



## Assessment of the Robustness and Resilience of the Water System in the Bogotá River Basin

Dairo Steven Muñoz Pinzón<sup>1</sup>, William J. Guerrero<sup>1\*</sup>, Leonardo José González Rodríguez<sup>2</sup>, and Marlene Amorim<sup>3</sup>

Received: 26/02/2025 / Accepted: 02/12/2025 / Published online: 16/04/2026

**Abstract** Human activities and climate change increasingly affect the dynamics of rivers and reservoirs, heightening the risks of floods and water shortages. Ensuring that water systems remain functional during extreme floods and shortages is central to risk reduction and water security. In the Bogotá River Basin, the performance of hydric infrastructure and operating rules under severe droughts and floods remains insufficiently understood. Here, we assessed the robustness and resilience of the Bogotá River Basin's hydric infrastructure under extreme climate scenarios. Focusing on minimizing flood areas and meeting water demand, we developed a multi-objective linear programming model that integrates the operation of reservoirs, sub-basins, and monitoring stations. Using metrics such as average flood duration, reservoir utilization and water-supply reliability, we quantified system performance and identified hydrological units and stations where risks concentrate. The analysis reveals trade-offs between reducing flooded areas and maintaining water demand fulfillment and shows how targeted changes in operating rules and transfer capacity could enhance robustness and resilience. The evidence supports local environmental and water management institutions in designing operational protocols and contingency plans. It also illustrates how robustness and resilience metrics derived from optimization models can support decision making for climate adaptation and water security planning in similar basins.

**Keywords:** climatic change, flooding, water shortage, robustness, resilience, disaster management.

---

<sup>1</sup> Faculty of Engineering, Universidad de La Sabana, Chía, Colombia

<sup>2</sup> Faculty of Engineering, Universidad del Magdalena, Santa Marta, Colombia

<sup>3</sup> Department of Economics, Management, Industrial Engineering and Tourism, Universidade de Aveiro, Aveiro, Portugal

\* Corresponding author email: william.guerrero1@unisabana.edu.co

## 1. INTRODUCTION

Water resource management plays a fundamental role in preventing floods and mitigating water scarcity, ensuring the sustainability of essential resources (Berg et al., 2024). In recent years, floods have become a critical global issue, exacerbated by climate change and uncontrolled urban development (Shahriar & Roy, 2024; Y. Xu et al., 2024). These events not only cause significant economic, social, and environmental impacts but also severely hinder sustainable urban development (Z. Wu et al., 2024). Conversely, droughts representing the opposite extreme of the hydrological cycle propose equally severe challenges that require an integrated management approach (Ward et al., 2020).

Climate variability, intensified by global warming, is reshaping precipitation patterns and increasing the frequency of hydrological extremes, pushing water management systems beyond their operational thresholds (Cui et al., 2022; W. Feng et al., 2024). One of the key drivers of this variability, especially in tropical regions, is the El Niño–Southern Oscillation (ENSO), which alternates between warmer (El Niño) and cooler (La Niña) phases in the equatorial Pacific. These shifts significantly influence rainfall and temperature patterns in northern South America, exacerbating both floods and droughts in hydrographic basins (World Meteorological Organization [WMO], 2022).

Within this evolving context, it becomes important to develop robust and resilient water systems that can minimize the impact of hydrological extremes and ensure rapid recovery (Guo et al., 2024; Mens et al., 2011). Robustness refers to a water system's ability to maintain its essential functions under fluctuating conditions, whereas resilience denotes its ability, when exposed to hazards, to resist, absorb, accommodate, adapt to and recover from their effects in a timely and efficient manner, while preserving or rapidly restoring its basic structures and functions through risk-management actions (Polo et al., 2023; Stricker & Lanza, 2014; United Nations Office for Disaster Risk Reduction [UNDRR], 2017). Building on these foundations, recent probabilistic frameworks, such as the Global Infrastructure Risk Model & Resilience Index (GIRI) (Coalition for Disaster Resilient Infrastructure [CDRI], 2025) and multi-stage stochastic models used in disaster logistics (Anilkumar & Kavitha, 2025) extend these concepts by enabling risk-sensitive adaptation under conditions of spatiotemporal uncertainty.

To respond effectively to water-related risks, various technical methodologies have been developed, including multi-objective optimization models, system dynamics simulations, and artificial intelligence techniques such as neural networks and fuzzy logic (Kamyabniya et al., 2024). While these approaches offer advanced analytical capabilities, many remain limited in scope, as they treat system elements in isolation and fail to fully consider the dynamic interactions and internal coordination of water systems. Furthermore, integrated assessments that simultaneously address droughts, floods, and energy shortages within a unified operational framework are still scarce, which restricts their practical applicability in managing complex urban environments. In this regard, multi-stage stochastic programming has shown promise by supporting adaptive resource allocation under uncertainty, as seen in applications ranging from hurricane logistics to flood reservoir operations (Anilkumar & Kavitha, 2025). These tools can

complement traditional linear programming by capturing evolving risk scenarios and improving coordination during hydrological stress.

Emerging evidence supports the adoption of a holistic approach that treats floods and droughts as interconnected extremes of the hydrological cycle. This perspective enables better resource optimization and reduces systemic vulnerabilities (Kandari et al., 2022; Ward et al., 2020), while also strengthening adaptive capacity in the face of extreme climate events (J. Feng et al., 2024; Z. Wu et al., 2024). Achieving this requires the use of accurate, up-to-date data to monitor key variables such as precipitation and extreme flows (Mazzoleni et al., 2024). However, water planning efforts are often fragmented and conducted in isolation, limiting opportunities for synergy and innovation in integrated resource management (Cardoso de Oliveira et al., 2025).

These global challenges are especially pronounced in urban basins, where high population density, intricate infrastructure, and frequent climate stressors converge, making them compelling case studies for examining systemic vulnerabilities and adaptive strategies. The Bogotá River basin in Cundinamarca, Colombia, exemplifies this context. It supplies water to over ten million inhabitants and has been repeatedly impacted by climate phenomena such as El Niño and La Niña. These events have triggered severe crises, including the 1992 energy shortage, the 2024–2025 water supply deficits, and the 2011 floods (Euscátegui & Hurtado, 2011; Mateus, 2016; Muñoz, 2025). The basin experienced an annual average of 213 flood events between 1999 and 2014 (Regional Autonomous Corporation of Cundinamarca [CAR], 2019), highlighting its exposure to hydrological extremes. Consequently, the basin provides a representative setting to evaluate robustness and resilience through quantitative modeling, with lessons for other regions facing similar climatic and structural conditions.

Guided by this context, our main objective was to assess the robustness and resilience of the Bogotá River Basin's hydric infrastructure under extreme climate scenarios, using a multi-objective linear programming model that focuses on minimizing flood areas and meeting water demand. We hypothesize that the current hydric infrastructure and operating rules are insufficient to manage such variability, which motivates integrated and targeted planning strategies to improve water security and overall system performance. To address this objective, we employ a multi-objective linear programming model to evaluate basin performance under extreme drought and flood scenarios.

The article proceeds as follows: first, it presents the methodology, including a detailed description of the study area and the modeling approach. Next, it outlines the key results and proposes a targeted management strategy. This is followed by a discussion of the findings. The article concludes with a summary of conclusions and references.

## 2. METHODOLOGY

### 2.1 Study Area

The Bogotá River Basin, as illustrated in Figure 1, is composed of 22 hydrographic sub-basins, 9 reservoirs, and 25 monitoring stations that together form the spatial and functional structure of the optimization model.

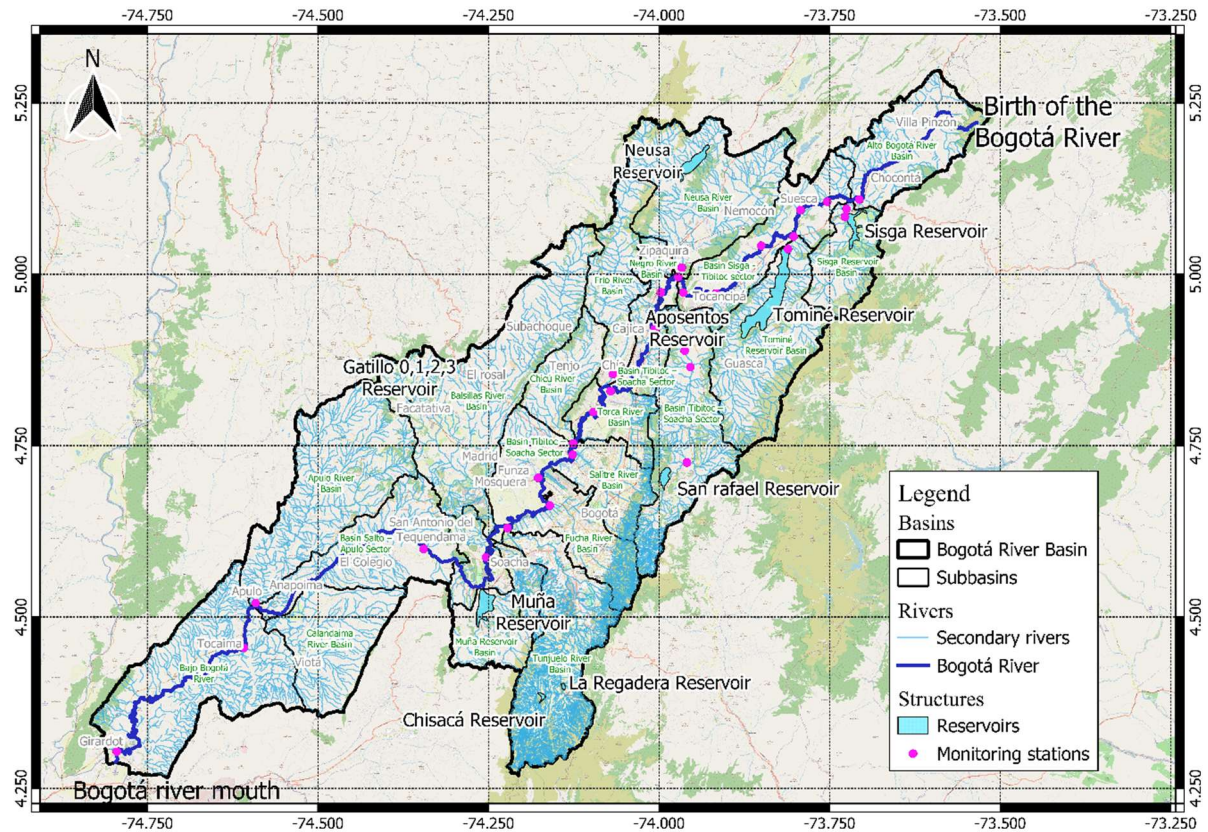


Figure 1. Bogotá River Basin

Source: Adapted from Agustín Codazzi Geographical Institute [IGAC], (2023); EAAB (2021, 2023a, 2023c, 2023b, 2023d); CAR (2021) using QGIS 3.32.3

Each sub-basin is modeled as a spatial node (indexed as  $i$ ), where the most representative parameters are the flow rate produced (expressed in  $m^3/s$  and denoted as  $CG_{ite}$  in the model) and the specific water demand ( $D_{ite}$ ). Reservoirs are represented as water storage nodes (indexed as  $j$ ), where the water inventory ( $INFI_{jte}$ ) plays a key role in regulating water flow to mitigate both water scarcity and flooding events. Among these, the Muña reservoir is modeled uniquely due to its hydroelectric generation capacity, incorporating turbine efficiency and assuming constant water velocity at both inflow and outflow points. Monitoring stations (indexed as  $k$ ) operated by the Regional Autonomous Corporation of Cundinamarca (CAR), the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), and the Bogotá Water and Sewerage Company (EAAB) provide discharge data used to calibrate flood-related constraints. Selected stations, located in flood-prone areas, help define overflow thresholds ( $LMAX_k$ ) and flooded area variables ( $A_{kte}$ ) within the model.

Hydrological and geographic datasets were compiled from public and official sources including CAR, EAAB, IDEAM, the District Institute for Risk Management and Climate Change (IDIGER), the Agustín Codazzi Geographic Institute (IGAC), and the Regional Environmental and Sustainable Development Observatory for the Bogotá River (ORARBO). These datasets provided key information on basin geometry, precipitation, water demand, and other relevant characteristics. Only complete records were retained, and these were used to define the model's parametric structure and boundary conditions. The integration process involved cross-referencing time series and spatial records across institutions to ensure data consistency and compatibility within the model's structure. To ensure model reliability and data consistency, the inclusion of system components followed the criteria and assumptions listed below:

- Only sub-basins and water units with complete and verifiable data were included.
- Micro-basins were excluded to maintain a system-level operational focus.
- Natural water bodies such as lakes and lagoons were aggregated within sub-basin surface areas and treated as part of the inflow estimates.
- Reservoirs were included based on their storage capacities and strategic relevance to water supply and flow regulation.
- Wastewater treatment plants were excluded due to insufficient data on volumes and limited influence on storage dynamics.
- Return flows from reservoirs were omitted due to a lack of reliable information on their destinations and volumes. However, if these flows re-enter the system downstream, they may influence flood dynamics.
- Groundwater was treated as a finite, non-rechargeable resource. Accordingly, it should not be considered a reliable primary source for meeting overall water demand.
- Electricity generation was modeled only for the Muña reservoir, the sole site with hydroelectric capacity, using constant flow velocity to estimate energy output.
- Constant water velocity was assumed at control points to simplify the calculation of maximum flows.

These assumptions and exclusions define the operational scope of the model but also impose practical limitations. By simplifying groundwater dynamics, assuming constant water velocities, and excluding wastewater treatment processes, return flows, and certain localized hydrological interactions, the model prioritizes large-scale basin behavior over fine-scale processes. As a result, some localized or short-term phenomena, particularly under extreme drought or flood conditions, may not be fully captured. Moreover, the absence of socio-political and behavioral variables means that operational challenges during real-time crisis management remain outside the model's scope. The results should therefore be interpreted with these boundaries in mind, and future refinements could address these gaps to enhance applicability.

Figure 2 shows the graph-based representation of the delimited study basin. This integrated structure ensures that each component, including sub-basins (i), reservoirs (j), and monitoring

stations (k), is explicitly and transparently represented in the mathematical formulation, reinforcing the model’s coherence and alignment with the optimization objectives.

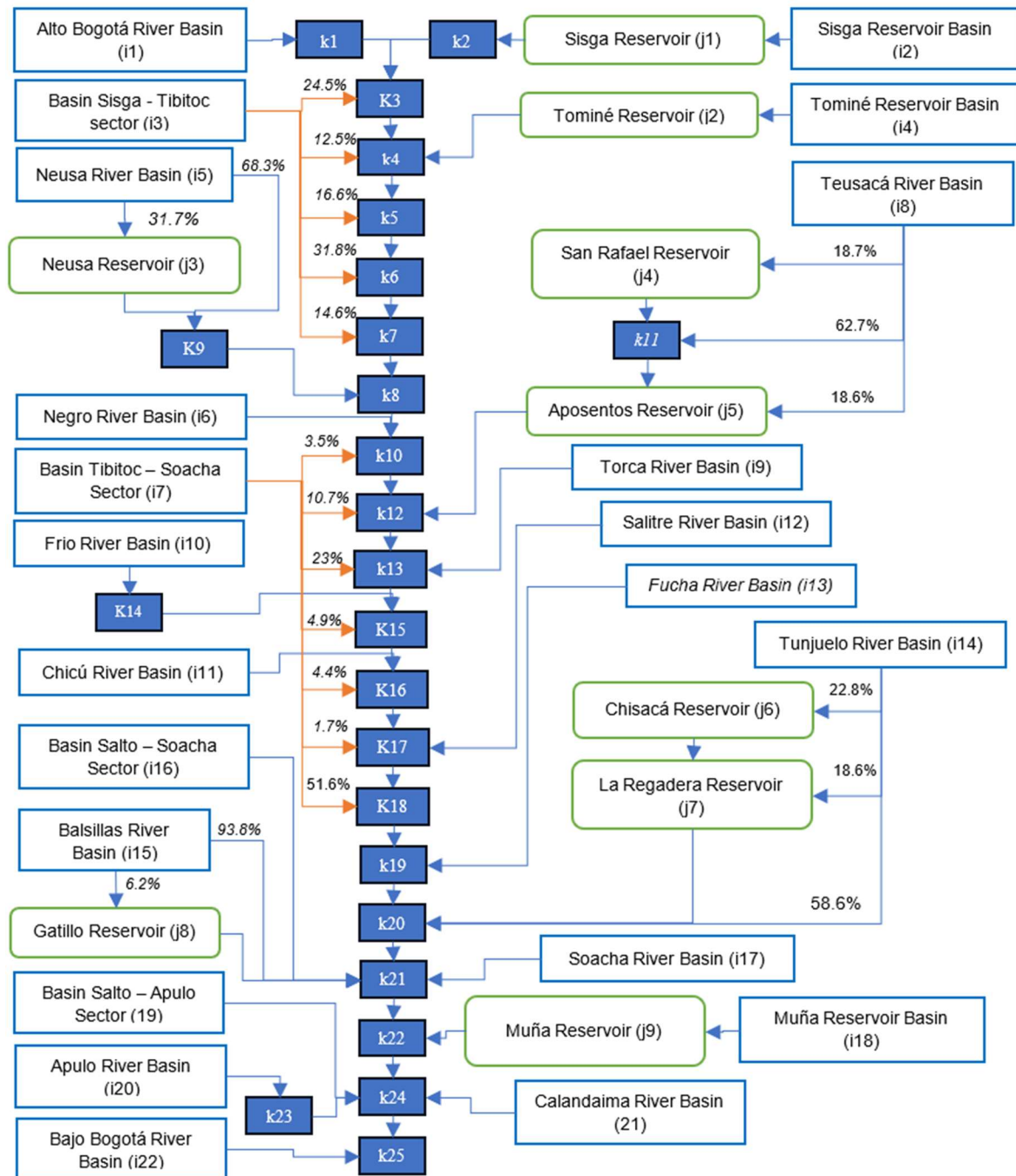


Figure 2. Delimited study basin

As shown in Figure 2, several sub-basins discharge their waters into the main channel of the Bogotá River through secondary flows at different locations. One example is the Sisga–Tibitoc basin sector (i3), which contributes to the river at five distinct points, with proportions of 24.5%, 12.5%, 16.6%, 31.8%, and 14.6%, measured at monitoring stations k3, k4, k5, k6, and k7, respectively. A similar pattern is observed in other sub-basins such as the Tibitoc–Soacha sector (i7), the Balsillas River basin (i15), and the Teusacá River basin (i8), whose water

contributions are naturally distributed across various points along the river or directed toward specific reservoirs.

## 2.2 Robustness–Resilience Evaluation Framework

The assessment was based on robustness analysis procedures from Tordecilla & González (2016), Tordecilla et al. (2017), Polo et al. (2019), Polo et al. (2023), Mens et al. (2011) and Puzyreva et al. (2022). We adapted the approach to the Bogotá River basin's water system by incorporating resilience metrics, operational characteristics, and disturbance parameters. Scenario generation was included to evaluate climatic variations and analyze the relationship between robustness and resilience. The adapted methodology for this study is presented below (Figure 3).

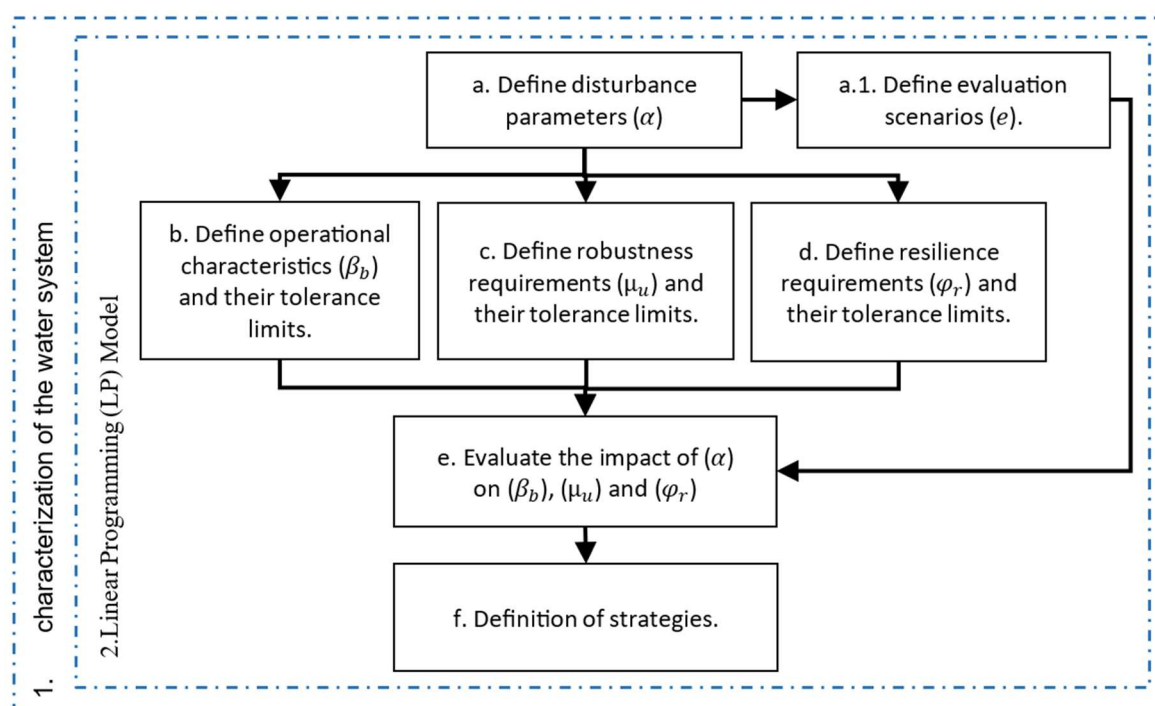


Figure 3. Flowchart of methodology

Source: Adapted from Tordecilla et al & González. (2016), Tordecilla et al. (2017), Polo et al. (2019), Mens et al. (2011) and Puzyreva et al. (2022)

The process began with identifying and characterizing key elements of the water system, including rivers, reservoirs, and sub-basins, based on data from relevant entities. A multi-objective LP model was then developed (see Appendix 1), integrating critical water units for regulation and flood prevention. The model defines disturbance parameters ( $\alpha$ ), scenarios ( $e$ ), operational characteristics ( $\beta$ ), robustness ( $\mu$ ), and resilience ( $\varphi$ ) requirements, along with their tolerance limits. The impact of ( $\alpha$ ) on ( $\beta$ ), ( $\mu$ ), and ( $\varphi$ ) is analyzed across scenarios to identify critical units requiring timely strategies.

To ensure solvability and comparability across multiple scenarios while retaining institutional interpretability, we adopt a linear programming formulation at the node scale

(subbasins, reservoirs and monitoring stations) and compute robustness and resilience indicators ex post as performance diagnostics. Embedding these indicators directly as objectives or constraints would require thresholds and time-window aggregations, introducing binary variables and sometimes nonlinearities and turning the problem into MILP or MINLP, a difficulty reported for multi-objective reservoir operation and large water network models (Giuliani et al., 2021a; Lai et al., 2022). In high-dimensional settings, many studies address this complexity using metaheuristics, decomposition schemes or surrogate-assisted optimization approaches (Lai et al., 2022; Rodríguez et al., 2021; C. Xu et al., 2024).

In this study, robustness and resilience indicators are not embedded as endogenous constraints or objectives within the LP formulation. Instead, they are computed ex-post based on the model’s solution outputs. Their role is diagnostic: they evaluate system performance under different scenarios and help identify vulnerabilities or opportunities for improvement. Although these indicators do not directly influence decision variables during the optimization process, they are conceptually and functionally correlated with the model’s objective functions. This correlation ensures that the optimized decisions align with desirable system behaviors, such as minimizing floods or maximizing water supply. This approach allows the model to first identify globally optimal solutions and then diagnose subsystem vulnerabilities, a strategy validated in similar frameworks (Tordecilla et al., 2017), (Polo et al., 2019). The evaluation parameters and requirements are detailed in Table 1.

**Table 1.** Indicators for robustness and resilience

Step	Definition <sup>4</sup>	Tolerance Limits <sup>5</sup>	Description <sup>6</sup>	Autor
a. Disturbance parameters ( $\alpha$ ) and scenarios (e)	$\alpha$ : Flow rate generated [ $\text{m}^3/\text{Week}$ ] in sub-basins per period and scenario.	N/A	The water produced in sub-basins impacts reservoir storage, flooding, and water supply, influencing overall system stability. This parameter is defined by $FE_{te}$ , $C_{MAX_{it}}$ , and $C_{MIN_{it}}$ (equation (1) in Appendix 1).	(Mens et al., 2011), (Ali & Jay, 2004), (Stricker & Lanza, 2014), (Tordecilla et al., 2017), (Polo et al., 2019), (Polo et al., 2023).
b. Operational characteristics ( $\beta$ )	$\beta$ : Reservoir index utilization.	$0 \leq \beta \leq 1$ LCL = 0.35 UCL = 0.90	This metric captures reservoir utilization, a critical indicator for both flood prevention and water supply management. It is derived from the behavior of key water inventory variables within the reservoir system (see equations (21) to (22) in Appendix 1). Values below 0.35 signal a potential scarcity risk, whereas values exceeding 0.90 indicate a heightened risk of overflow.	(Boulangue et al., 2021), (Mens et al., 2011), (Tordecilla et al., 2017), (Polo et al., 2019), (Polo et al., 2023), (CAR, 2018), (CAR, 2024).

<sup>4</sup> The indices of the sets presented will also be employed in the mathematical model.

<sup>5</sup> The proposed control limits can be adjusted based on risk managers’ assessment criteria. Up Control Limit (UCL), Low Control Limit (LCL), First Control Limit (FCL) and Second Control Limit (SCL).

<sup>6</sup> The equation is located in the appendix 1.

Step	Definition <sup>4</sup>	Tolerance Limits <sup>5</sup>	Description <sup>6</sup>	Autor
<b>c. Robustness requirements (<math>\mu_u</math>)</b>	$\mu_1$ : percentage of flooded areas with respect to the area established by the CAR.	$(0 \leq \mu_1 \leq 1)$ FCL = 0.2 SCL = 1	Indicates the flood magnitude relative to CAR-defined thresholds, based on the behavior of key flood area variables within the mathematical model. The ideal value is 0, representing full robustness. Values of $\mu_u > 1$ exceed CAR limits, with FCL set at 0.2 and SCL at 1 (see equation (23) in Appendix 1).	(Mens et al., 2011), (Ali & Jay, 2004), (Tordecilla et al., 2017), (Polo et al., 2019), (Polo et al., 2023).
	$\mu_2$ = average water height in relation to the flood area established by the CAR.	$(\mu_2 \geq 0)$ FCL = 0.15 SCL = 0.45	Indicates water height in flood areas. FCL (0.15 m) marks where water can sweep an adult, and SCL (0.45 m) marks where it can carry vehicles. Calculated using equation (24) in Appendix 1.	(Mens et al., 2011), (Ali & Jay, 2004), (Tordecilla et al., 2017), (Polo et al., 2019), (Polo et al., 2023), (National Weather Service, 2018).
	$\mu_3$ = percentage of water demand met in sub-basins.	$(0 \leq \mu_3 \leq 1)$ CL = 0.9	Evaluates robustness in meeting water demands, with an ideal value of 1 and a control limit (CL) of 0.9. It is calculated based on the behavior of key water supply variables using equations (25) and (26) in Appendix 1.	(Qiu et al., 2021), (Mens et al., 2011), (Ali & Jay, 2004), (Tordecilla et al., 2017), (Polo et al., 2019), (Polo et al., 2023).
	$\mu_4$ = percentage of water demand met in the reservoirs.	$(0 \leq \mu_4 \leq 1)$ CL = 0.9		
<b>d. Resilience requirements (<math>\varphi_r</math>)</b>	$\varphi_1$ : Flood Resilience Index.	$0 \leq \varphi_r \leq t$	Represents the time required for the system to recover and reach a robust state, ranging from 0 to t weeks in the case study. A value of 0 indicates that robustness was never lost, while 52 means the system remained outside the control limits for the entire year. This metric is calculated using Equations (29) to (34) in Appendix 1.	(Puzyreva et al., 2022), (Mens et al., 2011) and (Healey, 2006).
	$\varphi_2$ : Sub-Basin Water Shortage Resilience Index.			
	$\varphi_3$ : Reservoir Water Shortage Resilience Index.			

The indicators  $\beta$ ,  $\mu_u$ , and  $\varphi_r$  can be evaluated at different levels, including hydric unit, sector, period, or scenario, or overall average per scenario, depending on the system's analysis requirements. This flexibility enables a comprehensive assessment of system behavior under varying conditions.

The linear programming model, fully detailed in Appendix 1, integrates the hydrological and operational dynamics of the Bogotá River basin into a unified optimization framework. Its two objective functions are defined in Equation (2), which minimizes the total flooded area across

all scenarios, and Equation (3), which maximizes total water demand fulfillment from both sub-basins and reservoirs. These objectives are normalized and combined through the weighted formulation in Equation (4), enabling the exploration of trade-offs between flood mitigation and water-supply reliability. This structure ensures that the optimization directly reflects the system's robustness and resilience requirements while preserving computational tractability.

To test the hypothesis, we applied this optimization framework to evaluate the robustness and resilience of the Bogotá River Basin's water system (see Figure 2). The system was evaluated under 20 scenarios representing historical climate variability, including extreme droughts and rainfall events. For each scenario, we solved the multi-objective model to approximate the Pareto trade-off between minimizing flooded areas (OF1) and meeting water demand (OF2) and identify critical nodes across subbasins, reservoirs and monitoring stations. These diagnostics are presented in Section 3, where they serve as the basis for node-specific strategies under climatic variability.

The optimization model was validated by analyzing the coherence and behavior of key decision and state variables, ensuring consistency with patterns reported in the literature and with realistic system operation. All parameters and inputs were derived from the most reliable and representative hydrological and operational data available.

In addition, the optimization model was implemented in GAMS 1.15.5 using a linear programming (LP) formulation. All experiments were executed on a computer equipped with an Intel® Core™ i5 12th-generation processor and 16 GB of RAM. Under these conditions, the model consistently reached optimal solutions in less than one (1) second, highlighting its computational efficiency even when addressing a complex multi-objective water resources optimization problem.

### **3. RESULTS**

For the analysis, the results are organized into five sections. Section 3.1 discusses the objective function and the trade-off between total flooded area and total water supply. Sections 3.2 to 3.4 analyze the behavior of the indicators for dry season, rainy season and transition scenarios, respectively. Section 3.5 synthesizes these findings into a proposed management strategy. Detailed numerical results are provided in Appendix 2 as supplementary material.

#### **3.1 Analysis of the Objective Function**

We obtained the results of the model by considering each objective independently to determine the extreme values of the Pareto frontier: minimizing the total flooded area (OF1) and maximizing the total water supplied (OF2). After obtaining the optimal values, we applied Equation (4) to derive the integrated solution. The results for both objectives and the integrated approach are presented in Table 2.

**Table 2.** Results of the objective functions

<b>Objective Function</b>	<b>Total Flooded Area [Mm<sup>2</sup>]</b>	<b>Total Supplied Water [Mm<sup>3</sup>]</b>
<b>Minimizing OF1</b>	85118.71	14973.91
<b>Maximizing OF2</b>	813755.55	15335.88
<b>Minimizing Weighted Function Eq. (4)</b>	85118.71	15338.88

These results quantitatively illustrate the inherent trade-off between reducing flood impacts and increasing water supply, a core challenge in multi-objective basin management. Optimizing OF1 yields a minimum flooded area of 85118.71 Mm<sup>2</sup> with 14973.91 Mm<sup>3</sup> of supplied water, whereas optimizing OF2 maximizes supply to 15335.88 Mm<sup>3</sup> at the expense of expanding the flooded area to 813755.55 Mm<sup>2</sup>. The combined optimization produces a compromise solution (85118.71 Mm<sup>2</sup> of flooded area and 15338.88 Mm<sup>3</sup> of water supply) demonstrating that both objectives can be improved concurrently rather than being strictly antagonistic. This integrated result underscores the model’s practical value as a decision-support tool, offering basin managers a transparent, quantitative basis for evaluating trade-offs and selecting balanced interventions under competing hydrological goals.

### 3.2 Analysis for Dry Season Scenarios

This section examines scenarios e1 to e5, where e1 represents the driest conditions and e5 the least dry. Under these conditions, average reservoir utilization ranges from 16% to 26%, remaining below the proposed lower control limit (LCL). This indicates that the system cannot operate under critical conditions during drought events, especially in extreme cases, highlighting the need to strengthen reservoir management to better prepare for such events. These conditions pose a high risk of shortages for demand sectors, emphasizing the importance of exploring alternative recharge measures to ensure supply. Although the Neusa reservoir (j3) shows the least critical behavior, it does not always remain within control limits, and thus still requires preventive actions (see Figure 4). Overall, all reservoirs would benefit from improved operational strategies, including watershed capacity enhancement to retain and supply water during dry periods.

A similar pattern is observed at the reservoir level, where overall robustness generally remains close to the 0.90 CL, but several reservoirs lose performance under e1: Sisca (j1) and Chisacá (j6) drop to around 79%, and El Gatillo (j8) to about 84%. This heterogeneity indicates tail-risk exposure despite acceptable system averages, making targeted measures—such as pre-emptive storage reallocation, inter-reservoir transfers, demand management, and watershed retention actions—essential to maintain performance during extreme droughts.

In terms of robustness, water demand fulfillment in sub-basins (Figure 5) can drop to an overall average of 70% during the driest scenario (e1), well below the control limit (CL). This reflects the limited capacity of the hydric system to maintain supply, especially in basins with low rainfall during drought. The most critical cases are the Soacha River Basin (i17) and the Negro River Basin (i6), where fulfillment can fall to as low as 31% in e1. These basins require priority attention and measures to boost water production capacity and storage, ensuring a more stable supply in the future.

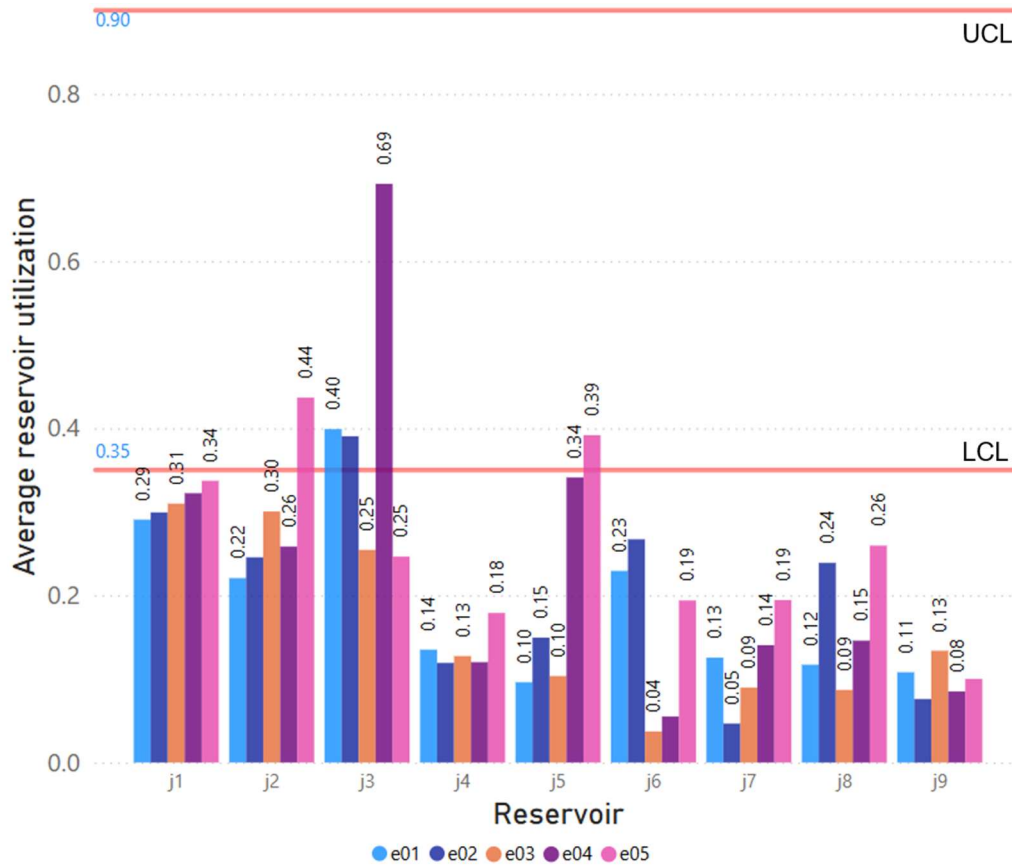


Figure 4. Average utilization per reservoir in dry season scenarios

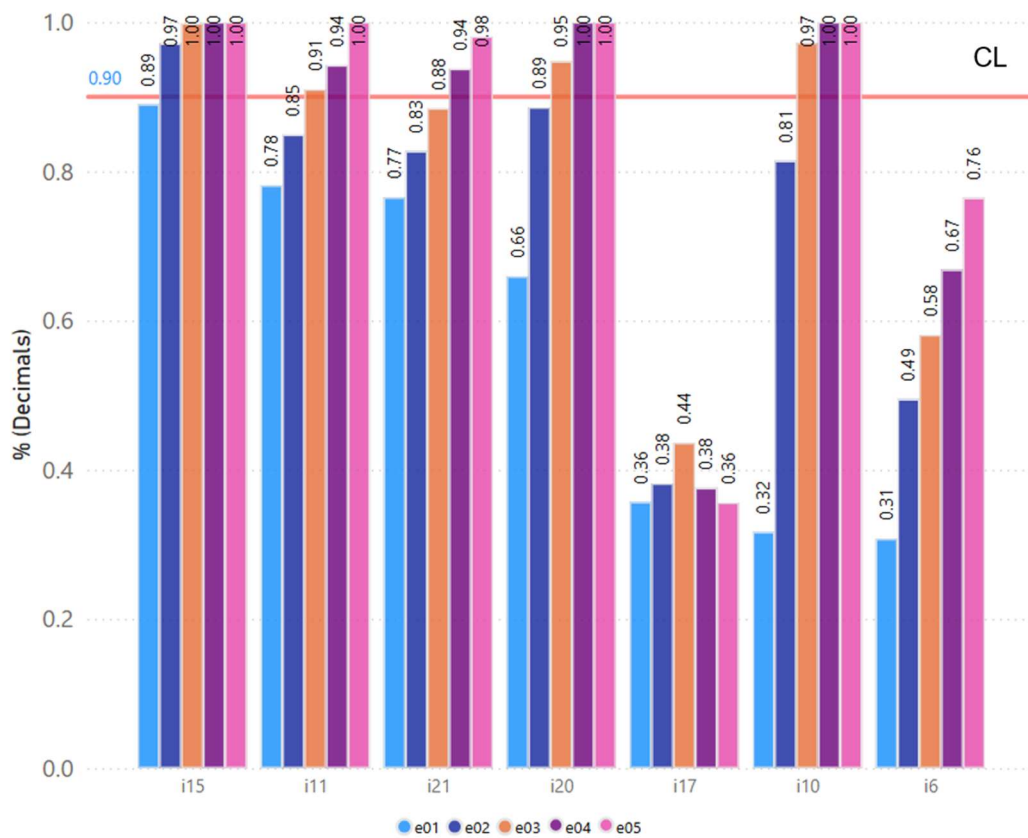


Figure 5. Average water demands fulfillment per sub-basin in dry season scenarios

Regarding resilience in sub-basins, the hydric system may require, on average, between 11 and 22 weeks to restore full water demand fulfillment during drought scenarios. However, in extreme cases (e1), some basins could face supply deficits for up to 52 weeks per year, making water rationing and replenishment plans essential. The Chicú River Basin (i11) and Calandaima River Basin (i21) show the lowest resilience (see Figure 6).

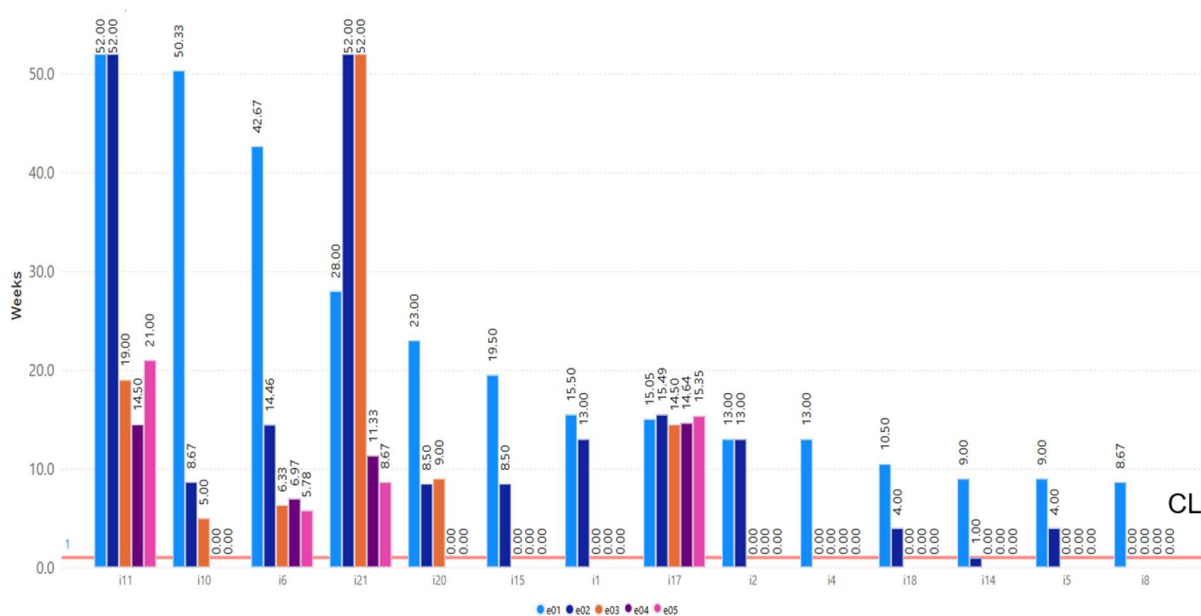


Figure 6. Average water shortages resilience per sub-basin in dry season scenarios

Reservoir resilience is more stable, with recovery times ranging from 1.6 to 12.9 weeks overall. However, critical cases such as the Gatillo Reservoir (j8) may require up to 35 weeks to recover under e1 conditions. Given that this reservoir is the main source for the Facatativá population, such prolonged recovery times could pose significant supply risks, emphasizing the need to diversify water sources and expand storage capacity.

Overall, the dry season scenarios reveal significant operational stress, marked by low reservoir utilization, reduced robustness in meeting water demands, and long recovery times that weaken system resilience. These results highlight the need for integrated basin-wide strategies that optimize storage, strengthen watershed retention, and implement drought contingency plans. Coordinated action across all components is essential, as isolated improvements are unlikely to secure a stable water supply under increasing climate variability.

### 3.3 Analysis of Rainy Season Scenarios

This section analyzes scenarios e7 to e11, where e11 represents the heaviest rainfall and e7 the least intense. Reservoir utilization remains relatively high, ranging from 63% in moderate rainfall (e7) to 80% in extreme rainfall (e11), staying within the proposed control limits. However, despite the overall stability, individual reservoirs show contrasting behaviors. For instance, Sisga (j1) and San Rafael (j4) drop below the LCL in e7, revealing potential availability issues even under wet conditions, while Chisacá (j6), La Regadera (j7), and El Gatillo (j8) often exceed the UCL, increasing downstream flood risks (see Figure 7). These

patterns suggest that flood prevention near high-utilization reservoirs should focus on expanding retention capacity and improving upstream regulation.

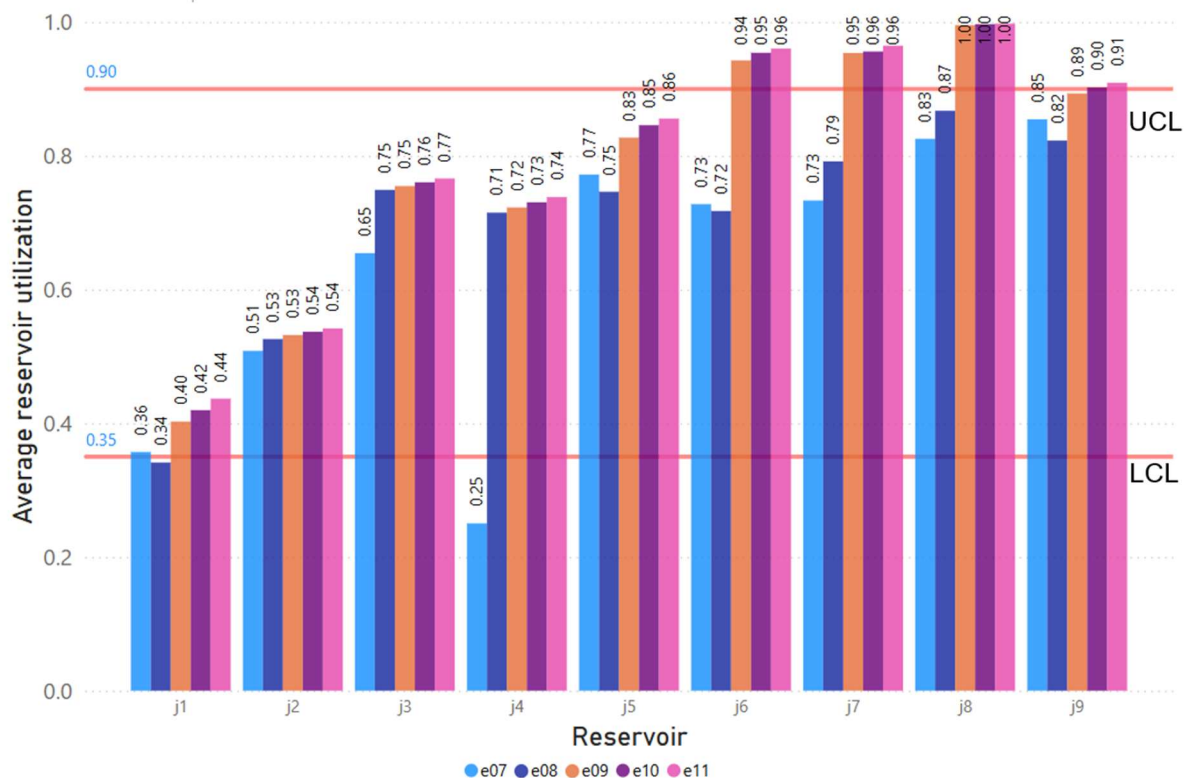


Figure 7. Average utilization per reservoir in rainy season scenarios

With respect to robustness, flooding risk intensifies during extreme rainfall events, with scenario e11 exceeding the first flood control limit (FCL) with an overall percentage of flooded areas of 25% with respect to the area established by the CAR. The most affected stations (k1, k20, k21, and k23) exceed the FCL, indicating urgent needs for structural upgrades and emergency planning. In contrast, stations like k8, k11, and k24 remain below thresholds but still require close monitoring, as high rainfall variability can rapidly alter conditions (see Figure 8). In the same line, flood severity is further illustrated by water height data: in e11, average depths reach up to 0.56 m across some locations, surpassing both the FCL (0.15 m) and SCL (0.45 m). Stations k1, k20, k21, k23, and k24 report the highest levels—up to 6.66 m in extreme cases, indicating potentially catastrophic consequences without timely intervention.

In terms of resilience, flood recovery times vary significantly: under extreme rainfall (e11), the most critical stations (k20 and k23) require up to 52 weeks to recover, with prolonged inundations severely impacting communities and economic activities. Moderate to high rainfall events can also result in extended recovery, with average times reaching 41 weeks across the system. Stations k1, k8, k11, k21, and k24 exhibit intermediate resilience, whereas k3, k4, and k5 recover within a week, demonstrating robust performance (see Figure 9).

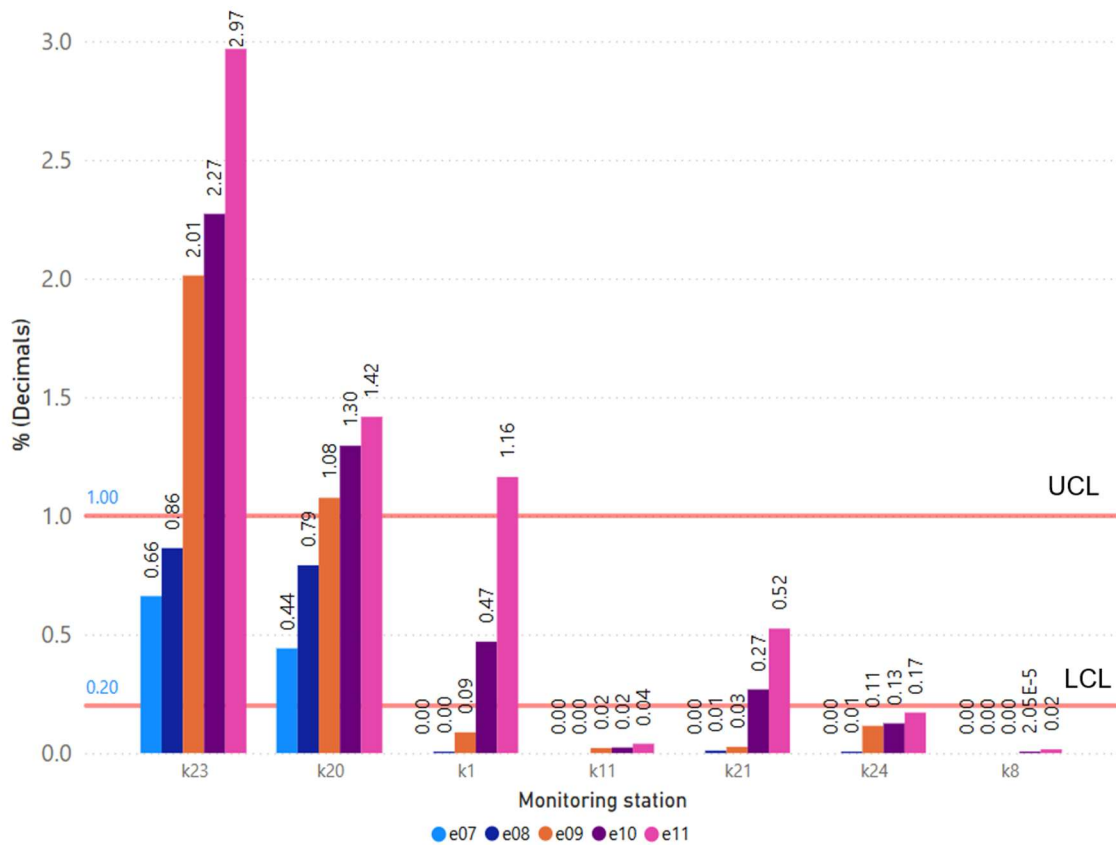


Figure 8. Average flooding area per monitoring station in rainy season scenarios

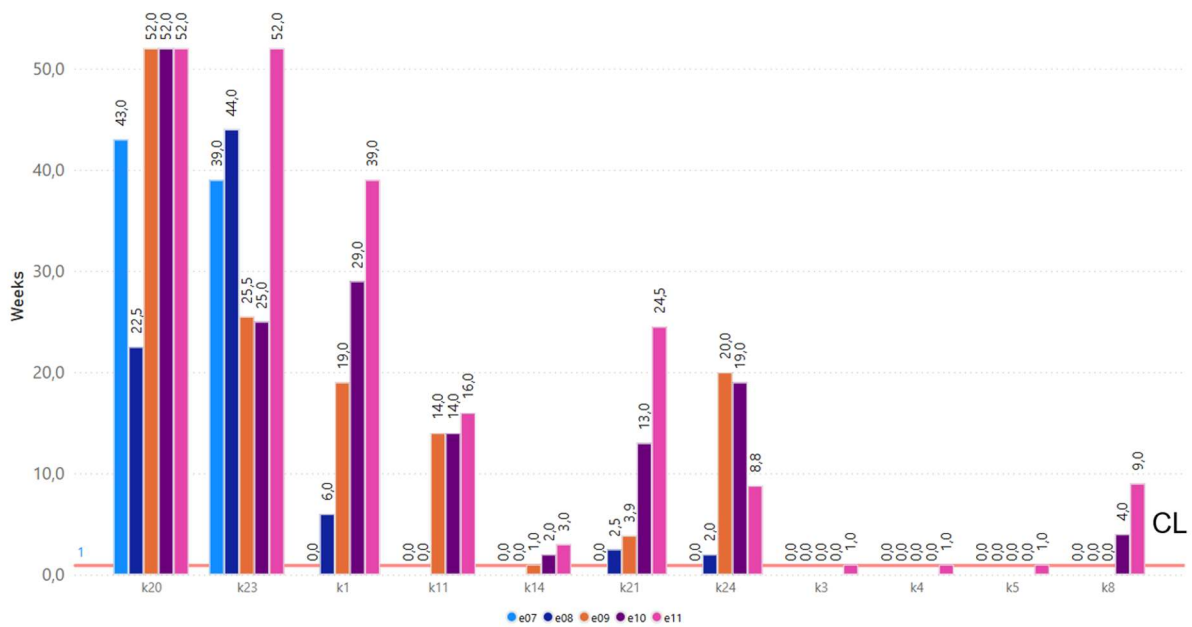


Figure 9. Average flooding resilience per monitoring station in rainy season scenarios

Regarding water demand robustness in sub-basins, overall fulfillment remains above 97% during rainy scenarios. However, the Soacha River Basin (i17) and Negro River Basin (i6) show significantly lower self-sufficiency, relying heavily on transfers from neighboring basins or reservoirs. In scenario e7, the Chicú River Basin (i11) drops to 78.16% fulfillment for the

agricultural sector (L1), while the Calandaima River Basin (i21) falls to 69.9% for the same sector, indicating vulnerability even under high precipitation conditions. For water shortage resilience, the Soacha (i17), Negro (i6), Chicú (i11), and Calandaima (i21) basins require between 6 and 52 weeks to restore supply capacity depending on the scenario. While performance improves under heavier rainfall, contingency planning remains essential to secure availability in both dry seasons and full raining seasons.

Overall, the rainy season analysis reveals a dual challenge: while high precipitation mitigates scarcity risks in most basins, it considerably increases flood hazards at critical monitoring stations. The coexistence of these risks calls for integrated management strategies that combine targeted infrastructure upgrades, enhanced watershed management, and flexible operational protocols to adapt to rapidly changing hydrological conditions.

### 3.4 Analysis of the Transition Scenarios

This section examines the four transition scenarios: e12 and e14 (drought-to-rainfall, with e12 transitioning faster) and e13 and e15 (rainfall-to-drought, with e13 transitioning faster). Overall, reservoir levels remain within proposed control limits, but performance differs between transition types. In drought-to-rainfall scenarios (e12 and e14), average utilization is lower, indicating slower recovery of storage stability. In rainfall-to-drought transitions (e13 and e15), utilization remains higher (65–75%), which enhances preparedness for subsequent dry conditions (see Figure 10). Nevertheless, Neusa (j3), San Rafael (j4), and Muña (j9) exhibit the greatest challenges in recovering volumes, with average utilizations of 12%, 8%, and 14% (all below the LCL), especially under gradual transitions.

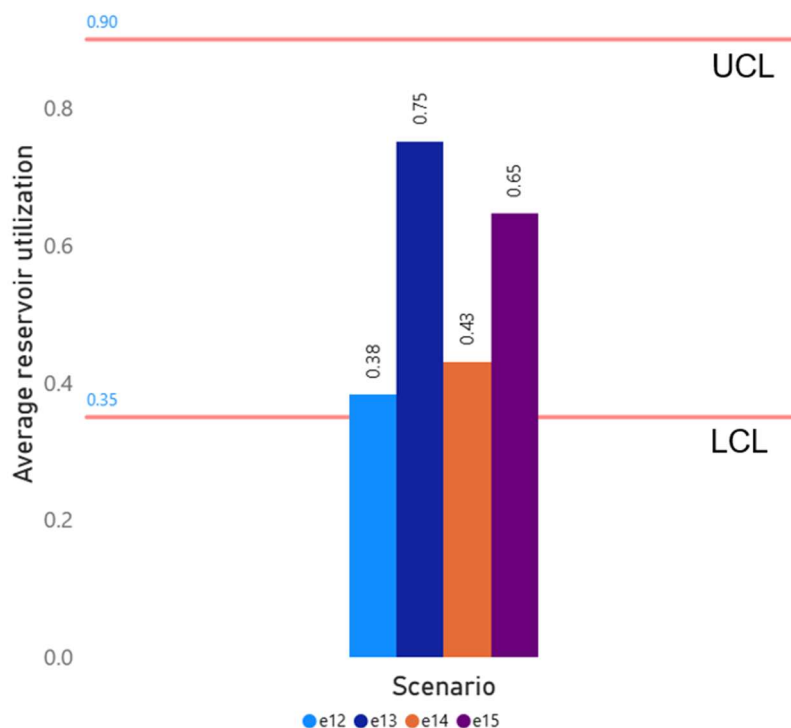


Figure 10. Average utilization in reservoirs in transition scenarios

In terms of robustness to flooding, the overall average percentage of inundated areas remains below 4% across scenarios. However, rainfall-to-drought transitions can still trigger localized flooding, particularly at stations k20 and k23, where inundated areas reach 51% and 55% in e13 due to initial heavy rainfall. These sites require targeted structural improvements and rapid-response protocols to minimize impacts during transitional periods.

Regarding water demand fulfillment, most sub-basins maintain values above the 90% control limit, indicating good systemic robustness during both transition types. However, the Soacha River Basin (i17) and Negro River Basin (i6) consistently underperform, with minimum fulfillment rates of 37% and 83%, respectively, in certain scenarios. These deficits highlight their high vulnerability to supply disruptions during transitional events and the need for pre-emptive allocation and storage strategies.

Flood resilience shows significant variation: drought-to-rainfall transitions recover in approximately 10-13 weeks, whereas rainfall-to-drought scenarios extend recovery times to 16-23 weeks. The longest durations are concentrated in stations k20, k21, k23, and k24, highlighting the need for localized flood mitigation actions in these areas. In terms of water shortage resilience, affected basins take between 7.6 and 18 weeks to return to full supply capacity, with Negro (i6), Frío (i10), Chicú (i11), Soacha (i17), Apulo (i20) and Calandaima (i21) showing the highest susceptibility to prolonged deficits.

Overall, transition scenarios reveal dual sensitivity: drought-to-rainfall periods challenge reservoir recovery, while rainfall-to-drought transitions intensify localized flood risks and extend recovery times. The persistence of vulnerabilities in specific basins and monitoring stations highlights the importance of integrating drought preparedness, flood mitigation, and adaptive operational protocols to maintain both robustness and resilience during these critical seasonal shifts.

### **3.5 Proposed Management Strategy for the Bogotá River Basin**

The strategies presented in this section are derived from the optimal results of the multi-objective optimization model, in which the trade-off between minimizing flooding and maximizing water supply was addressed through the best achievable solution. This means that all proposed operational ranges and measures are grounded in the most favorable performance of the objective functions and in the control of key operational variables, as shown in the analysis of extreme droughts, extreme rainfall, and transition scenarios.

For extreme and prolonged droughts (scenarios e1 to e5), the results showed that reservoir utilization frequently fell below the lower control limit (LCL), indicating low robustness in meeting demand, particularly in reservoirs such as Sisga (j1) and Chisacá (j6), and in sub-basins such as Soacha (i17) and Negro (i6). To counter this, it is recommended to operate reservoirs near their maximum allowable capacity, without exceeding the upper control limit (90%), thereby ensuring sufficient reserves to withstand long dry periods. For extreme rainfall scenarios (e6–e11), in which some reservoirs (e.g., j6, j7, j8, and j9) exceeded the upper limit, reducing their capacity to buffer high inflows and increasing downstream flood risks; it is

proposed to maintain storage between 60% and 80%, balancing supply security with flood regulation capacity.

During drought-to-rainfall transitions (e12 and e14), slower recovery of reservoir stability was observed, especially in j3, j4, and j9. To improve resilience, reservoir levels should be gradually increased from about 60% to 80%, following precipitation trends, thus avoiding abrupt changes that could cause uncontrolled spill events. Conversely, in rainfall-to-drought transitions (e13 and e15), where storage remained higher (65-75%) but certain stations still experienced localized flooding, it is advisable to start the dry period with reservoirs around 80% and progressively increase to 90% as rainfall decreases, while maintaining sufficient regulation capacity to unexpectedly high inflows.

In addition to these operational guidelines, the model revealed that the current system lacks adequate capacity to cope with extreme climate changes. Therefore, it is necessary to evaluate and implement structural and management measures to address existing vulnerabilities. This can be achieved through the implementation of alternative recharge mechanisms beyond direct precipitation, such as nature-based solutions, upstream watershed restoration, and groundwater recharge zones, especially in sub-basins that show shortages even during rainy seasons (e.g., i17, i6, i11, i21, and the basins that supply all reservoirs); preparing water rationing protocols and diversifying water sources to strengthen crisis management; expanding reservoir and transfer infrastructure to improve distribution to critical sub-basins; and reinforcing river levees combined with localized flood prevention plans in stations with prolonged inundation recovery times (e.g., monitoring stations k20 and k23). Likewise, the results highlight the importance of strengthening real-time monitoring during transition periods, focusing on the first stations affected by flooding (k1, k20, k21, k23) and on basins with the lowest drought resilience during rainfall-to-drought shifts (i6, i10, i11, i17, i20 and i21).

Overall, these recommendations provide an integrated operational and structural framework aimed at maximizing the Bogotá River basin's hydric system's robustness and resilience under the climatic variability. By aligning reservoir management with the optimal storage ranges suggested and by considering targeted structural interventions, there is potential to improve water availability, reduce flood risks, and increase adaptability to extreme climate events. It is important to note that these strategies were proposed specifically for this case study, and their implementation in other contexts would require evaluating results according to the unique characteristics of each hydric system.

#### 4. DISCUSSION

While several reviews warn that Pareto fronts can be difficult to operationalize in multi-objective problems (Giuliani et al., 2021b), this study shows that, under a basin-scale multi-objective linear programming (LP) scheme with multiple scenarios, it is possible to explore representative regions of the Pareto front and evaluate system-level performance using robustness ( $\mu$ ) and resilience ( $\varphi$ ) indicators, while simultaneously pursuing flood mitigation

(OF1) and water-supply reliability (OF2). In the Bogotá River basin, losses of robustness and resilience were concentrated mainly in a subset of sub-basins, reservoirs and monitoring stations (e.g., i6, i11, i17, i21; j1, j6, j8; k1, k20 and k23), as shown in Sections 3.1 to 3.5. This integration of objectives is consistent with recent literature on multipurpose reservoir operation, which combines flood control and water supply through multi-objective optimization at the storage–transfer network level (Lai et al., 2022; Zhang et al., 2024). Likewise, multi-objective methodologies with performance metrics have proven transferable to other complex network domains, such as logistics (Polo et al., 2023), which reinforces the applicability of the approach to hydric systems.

On the other hand, in this study, robustness and resilience are computed *ex post* from optimized operational variables at the node scale (subbasins *i*, reservoirs *j*, stations *k*). Embedding these indicators as decision variables would require logical thresholds and time-window aggregations, which typically introduce binary variables and/or nonlinearities, turning the problem into MILP/MINLP with higher computational burden and lower interpretability; this challenge is widely reported for multi-objective reservoir operation and large water-network models (Giuliani et al., 2021b; Lai et al., 2022). By computing them *ex-post*, we preserve LP linearity and comparability across scenarios and weightings while maintaining an explicit link to key variables (storage, satisfied demand, and flooded areas), enabling transparent node- and scenario-level readings consistent with reliability-resilience-vulnerability frameworks (Giuliani et al., 2021b).

In addition, for evaluation across multiple scenarios and high dimensionality, recent reviews emphasize parsimonious, tractable (often linear) formulations to map trade-offs and localize vulnerabilities transparently; as dimensionality grows, the literature documents the use of metaheuristics (e.g.,  $\epsilon$ -constraint with MOEAs), decomposition (Benders-type schemes), or surrogate-assisted approaches to manage complexity (Lai et al., 2022; Rodríguez et al., 2021). In our case, node-level LP screening provides a reliable, reproducible solution without unnecessary complexity, because it correlates indicators with key operational variables while preserving the transparency required for decision support.

The vulnerabilities identified in Sections 3.2 to 3.4 support a set of proposed measures with improvement potential if applied in a targeted manner. Specifically: (i) contingency and rationing protocols at critical points; (ii) selective adjustments to operational storage and targeted network reinforcements to transfer water toward drought-prone sub-basins and to increase flood-attenuation capacity at critical stations; and (iii) nature-based solutions, such as managed aquifer recharge and basin restoration. Recent evidence supports these levers: optimization-guided operation outperforms simple rule curves, especially when addressing bottlenecks or extreme climatic conditions (Kangrang et al., 2023; Lai et al., 2022); and nature-based solutions strengthen drought resilience where surface storage and transfer capacity are limited, provided siting and governance issues are addressed up front (Esraz-UI-Zannat et al., 2024; Lalonde et al., 2024; Sufyan et al., 2024).

From a governance and disaster risk management perspective, the applied workflow (scenario generation - LP optimization - assessment of robustness and resilience) provides a

workable bridge between technical analysis and operational preparedness for basin institutions. The literature shows that resilience has a greater impact when it is operationalized into practical indicators, loss estimates, and place-based protocols (Magnuszewski et al., 2019; Mulia & Handayani, 2024; Shahriar & Roy, 2024); the system-wide and node-specific assessment presented here is consistent with that orientation. Moreover, recent work describes that infrastructure performance translates into real improvements only when it is coupled with institutional capacity through shared operational thresholds, clearly defined roles, and inter-agency protocols (Crozier et al., 2024; Friedman et al., 2024). In this sense, our node-level results and the targeted measures provide the activation points and responsibilities needed to support that coupling.

We also acknowledge tensions in the literature. Several reviews note that resilience metrics may fail to capture systemic adaptability and social processes (Leštáková et al., 2024), and that reservoir operation and management is a multi-actor, multi-objective problem in which optimization needs to be complemented by institutional design and participatory processes (W. Wu et al., 2023). This study addresses part of that agenda: it offers an interpretable, system-scale baseline explicitly informed by the operational connections among key units (sub-basins, reservoirs, and stations), which identifies where complementary measures are most likely to be effective, without assuming the internalization of institutional behaviors.

Finally, the study did not represent groundwater recharge or micro-basin dynamics, treated the occurrence of scenarios deterministically, and did not include costs. This leads to four concrete directions: (i) integrate managed aquifer recharge and watershed restoration in sub-basins with persistent deficits, incorporating them as mass-balance constraints and operational limits; (ii) couple optimization with hydrologic simulation at the micro-basin scale to assess robustness and resilience in greater detail and identify critical nodes; (iii) represent uncertainty explicitly (e.g., ENSO) using stochastic approaches when evaluating network redesigns or new nodes; and (iv) incorporate costs and socio-institutional criteria to prioritize portfolios of targeted measures. Although calibrated for the Bogotá River, the approach is transferable to similar systems with adjustments to local rules and data, enabling analysis of where the proposed measures yield the greatest benefits (Giuliani et al., 2021b; Lai et al., 2022; Sufyan et al., 2024).

## 5. CONCLUSIONS

This study assessed the robustness and resilience of the Bogotá River Basin's water system under extreme climate scenarios, focusing on minimizing flood areas (OF1) and meeting water demand (OF2). The analysis shows that a compromise solution on the Pareto front is both necessary and feasible: it reduces flood impacts while improving supply performance, providing a transparent basis for trade-off decisions

The results reveal spatially heterogeneous vulnerabilities. Under extreme drought scenarios (e1–e5), reservoirs such as El Gatillo (j8), Sisga (j1), Chisacá (j6), and La Regadera (j7), and

sub-basins such as Negro (i6) and Frío (i10), exhibit prolonged recovery, up to 52 weeks in extreme cases, indicating substantial supply risk. Under extreme rainfall (e7–e11), monitoring stations k1, k20, k21, k23 present recurrent flooding, with exceedances of control thresholds that may persist for long periods. Transition scenarios confirm a dual sensitivity: drought-to-rainfall periods challenge storage recovery, while rainfall-to-drought transitions intensify localized flood hazards and extend recovery times at specific stations.

These patterns support targeted, node-specific actions rather than uniform rules. For drought-prone sub-basins Negro (i6) and Frío (i10), and for reservoirs with long recovery times (Sisga (j1), Chisacá (j6), La Regadera (j7), El Gatillo (j8)) priority actions include: (i) time-bounded contingency and rationing protocols triggered when reliability or storage fall below the control limits; and (ii) selective adjustments to operational storage levels and, where feasible, minor increases in transfer capacity toward these nodes. For flood-exposed monitoring stations k1, k20, k21, k23, actions focus on increasing attenuation capacity to reduce the frequency and duration of control-limit exceedances. In units that show persistent deficits even under wet scenarios, nature-based solutions. Notably managed aquifer recharge and watershed restoration can both reinforce dry-season availability and dampen peak flows. The node-level diagnostics (robustness, resilience, control-limit exceedances, recovery time) provide the activation points and responsibilities referenced in the Discussion, linking the optimization outputs to operational practice.

Finally, the results support the study's hypothesis: the current hydric infrastructure and operating rules are insufficient to maintain robustness and resilience under extreme drought and rainfall. At the same time, Pareto-compromise solutions and node-level diagnostics indicate that integrated, targeted planning, including contingency triggers, selective storage points and transfer reinforcements, and nature-based solutions, can materially improve system performance. These actions have not yet been implemented and should be validated in the future.

## **SUPPLEMENTARY MATERIAL**

Supplementary material, including the full mathematical model (Appendix 1) and the complete set of results in Power BI format (Appendix 2), is available in an open Zenodo repository (Muñoz et al., 2025).

## **FUTURE RESEARCH**

This study adopted a tractable screening approach that abstracts groundwater recharge and micro-basin hydraulics, treats scenario occurrence deterministically, and omits costs. Building on these boundaries and the node-level diagnostics, four directions follow: (i) integrate managed aquifer recharge and watershed restoration in deficit-prone sub-basins as mass-balance constraints and operational limits; (ii) couple the LP screening with micro-basin hydrologic simulation to test storage set-points, pre-release rules, and attenuation capacity, validating candidate operating policies at critical nodes; (iii) represent uncertainty explicitly (e.g., ENSO) via stochastic formulation when stress-testing network changes or new nodes;

and (iv) incorporate costs and socio-institutional criteria to prioritize targeted portfolios and assess implementability. Although calibrated for the Bogotá River, the framework is transferable with local rule and data adjustments. The targeted actions proposed here should be piloted and evaluated through coupled optimization-simulation before operational adoption.

## DECLARATIONS

**Funding:** We thank Universidad de La Sabana and the Science, Technology and Innovation Fund of the Colombian General Royalties System (FCTeI–SGR) for funding the project (ID: 25825670) entitled ROBUSTNESS AND RESILIENCE ANALYSIS OF THE HYDRIC SYSTEM IN THE BOGOTÁ RIVER BASIN CONSIDERING FLOODING, WATER AND ENERGY SHORTAGES through the “Becas de Excelencia Doctoral del Bicentenario” scholarship program for the PhD in Logistics and Supply Chain Management.

**Ethical Responsibilities:** The authors declare no conflicts of interest or financial relationships influencing the research. This article does not involve human or animal studies. ChatGPT-5 (OpenAI) was used for language editing; all analyses and interpretations are the authors’ responsibility.

## REFERENCES

- Agustín Codazzi Geographical Institute - IGAC. (2023, October 30). *Geoportal IGAC [IGAC Geoportal]*. <https://geoportal.igac.gov.co/contenido/datos-abiertos-cartografia-y-geografia>
- Ali, S., & Jay, H. (2004). Measuring the Robustness of a Resource Allocation. *IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS*. <https://www.engr.colostate.edu/~aam/pdf/journals/41.pdf>
- Anilkumar G., & Kavitha G. (2025). Stochastic Programming Approaches to Logistics and Resource Optimization in Hurricane, Earthquake, and Flood Disaster Response. *Journal of Information Systems Engineering and Management*, 10(42s), 262–272. <https://doi.org/10.52783/jisem.v10i42s.7882>
- Berg, M., Spray, C. J., Blom, A., Slinger, J. H., Stancanelli, L. M., Snoek, Y., & Schielen, R. M. J. (2024). Assessing the IUCN global standard as a framework for nature-based solutions in river flood management applications. *Science of The Total Environment*, 950, 175269. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.175269>
- Bogotá Water and Sewerage Company - EAAB. (2023a, January 16). *Cuenca. Bogotá D.C. [Watershed. Bogotá D.C.]*. <https://datosabiertos.bogota.gov.co/dataset/cuenca-bogota-d-c>
- Bogotá Water and Sewerage Company - EAAB. (2023b, January 16). *Cuerpo de Agua. Bogotá D.C. [Water body. Bogotá D.C.]*. <https://datosabiertos.bogota.gov.co/dataset/cuerpo-de-agua-bogota-d-c>
- Bogotá Water and Sewerage Company - EAAB. (2023c, January 16). *SubCuenca. Bogotá D.C. [Sub-basin. Bogotá D.C.]*. <https://datosabiertos.bogota.gov.co/dataset/subcuenca-bogota-d-c>
- Bogotá Water and Sewerage Company - EAAB. (2023d, September 14). *Geoportal: Niveles del Río Bogotá [Geoportal: Bogotá River levels]*. <https://Eab->

- Sigue.Maps.Arcgis.Com/Apps/Webappviewer/Index.Html?Id=7cd2224ceec4bc4b92a2303590326bc. <https://www.acueducto.com.co/wps/portal/EAB2/Home/acueducto-y-alcantarillado/la%20infraestructura%20de%20alcantarillado/mapasAlcantarillado>
- Bogotá Water and Sewerage Company [EAAB]. (2021, January 16). *Corriente de Agua. Bogotá D.C. [Watercourse. Bogotá D.C.]*. <https://datosabiertos.bogota.gov.co/dataset/corriente-de-agua-bogota-d-c>
- Boulange, J., Hanasaki, N., Yamazaki, D., & Pokhrel, Y. (2021). Role of dams in reducing global flood exposure under climate change. *Nature Communications*, 12(1). <https://doi.org/10.1038/s41467-020-20704-0>
- Cardoso de Oliveira, G., Bertone, E., Stewart, R. A., Sanjari, M. J., & Bortoni, E. C. (2025). Robust capacity sizing and operation scheduling optimisation for resilient precinct-scale energy–water system integration. *Energy Conversion and Management*, 326, 119351. <https://doi.org/https://doi.org/10.1016/j.enconman.2024.119351>
- Coalition for Disaster Resilient Infrastructure (CDRI). (2025, July 31). *Global Infrastructure Risk Model & Resilience Index (GIRI)*. <https://giri.unepgrid.ch/>
- Crozier, A., Lence, B. J., & Weijs, S. V. (2024). Resilience framework for urban water supply systems planning. *Sustainable and Resilient Infrastructure*, 9(4), 386–406. <https://doi.org/10.1080/23789689.2024.2340378>
- Cui, H., Jiang, S., Ren, L., Xiao, W., Yuan, F., Wang, M., & Wei, L. (2022). Dynamics and potential synchronization of regional precipitation concentration and drought-flood abrupt alternation under the influence of reservoir climate. *Journal of Hydrology: Regional Studies*, 42, 101147. <https://doi.org/https://doi.org/10.1016/j.ejrh.2022.101147>
- Esráz-Ul-Zannat, Md., Dedekorkut-Howes, A., & Morgan, E. A. (2024). A review of nature-based infrastructures and their effectiveness for urban flood risk mitigation. *WIREs Climate Change*, 15(5). <https://doi.org/10.1002/wcc.889>
- Euscátegui, C., & Hurtado, G. (2011). *Análisis del impacto del fenómeno La Niña 2010 - 2011 [Analysis of the impact of the La Niña 2010–2011 phenomenon]*. <http://www.ideam.gov.co/web/siac/ninoynina>
- Feng, J., Qin, T., Yan, D., Lv, X., Yan, D., Zhang, X., & Li, W. (2024). The role of large reservoirs in drought and flood disaster risk mitigation: A case of the Yellow River Basin. *Science of The Total Environment*, 949, 175255. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.175255>
- Feng, W., Lei, X., Jiang, Y., Wang, C., Liao, W., Wang, H., Xinghui, G., & Feng, Y. (2024). Coupling model predictive control and rules-based control for real-time control of urban river systems. *Journal of Hydrology*, 636, 131228. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131228>
- Friedman, M. B., Hughes, S., Kirchoff, C. J., Rauh, E., McOmber, C., Manshardt, D. J., & Prout, J. M. (2024). Broadening resilience: An evaluation of policy and planning for drinking water resilience in 100 US cities. *Global Environmental Change*, 84, 102798. <https://doi.org/10.1016/j.gloenvcha.2024.102798>
- Giuliani, M., Lamontagne, J. R., Reed, P. M., & Castelletti, A. (2021a). A State-of-the-Art Review of Optimal Reservoir Control for Managing Conflicting Demands in a Changing World. *Water Resources Research*, 57(12). <https://doi.org/10.1029/2021WR029927>

- Giuliani, M., Lamontagne, J. R., Reed, P. M., & Castelletti, A. (2021b). A State-of-the-Art Review of Optimal Reservoir Control for Managing Conflicting Demands in a Changing World. *Water Resources Research*, 57(12). <https://doi.org/10.1029/2021WR029927>
- Guo, J., Bian, Y., Li, M., & Du, J. (2024). Assessing resilience through social networks: A case study of flood disaster management in China. *International Journal of Disaster Risk Reduction*, 108, 104583. <https://doi.org/https://doi.org/10.1016/j.ijdr.2024.104583>
- Healey, S. (2006). Cultural resilience, identity and the restructuring of political power in Bolivia. *Survival of the Commons: Mounting Challenges and New Realities, the Eleventh Conference of the International Association for the Study of Common Property*. <https://dlc.dlib.indiana.edu/dlc/handle/10535/1488>
- Kamyabniya, A., Sauré, A., Salman, F. S., Bénichou, N., & Patrick, J. (2024). Optimization models for disaster response operations: a literature review. *OR Spectrum*. <https://doi.org/10.1007/s00291-024-00750-6>
- Kandari, S., Pasupuleti, R. S., & Samaddar, S. (2022). Cultural Systems in Water Management for Disaster Risk Reduction: The Case of the Ladakh Region. *IDRiM Journal*, 11(2), 28–56.
- Kangrang, A., Prasanchum, H., Sriworamas, K., Ashrafi, S. M., Hormwichian, R., Techarungruengsakul, R., & Ngamsert, R. (2023). Application of Optimization Techniques for Searching Optimal Reservoir Rule Curves: A Review. *Water*, 15(9), 1669. <https://doi.org/10.3390/w15091669>
- Lai, V., Huang, Y. F., Koo, C. H., Ahmed, A. N., & El-Shafie, A. (2022). A Review of Reservoir Operation Optimisations: from Traditional Models to Metaheuristic Algorithms. *Archives of Computational Methods in Engineering*, 29(5), 3435–3457. <https://doi.org/10.1007/s11831-021-09701-8>
- Lalonde, M., Drenkhan, F., Rau, P., Baiker, J. R., & Buytaert, W. (2024). Scientific evidence of the hydrological impacts of nature-based solutions at the catchment scale. *WIREs Water*, 11(5). <https://doi.org/10.1002/wat2.1744>
- Leštáková, M., Logan, K. T., Rehm, I.-S., Pelz, P. F., & Friesen, J. (2024). Do resilience metrics of water distribution systems really assess resilience? A critical review. *Water Research*, 248, 120820. <https://doi.org/10.1016/j.watres.2023.120820>
- Magnuszewski, P., Jarzabek, L., Keating, A., Mechler, R., French, A., Laurien, F., Arestegui, M., Etienne, E., Ilieva, L., Ferradas, P., McQuistan, C., & Mayor, B. (2019). The Flood Resilience Systems Framework: from Concept to Application. *Journal of Integrated Disaster Risk Management*, 9(1), 56–82. <https://doi.org/10.5595/idrim.2019.0348>
- Mateus, A. (2016). Crisis energética en Colombia [Energy crisis in Colombia]. *Tecnología, Investigación y Academia (TIA)*, 4(2). <https://revistas.udistrital.edu.co/index.php/tia/article/view/10411>
- Mazzoleni, M., Mondino, E., Matanó, A., Van Loon, A. F., & Barendrecht, M. H. (2024). Modelling the role of multiple risk attitudes in implementing adaptation measures to reduce drought and flood losses. *Journal of Hydrology*, 636, 131305. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131305>
- Mens, M. J. P., Klijn, F., de Bruijn, K. M., & van Beek, E. (2011). The meaning of system robustness for flood risk management. *Environmental Science & Policy*, 14(8), 1121–1131. <https://doi.org/https://doi.org/10.1016/j.envsci.2011.08.003>

- Mulia, F. A., & Handayani, W. (2024). Assessment and Comparison of Community Resilience to Floods and Tsunamis in Padang, Indonesia. *IDRiM Journal*, 14(1). <https://doi.org/10.5595/001c.115826>
- Muñoz, L. (2025, January 6). *CAR advierte que racionamiento de agua en Bogotá podría extenderse hasta mayo* [CAR warns that water rationing in Bogotá could extend until May]. <https://www.infobae.com/colombia/2025/01/06/car-advierete-que-racionamiento-de-agua-en-bogota-podria-extenderse-hasta-mayo/#:~:text=El%20racionamiento%20de%20agua%2C%20que%20se%20implement%C3%B3%20inicialmente%20en%202024,festividades%20de%20Fin%20de%20A%C3%B1o.>
- Muñoz P., D. S., Guerrero, W., González R., L. J., & Amorim, M. (2025). *APPENDIXES PAPER: ASSESSMENT OF THE ROBUSTNESS AND RESILIENCE OF THE WATER SYSTEM IN THE BOGOTÁ RIVER BASIN*. Zenodo. <https://doi.org/10.5281/zenodo.17795458>
- National Weather Service. (2018, November 29). *Flood Safety Tips and Resources*. <https://www.weather.gov/safety/flood>
- Polo, A., Escobar, J. W., & Montoya, M. P. (2023). Robust design of a logistics system using FePIA procedure and analysis of trade-offs between CO2 emissions and net present value. *Heliyon*, 9(8), e18444. <https://doi.org/https://doi.org/10.1016/j.heliyon.2023.e18444>
- Polo, A., Peña, N., Muñoz, D., Cañón, A., & Escobar, J. W. (2019). Robust design of a closed-loop supply chain under uncertainty conditions integrating financial criteria. *Omega*, 88, 110–132. <https://doi.org/https://doi.org/10.1016/j.omega.2018.09.003>
- Puzyreva, K., Henning, Z., Schelwald, R., Rassman, H., Borgnino, E., de Beus, P., Casartelli, S., & Leon, D. (2022). Professionalization of community engagement in flood risk management: Insights from four European countries. *International Journal of Disaster Risk Reduction*, 71. <https://doi.org/10.1016/j.ijdr.2022.102811>
- Qiu, H., Chen, L., Zhou, J., He, Z., & Zhang, H. (2021). Risk analysis of water supply-hydropower generation-environment nexus in the cascade reservoir operation. *Journal of Cleaner Production*, 283. <https://doi.org/10.1016/j.jclepro.2020.124239>
- Regional Autonomous Corporation of Cundinamarca [CAR]. (2018). *Reglamento operativo para el manejo integral del sistema hídrico de la cuenca del río Bogotá* [Operational regulation for the integrated management of the hydrological system of the Bogotá River basin] (pp. 1–70).
- Regional Autonomous Corporation of Cundinamarca [CAR]. (2019). *Plan de ordenación y manejo de la cuenca hidrográfica del río Bogotá - POMCA* [Plan for the management and planning of the Bogotá River Basin - POMCA]. <https://www.car.gov.co/vercontenido/41>
- Regional Autonomous Corporation of Cundinamarca [CAR]. (2021, April 27). *Delimitación de Subcuencas a escala 1:25.000 en la Jurisdicción CAR* [Delimitation of sub-basins at 1:25.000 scale within CAR jurisdiction]. <https://datosgeograficos.car.gov.co/datasets/CARCundinamarca::delimitaci%C3%B3n-de-subcuencas-a-escala-125-000-en-la-jurisdicci%C3%B3n-car/explore?location=5.263300%2C-73.972143%2C8.30>
- Regional Autonomous Corporation of Cundinamarca [CAR]. (2024, March 27). *Sistemas Regulados* [Regulated systems]. <https://www.car.gov.co/vercontenido/2523?txtTextoabuscarsistemas+regulados#>

- Rodríguez, J. A., Anjos, M. F., Côté, P., & Desaulniers, G. (2021). Accelerating Benders decomposition for short-term hydropower maintenance scheduling. *European Journal of Operational Research*, 289(1), 240–253. <https://doi.org/10.1016/j.ejor.2020.06.041>
- Shahriar, B., & Roy, U. (2024). Practical Indicators to Improve Urban Flood Resilience of a Community: A Case of Urban Flood Mitigation in Dhaka, Bangladesh. *IDRiM Journal*, 2, 292–319.
- Stricker, N., & Lanza, G. (2014). The Concept of Robustness in Production Systems and its Correlation to Disturbances. *Procedia CIRP*, 19, 87–92. <https://doi.org/https://doi.org/10.1016/j.procir.2014.04.078>
- Sufyan, M., Martelli, G., Teatini, P., Cherubini, C., & Goi, D. (2024). Managed Aquifer Recharge for Sustainable Groundwater Management: New Developments, Challenges, and Future Prospects. *Water*, 16(22), 3216. <https://doi.org/10.3390/w16223216>
- Tordecilla, R., & González, L. (2016). Aplicación del procedimiento FePIA en la medición de la robustez en cadenas de suministro [Application of the FePIA procedure in measuring robustness in supply chains]. *Revista Lasallista de Investigación*, 13, 65–75. <https://doi.org/10.22507/rli.v13n1a5>
- Tordecilla, R., Polo, A., Muñoz, D., & González-Rodríguez, L. (2017). A robust design for a Colombian dairy cooperative's milk storage and refrigeration logistics system using binary programming. *International Journal of Production Economics*, 183, 710–720. <https://doi.org/https://doi.org/10.1016/j.ijpe.2016.09.019>
- United Nations Office for Disaster Risk Reduction [UNDRR]. (2017). *The Sendai Framework Terminology on Disaster Risk Reduction. "Resilience"*. <https://www.undrr.org/terminology/resilience>
- Ward, P. J., de Ruiter, M. C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., von Uexkull, N., Wanders, N., AghaKouchak, A., Arnbjerg-Nielsen, K., Capewell, L., Carmen Llasat, M., Day, R., Dewals, B., Di Baldassarre, G., Huning, L. S., Kreibich, H., Mazzoleni, M., Savelli, E., ... Wens, M. (2020). The need to integrate flood and drought disaster risk reduction strategies. *Water Security*, 11, 100070. <https://doi.org/https://doi.org/10.1016/j.wasec.2020.100070>
- World Meteorological Organization (WMO). (2022, February). *El niño / la niña hoy [El Niño / La Niña today]*. <https://public.wmo.int/es/el-ni%C3%B1ola-ni%C3%B1a-hoy>
- Wu, W., Eamen, L., Dandy, G., Razavi, S., Kuczera, G., & Maier, H. R. (2023). Beyond engineering: A review of reservoir management through the lens of wickedness, competing objectives and uncertainty. *Environmental Modelling & Software*, 167, 105777. <https://doi.org/10.1016/j.envsoft.2023.105777>
- Wu, Z., Chen, Y., Zheng, X., Huang, S., Duan, C., & Wang, P. (2024). A novel framework for evidence-based assessment of flood resilience integrating multi-source evidence: A case study of the Yangtze River Economic Belt, China. *Ecological Indicators*, 167, 112705. <https://doi.org/https://doi.org/10.1016/j.ecolind.2024.112705>
- Xu, C., Xu, Z., Li, X., & Yang, Z. (2024). Integrated simulation-surrogate-optimization modeling framework for multiple tradeoffs among socioeconomic and ecological targets in reservoir operations. *Journal of Environmental Management*, 368, 122092. <https://doi.org/10.1016/j.jenvman.2024.122092>
- Xu, Y., Yang, Y., Wang, Z., Xiong, J., Yong, Z., Zhang, X., Liu, J., Chen, G., Zhao, Q., Hao, J., Xu, G., & Zhu, A. (2024). Dynamic response of flood risk in urban-township complex

to future uncertainty. *International Journal of Disaster Risk Reduction*, 114, 104999.  
<https://doi.org/https://doi.org/10.1016/j.ijdr.2024.104999>

Zhang, L., Feng, Z., Yao, X., Niu, W., Wang, Y., & Mo, L. (2024). A multi-objective operation optimization method for dynamic control of reservoir water level in evolving flood season environments. *Journal of Hydrology*, 643, 131940.  
<https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131940>