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Qualitative and quantitative assessment of sustainable urban stormwater management in Bogotá, Colombia

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Preface

This dissertation adopted a cumulative approach. The following publications are part of the thesis:

I. **Ortega, A. D.**, Rodríguez, J. P., & Bharati, L. (2023). Building flood-resilient cities by promoting SUDS adoption: a multi-sector analysis of barriers and benefits in Bogotá, Colombia. *International Journal of Disaster Risk Reduction*, 88, 103621. https://doi.org/10.1016/j.ijdrr.2023.103621
II. **Ortega, A. D.**, Rodríguez, J. P., & Bharati, L. (2023). A transdisciplinary approach for assessing the potential feasibility of Sustainable Urban Drainage Systems: case study, Bogotá, Colombia. *Urban Water Journal, 20*(8), 1081-1094. https://doi.org/10.1080/1573062X.2023.2233494
III. **Ortega, A. D.**, Sörensen, J., Rodríguez, J. P., & Bharati, L. (2023). Hydrologic-hydraulic assessment of SUDS control capacity using different modeling approaches: a case study in Bogotá, Colombia. *Water Science and Technology*, *87*(12), 3124-3145. https://doi.org/10.2166/wst.2023.173

The following conference participations took place during the course of this research:

i. *IWA (International Water Association) World Water Congress & Exhibition.* Copenhagen, Denmark (2022). Panelist at the “Nature-based solutions for climate-resilient cities in developing countries under change" workshop.
ii. *Flood Knowledge Summit – From Risks to Resilience*. UNU-MERIT, Maastricht, The Netherlands (2022). Poster presentation: Building flood resilient cities by integrating multi-stakeholder preferences in the selection of Sustainable Urban Drainage Systems (SUDS).
iii. *International Conference on Resilient Cities from the Global South* (2021). Video presentation: Exploring stakeholders' SUDS perceptions as urban flood risk management strategies in Bogotá, Colombia.
iv. *International Conference on Urban Drainage* (2021). Poster presentation: Exploring stakeholders' SUDS perceptions as urban flood risk management strategies in Bogotá, Colombia.

Additional conference participations related to the topic of this dissertation:

i. *NOVACTECH – 11th international conference on Urban Water*. Lyon, France (2023). Oral presentation: Feasibility methodology for selecting and locating urban nature-based solutions according to ecosystem services generation. Uribe, J., **Ortega, A. D.**, Rodríguez, J. P.

ii. *International Association for Hydro-Environment Engineering and Research (IAHR) – 40th IAHR World Congress*. Vienna, Austria (2023). Oral presentation: Feasibility methodology for selecting and locating urban nature-based solutions. Uribe, J., **Ortega, A. D.**, Rodríguez, J. P.

Additional publications as doctoral student at ZEF:

De Castro, A., **Ortega, A. D.**, Odamtten, G. (2022). Up around the bend? How transport poverty can lead to social exclusion in a low-income community in Lagos, Nigeria. *Journal of Transport Geography*, 102, 103388.

This work is dedicated to the memory of my father,
Yuri Mauricio Ortega Gordillo, who passed away in May 2021.
His memory will always hold a special place in my heart,
providing comfort like a warm embrace.

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I want to express my heartfelt thanks to my entire family. Even though my father is no longer with us, I still feel his unwavering support and company in my daily life. My mother's strength and unconditional love and my sister's kind and joyful spirit provided me with continuous motivation. Furthermore, I would like to thank my amazing old and new friends –Diana, Ellen, Hiwi, Tray, and Juli– for their unique perspectives and the many meaningful experiences we have shared together. I am lucky for have you all as part of my support system.

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ABSTRACT

Rapid population growth and urbanization have triggered abrupt changes in land use, intensifying impervious surfaces and the loss of green areas, thus reducing the soil's natural drainage capacity. These factors have increased exposure to flood risk in cities, which is aggravated by high intensity rainfall associated with climate change and the insufficient capacity of conventional pipe-ended drainage systems. Sustainable urban drainage systems (SUDS) are an appealing alternative to urban runoff and flood risk management. Their operation is mainly based on four dimensions: peak flow and total volume control, improvement of stormwater runoff quality, increase in biodiversity, and amenity provision. Based on the concepts of inter- and transdisciplinarity, this thesis aimed to fill three main gaps in the study of SUDS: (i) analysis of the factors that promote or hinder a greater uptake; (ii) methods for selection and location considering multidimensional local context constraints; and (iii) model-based evidence of hydraulic control capabilities.

This research was conducted at the community level in Bogotá, the capital city of Colombia, framing a relevant case study for the assessment of SUDS in highly urbanized flood-prone areas with several space constraints on public and private land. An interdisciplinary approach was used to explore the barriers to and benefits of SUDS implementation, considering the perspectives of the public sector, a private non-profit organization, urban developers, and community members. Data collection methods included semi-structured interviews and questionnaires, whereas thematic analysis supported by an inductive–deductive coding approach was employed to analyze the gathered data. After identifying and categorizing 39 barriers, it was evident that technical barriers continue to have a significant impact on SUDS adoption. Moreover, the evaluation of benefits yielded 34 results, demonstrating the broad scope of SUDS at a social, economic, and environmental level.

The categorization of barriers was used as input to develop a transdisciplinary methodology for the selection and location of SUDS that integrates not only the site's physical restrictions (soil characteristics, land-use suitability, and size constraints) but also local context limitations (cultural/behavioral, financial, institutional/organizational, technical, political, and urban form). Here, the concept of transdisciplinarity was incorporated through (i) the co-production of knowledge involving academic and non-academic actors, (ii) the participation of an expert panel pooling expertise on sustainable urban water management in six different regions around the world, and (iii) the use of multiple tools such as specialized literature, geographic information systems, fuzzy logic, and multi-criteria decision analysis. A 70-ha urban area was used as a case study to identify the most feasible SUDS typologies on both public and private land.

Thereafter, numerical models were employed to assess SUDS performance in a 50-ha neighborhood, and 24 scenarios were developed to contrast the hydrologic-hydraulic response of a highly discretized (HD) one-dimensional (1D) model and a coupled one- and two-dimensional (1D–2D) model. The selected SUDS typologies, i.e., rainwater harvesting systems and tree pits, arose from the application of the previously described transdisciplinary methodology and local management conditions on public land, respectively. An alternative scenario was modeled, including attenuation storage tanks, green roofs, and pervious pavements. Findings revealed that, in addition to their renowned hydrologic control capabilities (peak discharge and total volume), SUDS also aid in the reduction of the number of flooded junctions, overloaded conduits' length, overloading time, nodal inundation depth, and waterlogging extent. Furthermore, the HD 1D model was able to reproduce the results from the coupled 1D–2D model in terms of hydrologic response and some hydraulic control indicators.

Through the course of this thesis, it became evident that the implicit multidimensionality of the sustainable management of urban drainage requires continuous efforts by various communities of knowledge to bridge the numerous gaps that today prevent a more robust SUDS implementation. This dissertation proposes a novel approach by integrating inter- and transdisciplinary thinking within a field of knowledge that is typically approached from a technical perspective, providing significant tools and information to more firmly transition from traditional drainage approaches to multifunctional options such as SUDS. Although the findings of this research are framed within the socio-institutional-spatial features of a developing city such as Bogotá, it is expected that this thesis will influence the sustainable management of urban drainage—and urban water as such—in other contexts through the different methodological applications presented here and the positive results that, in light of current evidence, can be produced with this paradigm shift.

KURZFASSUNG

Rasantes Bevölkerungswachstum und Urbanisierung haben abrupte Veränderungen in der Landnutzung ausgelöst, die versiegelte Flächen verstärkt und den Verlust von Grünflächen zur Folge hatten. Diese Faktoren haben das Hochwasserrisiko in Städten erhöht, das durch Starkregen in Verbindung mit dem Klimawandel und die unzureichende Kapazität konventioneller Rohrleitungsentwässerungssysteme verschärft wird. Nachhaltige städtische Entwässerungssysteme (Sustainable Urban Drainage Systems, SUDS) stellen eine attraktive Alternative zur Bewältigung von Oberflächenabflüssen und Hochwasserrisiken dar. Basierend auf den Konzepten der Inter- und Transdisziplinarität hat diese Dissertation zum Ziel, drei Hauptlücken in der Erforschung von SUDS zu schließen: (i) Analyse der Faktoren, die eine größere Akzeptanz fördern oder behindern; (ii) Methoden zur Auswahl und Standortbestimmung unter Berücksichtigung multidimensionaler lokaler Kontextbeschränkungen; und (iii) modellbasierte Nachweise der hydraulischen Steuerungsfähigkeiten.

Die vorliegende Forschung wurde auf der Stadtteilebene in Bogotá, der Hauptstadt Kolumbiens, durchgeführt. Sie stellt eine relevante Fallstudie zur Bewertung von SUDS in stark urbanisierten, hochwassergefährdeten Gebieten vor. Ein interdisziplinärer Ansatz wurde verwendet, um die Hindernisse und Vorteile der Implementierung von SUDS zu erforschen. Hierbei wurden die Perspektiven von vier verschiedenen Interessengruppen berücksichtigt. Eine thematische Analyse unterstützt durch einen induktiv-deduktiven Kodierungsansatz, der zur Auswertung der gesammelten Daten verwendet wurde. Nach Identifizierung und Kategorisierung von 39 Hindernissen wurde deutlich, dass technische Barrieren weiterhin einen erheblichen Einfluss auf die Übernahme von SUDS haben. Darüber hinaus ergab die Bewertung der Vorteile 34 Ergebnisse, die das breite Anwendungsspektrum von SUDS auf sozialer, wirtschaftlicher und ökologischer Ebene demonstrieren.

Die Kategorisierung der Hindernisse wurde als Grundlage zur Entwicklung einer transdisziplinären Methodik für die Auswahl und Standortbestimmung von SUDS verwendet. Diese integrieren nicht nur die physikalischen Einschränkungen des Standorts, sondern auch lokale Kontextbeschränkungen. Hier wurde das Konzept der Transdisziplinarität durch (i) die gemeinsame Wissensproduktion unter Einbeziehung von akademischen und nicht-akademischen Akteuren, (ii) die Beteiligung eines Expertengremiums, und (iii) die Verwendung mehrerer Werkzeuge wie spezialisierter Literatur, geographischer Informationssysteme, Fuzzy-Logik und Mehrkriterien-Entscheidungsanalyse eingebunden.

Anschließend wurden numerische Modelle eingesetzt, um die Leistung von SUDS. Es wurden 24 Szenarien entwickelt, um den hydrologisch-hydraulischen Ansprechmechanismus eines stark diskretisierten (HD) eindimensionalen (1D) Modells und eines gekoppelten ein- und zweidimensionalen (1D–2D) Modells zu vergleichen. Die ausgewählten SUDS-Typologien waren Regenwassernutzungssysteme und Baumgruben. Es wurde ebenso ein alternatives Szenario modelliert, das

Speicherbehälter zur Dämpfung, begrünte Dächer und durchlässige Oberflächen umfasste. Die Ergebnisse haben gezeigt, dass SUDS neben ihren bekannten Fähigkeiten zur hydrologischen Kontrolle auch zur Verringerung der Anzahl überfluteter Kreuzungen, der Länge überlasteter Leitungen, der Überlastungszeit, der Überflutungstiefe an Knotenpunkten und des Umfangs von Wasseransammlungen beitragen. Darüber hinaus konnte das HD 1D-Modell die Ergebnisse des gekoppelten 1D–2D-Modells in Bezug auf die hydrologische Reaktion und einige hydraulische Kontrollindikatoren reproduzieren.

Im Verlauf dieser Arbeit wurde deutlich, dass die implizite Multidimensionalität des nachhaltigen Managements der städtischen Entwässerung kontinuierliche Bemühungen verschiedener Wissensgemeinschaften erfordert, um die zahlreichen Lücken zu überbrücken, die heute eine robustere Implementierung von SUDS verhindern. Diese Dissertation schlägt einen neuen Ansatz vor, indem sie das inter- und transdisziplinäre Denken in ein Wissensgebiet integriert, das typischerweise aus einer technischen Perspektive betrachtet wird. Sie bietet bedeutende Informationen, um den Übergang von traditionellen Entwässerungsansätzen zu multifunktionalen Optionen wie SUDS fester zu gestalten. Obwohl die Ergebnisse dieser Forschung im Rahmen der sozio-institutionellen und räumlichen Merkmale einer sich entwickelnden Stadt wie Bogotá betrachtet werden, wird erwartet, dass diese Arbeit das nachhaltige Management der städtischen Entwässerung - und des städtischen Wassers im Allgemeinen - in anderen Kontexten beeinflusst. Dies geschieht durch die verschiedenen methodischen Ansätze, die in dieser Dissertation vorgestellt werden, sowie durch die positiven Ergebnisse, die vor dem Hintergrund der aktuellen Erkenntnisse mit diesem Paradigmenwechsel erzielt werden können.

RESUMEN

El rápido crecimiento poblacional y urbanización han desencadenado cambios abruptos en el uso del suelo, intensificando las superficies impermeables y la pérdida de áreas verdes, reduciendo así la capacidad natural de drenaje del terreno. Estos factores han aumentado la exposición al riesgo de inundaciones en las ciudades, lo cual es agravado por las lluvias de alta intensidad asociadas con el cambio climático y la capacidad insuficiente de los sistemas tradicionales de drenaje. Los sistemas urbanos de drenaje sostenible (SUDS) son una alternativa atractiva en la gestión de escorrentía e inundaciones urbanas. Su funcionamiento está basado en cuatro dimensiones principalmente: control de volúmenes y picos de caudal, mejoramiento de la calidad de la escorrentía, incremento de la biodiversidad y provisión de amenidad. Basada en los conceptos de inter- y transdisciplinariedad, esta tesis abordó tres brechas principales dentro de la investigación de SUDS: 1) comprensión de los factores que promueven y obstaculizan una adopción más generalizada, 2) selección y localización considerando las limitaciones multidimensionales del contexto local y 3) exploración de las capacidades de control hidráulico.

Esta investigación fue conducida a escala vecinal en Bogotá, ciudad capital de Colombia, enmarcando un caso relevante para la evaluación de SUDS en zonas altamente urbanizadas, propensas a las inundaciones y con amplias limitaciones en el espacio público y privado. Un enfoque interdisciplinar para explorar las barreras y beneficios de la implementación de SUDS analizando las perspectivas del sector público, una organización privada sin fines de lucro, desarrolladores urbanos y miembros de la comunidad. Los métodos de recopilación de información incluyeron entrevistas semiestructuradas y cuestionarios, los cuales fueron sometidos a un análisis temático apoyado en un enfoque de codificación inductivo–deductivo. Luego de identificar y categorizar 39 barreras, se evidenció que las barreras técnicas aún tienen un gran impacto en la adopción de SUDS. Por su parte, la evaluación de beneficios reportó 34 resultados, demostrando el amplio alcance de los SUDS a nivel social, económico y ambiental.

La categorización de barreras se empleó como insumo para desarrollar una metodología transdisciplinar para la selección y localización de SUDS, integrando no sólo las restricciones físicas del lugar (características del terreno, uso del suelo y dimensiones requeridas) sino también las limitaciones del contexto local (culturales/comportamentales, financieras, institucionales/organizacionales, técnicas, políticas y configuración urbana). El concepto de transdisciplinariedad se incorporó a través de (i) la coproducción de conocimiento involucrando actores académicos y no académicos, (ii) la participación de un panel de expertos que reúne experiencia sobre gestión sostenible del agua urbana en seis regiones alrededor del mundo y (iii) el uso de múltiples herramientas como literatura especializada, sistemas de información geográfica, lógica difusa y análisis de decisión multicriterio. Un área urbana de 70 hectáreas fue empleada como caso de estudio para identificar las tipologías SUDS más viables tanto en espacio público como en espacio privado.

Posteriormente se aplicaron modelos numéricos para evaluar el desempeño de los SUDS en un vecindario de 50 hectáreas; 24 escenarios fueron desarrollados con el fin contrastar la respuesta hidrológica-hidráulica de un modelo altamente discretizado unidimensional (1D) y un modelo acoplado uni- y bidimensional (1D–2D). Las tipologías SUDS evaluadas, i.e., sistemas de aprovechamiento de aguas de lluvias y alcorques inundables, surgieron de la aplicación de la metodología transdisciplinar previamente descrita y condiciones locales de implementación en espacio público, respectivamente. Un escenario adicional fue modelado incluyendo tanques de almacenamiento, techos verdes y pavimentos permeables. Los hallazgos revelaron que, además de las ampliamente difundidas capacidades de control hidrológico (pico de descarga y volumen total), los SUDS también proveen control hidráulico respecto al número de nodos inundados, la longitud de sobrecarga en tuberías, el tiempo de sobrecarga, la profundidad de inundación nodal y la huella de encharcamiento. Además, el modelo 1D fue capaz de reproducir los resultados del modelo acoplado 1D–2D en términos de respuesta hidrológica y algunos de los indicadores de respuesta hidráulica.

Durante el desarrollo de esta tesis fue evidente que la multidimensionalidad implícita en la gestión sostenible del drenaje urbano requiere esfuerzos continuos por parte de diferentes comunidades del conocimiento para cerrar las diversas brechas que hoy impiden una implementación más robusta de los SUDS. Esta disertación propone un enfoque novedoso a través de la integración del pensamiento inter- y transdisciplinar dentro de un área de estudio comúnmente abordada desde una visión técnica, brindando herramientas e información relevantes para transicionar con mayor firmeza desde enfoques tradicionales de drenaje hacia opciones multifuncionales como los SUDS. Si bien los hallazgos de esta investigación se enmarcan dentro de las características socio-institucionales-espaciales de una ciudad en desarrollo como lo es Bogotá, se espera que esta tesis pueda influenciar la gestión sostenible del drenaje urbano –y del agua urbana como tal– en otros contextos, a través de las diferentes propuestas metodológicas anteriormente descritas y los resultados positivos que a la luz de la evidencia actual pueden ser obtenidos con este cambio de paradigma.

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List of abbreviations and acronyms

1D	One-dimensional
2D	Two-dimensional
A	Academic (participant)
AST	Attenuation storage tanks
BAU	Business-as-usual scenario
BGI	Blue-green infrastructure
BMP	Best management practices
BRS	Bio-retention systems
C	Community (participant)
CGBC	Colombian Green Building Council
CW	Constructed wetlands
DEM	Digital Elevation Model
ec	Excerpt counts
EDB	Extended dry basins
FBS	Final barrier score
FRM	Flood risk management
GI	Green infrastructure
GIS	Geographic Information Systems
GR	Green roofs
HD	Highly discretized
IB	Infiltration basins
IT	Infiltration trenches
LID	Low impact development (techniques)
LSE	Local Secretary of Environment
LSP	Local Secretary of Planning
LWU	Local Water Utility
MCDA	Multi-criteria Decision Analysis
MIX	Scenario combining rainwater harvesting systems and tree pits
MULT	Scenario combining rainwater harvesting systems, tree pits, attenuation storage tanks, green roofs, and pervious pavements
NSE	Nash-Sutcliffe Efficiency coefficient
O&M	Operation and maintenance
OBI	Overall barrier indicator
P	Ponds
PCSWMM	Personal Computer Storm Water Management Model
PP	Pervious pavements

PR	Private sector (participant)
Pr	Practitioner (participant)
PU	Public sector (participant)
RE	Relative Error
RMSE	Root Mean Square Error
RWHS	Rainwater harvesting systems
SDG	Sustainable development goal
SUDM	Sustainable urban drainage management
SUDS	Sustainable urban drainage systems
SUWM	Sustainable urban water management
T	Design storm's return period
TA	Thematic analysis
TP	Tree pits
UD	Urban developer (participant)
UDI	Urban Development Institute
UDM	Urban drainage management
UFRM	Urban flood risk management
VS	Vegetated swales
WAM	Weighted Average Method
WSUD	Water sensitive urban design

1 Introduction

Urban flooding is a growing concern influenced by factors such as urban growth, rapid urbanization, changes in land use, and mismanagement of spatial planning (Abass et al., 2020; Arnone et al., 2018; Ran & Nedovic-Budic, 2016). The degree of world urbanization has undergone a notable surge since the mid-twentieth century. In 1950, 30% of people worldwide resided in cities, a number that increased to 55% in 2018. This trend is alarming since, by 2050, 68% of the world's population is expected to live in urban settlements (UNDESA, 2019), and a greater concentration of people and infrastructure increases the flood risk exposure (Park & Lee, 2019). Rapid urbanization intensifies impervious surfaces, resulting in an increase in runoff volumes and peak discharges that disrupt natural hydrologic processes and flood patterns in cities (Akhter & Hewa, 2016; Qin, 2020; Schuetze & Chelleri, 2013). This is aggravated by high-intensity rains associated with climate change (IPCC, 2022).

In Colombia, additional geo-climatic and governance factors have exacerbated hydro-meteorological hazards. For instance, climate variability and the La Niña/El Niño weather phenomenon have caused a general increase in the intensity and recurrence of precipitation (Jha et al., 2012). Additionally, the scant harmonization of planning instruments and the ambiguity of regional competencies for risk management increase the population's vulnerability to floods (World Bank, 2012). In urban areas, the deficiency (and, in some cases, inexistence) of sewerage and stormwater drainage systems is an additional factor that intensifies the impacts of flood events (World Bank, 2012).

It is estimated that Colombia’s 2011 floods affected more than three million people and reduced the gross domestic product by 2% (Díaz, 2013; Jha et al., 2012). Nevertheless, the adverse effects of flood events extend beyond economic damage to include loss of human life, disruption of critical infrastructure, and environmental degradation (Hammond et al., 2013; Hilly et al., 2018). For this reason, within the framework of sustainable development goal (SDG) 11 "*Make cities and urban settlements inclusive, safe, resilient, and sustainable*" (UNDESA, 2022), there is a global challenge to find adaptive solutions for coping with hydrometeorological hazards, exacerbated by anthropogenic action.

Urban water management is directly related to this purpose due to the interaction between human activity and the natural water cycle, reflected in the fields of water supply, wastewater treatment, and urban drainage (Butler et al., 2018; Larsen & Gujer, 1997). Techniques for controlling water flows date back to the Neolithic era in Mesopotamia and Egypt (ca. 5700-3200 BC), mostly for agricultural irrigation (Angelakis & Zheng, 2015). Nonetheless, as cities were established in river basins, urban drainage management (UDM), also known as urban stormwater management (Fletcher et al., 2015), became increasingly important. For instance, river course redirection and cisterns, as large- and small-scale strategies, respectively, served multiple purposes, enhancing flood protection and water supply (Angelakis & Zheng, 2015). Moreover, today's traditional pipe-ended infrastructure resembles the ditches and sewers of the ancient drainage systems of the Chinese Han Dynasty (ca. 202 BC-220 AD) (Cun et al., 2019).

With the challenges posed by sustainable development, UDM has evolved to a more holistic approach, capable of providing greater benefits compared to traditional centralized (Marlow et al., 2013) and single-objective (Q. Zhou, 2014) systems. Therefore, new terminology has emerged since the late 1970s, which has been key to systematizing new developments in sustainable UDM (SUDM) and better communicating objectives and benefits (Fletcher et al., 2015; Qiao et al., 2018). For instance, the 'green infrastructure (GI)', 'best management practices (BMP)', and 'low impact development (LID) techniques' concepts are more common in North America and New Zealand, whereas the term 'water sensitive urban design (WSUD) has been widely promoted in Australia (Fletcher et al., 2015). Moreover, the United Kingdom (UK) has coined the 'sustainable urban drainage systems (SUDS)' concept, whereas China formally proposed the 'Sponge City Program' to address urban stormwater problems (Fletcher et al., 2015; Qi et al., 2020).

SUDS have gained significant attention since they attempt to replicate the natural pre-development drainage conditions (Perales-Momparler et al., 2017). SUDS are multi-objective SUDM strategies that, in addition to reducing runoff quantity, have the ability to improve water quality, provide amenity, and increase biodiversity in urban spots (Fletcher et al., 2015). Among the best-known SUDS typologies for residential, commercial, and public facility use are rainwater harvesting systems, green roofs, and attenuation storage tanks (City of Edmonton, 2014). Other SUDS typologies capable of managing larger stormwater runoff volumes due to their outdoor nature include bio-retention systems, infiltration basins, pervious pavements, and vegetated swales (Woods et al., 2015). Depending on the scale and land use distribution of the study site, SUDS can be implemented individually or interconnected (SUDS trains).

As a relatively new approach to managing urban stormwater, SUDS research has focused on performance assessment (stormwater quantity and quality control), optimization (design, selection, and location), benefit valuation, and cost-benefit analysis, primarily in developed contexts (Alves et al., 2016; Jia et al., 2012; Johnson & Geisendorf, 2019; Majidi et al., 2019). SUDS study and adoption have also spread to developing cities, where particular challenges of unsustainable urban sprawl, land tenure, and space restrictions have prompted its evaluation (Drosou et al., 2019; Jiménez et al., 2019; Mulligan et al., 2020). In Colombia, for example, the concept of SUDS gained momentum in 2017 through a resolution from the Ministry of Housing, City, and Territory, where the implementation of these measures was recommended to mitigate the effect of soil sealing generated from urban development (Ministry of Housing of Colombia, 2021).

Despite the evidence acquired during the last decades, the implementation of SUDM strategies is still slow-paced, with a weak overall interpretation, even in developed contexts (L. Li et al., 2020; Wihlborg et al., 2019). Previous studies from the UK, China, Canada, and Spain have pointed out that barriers hindering the transition to SUDM are more socio-political than technical (Brown & Farrelly, 2009a; L. Li et al., 2020; Perales-Momparler et al., 2015; Thorne et al., 2018). In contrast, a broad range of benefits have been demonstrated, spanning from the well-known functions of runoff reduction and flood control to property value enhancement (Alves, Gómez, et al., 2018; G. Zhang & He, 2021). Nevertheless, it is difficult to affirm that these factors that hamper or promote the implementation of SUDM strategies such as SUDS can be shared in places with other geographical, climatic, social, economic, cultural, and governance characteristics.

In this context and given the imminent challenges posed by urbanization and climate change, the adoption of SUDS is no longer linked to the "*why*" but to the "*how*." Scholars have highlighted that selection and location are key to achieving optimal performance and maximizing benefits (Jiménez et al., 2019; Uribe-Aguado et al., 2022). There are several methodologies available to support these critical tasks, including the assessment of physical environment features (Saadat Foomani & Malekmohammadi, 2020), ecosystem service provision (Uribe-Aguado et al., 2022), and stakeholders' perceptions (Aceves & Fuamba, 2016b; Alves, Gómez, et al., 2018). Nonetheless, there is a lack of studies comprehensively integrating the influence of technical aspects and local socio-institutional limitations.

The use of numerical models has proven effective in assessing SUDS performance, especially given that small- and large-scale deployments, i.e., pilot projects, may represent a financial burden on both public and private levels. However, the application of mathematical simulations has primarily focused on the study of the SUDS hydrologic response, i.e., stormwater runoff volume reduction and peak discharge attenuation, often neglecting or generalizing the interaction with the pipe-ended drainage network, i.e., the hydraulic response (Cui et al., 2019). This poses a great challenge in urbanized catchments, where there is a two-way interaction between one-dimensional (1D) sewer flows and two-dimensional (2D) overland flows, altered by flow-path modifying elements such as buildings, streets, and pavement curbs (Blanc et al., 2012).

The aforementioned knowledge gaps pose a multidimensional and, therefore, multidisciplinary problem in the sustainable management of urban runoff. According to Fratini et al. (2012), urban environments, in the context of urban flood risk management (UFRM) decision-making, are comprised of three systems, i.e., technical, natural, and social. Each system has different infrastructures and actors who play specific roles. This complexity of systems and stakeholders requires different perspectives and skills to develop multifunctional solutions that increase the resilience and adaptive capacity of cities. In view of the challenges ahead, the use of inter- and transdisciplinary approaches has proven to be a more efficient way to understand and implement sustainable urban water management (Brown et al., 2015; Wong et al., 2020).

Interdisciplinary thinking enables the integration of conceptual and theoretical approaches from different disciplines to address a problem (Biber-Freudenberger et al., 2018), whereas a transdisciplinary approach fosters a cross-fertilization of ideas between academic and non-academic actors (Avilés Irahola et al., 2022). Considering the above and the imminent interaction between technical, natural, and social systems in urban drainage, this dissertation appropriates inter- and transdisciplinary approaches to unravel the complex dynamics of sustainable urban stormwater management, highlighting the need for holistic approaches that consider factors beyond the technical domain.

1.1 Objectives

The overall aim of this thesis is to qualitatively and quantitatively study the aspects that influence the successful implementation and wider uptake of SUDM strategies, such as SUDS, in the context of Bogotá, the capital city of Colombia. By adopting an innovative approach in the field of UDM that integrates inter- and transdisciplinary methodologies, the specific objectives of this research are:

i. to understand the factors that promote and hinder the transition to SUDM, as well as the stakeholders' perceptions that facilitate a more robust implementation;
ii. to develop a methodology for SUDS selection and location, considering physical restrictions and the quantification of local context limitations;
iii. to assess the hydrologic-hydraulic performance of SUDS by contrasting the results from a highly discretized (HD) 1D model and a coupled 1D–2D model.

1.2 Structure of this thesis

This dissertation is divided into nine chapters. Chapter 1 serves as an introduction to the study, providing an overview of the problem and the knowledge gaps that this research seeks to address. Chapters 2 and 3 describe the theoretical framework that laid the foundations of the research. In Chapter 2, the concepts of UDM are introduced, covering the fundamental notions that describe the interaction between cities and the natural water cycle, existing numerical models, and current novel drainage approaches such as SUDS. Moreover, Chapter 3 introduces the ideas of inter- and transdisciplinarity and their application within the framework of sustainable management of urban drainage. Furthermore, Chapter 4 describes the main climatic, hydrological, spatial, and social characteristics of the study area.

Chapters 5, 6, and 7 are the resulting research papers of this thesis. Chapter 5, linked to objective i, addresses the barriers to and benefits of SUDS implementation from a multi-stakeholder perspective through an interdisciplinary approach. Chapter 6, which corresponds to objective ii, provides a transdisciplinary methodology for assessing the feasibility of SUDS implementation, considering physical characteristics and local context constraints in six different dimensions. Furthermore, Chapter 7, which addresses objective iii, presents a hydrological-hydraulic evaluation of SUDS performance through a comparative model-based approach comprised of a HD 1D model and a coupled 1D–2D model. Finally, Chapter 8 summarizes the findings and limitations of this study, whereas Chapter 9 provides an outlook for future research.

2 Urban drainage management

Historical records on urban drainage systems date back to at least 3000 BC, with three main objectives: rainwater collection, flooding protection, and waste conveyance (Burian & Edwards, 2002). The practice of combining water-borne wastes and stormwater is known as *combined sewer system*, whereas their separate collection and disposal are known as *separate sewer system*. Nevertheless, since the mid-twentieth century, the separate scheme has been promoted to minimize treatment, thereby differentiating between the sanitary sewerage system and the stormwater drainage system (Chocat et al., 2007; Walsh et al., 2012). With this distinction, it is common to interchange the terms '*urban stormwater management*' and '*urban drainage management*' (Fletcher et al., 2015). Therefore, these two expressions will be used synonymously throughout this thesis.

The importance of urban drainage management (UDM) lies in the impact of urbanization on soil permeability and the subsequent alteration of the natural water cycle (Figure 2.1). After precipitation, three main processes may occur: 1) Water returns to the atmosphere either by evaporation or transpiration by plants; 2) water infiltrates the surface, allowing groundwater recharge; and 3) water runs freely overland (Butler et al., 2018). Post-development conditions, i.e., the soil sealing effect, reduce the ground infiltration capacity, significantly increasing stormwater runoff volume, velocity, and peak flow.

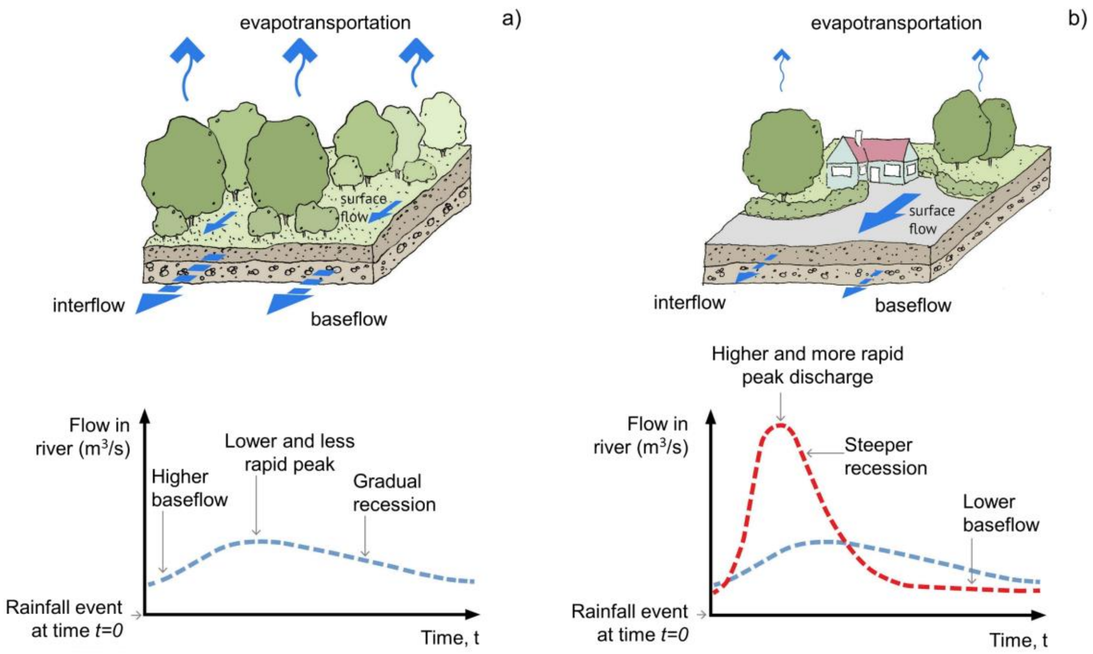

Figure 2.1 *Natural water cycle alteration due to urbanization: a) pre-development and b) post-development conditions (Susdrain, 2018)*

In urban environments, overland flow travels across the terrain, whether pervious (e.g., lawns) or impervious (e.g., roads), forming a surface flow network known as the '*major drainage system*.' Then, elements such as stormwater catchbasins or road gullies intercept this overland flow and deliver it to the underground drainage system, also called the '*minor drainage system'* (Figure 2.2), which is intended to convey surface runoff in a safe and convenient manner to natural water bodies such as streams and lakes (Gribbin, 2013). The design of conventional subsurface drainage systems does not employ the most extreme rainfall conditions as it would result in very expensive infrastructure difficult to operate and maintain (Schmitt et al., 2004). Instead, it is customary to use design storms, whose return period is associated to the study area's relevance and protection features. In Colombia, for instance, the recommended return period for the design of drainage sewer sections ranges between 3 and 10 years, depending on the size of the tributary area (Ministry of Housing of Colombia, 2021).

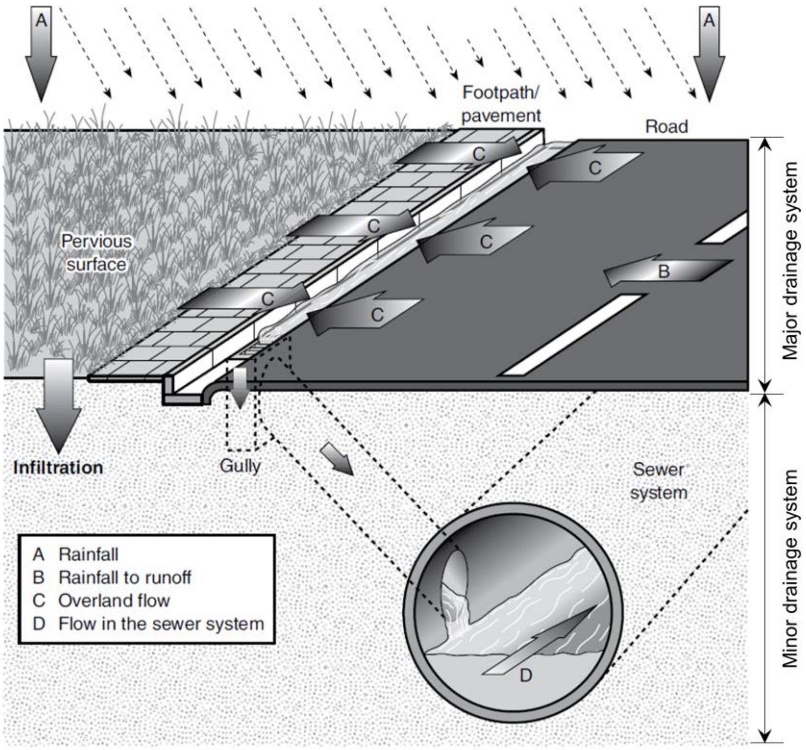

Figure 2.2 *Minor and major drainage systems in urban environments, adapted from Butler et al. (2018)*

Cities may be exposed to coastal (surge-induced), fluvial (river-induced), and pluvial (rain-induced) flooding. Pluvial floods are intrinsically linked to the flow interaction between the major and minor drainage systems (Sörensen et al., 2016); therefore, acknowledging this flow interchange is key not only for UFRM but also for comprehensive urban water planning. For instance, one of the most common causes of pluvial flooding is the limited drainage system capacity during an extreme rainfall event, which can result in sewer flow discharging to the surface, thus interacting with the major drainage system (Maksimović et al., 2009).

Addressing pluvial floods requires the understanding of two concepts: hydraulic surcharge and flooding. Surcharge (Figure 2.3a) refers to the condition in which stormwater is held under pressure within the sewer drainage system, preventing water from being released to the surface. Flooding instead occurs when stormwater is unable to enter the system (e.g., inlet capacity is insufficient) and remains on the surface (Figure 2.3b) or when the water level (WL) exceeds the ground level (Figure 2.3c), propagating in various directions. Therefore, even if the minor drainage system is properly designed, there may be cases of surface flooding without the pipe-ended system reaching maximum surcharge conditions and without extreme rainfall conditions (Sörensen, 2018).

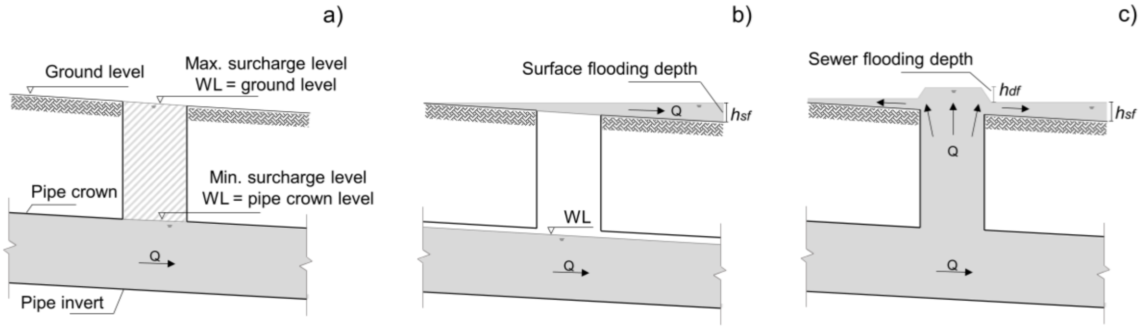

Figure 2.3 *Flow interaction between the minor and major drainage systems: a) surcharge condition in the pipe-ended system; b) surface flooding without surcharge condition; and c) combination of sewer and surface flooding, based on Maksimović et al. (2009) and Schmitt et al. (2004)*

As previously discussed, pluvial floods are greatly influenced by the urban environment, where the maximum discharge of the minor drainage system, the infiltration capacity of the major drainage system, and storm intensity all play a role. Furthermore, in developing contexts, constant urban sprawl (Jha et al., 2012) and poor waste management (Lamond et al., 2012) reduce local soil permeability and drainage system operation, increasing flood exposure. For this reason, and considering the challenges posed by sustainable urban development, urban stormwater management has evolved beyond the simple removal of overland water to more holistic, multi-objective approaches (Chocat et al., 2007; Fletcher et al., 2015).

The concept of 'nature-based solutions (NbS)', defined as "*solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience*" (European Commission, 2015), has been identified as an umbrella term for integrated UDM strategies such as BMP, GI, LID techniques, sponge cities, SUDS, and WSUD (Cohen-Shacham et al., 2019; Ferrans et al., 2022; Q. Zhou, 2014). Although all this terminology has grown in popularity since the 1970s, with more frequent use in developed contexts, indigenous peoples and local communities in Peru, Ecuador, and southern India have used traditional nature-based technologies (e.g., infiltration basins) for thousands of years to collect and infiltrate runoff (Cassin & Ochoa-Tocachi, 2021).

Nevertheless, the use of this *jargon* has enabled the systematization of small- and large-scale SUDM adoption, as well as the communication of objectives and benefits (Fletcher et al., 2015; Qiao et al., 2018). According to Davis & Naumann (2017), SUDS are a type of NbS that employs multiple natural processes to reduce runoff volumes and minimize downstream flood risks. Hence, considering the main focus of this thesis on urban drainage, the SUDS concept was adopted due to the extensive research and evidence that exists as complementary systems to traditional gray infrastructure (D'Ambrosio et al., 2022; Everett et al., 2016; Ferrans & Temprano, 2022; Fletcher et al., 2015; Gimenez-Maranges, Breuste, et al., 2020; Paredes, 2018; Potter & Vilcan, 2020; Raimondi et al., 2021; Viavattene & Ellis, 2013). Furthermore, while the SUDS term was coined in the UK, this approach has been widely adopted across Europe, with notable developments in regulatory frameworks, decision-making tools, public-private partnerships, and planning, design, and construction guidelines (Charlesworth et al., 2013; Davis & Naumann, 2017; Q. Zhou, 2014). The following section describes the operating principles, typologies, and gaps in knowledge of SUDS.

2.1 Sustainable urban drainage systems (SUDS): a novel alternative in urban drainage management

SUDS are multi-objective stormwater management tools, and their operation is based on four fundamental pillars (Figure 2.4): runoff quantity control, water quality enhancement, biodiversity augmentation, and amenity provision (Woods et al., 2015). This thesis is focused on the former one because of its direct relationship to UDM.

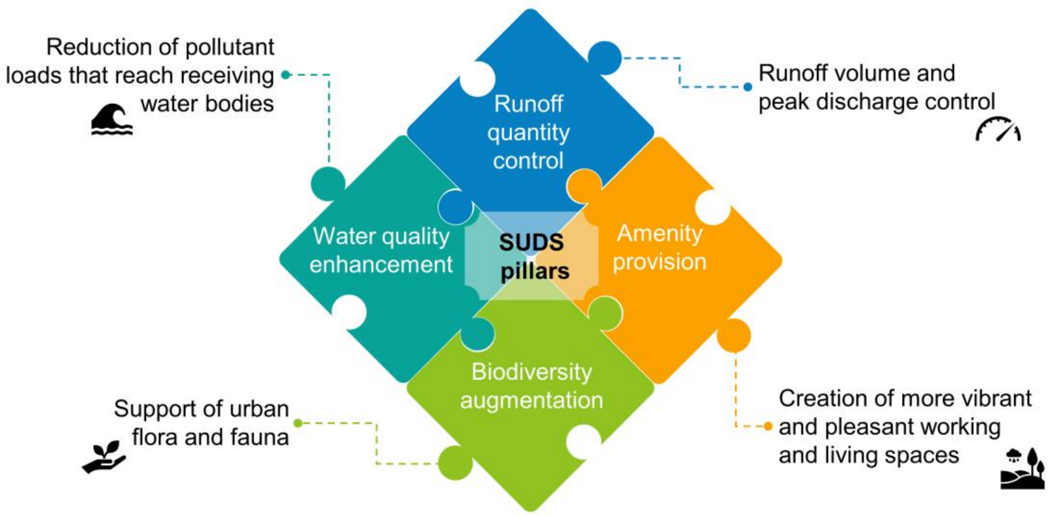

***Figure 2.4** SUDS pillars, based on Woods et al. (2015)*

SUDS design for stormwater runoff management can be addressed via conveyance, infiltration, retention, and storage. Therefore, there are multiple SUDS typologies that can be implemented in new developments and retrofits. Table 2.1 summarizes the different typologies and their main operating mechanisms, and Figure 2.5 depicts some examples of implementation.

Table 2.1 *SUDS typologies and stormwater runoff management mechanisms (based on Woods et al., 2015)*

SUDS typologies	**Mechanisms of stormwater runoff management**			
	Conveyance	Infiltration	Retention	Storage
Attenuation storage tanks			x	x
Bio-retention systems	x	x	x	
Constructed wetlands				x
Extended dry basins		x		
Green roofs			x	
Infiltration basins		x	x	
Infiltration trenches	x	x		
Pervious Pavements	x	x		
Ponds				x
Rainwater harvesting systems			x	x
Tree pits		x	x	
Vegetated swales	x			

Figure 2.5 *SUDS examples: a) bio-retention system in Soacha (a neighboring town of Bogotá) and b) prototype green roofs at the Universidad de los Andes, Bogotá*

The hydrologic control capacity of SUDS, i.e., runoff volume and peak discharge reduction, has received extensive attention (Alves et al., 2016; Ellis & Viavattene, 2014; Gimenez-Maranges, Breuste, et al., 2020; Loc et al., 2015; Webber et al., 2020). This potential is largely influenced by rainfall characteristics (magnitude and intensity), land-use distribution, percentage of imperviousness, and slope of the study area (Flores et al., 2015). For instance, a study assessing rainwater harvesting systems (RWHS), also known in the literature as rain barrels or cisterns, reported peak runoff reduction efficiencies of up to 93% under a design storm with a 50-year return period (V. Chen et al., 2021). Another study evaluating pervious pavements (PP), RWHS, and bio-retention systems (BRS), reported individual annual runoff reduction efficiencies ranging 3-40% and between 16-47% when practices were combined (Ahiablame & Shakya, 2016).

These studies accounted for multiple site-specific constraints and demonstrated the potential of SUDS to manage stormwater runoff quantity.

Although SUDS are complementary strategies rather than substitutes for the existing drainage network, the interaction between SUDS and the pipe-bound system is often neglected or generalized (Cui et al., 2019), affecting the assessment of SUDS potential in study areas with high urbanization levels. Few studies have demonstrated the hydraulic control capacity of SUDS. For instance, Movahedinia et al. (2019) evaluated the nodal flood reduction capacity of RWHS, BRS, and a combination of both under design storms of 2-, 5-, and 10-year return period, and evidenced efficiencies ranging from 25 to 100%. Furthermore, Cui et al. (2019) assessed the efficiency of PP and BRS and noticed a better impact on the reduction of surcharged pipes and ponding roads with small return periods and short-duration storms. These studies highlighted the importance of evaluating SUDS' hydrologic-hydraulic control capabilities to achieve informed sustainable urban water planning and efficient pluvial flood risk management. This is why research on more reliable modeling approaches that are also less computationally restrictive is necessary.

An additional gap in SUDS research has been fittingly addressed by the question posed by Marlow et al. (2013): "*Why [sustainable urban water management] SUWM concepts are so strongly supported in the academic literature, but still remain a niche innovation from the perspective of broader infrastructure provision [?]*." Surprisingly, this is true not only in developing contexts, where there are greater technical and financial limitations, but also in more developed environments (L. Li et al., 2020; Wihlborg et al., 2019). Scholars have tackled this concern from two perspectives: assessing the barriers, i.e., those factors that delay or block a wider adoption of SUDM strategies (Gashu & Gebre-Egziabher, 2019; Thaler et al., 2019), and identifying the benefits beyond the runoff quantity control, i.e., the elements that promote or encourage their implementation (Drosou et al., 2019; Raymond et al., 2017).

Both benefits and barriers are context-dependent, as is the implementation of SUDM strategies *per se*. In other words, applying one-size-fits-all models prevents the local needs of the site from being satisfied. The local context, i.e., the urban environment, involves a series of systems, subsystems, and actors that interact with each other (Fratini et al., 2012); therefore, the development of adaptive solutions within the framework of sustainable urban stormwater management requires holistic approaches that allow for successful long-term implementation.

In addition to the foregoing, stakeholders often refrain from assessing alternative UDM strategies (e.g., SUDS, BMP, LID techniques, or GI) due to unfamiliarity with the concept and lack of technical knowledge (Viavattene & Ellis, 2013), hence mainly supporting conventional solutions. To tackle this shortcoming, model-based evidence has emerged as a useful decision-making tool for quantifying the impact of SUDS on urban planning and assessing its feasibility (D'Ambrosio et al., 2022; Martínez et al., 2021).

According to the review performed by Ferrans et al. (2022), studies using modeling approaches to support SUDS selection, design, and location have primarily focused on water quantity, followed by water quality and economic analysis, and to a lesser extent, environmental and social benefits. Water quantity assessment, the focus of this thesis, is frequently accomplished using stormwater runoff models, which have been widely utilized as design, planning, diagnostic, and risk management instruments. The most common approaches in urban drainage modeling are described in the following section.

2.2 Urban drainage modeling

Numerical models are a powerful tool to understand the dynamics between the physical drainage system and the environment in a reliable and accurate manner (Rubinato et al., 2013). One-dimensional (1D) models are the most widely used approach due to their relatively simple construction, high efficiency, and shorter simulation run times (Chang et al., 2015). These models are based on two main modules: the rainfall-runoff module and the sewer-based module. One of most widely used hydrodynamic models for assessing urban stormwater dynamics is the US Environmental Protection Agency Storm Water Management Model (EPA SWMM5 or SWMM5) (Rossman & Simon, 2022), in which surface runoff outflow is given by Manning's equation, and flow routing within a conduit obeys Saint-Venant's continuity equation (Equation 2.1) and conservation of momentum equation (Equation 2.2) (James et al., 2010):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{2.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{2.2}$$

where x is the distance along the conduit, A is the cross-sectional area, t is time, Q is flow rate, H is the hydraulic head of water at the node, S_f is the friction slope, h_L is the local energy loss per unit length of the conduit, and g is the acceleration of gravity.

The main limitation of 1D models is their inability to accurately reproduce surface water accumulation and flooding processes (Pina et al., 2016). To overcome this, the first attempt at dual drainage modeling was the use of coupled 1D–1D models, in which the minor system remains the pipe-ended system whereas the major system is represented by a network of open channels and ponds (Djordjević et al., 1999). The interaction between the two systems is possible through weir- and orifice-type elements symbolizing stormwater inlets (Mark et al., 2004). Nevertheless, overland flow estimation in 1D–1D models involves a subjective definition of surface flow paths by the modeler, which sometimes may not realistically reflect overland flow processes (Maksimović et al., 2009).

The advancement of computational tools, the availability of high-quality data, and the inclusion of geographic information systems (GIS) have enabled the development of two-dimensional (2D) models, allowing for detailed overland flow description and flood propagation simulation through 2D grid cells. In 1D–2D models, the 2D free surface flow is solved by using the 1D Saint-Venant flow equations. One of the major benefits of coupled 1D–2D models is the realistic representation of flow-path modifying elements such as buildings, streets, and pavement curbs, as well as the dynamic flow exchange between the 1D and 2D domains (via inlet control bottom orifices or direct connections). This allows for the representation of backflow effects and flow transitions from sewer flows to overland flows (Vojinovic & Tutulic, 2009). However, despite the great advantage that coupled 1D–2D models represent in the analysis of urban runoff and floods, these approaches can be computationally expensive, prone to instabilities, and require high-resolution terrain data, which limits their reproducibility (Blanc et al., 2012; Maksimović et al., 2009; Yang et al., 2019).

As discussed in Section 2.1, SUDS analysis has focused on the hydrological response, which is fairly well achieved using rainfall-runoff models. SWMM allows explicit modeling of bio-retention cells, rain gardens (as bio-retention cells), green roofs, infiltration trenches, pervious pavements, rain barrels, rooftop disconnection (direct discharge to pervious landscaped areas), and vegetative swales (Rossman, 2015). These SUDS typologies (called LID controls in SWMM) are considered properties of a given sub-catchment (new or existing) and are represented by a combination of vertical layers (Figure 2.6) whose properties are defined on a per-unit-area basis. SWMM performs a moisture balance during a simulation to track how much water flows between and is stored within each LID layer (Rossman, 2015).

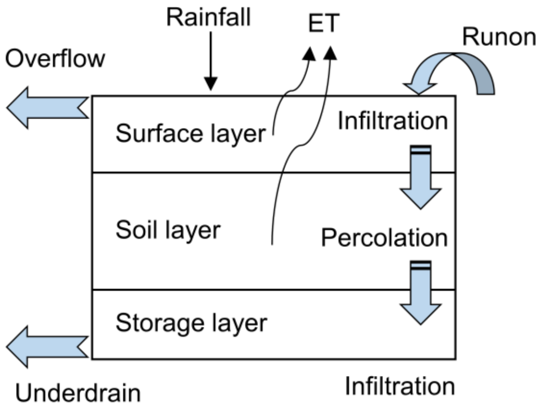

Figure 2.6 *Layer conceptualization of a LID control in SWMM (Rossman, 2015)*

Conversely, SUDS hydrological-hydraulic evaluation, comprehensively analyzing the interactions between the minor and major drainage systems, has most likely been compromised by the limitations of coupled 1D–2D models and the lack of commercial software extensions that allow for full inclusion of SUDS capabilities (Ellis & Viavattene, 2014). Therefore, there is a need for feasible modeling approaches that can be employed in data-scarce and resource-constrained places to support the assessment and implementation of SUDM strategies such as SUDS.

3 The need for inter- and transdisciplinary approaches in sustainable urban stormwater management

In the context of the UFRM decision-making process, urban environments are comprised of technical, natural, and social systems (Fratini et al., 2012). In this thesis, we take this framework of analysis a step back to address the sustainable management of urban stormwater (Figure 3.1) due to its direct relationship with the construction of flood-resilient cities, while also considering a wider application in the context of comprehensive urban water management. The natural system mainly encompasses the natural water cycle and all natural processes involving the city's water systems. The technical system consists of human-made UDM infrastructure, i.e., the minor and major drainage systems, whereas the social system is composed of all the individuals who are directly or indirectly involved in the urban stormwater decision-making process.

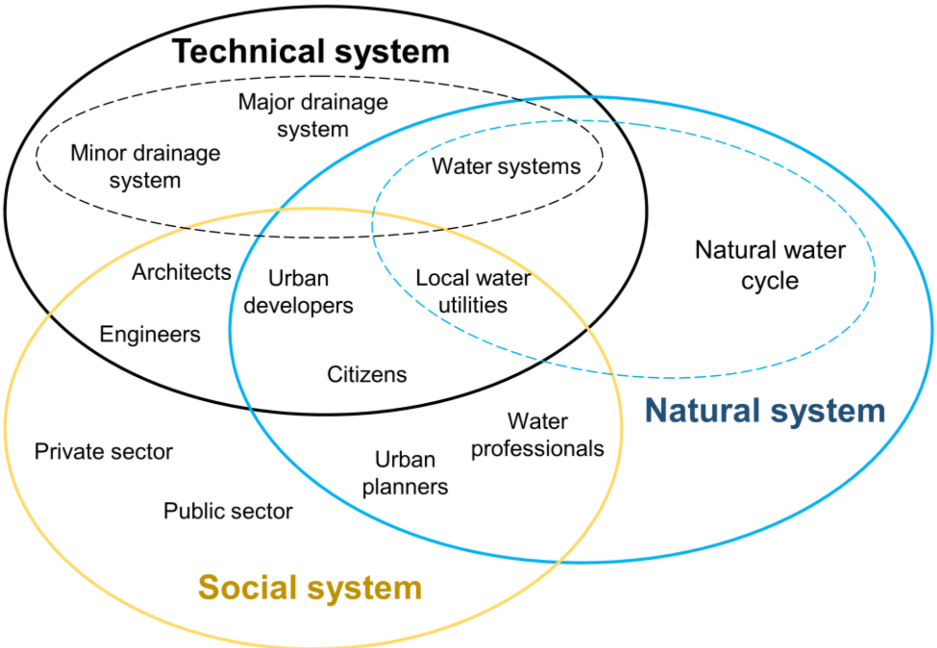

Figure 3.1 *Systems (solid lines) and subsystems (dashed lines) of sustainable urban stormwater management, based on Fratini et al. (2012)*

As seen in Figure 3.1, all these systems interact with each other; however, this understanding does not always translate from theory to practice. This is likely related to the prioritization of technical and natural systems, with the influence of the social system (of some sectors of it) being diminished. In the words of Brown et al. (2015), there is an "*inherent cultural hierarchy that often privileges the biophysical over the social sciences*." This shortcoming has highlighted the importance of inter- and transdisciplinary approaches not only in urban water management but also in the promotion of global sustainable development. Figure 3.2 illustrates the differences between these two concepts.

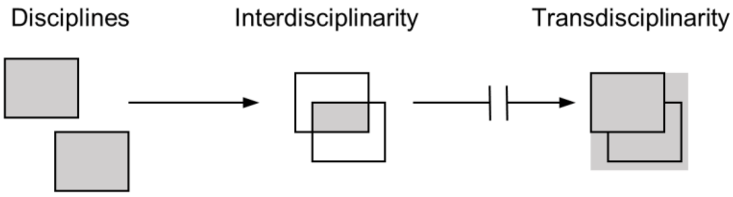

Figure 3.2 *Transformation of disciplines via inter- and transdisciplinary approaches, adapted from Ramadier (2004)*

In interdisciplinarity, an integration of conceptual and theoretical approaches from different disciplines takes place (Biber-Freudenberger et al., 2018). According to Ramadier (2004), there are two ways for this integration to occur. The first is that the employed disciplines submit to the principles of a particular discipline; in the second, the concepts of one discipline are appropriated by other disciplines. The call for interdisciplinarity in the field of SUDM and urban adaptation to climate change has been linked to the integration of different fields of knowledge, such as hydraulics, hydrology, urban studies, and geomorphology (D'Ambrosio et al., 2022), as well as the exploration of perspectives, opinions, and needs of the various stakeholders involved in the related decision-making process (Alves, Gómez, et al., 2018). In any case, interdisciplinary approaches have proven useful to develop and use new knowledge, which helps to bridge the socio-political and technical spheres (Carter et al., 2015; Grizzetti et al., 2016; Mulligan et al., 2020).

Transdisciplinarity, alternatively, is defined by several authors as a solution-oriented approach to addressing "real-world" problems (Jahn et al., 2012; Lang et al., 2012), such as urban flooding and sustainable stormwater management. According to Mauser et al. (2013), transdisciplinarity involves academic and non-academic actors whose integration occurs in three dimensions, i.e., scientific, international, and sectoral. In the scientific dimension of integration, both the exchange of knowledge and the incorporation of concepts and methods from different disciplines are encouraged. For its part, the international dimension strives to explore relevant knowledge at the local, national, and regional levels, whereas the sectoral dimension of integration addresses the co-production of knowledge involving political, institutional, market, and civil society stakeholders. This multidimensional integration is defined by other authors as a "*cross-fertilization of ideas*" (Avilés Irahola et al., 2022), which in the framework of urban water management has helped to bridge theory and practice, with incidence in policy-making (Collier et al., 2016).

The implementation of these approaches in the study of SUDM alternatives such as SUDS has revealed the great impact of socio-political factors in promoting this type of infrastructure (Bark et al., 2021; Hamlin & Nielsen-Pincus, 2021; L. Li et al., 2020; Perales-Momparler et al., 2015; Wihlborg et al., 2019). Furthermore, a balanced top-down and bottom-up approach has been pointed out as key to building community resilience and promoting innovation (Drosou et al., 2019; L. Liu & Jensen, 2018). This is why, in addition to addressing the SUDS' technical and natural aspects presented in Chapter 2, this research attempted to comprehensively include the influence of the social system.

The novelty of this dissertation lies in its distinctive approach, which integrates inter- and transdisciplinary thinking (Figure 3.3) to comprehensively assess the interactions of the three systems stated above in the study of sustainable urban drainage. The first manuscript (Chapter 5) examines the barriers to and benefits of SUDS implementation through the lenses of the public sector, urban developers, a private non-profit organization in the field of sustainable construction, and community members living in a flood-prone area in Bogotá, Colombia. Here, the application of an interdisciplinary approach is twofold: 1) from a practical point of view, by assessing the perceptions and needs of key social system actors, thereby enhancing understanding of their interactions with technical and natural systems; and 2) from a methodological point of view, by employing thematic analysis (a qualitative analysis tool) to explore a field typically subjected to quantitative examination, such as urban drainage, i.e., the concepts of one discipline are appropriated by another discipline.

Using the results of the first manuscript as input, the second manuscript (Chapter 6) transcends with the adoption of a transdisciplinary approach to develop a methodology that aids in the selection and location of SUDS by assessing physical restrictions and six types of local context limitations, i.e., cultural/behavioral, financial, institutional/organizational, technical, political, and urban form. Transdisciplinarity is reflected in 1) the co-production of knowledge involving academic and non-academic actors (*sectoral dimension*); 2) the participation of high-level SUDM experts (academics and practitioners) from six different regions around the world (*international dimension*); and 3) the use of tools from multiple disciplines such as specialized literature, GIS, fuzzy logic, and multi-criteria decision analysis (*scientific dimension*). This methodology was applied to evaluate the potential feasibility of SUDS on public and private land at the neighborhood level.

Subsequently, the hydrologic-hydraulic performance of the resulting SUDS strategies was assessed in the third manuscript (Chapter 7) through a comparative model-based approach considering a HD 1D model and a coupled 1D–2D model. Hence, paper number three employs a transdisciplinary approach by incorporating the findings of the two previous manuscripts both directly and indirectly, ultimately providing robust results to improve the decision-making process for sustainable urban stormwater management.

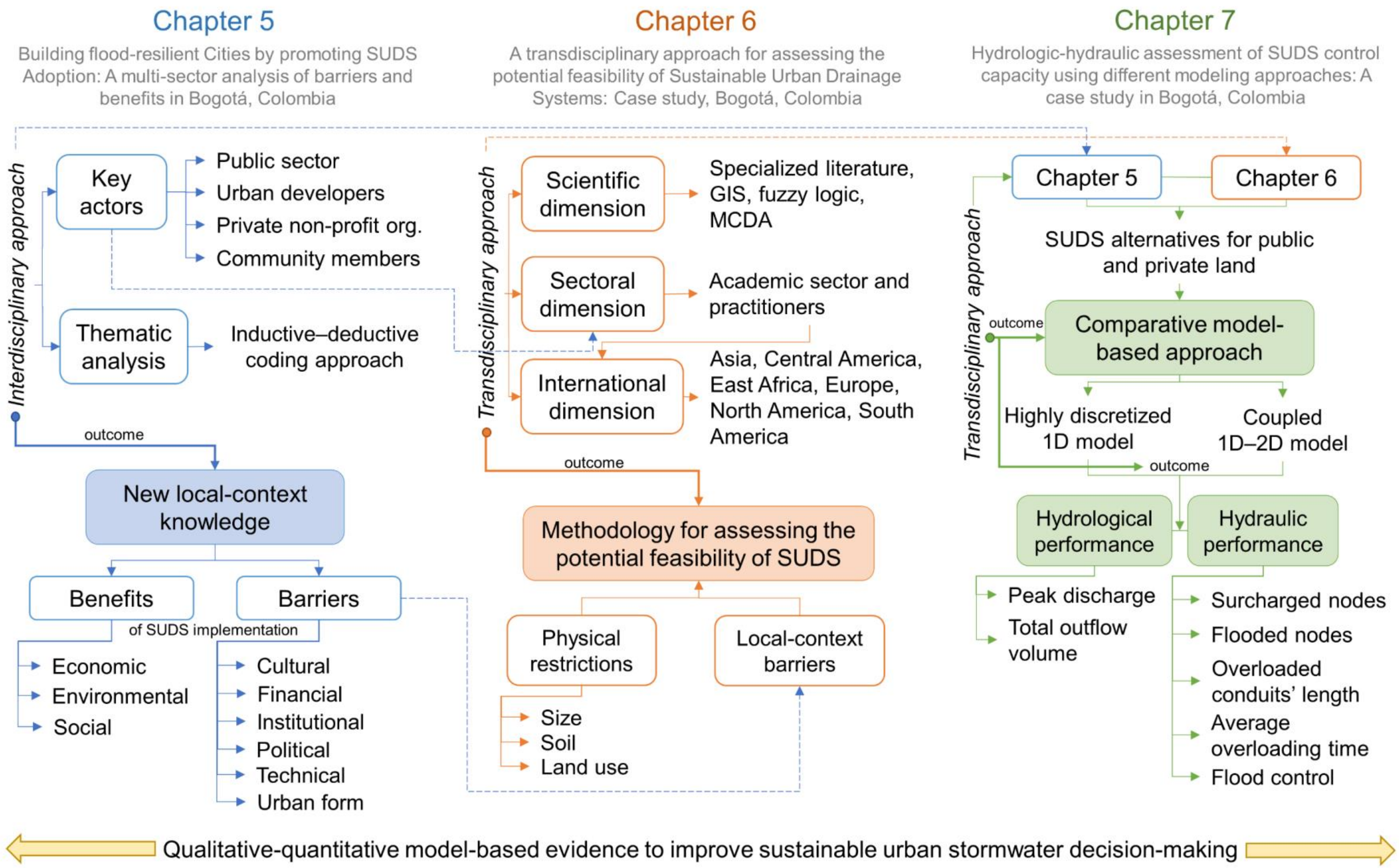

Figure 3.3 *Inter- and transdisciplinary approaches employed in this study to address qualitative and quantitative gaps in sustainable urban stormwater management*

4 Study area

The study of sustainable stormwater management in the context of Bogotá, Colombia's capital and largest city, is significant both locally and regionally. Climate, socio-spatial, and governance aspects combine to create an intriguing case study for promoting SUDM strategies such as SUDS in a developing context.

Bogotá, one of the most densely populated cities in the region and the world with 7 181 469 inhabitants (DANE, 2018), is located in the middle of the Andes Mountains, with elevations ranging from 2 510 to 3 780 MASL. The climate of Bogotá is categorized as cold–very dry, with a mean temperature of 13.1°C, and a mean annual total rainfall of 797 mm. The city has a bimodal climate: January-February and July-August are predominantly dry seasons, while the rainy season extends between March-June and September-December (Henríquez & Romero, 2019; IDEAM, 2014). Furthermore, Bogotá is affected by the occurrence of El Niño and La Niña phenomena that can occasionally generate significant changes in the normal precipitation and temperature regimes (IDEAM, 2005).

Before addressing the city's current hydrometeorological risks, it is necessary to understand its relationship with the surrounding natural water system. Bogotá was built on the flat land of the Bogotá River's eastern basin (Salazar Ferro, 2011). Since 1930, Bogotá's high-density compact development pattern has resulted in deterioration of the water systems, river channeling, and a drastic reduction of the original wetland system (IDIGER, 2018; Parés-Ramos et al., 2013; Rojas, 2018). Its geographical location at the foothills of the Andes has limited urban expansion, resulting in a striking phenomenon of densification and the development of informal settlements in peripheral low-lying river zones with additional geological problems (Salazar Ferro, 2011; Skinner, 2004). Furthermore, the city adds approximately 150 000 new residents each year as a result of natural growth and internal immigration, placing additional strain on land use and the natural water cycle. Unfortunately, rapid growth was not accompanied by institutional strengthening to effectively operate and manage the city (Salazar Ferro, 2011).

The city has been served by a separate sewage system since the mid-twentieth century. Bogotá’s urban stormwater management is based on the local natural drainage pattern, with three main basins draining about 90% of the current urbanized area, i.e., Salitre, Fucha, and Tunjuelo, and three additional basins that drain the northern, northwestern, and southwestern peripheral sectors, i.e., Torca, Jaboque, and Tintal (Figure 4.1). The final recipient of the entire city drainage system is the Bogotá River, whose floodplain, as well as that of its tributaries, have been heavily developed, resulting in rapid deforestation and uncontrolled expansion of impervious surfaces (IDIGER & SDP, 2021; Salazar Ferro, 2011).

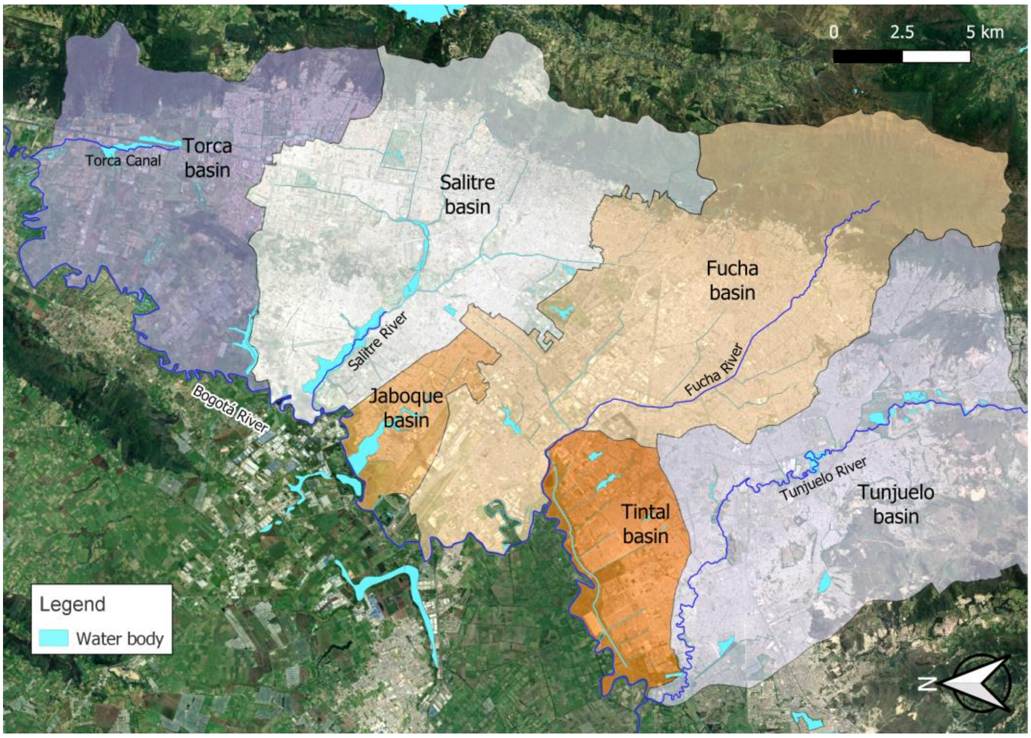

Figure 4.1 *Bogotá's drainage basins and water system*

In the last Land Management Plan (LMP) 2022-2035, Bogotá's Secretary of Planning and the Risk Management Office identified three types of flooding scenarios (IDIGER & SDP, 2021):

- Fluvial flooding scenario: it is caused by the progressive increase in river water depth levels due to persistent and widespread precipitation. From 2013 to 2018, the fluvial flood hazard in Bogotá decreased from 4.2% to 0.53% as a result of structural (e.g., river channeling and sewer system expansion) and non-structural (maintenance and awareness programs) measures for risk mitigation (IDIGER, 2018).
- River bank-collapse flooding scenario: corresponds mainly to emergencies caused by the failure of the Bogotá and Tunjuelo rivers' banks. Major river bank-collapse flooding implies overland water depths up to 50 cm and flow velocities under 0.20 m/s.
- Waterlogging scenario: it is characterized by overland water depths below 30 cm, produced by drainage network clogging, backflow effect, pumping system failure, and heavy rains superior to the design storm. Conceptually, this scenario is part of a pluvial flood scenario.

With the challenges posed by urbanization, population growth, and climate change, the adoption of SUDS has been on the table of the local administration since 2011 in order to "*enhance the water system's environmental value and contribute to the management of environmental risks associated with urban runoff*." (Secretary of Environment, 2011). Nevertheless, it was not until 2018 that SUDS began to play a greater role in the city through the design and construction guidelines issued by the local water utility (LWU), *Empresa de Acueducto y Alcantarillado de Bogotá (EAAB)*. These guidelines establish the technical aspects required to assess the feasibility of seven SUDS typologies (attenuation storage tanks, bio-retention systems, extended dry basins, infiltration trenches, pervious pavements, tree pits, and vegetated swales) as complementary structures to the conventional urban drainage system in terms of runoff volume control and water quality improvement (EAAB, 2018).

Furthermore, in 2019, Bogotá's Secretary of Environment, together with the Secretary of Planning, issued a regulatory instrument to encourage the adoption of SUDS (Secretary of Planning & Secretary of Environment, 2019). In general, when public infrastructure works are outsourced, the contractor must compensate for the loss of green space. The new compensation instrument includes the option of implementing SUDS to help fulfill the compensation quota more readily. Figure 4.2 depicts one of the Urban Development Institute's tree pits pilot projects, which adopts the compensation mechanism when executing works such as sidewalks, roundabouts, and lane dividers.

Figure 4.2 *a) Tree pit pilot project and b) maintenance performed by the Botanical Garden officials in Bogotá*

The most recent milestone in the promotion of SUDS on public land was the designation of evaluation, approval, and maintenance competencies, as specified in the LMP 2022-2035 (Bogotá's Mayor Office, 2021). For instance, the LWU is in charge of design approval, whereas maintenance of SUDS typologies with green cover was designated to the Botanical Garden and the Parks Management Authority. The maintenance of any type of SUDS implemented in private developments will be the property owner's responsibility.

This thesis was developed considering the previously discussed characteristics of climate, urbanization, drainage, and governance in Bogotá, as well as the city's commitment to sustainably face the challenges imposed by population growth, the loss of pervious surfaces, and climate change. Moreover, a neighborhood in Bosa, one of the

20 administrative divisions (*localidades*) of Bogotá (Figure 4.3a), was chosen for the qualitative and quantitative assessment of SUDS.

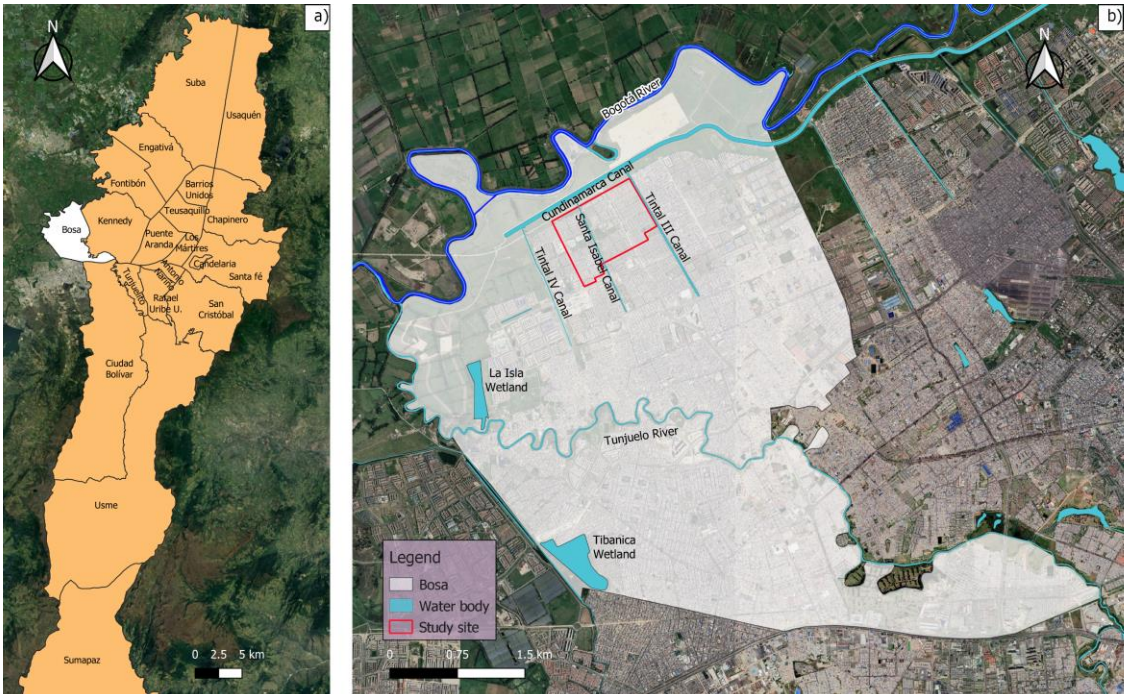

Figure 4.3 *a) Localidades of Bogotá and b) Bosa's main drainage system*

Bosa is located in a low-lying area to the south-west of the city, bordering the Bogotá River on this side (Figure 4.3b). This *localidad* was an agricultural and cattle land before being annexed to Bogotá in the middle of the twentieth century. The accelerated urbanization process taking place in Bogotá, especially between the 1950s and 1970s, exacerbated a demand for land that was covered by the occupation of wetlands and swampy areas of the city. In the case of Bosa, this occupation process occurred with the establishment of informal settlements, i.e., *barrios piratas* (pirate neighborhoods), outside the coverage perimeter of public service networks defined by the local administration (López-Ortego, 2021; Rojas, 2018; Skinner, 2004).

In response to this illegal market and the inherent housing needs, *Metrovivienda*, a public land bank, was created in 1999 to provide affordable alternatives for the low-income population, resulting in the displacement of this segment of society to the city's outskirts (Rojas, 2018). Thus, the construction of the first large social housing projects began in Bosa in 2000, namely, El Recreo and El Porvenir, each with 12 000 and 10 500 dwellings, respectively. These projects exposed the fragility of environmental protection mechanisms in favor of private interests, as evidenced by the reduction of Bogotá River's preservation zone from 300 m to 75 m (López-Ortego, 2021; Pinzón, 2014). Nonetheless, the establishment of informal settlements in flood-prone areas continued, and by 2005, 27% of Bosa's neighborhoods were illegal (Comisión Ambiental Local, 2012).

Parallel to the rapid urbanization process of Bogotá's western sector, the local administration proposed the construction of a separate sewer system. As a result, the current urban drainage system in Bosa (Figure 4.3b) is managed via the Río Tunjuelo and the Tintal basins. The latter is comprised of the Santa Isabel Canal, Tintal IV Canal, and Tintal III Canal, which run from east to west and end at the Cundinamarca Canal. These hard, human-engineered stormwater management approaches have resulted in socio-spatial segregation mechanisms within Bosa, whose infrastructure has not been designed to add recreational or environmental value to the community (López-Ortego, 2021). Subsequently, the stormwater is pumped 10 m through the Gibraltar Station to be delivered to the Bogotá River (Comisión Ambiental Local, 2012; Pinzón, 2014).

Bosa is one of the Bogotá's *localidades* with the lowest annual precipitation, i.e., 623-704 mm (IDEAM, 2005). Surprisingly, there is a latent hydrometeorological risk due to the fluvial flooding scenario posed by the Tunjuelo and the Bogotá Rivers (Comisión Ambiental Local, 2012; Sarmiento, 2020). The winter season at the end of 2011 exposed the challenges of Bosa's low-land nature and the aforementioned drainage system. Water depths and flows in the Bogotá River basin surpassed previously reported historical averages, gradually submerging the delivery and pumping systems. After a heavy rainfall event on December 6, the multiple canal system collapsed, causing a backflow effect that resulted in overland water depths (water-borne waste and stormwater) of up to 1.20 m. This emergency affected the *localidades* of Bosa and Kennedy; however, only in Bosa were approximately 6 000 properties affected, primarily in the urbanizations of El Recreo and Alameda del Río, another social housing project. Furthermore, according to interviews with EAAB technical officials, El Recreo is today considered a pluvial flood-prone sector with a permanent risk.

With 402 inhabitants per hectare (inhab./ha), Bosa has the greatest population density, compared to the city's average of 215 inhab./ha. During the field visits, disorganized urbanism, the presence of illegal settlements, green areas deficit, a preponderance of impervious surfaces, and the insufficiency of sewer and drainage systems were evident (Figure 4.4). These circumstances exacerbate Bosa's proclivity to fluvial and pluvial floods due to the increasingly reduced infiltration capacity of its natural soil.

Given the aforementioned socio-spatial and flood-prone conditions, Bosa's community was included in the multi-sector analysis of perceived benefits and barriers to SUDS implementation (Chapter 5). Furthermore, a study area belonging to El Recreo urbanization (Figure 4.3, delineated in red) was selected to analyze the potential feasibility of 12 different SUDS typologies (Chapter 6), as well as the hydrologic-hydraulic performance of rainwater harvesting systems and tree pits (Chapter 7). Bosa and the selected unit of analysis provide an insightful case study for qualitatively and quantitatively assessing the opportunities and challenges of SUDS as sustainable urban water management strategies.

Typical Bosa neighborhoods, with a predominance of impervious surfaces and a lack of green space.

Catchbasins are covered by community members due to unpleasant odors.

Figure 4.4 *Bosa's typical urban environment*

5 Building flood-resilient cities by promoting SUDS adoption: A multi-sector analysis of barriers and benefits in Bogotá, Colombia

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5.1 Abstract

In light of rapid urbanization and climate change, managing urban flood risk by combining traditional pipe-bound infrastructure with sustainable urban drainage systems (SUDS) has recently gained significant attention. SUDS provide a wide range of social, economic, and environmental advantages; nonetheless, there are perceptions, barriers, and benefits whose understanding is lacking, especially in the context of developing countries. To fill these gaps, a case study was conducted in the city of Bogotá, Colombia's capital city, systematically investigating the visions of four key actors, i.e., the public sector, urban developers, a private non-profit organization, and community members of a flood-prone area. Thematic analysis supported by an inductive–deductive coding approach was employed to analyze data collected from in-depth semi-structured interviews and questionnaires. After identifying and categorizing 39 barriers in Bogotá, technical and institutional/organizational barriers such as "operation and maintenance" and "unclear institutional responsibilities" prevailed over financial ones. The assessment of benefits yielded a total of 34 results and demonstrated the wide scope of SUDS strategies, ranging from "use of harvested water in secondary uses" to "promotion of environmental awareness" and "corporate image enhancement." Furthermore, there are direct relationships between barriers, benefits, and actors, strengthened by particular objectives, motivations, and needs. The findings of this study highlight the significance of interdisciplinary approaches to achieve comprehensive sustainable urban water planning and improved flood risk management. Further work on benefits quantification and participatory spatial-hydraulic modeling could foster SUDS interest, broadening the debate beyond the technical realm.

Keywords: climate change, flood resilience, inductive–deductive approach, interdisciplinary approach, sustainable urban water management, thematic analysis

5.2 Introduction

Urban flooding is a growing concern influenced by factors such as climate change (Charlesworth, 2010; Q. Zhou et al., 2013), urban growth (Abass et al., 2020; Pathirana et al., 2014), changes in land use (Arnone et al., 2018; Hussein et al., 2020), and mismanagement of spatial planning (Ran & Nedovic-Budic, 2016; Saber et al., 2020). In Colombia, additional geo-climatic and institutional factors, i.e., the La Niña/El Niño weather phenomenon and limited risk management capacity, have triggered unprecedented rain-related effects such as those evidenced in the 2011 floods, affecting more than three million people (Díaz, 2013; Jha et al., 2012). By 2050, 68% of the world's population is projected to be urban (UNDESA, 2019), and a greater concentration of people and infrastructure increases the exposure to flood risk (Park & Lee, 2019). Adverse impacts of flood events include loss of human life, economic damages, interruption of critical infrastructure, and environmental degradation (Hammond et al., 2013; Hilly et al., 2018). Therefore, there is a global challenge to find adaptative solutions to cope with multiple hydrometeorological hazards (Kumar et al., 2020) and the effects of human activities (Mori et al., 2021).

In this sense, researchers have proposed novel approaches for sustainable urban water management (SUWM) such as green infrastructure (GI), blue-GI (BGI), low impact development (LID) techniques, nature-based solutions (NbS), and sustainable urban drainage systems (SUDS) (Gimenez-Maranges, Pappalardo, et al., 2020; L. Liu & Jensen, 2018; Mguni et al., 2015; Miao et al., 2019; Pappalardo & La Rosa, 2020; Taji & Regulwar, 2019; Wihlborg et al., 2019). SUDS are multi-objective strategies for reducing runoff quantity, enhance stormwater quality, provide amenity, and increase biodiversity in urban spots (Woods et al., 2015). Attenuation storage tanks (AST), green roofs (GR), and rainwater harvesting systems (RWHS) are the most common SUDS typologies for residential, commercial, and public facility use (City of Edmonton, 2014). Other SUDS typologies that require more space and are thus better suited to outdoor land include bio-retention systems (BRS), constructed wetlands (CW), extended dry basins (EDB), infiltration basins (IB), infiltration trenches (IT), pervious pavements (PP), ponds (P), tree pits (TP), and vegetated swales (VS) (Jiménez et al., 2019). Depending on the scale and land use distribution, these strategies can be implemented on public or private land under an individual or interconnected (SUDS trains) scheme (Woods et al., 2015).

SUDS research has largely focused on technical aspects such as performance assessment, i.e., reduction of runoff volumes and flow peaks (Damodaram et al., 2010; Jia et al., 2012); selection, location, and size optimization (Alves et al., 2016; Jiménez et al., 2019); co-benefits evaluation (Alves, Gómez, et al., 2018; Majidi et al., 2019); and cost-benefit analysis (Johnson & Geisendorf, 2019). Furthermore, the study of SUDS has been led for several decades by developed countries such as Australia, Canada, the United Kingdom, and the United States (Fletcher et al., 2015). In contrast, developing countries have shown an incipient interest in the full spectrum of SUWM. For instance, pilot projects in Malaysia (Zakaria et al., 2003), Kenya (Mulligan et al., 2020), and Colombia (Jiménez et al., 2019) have stressed the importance of employing sustainable management of stormwater in tandem with pipe-bound systems, considering the particular challenges of unsustainable urban expansion, land tenure, and space constraints. Nevertheless, despite the evidence of the multiple advantages over conventional approaches, SUDS implementation has a slow pace and a weak overall interpretation, even in developed contexts (L. Li et al., 2020; Wihlborg et al., 2019).

It is still unclear which factors assist or hamper the integration of alternative stormwater management strategies in urban environments (Kim et al., 2017). Understanding the barriers allows for the identification of factors that delay the adoption of SUWM alternatives (Thaler et al., 2019), whereas assessing the perceived benefits enables one to recognize the particular needs of urban water-related sectors (G. Zhang & He, 2021). Several authors analyzing the context of developed countries claim that the transition to sustainable drainage approaches is hindered by socio-political rather than technical constraints (Brown & Farrelly, 2009b; L. Li et al., 2020; Thorne et al., 2018). Furthermore, a wide variety of benefits have been demonstrated, ranging from the well-known functions of runoff reduction and flood control (L. Li et al., 2020) to property value enhancement (Alves, Gómez, et al., 2018; G. Zhang & He, 2021). However, there is a lack of studies in other socio-economic and governance contexts.

Another factor that has been identified as critical for SUWM to achieve long-term effects is the involvement and participation of multiple stakeholders (Alves, Gómez, et al., 2018; Barbosa et al., 2012; D'Ambrosio et al., 2022; Sarabi et al., 2019). SUWM requires interdisciplinary approaches to integrate the visions of actors who often have conflicting interests (Alves, Gómez, et al., 2018) and to strengthen the related decision-making process (D'Ambrosio et al., 2022). The review performed by Sarabi et al. (Sarabi et al., 2019) identified four types of actors at micro-, meso-, macro-, and transboundary scales in the application of NbS that aid in the co-planning and co-management of this type of infrastructure. Furthermore, Venkataramanan et al. (2019) highlighted the use of interdisciplinary approaches to increase GI uptake, improve design, and provide a better understanding of the multidimensional benefits. Nevertheless, approaches to developing resilient solutions remain technocratic (Chelleri et al., 2016; L. Liu & Jensen, 2018), with few studies systematically investigating the diversity of opinions.

Considering the aforementioned gaps, this study aims to investigate the perceived barriers and benefits of SUDS implementation in Bogotá, Colombia, through the lenses of four key actors, i.e., the public sector, urban developers, a private non-profit organization, and community members living in a flood-prone area. The contribution of this research is threefold: i) expand the body of literature on factors that promote or stymie the transition to SUWM; ii) conduct a comprehensive assessment of experiences and knowledge from relevant urban water stakeholders; and iii) perform the analysis within the context of a developing city. To achieve this, semi-structured interviews and questionnaires were used as data collection methods, and thematic analysis supported by an inductive–deductive coding approach was employed to analyze the gathered data.

The remainder of the paper is structured as follows: Section 5.3 presents the rationale for the analysis of barriers and benefits of SUDS implementation based on a thorough review of the existing literature. In Section 5.4, we describe the case study, the participant sectors, and the data collection and analysis methods. Section 5.5 and Section 5.6 present the results and discussion of the multi-sector analysis of barriers to and benefits of SUDS implementation. The paper concludes with Section 5.7, which summarizes the findings and contributions of the study.

5.3 Barriers to and benefits of SUDS implementation

Understanding the barriers to and benefits of SUDS implementation is key to successful urban water planning, improved decision- and policy-making in flood risk management, and fostering large-scale adoption (Dhakal & Chevalier, 2017; Han & Kuhlicke, 2021; Kim et al., 2017; Mulligan et al., 2020; Wihlborg et al., 2019). The assessment presented in this study is based on an exhaustive literature review addressing these factors in the implementation of sustainable stormwater controls in urban environments such as GI, BGI, LID techniques, NbS, and SUDS.

Barriers are those factors that delay (Thaler et al., 2019), hamper (Kim et al., 2017), or block (Gashu & Gebre-Egziabher, 2019) the adoption of SUWM strategies. The identification and assessment of barriers allow for the anticipation of challenges that may arise during the planning or implementation stages (Deely et al., 2020). Previous studies addressing the barriers to implementation of BGI (Drosou et al., 2019; Thorne et al., 2018; Wihlborg et al., 2019), LID techniques (Kim et al., 2017), and SUDS (Andrés-Doménech et al., 2021) have listed multiple constraints and evidenced the need to classify them to achieve an accurate understanding. Such categorization is useful as many barriers are systemic or embedded in organizational cultures (O'Donnell et al., 2017).

The present study adopted six categories to classify the barriers to SUDS implementation (Table 5.1): cultural/behavioral, financial, institutional/organizational, political, technical, and urban form. Cultural/behavioral barriers reflect individual beliefs or perceptions, derived from a local context of time and space (Gashu & Gebre-Egziabher, 2019). Financial barriers involve constraints associated with financing and the costs of SUDS implementation (Drosou et al., 2019; O'Donnell et al., 2017). Institutional/organizational barriers stem from institutional dynamics, whether inter-governmental or inter-departmental (Johns, 2019), whereas political barriers are derived from government decisions or positions (Han & Kuhlicke, 2021; Wihlborg et al., 2019). Technical barriers are related to the planning, implementation, and operation of SUDS (Gashu & Gebre-Egziabher, 2019), whereas urban form barriers refer to the built environment hindrances (Johns, 2019). As observed, barriers to SUDS implementation cross multiple fields of knowledge (Deely et al., 2020) and may be related to or stem from one another (Dhakal & Chevalier, 2017; Mguni et al., 2015). Full descriptions and references for each barrier are listed in Supplementary material, Table S1.

On the other hand, the benefits of implementing SUWM strategies represent factors that influence greater adoption (Drosou et al., 2019), prominent drivers to promote upscaling interventions (Raymond et al., 2017), and aspects that should be considered to achieve a successful multifunctional design (L. Li et al., 2020). Literature addressing the benefits of GI (Alves, Gómez, et al., 2018; L. Li et al., 2020), NbS (Raymond et al., 2017), and

SUDS (Jiménez et al., 2019; Johnson & Geisendorf, 2019) has highlighted a wide range of advantages, beyond stormwater runoff control and flood management. Numerous studies have employed the ecosystem services categorization (provisioning, regulating, supporting, and cultural) (TEEB, 2020) for the assessment and valuation of these benefits (Johnson & Geisendorf, 2019; Uribe-Aguado et al., 2022; Vogel et al., 2015). Nevertheless, commercial, market-related, or economic advantages may lag behind under this classification.

Table 5.1 *Barriers to SUDS implementation*

Category	Barriers to SUDS implementation
Cultural/behavioral barriers	Lack of community ownership
	Lack of interest in SUDS
	Lack of private sector engagement
	Negative SUDS perceptions
	Path dependency
	Silo mentality
	Uncivil behaviors
Financial barriers	Financial burden
	Lack of financial resources
Institutional/organizational barriers	Inflexible and conflicting rules
	Lack of consultation
	Lack of design standards and guidance
	Lack of institutional coordination/communication
	Lack of supportive policy and legal framework
	Lack of regulatory binding instruments
	Position of power of the water utility
	Responsibility vs. authority dilemma
	Unclear institutional responsibilities
Political barriers	Electoral/administrative changes
	Lack of political leadership/will
Technical barriers	Diverse interpretations of the SUDS concept
	Efficiency uncertainty
	Lack of general knowledge
	Lack of local experience/benchmarks
	Lack of operational capacity
	Lack of quantitative evidence/performance information
	Lack of technical capacity
	Operation and maintenance
	Space constraints
	Workload that SUDS demand
Urban form barriers	Private land ownership
	Public land ownership
	Urban densification

The present study adopted a three-dimensional categorization of SUDS benefits (Table 5.2) in accordance with the three dimensions of sustainability (Alves, Gómez, et al., 2018; Drosou et al., 2019; L. Li et al., 2020): economic, environmental, and social. The economic benefits consider any type of cost reduction triggered by the implementation of SUDS (Ossa-Moreno et al., 2017). The environmental benefits refer to the improvement of biodiversity and ecological resilience (L. Li et al., 2020). Social benefits refer to the promotion of well-being and a healthier lifestyle for users (Raymond et al., 2017). The multifunctionality of SUWM strategies allows these benefits to occur in parallel; however, it should be noted that the classification shown in Table 5.2 is not intended to be universal but rather an indicator of the benefits that may be more evident. Full descriptions and references for each benefit are listed in Supplementary material, Table S2.

Table 5.2 *Benefits of SUDS implementation*

Benefits of SUDS implementation	**Type of benefit**		
	Economic	Environmental	Social
Air quality enhancement			X
Amenity			X
Aquifer recharge		X	
Biodiversity augmentation		X	
Climate change adaptation and mitigation	X	X	X
Decentralized water supply	X	X	X
Flood risk mitigation	X		X
Health and well-being improvement			X
Heat resilience	X		X
Noise reduction			X
Peak flow reduction	X		X
Promotion of ecosystem services		X	X
Promotion of environmental awareness		X	X
Promotion of multifunctional spaces	X	X	X
Recreation opportunities	X		X
Reduction in water treatment costs	X		
Runoff volume control	X		X
Stormwater management		X	
Tax reduction	X		
Use of harvested water in secondary uses	X	X	X
Water quality enhancement	X	X	X

The preceding list of barriers and benefits, as well as their respective categories, laid the foundation of this study. Nevertheless, since these two factors are highly dependent on the local context, it is natural for additional barriers and benefits to emerge during the analysis process, as will be demonstrated in the following sections. Therefore, this research contributes not only to the regional SUWM debate in cities with similar socio-economic and governance characteristics but also to the comprehensive participatory planning of urban environments in other contexts.

5.4 Methods

The multi-sector analysis of barriers to and benefits of SUDS implementation was conducted in the context of Bogotá, the capital city of Colombia. Data collection methods included semi-structured interviews and questionnaires, whereas thematic analysis supported by an inductive–deductive coding approach was employed to analyze the gathered data.

5.4.1 Case study description

Bogotá is Colombia's capital and largest city, with a population of 7,181,469 inhabitants (DANE, 2018). It is one of the Latin American metropolises, along with Buenos Aires, Mexico City, Santiago, and São Paulo, sharing similar features of urban growth, informal employment, and land privatization (Henríquez & Romero, 2019). Nonetheless, the urbanization process of Bogotá has been different compared to Lima and Quito, owing to its high-density compact development pattern (Parés-Ramos et al., 2013). Its geographical location at the foothills of the Andes has limited urban expansion, resulting in a striking phenomenon of densification (Salazar Ferro, 2011; Wessels et al., 2012) and the development of informal settlements in unsuitable construction areas (Salazar Ferro, 2011). These characteristics, intensified by the population growth pressure, have negatively impacted 80% of the wetlands in the city (Salazar Ferro, 2011) and, consequently, approximately one million people live in flood-prone areas (Rojas, 2018).

The climate of Bogotá is categorized as cold–very dry. The mean temperature is 13.1°C, and the mean annual total rainfall is 797 mm (IDEAM, 2014). The city has a bimodal climate with two dry seasons (January–February and July–August) and two rainy seasons (March–June and September–December). In order to ensure compliance with national FRM regulations, since 2007 the local authorities have performed a series of conventional river flood controls, i.e., channeling, hydraulic adaptation, and expansion of sewerage coverage, managing to reduce the fluvial flood risk level (IDIGER, 2018). Nonetheless, the rainy season in December 2011, aggravated by the La Niña phenomenon, triggered the Fucha River backflow and several sewer system failures, affecting approximately 18,000 households (Comisión Ambiental Local, 2012). In addition, pluvial flooding and waterlogging events are recurrent in the second rainy season because of the limited capacity of the drainage network (IDIGER, 2021).

Although integration of SUWM in urban planning processes is slow-paced in the Latin American region (Henríquez & Romero, 2019), multiple strategies have emerged in Bogotá within the framework of the sustainable development goals (SDGs), climate change, and urban water management. For instance, the Local Secretary of Environment implemented in 2014 the Bogotá Sustainable Building Program, aiming to promote biodiversity preservation and the incorporation of native species into urban projects. In addition, decree 528 of 2014 together with decree 088 of 2017, have leveraged SUDS as sustainable stormwater drainage strategies. Furthermore, the local water utility issued regulations for the design and construction of SUDS in 2018. As a great local and national milestone, the most recent Bogotá land-use plan (a road map to plan and order the territory between 2022 and 2035) designated liability for the construction and maintenance of SUDS both on public and private land.

Considering the above, Bogotá represents a city committed to addressing the challenges of sustainability and climate change. Therefore, the assessment of barriers and benefits of SUDS implementation might aid other developing cities in the context of stormwater management, disaster resilience, and urban planning.

5.4.2 Selection of participants

Reflecting on the need to incorporate interdisciplinary approaches to foster a wider SUDS adoption (Alves, Gómez, et al., 2018; Barbosa et al., 2012), the multi-sector analysis considered the participation of the public sector, urban developers, a non-profit organization, and members of the community.

The selection of the public sector interviewees considered the hybrid governance structure described by Van de Meene et al. (2011) to achieve an effective transition to SUWM. This incorporates three different approaches, i.e., hierarchical, network, and market governance, combining the provision of a formal administrative framework, interdisciplinary collaboration, and the efficient use of resources, respectively. In this way, local institutions/authorities with capacities in one or more of the previously described approaches were identified based on official information on SUDS pilot projects in Bogotá. A snowball sampling approach (Forrest et al., 2020; Giordano et al., 2020) allowed for the validation of this initial list. Then, a mapping exercise was performed through a two-dimensional matrix (De Lopez, 2001; Maskrey et al., 2016), linking the institution's potential to foster SUDS implementation and its influence on the related decision-making process. Figure 5.1 displays all assessed public stakeholders, i.e., the Local Secretary of Environment (LSE), the Local Secretary of Planning (LSP), the Local Water Utility (LWU), the Urban Development Institute (UDI), the Urban Development and Renovation Company (UDRC), and the Local Institute for Risk Management and Climate Change (IRMCC). Of the four relevant SUDS management bodies, contact was possible with the LSE, LWU, and UDI.

At the private sector level, this study focused the analysis on urban developers due to their influence on city planning and development (Jerome et al., 2019) and because the adoption of SUWM alternatives remains a challenge within this type of stakeholder (Connop et al., 2016). The invitation to participate was extended to five large companies, the most influential locally and nationally, but only three were confirmed. Furthermore, the Colombian Green Building Council (CGBC), a private non-profit organization with high national and international influence in urban planning and sustainable construction, was contacted.

Several authors have highlighted the necessity of addressing SUWM through a balanced top-down and bottom-up approach (Drosou et al., 2019; L. Liu & Jensen, 2018). Understanding the perceptions, motivations, and needs of the community is key to exploring opportunities for the co-creation and management of solutions (Lamond &

Everett, 2019), beyond the information-sharing role (Thaler et al., 2019). Therefore, members of a flood-prone community living in Bosa, one of the 20 administrative divisions (*localidades*) in Bogotá, were contacted for participation in this study.

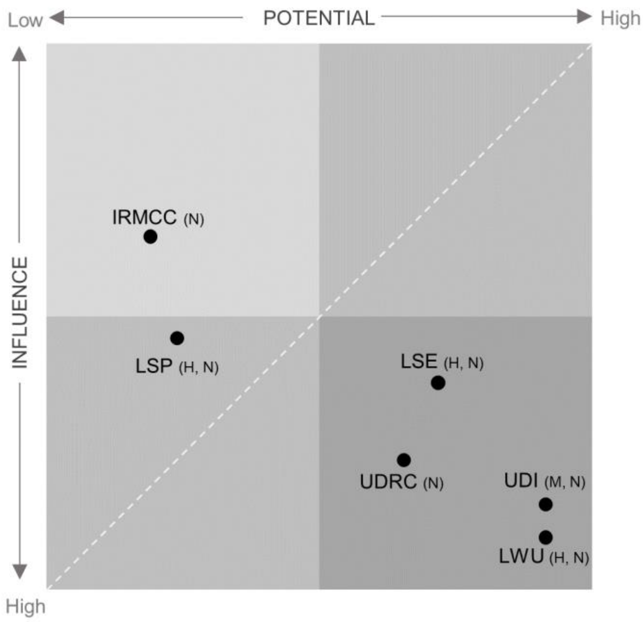

Figure 5.1 *Mapping of public stakeholders in Bogotá for SUDS management, including potential governance approaches (Van de Meene et al., 2011): H (hierarchical), N (network), and M (market)*

Since 2002, Bosa has had the highest concentration of people affected by flood events due to the poor performance of the drainage system and the direct influence of the Tunjuelo River, one of the tributaries of the Bogotá River (IDIGER, 2018). In addition, in 2012, 89.14% of the dwellings belonged to strata 2 (Galindo, 2013), a socio-economic classification that relates people's quality of life to the quality of the home they live in, with 1 being the lowest category and 6 the highest. The convergence of these socio-economic and risk conditions points to an imminent need to evaluate novel FRM strategies that consider local context characteristics and community perceptions.

5.4.3 Data collection

Semi-structured interviews

This study employed online in-depth semi-structured interviews with the public sector representatives (LSE, LWU, and UDI), the three urban development companies, and the private non-profit organization in the field of sustainable construction (CGBC). Interviews are one of the most common qualitative data collection methods, widely used in different disciplines, offering participants the opportunity to express themselves and discuss their opinions in an out-of-ordinary context (Mack et al., 2005). Following social distancing protocols based on COVID-19 restrictions, the use of video conference platforms is suitable for the approach, allowing data collection in real time, even with multiple participants in different locations (Torrentira, 2020). The semi-structured interviews in this study were conducted through the Zoom platform under the license acquired by the University of Bonn, allowing recordings and meetings for more than 40 min (the limit for free licenses). This technological consideration, along with stable connectivity (Roberts et al., 2021), was decisive for rapport building by allowing communication without involuntary time constraints and focusing on participants' attention.

All semi-structured interview participants were contacted via email first, and after acceptance, time was scheduled at their convenience and informed consent was sent. All interviews were conducted in Spanish, audio-recorded using a digital voice recorder (Sony ICD-PX470), and video-recorded with the Zoom feature as an additional backup with the participants' consent; field notes were taken simultaneously. Semi-structured interviews (*n = 10*), individual and in groups, were conducted between November 2020 and March 2021, lasting 40–96 min, with the participation of 15 interviewees. A set of open-ended questions was asked, along with prompts and follow-up questions, allowing participants to explore details that had not been initially elicited (Everett et al., 2018). Questions to public sector interviewees sought to understand FRM competencies, SUDS knowledge, perceived benefits and barriers, and current regulations. Urban development companies were inquired about management strategies within the framework of the SDGs, green building certifications (GBC), strategies to mitigate land-use changes, SUDS knowledge, perceived benefits and barriers, and regulation awareness. The interview with the GCBC sought to understand its competencies, partnerships, GBC processes, SUDS knowledge, common SUDS strategies in construction projects, and perceived barriers and benefits.

The visual aid was employed to facilitate the recognition of SUDS typologies. Details of the interviews are presented in Table 5.3, along with the alphanumeric codes for participant identification to maintain confidentiality.

***Table 5.3** Semi-structured interview details*

Date	Key actor	Sector	Interviewee code	Position/Department
19-11-2020	Colombian Green Building Council	Private non-profit organization	PR1	Technical director
			PR2	Technical leader
27-11-2020	Local water utility	Public sector	PU1	Specialized Engineer
30-11-2020	Local water utility	Public sector	PU2	Specialized Engineer
14-12-2020	Urban development company #1	Urban developer	UD1	Planning department director
			UD2	Planning coordinator
			UD3	Technical specialist
15-01-2021	Local Secretary of Environment	Public sector	PU3	Specialized Engineer
21-01-2021	Urban development company #2	Urban developer	UD4	Vice President of Innovation and Operations

21-01-2021	Urban Development Institute	Public sector	PU4	Specialized engineer and SUDS specialist
25-01-2021	Urban development company #2	Urban developer	UD5	Special business manager
28-01-2021	Urban development company #3	Urban developer	UD6	Urban development director
			UD7	Project manager
			UD8	Development manager
20-03-2021	Local water utility	Public sector	PU5	Social management coordinator

Questionnaires

In this study, questionnaires were distributed in person to members of a flood-prone community living in Bosa. Before the pandemic, this study had conceived FGD to collect data from the community sector. Nonetheless, considering COVID-19 regulatory constraints, a questionnaire technique was implemented outdoors, complying with all distancing and hygiene protocols. Although questionnaires are a quantitative research technique, their implementation with open-ended questions was intended to reflect the plurality of visions rather than show statistical significance (Carriquiry et al., 2020).

Initial contact with the Bosa community started via email through the Bosa Mayor's Office, giving a brief introduction to the project and inquiring about existing environmental community-led initiatives. Then, at the invitation of a spokesperson, questionnaires were distributed on April 3, 2021, as part of the closing event of an official project called “Huertas Urbanas” (Urban Farms). Community attendance was not as expected, so most of the participants interviewed (*n = 13*) were part of the organizing staff of the event, who were also local residents. The questionnaire was written in Spanish and included 19 questions comprising background information, multiple-choice, and open-ended questions (Aceves & Fuamba, 2016b; Drosou et al., 2019) to capture local knowledge about flood experiences, flood risk awareness, SUDS knowledge, and perceived benefits and barriers to implementation. Conversations were voice recorded with the informed consent of each participant, and field notes were taken simultaneously. Graphic materials were provided to recognize pre-selected SUDS. For anonymity, empirical evidence provided by the community participants was represented by alphanumeric codes ranging from C1 to C13.

5.4.4 Data analysis

We adopted thematic analysis (TA) supported by an inductive–deductive coding approach to analyze the data collected from semi-structured interviews and questionnaires. TA aims to identify, analyze, and report patterns (themes) within data (Braun & Clarke, 2006). It is a flexible yet rigorous approach that can be used to address most types of qualitative research questions (Braun & Clarke, 2013). TA has proven to be a robust and flexible method for drawing sound conclusions with implications for urban water decision- and policy-making (Bark et al., 2021; Davies et al., 2017; Drosou et al., 2019; Krkoška Lorencová et al., 2021). TA includes a coding process in which the data is organized into meaningful groups in a systematic fashion (Tuckett, 2005). This can be accomplished through a data-driven (inductive) approach when the themes depend on the data or through a theory-driven (deductive) approach, in which the researcher addresses the gathered information with specific questions in mind (Braun & Clarke, 2006). Since the successful integration of SUWM is strongly influenced by the study area context (Drosou et al., 2019), inductive–deductive reasoning serves to comprehensively address multi-stakeholder perspectives in data-scarce environments, nourished by local experience and knowledge and existing evidence from other contexts (Section 5.3).

All semi-structured interview and questionnaire recordings were fully transcribed verbatim after each session, supported by the field notes. These were edited to remove repetitions and irrelevant habitual phrases (Davies et al., 2017) while maintaining accuracy. The transcripts were analyzed using the foundational model of qualitative data analysis described by Kalpokaite & Radivojevic (2019), which combines an inductive–deductive coding approach. Atlas.ti version 9.1.7.0, a widely referenced text encoding software, was used for analysis (Drosou et al., 2019; Forrest et al., 2020; McEvoy et al., 2019). Figure 5.2 displays the followed steps. We started by developing a code book from existing literature (Johns, 2019) on barriers to and benefits of SUDS implementation (Table 5.1 and Table 5.2). A pre-coding process was performed to identify significant segments of the data. Then, a parallel process of initial coding and elaborative coding was performed, the latter with the aid of the code book. The “revision and grouping codes” stage is an iterative process in which the context of a code becomes relevant for its modification, elimination, or permanence within the final code list, whereas “focused coding” seeks to create data categories. After this process, network development allows visualizing links between codes. Memoing is an integral part of the entire coding process to keep track of decisions made during data analysis.

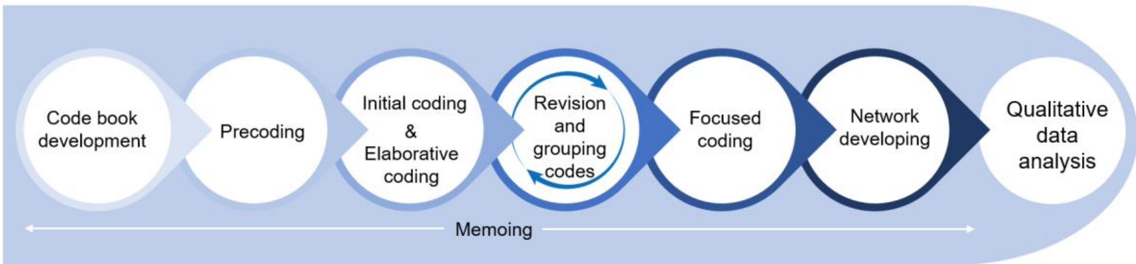

Figure 5.2 *Adaptation of the foundational model of qualitative data analysis from Kalpokaite & Radivojevic (2019)*

A complementary quantitative analysis of excerpt counts was also performed to determine the frequency with which a specific issue is addressed. This was intended to draw a topic’s relevance rather than participants’ position to it (Everett et al., 2018; L. Li et al., 2020).

5.5 Results

The exploration of perceived benefits and barriers related to SUDS implementation differed for each examined sector. Questionnaires conducted with community participants included questions inquiring about their perceptions about RWHS, GR, and BRS, as they are the SUDS typologies that best suit private land within a built environment. Semi-structured interviews with urban developers inquired about previous evaluation and implementation of eleven SUDS typologies previously analyzed in the context of Bogotá's public and private land (Jiménez et al., 2019), namely, AST, BRS, CW, GR, IB, IT, P, PP, RWHS, TP, and VS. In both cases, the open-ended question format allowed for the exploration of the reasons and motivations framing their perceptions. In the case of public sector representatives and the private non-profit organization, interviews did not explore specific SUDS typologies even though an open-ended question was asked inquiring about the most commonly used typologies based on the institution/company scope.

Direct quotations were used to provide robustness (Davies et al., 2017) and clarify key points made in relation to the selected themes (Braun & Clarke, 2006). After transcribing from the original Spanish, we did not attempt to change the grammar or expressions (Tseng & Penning-Rowsell, 2012). Respondents were identified alphanumerically, as described in Table 5.3 and *Questionnaires*. In some cases, the number of codings (excerpt counts) referring to a certain topic is also displayed in parentheses following this notation: (c = number of codings).

5.5.1 Analysis of perceived barriers

Barrier identification was enabled by a previously developed code book derived from the literature (Table 5.1) and when participants used statements that included words such as "affect," "barrier," "burden," "challenge," "complicated," "difficult," "dilemma," "doubts," "impossible," "inconvenience," "lack of," "limiting," "obstacle," "problem," "resistance," "unfortunately," and "worries" (O'Donnell et al., 2017). The inductive–deductive coding process yielded 39 barriers linked to 275 codings.

The distribution of barriers by category according to the inquired sectors is shown in Figure 5.3. Although the number of interviewees is heterogeneous among the participating sectors, this analysis is intended to portray the joint vision of four key sectors not only to foster SUDS uptake but also to improve understanding of SUWM, land-use, and built environment decision-making. Technical and institutional/organizational barriers received the most mentions, mostly from the public sector representatives and urban developers. Nonetheless, the analysis highlighted the significance placed on cultural/behavioral barriers, primarily by the public sector participants. Financial barriers, commonly considered as a great obstacle in sustainable-related projects, ranked fourth in the general analysis.

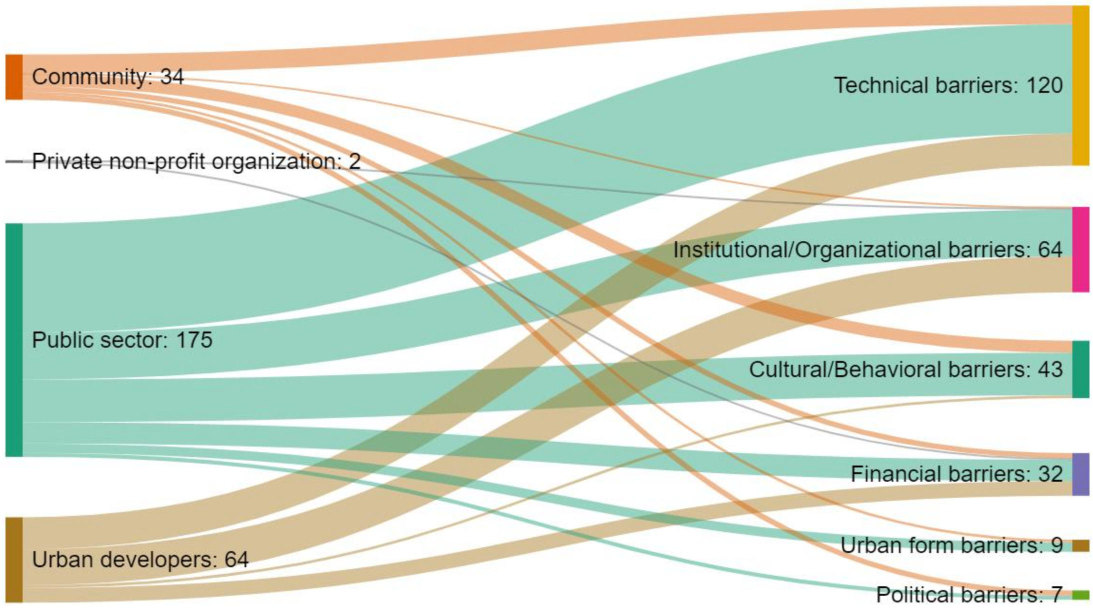

Figure 5.3 *Distribution of barrier codings by category according to the inquired sectors*

Community members and public sector professionals mentioned barriers in all six categories even though the number of total mentions differs from one sector to another, 34 and 175, respectively. Note that the public sector was represented by five interviewees from three different entities, whereas the community sector had the participation of 13 members. This suggests that when participants are more exposed to a given topic, the plurality of their opinions and perceptions increases. The data collection method may also be related to this phenomenon because, despite having a specific question to investigate the perceived barriers, the environment provided by the interviews to share individual experiences allows interviewees to explore additional information that may not have been initially considered (Louise Barriball & While, 1994).

Of the participants, professionals from the private non-profit organization made the fewest barriers references. This may be related to number of participants and to their consulting role in assisting the public and private sectors in developing public policies either for the built environment or new urban projects (PR1, PR2).

Table 5.4 summarizes the complete list of barriers and their respective excerpt counts. The thematic analysis allowed for the elucidation of six barriers that were not previously included in the code book, namely, “clogging effect,” “increase in water tariffs,” “indoor humidity conditions,” “performance reduction,” “risks to conventional drainage system performance,” and “waterlogging/inundation problems.” The following sections will examine the most relevant barriers and interconnections according to each participating sector.

***Table 5.4** Summary of barriers hindering SUDS implementation*

Category	Perceived barriers	C (*np=13*)	PR (*np=2*)	PU (*np=5*)	UD (*np=8*)	ec
Cultural/ behavioral barriers	Lack of community ownership	6	-	1	-	7
	Lack of interest in SUDS	2	-	-	1	3
	Lack of private sector engagement	-	-	3	-	3
	Negative SUDS perceptions	-	-	7	-	7
	Path dependency	-	-	4	-	4
	Silo mentality	-	-	9	-	9
	Uncivil behaviors	1	-	8	1	10
Financial barriers	Financial burden	-	1	9	11	21
	Increase in water tariffs	-	-	1	-	1
	Lack of financial resources	4	-	6	-	10
Institutional/ organizational barriers	Inflexible and conflicting rules	-	-	-	4	4
	Lack of consultation	1	-	-	-	1
	Lack of design standards and guidance	-	-	1	5	6
	Lack of institutional coordination/communication	-	-	6	-	6
	Lack of regulatory binding instruments	-	-	5	-	5
	Lack of supportive policy and legal framework	-	-	3	4	7
	Position of power of the water utility	-	1	7	3	11
	Responsibility vs. authority dilemma	-	-	7	-	7
	Unclear institutional responsibilities	-	-	6	11	17
Political barriers	Electoral/administrative changes	1	-	2	-	3
	Lack of political leadership/will	3	-	1	-	4
Technical barriers	Clogging effect	-	-	3	1	4
	Diverse interpretations of the SUDS concept	-	-	15	1	16
	Efficiency uncertainty	1	-	6	-	7
	Indoor humidity concerns	1	-	-	-	1
	Lack of general knowledge	5	-	3	2	10
	Lack of local experience/benchmarks	-	-	-	1	1
	Lack of operational capacity	-	-	4	1	5
	Lack of quantitative evidence/performance information	-	-	4	-	4
	Lack of technical capacity	3	-	6	1	10
	Operation and maintenance	-	-	21	14	35
	Performance reduction	-	-	3	3	6
	Risks to conventional drainage system performance	-	-	6	-	6
	Space constraints	3	-	2	-	5
	Waterlogging/inundation problems	-	-	2	-	2
	Workload that SUDS demand	1	-	7	-	8

Urban form barriers	Private land ownership	2	-	4	-	6
	Public land ownership	-	-	1	-	1
	Urban densification	-	-	2	-	2
	Total number of codings	34	2	175	64	275

C: community members; PR: private non-profit organization; PU: public sector representatives; UD: urban developers; np: number of participants; ec: excerpt counts

Perceived barriers by community members

As previously stated, community members mentioned barriers in all six categories. Interestingly, the most frequently reported barrier was the "lack of community ownership" (c = 6), followed by the "lack of general knowledge" (c = 5), which has cultural implications and may be related to the "lack of interest in SUDS" (c = 2). Public education and awareness campaigns may aid in addressing these limitations. It is noteworthy that knowledge dissemination is commonly relegated to SUDS champions, who mostly belong to academia or the public sector. This represents an opportunity to develop government-led initiatives not only to raise awareness but also to encourage further community participation in planning, implementation, surveillance, operation, and/or maintenance.

On the other hand, some participants also mentioned governance concerns related to the "lack of political leadership/will" (c = 3) and "electoral/administrative changes" (c = 1). In the words of participant C13: "there may be economic, institutional, and public resources, but if there is no political will, nothing can be done." This suggests a lack of trust in the local administration that can interfere with educational efforts and any public initiative. The provision of different communication channels may strengthen dialogue between these two types of actors.

Regarding the urban form barriers, two participants emphasized "private land ownership" issues, e.g., living under a horizontal property regime. This suggests that the analysis of SUDS' potential for private land such as GR or RWHS should consider not only the availability of private land but also land tenure implications. In turn, the "lack of financial resources" (c = 4) was accompanied by factors such as the "lack of technical capacity" (c = 3), "workload that SUDS demand" (c = 1), and "efficiency uncertainties" (c = 1), demonstrating the importance of knowledge in overcoming negative perceptions.

It should be noted that although participants were questioned about three specific SUDS typologies, i.e., RWHS, GR, and BRS, barriers such as "lack of community ownership," "uncivil behaviors," "lack of consultation," "electoral/administrative changes," and "lack of political leadership/will" can be considered hindrances preventing interest and participation in any type of project, whether it is a private initiative or a government-led program.

Perceived barriers by a private non-profit organization

The interview with the private non-profit organization was attended by two participants with high expertise in the field of sustainable construction practices. They discussed the financial burden that SUDS implementation may represent for urban developers because it is more difficult to increase the return on investment (ROI) of water-related strategies than it is for energy efficiency measures. According to PR1, since "water is unfortunately low-priced," it would be more effective to increase urban developers' interest from a normative perspective. It is worth noting that, at the national level, the water supply and sanitation regulations stipulate that new urban developments are required to mitigate the effect of soil imperviousness through the implementation of SUDS (Ministry of Housing of Colombia, 2021). However, this has exacerbated institutional barriers such as "inflexible and conflicting rules" (UD7) and the "responsibility vs. authority dilemma" (PU2).

The private non-profit organization's participants also mentioned the "position of power of the water utility" as a barrier: "When working with urban projects, the water utility is not so interested in being handed over SUDS vs. other types of water management structures" (PR1). This hindrance might be related to cultural/behavioral barriers such as "path dependency" and "silo mentality" that prevent the evaluation of SUWM strategies, coupled with a lack of technical knowledge. Some authors also refer to this as "risk aversion" or "resistance to change" (Sarabi et al., 2020). This appreciation was confirmed when interviewing one of the LWU representatives: "The conventional drainage system is designed to operate for a lifespan of 50 years; the equipment for its maintenance is already known. In the case of the SUDS, there is little knowledge" (PU1).

Perceived barriers by public sector representatives

As well as for community members, technical barriers received the highest number of mentions from the public sector (c = 82). Their considerations are primarily based on the short experience with local pilot projects and perceptions about future scenarios in which the implementation of SUDS is massive. In this sense, "operation and maintenance (O&M)" is the most concerning barrier among the LWU, LSE, and UDI. According to the co-occurrence analysis, O&M had direct links to eight additional barriers, as shown in Figure 5.4. These connections are supported by the interviewees' quotations (See Supplementary material, Table S3). Interestingly, O&M was related to cultural/behavioral, financial, institutional/organizational, and technical barriers, with the latter being the most influential.

From the perspective of the LWU, there is a lack of local-context quantitative evidence regarding O&M, which might be exacerbated by the "lack of financial resources" and scarce technical and operational capacity. Participants PU1 and PU2 were also concerned about the "workload that SUDS demand" if they were implemented as multiple localized systems throughout the city. This suggests a preference for large-scale measures.

Additionally, there was widespread distress regarding the "risks to conventional drainage system performance" as the LWU's responsibilities for the city's urban drainage might be compromised:

"If the construction, design, operation and maintenance of the drainage system of the city of Bogotá is LWU's responsibility, the LWU is also responsible for defining which of the technical alternatives are the ones that best fit a specific need. (…) SUDS in parallel must compete with other technical alternatives to solve the problem identified. This means that it is not placing SUDS for no reason, but rather a technical, operational, economic, social, and environmental evaluation should be made" (PU1).

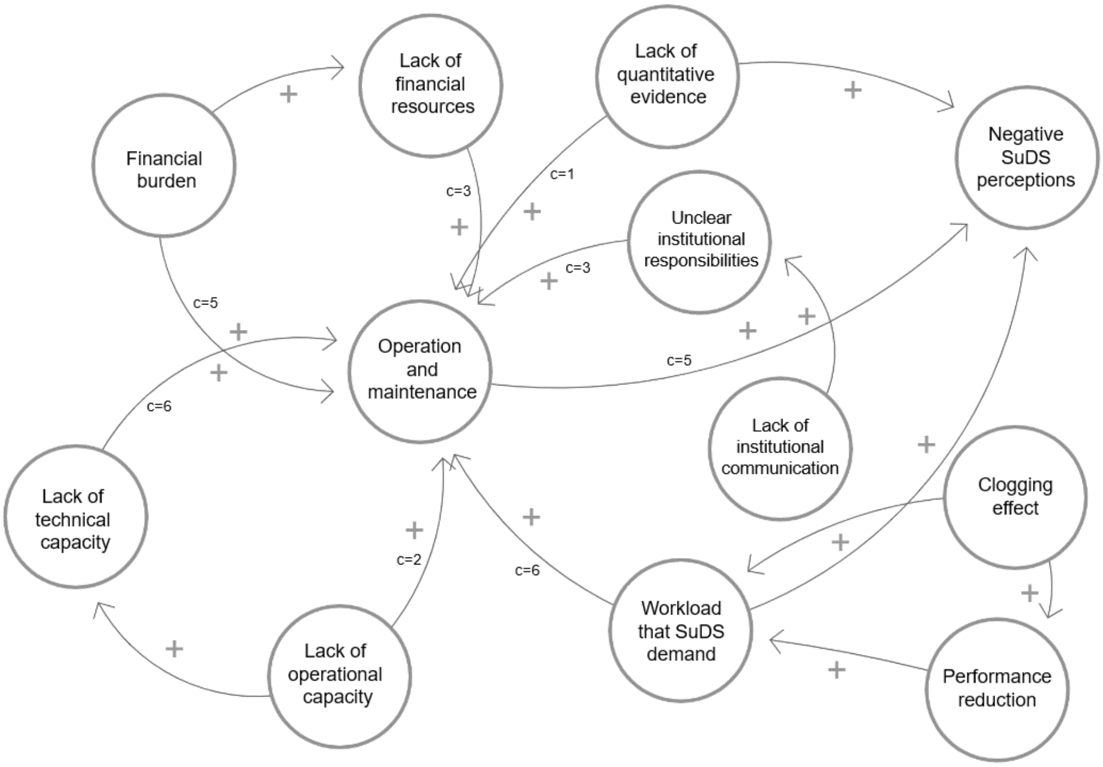

Figure 5.4 *"Operation and maintenance" barrier from the public sector's viewpoint*

LSE's and UDI's participants agreed that the LWU is reluctant toward SUDS due to O&M concerns, which have intensified institutional/organizational barriers such as "lack of institutional coordination/communication," "unclear institutional responsibilities," and "position of power of the water utility." For this reason, participant PU3 claimed the urgency of developing pilot projects: "until we implement SUDS, we will not know how they work or what their real maintenance costs are."

The second most frequent barrier derived from public sector participants' references was "diverse interpretations of the SUDS concept." From the general analysis, 12 of the 15 codings linked to this barrier were made by LWU participants. They referred to dry reservoirs, streams, and even a river (Río Tunjuelo) as if they were SUDS (PU1, PU2), presumably because they are part of the stormwater management infrastructure within the built environment of Bogotá. Conceptual divergences may have implications in knowledge dissemination among residents or other institutions, as well as in increasing support for SUWM strategies (Han & Kuhlicke, 2021). Therefore, a consensus is relevant in either a top-down or bottom-up approach.

Institutional/organizational barriers were those with the second highest presence in the analysis of public sector representatives' data (c = 35). "Responsibility vs. authority dilemma" and "position of power of the water utility" were the hindrances with the highest number of codings, followed by "unclear institutional responsibilities" and "lack of institutional coordination/communication." These barriers suggest self-awareness of internal and inter-departmental shortcomings, which, in the best cases, allows timely solutions to encourage SUDS uptake.

On the other hand, it was noteworthy that the two most relevant cultural/behavioral barriers across the public sector were "silo mentality" and "uncivil behaviors," expressed in relation to different actors. For instance, the "silo mentality" barrier was elucidated in quotations where participants expressed their individual preferences for large SUDS (PU1), the lack of trust in community engagement (PU3), and the disciplinary boundaries of urban planners, environmental engineers, and drainage professionals when designing SUDS (PU4). Conversely, the "uncivil behaviors" barrier was a concern only regarding the attitudes of some citizens, e.g., vandalism and littering, which discourage the promotion of SUDS in public spaces. In fact, community members (C4, C11, C13) mentioned that poor solid waste disposal by some neighbors had led to the clogging of stormwater inlets, causing drainage problems during the rainy season.

Financial barriers can be portrayed as a "lack of financial resources" considering SUDS construction or as a "financial burden" regarding O&M. One of the most striking barriers in this category was the "increase in water tariffs." The rationale behind this is that RWHS intensification could result in lower drinking water consumption, and therefore, the LWU would be forced to increase rates. This hindrance highlights the "position of power of the water utility," another barrier mentioned by participants from the other inquired sectors, excluding community members.

Urban barriers (c = 7) outweighed political barriers (c = 3), mainly due to "private land ownership" issues. According to the PU4 participant, about 84% of the space in Bogotá belongs to private-land use. Participant PU2 added that "if some private-land users do not advocate SUDS implementation, the initiative will not develop as it should." Therefore, it is essential to promote suitable SUDS typologies for these urban conditions.

Perceived barriers by urban developers

Institutional/organizational barriers were the most relevant during the analysis of urban developers' data (c = 27). Participants exposed past problems with the implementation of IB, IT, and TP due to "unclear institutional responsibilities" and "inflexible and conflicting rules". The "position of power of the water utility" barrier was also mentioned in the context of Bogotá and other Colombian cities, aggravated by the "lack of design standards and guidance" and the "lack of supportive policy and legal framework". To explain this, participant UD2 commented that some water utilities are not willing to receive SUWM systems. Despite being successful in one city, in another "you have to start over from scratch because the authorities are different." This has triggered feelings of frustration and disempowerment. Furthermore, it is worth noting that the aforementioned institutional/organizational barriers may impact housing projects' feasibility. For instance, if the SUDS design is not approved despite presenting the corresponding technical support, the companies are forced to adopt conventional strategies (UD4, UD7).

On the other hand, as well as for the public sector, O&M was the most commented technical barrier by urban developers, accounting for 14 codings. This barrier was linked to four more barriers, namely, "unclear institutional responsibilities" (UD1, UD3, UD7), "lack of supportive policy and legal framework" (UD3, UD7), "lack of technical capacity" (UD7), and "lack of operational capacity" (UD7). These relationships are shown in Figure 5.5; examples of the empirical evidence can be found in Supplementary material, Table S4.

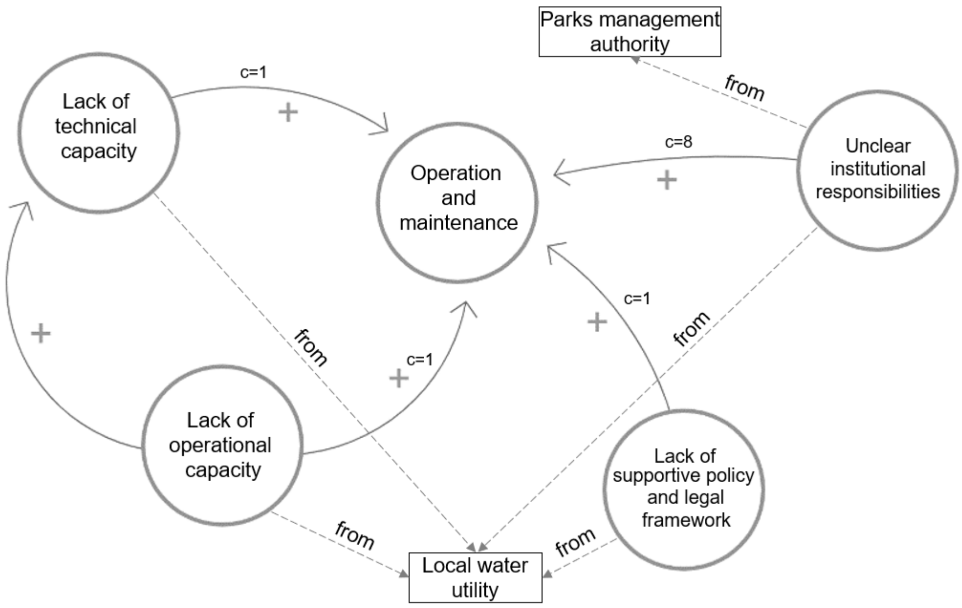

Figure 5.5 *"Operation and maintenance" barrier from urban developers' viewpoint*

According to the co-occurrence analysis, the "unclear institutional responsibilities" barrier significantly affects O&M management. Developers addressed this relationship by referring to SUDS projects that, because of their obligations to the city, must be implemented in the public space. The long-term commitment generated by O&M raised feelings of rejection:

> "When the project or building is ours, in those cases we are interested in doing the operation and maintenance (…) But in urbanisms, no, we are not interested in staying to operate" (UD8).

Additionally, it is worth highlighting that the two technical barriers linked to O&M, i.e., "lack of operational capacity" and "lack of technical capacity," were commented only referring to the LWU capabilities:

> "They [LWU] do not maintain and operate the main ones, say, an open or concrete-lined channel or the pipes itself… We find operation and maintenance problems every day. Since these systems [SUDS], which, in quotes, are a little more specialized and with a little more delicate maintenance, we have always found resistance on this issue" (UD8).

Furthermore, although financial barriers ranked third in the overall analysis by category, the second most commented barrier from the urban developers' viewpoint was the financial burden that SUDS represent. As their current business focus, all companies referred to Housing of Social Interest (VIS, for its acronym in Spanish), a type of real estate project with a maximum sale value of 135 monthly legal minimum wages (Ministry of Housing of Colombia, 2020). According to the questioned participants, this price restricts construction budgets, leaving little room for novel strategies such as SUDS. For instance, participant UD3 explained that implementation of RWHS is not feasible because "the price of water in Colombia is very cheap," so it is difficult to make a profit with water storage techniques.

Surprisingly, there were no references to urban form barriers. This may be related to the interest and conviction shown by the three companies, for which the implementation of SUDS has been an opportunity to develop sustainable projects and strategies, as will be addressed in *Perceived benefits by urban developers*. Political barriers were also irrelevant for urban developers, presumably due to the little interaction with political actors during project planning.

5.5.2 Analysis of perceived benefits

The inductive–deductive coding process yielded 34 benefits linked to 104 codings, and identification was enabled using a previously developed code book derived from the literature (Table 5.2). Benefits not initially included in the codebook ($n = 13$) included "compensation of green area debt," "corporate image enhancement," "delaying water supply network expansion," "flexibility for repair and maintenance work," "hedonic housing prices," "improvement of customer's quality of life," "pipe diameter optimization," "promotion of urban farm projects," "protection of endangered vegetative species," "reduction of imperviousness," "reduction of the social gap," "social responsibility," and "water pumping system optimization." This demonstrates the enormous environmental, social, and market-related potential that SUWM strategies such as SUDS provide to various segments of society. Table 5.5 shows the classification and distribution of all benefits found in this study based on the sectors investigated.

The participants from the public sector, urban developers, and community members had a homogeneous number of benefit-related codings. The number of references made by the private non-profit organization is reduced, presumably because of the number of participants and their role as consultants, describing the general benefits identified of their work with urban developers. The analysis of the perceived benefits according to each sector will be analyzed in the following sections.

Table 5.5 *Summary of perceived benefits of SUDS implementation*

Perceived benefits	**C** (*np = 13*)	**PR** (*np = 2*)	**PU** (*np = 5*)	**UD** (*np = 8*)	**ec**
Air quality enhancement	-	-	1	-	1
Amenity	4	-	2	1	7
Aquifer recharge	-	-	-	3	3
Biodiversity augmentation	1	-	1	-	2
Climate change adaptation and mitigation	-	-	1	-	1
Compensation of green area debt	-	-	1	-	1
Corporate image enhancement	-	-	-	1	1
Decentralized water supply	1	-	-	-	1
Delaying water supply network expansion	-	-	1	-	1
Flexibility for repair/maintenance work	-	-	1	-	1
Flood risk mitigation	4	-	5	1	10
Health and well-being improvement	1	1	-	-	2
Heat resilience	-	-	2	1	3
Hedonic housing prices	-	-	1	-	1
Improvement of customer's quality of life	-	-	-	1	1
Noise reduction	-	-	2	-	2
Peak flow reduction	-	-	2	1	3
Pipe diameter optimization	-	-	-	5	5
Promotion of ecosystem services	1	-	-	-	1
Promotion of environmental awareness	2	-	2	3	7
Promotion of multifunctional spaces	2	1	-	1	4
Promotion of urban farm projects	1	-	-	-	1
Protection of endangered vegetative species	1	-	-	-	1
Recreation opportunities	-	-	-	1	1
Reduction in water treatment costs	-	-	1	-	1
Reduction of imperviousness	-	-	2	2	4
Reduction of the social gap	1	-	-	-	1
Runoff volume control	2	1	5	1	9
Social responsibility	-	-	-	1	1
Stormwater management	-	-	-	2	2
Tax reduction	-	-	-	1	1
Use of harvested water in secondary uses	11	-	-	7	18
Water pumping system optimization	-	-	-	1	1
Water quality enhancement	1	-	4	-	5
Total number of codings	33	3	34	34	104

C: community members; PR: private non-profit organization; PU: public sector; UD: urban developers; np: number of participants; ec: excerpt counts

Perceived benefits by community members

Three typologies that best adapt to the built environment on private land were pre-selected for evaluation by the community participants: RWHS, BRS, and GR. Of 14 benefits distributed in 33 mentions, the "use of harvested water in secondary uses" (c = 11) stood out. Alternative uses comprised cleaning purposes (C3, C8, C9, C11), toilet flushing (C3, C7, C11), dish washing (C7), gardening (C3, C4, C6), and urban farm irrigation (C8, C9). Moreover, participant C12 highlighted the relevance of the "decentralized water supply" benefit when there are unexpected water cuts.

In most cases, "flood risk mitigation" (c = 4) was mentioned as a consequence of the use of harvested rainwater in daily tasks. According to the participants, the less stormwater that circulates in the streets, the lower the risk of flooding. It is worth noting that the community members consulted in the present study belong to a waterlogging- and flood-prone area due to the low-land nature of the site (Rojas, 2018) and the insufficient capacity of the local drainage system (Comisión Ambiental Local, 2012). Therefore, it would be interesting to quantify the impact of RWHS on reducing flood extents and depths.

"Amenity" (c = 4), "promotion of multifunctional spaces" (c = 2), "runoff volume control" (c = 2), and "promotion of environmental awareness" (c = 2) followed as the most mentioned benefits. They all provide social, economic, and environmental benefits, reflecting the ability of SUDS strategies to provide attractive spaces for community members. Moreover, one of the most striking benefits, which was not mentioned by participants from other sectors, was the "reduction of the social gap." According to participant C13, the implementation of SUDS provides an opportunity for low-income sectors to enjoy pleasant environments:

> "I am sorry for what I'm going to say, but that the *** that comes from the city not only arrives to the southern part and then, those of us living here, have to put up with it. Quite the opposite, that [our neighborhood] also looks good, looks nice" (C13).

Most of the benefits with a single mention, i.e., "biodiversity augmentation," "health and well-being improvement," "promotion of ecosystem services," "protection of endangered vegetative species," and "reduction of the social gap," were remarked by the same participant, C13, an environmental engineering student. The C13 participant showed enthusiasm about "supporting [environmental strategies] and working in the territory," which can be key for developing community-led projects.

Examples of quotations of all mentioned benefits by the community members can be found in Supplementary material, Table S5.

Perceived benefits by a private non-profit organization

Three benefits were mentioned by the CGBC representatives, i.e., "promotion of multifunctional spaces" (PR2), "runoff volume control" (PR1), and "health and well-being improvement" (PR2). Note that these benefits arose from their perspective as consultants when housing companies apply for GBC. In fact, some urban developers who participated in the present study illustrated their own examples of these benefits. For instance, participant UD6 highlighted the benefits of GR implementation on walkable roofs since these places "have become passive recreation areas for the inhabitants." Additionally, participant UD4 commented on some advantages of RWHS in the company building, such as providing an alternative water supply for cleaning tasks and thus reducing drinking water consumption.

The key role that private non-profit organizations supporting sustainable practices play in promoting the benefits of SUWM was evidenced in this study. For instance, one of CGBC's strategic lines to strengthen sustainable construction practices is knowledge dissemination through open-access training and market mobilization. In this sense, the CGBC offers valuable tools for water demand assessment, performing water balance models to replicate natural flows, and providing guidance for implementing water-saving devices (PR1, PR2). Moreover, the CBGC is consulted for urban policy-making at the regional and national levels in order to develop long-term strategies within the framework of the SDGs.

Perceived benefits by public sector representatives

Public sector representatives referred to 17 benefits through 34 codings. The most prominent benefits include "runoff volume control" (c = 5), "flood risk mitigation" (c = 5), and "water quality enhancement" (c = 4). This suggests consensus within the public sector about the quality and quantity control capabilities of SUDS. Furthermore, participant PU4 (renowned local SUDS champion) highlighted the importance of quantifying benefits such as "heat resilience," "amenity," and "improving health and well-being" within the cost-benefit analysis to increase civil engineers' interest: "the conclusion [from the scientific literature on O&M] is that yes, they are expensive, but because all the benefits of SUDS implementation are not quantified."

Additional benefits mentioned by the public sector participants are narrowly related to ecosystem services, i.e., "amenity," "heat resilience," "peak flow reduction," "biodiversity augmentation," "air quality enhancement," and "climate change adaptation and mitigation." This demonstrates the great environmental and social scope of SUWM strategies such as SUDS. On the other hand, several benefits are technical in nature, aligned with the professional background of some participants, and have been poorly explored within the SUDS literature. For instance, participant PU2 mentioned that large-scale SUDS implementation could support the "delay of water supply network expansion": "if this becomes a very massive thing where drinking water consumption is reduced (…) there will be benefits such as delaying investments for projects to expand supply systems." PU2 also referred to the "flexibility for repair and maintenance work" that SUDS represent compared with conventional drainage systems, alluding to issues of urban densification and traffic congestion:

> "In a network that is getting older and older and, in a city, as dense and complex as Bogotá, well, thinking of changing a pipe of, I don't know, 800 mm and

> changing it to 1200 mm, (…) each time a different calculation is made, it is simply unfeasible, not even from an economic point of view, but from the point of view of the city, given the traffic jam that this type of work often generates.” (PU2).

In addition, participant PU4 mentioned the “compensation of green area debt” benefit, which arose from a public policy created by the LSE and UDI to encourage the implementation of SUDS in road renovation projects. PU4 also commented on the hedonic prices in the real estate market, arguing that “landscape benefits can be seen as a potential benefit for the implementation of SUDS in private properties.”

Examples of quotations of all benefits mentioned by public sector representatives can be found in Supplementary material, Table S6.

Perceived benefits by urban developers

Urban developers referred to 18 benefits through 34 codings, highlighting the “use of harvested water in secondary uses” (c = 7). Alternative uses included maintenance activities (UD2 and UD3), gardening (UD2, UD5, UD6, and UD7), common areas cleaning (UD4 and UD6), and toilet flushing (UD4). This benefit, along with “stormwater management” and “runoff volume control,” was identified as decisive in the process of certification of sustainable constructions (UD2, UD4, and UD6). This reflects the importance of understanding the needs of all types of actors involved in SUWM because, although the “use of harvested water in secondary uses” was also the benefit most mentioned by community members, the motivations were different.

Benefits such as “pipe diameter optimization” (c = 5) and “water pumping system optimization” (c = 1) were primarily associated with economic gains because SUDS should function as complementary components to the traditional drainage system. Despite having completed the corresponding technical study, participants (UD3, UD7) stated that obstacles such as the "lack of design standards and guidance" and the "position of power of the water utility" have reduced these opportunities. Participant UD4 added that “if one goes over budget, it is absolutely impossible to compete.” These interests, including “corporate image enhancement” (c = 1), are underexplored in the literature and are key to increasing SUDS uptake in all relevant sectors.

Conversely, “amenity,” “flood risk mitigation,” “heat resilience,” “peak flow reduction,” “promotion of multifunctional spaces,” “recreation opportunities,” and “runoff volume control” were benefits with a social component in the interviewees’ speech, evoking mainly the improvement of the citizens’ welfare. In fact, participant UD5 mentioned “improvement of customer’s quality of life” as a key benefit of SUDS implementation in their housing projects. This highlights the ability of SUDS to create end-to-end solutions that transcend the urban developer’s profits.

Examples of quotations of all benefits mentioned by urban developers can be found in Supplementary material, Table S7.

5.6 Discussion

This work is consistent with the efforts of several authors exploring comprehensive management of natural hazards such as urban flooding (McVittie et al., 2018), aiming to facilitate public participation (Pappalardo et al., 2017; Wehn et al., 2015), implement efficient non-structural strategies (Buchecker et al., 2016; Rubinato et al., 2019), create flood-resilient communities (Mohanty et al., 2020), and raise levels of acceptance of new measures (Giordano et al., 2020; Qiu et al., 2014; Santoro et al., 2019). Nevertheless, the lack of research addressing the challenges of SUWM in the context of developing countries (V. Chen et al., 2021; Pappalardo & La Rosa, 2020) was confirmed.

This study introduces three main novelties. The first is sectoral representativeness, as evidenced in the investigation of four key actors: the public sector, urban developers, a private non-profit organization in the field of sustainable construction, and community members living in flood-prone areas. The second is an analysis in the context of Bogotá, the capital city of Colombia (a developing country), offering sound evidence for regions sharing socio-geographical similarities. Finally, the systematic identification and evaluation of factors that promote or hinder the transition to SUWM.

5.6.1 Perceived barriers

The present analysis revealed that technical barriers still have great relevance in the adoption of SUDS, mainly from the perspective of the public sector and urban developers. This contrasts with previous research in developed countries that claims that major barriers impeding SUDS uptake are more socio-political rather than technical (Bark & Acreman, 2020; Gimenez-Maranges, Pappalardo, et al., 2020; Hamlin & Nielsen-Pincus, 2021; Wihlborg et al., 2019). Nonetheless, institutional/organizational barriers played an important role in understanding inter- and cross-sectoral dynamics, so hindrances in other areas could be more easily addressed. It should be noted that all the public authorities investigated in the present study were aware of their institutional shortcomings, either at the individual or inter-departmental level. A dialogue with urban developers, for whom institutional/organizational barriers were the most significant, could improve the capabilities of both sectors in the transition to SUWM.

The “Operation and maintenance (O&M)” technical barrier, was mostly referenced by the above-mentioned sectors, in line with the findings of earlier studies. For instance, Nguyen et al. (Nguyen et al., 2019) noted that O&M of urban flood adaptation measures may require more expertise and skills than conventional drainage systems. Added to this, the maintenance costs of GI and BGI raised the concerns of designers and managers in Nairobi, Kenya (Mulligan et al., 2020). The network analysis in this study elucidated direct links between O&M and important technical, financial, and institutional/organizational constraints, which are also covered in previous research (Dhakal & Chevalier, 2017; Mguni et al., 2015; Mulligan et al., 2020). This emphasizes the significance of multi-stakeholder partnerships in supporting the transition to SUWM to ensure successful long-term implementation. Furthermore, in cities where SUWM interest is recent, using low-maintenance techniques can increase buy-in and uptake (L. Li et al., 2020; Nguyen et al., 2019).

This study confirmed the relevance of exploring cultural/behavioral barriers highlighted in former research (Gashu & Gebre-Egziabher, 2019; Johns, 2019), which, in the general analysis, were above financial constraints. Note that the recognition of these types of barriers is not straightforward since they are derived from intangible factors such as mindset, fear, attitudes, and perceptions (Dhakal & Chevalier, 2017). Herein lies the importance of their analysis since they can boost other types of hindrances. For instance, "path dependency," which includes vested interests in grey infrastructure (Dhakal & Chevalier, 2017; Johns, 2019), may be related to the risk aversion barrier described by Sarabi et al. (Sarabi et al., 2020), as public and private sectors are concerned with financial losses. In turn, "silo mentality" shrinks efforts to increase knowledge (Han & Kuhlicke, 2021) and joint learning (Mukhtarov et al., 2019). Furthermore, the "uncivil behaviors" barrier, mentioned mainly by the public sector in relation to citizens' attitudes, can reduce SUDS overall performance (Lamond et al., 2020). This barrier was identified as the main challenge for developing sustainable practices by some community and public sector participants in a previous study (Carriquiry et al., 2020).

On the other hand, financial hindrances have been identified by several authors as relevant in the implementation of SUWM strategies (Drosou et al., 2019; Mukhtarov et al., 2019). Although, in this analysis, this category was surpassed by technical, institutional/organizational, and cultural/behavioral barriers, all participating sectors mentioned either the lack of financial resources (community and the public sector) or the financial burden (the public sector, private non-profit organization, and urban developers) that SUDS represent. In the latter case, the conception that water supply is inexpensive in Colombia prevents the promotion of typologies such as RWHS due to low ROI. This opinion contrasts with the willingness of a low-income community surveyed in Ciudad Verde (neighboring area of Bosa) to resort to water-saving practices due to high drinking water and sewage service costs (Universidad de los Andes, 2020). This highlights the significance of investigating different perspectives on urban water management, whether to promote the co-creation of solutions or implement government-led initiatives.

Community members inquired in this research highlighted the "lack of community ownership" followed by the "lack of general knowledge" as major barriers hindering further SUDS implementation. Similar results were found in a study conducted in the Gregório stream catchment, São Paulo, Brazil, where local residents ranked the lack of community engagement as the most important barrier in adopting SUWM (Vasconcelos et al., 2022). According to Thorne et al. (2018), improving access to information might increase community ownership and buy-in. Therefore, campaigns to raise awareness of both the growing problem of urban flooding and the opportunities provided by multifunctional solutions such as SUDS can aid in the development of community-led initiatives.

The development of a code book to perform the inductive–deductive analysis revealed some peculiarities. To the best of the authors' knowledge, the barrier "increase in water tariffs" commented by participant PU2 (LWU specialist) has not been thoroughly investigated. In turn, it is directly related to the "position of power of the water utility" barrier, which ranked fifth in the overall study but has received little attention in the literature. Since water authorities are often the most powerful actors and they tend to favor specific and mono-functional objectives (Janssen et al., 2020), interdisciplinary initiatives might enable greater leadership. Another barrier that lacks research support is the creation of indoor humidity conditions mentioned by participant C4, alluding to the operation of RWHS. Contrary to this, members of the Bon Pastor neighborhood in Spain indicated a reduction in humidity problems due to an SUDS scheme in public areas composed of hollowed gardens, permeable pavements, bio-retention strips, and new stormwater collectors (Carriquiry et al., 2020). Both are community perceptions worth evaluating to improve SUDS uptake.

Alternatively, technical barriers such as “clogging effect,” “performance reduction,” and “risks to conventional drainage system performance” have been widely investigated through hydraulic, hydrologic, and optimization models (D’Aniello et al., 2019; Ellis & Viavattene, 2014; Hu et al., 2018; Krebs et al., 2013). However, there is a lack of evidence from participatory studies. All citations referring to these barriers (a total of 18) stemmed from perceptions and misconceptions from the public sector participants and urban developers. This may be linked to other technical barriers such as “lack of quantitative evidence/performance information” and “lack of local experience/benchmarks.” However, participant UD3 mentioned having performed technical tests in the company's Research and Development division. Unfortunately, the tested PP did not produce the expected results in terms of visual appearance and maintenance. This highlights the critical role that knowledge supported by technical evidence plays in increasing the adoption of SUWM strategies.

The data collection and data analysis methods used in this study revealed that participants’ opinions are enriched by their exposure to a given topic and the role they play. For instance, the analysis of perceived barriers resulted in 175 mentions made by five public sector representatives, whereas the 13 surveyed community members made 34 mentions. The most obvious reason for this disparity is the lack of SUDS knowledge. However, this also exposes the strong top-down approach in both stormwater management and urban planning decision-making. Previous researchers called for a balance between technocratic and bottom-up approaches (Drosou et al., 2019; L. Liu & Jensen, 2018). Nonetheless, it is important to consider the influence of the local institutional and economic context (Ferguson et al., 2013; Krkoška Lorencová et al., 2021; Wild et al., 2017).

5.6.2 Perceived benefits

The general analysis of benefits perceived by the four sectors investigated evidenced the narrow link to ecosystem services (ES) in all categories, i.e., provisioning, regulating, supporting, and cultural (Sukhdev et al., 2010). Connop et al. (2016) indicate that SUDS allow the leveraging of additional ES, whereas Alves et al. (2020) and Bark & Acreman (2020) agree that ES enhances the potential and acceptance of SUDS. In any case, economic and social benefits found in this study, such as “hedonic housing prices,” "promotion of environmental awareness," and "reduction of social gap," highlighted the wide scope and impact of SUDS in the urban dynamics.

The present analysis demonstrated the importance of including relevant sectors of SUDS management at the private level, such as urban developers, who mentioned benefits not previously discussed in the literature, i.e., "improvement of customers' quality of life" and "corporate image enhancement." The latter may be related to marketing, one of the facilitators for the application of LID (Kim et al., 2017) and NbS (Han & Kuhlicke, 2021). Others, such as "pipe diameter optimization" and "water pumping system optimization," reflect the relevance of considering economic factors to improve the feasibility of projects promoting SUWM strategies. On the other hand, benefits mentioned by public sector representatives such as "compensation of green area debt," "flexibility for repair and maintenance work," "delaying of water supply network expansion," and "reduction in water treatment costs," revealed how SUDS, in addition to providing multiple benefits, may assist public management and policy-making. Identifying and quantifying all possible benefits and co-benefits allows leveraging public investment (Kok et al., 2021; L. Li et al., 2020) and reducing financial constraints (Nguyen et al., 2019). Future research might be valuable based on the local socio-economic context of Bogotá.

Furthermore, previous studies have emphasized the relevance of adopting bottom-up approaches in urban water management when top-down structures have proven to be ineffective (Drosou et al., 2019; Mguni et al., 2015). For this reason, the study of perceived benefits by citizens is key to achieving successful community participation. Even though time constraints did not allow for a representative sample of this sector and definitive conclusions cannot be drawn, participants cited a wide range of social, economic, and environmental benefits worth evaluating. Moreover, Bogotá has great potential for implementing property-level strategies such as RWHS and GR, considering that 84% of the city's land is privately owned (PU4). In this sense, knowledge dissemination and benefit awareness initiatives, in addition to incentive-based policies (Roy et al., 2008), are key to encouraging SUWM.

Although delving into solutions to overcome barriers hindering SUDS implementation was beyond the scope of this study, several authors have highlighted some of the presented benefits as drivers, facilitators, or enablers to foster wider adoption of SUDS (Han & Kuhlicke, 2021; Kim et al., 2017; L. Li et al., 2020; Wihlborg et al., 2019). In addition, according to Gashu & Gebre-Egziabher (2019), identifying barriers and working to overcome them facilitate GI planning and development. Thus, this study offers 73 key starting points (39 barriers and 34 benefits) to unravel the complex dynamics of efficient urban water planning and sustainable hydro-meteorological risk management. This task is eased by an understanding of barriers and benefits relationships, also evidenced in this study and previous research (Han & Kuhlicke, 2021; O'Donnell et al., 2017; Sarabi et al., 2020; Wihlborg et al., 2019).

5.7 Conclusions

This study aimed to identify and assess the factors that promote and hinder the transition to SUWM by investigating the perceived barriers to and benefits of SUDS adoption from the viewpoints of four key urban water sectors in Bogotá, Colombia. The main findings include the following: (i) multi-sector analysis provides valuable insights for understanding the local-context strengths and constraints in alternative urban water management and city planning; (ii) technical barriers still have a great impact on SUDS uptake, contrasting with some studies from developed countries where socio-political barriers prevail; (iii) institutional/organizational and cultural/behavioral barriers may surpass financial constraints; (iv) there is a strong relationship between SUDS benefits and ecosystem services even though some economic, social, and environmental advantages are beyond this categorization; and (v) there are direct links between barriers, benefits, and actors that should be considered in the comprehensive planning of stormwater management solutions.

In line with the research gaps we sought to address, there are two main limitations for this study to be conclusive. Although the number of participants is reduced, findings derived from the multisectoral analysis are more exploratory (McEvoy et al., 2019), offer representativeness in the local context (Francesch-Huidobro, 2015), and portray the diversity of views (Carriquiry et al., 2020) on sustainable strategies. Furthermore, lessons learned from a single-case study are informative and insightful (Yin, 2009), laying the basis for future research. The other limitation refers to the data collection method used in the community sector. Initially, the interaction was devised as FGD, but because of the COVID-19 pandemic issues, it had to be modified, which may have influenced the scope of participating members. Nonetheless, questionnaires with open-ended questions facilitated the creation of a more fluent communication channel and the manifestation of preferences and perceptions.

Our findings stress the importance of future research on multiple areas: (i) an economic assessment of SUDS benefits based on this study to leverage interest and help overcome some of the presented barriers; (ii) the exploration of other demographic and socio-economic contexts, whether local, national, or Latin American, to contribute to the regional and international debate on sustainable urban planning; and (iii) the development of participatory spatial-hydraulic modeling-based investigations to assess SUDS impact on local FRM.

This research does not seek to draw universally applicable assertions or definitive conclusions for the city of Bogotá. The results of this study emphasize the importance of employing interdisciplinary approaches to achieve an efficient transition to SUWM and provide a sound basis for such analysis in cities with comparable features in terms of urban planning and growth, stormwater management, and socio-economic-institutional dynamics. Moreover, acknowledging the above-mentioned limitations and future work scope, the adopted methodology proved to be flexible and effective for analyzing multisectoral opinions, reducing the inherent biases of qualitative research, and can be easily exported to other contexts worldwide. We hope that our study spurs greater interest in all relevant sectors, encourages cross-sector partnerships, and that our findings can be useful in sustainable flood risk management.

6 A transdisciplinary approach for assessing the potential feasibility of Sustainable Urban Drainage Systems: Case study, Bogotá, Colombia

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6.1 Abstract

Rapid population growth and urban sprawl have expanded built-up areas, affecting flood patterns in cities. Sustainable urban drainage systems (SUDS) have gained significant attention by attempting to replicate natural pre-development drainage conditions. This paper presents a new transdisciplinary methodology for assessing the potential feasibility of 12 different SUDS typologies by considering physical restrictions and six types of contextual barriers. The approach integrates input from academic and non-academic actors, fuzzy logic, geographic information system tools, and multi-criteria decision analysis. A neighborhood in Bogotá, Colombia, was selected as the unit of analysis, framing a relevant case study for highly urbanized areas. The findings demonstrate the differential impact of local context constraints and emphasize the importance of comprehensive approaches to SUDS planning that consider criteria other than technical. The methodology is a tool to support architects, engineers, urban planners, and urban water decision-makers in the planning of sustainable and flood-resilient cities.

Keywords: flood resilience, fuzzy logic, green infrastructure, multi-criteria analysis, transdisciplinary methods, urbanization

6.2 Introduction

The increase of water-impervious areas in response to rapid population growth and urban sprawl (Q. Zhou et al., 2019) has exacerbated flood patterns in cities (Berndtsson et al., 2019). This problem is further aggravated by high-intensity rains associated with climate change (IPCC, 2022) and the insufficient capacity of conventional drainage systems (A. S. Chen et al., 2010). Effects range from nuisance flooding to adverse impacts on human life, the local economy, city services, and the natural environment (Hammond et al., 2013). Since 68% of the world's population is expected to live in cities by 2050 (UNDESA, 2019), the attendant concentration of people and infrastructure emphasizes the need for adaptive solutions to cope with the growing exposure to flood risk.

The urban flood risk management (UFRM) paradigm constitutes a transition from a mitigation and resistance approach to a concept of flood resilience (Hettiarachchi et al., 2022), recognizing that complete elimination of risk is not feasible (Figueiredo et al., 2009). Sustainable urban drainage systems (SUDS) are novel sustainable urban water management (SUWM) strategies that are able to address the complex dynamics of UFRM (O'Donnell et al., 2020) with capabilities for surface runoff attenuation, stormwater quality improvement, amenity provision, and biodiversity augmentation (Lamond et al., 2015).

Research on SUDS, also comparable in the literature to "green infrastructure (GI)," "best management practices (BMP)," and "nature-based solutions (NbS)" (Fletcher et al., 2015), has focused on design, installation, and performance assessment (Semadeni-Davies et al., 2008). Although SUDS research lags further behind in the context of developing cities (Pappalardo & La Rosa, 2020), both the overall understanding and implementation are still weak even in developed countries (L. Li et al., 2020; Wihlborg et al., 2019). Many authors have highlighted that factors hampering greater uptake are more socio-political than technical (Brown & Farrelly, 2009b; Thorne et al., 2018). Nevertheless, there are also cultural, institutional, legal, spatial, and financial constraints (Drosou et al., 2019; Gashu & Gebre-Egziabher, 2019; Johns, 2019; O'Donnell et al., 2017) that are worth evaluating, since they represent the local context factors that delay the adoption of sustainable multifunctional strategies (Thaler et al., 2019). In this sense, the selection and location of SUDS, which by nature require transdisciplinary approaches (Mguni et al., 2015), should fully recognize the barriers involved in the decision-making process (Ellis et al., 2004).

According to Mauser et al. (2013), transdisciplinarity involves academic and non-academic actors whose integration occurs in three dimensions, i.e., scientific, international, and sectoral. Reflecting on these three dimensions of knowledge integration, this study presents a new transdisciplinary methodology to aid in the selection and distribution of SUDS through the evaluation of their potential feasibility. The novelty of the proposed methodology is threefold. First, it quantifies the impact of six types of barriers (cultural/behavioral, financial, institutional/organizational, technical, political, and urban form) on 12 different SUDS typologies, based on an exhaustive literature review and input from an expert panel with high-level expertise in SUWM in six different regions around the world. Secondly, the methodology employs Multi-criteria Decision Analysis (MCDA), which allows for transparent and systematic decision-making (Ruangpan et al., 2021), to perform a local context barrier assessment. This use of MCDA proposes an alternative weight elicitation method with the ability to incorporate the perspectives and knowledge of relevant urban water actors; however, the flexibility of the proposed methodology allows other approaches to be used. Third, the methodology is able to provide a ranking of alternatives through the integration of the barrier impact assessment and a GIS-based approach coupled with fuzzy logic, thereby facilitating both the SUDS selection and location from a more realistic point of view.

The aim of this diagnostic tool is to assist architects, engineers, urban planners, and urban water decision-makers in fostering sustainable urban planning and urban water management by integrating the capabilities associated with the physical, financial, and socio-political context of the specific site. For proof of concept, the methodology was applied at the neighborhood level in Bogotá, the capital city of Colombia.

6.3 Materials and methods

The proposed methodology to assess the potential feasibility of SUDS allows for the valuation of 12 typologies (Figure 6.1). The methodology is divided into three steps: (i) barrier impact assessment, (ii) GIS-based analysis of physical restrictions, and (iii) evaluation of the potential feasibility of SUDS implementation. The following sections describe in detail the steps involved in the methodology.

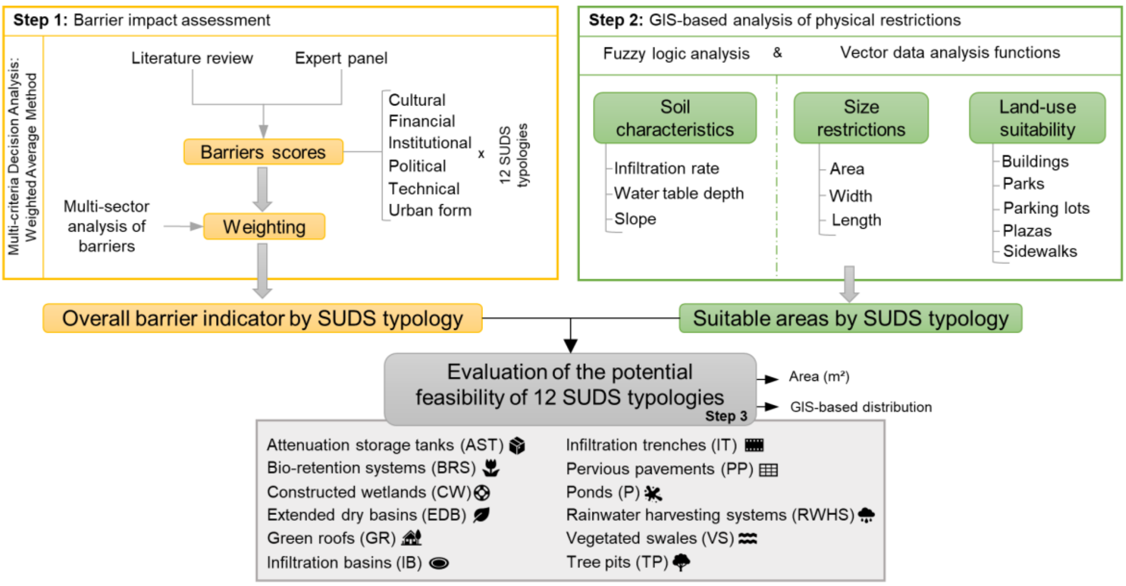


Figure 6.1 *Methodology to assess the potential feasibility of sustainable urban drainage systems*

6.3.1 Step 1: Barrier impact assessment

Scoring

An exhaustive literature review and an expert panel provided the basis for a score serving as an evaluation of the influence of the six types of barriers to SUDS adoption, i.e., cultural/behavioral, financial, institutional/organizational, political, technical, and urban form. Cultural/behavioral barriers are individual beliefs that can influence certain positions or opinions (Gashu & Gebre-Egziabher, 2019). Financial constraints are those associated with the financing and costs of SUDS implementation and operation (O'Donnell et al., 2017). Institutional/organizational barriers are related to inter-governmental or inter-departmental dynamics (e.g., water and planning departments) (Johns, 2019), whereas political hindrances are more associated with government decisions or positions (Wihlborg et al., 2019). Technical barriers refer to the particular knowledge, skills, and infrastructure needed to achieve efficient SUDS planning, implementation, and operation (Gashu & Gebre-Egziabher, 2019). Urban form constraints stem from interaction with the built environment (Johns, 2019).

The key sources for the literature review (Supplementary material, Table S8) included scientific articles and project reports in which the barriers' influence on a specific SUDS typology was clearly denoted. The information density for each barrier–typology combination was used as initial barrier score. Meanwhile, expert elicitation started by contacting 28 potential participants with high-level expertise in SUWM via email and in academic encounters, inquiring whether they would be willing to participate in the research, and, if so, offering them the option to fill out a questionnaire during a video call or after receiving it by email. From 28 potential participants, 19 positive responses were received, zero were negative, and no response was received in nine cases.

The final expert panel included researchers (*n = 13*) and practitioners (*n = 6*), pooling expertise in six different regions around the world, i.e., Asia, Central America, East Africa, Europe, North America, and South America. This diversity of participants, framed by their high-level expertise in SUWM, represents a great novelty in the co-production of knowledge, enabling informed decision-making in the construction of flood-resilient cities. Participants were asked to assign values from 0 to 5, evaluating the impact that six types of barriers might have on the adoption of each of the 12 SUDS typologies, with 0 for no impact; 1, very low impact; 2, low impact; 3, medium impact; 4, high impact; and 5, very high impact. In addition to rating the barriers, participants were also asked to indicate their level of knowledge of each SUDS typology on a scale from 0 to 5, with the same rationale as explained previously. Only barrier scores from participants with a level of knowledge equal to or greater than 3 for that SUDS typology were considered. A draft with the instructions and the decision matrix can be found in Supplementary material S9. The mode values for each barrier–typology combination were utilized as initial barrier scores to better represent the majority of participants' responses (Aceves & Fuamba, 2016b).

Normalization

After the initial scoring, the results from both the literature review and the expert panel were subjected to a normalization process. Previous studies have indicated the influence of the normalization method on the MCDA outputs, highlighting in particular the effects of the normalization method on the ranking of alternatives (Mathew et al., 2017; Vafaei et al., 2021). Therefore, three linear normalization methods were tested, i.e., Sum, Max, and Max–Min, by applying them according to equations 6.1, 6.2, and 6.3, respectively.

$$\bar{X}_{ij} = \frac{X_{ij}}{\sum_{j=1}^{N} X_{ij}} \tag{6.1}$$

$$\bar{X}_{ij} = \frac{X_{ij}}{X_j^{Max}} \tag{6.2}$$

$$\bar{X}_{ij} = \frac{X_{ij} - X_j^{Min}}{X_j^{Max} - X_j^{Min}} \tag{6.3}$$

Here $\bar{X}_{ij}$ is the normalized value of barrier score *j* for SUDS typology *i*, X_{ij} is the initial value of the barrier score, *N* is the total number of barriers, and X_j^{Max} and X_j^{Min} refer to the maximum and minimum scores, respectively, for barrier *j*.

Final barriers' scores

The final barriers' scores (FBSs) were the result of averaging the normalized values of the data collected from the literature review and the normalized values of the data collected from the expert panel, thus assigning the same level of importance to each.

MCDA application for overall barrier indicator

The sole reliance on the FBSs may result in an over- or underestimation of the study site's capabilities. To reduce potential biases, the present methodology employed MCDA due to its effectiveness in structuring complex decision-making problems, incorporating technical criteria and stakeholder-derived values for the selection of the best alternative in a clear and logical manner (Linkov & Moberg, 2011). The two widely used MCDA methods in flood risk management are the Analytical Hierarchy Process (AHP) and the Weighted Average Method (WAM) (De Brito & Evers, 2016). Both methods have the ability to balance multiple priorities (Croeser et al., 2021) while minimizing human bias when evaluating different alternatives (Young et al., 2010). In the present study, WAM was employed as an analysis tool, allowing comprehensive results and comparability among alternatives (Aceves & Fuamba, 2016a).

Criterion weights in MCDA are usually derived from an examination of stakeholder or expert preferences—potentially a challenging and time-consuming task (Schuwirth et al., 2012). Furthermore, depending on the scope of the study, the analysis of these responses may become mired unless it is given structure by a comprehensive assessment of the socio-spatial and socio-political context. Weight elicitation in the present study resulted from a previous analysis of perceived barriers to SUDS implementation in Bogotá, Colombia's capital city (Ortega et al., 2023b). In this work, data from questionnaires (applied to community members) and semi-structured interviews (applied to public sector representatives, urban developers, and a private non-profit organization) were subjected to an inductive–deductive coding approach, quantifying the results via excerpt counts. The present study aimed to upscale this analysis of perceived barriers by transposing the excerpt counts as MCDA weights. The aggregation of the FBSs for each SUDS typology using the WAM proceeded according to:

$$OBI_i = \left(\sum_{j=1}^{N} W_j \ FBS_{ij}\right) * 100 \tag{6.4}$$

where OBI_i is the overall barrier indicator (%) for SUDS typology i, W_j is the barrier weight, FBS_{ij} is the final score for SUDS typology i for barrier j, and N is the total number of barriers. Nevertheless, the flexibility of the proposed methodology allows other weight elicitation approaches to be used.

6.3.2 Step 2: GIS-based analysis of physical restrictions

Criterion definition

Proper design and SUDS selection require consideration of local site characteristics and spatial distribution assessment (Charlesworth et al., 2019; Fluhrer et al., 2021). Reflecting on previous optimization studies (Uribe-Aguado et al., 2022) and on the need to comprehensively assess key site conditions, the physical restrictions included in the present methodology considered (i) soil characteristics (water table depth, infiltration rate, and slope), (ii) size constraints (area, length, and width), and (iii) land-use suitability for both public and private land (buildings, parking lots, parks/open space, plazas, and sidewalks). The reference values of these parameters according to each SUDS typology are shown in Supplementary material, Table S10. The flexibility of this methodology allows for the inclusion of other variables depending on the scope and objectives of the study.

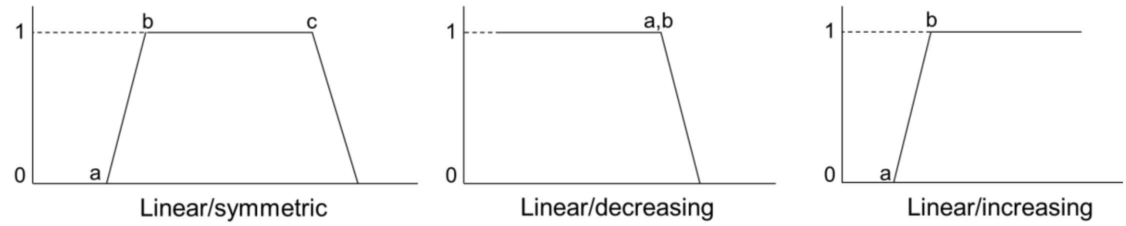
Method of analysis

Fuzzy logic provides a formal mathematical framework for handling the inherent uncertainties of complex system decision-making (Makropoulos & Butler, 2004). Fuzzy logic assessment begins with a fuzzification process aiming to assign a degree of membership to the attribute values, with 0 for the least suitable and 1 for the most suitable, according to value functions, e.g., sigmoidal, J-shaped, linear, or user-defined (Saadat Foomani & Malekmohammadi, 2020). Next, fuzzy operators, e.g., AND, OR, PRODUCT, SUM, and gamma (γ), are employed to combine the selected criteria (Ki & Ray, 2014). Several authors have demonstrated the ability of combining fuzzy logic with GIS tools to improve the quality of spatial decision-making (Bick et al., 2018; Ki & Ray, 2014; Makropoulos & Butler, 2004; Saadat Foomani & Malekmohammadi, 2020). In the present study, fuzzy logic was applied to evaluate the criteria in raster format, i.e., slope, water table depth, and infiltration rate.

Table 6.1 lists the fuzzy value functions and control points according to the reference values for physical restrictions (Supplementary material, Table S10). AND (intersection operator) was the selected fuzzy logic argument used to represent the compulsory relationship between these conditions. As a result, a raster layer was obtained for each typology meeting the three previously mentioned criteria, with an exception made for GR and RWHS due to their above-ground nature.

Table 6.1 *Fuzzy membership value functions and control points for raster data*

Types of fuzzy membership value functions



Function control points

SUDS typology	Water table depth		Slope		Infiltration rate	
	Fuzzy value function	Control points*	Fuzzy value function	Control points*	Fuzzy value function	Control points*
AST	Linear/ increasing	a = 0, b = 1	n/a	n/a	n/a	n/a
BRS	Linear/ increasing	a = 0, b = 1.8	Linear/ decreasing	a = 0, b = 10	Linear/ increasing	a = 0, b = 7
CW	Linear/ increasing	a = 0, b = 1.2	Linear/ decreasing	a = 0, b = 1	n/a	n/a
EDB	Linear/ increasing	a = 0, b = 3	Linear/ symmetric	a = 0, b = 1, c = 15	Linear/ increasing	a = 0, b = 7
IB	Linear/ increasing	a = 0, b = 1.2	Linear/ decreasing	a = 0, b = 15	Linear/ increasing	a = 0, b = 13
IT	Linear/ increasing	a = 0, b = 1.2	Linear/ decreasing	a = 0, b = 15	Linear/ increasing	a = 0, b = 7
PP	Linear/ increasing	a = 0, b = 1	Linear/ symmetric	a = 0, b = 0.5, c = 5	n/a	n/a
P	Linear/ increasing	a = 0, b = 1.2	Linear/ decreasing	a = 0, b = 1	n/a	n/a
VS	Linear/ increasing	a = 0, b = 1	Linear/ symmetric	a = 0, b = 0.5, c = 6	n/a	n/a
TP	n/a	n/a	Linear/ decreasing	a = 0, b = 2	n/a	n/a

* According to the reference values for physical restrictions (Supplementary material, Table S10)
n/a = not applicable

Afterward, with the aid of QGIS' vector geometry tools, a vector layer was created for each of the 12 SUDS typologies. Each vector layer contained the polygons meeting the land-use suitability and geometry criteria described in Supplementary material, Table S10. The fuzzy logic analysis results for each typology were then processed by overlaying its corresponding vector layer using QGIS' raster extraction functions. The output vector layer features represent the total area A_i (m^2) and locations satisfying all of the assessed physical constraints.

6.3.3 Step 3: Evaluation of the potential feasibility of SUDS implementation

Potential feasibility was defined as the existence of suitable area and one or more suitable sites for SUDS implementation, considering the physical restrictions and six types of local context limitations of the study area. Therefore, the present methodology determined the potential feasibility of each of the 12 SUDS typologies by combining the results of the barrier impact assessment (Step 1) and the GIS-based analysis (Step 2) according to

$$R_i = A_i * (100\% - OBI_i) \tag{6.5}$$

where R_i is the potential feasibility (m^2) of implementation of SUDS typology *i*, A_i is its suitable area (m^2) according to the evaluation of physical constraints, and OBI_i is its overall barrier indicator (%). The rationale for this assessment was that A_i (which considered only soil characteristics, size constraints, and land-use suitability criteria) is negatively affected by the limitations of the local context, i.e., the factors that delay the adoption and transition to SUWM (Thaler et al., 2019). The potential feasibility is then assessed using a ranking of alternatives (SUDS typologies), with a higher R_i indicating a greater potential feasibility within the study site.

6.3.4 Case study

The methodology to assess the potential feasibility of SUDS implementation was applied in an urban area belonging to Bosa, one of the 20 administrative divisions (*localidades*) of Bogotá, the capital city of Colombia. Although Bosa is one of the *localidades* with the lowest annual precipitation, i.e., 600–700 mm (IDEAM, 2005), its main hydrometeorological-related hazard is flooding (Sarmiento, 2020). Various factors have influenced Bosa's flood risk proneness, such as the low-lying nature of the land and the large social housing projects built starting in the early 2000s (Rojas, 2018), affecting the soil's natural permeability. Flood risk mitigation projects have focused on channeling and expansion of stormwater drainage coverage; nevertheless, hard gray infrastructure has exacerbated problems of socio-spatial segregation (López-Ortego, 2021). Given the aforementioned conditions, a 71.69-ha neighborhood was selected as a representative case study of a highly urbanized unit in a developing city. The study area location and land-use distribution are portrayed in Figure 6.2.

Data collection

Data collection in the present study considered land-use distribution, terrain condition, and soil characteristics. QGIS Desktop software v3.16.0-Hannover was employed for data processing. The land-use distribution data included vector layers of buildings, parks, and sidewalks, freely available from Bogotá's Spatial Data Network (www.ideca.gov.co). Parking lot and plaza polygons were discretized with the aid of Google Earth Pro version 7.3.4.8248 and field investigations.

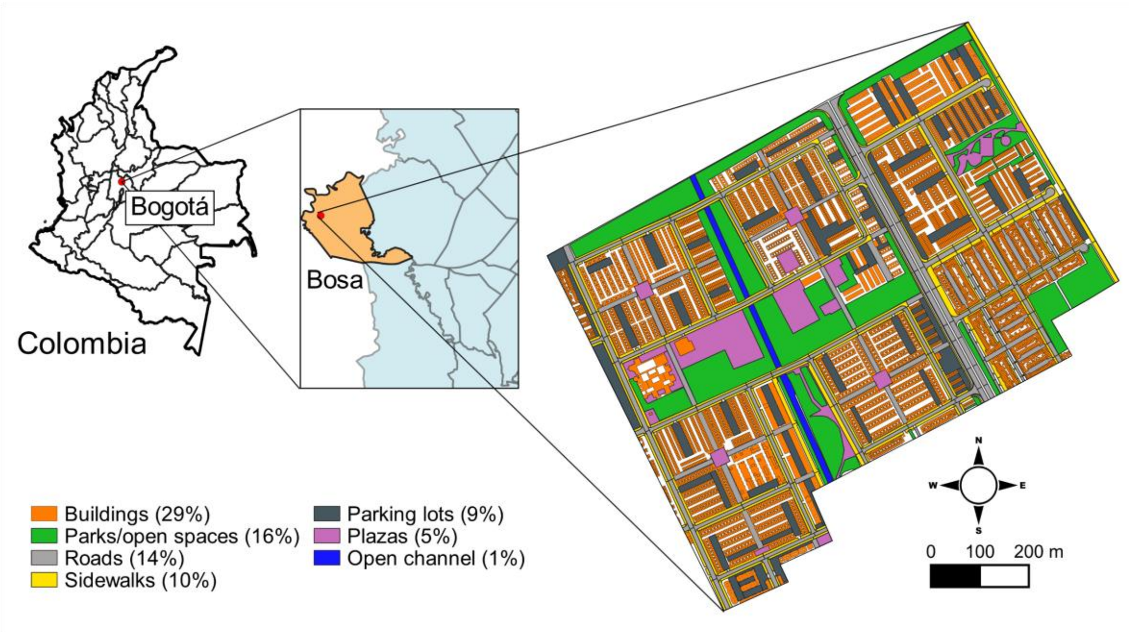


Figure 6.2 *Location and land-use distribution of study area*

A digital elevation model was generated from 1-meter contour line information provided by the local water utility (LWU), allowing the extraction of slope data for parks/open spaces, roads, sidewalks, parking lots, plazas, and open channel land uses. Slope values for the building polygons were assigned according to field surveys and with the aid of Google Maps' street view tool, ranging from 2% to 30%. Raster data for infiltration capacity (50-meter cell size) and water table depth (250-meter cell size) were obtained from a city-scale project led by the Secretary of the Environment and the LWU to develop SUDS planning and design guidelines (Universidad de los Andes, 2015).

Furthermore, citizens' preferences for BRS, GR, and RWHS were investigated, as these are suitable household-level SUDS typologies (Coleman et al., 2018). Given the predominant residential land use in the study area (*buildings* in Figure 6.2), these infrastructures hold high potential for implementation. The Research Ethics Board of the Center for Development Research (ZEF), University of Bonn, provided approval for the use of human subjects before commencing the research (registration code: 10c_21_AO). The point of opportunity interaction method was employed; in this method, people are approached outside their homes, thus avoiding self-selection bias (Everett et al., 2018). Contact with community members occurred on April 3, 2021, and during the period from February 18 to March 3, 2022, throughout the *localidad* of Bosa. Conversations were conducted in Spanish and audio-recorded using a digital voice recorder (Sony ICD-PX470) with the informed consent of each participant. Rather than seeking statistical significance, the goal of this assessment was to map the diversity of opinions and contrast the responses of the most appealing typologies for participants with the results of the potential feasibility ranking.

6.4 Results

6.4.1 Step 1: Barrier impact assessment

Scoring

The literature review yielded a total of 323 entries; the corresponding initial scores are displayed in Supplementary material, Table S11. While a vast amount of information addressed technical barriers (*n = 138*), only a small amount addressed political (*n = 4*) and urban form (*n = 5*) barriers. Cultural/behavioral (*n = 60*), financial (*n = 59*), and institutional/organizational (*n = 57*) barriers shared similar information density, but key differences among typologies were noted. For instance, there were no explicit records of cultural/behavioral and institutional/organizational barriers for AST, whereas the information density for these two types of barriers in the case of TP was 18 and 16 entries, respectively. Alternatives with plentiful information on barriers were TP (*n = 63*), GR (*n = 53*), and RWHS (*n = 50*), whereas few records were found in the cases of EDB (*n = 10*) and AST (*n = 8*).

The initial scores derived from the expert panel are shown in Supplementary material, Table S12. IB and IT were joined in the infiltration systems group, and P was included in the CW category (Woods et al., 2015) to facilitate the scoring process. The highest value (*score = 5*) was recorded in GR (technical barriers), followed by those typologies that require a larger area to function properly, CW & P and EDB, with a score of 4 in cultural/behavioral, financial, and urban form barriers. AST received the lowest score (*score = 1*) in cultural/behavioral, institutional/organizational, and political barriers. In the cases of GR and AST, these values correspond, to a certain extent, with the information density derived from the literature review.

Although an in-depth evaluation of the expert panel's inputs according to their geographic context of analysis was not included in the scope of this study, simple descriptive statistics, i.e., average and standard deviation (SD), were employed to contribute to the SUWM debate from a regionalized perspective. Figure 6.3a displays the expert panel's response according to the six types of barriers.

Institutional/organizational, financial, technical, and urban form barriers registered the highest values in the East African context, whereas political barriers obtained the maximum score in the South American perspective. For their part, cultural/behavioral barriers obtained the highest result in the European setting. SD per type of barrier ranged from 0.31 to 0.72, with the highest value corresponding to the technical and institutional/organizational barriers. These results emphasize the significance of the co-production of knowledge supported by local evidence, as the facilitators and barriers to SUWM adoption are highly dependent on the study area context.

Conversely, Figure 6.3b displays the assessment considering the expert panel's context of analysis and the averaged aggregation of the six barriers' scores per SUDS typology. CW & P scored highest in five of the six regions, i.e., Europe (22), South America (21.67), Asia (25), North America (23.50), and Central America (23.71). In the East African context, the SUDS typology with the highest barrier score was GR (26). The SUDS typologies with the lowest barrier scores across all the participants' contexts of analysis were RWHS and TP.

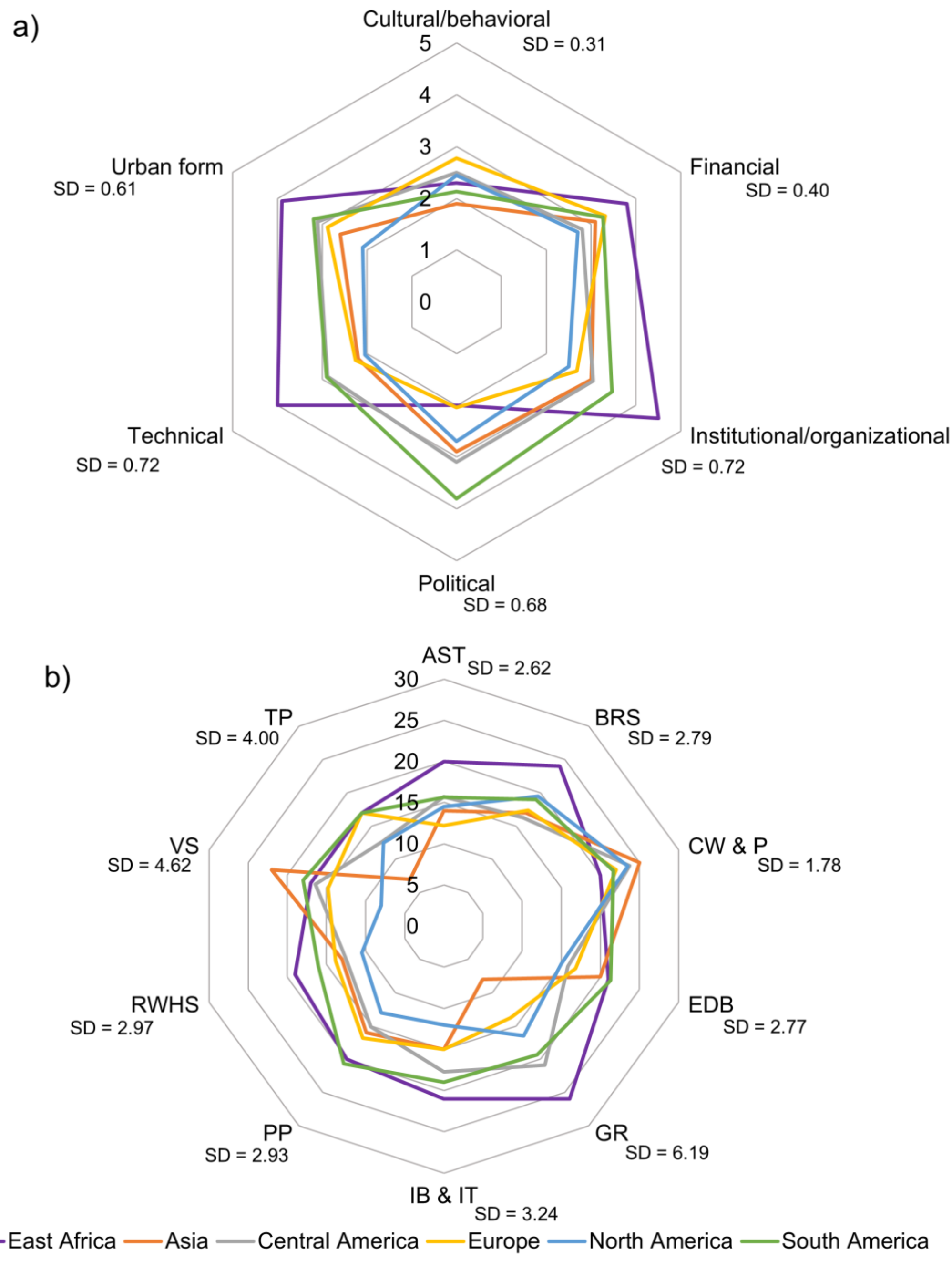


Figure 6.3 *Expert panel assessment of a) barrier types and b) their influence on different SUDS typologies, according to the geographical contexts of analysis, with corresponding standard deviations (SD)*

Figure 6.3b also portrays at some extent the general scene of SUDS knowledge. From a comprehensive perspective of the 12 typologies evaluated, the lowest aggregate scores are presented in the European and North American context, regions that have led the promotion of SUDS since its inception (Fletcher et al., 2015). Although the results presented here are not intended to be definitive, it is evident that a broader and more successful implementation of SUWM strategies is directly related to the dissemination and application of knowledge.

The interdependence between some barriers became evident during the online expert panel interactions (*n = 9*) with academics (A) and practitioners (Pr). For instance, the lack of general knowledge was related to other cultural/behavioral barriers such as negative perceptions (Pr1 and A5) and a lack of operational understanding (Pr3 and A10). Furthermore, the lack of technical knowledge was linked to maintenance uncertainties, SUDS performance reduction, and poor local experience (Pr1, Pr2, Pr4). Moreover, the lack of intersectoral coordination was one of the most frequently mentioned institutional/organizational barriers, implying that the more institutions involved in the decision-making process, the more difficult it will be to reach a consensus (Pr2, Pr4, A10, and A12). Several participants stated that regardless of the type of barrier, cross-cutting solutions such as improving the communication of benefits (A11), increasing political leadership at the national level (Pr1 and Pr4), a good design and sound technical knowledge (Pr1, Pr2, and Pr4), and fostering early integration and collaboration among different fields of knowledge (A5, A10, and Pr4) are key for reducing the multifaceted limitations and increasing buy-in.

Normalization

Figure 6.4 clearly illustrates the influence of the normalization method on the OBI for all SUDS typologies, showing a greater impact on GR, CW & P, and PP, whereas for AST the difference is more nuanced.

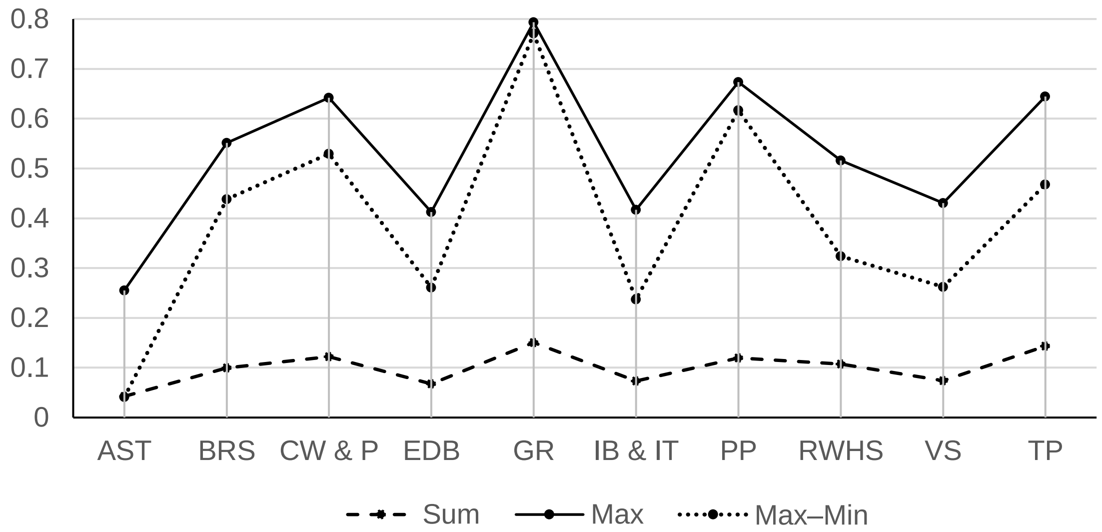


Figure 6.4 *Impact of three normalization methods on the Overall Barrier Indicator of each SUDS typology*

Mathew et al. (2017) and Vafaei et al. (2021) assessed the impact of four and six normalization techniques, respectively, using the WAM. In these studies, the normalization methods with the best performance were Max–Min (Mathew et al., 2017) and Max and Max–Min (Vafaei et al., 2021), according to Spearman's rank correlation coefficient and plurality voting, respectively. Although several authors have evaluated the influence of multiple normalization techniques with quantitative criteria (Jahan & Edwards, 2015), there is still a knowledge gap regarding qualitative criteria from scoring scales.

In the present study, the Max–Min normalization method was discarded due to the nature of its calculation (see Equation 6.3), where the lowest scores are invalidated with a value of zero, downplaying the values provided by some expert panel participants. Therefore, considering the above-mentioned studies, the selected normalization method was Linear Normalization (Max).

Final barriers' scores

The FBSs are presented in Table 6.2. Values vary from 0 to 1.00; the higher the score, the greater the barrier impact on SUDS implementation. The score distribution is quite heterogeneous (0.13-1); however, the highest values were found in technical and financial barriers. Political and urban form barriers appeared to have a more homogeneous influence across all SUDS typologies. The lowest impact in four out of the six types of barriers was found in AST, i.e., cultural/behavioral (0.13), institutional/organizational (0.13), political (0.17), and technical (0.32), whereas the lowest financial and urban form barrier impacts were found in IB & IT (0.31) and BRS and VS (0.25), respectively. The highest scores in cultural/behavioral (0.75), institutional/organizational (0.88), and political (1.00) barriers were found in TP, although the highest scores for financial (0.82) and technical (1.00) barriers were found in GR. Urban form barriers had the greatest impact on CW & P selection (1.00).

Table 6.2 *Final Barriers' Scores of 12 SUDS typologies*

SUDS typologies	Cultural/ behavioral	Financial	Institutional/ organizational	Political	Technical	Urban form
AST	0.13	0.43	0.13	0.17	0.32	0.38
BRS	0.57	0.49	0.66	0.33	0.54	0.25
CW & P	0.61	0.62	0.81	0.67	0.54	1.00
EDB	0.53	0.53	0.38	0.33	0.34	0.75
GR	0.72	0.82	0.53	0.33	1.00	0.50
IB & IT	0.33	0.31	0.31	0.33	0.54	0.38
PP	0.51	0.71	0.63	0.33	0.78	0.50
RWHS	0.56	0.75	0.50	0.33	0.46	0.50
VS	0.21	0.40	0.59	0.50	0.44	0.25
TP	0.75	0.54	0.88	1.00	0.50	0.50

MCDA application for overall barrier indicator

The MCDA weights employed in the present study were derived from a qualitative study performed in the same study area (Ortega et al., 2023b): cultural/behavioral, 0.156; financial, 0.116; institutional/organizational, 0.233; technical, 0.436; political, 0.025; and urban form, 0.033. The OBIs, calculated according to Equation 6.4, are presented in Figure 6.5.

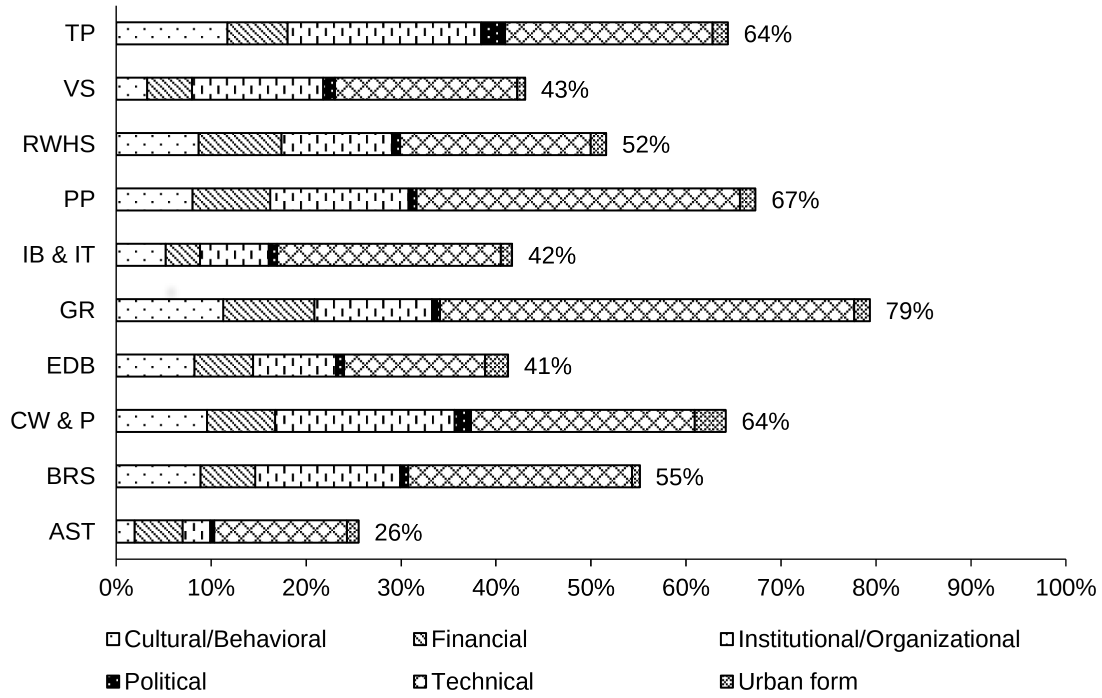


Figure 6.5 *Overall Barrier Indicator for 12 SUDS typologies*

The OBIs demonstrated the differential impact of each type of barrier across all SUDS alternatives. GR, PP, and TP were the most affected typologies, with factors of 79%, 67%, and 64%, respectively, whereas only a quarter of the potential of AST (26%) was restricted. As expected according to the FBSs and the WAM weights, technical barriers had the greatest influence across all SUDS typologies, whereas political and urban form barriers had the least impact. In turn, the influence of institutional barriers over financial ones was evident in all typologies, although to a lesser extent in AST (3%).

SUDS typologies with greater suitability in private land, i.e., AST, RWHS, and GR, had a low- (26%), medium- (52%), and high- (79%) impact OBI, respectively. This suggests that a relevant uptake might be subject to the socio-economic and socio-spatial context of analysis. Conversely, it was observed that suitable alternatives for parks/open spaces, i.e., CW & P, EDB, IB & IT, and VS, had medium-impact OBIs. This implies that their implementation might depend on other suitable land uses for each case in order to maximize their benefits. On the other hand, although BRS, TP, and PP shared some suitable spaces on public land such as plazas and sidewalks, PP had the highest OBI

(67%) among these options, suggesting a more effective application in other suitable areas such as parking lots.

6.4.2 Step 2: GIS-based analysis of physical restrictions

The results of the GIS-based analysis combining fuzzy logic and vector data analysis functions are presented in Figure 6.6. The area (%) from the suitable land use (A_{SLU}) and the area (%) from the overall study site (A_{OS}) are also displayed for each of the SUDS typologies analyzed.

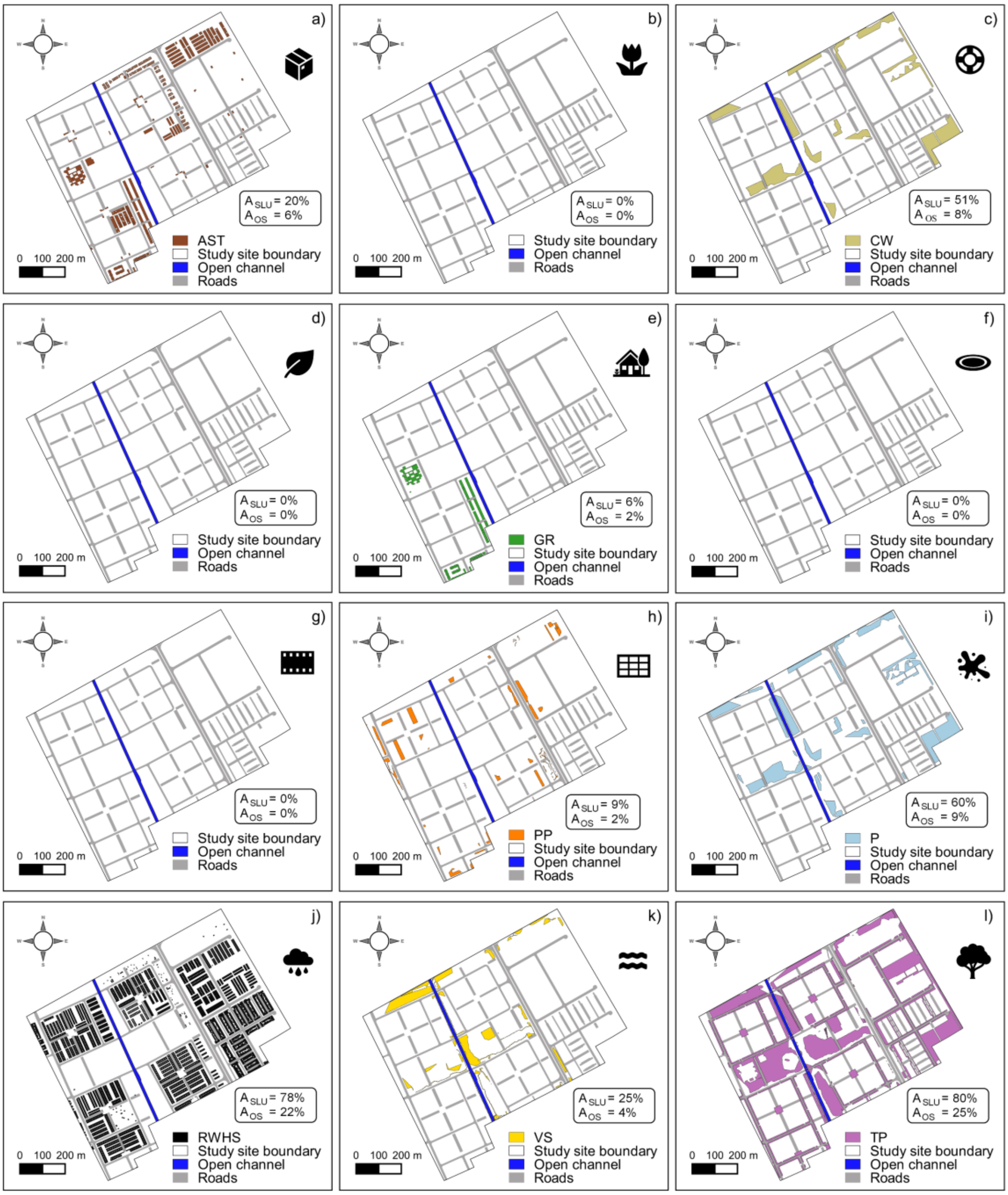


Figure 6.6 *GIS-based suitable spatial distribution of a) attenuation storage tanks (AST), b) bio-retention systems (BRS), c) constructed wetlands (CW), d) extended dry basins (EDB), e) green*

roofs (GR), f) infiltration basins (IB), g) infiltration trenches (IT), h) pervious pavements (PP), i) ponds (P), j) rainwater harvesting systems (RWHS), k) vegetated swales (VS), and l) tree pits (TP), with corresponding values of area (%) from both the suitable land use (A_{SLU}) and the overall study site (A_{OS})

BRS, EDB, IB, and IT yielded no suitable areas due to the study site's poor infiltration capacity, thus reducing the analysis from 12 initial typologies to eight alternatives that met all the physical restrictions. After the assessment of soil, size, and land-use suitability restrictions, RWHS and TP were the SUDS alternatives with the utmost capacity in the entire study area, at 22% and 25%, respectively. It is worth noting that application of both typologies would represent a mixed-land scheme since RWHS suitability is limited to private land uses (A_{SLU} = 78%), whereas TP eligibility for the present study was restricted to public space (A_{SLU} = 80%).

On the other hand, the SUDS typologies with the least competence in the entire study area were GR, PP, and VS, with A_{OS} values of 2%, 2%, and 4%, respectively. In the case of GR, the slope criterion played an important role since the prevailing slopes in the study area are above the recommended range of 0.5-5% (Hanna et al., 2019; Núñez Collado et al., 2019). Furthermore, although PP had greater chances in terms of land-use distribution suitability (plazas, parking lots, and sidewalks) compared to VS (parks/open spaces), the water table depth criterion limited the final distribution.

Conversely, CW, P, and VS (suitable in parks/open spaces) recorded A_{SLU} values of 51%, 60%, and 25%, respectively. Nevertheless, CW and P require large areas for proper performance, and their implementation might be affected by the need to compete with local recreational uses. By way of contrast, AST, GR, and RWHS were analyzed considering their suitability in buildings, with A_{SLU} values of 20%, 6%, and 78%, respectively. In this case, the tributary area restrictions were key to giving greater advantage to RWHS (5-50m^2; City of Toronto, 2021); however, its implementation can be challenging as it largely depends on the owners' will and priorities.

6.4.3 Step 3: Evaluation of the potential feasibility of SUDS implementation

The potential feasibility of SUDS implementation for the selected study site is presented in Table 6.3, contrasting the initial capacity according to the GIS-based analysis with the potential feasibility after the OBIs application. In a general analysis, it was evident the significant impact that OBIs had in SUDS planning.

For instance, considering the evaluation of 12 typologies in the study area, the potential decreased from 78% (GIS-based) to 33% (potential feasibility). Although RWHS and TP continued to report the greatest capacity, their potential was greatly reduced as a result of their high OBIs values: from 22% to 11% and from 25% to 9%, respectively. In the case of GR, the feasibility was totally annulled after the application of its OBI. Furthermore, there was a change in the ranking of alternatives. In the GIS-based analysis, TP (typology for public space) ranked first, whereas the option with greater potential feasibility was RWHS (typology for private land). A similar change was also perceived in the cases of P and CW. This prioritization, which considers limitations beyond physical restrictions, might aid in the urban water decision-making process by distributing human and financial resources more efficiently.

Table 6.3 *GIS-based potential and potential feasibility of SUDS implementation*

Initial potential A_i (GIS-based)			**Potential feasibility R_i**		
A_i (m^2)	A_i (%)	Ranking	R_i (m^2)	R_i (%)	Ranking
178 064	25%	1 TP	77 692	11%	1 RWHS
160 548	22%	2 RWHS	63 351	9%	2 TP
67 371	9%	3 P	30 722	4%	3 AST
57 725	8%	4 CW	24 129	3%	4 P
41 253	6%	5 AST	20 674	3%	5 CW
28 211	4%	6 VS	16 060	2%	6 VS
15 436	2%	7 PP	5 045	1%	7 PP
11 842	2%	8 GR	2 444	0%	- GR
0	0%	- BRS	0	0%	- BRS
0	0%	- EDB	0	0%	- EDB
0	0%	- IB	0	0%	- IB
0	0%	- IT	0	0%	- IT
Totals	78%			33%	

The results of the community consultation on three potential private land SUDS typologies, i.e., RWHS, GR, and BRS, were intriguing and merit further exploration. Of a total of 148 interactions, 96 community members decided to participate, and 52 refrained from responding. Surprisingly, of the 112 opinions received (some participants indicated more than one alternative), 42% indicated that they would not be willing to implement any of these options, citing property ownership issues, lack of financial resources, time and work burden, and lack of space. This might be critical to achieving effective adoption of SUWM strategies if community-led programs must be prioritized. The rest of the opinions revealed interest in RWHS, GR, and BRS at 34%, 13%, and 12%, respectively. As RWHS ranked highest in the potential feasibility analysis, its popularity among community members can inform the development of bottom-up and top-down initiatives. Conversely, although some respondents expressed interest in GR and BRS, implementation of the former alternative sharply contrasts with its potential feasibility results (0%), whereas the second one was excluded from further analysis due to the poor infiltration capacity of the study area's soil. This emphasizes the significance of understanding potential users' motivations, which should be supplemented by education and awareness campaigns.

6.5 Discussion

A transdisciplinary method to assess the potential feasibility of SUDS was developed with the aim of assisting in the promotion of SUWM strategies and complementing scholars' efforts in the efficient selection and location of these strategies (Aceves & Fuamba, 2016b; Alves, Gersonius, et al., 2018; Jia et al., 2013).

The first step of the methodology is the *Barrier impact assessment*. Although several studies have addressed the hindrances to the adoption of SUWM strategies (Gashu & Gebre-Egziabher, 2019; Kim et al., 2017; Wihlborg et al., 2019), to the best of our knowledge, the quantification of these limitations according to each typology has not been comprehensively covered in the literature. The present study demonstrated the differential impacts of six types of local context constraints on SUDS planning and provided a robust matrix with individual scores for 12 different SUDS typologies (Table 6.2). Contrary to previous research in which socio-political barriers had greater influence (L. Li et al., 2020; Thorne et al., 2018), technical and financial barriers were found to have a significant impact.

It is worth noting that the FBSs results are intended to be indicative rather than definitive. Nevertheless, input from both academics and practitioners provides valuable knowledge for places with incipient experience in SUDS planning, and the inclusion of stakeholder-derived MCDA weights strengthens the barrier impact assessment by considering the challenges of the local context. This improves representativeness and facilitates a more comprehensive understanding of the hindrances that must be overcome for effective SUDS implementation and long-term operation.

The second step of the proposed methodology is the *GIS-based analysis of physical restrictions*. The coupling of fuzzy logic with GIS tools has proven to be a robust approach to managing large amounts of data and providing informed results, useful in spatial planning and urban water management. Many authors have highlighted the importance of considering site conditions in the selection of sustainable alternatives for stormwater runoff management (Saadat Foomani & Malekmohammadi, 2020; Young et al., 2010). In the present methodology, this is not a concern since soil characteristics, size constraints, and land-use suitability are required and incorruptible criteria of analysis. This represents an advantage within the decision-making space because it resembles a preselection of alternatives, thus avoiding conflicts with further assessment of stakeholders' preferences on a theoretical basis. Nevertheless, it should be noted that GIS-based analysis results depend directly on the quality of the information (Arthur & Hack, 2022).

The third and final step is the *Evaluation of the potential feasibility of SUDS implementation*. This stage, in addition to integrating steps 1 and 2, reflects the three *dimensions of integration* described by Mauser et al. (2013), i.e., scientific, international, and sectoral, through a co-production of knowledge enabled by the contributions of relevant actors in urban water management (academics, practitioners, the public and private sectors, and community members) and concepts and methods from different disciplines (specialized SUWM literature, MCDA, fuzzy logic, and GIS tools). The results of Step 3 are intended to facilitate the assessment of SUWM strategies from a more realistic point of view, as they provide a useful ranking derived from the comprehensive evaluation of the physical restrictions and local context limitations. This contribution is highly relevant for decision-making in regions where SUDS implementation is poor or nonexistent, in order to redirect efforts and funding towards options that have a greater chance to demonstrate effective operation (Roy et al., 2008). The SUDS distribution provided in Step 2 can be used to supplement the results of Step 3, as the GIS-based analysis identified the sites with the greatest physical capacity, providing a reliable approximation of the optimal site. Further research might consider maximization of benefits for the final SUDS placement (Uribe-Aguado et al., 2022).

The methodology was successfully tested at the neighborhood scale in Bogotá, Colombia. The selected case study is relevant to the analysis of alternative stormwater runoff management and sustainable urban planning due to its highly urbanized condition in a developing city. The results of the SUDS potential feasibility evaluation revealed how the initial GIS-based potential can be considerably reduced when local constraints are considered. Furthermore, community preferences were investigated and contrasted with the results of the potential feasibility analysis, which differed from the built environment's capabilities to some extent. Although the results of this consultation process might diverge if the perceptions of neighborhood associations (Carriquiry et al., 2020) or community groups (Thaler et al., 2019) are investigated, identifying potential users' motivations and needs is the first step toward raising society's awareness and effectively involving communities in the design, construction, and operation of SUDS (Lamond et al., 2020).

6.6 Conclusions

This paper proposed a transdisciplinary approach to more effective SUDS planning and implementation. The main contributions include (i) a barrier impact quantification for each of the 12 different SUDS typologies and (ii) a framework for the comprehensive evaluation of the potential feasibility considering physical constraints and six types of local context limitations. This study is highly relevant in regions where SUDS implementation is poor or nonexistent since it allows efforts and funding to be conveyed towards options with a greater chance of presenting significant results. Nevertheless, the proposed three-step approach is flexible and can be easily adapted to a range of settings beyond the immediate study area. The methodology is a complementary and holistic tool to assist architects, engineers, urban planners, and urban water decision-makers, not only for the efficient planning of SUDS but also to tackle the decision- and policy-making challenges of highly urbanized areas for the construction of sustainable and flood-resilient cities.

The greatest limitation of the present study is the degree of involvement of the participants, obtained through a consulting transdisciplinary approach. Further research is needed to achieve participatory transdisciplinarity (Mobjörk, 2010), fostering knowledge exchange and re-integration of knowledge into social practice. Moreover, since the analysis of interrelationships among barriers was outside the scope of this study, future work may investigate the impact of these connections to simplify the scoring. Furthermore, incorporating hydrological-hydraulic models would also strengthen the assessment of the physical criteria and a multi-scenario analysis.

7 Hydrologic-hydraulic assessment of SUDS control capacity using different modeling approaches: A case study in Bogotá, Colombia

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7.1 Abstract

Urban flooding has increased in response to impervious surface intensification, the loss of green areas, and high-intensity rainfall associated with climate change. Sustainable urban drainage systems (SUDS) are an appealing option for stormwater management; however, their hydraulic control capabilities have received little attention. We developed a comparative model-based approach with 24 scenarios to contrast the hydrologic and hydraulic response of a highly discretized (HD) 1D model and a coupled 1D–2D model, considering the impact of rainwater harvesting systems and tree pits. An additional scenario was modeled including attenuation storage tanks, green roofs, and pervious pavements. A heavily urbanized flood-prone catchment with severe land-use constraints in the city of Bogotá, Colombia, was selected for analysis. The findings revealed that SUDS can contribute to reducing the number of flooded junctions, overloaded conduits' length, overloading time, nodal inundation depth, and waterlogging extent. Furthermore, the HD 1D model can reproduce the coupled 1D–2D model results in terms of hydrologic response and some hydraulic control indicators. Further research is needed for an accurate description of the internal hydraulic mechanisms of SUDS interacting with overland flow. The key findings of this study provide model-based evidence to support urban stormwater management decision-making in data-scarce environments.

Keywords: 1D model, 2D model, green infrastructure, hydraulic response, stormwater management, overland flow

7.2 Introduction

Rapid urbanization has induced abrupt changes in land use, affecting natural hydrologic processes and flood patterns in cities (Akhter & Hewa, 2016). The loss of green areas and the intensification of impervious surfaces have produced an adverse increase in runoff volumes and peak discharges (Qin, 2020). This is aggravated by high-intensity rains associated with climate change (IPCC, 2022). Furthermore, the limited capacity of the existing drainage network increases the risk of waterlogging and pluvial flooding (Maksimović et al., 2009). In some cases, expansion of the conventional pipe-ended drainage system is not always feasible due to space restrictions or financial constraints (Taji & Regulwar, 2019). Therefore, past studies have stressed the importance of studying sustainable urban drainage management (SUDM) strategies such as best management practices (BMP), green infrastructure (GI), low impact development (LID) techniques, and sustainable urban drainage systems (SUDS) (Vogel et al., 2015).

SUDS have gained significant attention as urban flood risk management strategies (Gimenez-Maranges, Breuste, et al., 2020) since they attempt to replicate the natural pre-development drainage conditions. The Ministry of Housing, City, and Territory of Colombia introduced the concept of SUDS in 2017 as a strategy to mitigate the effect of soil sealing caused by new urban developments (Ministry of Housing of Colombia, 2021). Bogotá, the capital city of Colombia, has championed SUDS implementation through local design and construction guidelines since 2018 (EAAB, 2018). Despite this, urban water decision makers are still hesitant regarding SUDS' hydraulic control capabilities and the impact on the existing drainage system due to efficiency uncertainties and a lack of quantitative evidence (Ortega et al., 2023b).

The most widely used hydrodynamic models for assessing the performance of SUDM strategies include the US Environmental Protection Agency Storm Water Management Model (EPA SWMM5 or SWMM5) (Rossman & Simon, 2022), the Personal Computer Storm Water Management Model (PCSWMM) (Computational Hydraulics International (CHI), 2023), MIKE URBAN (DHI, 2019), the Model for Urban Stormwater Improvement Conceptualization (MUSIC) (eWater, 2015), and InfoWorks ICM model (Innovyze, 2019). The application of these models in the study of SUDM has primarily focused on the hydrologic response (e.g., reduction of runoff volume and peak discharge), often neglecting or generalizing the interaction with the pipe-ended drainage network (Cui et al., 2019). Nevertheless, the complexity of urban systems requires more advanced approaches that consider the interaction between one-dimensional (1D) sewer flows and two-dimensional (2D) overland flows (Chang et al., 2015), which are altered by flow-path modifying elements such as buildings, streets, and pavement curbs (Blanc et al., 2012).

The increase in high-quality information availability, advanced computer capacity, the inclusion of geographic information systems (GIS), and new mathematical approaches have enabled the development of coupled 1D–2D models (Pina et al., 2016). Coupled 1D–2D models simulate flood propagation on the ground surface through 2D grid cells (Chang et al., 2015) and can represent the bidirectional discharge between the 1D and 2D domains using direct links or weir/orifice-type elements (Maksimović et al., 2009). Few studies have assessed SUDM alternatives' performance through coupled 1D–2D models, mainly focusing on their flood mitigation capabilities. For instance, Ellis and Viavattene (2014) reported an improved visualization of the flooding mechanisms at any location by adopting a 1D–2D flow model to investigate the most suitable SUDS options to reduce flood extent and depth. Moreover, Haghighatafshar et al. (2018) investigated the collective impact of blue-green retrofits in reducing flood volumes and depths through a coupled 1D–2D model, which facilitated the analysis of the interaction between the existing pipe-ended drainage system and the overland flow at a catchment/neighborhood scale. These studies highlighted the complexity of urbanized watersheds due to the topographic surface, interaction with drainage infrastructure, and land use conflicts. Nevertheless, research assessing the hydraulic control capabilities of SUDM strategies, i.e., the impact on the surcharging and flooding dynamics of the existing drainage network elements such as manholes and pipes (Cui et al., 2019; Mu et al., 2022), is lacking.

Coupled 1D–2D models enable a more detailed representation of surface geometry and flow physics (Vojinovic & Tutulic, 2009) while avoiding simplifications of the hydrologic processes and the hydraulic network (Pina et al., 2016). Nonetheless, these robust modeling approaches require high-resolution terrain data and can be computationally prohibitive, limiting their reproducibility (Blanc et al., 2012; Maksimović et al., 2009). Therefore, there is a need for feasible modeling alternatives that can be employed in data-scarce places to foster the implementation of SUDM.

Considering the aforementioned gaps, the present study aims to develop a comparative model-based approach comprised of a highly discretized (HD) 1D sewer model and a coupled 1D–2D hydrodynamic model. The objectives are to contrast (i) data requirements, model construction process, and computational costs; (ii) the ability of the HD 1D model to reproduce the hydrologic and hydraulic response of the 1D–2D model; (iii) SUDS hydrologic performance in terms of peak discharge and total outflow volume reduction; (iv) SUDS hydraulic control capabilities according to the number of surcharged junctions, the number of flooded junctions, the overloaded conduits' length, and the average overloading time; and (v) SUDS flood control potential in terms of maximum nodal inundation depth and waterlogging extent. The study site is a highly urbanized catchment in Bogotá that frames an interesting case study for improved sustainable stormwater management given its particular condition as waterlogging- and flood-prone area, with limited potential for SUDS implementation on both private and public land.

7.3 Methodology

7.3.1 Study area

The study site is located in Bosa, one of the twenty administrative divisions (*localidades*) of Bogotá, the capital city of Colombia. Bosa is located to the south-west of Bogotá with a predominant residential land use (87%) (Galindo, 2013). The mean annual precipitation in Bosa ranges between 620-700 mm with a bimodal distribution: the first rainy period corresponds to April and May and the second falls from October to December. Although Bosa is served by a separate storm sewer system, by 2012 about 68% of its total area registered some level of flood exposure. The low-lying nature of the land, as well as large social housing projects that have reduced the soil's natural permeability, have contributed to Bosa's flood vulnerability (Rojas, 2018).

The selected 50-ha neighborhood has a permanent waterlogging exposure and belongs to the area disturbed by a massive sewage and drainage backflow effect that affected over 6 000 households in December 2011, triggered by the submersion of the delivery and pumping systems during that winter season (FOPAE, 2011). The study area location and land-use distribution are portrayed in Figure 7.1. The study site is occupied by 28% of buildings, 16% of pervious areas, 12% of roads, 9% of sidewalks, 6% of plazas, 3% of corridors (mix of pervious and impervious surfaces), and 1% of water bodies, i.e., an open channel. The remaining 25% is under the category “others” and is considered an impervious surface. Therefore, around 81% of the study area is assumed to be impervious. The highly urbanized and waterlogging- and flood-prone conditions of the study site provide an insightful case study for assessing the opportunities and limitations of SUDS as sustainable stormwater and flood management strategies, both on public and private land.

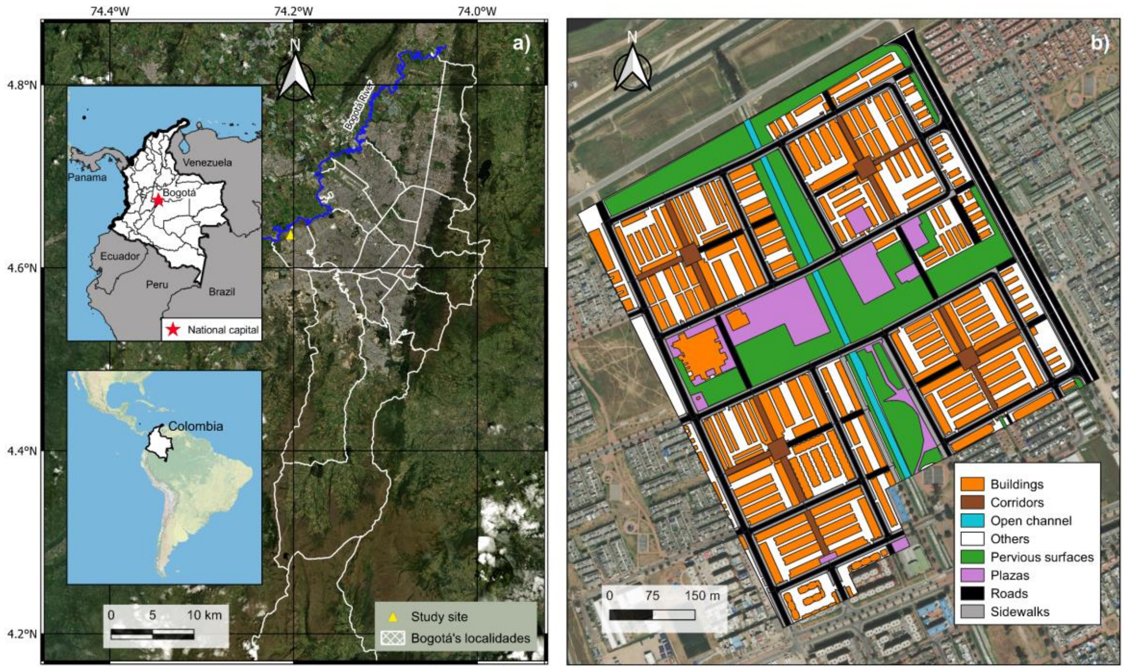

***Figure 7.1** Study site a) location and b) land-use distribution*

Data collection and pre-processing

Input data used to create the HD 1D sewer model and the coupled 1D–2D model included terrain condition, land-use distribution, and drainage network information. Catchment delineation and data pre-processing were performed using QGIS Desktop software version 3.16.0-Hannover.

A digital elevation model (DEM) was developed from 1-meter contour line information provided by the local water utility (LWU) from a terrestrial LiDAR survey. Land-use discretization was performed with vector layer data freely available in Bogotá’s Spatial Data Network (www.ideca.gov.co). In the case of unclear information, field observations and Google Earth Pro version 7.3.4.8248 were used to contrast the polygon vector information. Raster data for infiltration capacity (50-meter cell size) and water table depth (250-meter cell size) were obtained from a city-scale project led by the Secretary of the Environment and the LWU to develop SUDS planning and design guidelines (Universidad de los Andes, 2015).

Drainage system information was provided as vector layer data by the LWU. Duplicated elements (manholes, pipes, and outfalls), unconnected manholes, and dead-end pipes were removed in order to achieve model accuracy (Hua et al., 2020). Then, manholes' and pipes' invert elevations were inspected to detect anomalies. During this process, it was found that none of these elevations agreed with realistic values according to the study site's ground elevation as extracted from DEM (on average 30 m above ground level). For this reason, manholes' rim and invert elevations, as well as pipes' inlet and outlet elevations, were adjusted using DEM elevations and drainage system geometry information.

Observed data to perform a calibration process was not available as drainage sewer flow is not routinely monitored by local authorities in Bogotá. Therefore, flow observation campaigns were conducted between April 29 and May 14, 2022, at one of the open channel's outlets; however, the results only reflected the contributions to baseflow, and an adequate representation of the local drainage system's response to a rainfall event was unsatisfactory.

Data scarcity for calibrating flood models is a technical and financial challenge often present in urban areas (Schmitt et al., 2004); therefore, finding flexible solutions to provide significant results within the framework of urban water decision-making is key. Alternative approaches include the use of information from citizen's observations, news, surveillance cameras, and social media images (Assumpção et al., 2018; Moy de Vitry & Leitão, 2020). In the case of Bosa, information from an official report of the local risk management authority (IDIGER, by its acronym in Spanish) was used in a validation process, which described a sudden rise of 0.95 m in the open channel's water level (Santa Isabel Channel) after a 30.4 mm rainfall event on December 14, 2011 (FOPAE, 2011). Rainfall data of 5-minute resolution was retrieved from an online platform (www.sire.gov.co) managed by IDIGER.

7.3.2 Model theory

The present study employed PCSWMM to develop the HD 1D model and the coupled 1D–2D model. PCSWMM uses the EPA SWMM5's hydrology and hydraulic engine and additional group-decision support tools such as GIS technology (James et al., 2010) to provide strong and powerful simulation capacities in urban environments. SWMM5 is a physically based, discrete-time simulation model in which surface runoff outflow is given by Manning's equation and flow routing within a conduit obeys Saint-Venant's continuity and conservation of momentum equations (James et al., 2010). Depending on the level of sophistication and modeling needs, three routing methods can be selected: steady flow, kinematic, and dynamic wave routing. Furthermore, infiltration outflow can be modeled by Horton's equation, the Green-Ampt Method, and the Curve Number Method.

In the 1D domain, each sub-catchment is treated as a non-linear reservoir. Inflow comes from rainfall or any user-defined upstream flow, and surface runoff occurs when the depth of water in the reservoir exceeds the maximum depression storage (James et al., 2010). On the other hand, the 2D domain is discretized as a set of nodes (2D junctions) and open conduits without walls (2D conduits), constituting a 2D mesh that captures the topography extracted from DEM (Leitão et al., 2010). Free surface flow between the 2D junctions and the 2D conduits is solved by using the 1D Saint-Venant flow equations. Moreover, a simultaneous transition between the 1D and 2D domains is possible according to the connectivity of the link-node system, i.e., inlet control bottom orifices or direct connections.

7.3.3 Model setup

This study adopted dynamic wave theory to estimate flow routing. Dynamic wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results (Butler et al., 2018), allowing for an adequate representation of the nodal surcharging and flooding conditions as well as the flow interaction between the major and minor drainage systems. A schematic representation of the HD 1D model and the coupled 1D–2D model development is shown in Figure 7.2. A full description of the model setup in the two modeling approaches is given below.

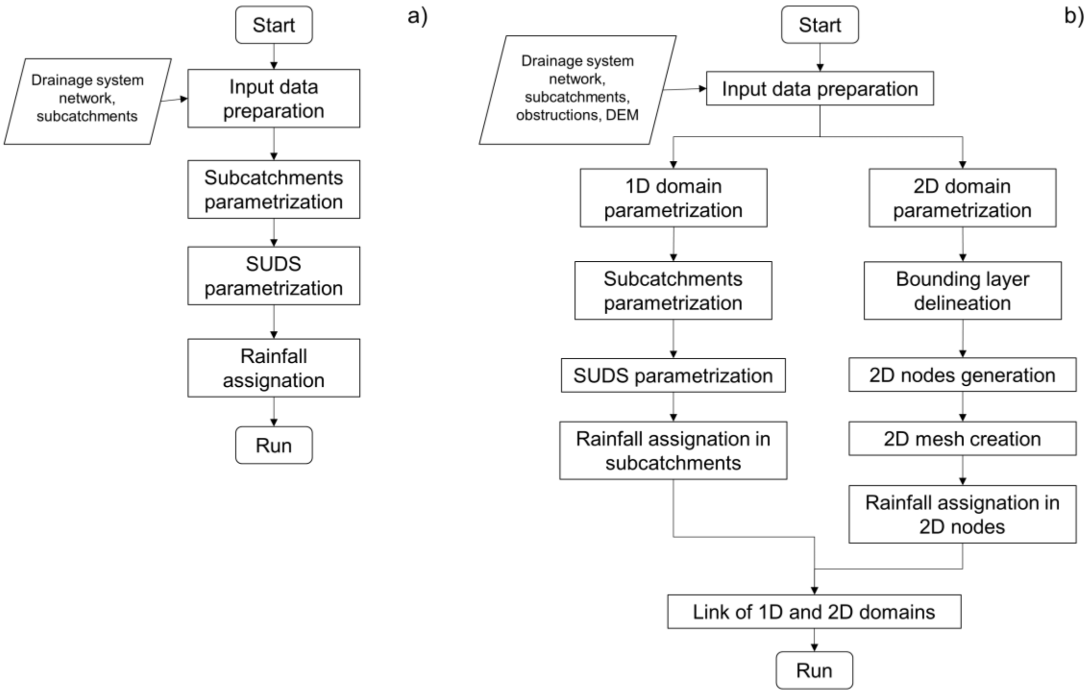

Figure 7.2 *Schematic representation of the model setup considering SUDS assessment in a) the highly discretized 1D model and b) the coupled 1D–2D model*

Highly discretized 1D model parametrization and setup

A 1D rainfall-runoff model was developed considering the drainage network information (manholes or junctions, pipes or conduits, and outfalls) and the highly discretized land-use distribution of the study site. An inflow boundary condition was defined by delineating the corresponding upstream land-use distribution (buildings, roads, and pervious surfaces) and the drainage network.

The conduits' roughness attribute, i.e., Manning's roughness coefficient, was assigned according to the material type, being 0.015 for concrete pipes and 0.01 for PVC pipes. The trapezoidal open channel (see Figure 7.1) was delineated through multiple conduits with concrete lining, i.e., Manning's roughness coefficient of 0.015. An entrance loss coefficient of 0.05 was assigned to all conduits, whereas an exit loss coefficient of 1 was assigned to those elements discharging into the receiving water body (Butler et al., 2018), i.e., the open channel. Excess volume was assumed to pond over the manhole, preventing water from being lost from the system. Therefore, all 1D junctions were assigned a ponding area of 400 m^2 whereas this parameter for the open channel junctions was expressed according to the upstream and downstream conduits' length. The ponding area value is irrelevant within the framework of analysis in this study, since it is not intended to compare the flooding volume produced by the two modeling approaches. Nonetheless, using a non-zero ponding area instead of surcharge depths enables flow excess to accumulate atop the node and reenter the system when downstream capacity becomes available.

In order to have a realistic approximation to the overland flow generated by the 2D approach, each polygon of all land-use vector layers (buildings, corridors, roads, pervious areas, plazas, sidewalks, and others) was treated as a unique sub-catchment. Parameters of slope (%), area (m^2), width (m), impervious percentage area (%), Manning's *n* overland roughness values, and depression storage (mm) are summarized in Table 7.1.

Table 7.1 *Summary of sub-catchment attributes in the highly discretized 1D model*

Type of sub-catchment	Slope (%)	Area (m^2)	Width (m)	Imperv. (%)	Manning's *n* – overland flow	Depression storage (mm)
Buildings	2–30	10–5200	0.09–140	100	0.01 (I)	0.128–0.495
Corridors	0–1	670–1000	0.80	40	0.014 (I); 0.15 (P)	0.747 (I); 2.285 (P)
Others	0–8	10–2300	0.80	100	0.05 (I)	0.873*
Pervious surfaces	0–9	80–14900	0.80	0	0.15 (P)	2.285*
Plazas	0–3	160–12000	0.80	100	0.014 (I)	0.875*
Roads	0–5	100–1400	0.80	100	0.1 (I)	0.836*
Sidewalks	0–11	30–900	0.80	100	0.12 (I)	0.747*

I: Impervious surface; P: Pervious surface
*Calculated with the average slope

Slope values for the building sub-catchments, i.e., buildings' rooftops, were assigned according to field investigations and with the aid of Google Maps' street view tool. In the remaining land uses, the slope attribute was calculated from the DEM. Area and flow length for buildings' sub-catchments were calculated using QGIS; the width attribute was computed as the ratio of area to flow length. In the remaining sub-catchment types (corridors, others, pervious surfaces, plazas, roads, and sidewalks), area was also calculated through QGIS, but the width parameter was adjusted to a uniform value of 0.80 m as a result of the validation process (see Section 7.4.1). With the aim of replicating the 2D overland flow propagation, a flow routing strategy to the nearest element was defined: building runoff to sidewalks; sidewalk and others runoff to roads; and runoff from pervious surfaces, corridors, and roads to manholes. The depression storage was calculated as

$$d = \frac{\sqrt{k}}{s} \tag{7.1}$$

where *d* (mm) is the depth of depression storage, *k* is a coefficient depending on surface type (0.07 and 0.28 for impervious and pervious surfaces, respectively), and *s* is the sub-catchment slope (Butler et al. 2018). Manning's *n* overland flow roughness values were assigned considering the surface material, following the recommendations found in James et al. (2010).

The Horton equation was employed to estimate infiltration losses, considering its practical utility, simplified data requirements, and ability to reflect in-situ conditions (Rasool et al., 2021). The semi-empirical Horton model has proven to be efficient in predicting infiltration processes in lawn soils (Duan et al., 2011) with low infiltration rates (Rasool et al., 2021), both characteristics of the present case study. The values used for initial and final (soil's saturated hydraulic conductivity) infiltration rates were 1.80 mm/h and 0.05 mm/h, respectively, according to infiltration raster data (see *Data collection and pre-processing*). The decay constant and drying time values were 2 (1/hours) and 7 (days), respectively (Butler et al., 2018; Rossman, 2015), considering Sandy Clay Loam is predominant in the study area. Finally, the HD 1D model consisted of 95 1D conduits, 95 1D junctions, 1 outfall, and 804 sub-catchments, excluding the elements from the upstream boundary condition.

Coupled 1D–2D model parametrization and setup

An integrated 1D–2D model allows for the representation of the interaction between the minor and major drainage systems (1D and 2D domains, respectively), considering the multiple flow pathways around and through obstructions such as buildings and walls. Due to the high computational load, the 1D–2D approach did not model the upstream boundary condition as in the HD 1D model (see *Highly discretized 1D model parametrization and setup*). Instead, inflow hydrographs were assigned to the most upstream open channel junction.

The 1D domain of the coupled 1D–2D model replicated the drainage system parametrization employed in the HD 1D model. Nevertheless, instead of using a ponding area in the network junctions, a surcharge depth of 30 m was assigned to avoid double accounting of overland flow. Furthermore, only building and sidewalk polygons were assigned as sub-catchments, leaving the rest of the land uses within the 2D domain. This is done in order to reduce the computational load involved in creating the 2D mesh with multiple (buildings) and narrow (sidewalks) polygons. The routing strategy considered building runoff to sidewalks and sidewalk runoff to the nearest 2D junction. The 1D domain of the 1D–2D model consisted of 95 1D conduits, 95 1D junctions, 1 outfall, and 424 sub-catchments.

The 2D domain construction in PCSWMM comprises three main steps, i.e., bounding layer delineation, 2D node generation, and 2D mesh creation. The bounding layer defines the extent of the 2D model and can consist of multiple polygons to represent subareas' roughness and infiltration parameters. In the present study, the bounding layer included pervious surfaces, roads, and the overall bounding polygons. Type of mesh, resolution, roughness, and seepage rates (to represent infiltration within the 2D cells) are described in Table 7.2. Mesh types in PCSWMM include hexagonal, rectangular, directional, and adaptive. Hexagonal and rectangular mesh types, which generate uniform cells specified by the cell resolution, provide a better representation of open areas and roadways, respectively. Moreover, the PCSWMM's 2D interface allows adding an obstructions layer, which in this study included the building and sidewalk polygons.

Table 7.2 *Attributes of the bounding layer for 2D nodes generation*

Bounding layer polygons	Mesh type	Resolution (m)	Roughness	Seepage rate (mm/h)
Overall bounding polygon	Hexagonal	5	0.05 (urban surfaces)[a]	n/a
Pervious surfaces	Hexagonal	5	0.15 (grass, short)[a]	0.351[b]
Roads	Rectangular	3	0.011 (smooth asphalt)[a]	n/a

[a] Butler et al. (2018)
[b] Raster calculation with Zonal Statistics tool in QGIS
n/a: not applicable

After parametrizing the bounding layer, 2D nodes are generated, allowing the 2D cells' approximate locations and their elevations from DEM to be defined. In this step, elevations of 2D nodes within the roads and pervious surfaces bounding polygons were lowered by 1 mm and 2 mm, respectively, to represent the depression storage parameter. Afterwards, the 2D mesh is created, allowing 2D nodes to be connected through 2D conduits (open rectangular channels). The 2D model was comprised of 11 475 2D junctions, 22 875 2D conduits, and 11 474 2D cells.

The present study adopted bottom orifices to connect the 1D and 2D domains. Orifices can represent the catchbasins into which overland flow enters and is then conveyed by the pipe-ended system. Therefore, bottom orifices were defined by a rectangular cross-section with 1.20 m of width (to represent two 0.60 m-catchbasins per manhole) and 0.12 m of height (according to field observations). The dynamic wave routing method selected to solve the 2D approach allows two inlet capacity constraints to be modeled using bottom orifices, i.e., inflow or upwelling. This is useful to represent surface flooding from a surcharged manhole.

7.3.4 Model validation

Calibration of urban drainage models is a challenging task, constrained by the availability of detailed monitoring data that considers major and minor drainage system interactions (Hunter et al., 2008; Moy de Vitry & Leitão, 2020; Schmitt et al., 2004). Nevertheless, accurate flow path description (Schmitt et al., 2004) and the use of plausible ranges of friction parameters (Hunter et al., 2008) can reduce the uncertainty of model predictions. This is the case for the HD 1D model and the coupled 1D–2D model developed in the present study. Considering the above and the absence of monitored data from the local drainage network, a validation strategy was established based on (i) open channel water depth information and (ii) a hydrologic-hydraulic performance comparison between the two modeling approaches.

The water depth results in the open channel, from both the HD 1D model and the coupled 1D–2D model, were compared with information from an official report on a severe rainfall event during the second rainy season of 2011 (see *Data collection and pre-processing*). The relative error (RE) was employed as evaluation criteria, according to

$$RE = \frac{x_o - x_s}{x_o} \tag{7.2}$$

where x_o is the observed water depth value (0.95 m) and x_s is the average simulated water depth in the open channel' conduits.

1D–2D models are a solid tool for modeling urban floods, being able to provide enough detailed data in terms of discharge through inlets and water levels (Leandro et al., 2011). The use of both a fine grid resolution and the same drainage network boundary conditions (Leandro et al., 2009) enables meaningful comparisons between sewer-based model and sewer/surface model results. The present study employed a 1 m x 1 m grid cell resolution and the same drainage network parametrization in the two developed models. Therefore, the 1D–2D model's outfall discharge time series was employed as a benchmark for the HD 1D model. Fitness of the model was evaluated through the Nash-Sutcliffe Efficiency (NSE) coefficient, where $NSE<0.65$ is unsatisfactory; $0.65<NSE<0.80$, acceptable; $0.80<NSE<0.90$, good; and $NSE\geq0.90$, very good (Ritter & Muñoz-Carpena, 2013). Furthermore, the hydraulic performance agreement was assessed according to the number of surcharged nodes, the number of flooded nodes, the overloaded conduits' length, and the average overloading time. RE (Equation 7.2) was employed as evaluation criteria for this assessment, considering the 1D–2D results as observed data (x_o).

7.3.5 Comparison of the two modeling approaches

Relative error (RE) and root mean square error (RMSE) were chosen as indicators to compare the degree of similarity between the results achieved by the 1D HD model and the coupled 1D–2D model. RE denotes the reliability of the predicted value (C. Li et al., 2018), and it was employed to compare the reproducibility capacity of the HD 1D model against the more accurate results of the 1D–2D model (Leandro et al., 2011), following Equation 7.2. RMSE is also an indicator to evaluate the fitness of the model in terms of the units of the variable, where values close to zero indicate satisfactory model performance (Ritter & Muñoz-Carpena, 2013):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \tag{7.3}$$

where O_i and P_i represent the observed (1D–2D model results) and model estimates (HD 1D model results) values, respectively, and N represents the number of observations, which in the present study correspond to the number of scenarios (12).

7.3.6 Scenario analysis

Selection, location, and parametrization of SUDS

The present study assessed different SUDS typologies for implementation on public and private land. For private land, three SUDS typologies (green roofs, rainwater harvesting systems, and attenuation storage tanks) were considered and evaluated using the transdisciplinary approach for assessing the SUDS potential feasibility proposed by Ortega et al. (2023a). In this approach, the GIS-based results of a physical restrictions assessment (soil characteristics, size constraints, and land-use suitability) are constrained by the evaluation of six local context barriers (cultural/behavioral, financial, institutional/organizational, technical, political, and urban form), providing a percentage of feasible implementation. After this assessment, rainwater harvesting systems (RWHS) were selected and distributed according to a potential feasibility rate of 48%.

Furthermore, tree pits (TP) were selected as SUDS typologies for public land, obeying current conditions of SUDS implementation in the city of Bogotá. Bogotá's LWU issued design and construction guidelines in 2018 to foster the implementation of attenuation storage tanks, bio-retention systems, extended dry basins, pervious pavements, infiltration trenches, and TP. Nevertheless, operation and maintenance liabilities have affected the assessment of large-sized strategies, turning most of the efforts towards TP pilot projects. Therefore, after the evaluation of physical restrictions, the present study used the current tree distribution of the study area for TP location. This approach is an attempt to determine if the conversion of tree units to TP units could have a hydrologic-hydraulic impact on the study site. In summary, alongside with considering physical constraints, RWHS and TP were selected based on the assessment of local context barriers and current pilot projects, respectively. Moreover, a combination of these two

SUDS measures was tested as a representation of a complete scheme operating on both public and private land.

SUDS can be modeled in PCSWMM as LID controls. They are considered properties of a given sub-catchment (new or existing) and are designed to capture surface runoff via infiltration, detention, and/or evapotranspiration processes through different vertical layers whose properties are defined on a per-unit-area basis (James et al., 2010). Therefore, in both the HD 1D model and the coupled 1D–2D model, RWHS were assigned as units to building polygons, whereas TP were assigned as units to sidewalk polygons. Table 7.3 shows the parameters employed in this study to describe the different layers of RWHS and TP based on specialized literature and detailed construction drawings utilized by the urban development institute (IDU, by its acronym in Spanish) in the city of Bogotá.

Table 7.3 *Parameter values for SUDS design*

Layer	Parameter	TP	RWHS
Surface	Berm height (mm)	200 [a]	n/a
	Vegetation volume (fraction)	0.1 [b]	n/a
	Surface roughness (Manning's n)	0 [b]	n/a
	Surface slope (%)	0 [b]	n/a
	Swale side slope (run/rise)	n/a	n/a
Soil	Thickness (mm)	800 [a]	n/a
	Porosity (volume fraction)	0.6 [a]	n/a
	Field capacity (volume fraction)	0.11 [b]	n/a
	Wilting point (volume fraction)	0.05 [b]	n/a
	Conductivity (mm/hr)	70 [c]	n/a
	Conductivity slope	5 [b]	n/a
	Suction head (mm)	61 [b]	n/a
Storage	Thickness (mm)	700 [a]	900 [d]
	Void ratio (voids/solids)	0.5 [b]	n/a
	Seepage rate (mm/hr)	500 [b]	n/a
	Clogging factor	0	n/a
Underdrain	Drain coefficient (mm/hr)	3 [b]	2.5 [b]
	Drain exponent	0.5 [b]	0.5 [b]
	Drain offset height (mm)	200 [a]	100
	Drain delay (hours)	n/a	24

[a] IDU (2019); [b] James et al. (2010); [c] Universidad de los Andes (2017); [d] Baek et al. (2015)
n/a: not applicable

Design storms

Cities' drainage systems are designed to retain runoff generated by storms of a certain return period since using the most extreme rainfall conditions would result in very expensive infrastructure to build and operate (Schmitt et al., 2004). Therefore, analyzing SUDS under local design storms allows for the verification of their hydrologic and hydraulic control potential as complementary systems to the existing drainage network

(Haghighatafshar et al., 2020). This is especially useful at sites where monitored data is unavailable, as is common in overland flow assessments.

In the present study, the hydrologic-hydraulic impact of RWHS and TP on a highly urbanized watershed was assessed with synthetic storm events of 5-, 10-, and 100-year return period, corresponding to Bogotá's drainage system design criteria for the local network, major arterials, and open channels, respectively (EAAB, 2020). In a previous study, the intensity-duration-frequency curves were calculated using data from an adjacent rain gauge (4°36'45.5"N, 74°11'05.9"W; ≈3 km from the study site centroid), assessing annual rainfall time series of maximum intensities for durations between 15 and 360 minutes (INGETEC, 2014). The local parametric equation is given by

$$I = \frac{1\,511.9\,T^{0.143}}{D^{0.99} + 24.6} \tag{7.4}$$

where *I* is the storm intensity (mm/h), *T* is the return period (year), and *D* is the storm duration (min). The local rainfall patterns were calculated using the alternating block method (Movahedinia et al., 2019) and 180 minutes of rainfall duration, which was indicated as the maximum threshold from which discharged flows tend to be constant (INGETEC, 2014). The calculated synthetic hyetographs are shown in Figure 7.3.

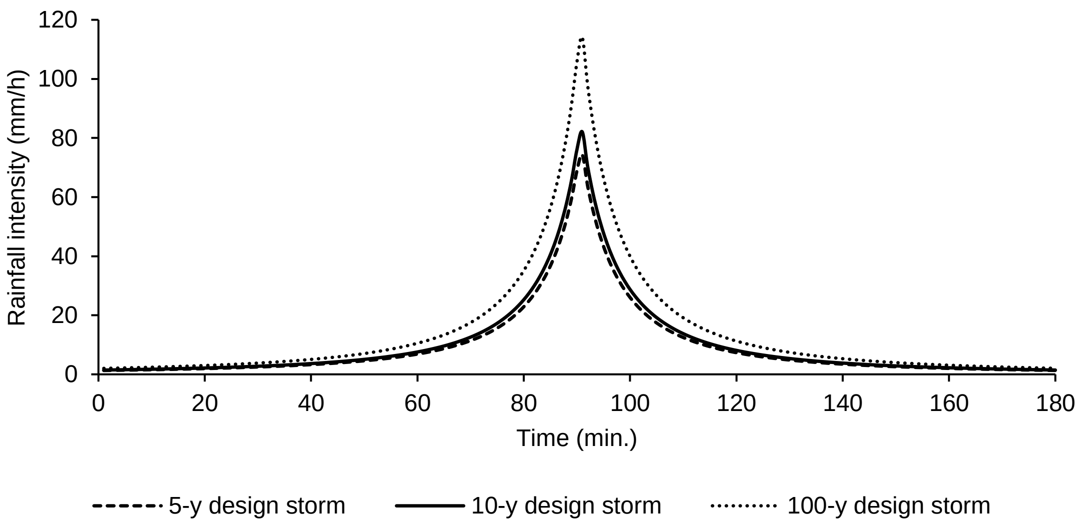

Figure 7.3 *Study site synthetic hyetographs used for scenario analysis*

Rainfall assignation was different according to the modeling approach. In the HD 1D model and in the 1D domain of the coupled 1D–2D model, rainfall data was assigned to all sub-catchments as intensity time series (mm/h). In the 2D domain of the coupled 1D–2D model, all the rainfall volume is assumed to be available for hydraulic routing, and rainfall time series are assigned as a baseline inflow time series (m/s) to the 2D junctions. A representative rainfall volume is obtained by multiplying the cell area (m^2) by the converted rainfall.

Scenarios

This study employed a comparative model-based and scenario approach to assess the hydrologic-hydraulic impact of SUDS. 12 scenarios were created based on the three design storms (section 2.6.2) and four different SUDS implementation settings: 1) business-as-usual (BAU), to represent the current conditions in the absence of SUDS; 2) RWHS, as the sole implementation of rainwater harvesting systems; 3) TP, as the sole implementation of tree pits; and 4) MIX, as a combined implementation of both RWHS and TP. For the remainder of this manuscript, each scenario will be addressed in a coded form based on its setting (BAU, RWHS, TP, or MIX) and design storm (5, 10, or 100), e.g., BAU5. The 12 scenarios were replicated in each modeling approach (HD 1D and coupled 1D–2D), for a total of 24 simulations.

Furthermore, we modeled an additional scenario (MULT100) considering extreme rainfall conditions (100-y *T* design storm) and the collective impact of five SUDS typologies: 1) RHWS under a 100% implementation scheme; 2) TP, doubling the number of units used previously; 3) green roofs (GR) and attenuation storage tanks (AST) in residential sectors where RWHS were not suitable according to slope and tributary area; and 4) pervious pavements (PP) in corridors, plazas, and others land uses. Design parameters were assigned according to Núñez Collado et al. (2019) and City of Toronto (2021).

Metrics for multi-scenario assessment

The RWHS-, TP-, and MIX-scenarios were assessed by contrasting their results with the BAU-scenario conditions. The hydrologic performance was measured in terms of peak discharge (m^3/s) and total outflow volume (m^3). The impact on the conventional pipe-ended drainage system was assessed considering the number of surcharged junctions, the number of flooded junctions, the overloaded conduits' length (km), and the average overloading time (min).

Surcharge and overloading conditions are useful indicators for predicting localized flooding in urban areas (Schmitt et al., 2004) and preventive maintenance of the drainage network. A surcharged condition at a junction occurs when the water surface elevation (WSE) is above the crown of its highest connected conduit. Alternatively, a junction is flooded when the computed WSE exceeds its rim elevation. The overloading condition in a conduit occurs when its upstream end is full and the hydraulic grade line slope is greater than the conduit slope. Furthermore, the flood control potential was assessed in terms of maximum nodal inundation depth (cm) and waterlogging extent (m^2) in moderate (15 cm ≤ overland water depth < 30 cm) and severe (overland water depth ≥ 30 cm) conditions.

7.4 Results

7.4.1 Validation

The simulation run started at 12:00 on December 14, 2011 and ended at 9:00 on December 15, 2011, aiming to reflect antecedent conditions and reduce model instabilities. The total simulation run time in the HD 1D model was four seconds, while the coupled 1D–2D modeling approach took 51 min, i.e., the 1D–2D simulation run time was around 600 times longer. Figure 7.4 shows the preliminary values of water depth in the open channel's conduits according to the HD 1D model (Figure 7.4a) and the coupled 1D–2D model (Figure 7.4b), with an average RE of -10.61% and -0.36%, respectively. Negative values represent an overestimation of the simulated water depth in comparison with the observed value (0.95 m). The peak discharge curve agreement between the two modeling approaches is displayed in Figure 7.4c with an NSE coefficient of 0.861.

Despite the satisfactory agreement in the open channel water depths and the peak discharge hydrographs, there was a wide discrepancy in the number of both surcharged and flooded nodes. Therefore, a sensitivity analysis was performed to evaluate the parameters that most affect the hydraulic performance of the HD 1D model, with the 1D–2D model results serving as a benchmark (Leandro et al., 2011). The chosen parameters were slope, width, Manning's *n* coefficient (pervious and impervious surfaces), impervious percentage area, depression storage (pervious and impervious surfaces), maximum infiltration rate, and minimum infiltration rate. These parameters were selected according to previous studies on SUDM (Ahiablame & Shakya, 2016; Akhter & Hewa, 2016; Baek et al., 2015) and the uncertainty ranges were assigned according to specifications found in Rossman (2015).

The width parameter showed a significant influence on the number of flooded junctions. Therefore, a uniform width value of 0.05–1 m was tested in all the sub-catchments corresponding to corridors, plazas, sidewalks, roads, pervious areas, and others. A value of 0.80 m was finally chosen, reducing the number of flooded junctions from 25 to 6 (Table 7.4). Although there was no significant improvement in the number of surcharged nodes, the behavior of the remaining hydraulic parameters was satisfactory. Furthermore, the hydrographs' agreement between the HD 1D model and the coupled 1D–2D model reached an NSE coefficient of 1 (not displayed here to avoid redundancy).

Table 7.4 *Summary of compared values for hydraulic component validation*

Validation parameter	Before validation			After validation (width* = 0.80 m)		
	HD 1D	1D–2D	RE (%)	HD 1D	1D–2D	RE (%)
Number of surcharged junctions	28	3	-833	22	2	-1000
Number of flooded junctions	25	2	-1150	6	2	-200
Overloaded conduits' length (km)	3.5	1.9	-82	2.1	1.7	-21
Average overloading time (min)	5.86	2.00	-193	2.33	2.1	-11

*Width parameter adjustment only in corridors, plazas, sidewalks, roads, pervious areas, and others sub-catchments

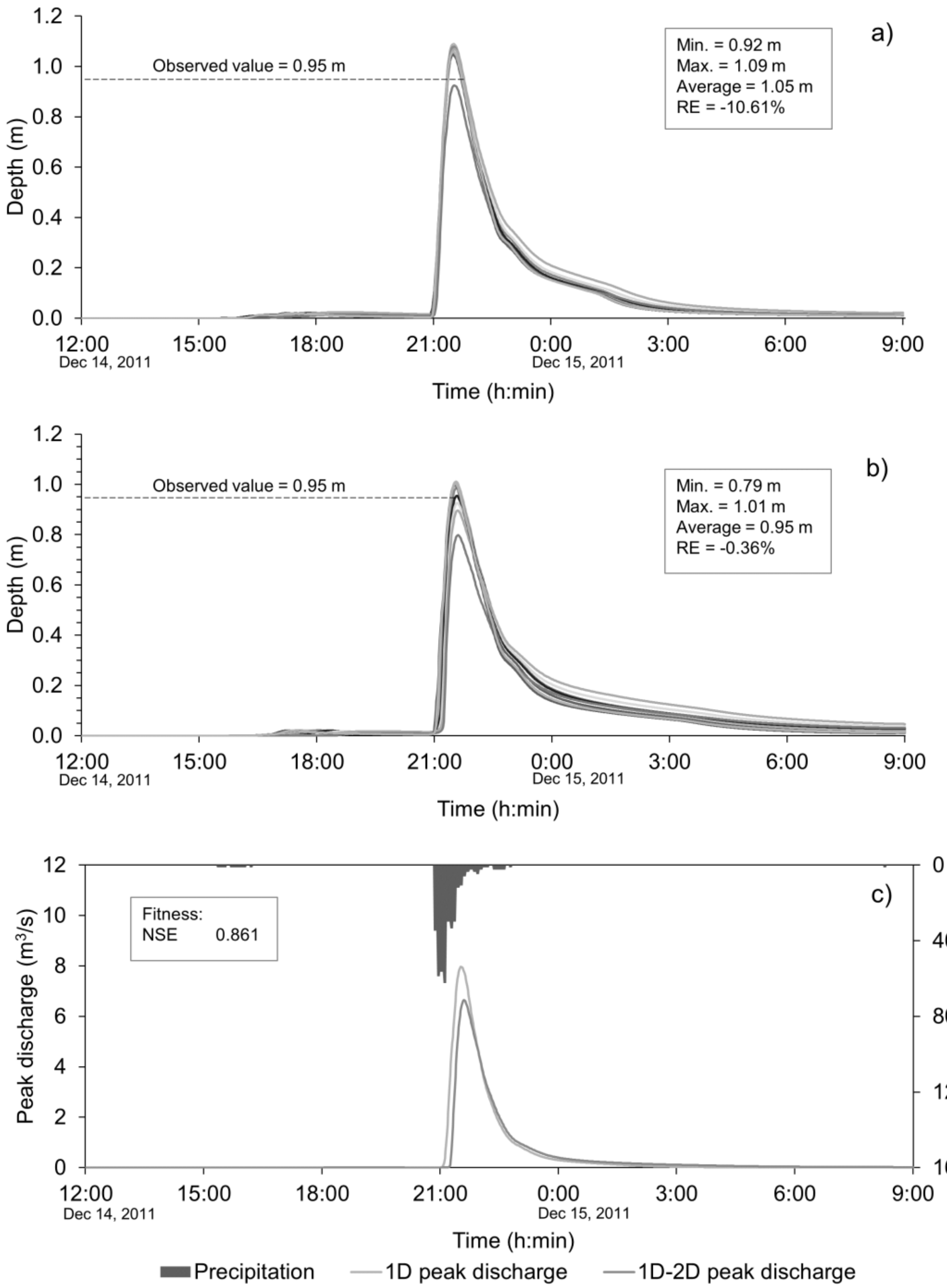

Figure 7.4 *Preliminary validation results: a) water depth in open channel conduits at several places using the highly discretized 1D model b) and the 1D–2D model, and c) peak discharge hydrograph agreement between the two modeling approaches*

7.4.2 Comparison of the two modeling approaches

Model development

As described in Sections 2.3.1 and 2.3.2, the two modeling approaches employed the same drainage network. The biggest difference in terms of model setup was found in the effective description of the rainfall-runoff response. In the case of the HD 1D model, the sub-catchments' parametrization was a time-consuming task since each land use polygon was considered a unique sub-catchment, avoiding attribute averaging. Moreover, a flow routing strategy had to be defined to accurately represent the overland flow dynamics. Therefore, additional tasks of geometry simplification and tag identification were necessary to facilitate the parametrization of each sub-catchment in terms of slope, flow length, and impervious percentage area.

In the case of the 1D–2D model, sub-catchments' parametrization was a simpler task since only building and sidewalk polygons were described as sub-catchments. The rest of the land uses were modeled in the 2D domain. Nevertheless, the 1D–2D model construction requires special attention to avoid underestimation or double accounting of the flow processes. It is worth noting that a comprehensive modeling tool is key to reducing 1D–2D model setup times. For instance, PCSWMM integrates GIS capabilities and is a rainfall-runoff-routing modeling software; therefore, no additional tools are needed to create the 2D nodes and cells. Figure 7.5 shows a schematic representation of the two modeling approaches developed through PCSWMM.

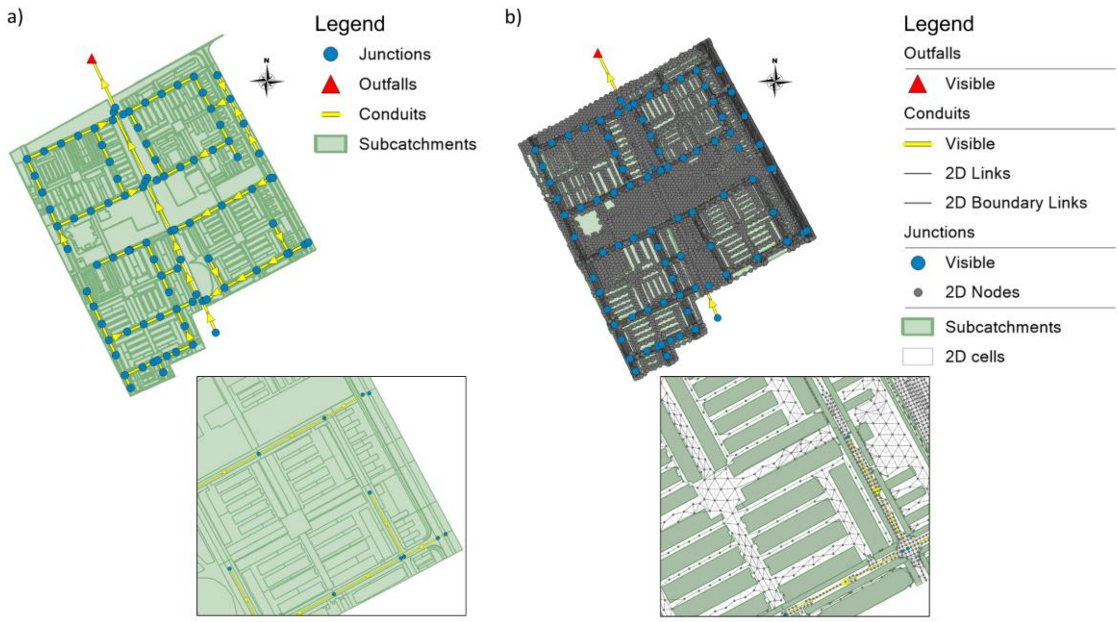

Figure 7.5 *Modeling environment in PCSWMM to develop a) the highly discretized 1D model and b) the coupled 1D–2D model*

The simulation run time of all 1D scenarios was 1 second, while the average time in the 1D–2D simulations was 8 minutes. The average size of the output file following a 1D model approach was 0.01 gigabytes (GB), while in the case of the coupled 1D–2D model it was 0.27 GB. It is worth noting that the 2D nodes and mesh generation require additional time and more computer power and memory, which are avoided in the 1D model approach.

The runoff continuity (RC) and flow routing continuity (FRC) errors were negligible (ranging 0.03%-0.58%) and did not exceed the reasonable threshold of 10% (James et al., 2010) in the two modeling approaches. Nevertheless, the simulations with the 100-y *T* rainfall event through the 1D–2D model posed an additional computational challenge with an extremely high FRC error (-7 856 430.2%). This condition is likely related to the 2D junction's rainfall assignation and the 2D conduits' routing capabilities, which are affected by the low-lying nature of the study area. Therefore, the dynamic wave's normal flow criterion (which determines when supercritical flow occurs in a conduit) was changed from "Slope & Froude" to "Froude number (FN)" only, i.e., FN > 1.0. After this substitution, the simulations with a design storm of 100-y *T* achieved an average FRC error of 0.45%.

Reproducibility of 1D–2D model results via the HD 1D model

Table 7.5 displays the average RE and RMSE values for each hydrologic and hydraulic performance metric. Flood control potential indicators were not included given the reduced capacity of simpler models to reproduce the overland flow response, which may lead to a biased comparison with the coupled 1D–2D model results.

Table 7.5 *Average relative error and root mean square error results from comparing the two modeling approaches*

Parameter	Average relative error (%)	RMSE
Hydrologic control		
Peak discharge	1	0.15 m^3/s
Total outflow volume	1	556 m^3
Hydraulic control		
Number of surcharged nodes	-1260	27 junctions
Number of flooded nodes	-103	2 junctions
Overloaded conduits' length	-14	0.26 km
Average overloading time	-32	0.95 min

The HD 1D model's ability to reproduce the hydrologic response simulated by the coupled 1D–2D model was satisfactory, in line with the validation results. In terms of hydraulic response, the general tendency of the HD 1D model is to overestimate the results of the dual drainage model. The best agreement was obtained in predicting the overloaded conduits' length and the average overloading time, with RMSE values of 0.26 km and 0.95 min, respectively. Although the RE results for the number of flooded nodes were above 50%, the RMSE value of 2 junctions indicates acceptable model performance. The results of both RE and RMSE for the number of surcharged junctions revealed an unsatisfactory performance of the HD 1D model in this regard.

7.4.3 SUDS performance

This section shows the performance results obtained using the coupled 1D–2D model, as dual drainage models provide more accurate results due to the detailed representation of surface geometry, representation of 1D and 2D flow interactions, and overland flow simulation capacity (Blanc et al., 2012; Chang et al., 2015; Leandro et al., 2009; Vojinovic & Tutulic, 2009).

Peak discharge and total outflow volume

Figure 7.6 depicts the peak discharge and total outflow volume values, as well as the corresponding reduction efficiencies. The impact of rainfall characteristics on SUDS performance was evident, i.e., as design storm *T* increases, so does peak discharge and total volume reduction potential.

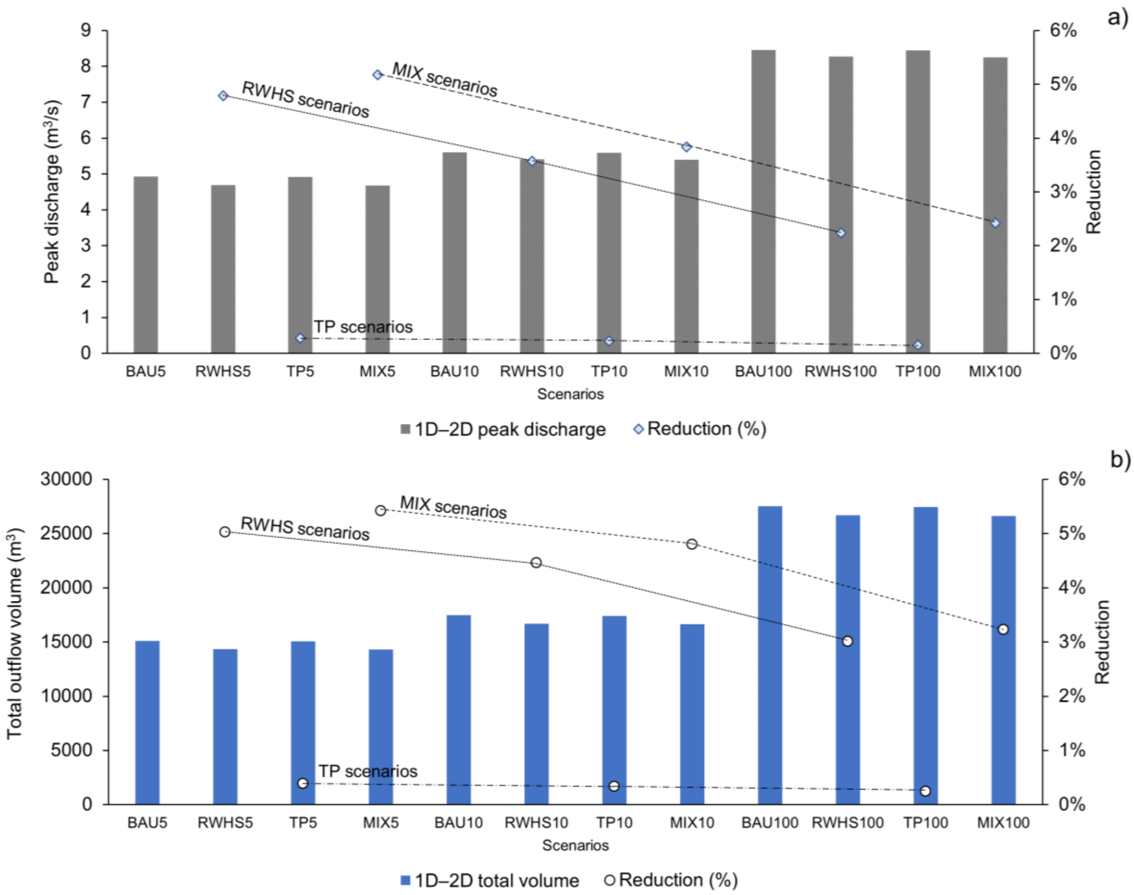

Figure 7.6 *SUDS hydrologic control capacity: a) peak discharge and b) total outflow volume in each of the tested scenarios, following the coupled 1D–2D modeling approach*

The MIX5 scenario yielded the highest reduction efficiencies in both peak discharge (5.2%) and total volume (5.4%). It is worth noting that the results of the two hydrologic control capacity indicators in the MIX scenarios were consistent with the individual RWHS and TP performance results, suggesting a cumulative effect. For instance, although RWHS potential to reduce peak discharge ranged between 2.2%-4.8% and TP efficiencies were quite reduced in all cases (below 1%), the two SUDS strategies worked in tandem, resulting in better performance under the MIX scenarios.

Surcharged and flooded nodes

The maximum number of surcharged and flooded nodes, i.e., 3 and 4, respectively, occurred in the 100-y storm scenarios, which represents only 3% and 5% of the total number of nodes in the study area. This indicates an acceptable design capacity of the drainage network under mild and heavy rain conditions.

RWHS proved to be efficient in reducing the number of flooded nodes under 5-y and 100-y *T* design storms: from 2 to 0 and from 4 to 3, respectively. The MIX scenarios achieved the same efficiencies as the RWHS simulations, most likely due to the null efficiency demonstrated in all TP scenarios, i.e., no additional hydraulic control contribution for the MIX scenarios. Moreover, none of the SUDS scenarios were effective in reducing the number of surcharged nodes.

Overloaded conduits' length and average overloading time

Figure 7.7 shows the hydraulic control results in terms of overloaded conduits' length and average overloading time.

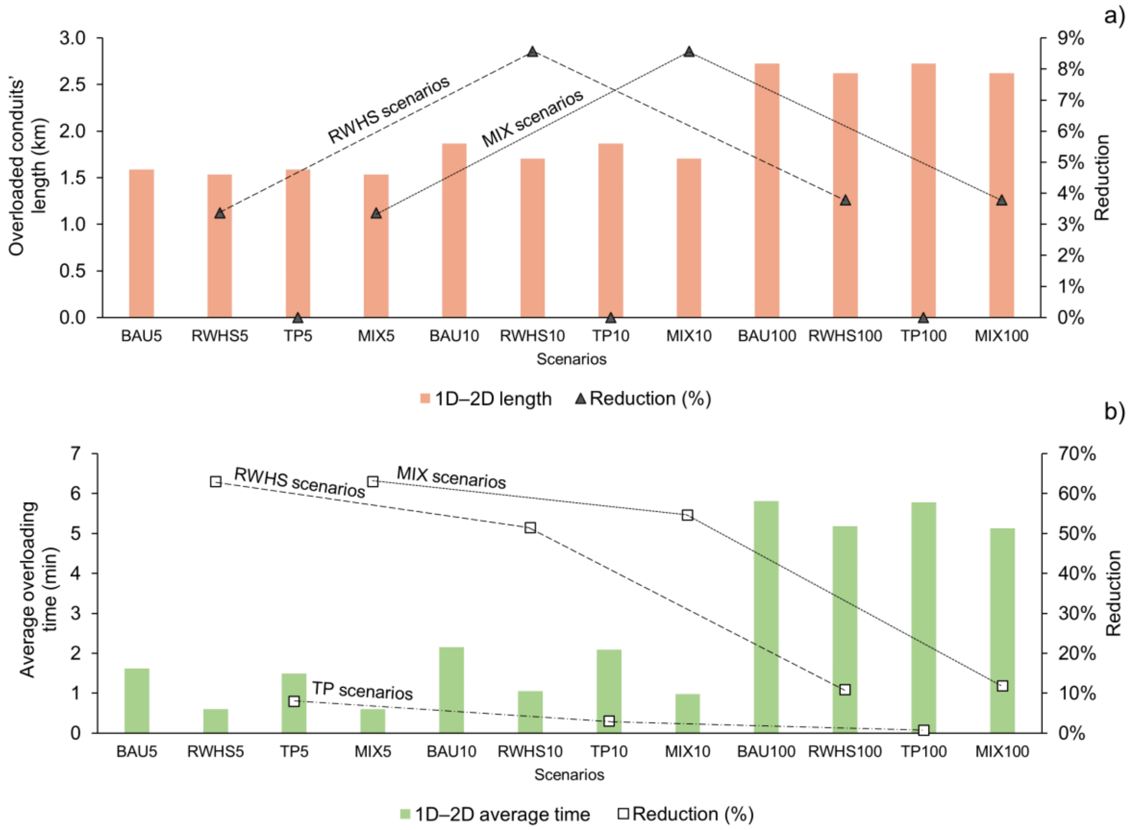

Figure 7.7 *SUDS hydraulic control capacity: a) overloaded conduits' length and b) average overloading time in each of the tested scenarios, following the coupled 1D–2D modeling approach*

Overloaded length reductions obtained through the RWHS scenarios ranged between 3.4%-8.6%; the best result was obtained under the 10-y *T* rainfall condition. TP were ineffective in all the modeled scenarios, whereas the MIX scenarios always showed the same efficiency as the RWHS implementation, likely due to the TP null control capacity.

The reduction of overloading time ranged between 11%-63% and 12%-63% through the RWHS and MIX scenarios, respectively. The best performance was achieved through the RWHS5 scenario. According to the time reduction efficiencies achieved via TP scenarios ranging between 1%-8%, the MIX scenarios reflected a cumulative effect of RWHS and TP capabilities. Furthermore, unlike the overloading length results, the overloading time reduction potential tends to decrease when rainfall *T* increases.

Flood control potential

Table 7.6 summarizes each modeled scenario's flood control potential in terms of nodal inundation depth, moderate waterlogging condition, and severe waterlogging condition reductions. The maximum nodal inundation depth was 7 cm (100-y T design storm), which contrasts with the presence of waterlogged areas (water depth ≥ 15 cm). This indicates i) an acceptable drainage network performance under extreme rainfall conditions and ii) the significant influence of the study area's low-land nature on overland flows.

Table 7.6 *Flood control potential in the coupled 1D–2D modeling approach*

Design storm *T* (years)	Scenar.	Nodal inundation depth		Area; moderate waterlog. condition*		Area; severe waterlog. condition**	
		Max. (cm)	Reduction (%)	Total (m^2)	Reduction (%)	Total (m^2)	Reduction (%)
5	BAU	2		11 842		1 045	
	RWHS	0	100	11 507	2.8	997	4.6
	TP	1	50	11 764	0.7	1 045	0.0
	MIX	0	100	11 507	2.8	997	4.6
10	BAU	3		15 154		1 126	
	RWHS	1	67	14 839	2.1	1 107	1.7
	TP	3	0	15 079	0.5	1 126	0.0
	MIX	1	67	14 828	2.2	1 107	1.7
100	BAU	7		20 286		1 493	
	RWHS	6	14	19 683	3.0	1 492	0.1
	TP	7	0	20 250	0.2	1 493	0.0
	MIX	6	14	19 610	3.3	1 492	0.1

*Moderate waterlogging condition: 15 cm ≤ overland water depth < 30 cm
**Severe waterlogging condition: overland water depth ≥ 30 cm

Most of the flood control indicators performed better under the mildest design storm (5-y T), although the best moderate waterlogging control efficiencies were achieved under the 100-y scenario. RWHS demonstrated flood control capacity in all tested scenarios to some extent, although efficiencies achieved under more severe rainfall conditions (10-y and 100-y design storms) were quite low. TP implementation showed a positive impact on nodal inundation reduction only under the 5-y rainfall condition and a negligible or null impact in all scenarios of moderate and severe waterlogging conditions. This most likely influenced the efficiencies achieved by the MIX scenarios, which were very similar to the impact produced by the RWHS implementation.

SUDS implementation: local constraints vs full potential

All the results presented above were derived from the SUDS implementation strategy described in 2.6.1, considering the assessment of local context barriers (RWHS) and current pilot projects (TP). Nevertheless, in light of the challenges posed by climate change and accelerated urbanization, scholars have urged the evaluation of multiple SUDS typologies and different percentages of installation (Aceves & Fuamba, 2016b). Figure 7.8 displays the SUDS setting in the MIX scenarios and the MULT100 scenario (implementation of rainwater harvesting systems, tree pits, green roofs, attenuation storage tanks, and pervious pavements; see *Scenarios*). Moreover, Table 7.7 compares the hydrologic and hydraulic response results of the BAU100, MIX100, and MULT100 scenarios.

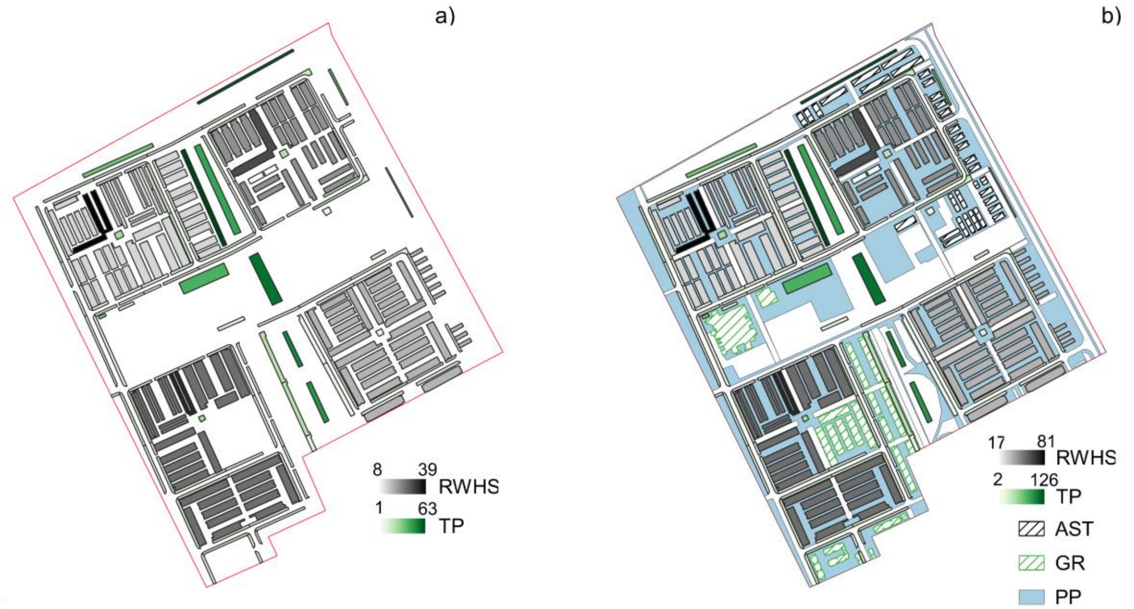

Figure 7.8 *SUDS setting in a) MIX scenarios and b) MULT100 scenario. Color gradients represent the number of units of RWHS and TP, per building and sidewalk, respectively. RWHS: rainwater harvesting systems; TP: tree pits; AST: attenuation storage tanks; GR: green roofs; PP: pervious pavements.*

As expected, the peak discharge and the total outflow volume values decreased even more in the MULT100 scenario, with reductions of up to 11% and 15%, respectively, as compared to 2% and 3% for the MIX100 scenario. Furthermore, with the exception of the number of surcharged nodes, all hydraulic evaluation parameters showed a positive impact, with a significant reduction in average overloading time (83%).

Table 7.7 *Hydrologic and hydraulic performance of SUDS in BAU100, MIX100, and MULT100 scenarios*

Performance indicator	BAU100	MIX100	MULT100
Peak discharge (m^3/s)	8.46	8.25	7.51
Total outflow volume (m^3)	27530	26640	23270
Number of surcharged nodes	3	3	3
Number of flooded nodes	4	3	2
Overloaded conduits' length (km)	2.7	2.6	2.1
Average overloading time (min)	5.81	5.13	0.97
Max. Nodal inundation depth (cm)	7	6	3
Area, moderate waterlogging condition (m^2)*	20286	19610	12589
Area, severe waterlogging condition (m^2)**	1493	1492	1171

*Moderate waterlogging condition: 15 cm ≤ overland water depth < 30 cm

**Severe waterlogging condition: overland water depth ≥ 30 cm

Area reductions via MULT100 scenario in moderate and severe waterlogging conditions, 38% and 22%, respectively, demonstrated PP overland flow control capacity in low-land nature sites. This is best illustrated by comparing the waterlogging extent (water depths ≥ 15 cm) in the BAU100, MIX100, and MULT100 scenarios, as displayed in Figure 7.9.

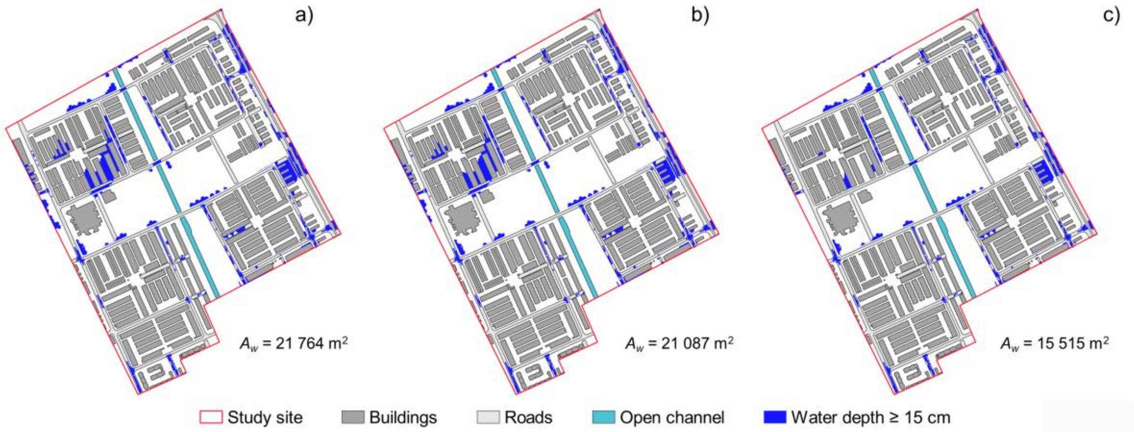

Figure 7.9 *Waterlogged areas (A_W), i.e., water depth ≥ 15 cm in a) BAU100 scenario, b) MIX100 scenario, and c) MULT100 scenario*

7.5 Discussion

7.5.1 Model development

The model development process confirmed the observations of several authors stressing the high computational cost in terms of time, memory, and power (Leandro et al., 2009; Leitão et al., 2010) and the propensity for instability of 1D–2D models (Vojinovic & Tutulic, 2009). Depending on the case study, this can restrict the number of iterations and/or simulations, affecting the significance of the results. However, the final application, the study area size, and the available computational tools (processing and modeling) might aid in the reduction of these limitations.

The relatively easy setup and parametrization of sewer-based models have been highlighted as advantages compared to sewer/surface approaches (Chang et al., 2015; Pina et al., 2016; Vojinovic & Tutulic, 2009). Nevertheless, time-consuming tasks under the HD 1D model, such as sub-catchments' attribute assignation and flow routing definition, can be simplified using coupled 1D–2D models when a high-resolution DEM is available. This suggests that, in addition to the well-known benefits of the more complex models in terms of results accuracy and visualization, model construction may be an additional advantage depending on the size of the study area and the model's final application.

The accurate representation of the flow interactions between TP and the drainage system posed a challenge in the present study. The current option to represent any type of SUDS in SWMM (and therefore, in PCSWMM) is as an attribute of a given sub-catchment. This approach is useful for the hydrologic control analysis; however, the hydraulic control assessment may be affected. This limitation could be overcome through a "virtual node-orifice-flap valve" scheme, suggested by Pina et al. (2016) for linking the major and minor drainage systems in simpler models. In this method, virtual nodes allow overland flow (from sub-catchments) to be discharged to the pipe-ended system, orifices represent sewer inlets (with limited capacity), and flap valves allow the transition of sewer flow to the surface. Nevertheless, given the resolution of both the HD 1D model and the coupled 1D–2D model, this would imply a time-consuming task for each of the implemented TP units. Furthermore, the representation of TP's internal hydraulic processes (e.g., backflow effect) cannot be fully represented. Further development is required to improve the hydrodynamic assessment of SUDS at micro (on-site) scale, with either 1D or 1D–2D modeling approaches.

7.5.2 Reproducibility of 1D–2D model results via the HD 1D model

The majority of comparative studies addressing the performance of sewer-based models and sewer/surface approaches have focused on flood impact assessment in terms of water depth and extent (Chang et al., 2015; Vojinovic & Tutulic, 2009). The present study aimed to broaden the existent literature by assessing the hydrologic-hydraulic performance of SUDS under a sewer-based HD 1D model and a sewer/surface coupled 1D–2D model. The outcomes of these two modeling approaches revealed both similarities and differences, depending on the aspect evaluated. For instance, peak discharge and total outflow volume reductions were overestimated by the 1D approach by a maximum of 3% and 4%, respectively. This contrasts with a previous study comparing a semi-distributed (sewer-based) and a fully-distributed (sewer/surface) model in which the former overestimated the volume discharged by up to 100% (Pina et al., 2016). The consistency of the results from the two modeling approaches in the present work could be attributed to the level of discretization of the simplest model, which avoided parameter averaging. This suggests that a HD 1D model can provide comparable results to a coupled 1D–2D model when assessing the hydrologic control capacity of SUDS strategies such as RWHS and TP.

Regarding the SUDS hydraulic control capabilities, the differences between the results provided by the HD 1D and the 1D–2D modeling approaches were not as uniform as the hydrologic performance values. This outcome is reasonable considering the detailed flow path representation offered by the 2D mesh, whereas a routing strategy was followed in the HD 1D model to recreate this effect. However, as observed during the validation process, the width parameter had a great influence on the hydraulic control capabilities. Although the 1D model continued to overestimate the results of the 1D–2D model, the best agreement between the two modeling approaches was found in the number of flooded nodes and the overloaded conduits' length. It is worth noting that the hydraulic control results are subject to the quality of the terrain information and the urban configuration of the study area (Leandro et al., 2009; Vojinovic & Tutulic, 2009). Nevertheless, the results of the present study suggest that a HD 1D model can provide meaningful results for the vulnerability assessment of the drainage network, enabling a more efficient response to avoid waterlogging and urban flood inundation in less extreme rainfall events.

The ability to reproduce the hydrologic and hydraulic control results of a coupled 1D–2D model through a HD 1D model represents an advantage in terms of computational cost, data acquisition and processing, and model development. This is useful for urban water decision-making when large areas and multiple scenarios need to be assessed. However, for the results to be conclusive, a proper calibration process with observed data must be performed.

7.5.3 SUDS performance

The study of SUDS' hydrologic control capabilities have been widely covered in the literature of RWHS (Aceves & Fuamba, 2016b; Hua et al., 2020) and TP (Grey et al., 2018). RWHS demonstrated greater capacity than TP in terms of peak discharge and total outflow volume reductions. However, better efficiencies were achieved under the MIX scenarios. This confirmed the findings of previous studies in which greater hydrologic control effectiveness is reached when multiple typologies are implemented (Ahiablame & Shakya, 2016; Cui et al., 2019). The percentage of implementation (Hua et al., 2020) and the land-use distribution (Pina et al., 2016) play an important role in achieving better efficiencies, either individually or in combination. Furthermore, the hydrologic control capacity of both RWHS and TP was reduced with the most extreme rainfall event (100-y *T*), which has been described in previous studies indicating better efficiencies for mild events (Grey et al., 2018; Huang et al., 2018; Mu et al., 2022).

The hydraulic control provided by RWHS and TP, assessed using two different modeling approaches, represents a novelty in the study of SUDS. The present research revealed that, in addition to hydrologic control capabilities, RWHS can aid in the reduction of the number of flooded junctions, the overloaded conduits' length, the overloading time, the nodal inundation depth, and the waterlogging extent (moderate and severe condition).

Furthermore, although to a much lesser extent, TP demonstrated efficiency in reducing average overloading time and nodal inundation depth. Previous studies assessing the impact of rain gardens, whose water balance is theoretically similar to that of TP, have found better hydraulic control efficiencies (Cui et al., 2019; Movahedinia et al., 2019). This suggests that higher implementation densities or TP management trains might enhance TP's hydraulic control efficiency. Nevertheless, as with hydrologic control capabilities, the hydraulic control effectiveness is subject to the impact of rainfall volume and intensity (Cui et al., 2019; Hua et al., 2020; Mu et al., 2022).

The SUDS implementation strategy adopted in the present study was an attempt to represent a realistic implementation in both public and private land: while RWHS implementation potential was reduced by more than 50% due to physical restrictions and local context constraints, the final distribution of TP considered the current tree distribution, capturing the preferences and operation and maintenance capabilities of the local administration. The present study demonstrated that, under these limitations, TP do not provide substantial hydrologic-hydraulic control effectiveness. Nevertheless, previous research have demonstrated TP's significant contribution to reducing urban runoff under careful planning (Grey et al., 2018). Other benefits such as temperature regulation, improved stormwater runoff quality, increased biodiversity, and aesthetic value (Lamond et al., 2015) are relevant for assessing TP impact given the study area's high urbanization rate (81%).

The scenario approach proved to be a useful tool for assessing the role of SUDS in supplementing the existing drainage network at catchment scale. Greater efficiencies in the reduction of all hydrologic and hydraulic control indicators were seen with the implementation of multiple SUDS typologies and higher percentages of installation (MULT100 scenario). Earlier studies have discussed that ponds and natural low-lying areas are important for flood control as they provide a large volume for the detention of excess water (J. Sörensen & Emilsson, 2019; Villarreal et al., 2004). However, these measures were not tested in the MULT100 scenario considering the high limitations of the built environment. Despite this, the reduction of the moderate and severe waterlogging extents was efficient to a certain extent. Further discussion is needed to assess the cost-effectiveness of an integrated scheme implementing RWHS, TP, GR, AST, and PP.

7.6 Conclusion

This study tests and discusses data requirements (quality and quantity), methodological differences, computational limitations, and the hydrologic-hydraulic performance of SUDS using a highly discretized 1D model and a coupled 1D–2D model using PCSWMM. After 24 simulations, it was evident that highly discretized 1D models are able to reproduce the hydrologic and hydraulic response produced by coupled 1D–2D models. This represents a significant advantage for analyzing the vulnerability of the existing drainage network and SUDS' complementary performance in data-scarce environments while avoiding the high computational costs of sewer/surface models.

Furthermore, in addition to the well-known hydrologic control capabilities (peak discharge and total outflow volume control), findings revealed that SUDS can aid in the reduction of the number of flooded junctions, overloaded conduits' length, overloading time, nodal inundation depth, and waterlogging extent. The use of multiple SUDS typologies and/or higher percentages of installation, aiming to improve on-site and catchment scale stormwater control, is key to achieving better efficiencies. Moreover, performance results across all evaluated criteria demonstrated that, even in highly urbanized, waterlogging- and flood-prone catchments with limited implementation potential on both public and private land, SUDS can provide hydrologic-hydraulic control to some extent, mainly during less extreme precipitation events.

The main limitation of the present study was the lack of observed data to perform a proper calibration process. Nevertheless, the validation strategy, along with the comparative model-based multi-scenario assessment, enables the present study to provide significant results for supporting sustainable stormwater decision-making and SUDS planning at the urban scale in flood-prone areas with a highly restricted land use. Further development is needed for an accurate description of the internal hydraulic mechanisms of SUDS typologies that interact with overland flow to improve the understanding of particular hydraulic phenomena such as the backflow effect and flow aggregation from multiple sources.

8 Synthesis

This applied research significantly contributes to improved urban drainage management by addressing qualitative and quantitative knowledge gaps in SUDM planning with the aid of inter- and transdisciplinary approaches. The main findings are described below from both a disciplinary and a study site perspective.

8.1 Disciplinary perspective

There are several studies on the barriers to and benefits of GI, BGI, LID techniques, NbS, and SUDS implementation (Brudermann & Sangkakool, 2017; Kabisch et al., 2016; Kim et al., 2017; Kok et al., 2021; L. Li et al., 2020; Thorne et al., 2018; Wihlborg et al., 2019; G. Zhang & He, 2021). However, the vast majority have been produced in developed contexts, coinciding with the most experienced countries in SUDM, e.g., Australia, the United Kingdom, and the United States. The literature review in Chapter 5 that served as a conceptual framework for identifying and analyzing the barriers (Table 5.1) to and benefits (Table 5.2) of SUDS implementation yielded 33 and 21 results, respectively. Barriers were categorized as cultural/behavioral, financial, institutional/organizational, political, technical, and urban form, whereas benefits were classified according to their economic, environmental, and social impacts. Nonetheless, semi-structured interviews and questionnaires, as well as the thematic analysis employed in the case study, proved effective in elucidating new factors that hinder or promote SUDM strategies, resulting in 6 and 13 additional barriers and benefits, respectively, all of which have been poorly or not even addressed in the literature to date. The relevance of these findings is that they serve as planning, management, or diagnosis tools regardless of the geographic, climatic, and socio-political features, enabling a more comprehensive assessment of the study site.

Another contribution of Chapter 5 is the sectorial representativeness, which is a call for the adoption of interdisciplinary approaches that allow both the understanding of individual positions and the integration of competing visions in SUDM. It is worth highlighting the influence of the data collection and analysis methods, which contribute to another aspect of interdisciplinarity when applied in a field of knowledge dominated by quantitative methods, such as urban drainage. This demonstrated that adoption of SUDM alternatives cannot be addressed solely from the technical realm; in fact, many authors insist that stakeholder engagement is essential for the success of SUDM initiatives (Ferreira et al., 2020; Krkoška Lorencová et al., 2021; Lamond et al., 2020; Thaler & Levin-Keitel, 2016). I agree with this; however, transitioning from an inclusive engagement to a participatory engagement (Quick & Feldman, 2011) is challenging when the particular perspectives and needs have not been fully identified and understood.

The main contribution of Chapter 6 is the methodology for assessing the potential feasibility of SUDS strategies, considering physical constraints and the six categories of barriers identified in Chapter 5. Several methodologies have been developed to assist in the selection and location of SUDS based on performance criteria and a wide range of economic, environmental, and social benefits (Aceves & Fuamba, 2016b; Alves, Gómez, et al., 2018; Jiménez et al., 2019; Uribe-Aguado et al., 2022). However, since the identification of barriers allows anticipating the challenges that may arise in the different phases of planning and implementation (Deely et al., 2020), a methodology that considers the local context's limitations can be especially beneficial for places where SUDS implementation is incipient in order to make more efficient use of the available financial and human resources. It is worth noting that the approach described in Chapter 6 was developed as a complementary tool rather than a definitive one within the urban stormwater management decision-making process, which must, of course, be supported by a hydrologic-hydraulic performance assessment.

Another significant contribution of Chapter 6 is the evaluation of the differential impact of local context constraints on the selection of 12 SUDS typologies, which has not been thoroughly covered in the literature. The matrix provided in Table 6.2, created with input from an international expert panel and specialized literature, revealed the high influence of technical and financial barriers on the adoption of SUDM strategies. Furthermore, at the typology level, it was observed that TP, GR, CW, and P may require more attention in the planning stage. Chapter 6 also provided an alternative weight elicitation method for use in MCDA to support SUDM decision-making, built from the inductive–deductive multisectoral analysis of perceived barriers from Chapter 5. This approach brings three novelties: (i) explicit preferences on SUDS typologies or MCDA criteria are not incorporated, thus reducing the possibility of biased responses from participants towards a list of multiple alternatives; (ii) the excerpt counts (transformed into MCDA weights) arose from the analysis of previous experiences (or the lack of them) with SUDS; and (iii) it allowed for a comprehensive assessment of key urban water actors' opinions. Nevertheless, the flexibility of the proposed methodology allows other approaches to be used.

The contributions of Chapter 7 to the body of literature on SUDS performance and modeling are framed by the need for model-based evidence, which is particularly significant when pilot projects represent a financial and organizational challenge. Firstly, it provides evidence on the reproducibility capacity of the most complex hydrologic-hydraulic models (coupled 1D–2D model) through simpler approaches (HD 1D model). Secondly, it comprehensively investigates SUDS hydrologic-hydraulic control capabilities.

Although coupled 1D–2D models provide a more accurate representation of the land surface and the interaction between the major and minor drainage systems, their wider use is limited due to the high computational costs and instability proneness (Blanc et al., 2012; Maksimović et al., 2009; Vojinovic & Tutulic, 2009). This was verified across 24 modeling scenarios, where 1D–2D models required 470 times more running time on average and were also very sensitive to stability under more extreme design storms (100-year return period). Nevertheless, after assessing the capabilities of the HD 1D and

1D–2D modeling approaches, it became apparent that comparable hydrologic-hydraulic results could be produced. This represents a great novelty in the evaluation of SUDM strategies in data-scarce and financially constrained environments.

As pointed out in Section 2.1, despite SUDS' complementary nature to the traditional urban drainage system, the interaction with the pipe-ended network has been poorly investigated. The present dissertation provides solid evidence on SUDS hydraulic control capacity in terms of number of surcharged and flooded junctions, overloaded conduits' length, and average overloading time. Furthermore, the flood control potential was assessed in terms of nodal flood inundation and waterlogging extent (moderate and severe). Due to the interdisciplinary nature of urban stormwater management, evidence on the SUDS hydraulic control potential enables informed decision-making, reduces the level of uncertainty, and strengthens the transition toward SUDM.

8.2 Study site perspective

The analysis of benefits and barriers provided in Chapter 5 demonstrated the impact of the local context and the importance of conducting this type of study considering the perspectives and needs of local actors. For instance, the barriers assessment in Bogotá's scenario revealed that technical factors continue to play a significant role in the decision to adopt or not SUDS. This contrasts with evidence from developed contexts where socio-political factors prevail (Bark & Acreman, 2020; Brown & Farrelly, 2009a; Thorne et al., 2018), owing to extensive experience with pilot projects and scenario analysis to improve performance evaluation (Gimenez-Maranges, Pappalardo, et al., 2020). Nonetheless, following the technical barriers, the institutional/organizational and cultural/behavioral constraints proved to be relevant, even outweighing the financial factors. This emphasizes the importance of institutional strengthening and awareness-raising campaigns to find balanced top-down/ bottom-up approaches, pointed out as key to successful sustainable urban water management (Drosou et al., 2019; L. Liu & Jensen, 2018).

Furthermore, the benefits assessment evidenced the significant environmental, market-related, and social potential of SUDS implementation, with interesting mentions from urban developers, the public sector, and community members such as "corporate image enhancement," "flexibility for repair and maintenance work," and "reduction of the social gap," respectively. Previous research has shown the importance of the communication of benefits, which is linked to knowledge dissemination and aims to increase acceptance and willingness to implement SUDM strategies (Connop et al., 2016; Everett et al., 2018; Kronenberg, 2015; Watkin et al., 2019). This became evident during discussions with the expert panel participants in Chapter 6, who underlined the importance of both general and technical knowledge in deconstructing negative perceptions and promoting the implementation of multifunctional solutions. Therefore, considering that 13 additional benefits were discovered in the context of Bogotá, there is a significant opportunity for the development of community-based initiatives and government-led programs.

The methodology developed in Chapter 6 was applied in a highly urbanized neighborhood in the city of Bogotá, with a latent risk of fluvial and pluvial flooding. The GIS-based analysis of physical constraints allowed to easily discard four SUDS typologies (BRS, EDB, IB, and IT) due to the study site's poor infiltration capacity. Then, after developing the robust FBSs matrix (Table 6.2), the perceptions of all investigated actors in Chapter 5 were integrated into the OBIs calculation. The results of the potential feasibility assessment revealed that barriers to SUDS implementation have a significant impact, reducing the feasible area of implementation from 78% to 33%. RWHS and TP were the top-ranked typologies, and they were used in Chapter 7 for implementation on private and public land, respectively. The potential feasibility findings were compared to the preferences of community members, who were inquired about three common SUDS typologies in residential areas, i.e., RWHS, GR, and BRS. Surprisingly, 42% of the opinions expressed a lack of willingness to implement any of these options, citing previously investigated barriers in Chapter 5 such as “private land ownership,” “lack of financial resources,” and “workload that SUDS demand.” Once again, the influence of barriers on the intention to adopt SUDM strategies was evident. These results highlighted the importance of identifying particular preferences and motivations in order to entice potential users.

In Chapter 7, RWHS were modeled using its OBI (Chapter 6, Figure 6.5) as distribution potential, whereas TP were located according to the current tree scheme of the study site. This approach was an attempt to reflect more realistic conditions for SUDS adoption instead of assigning user-defined implementation percentages, which can overestimate their potential. The modeling findings revealed the significant hydrologic and hydraulic control capacity of RWHS, whereas TP did not demonstrate relevant efficiency in any of the evaluated parameters under the chosen distribution. Nevertheless, given that 81% of the modeled surface is impervious, other criteria beyond runoff control, such as temperature regulation, biodiversity enhancement, and amenity, should be considered. Furthermore, the scenario including RHWS, TP, GR, AST, and PP demonstrated the beneficial effect of adopting multiple typologies with differential control capabilities at on-site and catchment scale to achieve better efficiencies during more extreme rainfall events (100-year return period).

9 Outlook

Amidst the pressing challenges posed by rapid urbanization and climate change, the findings and limitations of this study provide a compelling basis for further research in the field of SUDM. Moreover, these outcomes have practical implications for advancing a more robust implementation of SUDS in the context of Bogotá.

For instance, the multi-sectoral qualitative analysis of SUDS benefits and barriers in Chapter 5 was derived from a single case study, providing exploratory conclusions and representativeness of the local context. Similar studies might be conducted at the national or even regional levels, in which more far-reaching data collection methods can be used (e.g., focus group discussions). This could yield a more comprehensive perspective on the factors influencing successful sustainable urban drainage planning and the identification of the most effective practices, thus assisting in the establishment of a robust platform for informed policy-making.

Furthermore, a cost-benefit analysis considering the 34 benefits within the context of Bogotá could inform local urban water decision-makers for the formulation of community-based or government-led initiatives that, in addition to promoting the multifunctionality of SUDS, allow for both the reduction of financial constraints and increased market mobilization. This might potentially be scaled up to the national level, leveraging the interest in policy development under the SDGs framework.

Regarding Chapter 6, the greatest limitation was the degree of involvement of the participants, obtained through a consulting transdisciplinary approach. Further research is needed to achieve participatory transdisciplinarity, which fosters the exchange of information and the re-integration of knowledge into social practice, hence strengthening the SUDM planning process. For instance, by harnessing the local interest in pilot projects as valuable tools to gauge the biophysical, social, and institutional capabilities, a continuous exchange of ideas among the key actors involved (e.g., community members and the public sector) can facilitate successful long-term implementation. This approach not only promotes more effective engagement during the operation and maintenance phases but also ensures the overall sustainability of the system.

It is worth highlighting that one of the major concerns across all the investigated sectors in Chapters 5 and 6 was the operation and maintenance of SUDM strategies that involve different management levels. The city of Bogotá recently delegated this responsibility to the Parks Management Authority and the Botanical Garden, but only in the case of vegetated SUDS strategies. More evidence is required to decrease the degree of uncertainty regarding workload and operational costs associated with other SUDS typologies, thus promoting the implementation of both on-site and train schemes.

Finally, Chapter 7 concluded that highly discretized 1D models are capable of reproducing the results of coupled 1D–2D models. Although this was feasible after a sensitivity analysis and a two-stage validation process, the main limitation of this study was the lack of observed data to perform a calibration process. Future research could include monitoring data from both overland and sewer flow, thus providing additional evidence for those sectors that are still hesitant about the hydrologic-hydraulic capabilities of SUDS at the micro-, meso-, and macroscales.

Moreover, acknowledging the comparable performance of both modeling approaches, large-scale HD 1D models could be employed to develop different climate change and urbanization scenarios with implications for decision- and policy-making. Since higher efficiencies in all hydrologic and hydraulic control indicators were achieved through the MULT100 scenario, further investigation is needed to assess the cost-effectiveness of a scheme integrating RWHS, TP, AST, GR, and PP. Further development is also needed for an accurate description of the internal hydraulic mechanisms of SUDS typologies that interact with overland flow, such as BRS, IT, and TP. This is greatly significant given the supplementary nature of any SUDM strategy to the new or existing pipe-ended drainage network, the undesirable occurrence of reverse flow, or a sudden clogging effect in these SUDS typologies.

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Supplementary material

Table S1 *Code book of barriers to SUDS implementation*

Barriers	Description and references in sustainable urban water management literature
Diverse interpretations of the SUDS concept	Different points of view regarding SUDS may lead to conflict among stakeholders due to their own priorities or competing interests (Carriquiry et al., 2020; Gashu & Gebre-Egziabher, 2019; Han & Kuhlicke, 2021).
Efficiency uncertainty	It refers to the lack of scientific data supporting SUDS performance that may hinder their consideration (Alves et al., 2020; Drosou et al., 2019; Hamlin & Nielsen-Pincus, 2021; Y. Liu et al., 2018; McEvoy et al., 2019; Mulligan et al., 2020; Thorne et al., 2018).
Electoral/administrative changes	Electoral changes can impact the continuation of ongoing strategies or the possibility of future ones, if the government in power is not close to this vision (Carter et al., 2015; Perales-Momparler et al., 2015).
Financial burden	It refers to limited budgets where the inclusion of SUDS might be seen as unexpected expense (Drosou et al., 2019; Kim et al., 2017; L. Li et al., 2020; L. Liu & Jensen, 2018).
Inflexible and conflicting rules	Because SUDS is an emerging concept in some places, there may be a mismatch between local and regional regulations (Dhakal & Chevalier, 2017; Gashu & Gebre-Egziabher, 2019).
Lack of community ownership	Insufficient interest on the part of the community can impact schemes where its ownership is required (Thorne et al., 2018).
Lack of consultation	Ignorance of the needs and priorities of users can lead to the failure of innovative strategies such as SUDS (Han & Kuhlicke, 2021; Thaler et al., 2019).
Lack of design standards and guidance	It refers to the availability of standards for proper planning, design, and construction of SUDS (Dhakal & Chevalier, 2017; Mulligan et al., 2020; Sarabi et al., 2020; Shafique & Kim, 2017).
Lack of financial resources	Lack of capital to invest despite the existence of conviction or will (Dhakal & Chevalier, 2017; Drosou et al., 2019; Mukhtarov et al., 2019).
Lack of general knowledge	It refers to a basic notion of SUDS functions, benefits, and importance to the built environment (Alves et al., 2020; Carriquiry et al., 2020; Drosou et al., 2019; Hamlin & Nielsen-Pincus, 2021; McEvoy et al., 2019; Mulligan et al., 2020).
Lack of institutional coordination/ communication	Poor communication across and between institutions (disciplines) affect organizational and decision-making processes (Gashu & Gebre-Egziabher, 2019; Johns, 2019; Krkoška Lorencová et al., 2021; Mguni et al., 2015; Zingraff-Hamed et al., 2021).
Lack of interest in SUDS	It is related to the limited sense of urgency when people have not been directly affected by environmental issues (Carriquiry et al., 2020).
Lack of local experience/benchmarks	Pilots are necessary to reflect the behavior of novel systems in local-context conditions (Kim et al., 2017; Shafique & Kim, 2017).

Lack of operational capacity	It refers to the lack of human resources and limited scope of the authority in charge (Han & Kuhlicke, 2021).
Lack of political leadership/will	Political leadership is key to foster sector-wide commitment and mobilize resources (Ferguson et al., 2013; Francesch-Huidobro, 2015; Krkoška Lorencová et al., 2021; Shafique & Kim, 2017; Sussams et al., 2015).
Lack of private sector engagement	Private sector has a critical role in sustainable urban water management (Crick et al., 2018; Johns, 2019; Perales-Momparler et al., 2015; Wihlborg et al., 2019).
Lack of quantitative evidence/ performance information	This is related to the lack of real-life data of SUDS performance considering the local-context conditions (Dhakal & Chevalier, 2017; Gashu & Gebre-Egziabher, 2019; Grizzetti et al., 2016; Shafique & Kim, 2017).
Lack of regulatory binding instruments	A weak enforcement of regulations can reduce the chances of SUDS implementation (L. Li et al., 2020).
Lack of supportive policy and legal framework	Clear legislation enhances interest and willingness to adopt SUDS (Drosou et al., 2019; Ferguson et al., 2013; L. Li et al., 2020; Ossa-Moreno et al., 2017).
Lack of technical capacity	It refers to limited technical resources such as equipment and material (Dhakal & Chevalier, 2017; Kim et al., 2017; Shafique & Kim, 2017; Wamsler et al., 2020).
Negative SUDS perceptions	It refers to negative perceptions about the suitability of SUDS for urban water management (Connop et al., 2016; Everett et al., 2018; Krkoška Lorencová et al., 2021; Sarabi et al., 2020; Shafique & Kim, 2017).
Operation and maintenance	Responsibilities (costs, management, ensuring efficiency) of operation and maintenance of SUDS (Everett et al., 2018; Malekpour et al., 2016; Nguyen et al., 2019; Thorne et al., 2018; Wihlborg et al., 2019).
Path dependency	It is related to the preference for traditional systems (Dhakal & Chevalier, 2017; Han & Kuhlicke, 2021; Janssen et al., 2020; McEvoy et al., 2019).
Position of power of the water utility	Water utilities are often the most powerful actor, then the adoption of alternative drainage strategies might be frustrated by your particular goals (Janssen et al., 2020; Johns, 2019).
Private land ownership	It refers to obstacles posed by particular interests of private land owners (Gashu & Gebre-Egziabher, 2019; Han & Kuhlicke, 2021; Johns, 2019; Mguni et al., 2015; Sarabi et al., 2020).
Public land ownership	It refers to the stormwater management responsibilities according to the portion of public land to be intervened (Dhakal & Chevalier, 2017).
Responsibility vs. authority dilemma	“Cities have no direct authority to control stormwater from private parcels but has responsibility to manage it” (Dhakal & Chevalier, 2017).
Silo mentality	It refers to the operation of departments and institutions mainly under their particular disciplinary vision (Han & Kuhlicke, 2021; Mukhtarov et al., 2019; O’Donnell et al., 2017; Sarabi et al., 2020; Wamsler et al., 2020).
Space constraints	For particular SUDS typologies, size and shape of the site might be a limitation (Kim et al., 2017; L. Liu & Jensen, 2018) .
Uncivil behaviors	It includes vandalism and littering, which affects SUDS management (Carriquiry et al., 2020).
Unclear institutional responsibilities	Unclear liability, either between the local government or organizational structures, might cause conflicts of interest

	and affect the decision-making transparency (Berndtsson et al., 2019; Han & Kuhlicke, 2021; L. Li et al., 2020).
Urban densification	It relates to local-government priorities of housing development due to population forecast, reducing the available space for urban water management solutions such as SUDS (Wihlborg et al., 2019).
Workload that SUDS demand	It depends on the level of importance given to SUDS, where its implementation lags behind other demands (Han & Kuhlicke, 2021; Wihlborg et al., 2019).
Additional barriers found in the present study	
Clogging effect	Although this barrier has been widely investigated through hydraulic, hydrologic, and optimization models, to the best of the author's knowledge it has not been specifically referred to as a barrier to SUDS implementation. Clogging is caused due to the presence of small-sized silt and fine particles in the run-off (Shafique, 2016), and can impact hydraulic conductivity.
Increase in water tariffs	To the best of the authors' knowledge, this barrier has not been addressed in the literature. This barrier was mentioned from the perspective of the local water utility, where the reduction in drinking water consumption implies less profit, and therefore, an adjustment should be made to the water tariffs.
Indoor humidity concerns	This barrier was mentioned alluding to the operation of rainwater harvesting systems, even more so in a cold-very dry climate like Bogotá.
Performance reduction	Although this barrier has been widely investigated through hydraulic, hydrologic, and optimization models, to the best of the author's knowledge it has not been specifically referred to as a barrier to SUDS implementation. However, lack of proper design and poor maintenance might lead to a reduction of SUDS performance.
Risks to conventional drainage system performance	Although this barrier has been widely investigated through hydraulic, hydrologic, and optimization models, to the best of the author's knowledge it has not been specifically referred to as a barrier to SUDS implementation. This barrier was mentioned due to the fear of SUDS efficiency uncertainty, which may impact redesigned conventional systems.
Waterlogging/ inundation problems	This barrier was mentioned from the perspective of a local water utility representative alluding that waterlogging might be a consequence of a clogging problem, affecting the local population.

Table S2 *Code book of benefits of SUDS implementation*

Benefits	Description and references in sustainable urban water management literature
Air quality enhancement	The use of grass, trees, or green infrastructures improves the air quality by capturing dust particles or absorption of carbon dioxide (Everett et al., 2018; Ossa-Moreno et al., 2017; Reynaud et al., 2017; Woods et al., 2015).
Amenity	It refers to SUDS ability to offer attractive and pleasant places (Ferguson et al., 2013; Han & Kuhlicke, 2021; Maskrey et al., 2020; Mulligan et al., 2020; Santoro et al., 2019).
Aquifer recharge	Infiltration techniques allow groundwater recharge (Carriquiry et al., 2020; Ossa-Moreno et al., 2017).
Biodiversity augmentation	Different SUDS typologies can include a variety of planting, thus contributing to urban biodiversity (Everett et al., 2018; Fenner et al., 2019).
Climate change adaptation and mitigation	The integration of the multiple environmental benefits that SUDS provide assists the climate change mitigation and adaptation management (Carter, 2018; Hernández-González et al., 2016; Sussams et al., 2015; Wihlborg et al., 2019).
Decentralized water supply	Retention techniques such as rain water harvesting systems can serve as a backup water supply (Santoro et al., 2019).
Flood risk mitigation	The most well-known SUDS benefit is their ability to control runoff and peak flows, which directly impacts flood risk management (Krkoška Lorencová et al., 2021; L. Li et al., 2020; Nguyen et al., 2019; Reynaud et al., 2017; Wardekker et al., 2020).
Heat resilience	SUDS can help in regulating building temperatures and cooling local-climate conditions (Connop et al., 2016; Ossa-Moreno et al., 2017; Sussams et al., 2015; Wardekker et al., 2020).
Improving health and well-being	“Publicly accessible green and blue infrastructure supports health and well-being benefits” (Woods et al., 2015).
Noise reduction	SUDS can act as a noise barrier to avoid surrounding noises from nearby main roads (Connop et al., 2016; Ossa-Moreno et al., 2017).
Peak flow reduction	Specific SUDS benefit related to their flood risk management capacity and complementarity to the conventional drainage system (Voskamp & Van de Ven, 2015).
Promotion of ecosystem services	The degradation of ecosystem services, e.g., habitat, cultural, and regulating, can be enhanced through implementation of green infrastructures (Connop et al., 2016).
Promotion of environmental awareness	Environmental awareness is an element of capacity building for flood risk management, raised by having contact with green infrastructures (Bark et al., 2021; Maskrey et al., 2020; O’Donnell et al., 2017).
Promotion of multifunctional spaces	SUDS are multifunctional solutions, covering a wide range of social and environmental issues (Connop et al., 2016; Maskrey et al., 2016; O’Donnell et al., 2017).

Recreation opportunities	The urban landscape can be enriched by multiple SUDS typologies, offering recreational value (Bark et al., 2021; Nguyen et al., 2019; Reynaud et al., 2017; Santoro et al., 2019).
Reduction in water treatment costs	SUDS can provide cost-effective solutions for removal or trapped pollutant loads (Ossa-Moreno et al., 2017; Wihlborg et al., 2019; Woods et al., 2015).
Runoff volume control	Specific SUDS benefit related to their flood risk management capacity and complementarity to the conventional drainage system (Carriquiry et al., 2020; Voskamp & Van de Ven, 2015).
Stormwater management	SUDS promote a comprehensive stormwater management as integral part of the urban design (Casal-Campos et al., 2012; L. Li et al., 2020; Perales-Momparler et al., 2015).
Tax reduction	It relates to a two-way relationship in which tax incentives could encourage SUDS investment and vice versa (McEvoy et al., 2019).
Use of harvested water in secondary uses	E.g., gardening, cleaning, car washing, toilet flushing (Connop et al., 2016; Ossa-Moreno et al., 2017).
Water quality enhancement	Diffuse urban pollution can be managed via SUDS, enhancing the quality of the receiving water bodies (Bark et al., 2021; Everett et al., 2018; Ferguson et al., 2013; Ossa-Moreno et al., 2017; Woods et al., 2015).
Additional benefits found in the present study	
Compensation of green area debt	This benefit was mentioned from the public sector's perspective as a tool currently used to encourage the implementation of SUDS in public works.
Corporate image enhancement	To the best of the authors' knowledge, this benefit has not been widely addressed in the literature. This benefit was commented from the urban developers' perspective, suggesting that SUDS implementation can be perceived positively due to its relationship with environmental and social issues
Delaying water supply network expansion	This benefit was mentioned from the public sector's perspective, related to the benefit of having a decentralized water supply system.
Flexibility for repair and maintenance work	This benefit was mentioned from the public sector's perspective, comparing SUDS to conventional drainage system management.
Hedonic housing prices	This benefit was mentioned alluding to the real estate market, which may benefit due to the potential of SUDS to beautify the landscape.
Improvement of customer's quality of life	To the best of the authors' knowledge, this benefit has not been widely addressed in the literature. This benefit was commented from the urban developers' perspective, alluding to the added value that can be offered to customers through the greening.
Pipe diameter optimization	This benefit was mentioned considering that, by achieving a proper design, SUDS can fulfill a complementary function to the conventional drainage system, allowing for material savings.
Promotion of urban farm projects	This benefit was mentioned considering the possibility of storing water for secondary uses, for instance, from a rainwater harvesting system.

Protection of endangered vegetative species	This alludes to an environmental benefit since SUDS can promote the increase of biodiversity and the protection of ecosystems.
Reduction of imperviousness	Studies have shown that SUDS have the ability to replicate pre-development drainage conditions (Perales-Momparler et al., 2017).
Reduction of the social gap	This benefit was mentioned from the perspective of a community member who considered that SUDS have the opportunity to increase environmental justice, so that regardless of where they live, citizens enjoy a healthy and beautiful environment.
Social responsibility	This benefit was mentioned from an urban developer's perspective who considers relevant the promotion of environmental and social awareness, beyond their role as housing provider.
Water pumping system optimization	This benefit was mentioned considering that, by achieving a proper design, SUDS might have an effect on the reduction of pumping systems.

***Table S3** Linkages of "operation and maintenance" barrier with other barriers according to the quotations of public sector representatives*

Barrier	Examples of empirical evidence
Financial burden	"We may have the resources to cut the ribbon and inaugurate SUDS, but nowadays, in the company's organizational structure, there is no item allowing the water utility to collect an operation and maintenance tariff" (PU2).
Lack of financial resources	"We do not have the equipment or the resources to be able to start operating and maintain SUDS" (PU2).
Lack of operational capacity	"The water utility has shown great resistance to the maintenance issue because they allege they are already overwhelmed with their functions" (PU3).
Lack of quantitative evidence/ performance information	"What worries us about this topic [SUDS implementation] is the maintenance of the SUDS because, unfortunately, there is not much information at the national and international level" (PU1).
Lack of technical capacity (human skills)	"Our operators have the experience in pipes maintenance, not in changing SUDS substrate to regain the infiltration design capacity" (PU2).
Lack of technical capacity (equipment)	"[for the conventional system] It is known which equipment is used for its maintenance, for network cleaning, etc. Not much is known about SUDS" (PU1).
Negative SUDS perceptions	"Well, the first barrier is like the institutional part, because of the suspicion officials have about the implementation of this type of technology, especially in the maintenance part, that is like the Achilles' heel" (PU3)
Unclear institutional responsibilities	"The maintenance issue is still a bit vague, in whom the responsibility will fall" (PU4).
Workload that SUDS demand	"If you implement large SUDS or macro-SUDS, you have concentrated the maintenance on very little, then if you have a large amount in the city, it is a serious problem" (PU1).

***Table S4** Linkages of "operation and maintenance" barrier with other barriers according to the quotations of urban developers*

Barrier	Examples of empirical evidence
Lack of supportive policy and legal framework	"If one looks at municipalities' regulations, they do not even have regulations for urban space. Then, come up with an idea like this [SUDS] and tell them, they have to operate it and take care of… no, they won't" (UD7).
Lack of technical capacity and lack of operational capacity	"If they [water utility] do not do maintenance to the main infrastructure, like open channels or pipes themselves (…) well, these systems [SUDS], which in quotation marks are a little more specialized and with little more sensitive maintenance… we have always encountered resistance on this issue" (UD7).
Unclear institutional responsibilities	"The problem we see right now is that the water utility is demanding it [SUDS implementation] but it has already happened to us in several projects, that they ask for it, but they still are not very clear on how the maintenance will be" (UD3). "When you tell IDRD you are going to implement a SUDS such as a detention basin, then IDRD says no, that's not mine anymore, I can't operate and maintain that, so it's up to the water utility. The water utility says no, I cannot operate and maintain that because it is within a park" (UD7).

Table S5 *Quotations of perceived benefits of SUDS implementation by community participants*

Benefits	Number of quotations	Examples of empirical evidence
Use of harvested water in secondary uses	11	"For toilet [flushing] and to clean the house" (C3). "To avoid the use of drinking water. That water would be used for toilets [flushing], also for dish washing" (C7).
Amenity	4	"First, help beautify the environment" (C2). "It is a way to create green areas" (C6).
Flood risk mitigation	4	"Rainwater would be used and floods would be avoided in this way" (C1). "Prevent flooding" (C11).
Promotion of multifunctional spaces	2	"Create other spaces within the same neighborhood. If gardens are implemented, it gives another aspect to the space" (C10).
Runoff volume control	2	"The most logical benefit is to reduce the amount of runoff that flows into the tributaries, which would be the Bogotá River" (C6).
Promotion of environmental awareness	2	"Another [benefit] is to raise awareness and environmental education in the community, knowing that we are facing a climate change problem" (C6).
Biodiversity augmentation	1	"With these [SUDS strategies], ecological corridors can be expanded" (C13).
Decentralized water supply	1	"In case there is a water cut, it will be a point where the community can go and get water while the repairs are made" (C12).
Health and well-being improvement	1	"To reduce public health related issues" (C13).
Promotion of ecosystem services	1	"[it allows] conditions of adequate environmental ecosystem services" (C13).
Promotion of urban farms projects	1	"This [bioretention systems] can be urban gardens, just like here" (C5).
Protection of endangered vegetative species	1	"We can handle the issue of native aquatic plants that are on the way to extinction" (C13).
Reduction of the social gap	1	"I am sorry for what I'm going to say, but that the *** that comes from the city not only arrives in the southern part and then those of us who are living here have to put up with it. [It would be] quite the opposite, that [our neighborhood] also looks good, looks nice" (C13).

Water quality enhancement	1	“Decrease in the amount of polluted water” (C6).

Table S6 *Quotations of perceived benefits of SUDS implementation by public sector representatives*

Benefits	Number of quotations	Examples of empirical evidences
Runoff volume control	5	“Reduction of runoff peaks, both volume and peak flow” (PU2).
Flood risk mitigation	5	“To control water volumes entering the drainage system in a coordinated manner and to prevent downstream flooding” (PU1).
Water quality enhancement	4	“SUDS basically have 2 objectives (…), one is runoff control for flood prevention and mitigation and the other is water quality” (PU3).
Amenity	2	“Another goal is to improve the amenity of public space, to make it green” (PU1).
Promotion of environmental awareness	2	“Awareness is also raised about the environmental benefits generated by this type of infrastructure” (PU1).
Heat resilience	2	“The inclusion of SUDS brings environmental benefits, reducing the heat island [effect]” (PU4).
Noise reduction	2	“Noise reduction” (PU4).
Peak flow reduction	2	“To reduce flood peaks that can be derived from runoff in rain events” (PU1).
Reduction of imperviousness	2	“Permeability conditions of that section where SUDS are incorporated can be improved” (PU4).
Air quality enhancement	1	“Reduction of air pollution” (PU4).
Biodiversity augmentation	1	“To improve the biodiversity of an urban area” (PU4).
Climate change adaptation and mitigation	1	“SUDS are included in the 2017 national climate change policy” (PU4).
Compensation of green areas debt	1	“IDU together with SDA worked on modifying the resolution 001 of 2019, which deals with the compensation of green areas [through SUDS implementation]” (PU4).
Delay water supply network expansion	1	“There are going to be benefits such as delaying investments for projects of supply system expansion” (PU2).
Flexibility for repair and maintenance work	1	“[compared to SUDS], changing an 800mm pipe to a 1200mm pipe in such a densely populated city (...) it is simply not feasible” (PU2).
Hedonic housing prices	1	“If you incorporate SUDS into your urban development project, it has to do with hedonic prices. The property value increases as it has

		access to natural coverage or an internal lake" (PU4).
Reduction in water treatment costs	1	"If you as landowner, take the burden off the existing drainage system by managing your own runoff volume, that can be seen as a monetary benefit" (PU4).

Table S7 *Quotations of perceived benefits of SUDS implementation by urban developers*

Benefits	Number of quotations	Examples of empirical evidence
Use of harvested water in secondary uses	7	"We already have concrete tanks (…), we collect stormwater for later reuse in maintenance works" (UD3). "As an example, in the company's building, we collect all the stormwater. We have a very simple treatment plant to reuse stormwater for toilets flushing and common areas cleaning" (UD4).
Pipe diameter optimization	5	"At some point, pipe diameters have to be reduced because the water we have to handle is [going to be] less" (UD7). "We have evaluated how else we can use this type of systems [SUDS], especially for diameters optimization" (UD3).
Promotion of environmental awareness	3	"To make people aware, let's say in projects, about the importance of trying to restore the natural water cycle" (UD3).
Aquifer recharge	3	"It seems to me that it is worthwhile, not only to study it [SUDS] as flood control, but also to think about infiltration to improve groundwater sources" (UD6).
Reduction of imperviousness	2	"We seek to mitigate the imperviousness peak that is generated by including surfaces other than those that normally exist" (UD7).
Stormwater management	2	"We, together with UD1, began to have contact with this type of strategies [SUDS] for stormwater management, since 2016-2017" (UD2).
Runoff volume control	1	"It seems to me that it is worthwhile, not only to study it [SUDS] as flood control, but also to think about infiltration to improve groundwater sources" (UD6).
Flood risk mitigation	1	"To control runoff volumes to prevent flooding" (UD6).
Amenity	1	"So, the visual they [clients] have is a green visual, a very pleasant space because when they walk between the buildings we made, it is basically a garden" (UD5).
Heat resilience	1	"We have implemented them [green roofs] more as a thermal insulation strategy" (UD4).
Peak flow reduction	1	"We seek to mitigate the imperviousness peak that is generated by including surfaces other than those that normally exist" (UD7).
Promotion of multifunctional spaces	1	"[we developed] living spaces such as squares and people feel very happy when one as an urban developer (…) builds in an orderly way" (UD5).

Company image	1	“Benefits from a commercial point of view, from the point of view of the company's image” (UD4).
Improvement of customer's quality of life	1	“To improve the quality of life (…), the company has always thought of leaving a footprint that does not cause such an impact on nature” (UD5).
Recreation opportunities	1	“Rooftops have now become passive recreation areas for inhabitants, then green roofs are being implemented” (UD6).
Social responsibility	1	“Social responsibility, we must also be more aware of the environment” (UD2).
Tax reduction	1	“There are a number of tax benefits that help us implement some of these strategies [SUDS]” (UD4).
Water pumping systems optimization	1	“In a well implemented system, pipe diameters should be reduced and obviously, if there is a pumping system, then it should also be adjusted” (UD7).

Table S8 *Literature addressing the barriers to the implementation of different SUDS typologies*

SUDS typology	References
Attenuation storage tanks (AST)	(Campisano et al., 2017; Deng, 2021; Kimic & Ostrysz, 2021)
Bio-retention systems (BRS)	(Brown & Farrelly, 2009a; Carriquiry et al., 2020; Chaffin et al., 2016; Coleman et al., 2018; Shafique, 2016)
Constructed wetlands (CW), including Ponds (P)	(Alikhani et al., 2021; Brown & Farrelly, 2009a; Goosen & Vellinga, 2004; Guittonny-Philippe et al., 2014; Kimic & Ostrysz, 2021; Lucas et al., 2015; Parkinson & Tayler, 2003; Pour et al., 2020; Stefanakis, 2019; Takavakoglou et al., 2022; T. Zhou & Penning-Rowsell, 2021)
Extended dry basins (EDB)	(Lee & Li, 2009; Nascimento et al., 1999)
Green roofs (GR)	(Aparicio Uribe et al., 2022; Brudermann & Sangkakool, 2017; Krkoška Lorencová et al., 2021; T. Liu et al., 2021; Perales-Momparler et al., 2017; Shafique et al., 2018; Xiao et al., 2014; Zahir et al., 2014; G. Zhang & He, 2021; X. Zhang et al., 2012)
Infiltration systems: include Infiltration Basins (IB) and Infiltration Trenches (IT)	(Brown & Farrelly, 2009a; Coleman et al., 2018; Kimic & Ostrysz, 2021; T. Liu et al., 2021; Perales-Momparler et al., 2017; Simperler et al., 2020; Sleegers, 2013)
Pervious pavements (PP)	(Brown & Farrelly, 2009a; Coleman et al., 2018; Harvey et al., 2017; Jadhav et al., 2022; Kuruppu et al., 2019; Labadie, 2011; T. Liu et al., 2021; Monrose & Tota-Maharaj, 2018; Pour et al., 2020; Uittenbroek, 2016)
Rainwater harvesting systems (RWHS)	(Akuffobea-Essilfie et al., 2020; Campisano et al., 2017; Coleman et al., 2018; Lani et al., 2018; Leidl et al., 2010; T. Liu et al., 2021; Ndeketeya & Dundu, 2019; Temesgen et al., 2016)
Vegetated swales (VS)	(Brown & Farrelly, 2009a; Everett et al., 2018; Labadie, 2011; T. Liu et al., 2021; Perales-Momparler et al., 2017)
Tree pits (TP)	(Brown & Farrelly, 2009a; Coleman et al., 2018; Driscoll et al., 2015; Kimic & Ostrysz, 2021; Kronenberg, 2015; Toxopeus & Polzin, 2021)

Supplementary Material S9 *– Support material for expert panel interactions*

INTRODUCTION

Dear expert,

Thank you very much for your interest and willingness to participate in this research.

My name is Abby Ortega, doctoral student at ZEF (University of Bonn, Germany) and I'm working with urban flood risk management, assessing the impact of sustainable urban drainage systems (SUDS). In the first stage of my research I had the opportunity to analyze the perceptions of four key urban water sectors in Bogotá, Colombia, regarding the benefits and barriers of SUDS. Now I would like to use these perceptions as a selection criteria of multiple SUDS typologies, reason why I decided to contact you.

In the matrix on the next page, please rate from 0 to 5 your level of knowledge (design, planning and/or implementation) regarding ten SUDS typologies. Then, please rate from 0 to 5 the impact that six categories of barriers might have on the selection of those SUDS typologies. The scoring system for the two cases is described above the matrix.

Please consider the next brief barriers description:

Barrier category	Brief description	Included barriers
Cultural/Behavioral barriers	Reflect individual beliefs or perceptions, derived from a local context of time and space.	Lack of general knowledge/ awareness, conflicts between stakeholders, lack of community engagement/ ownership, lack of interest, lack of private sector engagement, limited sense of urgency, negative SUDS perceptions, path dependency, silo mentality, skepticism, uncivil behaviors.
Financial barriers	Involve constraints associated with financing and costs associated with the implementation of SUDS.	Implementation and operation costs, information gap on the return of investments, lack of cost-benefit quantification, lack of financial resources, lack of individual willing to pay, low profitability, negative impact on property values.
Institutional/ Organizational barriers	Stem from institutional dynamics, whether inter-governmental or inter-departmental.	Inflexible and conflicting rules, lack of consultation, lack of design standards and guidelines, lack of institutional coordination, lack of policy instruments, unclear responsibilities, lack of promotion.
Political barriers	Derived from government decisions or positions.	Lack of political will/leadership, electoral/ administrative changes.
Technical barriers	Related to the knowledge, planning, implementation, and operation of SUDS.	Lack of technical knowledge, operation and maintenance, lack of monitoring, efficiency uncertainty, health and safety issues, lack of local experience, lack of operational and technical capacity, performance reduction, property damage, space constraints, seasonality/ climate impact on the performance.
Urban forma barriers	Refer to the build environment hindrances.	Land use priorities, private/public land ownership, property ownership, urban densification.

MATRIX TO ASSESS THE IMPACT OF BARRIERS IN THE IMPLEMENTATION OF SUDS

As specified before, please rate from 0 to 5 your level of knowledge (design, planning, and/or implementation) regarding ten SUDS typologies. Then, please rate from 0 to 5 the impact that six categories of barriers might have on the selection of those SUDS typologies.

Thank you very much for your participation!

Scoring *knowledge*	
0	None
1	Very low
2	Low
3	Medium
4	High
5	Very high

Scoring *barriers impact*	
0	No impact
1	Very low impact
2	Low impact
3	Medium impact
4	High impact
5	Very high impact

Geographic context of your assessment:

SUDS typologies	**Level of Knowledge**	**Barriers**					
		Cultural/ Behavioral	***Financial***	***Institutional/ Organizational***	***Political***	***Technical***	***Urban form***
Attenuation storage tanks	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Bio-retention systems	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Constructed wetlands	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Extended dry basins	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Green roofs	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Infiltration systems	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Pervious pavements	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Rainwater harvesting systems	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Swales	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Tree pits	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.

Additional comments or suggestions?

Table S10 *Reference values for physical restrictions in different SUDS typologies*

SUDS typology	**Soil characteristics**			**Geometry constraints**			**Land-use suitability**			
	Slope (%)	Water table depth (m)	Infiltration rate (mm/h)	Area (m^2)	Width (m)	Length (m)	Public land		Private land	
AST	n/a[c,d]	≥1[c,d]	n/a[c,d]	50-3000*[d]	n/a	n/a	Not suitable		Residential, commercial, industrial [c]	x
BRS	0-10[f]	≥1.80[f]	≥7[a,f]	≥18[e]	≥3[e]	≥6[e]	Parks/ open space, sidewalks, plazas [c,h]	x	Residential, commercial use, public facilities [c,h]	
CW	≤1[a]	≥1.20[b]	Any[a]	≥1000[h]	≥18[h]	≥56[h]	Parks/ open space [h]	x	Not practical in ultra-urbanized areas [b]	
EDB	1-15[f]	≥3[f]	≥7[f]	≥4050[f]	≥45[f]	≥90[f]	Parks/open space [h]	x	Residential use, commercial use, public facilities [h]	
GR	0.5-5[e,g]	n/a[c,d]	n/a[a,c,d]	≥20*[c]	n/a	n/a	Not suitable		Residential, commercial, industrial [c]	x
IB	≤15[a,b]	≥1.20[b]	≥13[b]	≥45[i]	≥5[i]	≥9[i]	Parks/open space [h]	x	Not suitable	
IT	≤15[a,b,d]	≥1.20[b]	≥7[a,f]	≥15[i]	≥0.5[i]	≥30[i]	Parks/open space [h]	x	Residential use, commercial use, public facilities [h]	
PP	0.5-5[f]	≥1[c,d]	Any[a] (low IR with underdrain[c,d,e])	≥1[i]	≥1[i]	≥1[i]	Plazas, parking lots, sidewalks [h]	x	Residential, commercial, industrial, public facilities [c,h]	
P	≤1[a]	≥1.20[b]	Any[a]	≥150[h]	≥8[h]	≥20[h]	Parks/open space [h]	x	Commercial use, public facilities h, not practical in ultra-urbanized [b]	
RWHS	n/a	n/a d	n/a[c,d]	5-50*[d]	n/a	n/a	Not suitable		Residential, commercial, industrial [c]	x
VS	0.5-6[d]	≥1[c,d]	Any[a] (low IR with underdrain[c])	≥0.75[e]	≥0.50[e,f]	≥1.50[e]	Parks/open space [c,h]	x	Residential use, commercial use, public facilities, industrial [c,h]	
TP	0-2[c,d]	n/a[c,d]	Any[a,c,d]	≥2.2[i]	≥1.5[i]	≥1.5[i]	Parks/ open space, plazas, sidewalks [h]	x	Residential use, commercial use, public facilities [c,h]	

[a] County of Los Angeles (2014); [b] Maryland Department of the Environment Water Management Administration (2009); [c] City of Edmonton (2014); [d] City of Toronto (2021); [e] Núñez Collado et al. (2019); [f] Empresa de Acueducto y Alcantarillado de Bogotá (2018); [g] Hanna et al. (2019); [h] Jiménez et al. (2019); [i] Uribe-Aguado et al. (2022)

***** Refers to tributary area

x Refers to selected land-use suitability for the study site

n/a = not applicable

Table S11 *Initial barrier scores resulting from the literature review*

SUDS typologies	Cultural/ Behavioral	Financial	Institutional/ Organizational	Political	Technical	Urban form	Info. density
AST	0	2	0	0	6	0	8
BRS	7	4	5	0	7	0	23
CW & P	4	4	10	1	17	2	38
EDB	1	1	0	0	7	1	10
GR	8	11	9	0	25	0	53
IB & IT	3	2	2	0	17	0	24
PP	5	7	4	0	19	0	35
RWHS	11	17	8	0	13	1	50
VS	3	1	3	0	12	0	19
TP	18	10	16	3	15	1	63
Info. density	60	59	57	4	138	5	323

Table S12 *Initial barrier scores resulting from the expert panel*

SUDS typologies	Cultural/ Behavioral	Financial	Institutional/ Organizational	Political	Technical	Urban form
AST	1	3	1	1	2	3
BRS	3	3	4	2	4	2
CW & P	4	4	4	3	2	4
EDB	4	4	3	2	2	4
GR	4	4	2	2	5	4
IB & IT	2	2	2	2	2	3
PP	3	4	4	2	4	4
RWHS	2	2	2	2	2	2
VS	1	3	4	3	2	2
TP	2	2	3	3	2	2