

## SUDS as a Response to Climate-Related Challenges in Bogotá: A Multi-Hazard Assessment Using Machine Learning Models and Climate Change Scenarios

Les techniques alternatives en réponse aux enjeux climatiques à Bogotá : Une évaluation multi-risques basée sur des modèles d'apprentissage automatique et des scénarios de changement climatique

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### RÉSUMÉ

Bogotá est exposée à une forte récurrence d'incendies de forêt, d'inondations urbaines, d'épisodes d'accumulation d'eau (waterlogging) et de mouvements de terrain, des phénomènes amplifiés par la variabilité climatique et l'expansion urbaine. Cette étude intègre plus de 80 000 incidents hydrométéorologiques documentés par le système officiel d'information pour la gestion du risque et du changement climatique de Bogotá, ainsi que des séries historiques provenant de 81 stations météorologiques exploitées par l'IDEAM, l'autorité nationale en matière d'hydrologie et de météorologie (Institut d'Hydrologie, de Météorologie et d'Études Environnementales), et par l'IDIGER, l'entité responsable du Système de Gestion du Risque du district. Des matrices antécédentes allant jusqu'à 60 jours ont été construites, et des modèles Extreme Gradient Boosting (XGBoost) ont été entraînés pour identifier des fenêtres temporelles optimales capables de reproduire les dynamiques historiques et de générer des scénarios futurs. Des fenêtres de 14, 21 et 16 jours ont montré des performances robustes pour les incendies, les inondations et les mouvements de terrain. Le réanalyse historique et les projections selon les scénarios SSP révèlent des variations spatiales significatives et des augmentations différentielles de la probabilité future d'occurrence. La comparaison entre ces probabilités et la localisation actuelle des SUDS met en évidence un décalage marqué avec les zones de vulnérabilité projetée, soulignant la nécessité d'intégrer des modèles prédictifs, des scénarios climatiques et des solutions fondées sur la nature dans les protocoles de planification urbaine et de gestion du risque.

### ABSTRACT

Bogotá faces frequent wildfires, urban floods, waterlogging and landslides—hazards intensified by climatic variability and rapid urban expansion. This study integrates more than 80,000 hydrometeorological incidents reported through Bogotá's official risk and climate-information system, along with historical records from 81 meteorological stations operated by IDEAM, the national authority in hydrology and meteorology (Instituto de Hidrología, Meteorología y Estudios Ambientales), and IDIGER, the agency leading the District Risk Management System. Retrospective matrices of up to 60 antecedent days were constructed, and Extreme Gradient Boosting (XGBoost) models were trained to identify optimal windows capable of reproducing historical dynamics and generating future scenarios. Windows of 14, 21 and 16 days produced robust performance for wildfires, flooding and landslides, with metrics consistent with official records. Historical reanalysis and SSP-based projections reveal spatial variability and differential increases in future hazard probabilities. Comparison with the current distribution of SUDS highlights a structural mismatch between existing infrastructure and areas of highest projected vulnerability. These findings underscore the need to integrate predictive models, climate scenarios and nature-based solutions into urban planning and risk-management protocols to strengthen resilience and climate adaptation in Bogotá.

### KEYWORDS

Climate Change, Forest Fires, Machine Learning, SUDS, Urban Flooding

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## 1. Background

Urban regions worldwide are increasingly exposed to complex hydrometeorological pressures, which has led to the evolution of Sustainable Urban Drainage Systems (SUDS) (Arnbjerg-Nielsen, 2012a; Harremoës, 1997; Zhou et al., 2012) from single-purpose drainage interventions to multipurpose SUDS capable of delivering co-benefits such as water retention, ecosystem enhancement and microclimate regulation. Under accelerating climate variability, international guidelines increasingly promote the development of SUDS designed for—or robust under—climate change scenarios, emphasizing the need for planning frameworks that integrate future hazard trajectories rather than solely present-day conditions (Bertrand-Krajewski, 2021; Fletcher et al., 2013; Hatt et al., 2006; Mitchell et al., 2006).

Bogotá, located within a high Andean basin characterized by the complex interplay of topography, climate and accelerated urban expansion, faces a broad spectrum of hydrometeorological hazards that recurrently disrupt its urban functioning. Phenomena such as wildfires, fluvial flooding, pluvial flooding, urban waterlogging and landslides along the steep hillslopes constitute high-priority threats for the District Disaster Risk Management System (SDGR). The city's vulnerability is amplified by pronounced interannual climatic variability, strong altitudinal gradients, pressure on strategic ecosystems and continued expansion into increasingly susceptible areas (Charlesworth, 2010; Zhai et al., 2018).

The historical characterization of these hazards has been systematically documented by Bogotá's official Risk and Climate Change Information System (SIRE), which consolidates emergency reports associated with more than 80,000 climate-related incidents between 2005 and 2025—including wildfires, floods, waterlogging, channel overflows, landslides and failures of the urban tree canopy. This repository is one of the most comprehensive urban-risk databases in Colombia and provides essential insight into the spatial and temporal dynamics of hydrometeorological hazard occurrence (D'Ambrosio et al., 2020).

Despite the magnitude of available information, current urban-planning and adaptation mechanisms remain limited in their ability to anticipate how these hazards may evolve under climate-change scenarios. The implementation of Sustainable Urban Drainage Systems (SUDS), in particular, has historically responded to urban-renewal projects or localized interventions, rather than being directly informed by projected risk patterns. As a result, substantial gaps exist between the spatial distribution of SUDS and the areas where climate-related incident probabilities are expected to intensify in the coming decades.

In this context, there is a growing need to integrate methodologies based on the modeling of antecedent conditions and Machine Learning algorithms capable of capturing non-linear relationships between meteorological drivers and climate-related incident occurrence. The integration of historical records from 81 IDEAM and IDIGER meteorological stations, more than 80,000 SIRE climate-related incidents, and climate projections from the Fourth National Communication on Climate Change enables the development of robust predictive models for identifying spatial and temporal vulnerability patterns (Arnbjerg-Nielsen, 2012b). This approach provides a strategic foundation for guiding the design, prioritization and implementation of SUDS within a prospective, climate-responsive and multi-hazard framework aligned with the challenges faced by Bogotá.

## 2. Data Setup

The analysis was based on historical hydrometeorological records from 81 stations operated by IDEAM and IDIGER between 2000 and 2025. IDEAM, the national authority in hydrology, meteorology and environmental studies (Instituto de Hidrología, Meteorología y Estudios Ambientales), contributed 21 stations with a standardized 10-minute temporal resolution, located within Bogotá, its peri-urban surroundings and nearby municipalities. This configuration provides broad coverage of regional climatic gradients and captures the synoptic and mesoscale variability that influences the city.

The IDIGER network—managed by the entity leading Bogotá's District Risk Management System—provided the remaining stations, whose temporal resolution has evolved over time. Before 2010, stations recorded data at 5- and 10-minute intervals, reflecting early configurations of the network. After 2010, a gradual modernization and standardization process led to a one-minute resolution for all operational stations. The network has expanded continuously, from approximately 20 initial stations to nearly 60 stations included in this study. To ensure statistical stability and consistency, only stations with at least five years of continuous data were considered, and

stations installed after 2020 were excluded due to insufficient record length.

Spatially, IDIGER stations are concentrated primarily within Bogotá's urban area, with higher density in the eastern foothills, where the city experiences the highest rainfall intensities and the greatest number of climate-related incidents. This urban-focused distribution complements the more regional coverage of the IDEAM network, allowing the combined dataset to represent both local urban processes and broader hydrometeorological gradients. Based on this integrated network, daily climatological surfaces of accumulated precipitation, maximum hourly rainfall intensity and daily maximum, mean and minimum temperature were generated using Inverse Distance Weighting (IDW) interpolation. These continuous spatial surfaces enabled the extraction of antecedent conditions at the exact coordinates of climate-related incidents, producing retrospective series of up to 60 days prior for all variables—an essential input for the Extreme Gradient Boosting (XGBoost) models developed in this study.

Complementarily, daily precipitation and temperature NetCDF surfaces were incorporated from IDEAM's Fourth National Communication on Climate Change, covering the period 2020–2100 under the SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5 scenarios. Together, the historical monitoring records and the spatially explicit climate-projection surfaces form the integrated dataset underpinning the multi-hazard predictive analysis presented in this study.

### 3. Methodology

The methodological framework begins with the characterization of antecedent hydrometeorological conditions associated with wildfires, floods, and landslides in Bogotá. For each climate-related incident recorded in SIRE, retrospective matrices of up to 60 days prior were constructed, integrating daily accumulated precipitation, maximum hourly rainfall intensity within a 24-hour window, daily maximum, mean and minimum precipitation, and the spatialized temperature variables generated in the data-preparation stage. This process captures the hydrometeorological memory relevant to the activation of each hazard, producing a multitemporal dataset that forms the foundation of the predictive modelling framework.

Building on these matrices, analysis windows ranging from 2 to 60 antecedent days were evaluated. For each window and hazard type, 500 independent models were trained using the Extreme Gradient Boosting (XGBoost) algorithm under a cross-validation scheme with a 70–30 split between training and evaluation. Model performance was assessed using AUC, F1-score, accuracy, Kappa and log-loss, allowing evaluation of both discriminative capacity and temporal stability across varying antecedent periods. Model selection was embedded directly within this process by comparing consecutive windows through the paired Wilcoxon test, which enabled the identification of the minimum number of antecedent days that achieved statistically equivalent performance to more complex configurations. This parsimonious approach yielded optimal windows of 14 days for wildfires, 21 days for flooding and 16 days for landslides (Q. Li et al., 2026; S. Li et al., 2025; Mechantel et al., 2024; Nadim et al., 2025).

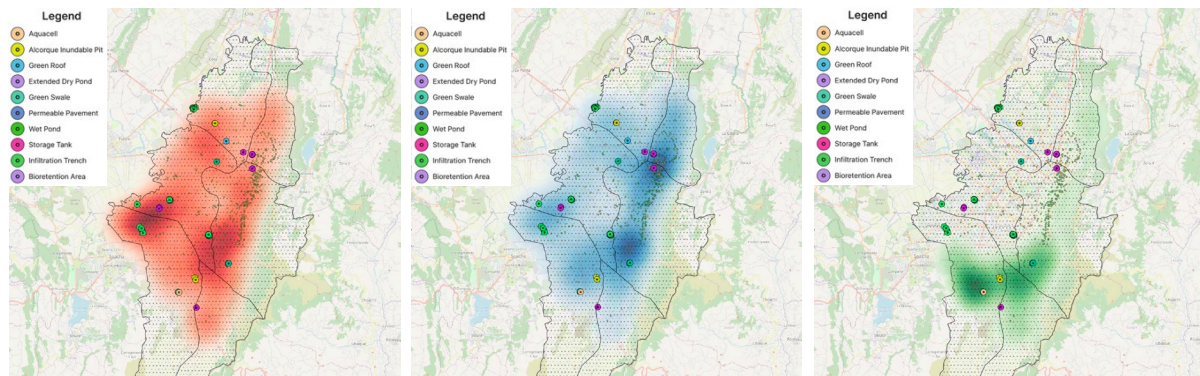
The selected models were subsequently used for a dual predictive assessment. First, they were applied to historical antecedent conditions to estimate the probability of occurrence of each hazard during the observed period, generating probability surfaces that reflect the spatial patterns of susceptibility captured in the more than 80,000 climate-related incidents documented in the city. Second, the models were forced with daily NetCDF precipitation and temperature surfaces from IDEAM's official climate projections included in the Fourth National Communication on Climate Change, covering 2020–2100 under the SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5 scenarios. This enabled the estimation of future probabilities of wildfires, flooding and landslides under different climate trajectories. Finally, both historical and projected probability surfaces were integrated with the spatial distribution of existing SUDS to assess their adequacy and responsiveness relative to the evolving spatial configuration of climate-driven hazards in Bogotá.

### 4. Results

The models trained from antecedent conditions exhibited consistent performance across the three hazards analyzed. The optimal windows identified—14 days for wildfires, 21 days for flooding/waterlogging, and 16 days for landslides—yielded stable and robust metrics, with average Kappa values close to 0.60, F1-scores ranging from 0.79 to 0.82, and accuracies above 80%. These results demonstrate the models' ability to adequately represent the hydrometeorological dynamics associated with the events recorded in SIRE. The historical reanalysis confirmed that the estimated probabilities coherently reproduce the spatial patterns of the more than

80,000 documented events in the city, aligning with areas traditionally affected according to the official database.

The prospective assessment under SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 reveals differential increases in hazard probability toward the end of the 21st century. In general, wildfires show higher probabilities along the urban periphery, particularly under warmer and drier scenarios; flooding probabilities increase in northern, central, and western sectors of the city, linked to intensified hydrological extremes; and landslides exhibit higher susceptibility along the eastern hillslopes and southern corridors. Pronounced spatial variability is observed across the city, dependent on the projected climatic trajectories.



**Figure 1.** Existing SUDS (see legend) in Bogotá, and combined historical and future probabilities of occurrence for wildfires (left), floods (center), and landslides (right).

Figure 1 presents the integrated probability of occurrence for wildfires, floods and landslides in Bogotá, derived from the combined computation of historical antecedent conditions and future climate-change scenarios. This synthesized surface captures the spatial distribution of overall hazard probability, capturing both the historical patterns identified from the 80,000 climate-related incidents and the projected trajectories under SSP-based climate projections. The resulting spatial shifts emphasize the relevance of incorporating prospective climate information into urban planning and into the evaluation of sustainable drainage solutions. Furthermore, the comparison between historical and projected probabilities and the current distribution of SUDS (Figure 1) reveals a structural misalignment between existing infrastructure and areas where vulnerability is expected to intensify.

## 5. Conclusions

The results demonstrate that modeling antecedent conditions through Machine Learning algorithms such as XGBoost enables the high-fidelity reconstruction of historical hydrometeorological dynamics recorded in SIRE, while also supporting the generation of robust probability scenarios under multiple climate-change trajectories. These models constitute a strategic decision-support tool, as they reveal spatial and temporal patterns of hazard occurrence and reinforce risk-management protocols with evidence-based, multi-temporal insights. Their capacity to capture intra-urban variability provides a solid basis for anticipating operational conditions and prioritizing critical zones according to the evolving behavior of climate-related hazards.

The integrated surface of historical and projected probabilities offers a powerful basis for evaluating the alignment of existing SUDS with both current and future hazard conditions, highlighting the need for adaptive, climate-responsive, multi-hazard planning frameworks. This finding underscores the need to advance toward urban-planning frameworks that systematically incorporate predictive modelling, climate scenarios and nature-based solutions. As a natural next step, the identification of high-risk areas paves the way for developing a comprehensive methodology and a set of global design principles for SUDS and green–blue infrastructure—solutions capable of jointly mitigating multi-hazard climate risks. This forward-looking perspective reinforces the importance of embedding advanced modelling approaches into the formulation of policies, technical guidelines and long-term planning strategies aimed at enhancing urban resilience and climate adaptation.

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