Stochastic Modelling of climate-resilient SuDS: A Design Approach for Bogotá

Modélisation stochastique des SuDS résilients au climat : Une approche de conception pour Bogotá

V. Quintero-Chacón [a]*, J. D. Giraldo-Osorio[a], A. Torres[a,b]
[a]Master's Program in Hydrosystems, Faculty of Engineering, Pontificia Universidad Javeriana. Research Group Ciencia e Ingeniería del Agua y el Ambiente.
[b]Instituto Javeriano del Agua, Pontificia Universidad Javeriana
[a]* Corresponding author. E-mail: quinterovalery@javeriana.edu.co

RÉSUMÉ

L'urbanisation rapide et le changement climatique ont accru les pressions sur les systèmes de drainage conventionnels dans des villes comme Bogotá, favorisant l'adoption de Systèmes de Drainage Urbain Durable (SuDS). Cette étude propose le développement d'une méthodologie flexible pour la conception de SuDS, dans le but d'atténuer divers impacts du changement climatique. La méthodologie a été appliquée à un cas d'étude à Bogotá, axé sur la conception de tranchées de biorétention dans un bassin versant urbain situé à Teusaquillo (Bogotá), en tenant compte des scénarios climatiques futurs. Les données historiques (1981–2009) et les projections CMIP6 ont été intégrées en utilisant un modèle de bilan hydrique journalier et une simulation stochastique de Monte Carlo. Les résultats montrent une diminution des performances dans les scénarios plus chauds et plus secs, bien que les configurations optimisées atteignent des efficacités proches de 30 %, surpassant largement le modèle de référence (<1 %). La méthodologie proposée démontre la faisabilité et la résilience des SuDS face au changement climatique, tout en offrant un cadre reproductible pour leur évaluation et leur conception dans les villes d'Amérique latine confrontées à des contraintes urbaines et de disponibilité de données fiables.

ABSTRACT

Rapid urbanization and climate change have increasingly challenged conventional drainage systems in cities like Bogotá, prompting the adoption of Sustainable Drainage Systems (SuDS). This study proposes the development of a flexible methodology for the design of SuDS, aimed at mitigating various impacts of climate change. The methodology was applied to a case study in Bogotá, focused on the design of bioretention trenches under future climate scenarios in an urban catchment located in Teusaquillo (Bogotá). Historical records (1981–2009) and CMIP6 projections were integrated, applying a daily water balance model and a Monte Carlo stochastic simulation. Results indicate a decrease in performance under warmer and drier scenarios, although optimized configurations reach efficiencies close to 30%, significantly outperforming the baseline model (<1%). The proposed methodology demonstrates the feasibility and resilience of SuDS under climate change, providing a replicable framework for their evaluation and design in Latin American cities with similar urban and data constraints.

KEYWORDS

Sustainable Drainage Systems (SuDS), climate change, water balance, Monte Carlo simulation, hydraulic efficiency, urban resilience.

1 INTRODUCTION

Rapid urbanization and climate change are reshaping urban hydrology and stressing existing drainage infrastructure. Projections from UN Habitat show that by 2050, around 88% of the population in Latin America and the Caribbean will reside in urban areas, directly increasing impervious surface runoff, reducing infiltration, and intensifying pluvial flood frequency (World Cities Report 2022; Fletcher et al., 2013). Regional flood-risk assessments in cities such as São Paulo and Mexico City confirm similar increases in pluvial flood severity (CETESB, 2020; CONAGUA, 2021). Recent observations indicate extreme precipitation anomalies of 40–50% for short-duration storms affecting central and coastal regions of Colombia (World Meteorological Organization, 2024).

In Colombia, Sustainable Drainage Systems (SuDS) have gained relevance, but adoption remains slow due to short monitoring chronicles, missing data, little uncertainty analysis, and lack of standardized criteria for comparing configurations across urban watersheds (Barrett, 2008; Sabbagh et al., 2025). Most regional studies model only discrete rainfall events, ignoring multi-annual wet–dry transitions and substrate recovery cycles (Versini et al., 2015; Versini, 2017). These limitations point to a need for long-term continuous hydrological approaches to avoid runoff and performance underestimation.

Bioretention infrastructures represent a robust SuDS typology for multi-process integration (CIIA, 2017). Nevertheless, performance assessments for traditional trench dimensions in Bogotá often fall below 1% efficiency if geometry or substrate composition is not optimized (Ortega et al., 2023). In response, this work proposes a continuous and stochastic design methodology for SuDS sizing and screening in Bogotá urban corridors, explicitly coupling hydraulic and ecological processes using long-term climate cubes and Monte Carlo configuration exploration.

2 MATERIALS AND METHODS

2.1 Study Area

The SuDS intervention zone corresponds to the median strip along the Calle 26 arterial road in Teusaquillo (Bogota), situated between stormwater inlets to maximize runoff capture and enable continuous substrate behavior evaluation. Climatic characterization used daily gridded records of precipitation (P), maximum temperature (Tmax), and minimum temperature (Tmin) extracted from the Colombian national climate data cube produced by the national authority in hydrology and meteorology (Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM), covering the 1981–2020 interpolation grid. Historical records from 1981–2009 were used as baseline analysis input, matching equivalent 28-year temporal windows applied for the projected analysis envelope. The daily runoff volume entering the bioretention trench (E) is computed using the impervious-lane-driven runoff coefficient (Cr = 0.8) and the durable external contributing drainage area upstream (Aa = 800 m^2), scaled using multi-annual Julian-day-linked precipitation for comparability across 365-day windows. Climate trajectories SSP1-2.6 (low emissions), SSP2-4.5 (moderate forcing), SSP3-7.0 (high forcing), and SSP5-8.5 (severe warming/drying) from the Colombian 2021–2100 CMIP6 ensemble were used. These scenarios were extracted from IDEAM's climate cube for the same spatial coordinate envelope employed in observed chronicles, guaranteeing geospatial consistency for SuDS evaluation under minimal monitoring constraints.

The bioretention trench was chosen as the SuDS typology for the proposed model because of its strong hydrological performance and adaptability to Bogotá's urban context (CIIA, 2017). Its design integrates retention, infiltration, filtration, and evapotranspiration, outperforming other alternatives such as infiltration trenches and permeable pavements under intense rainfall conditions (CIIA, 2017). Native plant species from the Sabana de Bogotá altiplano region were prioritized to support infiltration enhancement, compaction reduction, wet–dry tolerance, invasive-species suppression, and ornamental integration (Corduan & Kühn, 2024). Plants were represented using crop coefficients (Kc) from Allen, Pereira, Raes & Smith (1998) guidelines contained within Crop evapotranspiration: FAO 56, enabling estimation of real evapotranpiatration (ETc) under shallow substrate interactions using only commonly available variables (Rainfall, Tmax, Tmin, Ra).

2.2 Methodology proposed

The model estimates the fraction of water retained in the substrate that remains available to vegetation before drainage occurs. Using FAO methodology (Allen et al., 1998), Total Available Water is calculated from field capacity, wilting point, and rooting depth to derive effective storage volume. Reference evapotranspiration was computed with the Hargreaves–Samani method, and crop evapotranspiration was obtained by applying crop coefficients and bioretention surface area. Precipitation was converted to cubic meters for runoff inflow simulation, and daily captured runoff was compared to substrate storage capacity. Excess water beyond this capacity was considered underdrain discharge or overflow.

System efficiency was defined as the ability of the bioretention trench to reduce runoff entering the sewer network. Average annual efficiency was calculated using a 365-day moving window. A cost–benefit indicator was then derived, relating construction cost—including materials, labor, and equipment—to hydraulic performance. Unit prices were sourced from official Bogotá references, considering components such as concrete, steel reinforcement, substrate mix, drainage pipes, and excavation. A low ratio indicates high efficiency at low cost, while a high ratio reflects reduced economic viability.

A stochastic model based on Monte Carlo simulations generated 1,000 design scenarios by varying trench geometry and substrate composition, while keeping climate, vegetation, and hydraulic parameters fixed. Each configuration was evaluated for efficiency and cost, enabling identification of designs that maximize performance at minimal cost. Convergence analysis confirmed that 1,000 simulations were sufficient to capture variability and select optimal alternatives. Ranking of SuDS options used cost-to-efficiency screening and non-parametric significance testing, requiring configurations to show statistically significant performance improvement, maintain at least 25% efficiency under all climate scenarios, and avoid water accumulation beyond design thresholds during droughts.

3 RESULTS

The baseline trench configuration modeled without geometry or substrate proportion optimization showed hydraulic efficiencies close to 0.8% (figure 1), consistent with studies pointing to poor performance (<1%) of nominal SuDS trench sizing for Bogotá under climate forcing if no adjustments are applied.

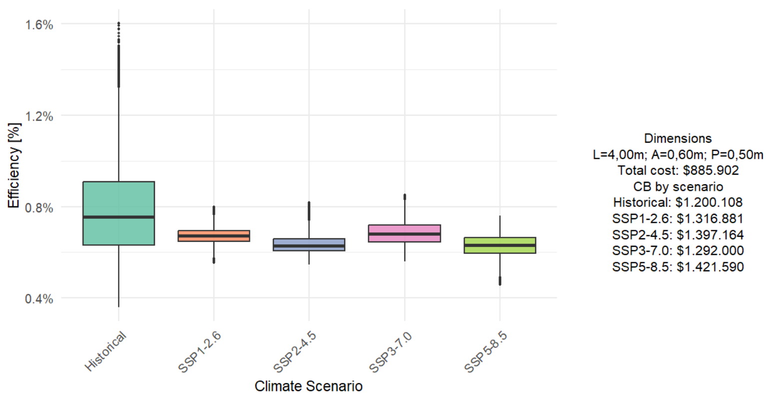

Figure 1. Efficiency by period for the baseline trench designed using the Technical SuDS Guide of CIIA (2017), under historical conditions and CMIP6 climate projections.

In contrast, optimized designs extracted from Monte Carlo stochastic screening achieved annual hydraulic efficiencies close to 30% (figure 2), more than 30× the baseline reference, demonstrating meaningful gains for SuDS. As projected climates become warmer and drier, hydraulic performance progressively declines, especially under SSP3-7.0 and SSP5-8.5 pathways, confirming system sensitivity to temperature and drought forcing. Nevertheless, the final screened, selected configuration preserved hydraulic performance remaining ≥25% under every climate trajectory evaluated, confirming operational SuDS resiliency under input-scarce urban hydrological contexts.

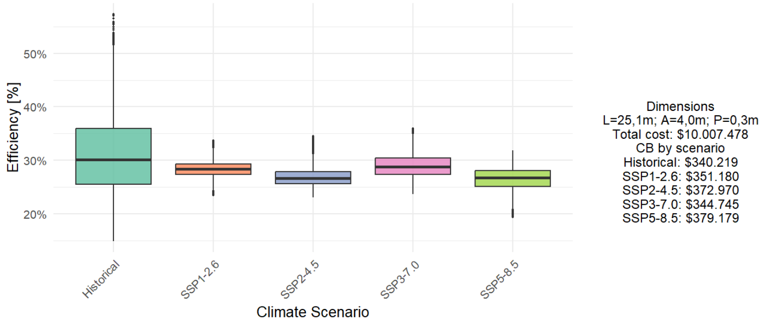

Figure 2. Efficiency by period for optimized designs trench (configuration selected after the comparative analysis), under historical conditions and CMIP6 climate projections.

4 CONCLUSIONS

The main contribution of this study is the development of a stochastic and continuous hydrological evaluation methodology for bioretention-based SuDS, relying exclusively on widely accessible climate variables. This approach enables robust infrastructure comparison under hydro-meteorological uncertainty. Model application demonstrated that hydraulic efficiency can be substantially enhanced through appropriate trench sizing, optimized substrate storage, vegetation integration, and probabilistic parameter inference within long-term simulation windows. The optimal configuration maintained efficiencies above 25% under both historical (1981–2009) and projected climate conditions (2073–2100), confirming bioretention trenches as an effective strategy for mitigating urban flooding and strengthening climate resilience in roadway corridors with high hydraulic connectivity. Findings highlight the need to evaluate SuDS performance through soil–plant–atmosphere interactions, as vegetation and substrate dynamics are critical to runoff reduction. The proposed methodology is replicable and adaptable to other SuDS typologies by adjusting key hydraulic parameters, providing a robust foundation for adaptive urban planning frameworks in data-limited Latin American cities.

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