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RESEARCH ARTICLE

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A conceptual framework for the comprehensive analysis of engineering and socio-ecological resilience to improve the sustainability of urban drainage systems

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ABSTRACT
Resilience contributes to improving the sustainability of urban drainage systems (UDSs), which has recently begun to be considered in UDS management, but generally as engineering (ER) or as socio-ecological (SER) resilience separately. This article proposes and discusses a conceptual framework that can analyse ER and SER through a comprehensive resilience (CR) index in a UDS with a focus on floods, considering national and international experiences and methodologies related to resilience analyses and is applicable to UDSs. The framework was evaluated in the Southern Drainage System (SDS) of the city of Cali, Colombia, obtaining moderate values of ER and the CR index, and low values of SER. The drainage areas and infrastructure components of the SDS were hydrodynamically modelled in the Storm Water Management Model (SWMM). This conceptual framework can be useful for decision-makers in UDSs management and should be evaluated considering different threat scenarios and mitigation strategies.

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1. Introduction

Resilience is *'the ability of a system, community or society exposed to a threat to resist, absorb, adapt and recover from its effects in a timely and effective manner, which includes the preservation and restoration of its basic structures and functions'* (UNISDR 2009). Although this concept has been used in other areas of knowledge and has recently been formulated as a key concept for urban sustainability, it is often not used in contemporary urban design and planning (Ahern 2011).

For urban drainage systems (UDSs) to be able to face emerging threats of the 21st century, such as climate change, population and urban growth and weak governance, resilience should be involved in their planning, design, construction and operation (Butler et al. 2014; Juan-García et al. 2017). A change in urban water management is necessary to improve the sustainability of the UDSs, with comprehensive consideration given to environmental, economic and social aspects (Galvis et al. 2014).

Recent studies have shown significant progress towards understanding and assessing resilience (Hosseini, Barker, and Ramirez-Marquez 2016; Mottahedi et al. 2021). However, as shown in Table 1, few conceptual frameworks have focused on the development of methodologies that can analyse resilience in UDSs, thus indicating that this concept requires further research (Juan-García et al. 2017; van Duin et al. 2021).

In general, existing frameworks address resilience either from an engineering approach (ER) or from a socio-ecological approach (SER). The engineering approach is *'the degree to which the system minimises level of service failure magnitude and duration over its design life when subjected to exceptional conditions'* (Butler et al. 2014, 2016), while the socio-ecological approach is *'the potential that the socio-ecological system (SES) has to tolerate failures, without collapsing towards a qualitatively different state, maintaining its structure and functions, which involves its ability to adapt following changes driven by threats'* (Walker et al. 2004).

Clearly, new frameworks are needed that can analyse resilience, which is key to sustainability, thus allowing policymakers and decision-makers to have adequate tools for managing UDSs (Suárez et al. 2016). In this sense, a comprehensive approach to ER and SER can contribute to a holistic analysis of UDSs resilience and help guarantee their sustainability (Beccari 2016; Folke 2006; Juan-García et al. 2017).

Considering that resilience is of great importance in UDSs management (Huskova et al. 2016; van Duin et al. 2021), this article's novelty is that it proposes a conceptual framework to analyse resilience with a focus on water quantity (floods) and, additionally incorporates both engineering and socio-ecological aspects through a comprehensive resilience (CR) index evaluated in a real case study. As shown in Table 2, 26% on average of the articles reviewed consider SER indicators. In addition, although

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Table 1. Conceptual frameworks of resilience analysis applicable in UDSs.

Resilience approach	Conceptual frameworks	Framework evaluation	Source
Engineering resilience (ER)	Safe, sustainable and resilient approach	Not evaluated	Butler et al. (2016)
	Sustainability of urban drainage management	UDS of Sanya City, China	Ning et al. (2013)
	Global resilience analysis approach	UDS of Nakivubo river basin, Kampala, Uganda	Mugume et al. (2015)
	Resilience of urban drainage system in adaptation to climate change	UDS from north Tehran, Iran	Binesh et al. (2018)
	Redundancy assessment in resilience management in urban drainage systems	UDS of Lili river subbasin, Cali, Colombia	Domínguez and Galvis (2018)
	Resilience framework for urban stormwater systems	Not evaluated	Barreiro et al. (2024)
Socio-ecological resilience (SER)	Adaptive urban planning and design	Not evaluated	Ahern, Cilliers, and Niemelä (2014)
	Socio-ecological index for measuring flood resilience	UDS of Eden district, Cape Town, South Africa	Kotzee and Reyers (2016)
	Social-ecological system framework for urban stormwater management	Not evaluated	Flynn and Davidson (2016)
	Community resilience to flood hazards	UDS of Charsadd, Nowshera and Peshawa cities, Khyber Pukhthunkhwa province, Pakistan	Qasim et al. (2016)
	Multicriteria approach for assessing urban flood resilience	UDS of Tehran city, Iran	Moghadas et al. (2019)
	Framework to evaluate urban flood resilience	UDS of Canal do Mangue basin, Rio de Janeiro, Brazil	Rezende et al. (2019)
	Framework for evaluating policies to improve urban flood resilience	UDS of Raval district, Barcelona, Spain	Hammond et al. (2018)

Table 2. Factors, variables and key indicators of resilience in urban drainage systems (UDSs).

Resilience approach	Factors	Variables	Indicators	Source	Percentage of authors citing the indicator
Engineering resilience (ER)	Flexibility Resourcefulness Redundancy Robustness	UDS performance	*Engineering resilience (ER)* $ER = \frac{1}{t_n - t_{fs}} \int_{t_{fs}}^{t_n} P(t)dt$ t_n : Total elapsed time until flood is over; t_{fs} : Flood start time; *P(t)* : Performance function [0, 1]	1, 2, 3, 4, 5, 6	32
Socio-ecological resilience (SER)	Social	Governance	*Institutional coordination level* High Moderate Low	8, 9, 10, 11, 12, 13, 15	37
			Informal settlements IS (%) = # Informal housing/# Total houses	9, 10, 11, 15, 18, 19	32
		Flood risk	*Area in high-risk flooding zone* AHRFZ (%) = Area in a high-risk flood zone/Urban basin area	10, 12, 13, 17, 19	26
		Solid waste in the UDS	*Solid waste in channels and rivers* SW (%) = Average annual volume of solid waste removed from channels and rivers/Useful volume of channels and rivers	10, 11	10
		Economic development of the population	*Households with unsatisfied basic needs (UBN)* UBN (%) = # Households without satisfying one of the UBN/# Total households	7, 8, 9, 10, 11, 15	32
	Ecological	Physical characteristics of the urban basin	*Predominant land slope* LS (%) = Average land slope	7, 14, 17, 18	21
			Impervious area IA (%) = Percentage of impervious area in the urban basin	11, 14, 16, 18	21
		Flood regulation	*Green areas* GA (%) = Green areas/Urban basin area	7, 8, 9, 11, 14, 16	26
			Water bodies areas WBA (%) = Water bodies area/Urban basin area	7, 8, 9, 14, 16	26

Sources: 1 (Binesh et al. 2018); 2 (Domínguez and Galvis 2018); 3 (Butler et al. 2016); 4 (Tahmasebi and Yazdandoost 2015); 5 (Mugume et al. 2015); 6 (Ning et al. 2013); 7 (Prouty, Mohebbi, and Zhang 2020); 8 (Fenner et al. 2019); 9 (Rezende et al. 2019); 10 (Moghadas et al. 2019); 11 (Mahmoud, Hussein, and Mahmoud 2019); 12 (Makropoulos et al. 2018); 13 (Tahmasebi Birgani and Yazdandoost 2018); 14 (Hammond et al. 2018); 15 (Qasim et al. 2016); 16 (Kotzee and Reyers 2016); 17 (Flynn and Davidson 2016); 18 (Moores and Semadeni-Davies 2015); 19 (Ahern, Cilliers, and Niemelä 2014).

some articles mention the SER approach, they do not present practical applications, so this study seeks to incorporate ER and SER analysis into UDSs, filling the gap of the lack of frameworks that address these two approaches comprehensively. This framework provides more elements of importance for UDSs planning and management and considers threats that alter their original state; thus, it is able to support more informed decisions that contribute to improving UDSs resilience and sustainability.

The proposed framework allows for the identification of critical components of the UDS, a better understanding of the processes that occur in the UDS and a focus on strategies to improve their resilience. By applying this framework, UDS resilience can be analysed under three conditions: *i*. In its baseline condition (before the threats were presented); *ii*. In the face of different threats (with threat scenarios); and *iii*. When strategies to improve resilience are implemented (with mitigation strategies).

An evaluation of this framework was conducted for the Southern Drainage System (SDS) of Cali, Colombia, to validate its general structure and the framework's predictions, allowing obtaining representative results of its UDS and comparing them with results obtained from other evaluations of conceptual frameworks of resilience analysis for the UDSs of cities in similar developing countries.

2. Methodology

2.1. Formulation of the conceptual framework

To construct the conceptual framework, the conceptual elements, components, structure, characteristics, principles of operation and form of analysis for the resilience of the frameworks presented in Table 1 were identified, considering the approaches of both ER and SER. Furthermore, information was included from discussions held with experts in urban drainage and resilience and professionals from national and international institutions in the water and sanitation sector. The proposed framework was formulated considering the following four cyclically connected thematic blocks:

(1) *UDS Definition*. In this block, the necessary information was established to delimit and characterize the UDS to be studied in its baseline condition, considering engineering (infrastructure and the processes that are developed in it) and socio-ecological components (institutions, users, basin and the ecosystem service of flood regulation). This block is considered essential since it describes the components that make up the UDS and its initial relationships; this information is used to analyse the resilience of the UDS.

(2) *Threat Scenarios*. This block was developed to identify threats and formulate their related scenarios. To facilitate the identification and formulation of threat scenarios, the classification of Butler et al. (2016) was adopted: external (those of the natural or built environment and regulatory institutions) and internal (those that originate within the UDS due to the infrastructure, the service provider and the users). The threats that were considered in this study were selected from those that can cause flooding due to UDS failures. In the proposed framework, threats must be treated individually, and the framework users must prioritize them to identify those that are most common and would cause the greatest reduction in resilience.

(3) *Resilience Analysis*. This block was formulated to carry out the analyses of ER, SER and their integration through a comprehensive resilience (CR) index, which connects the engineering and socio-ecological approaches, with the aim of obtaining qualitative and quantitative resilience values for the UDS studied. The resilience analysis uses the factors, variables and key indicators of resilience in the UDS from Table 2, which were selected through a bibliometric analysis complemented with discussions in meetings, workshops and interviews with experts in urban drainage and resilience and professionals in the water and sanitation sector. This block establishes how the factors, variables and indicators affects the UDS, generating changes in its behaviour, which reflects changes in resilience.

The ER analysis was performed through the following steps:

- *Graph the performance function of the UDS*. The performance function was graphed using Equation 1 (Domínguez and Galvis 2018), considering flows or levels with a medium-risk return period (TR) in the primary drainage (channels and rivers) and rain events with a low-risk return period in the secondary drainage (surface drainage). This analysis was performed both for the baseline condition and for the threat scenarios and mitigation strategies considered.

$$P(t) = 1 - \frac{F(t)}{I(t)} \quad (1)$$

Where *P(t)* is the performance function [0, 1], *F(t)* is the flood volume caused by rainfall-runoff, and *I(t)* is the volume of runoff that enters the UDS. Figure 1 illustrates the theoretical performance function graph. The blue solid line, P_0 represents the original performance before implementation of engineering mitigation strategies. The blue dotted line, P_0 represents the improved performance after implementation of engineering mitigation strategies. The red dotted line, P_a represents a lower but acceptable level of service (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

- *Calculate the ER and its factors*. ER and ER factors, robustness (Cimellaro, Reinhorn, and Bruneau 2010) and flexibility (McDaniels et al. 2008), were calculated via Equations (2-4), respectively.

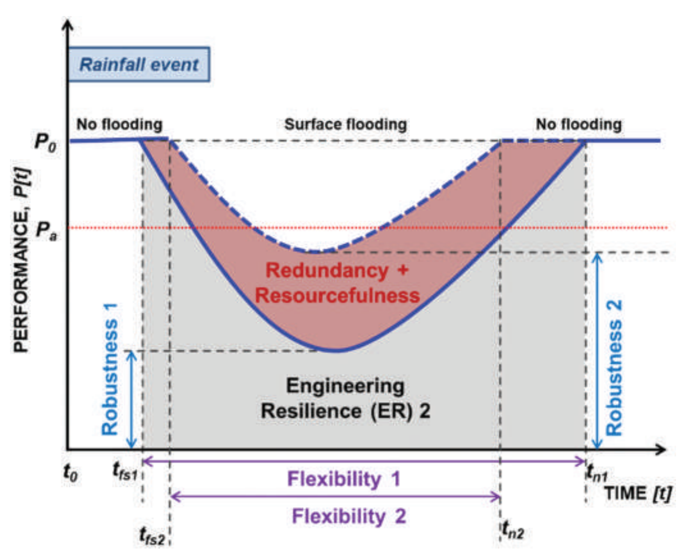

Figure 1. Theoretical performance function graph for engineering resilience (ER) analysis of urban drainage systems (UDSs). Source: Adapted from Mugume et al. (2015)

$$ER = \frac{1}{t_n - t_{fs}} \int_{t_{fs}}^{t_n} P(t)dt \quad (2)$$

$$Robustness = \min P(t) \quad (3)$$

$$Flexibility = t_n - t_{fs} \quad (4)$$

Where t_n is the total time elapsed until flood is over and t_{fs} is the start time of the flood.

The redundancy and resourcefulness factors were calculated as the area between the performance function before and after implementation of engineering mitigation strategies in the UDS as illustrated in Figure 1. Therefore, these ER factors were obtained based on the result of the difference in ER calculations before and after the implementation of these strategies.

The analysis of SER was carried out through the construction of a composite index that adds the factors, variables and key indicators of SER from Table 2, according to the following steps:

- *Measurement of SER indicators*. These measurements were carried out by searching the values of the indicators in records kept by local authorities and entities in charge of providing the sewerage service.
- *Standardization of SER indicators*. An interval from 0 to 1 was defined, where the indicators in percentage were divided by 100 and the qualitative indicators were normalized by categorizing scales (Schuschny et al. 2009).
- *Weighting of factors, variables and indicators of SER*. In the present study, the proportional weights in Table 3 were adopted according to a statistical analysis of the responses from experts in urban drainage and resilience interviewed at scientific events and professionals from institutions in the water and sanitation sector interviewed in a workshop about resilience in UDSs developed in Cali, Colombia; these responses showed that all socio-ecological dimensions of the subject under analysis, in this case, can be considered equally.
- *Aggregation of factors, variables and indicators of SER*. The aggregation method adopted was the weighted sum method (WSM) (Schuschny et al. 2009) because it simultaneously considers multiple factors, variables and indicators that represent different dimensions, and the factors, variables and indicators can be weighted to reflect their relative importance within a particular context. According to the WSM, the value of each variable V_j was calculated as the sum of the weight W_i of each indicator by the value of the normalized indicator $\bar{I}_i$, as follows:

$$V_j = \sum_{i=1}^{n} W_i \bar{I}_i \quad (5)$$

Afterwards, the value of each socio-ecological factor F_{SE} was calculated as the sum of the weight W_j of each variable according to the value obtained by each variable V_j of the corresponding factor F_{SE}, as follows:

$$F_{SE} = \sum_{j=1}^{m} W_j V_j \quad (6)$$

Subsequently, the SER was calculated as the sum of the weight of each factor according to the value obtained from each corresponding factor, as follows:

$$SER = W_{SOC} \times F_{SOC} + W_{ECO} \times F_{ECO} \quad (7)$$

Where W_{SOC} and W_{ECO} are the weights, and F_{SOC} and F_{ECO} are the values of each social and ecological factor, respectively.

Finally, to quantify the comprehensive resilience (CR) index, Equation 8 was adopted, calculated with the results of the analysis of ER (Equation 2) and SER (Equation 7), as follows:

$$CR = W_E \times ER + W_{SE} \times SER \quad (8)$$

Where W_E and W_{SE} are the weights of ER and SER, respectively. In the conceptual framework, to avoid the double counting that could occur due to the correlations between some SER indicators and the ER and thus balance their weights to calculate the CR index, the degree of correlation between the indicators was evaluated, and the weights W_E and W_{SE} were estimated by 100,000 stochastic Monte Carlo simulations.

To carry out these simulations, uniform distributions were defined for the indicators that present equal probability and distributions of the program evaluation and review technique (PERT) type for the other indicators, which is recommended for indicators that do not have historical records (Ang and Tang 2007), as is the case of some indicators of the proposed framework. Table 4 shows the selected probability distributions for each indicator with their respective distribution parameters where the values of the statistical parameters (minimum, maximum and most likely) were defined through a literature review in studies carried out by institutions that compile these indicators.

The ER, SER and the CR index measure resilience (scale from 0.00 to 1.00), which was categorized into the five quantitative and qualitative ranges of resilience that are presented in Table 5, which were adapted from scales proposed by Sweya et al. (2021) and Zhang, Oh, and Park (2021) for measuring

Table 3. Weights of factors, variables and indicators of socio-ecological resilience (SER) in urban drainage systems (UDSs).

Factors	Weight (%)	Variables	Weight (%)	Indicators	Weight (%)
Social	50	Governance	12.5	*Institutional coordination level*	6.25
				Informal settlements	6.25
		Flood risk	12.5	*Area in high-risk flooding zone*	12.5
		Solid waste in the UDS	12.5	*Solid waste in channels and rivers*	12.5
		Economic development of the population	12.5	*Households with unsatisfied basic needs (UBN)*	12.5
Ecological	50	Physical characteristics of the urban basin	25.0	*Predominant land slope*	12.5
				Impervious area	12.5
		Flood regulation	25.0	*Green areas*	12.5
				Water bodies areas	12.5
Total	100		100		100

Table 4. Probability distributions assigned to the indicators.

Indicators	Distribution	Distribution parameters			Source
		Minimum	Maximum	Most likely	
Engineering resilience (ER)	Uniform	0.3	0.7	–	–
Institutional coordination level	PERT	0	1	0.5	–
Informal settlements	PERT	0	60	28	DANE (2018)
Area in high-risk flooding zone	PERT	0	80	15	IDEAM (2018)
Solid waste in channels and rivers	Uniform	0	50	–	SUPERSERVICIOS (2020)
Households with unsatisfied basic needs (UBN)	PERT	3	68	17	DANE (2018)
Predominant land slope	Uniform	0	25	–	IGAC (2021)
Impervious area	Uniform	0	80	–	IGAC (2021)
Green areas	Uniform	0	20	–	IGAC (2021)
Water bodies areas	Uniform	0	10	–	IGAC (2021)

Table 5. Scale of the engineering resilience (ER), socio-ecological resilience (SER) and comprehensive resilience (CR) index.

Quantitative scale	Qualitative scale	Description
0.00–0.29	Very low	UDS that frequently fails during low-risk events causing damage or losses of high magnitude
0.30–0.49	Low	UDS that frequently fails during medium-risk events causing damage or loss of medium or high magnitude
0.50–0.69	Moderate	UDS that occasionally fails during medium-risk events causing damage or losses of medium magnitude
0.70–0.89	High	UDS that occasionally fails during high-risk events causing damage or losses of low magnitude
0.90–1.00	Very high	UDS that fails only during catastrophic events

Source: Adapted from Sweya et al. (2021) and Zhang, Oh, and Park (2021).

resilience of water supply systems and sewer networks, respectively.

(4) *Formulation of Strategies*. To improve resilience, a final block for the formulation of engineering and/or socio-ecological mitigation strategies was proposed in the framework, which can be associated with the threat scenarios formulated to evaluate their impact on resilience. The framework also allows prioritization of mitigation strategies, for which it is necessary to incorporate different strategies into the UDS, then evaluate them in the framework and finally select those that generate the highest CR index.

To obtain a list of strategies to include in the framework, the engineering and socio-ecological mitigation strategies in the UDS were reviewed in the literature; of these, only those that mitigate the risk of flooding were selected. The framework considers the following engineering strategies: channels, change in the operation of pumps, dams, reservoirs, cleaning and/or maintenance of the infrastructure, rehabilitation of the system, pumping systems, sustainable urban drainage systems (SUDS) and storage tanks; and the following socio-ecological strategies: environmental education, improve institutional coordination, urban planning and land use regulations. These strategies can be combined to assess synergistic effects on reducing flood risk and increasing resilience (Butler et al. 2016).

2.2. Evaluation of the conceptual framework

2.2.1. Description of the study area

The Southern Drainage System (SDS) of the city of Cali, Colombia, was used as the study area, which is located to the southwest of the city of Cali in the upper basin of the Cauca River and is made up of the subbasins of the Cañaveralejo, Lili and Meléndez rivers and the urban subbasin of the Ferrocarril Channel. The SDS works by gravity, draining rainwater and wastewater from the southern part of the city via combined and separate sewerage system them into the South Channel, which collects them and finally delivers them to the Cauca River.

The hydrographic basin has an approximate area of 74.6 km^2 (11.5 km^2 Cañaveralejo; 16.0 km^2 Lili; 37.4 km^2 Meléndez; and 9.7 km^2 Ferrocarril) and a population of 1'876,859 inhabitants, of which 99% are located in urban areas and 1% in rural areas (DANE 2018; CVC 2019). Fifty-one percent of the area is urban and 49% is rural, 52% of the area is permeable and 48% is impermeable, with altitudes, starting from the Cauca River, of 950 metres above sea level, up to 3100 metres above sea level, in the Natural National Park Farallones de Cali (CVC 2019). The Cañaveralejo reservoir is located in the SDS, which has an area of 78,492 m^2 and is an artificial system for regulating the flow of the Cañaveralejo River. Figure 2 shows the main components of the SDS of Cali.

2.2.2. Schematization and calibration in SWMM of the study area

The drainage areas and infrastructure components of the SDS were hydrodynamically modelled in the Storm Water Management Model (SWMM) (Rossman 2015). The drainage areas were defined for the combined and separate sewerage systems according to the topography, land use and area of influence of the collectors and combined sewer overflows (CSOs). In this process, the calibration results of the SWMM model from previous studies, such as those of Barahona and Galvis (2018) and Toledo and Galvis (2022) for the subbasins of the Cañaveralejo and Meléndez rivers, respectively, were taken as the calibration parameters for the SDS as a whole.

Barahona and Galvis (2018) used the generalized likelihood uncertainty estimation (GLUE) and shuffled complex evolution (SCE) methodologies, with the Nash-Sutcliffe efficiency (NSE) coefficient as an adjustment measure, obtaining values of 0.90 for the GLUE method and 0.93 for the SCE method. Toledo and Galvis (2022) used an *ad hoc* calibration/verification methodology in deterministic urban drainage models, obtaining a value

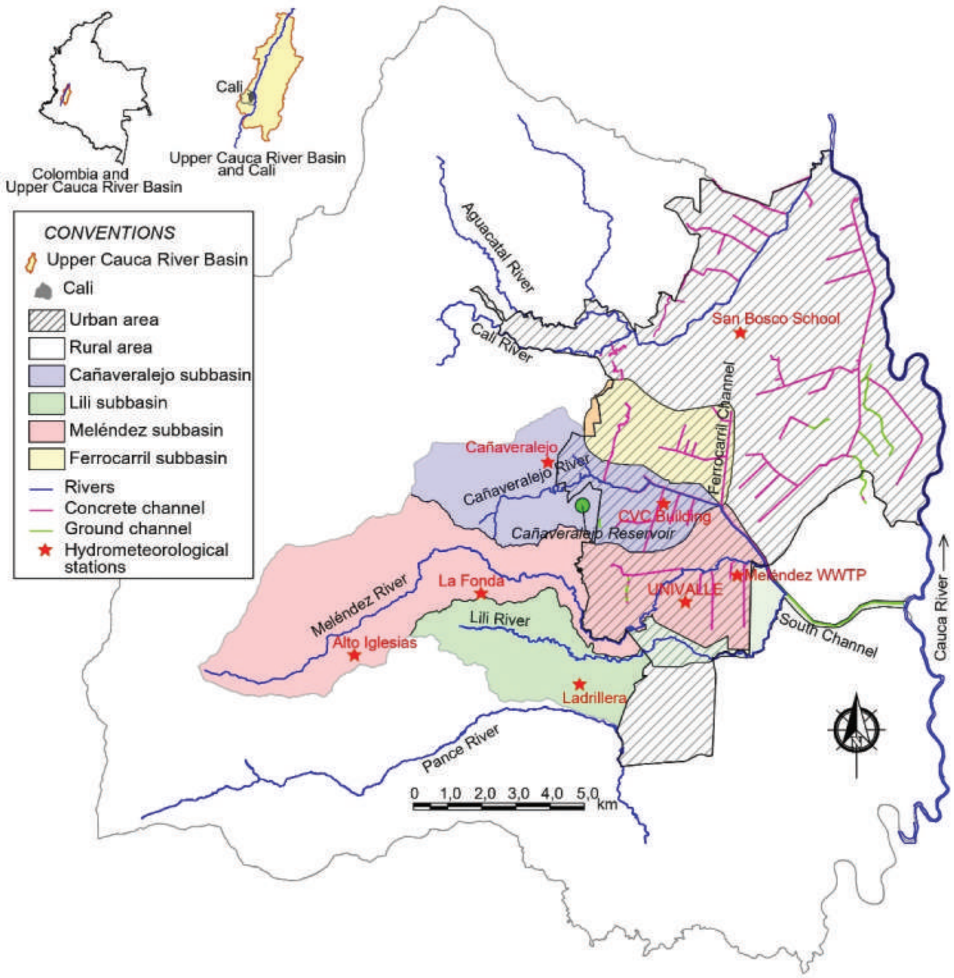

Figure 2. Southern Drainage System (SDS) of the city of Cali, Colombia. Source: Adapted from DAPM (2014) and CVC (2019)

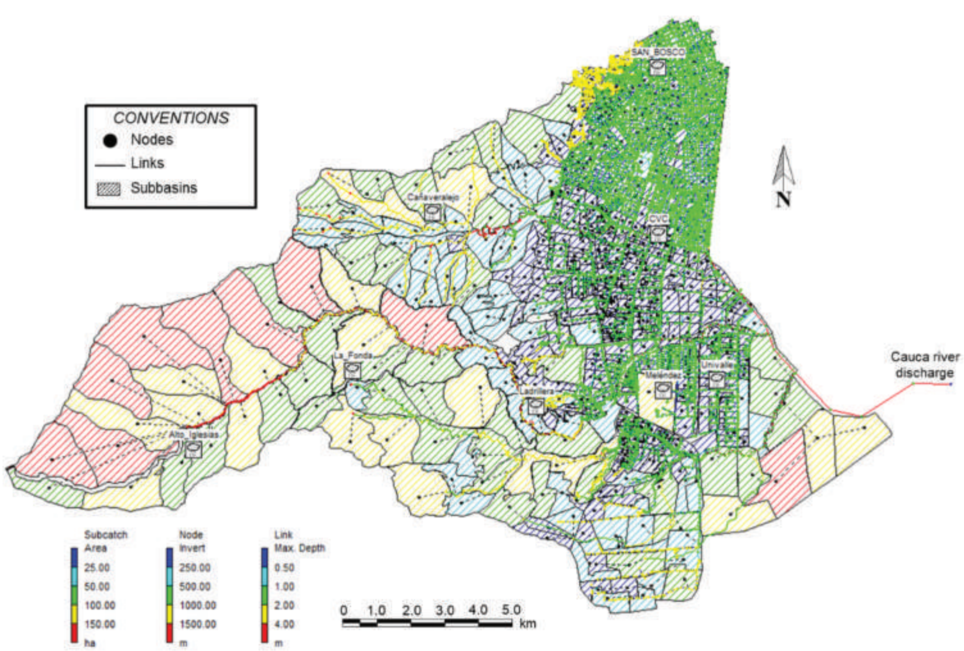

Figure 3. SWMM schematization of the Southern Drainage System (SDS) of the city of Cali, Colombia.

of 0.98; SES values close to 1.0 indicate that the data are adequately adjusted (Gupta et al. 2009). Figure 3 presents the SWMM schematization of the SDS.

2.2.3. Evaluation of the conceptual framework

The proposed framework was evaluated following the methodology suggested by Wang and Grant (2019), which consists of the following steps:

(1) *Evaluate the structure of the framework*. The framework was evaluated in the SDS, validating that the results were representative of this UDS. For this, an analysis of ER, SER and CR index of the SDS was carried out in its baseline condition as presented below:

The ER analysis was carried out using SWMM model, simulating flows with a return period of 50 years in the Cañaveralejo, Lili and Meléndez rivers and in the Ferrocarril and Sur channels and a water level with a return period of 50 years in the Cauca River, which is the final receiving body of the SDS. Rain events with a return period of 5 years and durations of 60 minutes were simulated using SWMM. These were recorded on 22 March 2021 in the 8 hydrometeorological stations located in the SDS, day when flooding occurred in this UDS (CVC 2021).

For the values of the SER indicators, information came from studies carried out by the following local government institutions: Comptroller General of Santiago de Cali -CGSC (2019), Administrative Department of Municipal Planning of Cali -DAPM (2014) and Public Services Company of Cali -EMCALI (2016); of the Regional Autonomous Corporation of Valle del Cauca -CVC (2019); and the National Department of Statistics -DANE (2018).

To obtain the values of the SER indicators of the SDS as a whole, Equation 9 was used:

$$SDS = \frac{\sum_{i=1}^{n} A_i I_i}{A_{SDS}} \quad (9)$$

Where A_i is the area of each subbasin, A_{SDS} is the total area of the SDS and I_i is the value of the SER indicator in each subbasin.

The CR index was obtained using Equation 8 calculated with the results of the ER and SER analysis.

(2) *Validate the concordance of the framework predictions*. A hypothetical threat scenario was formulated consisting of a 50% reduction in the permeability of the soil, green areas and areas of water bodies in the SDS in relation to the baseline condition. This threat scenario was selected because it is common in UDSs of developing countries (Parkinson and Mark 2015) and it occurs frequently in the SDS.

To improve the resilience of the SDS, two engineering strategies were formulated, the first consisting of the annual cleaning of 100% of solid waste (garbage, debris and sediments) in channels and rivers; the second consisting of constructing of four reservoirs located at the points of the most critical areas of each subbasin, each with a storage volume equivalent to 10% of the total flood volume of each subbasin in the baseline condition; and a socio-ecological strategy for land use regulation, considering an increase of 50% in the permeable area, the green areas and the areas of water bodies in relation to the baseline condition.

These three mitigation strategies were implemented simultaneously, initially calculating the ER and SER separately and subsequently calculating the CR index to evaluate the effect of the combination of these strategies on the three resilience approaches compared to the results of the baseline condition.

(3) *Evaluate the sensitivity of the framework to changes in the indicators*. The sensitivity of the framework indicators was evaluated through 100,000 Monte Carlo simulations considering the same probability distributions showed previously in Table 4.

3. Results and discussion

In Figure 4, the proposed conceptual framework for the analysis of the resilience of UDSs is presented.

In relation to the ER frameworks shown in Table 1, this framework also allows for a resilience analysis of water quantity (floods). However, these other frameworks do not yet account socio-ecological aspects key for UDSs of developing countries; furthermore, they have not considered that their configurations can be used to evaluate and improve ER factors. This framework was formulated to know in detail the changes that occur in these factors when mitigation strategies are implemented.

Likewise, the proposed framework differs from the SER frameworks shown in Table 1 because in addition to involving the engineering component, it allows the development of a SER analysis process more focused on the threats that affect the resilience of the UDSs and the strategies that these systems can incorporate to improve resilience.

It was estimated that the weight of the ER and SER to calculate the CR index to avoid double counting due to the correlations between indicators should be $W_E = 55.2\%$ and $W_{SE} = 44.8\%$. Table 6 presents the consolidated results of the resilience (ER and SER), as well as the CR index of the SDS and its subbasins for: *i*. Baseline condition; *ii*. Soil permeability reduction threat scenario; and *iii*. Engineering mitigation strategies for cleaning of channels and rivers and reservoirs in the most critical points of each subbasin and a socio-ecological mitigation strategy for regulation of land use.

The results for the baseline condition indicate that each subbasin presents a specific behaviour; while those of Cañaveralejo, Meléndez and Ferrocarril have a low ER, SER and CR index (between 0.30 and 0.49), the Lili subbasin presents a high ER and CR index (between 0.70 and 0.89) and a moderate SER (between 0.50 and 0.69). The global analysis of the SDS shows a moderate ER and CR index (between 0.50 and 0.69) and a low SER (between 0.30 and 0.49).

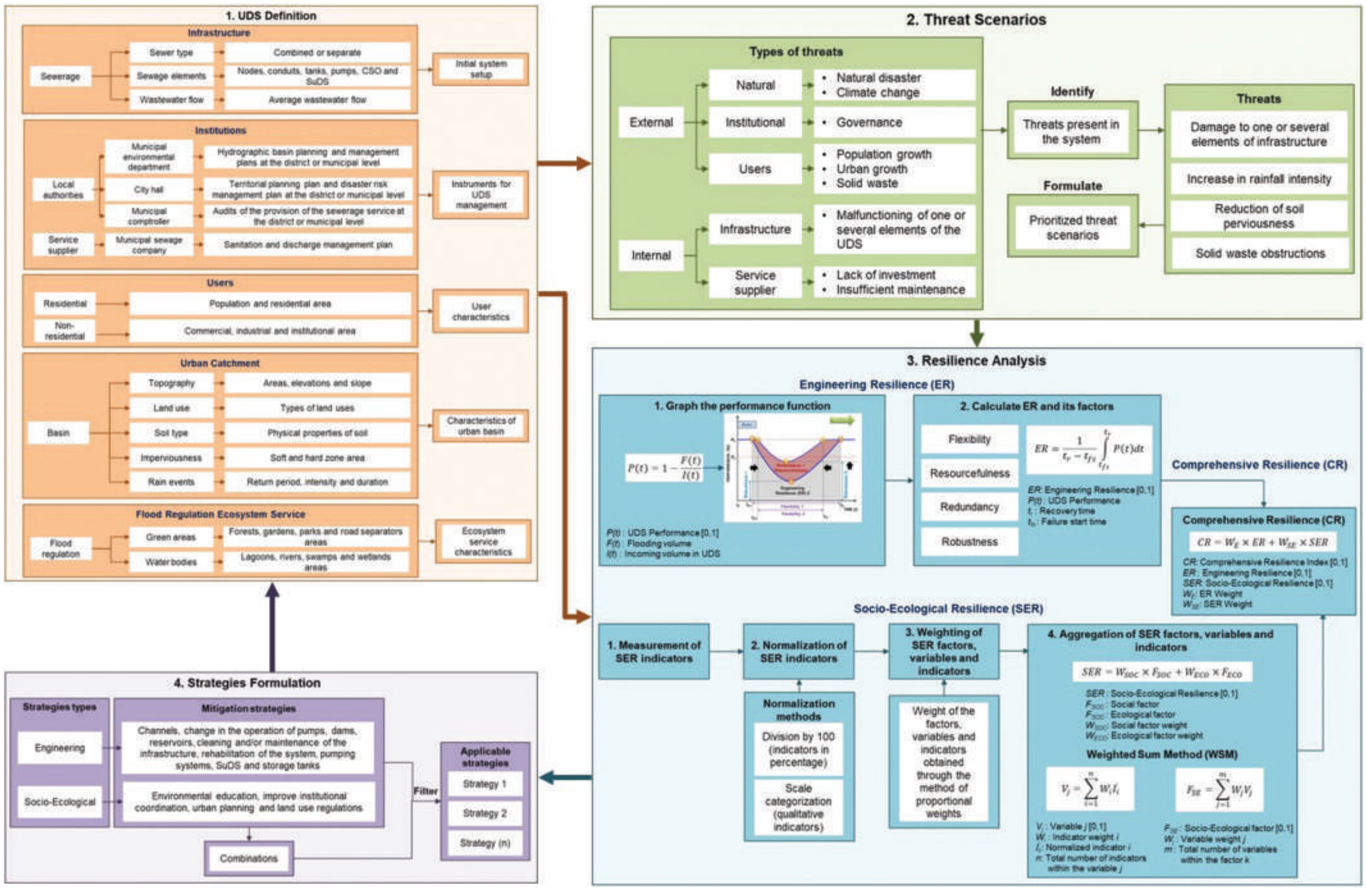

Figure 4. Conceptual framework for resilience analysis of urban drainage systems (UDSs).

Table 6. Resilience of the southern drainage system (SDS) of Cali and its subbasins.

	Baseline			Threat scenario			Mitigation strategies		
Subbasin	ER	SER	CR index	ER	SER	CR index	ER	SER	CR index
Cañaveralejo	0.46	0.42	0.44	0.43	0.39	0.41	0.73	0.45	0.60
Lili	0.85	0.51	0.70	0.75	0.48	0.63	0.98	0.54	0.78
Melendez	0.35	0.48	0.41	0.25	0.46	0.34	0.60	0.50	0.55
Ferrocarril	0.38	0.42	0.40	0.31	0.38	0.34	0.72	0.46	0.61
SDS of Cali	0.54	0.47	0.51	0.50	0.44	0.47	0.65	0.49	0.58

These results are consistent with the results of similar investigations obtained in UDS of cities in developing countries using ER frameworks developed by Mugume et al. (2015) (ER less than 0.80) and Binesh et al. (2018) (ER less than 0.94) and in SER frameworks developed by Kotzee and Reyers (2016) (SER less than 0.70), Qasim et al. (2016) (SER less than 0.33), Moghadas et al. (2019) (SER less than 0.70), and Rezende et al. (2019) (SER less than 0.50).

In relation to the threat scenario, reductions in the permeability of the soil decreased the ER by 7%, 12%, 29% and 18%, the SER by 7%, 5%, 5% and 10% and the CR index by 7%. 10%, 16% and 14% in the Cañaveralejo, Lili, Meléndez and Ferrocarril subbasins, respectively, compared to the baseline condition, with the Meléndez decreasing the most (16%) and the Cañaveralejo decreasing the least (7%). On the other hand, in the SDS, the ER was reduced by 7%, the SER by 6% and the CR index by 7% compared to the baseline condition.

The results indicate that the engineering and socio-ecological mitigation strategies increased the ER by 59%, 15%, 71% and 89%, the SER by 7%, 5%, 4% and 10% and the CR index by 37%, 12%, 36% and 52% in the Cañaveralejo, Lili, Meléndez and Ferrocarril subbasins, respectively, which generated an increase in the SDS of the ER of 20%, the SER of 6% and the CR index of 14% in comparison with the baseline condition.

The SER did not vary significantly with the implemented socio-ecological strategy because the SDS has low percentages of permeable areas, green areas and water bodies (CVC 2019), which indicates that a strategy does not necessarily contribute to the mitigation of all types of threats (Bucherie et al. 2022; Butler et al. 2016). It is highlighted that the Ferrocarril subbasin was the one that increased its CR index the most (52%) when the mitigation strategies were combined, while the Lili subbasin was the one that increased the least (12%).

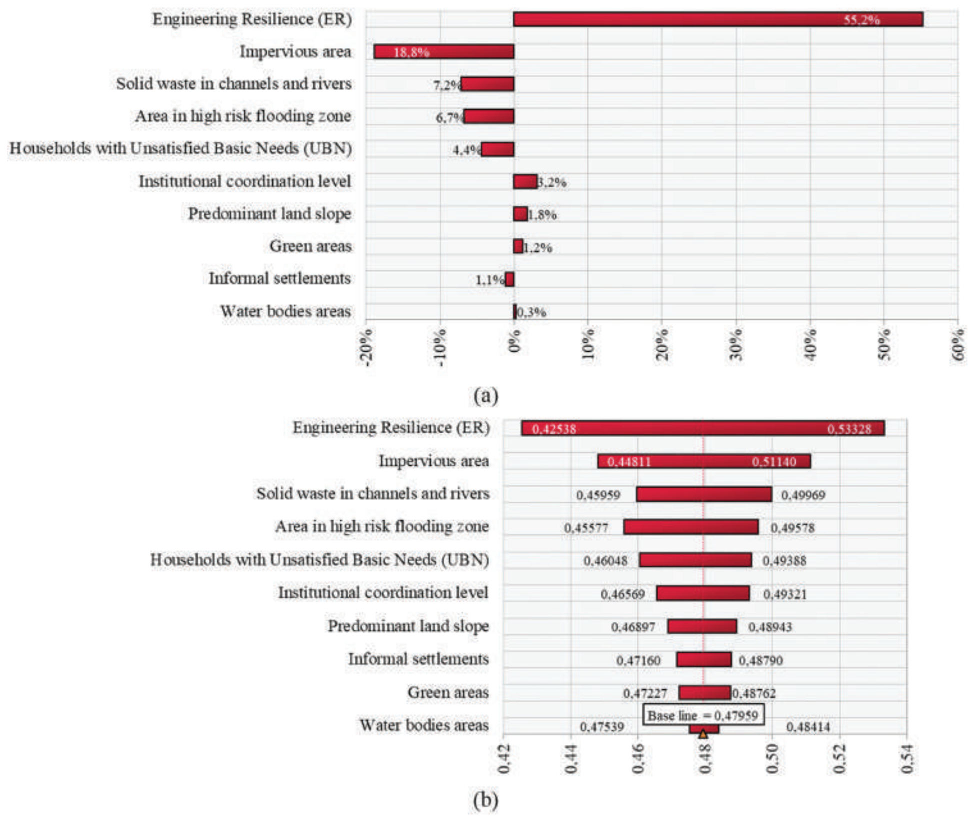

Figure 5. Sensitivity analysis of the conceptual framework (a) sensitivity of the indicators regarding the contribution to the variance; (b) uncertainty of the indicators with respect to the mean of the comprehensive resilience (CR) index.

In summary, the Ferrocarril subbasin is the most critical, and more attention should be given to this subbasin and/or more mitigation strategies formulated. In this subbasin, low resilience values were obtained for the baseline condition. When the threat scenario was evaluated, the CR index decreased by 14%, while the proposed mitigation strategies increased this index by 52% for this subbasin.

Figure 5 shows the results of the evaluation of the sensitivity of the framework to changes in the resilience indicators via Monte Carlo simulations.

The results indicate that the conceptual framework, in general, has high sensitivity to changes in the ER indicator (55%), medium sensitivity to changes in the SER indicators: impervious area (19%), solid waste in channels and rivers (7%) and area in a high-risk flooding zone (7%), and low sensitivity in the other SER indicators, which is consistent with studies that highlight the importance of ER indicators to improve the resilience of urban water (Huang et al. 2021; Zhu et al. 2023).

The uncertainty results indicate that with a confidence level of 90%, the ER indicator presents a medium uncertainty range (±0.10791), while the other indicators present a low uncertainty range (less than ±0.06329). The greater uncertainty of the ER indicator is due to its high sensitivity compared to the other indicators.

Finally, it is recommended to use this framework in UDSs of developing countries due to the social components considered in its formulation which are more specific to the context of these countries, taking into account the following limitations: *i*. The estimation of ER only considers the performance of the UDS obtained by means of hydrodynamic modelling of the UDS; *ii*. The ER indicator has a high sensitivity, so it is recommended to calibrate the hydrodynamic model to obtain results closer to reality; and *iii*. To measure SER indicators for very small urban basins does not appear to make sense because variables such as governance, flood risk and solid waste in the UDS reflected better in medium and large basins. It should be noted that the basin under study has an area of 74.6 km^2.

The proposed conceptual framework could also be expanded to include not only the performance of the UDS but also the topology, redundancy and flexibility of the UDS in the ER analysis, as defined in the resilience criterion of the sanitation system analysis tool SAmpSONS (ifak 2021; Schütze et al. 2019). Furthermore, for simulative analysis of resilience using hydrodynamic sewer simulation, also recent additions to the Simba# simulator could be used (Alex et al. 2024).

4. Conclusions

The conceptual framework for analysing the resilience of urban drainage systems (UDSs) integrates engineering resilience (ER) and socio-ecological resilience (SER) through the comprehensive resilience (CR) index. The framework is made up of four thematic blocks: *i*. UDS Definition; *ii*. Threat Scenarios; *iii*. Resilience Analysis; and *iv*. Formulation of Strategies. In the first block, the characteristics of the UDS are defined, which allows us to establish its initial condition. In the second block, the threats that the UDS can face are identified, and the prioritized threat scenarios are formulated. In the third block, the resilience factors, variables and indicators are used to establish the level of resilience of the UDS. Finally, in the fourth block, the mitigation strategies that can be incorporated into the UDS are established in such a way that they can improve the resilience. Once the strategies are incorporated, a new analysis begins.

With the evaluation of the framework in the Southern Drainage System (SDS) of Cali, moderate ER values and CR index and low SER were obtained in its baseline condition. When the threat scenario of reducing the permeability of the soil by 50% was evaluated, the values of ER, SER and the CR index decreased by 7%, 6% and 7%, respectively. For its part, engineering mitigation strategies, consisting of cleaning channels and rivers and reservoirs in the most critical points of each subbasin, and a socio-ecological strategy, through the regulation of land use, allowed increases in the ER, SER and the CR index by 20%, 6% and 14%, respectively.

It was found that the framework has high sensitivity to changes in the ER indicator; medium sensitivity to changes in the SER indicators, including impervious area, solid waste in channels and rivers, and area in high-risk flooding zone; and decreases in the other SER indicators.

The framework developed is a planning tool that facilitates the analysis of UDSs resilience in developing countries. The characteristics that stand out in the framework are as follows: *i*. The framework allows an integrated analysis of the ER and SER of a UDS by water quantity (floods) in its initial condition and in the face of threat scenarios; *ii*. It emphasizes on engineering aspects of the performance of the UDS and institutional socio-ecological performance, the users, the basin and the ecosystem service of flood regulation; and *iii*. It considers incorporating engineering and/or socio-ecological mitigation strategies to improve resilience.

To adjust and optimize this framework, it should be evaluated in other UDSs, and other threat scenarios and engineering and socio-ecological mitigation strategies should be considered.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

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