in each of the conduits.

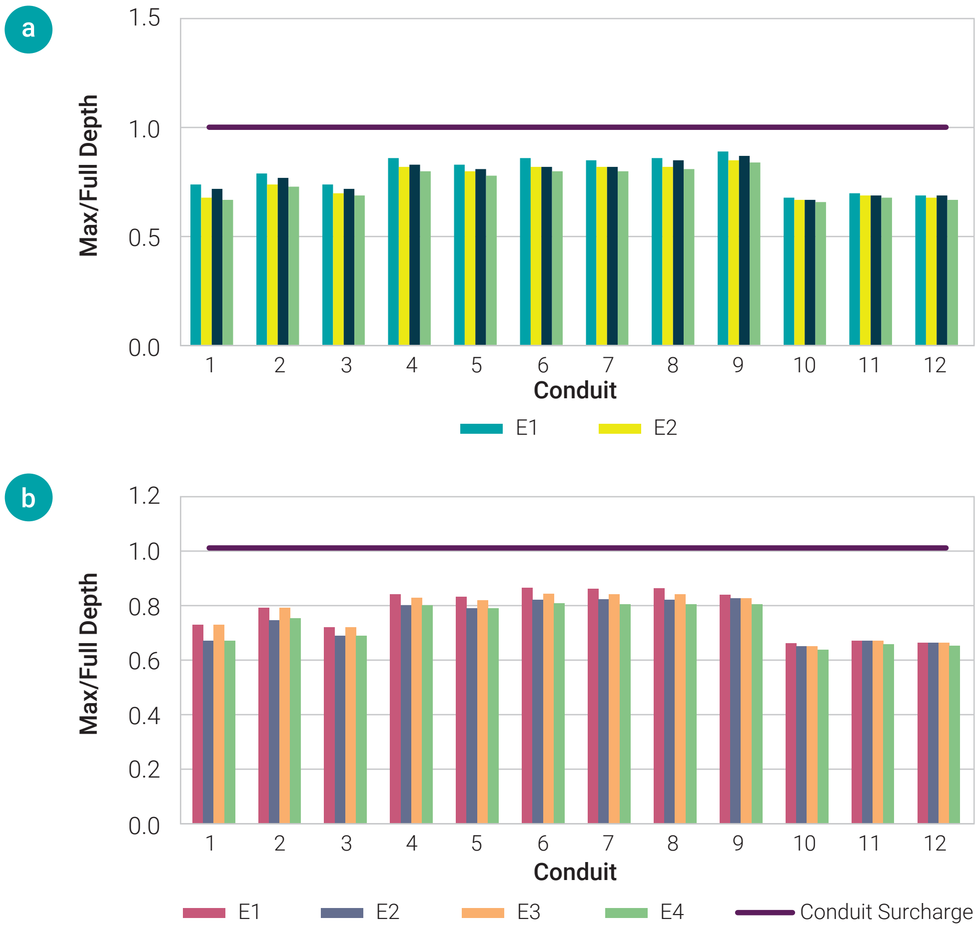


Fig. 8. Results of the overload in conduits (Max/Full-depth) for (a) Event 1 and (b) Event 2.
Source: own work

According to figure 8, the network presents a stable behavior in pipelines without overloading any of the sections and by including the different alternatives with SUDS, an improvement in the functioning of the entire system is achieved, in addition to allowing sections 4 to 9, where there is more risk of overloading, to have more safety and protection in its functioning.

3.3.4. Economic comparison

For this aspect, in the Villa Panorama sector, it was made a comparison between the information gathered on the total construction costs of the scenario (E1) and a new scenario (E5) that includes modifications to the initial configuration of the proposed conduits in order to see the economic impact that the implementation of SUDS can produce in the design of urban drainage. For this purpose, the alternative of the scenario (E4) was taken, since it showed the best performance and with the previous results, the lengths in plant of the network were modified, taking into account the configuration of the area allowing to maintain the optimal hydraulic performance of the system. Therefore, the material of the pipelines (n=0.01), discharge point, drainage areas, well topography and number of conduits were preserved. With these modifications in the area, the total construction costs of the new scenario were estimated, including activities of land excavation, the supply, and installation of pipelines, and the construction costs of the SUDS (See table 1), thus, table 4 it is shown a summary of the general budget of activities for both proposed alternatives.

Table 4. Costs of comparison of alternatives in the Villa Panorama sector.

Alternative	Description	Costs (TRM)
1. Rainwater collector in the area	Total rainwater collector with excavations, supply and installation of conduits. Total length: 631.5 m	251176
2. Rainwater collector including SUDS	Total inclusion of SUDS with excavations and materials and the rainwater collector with excavations, supply, and installation of pipelines. Total length: 593 m	261443

Source: own work

According to the previous information, the new proposed scenario, with the modifications to the network, presents an increase of approximately 4% in total construction costs compared to the initial alternative proposed by the municipality. This is due to the fact that the reductions made do not offset the additional construction costs of the SUDS, since under the proposed local and alternative conditions it was not possible to reduce, by an order of magnitude, the initial diameters established for the network.

4. DISCUSSION AND CONCLUSIONS

In this case study, it was found that SUDS cannot replace the conventional sewage systems proposed by the municipal renovation plan; however, they can be considered a complement to their functioning, in accordance with the defined operational objectives, to achieve more integral rainwater management and control. In this way, these systems can influence the final design of drainage systems in an area, since, as shown by the modeling, their implementation allows the consideration of shorter networks under the same demands and design requirements.

Regarding the economic aspects analyzed in the study, the total costs reflect an increase in investment with the implementation of SUDS structures. Nevertheless, given the proposed scope and results obtained, it is necessary to evaluate additional benefits that their implementation can bring, such as landscaping, social and environmental impacts, as well as operation and maintenance costs, all of which may affect the selection of alternatives for urban drainage networks.

Likewise, in areas without previous studies, the analysis and design for the implementation of SUDS may require direct measurement of different site-specific factors, such as precipitation data, area topography, soil and subsoil characteristics, network cadastre, sanitary connections, and runoff conditions. These parameters allow adjustments to be made in the selection of structures and help define, when appropriate, complementary elements required to ensure optimal operation of the systems according to site-specific conditions.

Finally, for the implementation of SUDS in urban areas, it is necessary to promote citizen participation in decision-making, as well as the involvement of various local and regional authorities, to guide, implement, and participate in urban planning policies aimed at more sustainable development. Given the current situation found in this study—where the distribution and/or recovery of spaces represents a limitation—clear methodologies and structured actions are required to integrate SUDS into new projects from their initial stages. This will allow an adequate distribution and definition of spaces, ensuring their optimal functioning and connection with their surroundings.

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