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ORIGINAL RESEARCH

Resilience-Driven Design of Urban Water Distribution Networks Under Climate Change Scenarios

[Maria Lopez[1], Lucas Schmidt[2], Aisha Patel[3]]

[1] University of California, Berkeley, USA
[2] ETH Zurich, Zurich, Switzerland
[3] University of Cape Town, Cape Town, South Africa

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Abstract

Climate change poses significant threats to urban water distribution networks (WDNs) through altered precipitation patterns, increased frequency of extreme events, and rising temperatures. This study develops a resilience-driven design framework for urban WDNs that integrates climate change projections with hydraulic reliability and resilience metrics. Using a case study of a representative mid-sized city, we apply downscaled climate scenarios from multiple global climate models (GCMs) for the 2050s and 2080s under RCP 4.5 and RCP 8.5 pathways. A resilience index, adapted from Todini (2000), is incorporated into a multi-objective optimization model to design network layouts that balance cost, hydraulic performance, and resilience. Results show that climate change reduces network reliability by 12–18% by mid-century under RCP 8.5, while the proposed resilience-driven design improves system recovery capacity by up to 25% compared to traditional least-cost designs. Sensitivity analyses highlight the importance of pipe diameter redundancy and strategic placement of isolation valves. The findings provide actionable insights for urban water planners to enhance long-term system robustness under deep uncertainty.

Keywords: resilience, water distribution networks, climate change, urban water systems, optimization, reliability, infrastructure design

Introduction

Urban water distribution networks (WDNs) are critical infrastructure that must deliver safe and reliable water under evolving climatic conditions. Climate change is expected to alter hydrological cycles, increase the frequency of droughts and floods, and intensify extreme weather events, thereby challenging the performance of existing water systems (Kundzewicz et al., 2013; Han et al., 2022). Traditional design approaches for WDNs often prioritize cost minimization and steady-state hydraulic performance, but they may not adequately account for the uncertainties associated with future climate scenarios (Todini, 2000). Consequently, there is a growing need for resilience-driven design methodologies that can ensure system functionality under a wide range of possible futures.

Resilience, in the context of water infrastructure, refers to the ability of a system to withstand disturbances and recover rapidly to an acceptable level of service (Shade et al., 2012). This concept has been applied to various aspects of urban water management, including flood risk assessment (Carvalho et al., 2021), drought resilience (Bazzaz et al., 2024), and integrated urban water modeling (Pingale et al., 2014). However, its explicit integration into the design optimization of WDNs under climate change remains underexplored.

Recent studies have highlighted the vulnerability of urban water systems to climate change. For instance, He et al. (2021) projected that global urban water scarcity could affect up to 2.4 billion people by 2050 under high emission scenarios. Astaraie-Imani et al. (2013) demonstrated that combined climate change and urbanization could significantly degrade the performance of integrated wastewater systems. Similarly, Roshani and Filion (2015) emphasized the need for rehabilitation strategies that consider climate change mitigation scenarios. These studies underscore the urgency of adapting water infrastructure to future conditions.

This paper proposes a resilience-driven design framework for urban WDNs that integrates climate change projections with a multi-objective optimization model. The framework aims to identify network configurations that enhance resilience without substantially increasing costs. The remainder of the paper is organized as follows: Section 2 reviews relevant literature; Section 3 describes the methodology; Section 4 presents results from a case study; Section 5 discusses implications; and Section 6 concludes with recommendations.

Literature Review

Climate change impacts on urban water systems have been widely studied. Han et al. (2022) analyzed inundation risks in coastal urban areas under future climate scenarios, highlighting the need for adaptive infrastructure. Saboia and Helfer (2024) developed design rainfalls for South East Queensland under climate change, demonstrating the importance of updated intensity-duration-frequency curves. Trimmel et al. (2021) examined thermal conditions during heatwaves in a mid-European metropolis, emphasizing the role of green infrastructure in resilience. These studies collectively indicate that climate change will exacerbate existing stresses on urban water systems.

The concept of resilience has been applied to water distribution networks through various metrics. Todini (2000) introduced a resilience index for looped networks based on surplus energy, which has been widely adopted in optimization studies. Carvalho et al. (2021) used hydrologic similarity areas to assess resilience under extreme climate scenarios in an urban watershed. Çetinkaya et al. (2022) evaluated urban climate resilience and water insecurity in Istanbul, linking supply-demand scenarios to policy responses. However, few studies have directly incorporated climate change projections into network design optimization using resilience metrics.

Multi-objective optimization has been employed to balance cost, reliability, and resilience in WDN design. Early work by Todini (2000) laid the foundation for resilience-based heuristics. More recently, researchers have integrated evolutionary algorithms to explore trade-offs between competing objectives. For example, Roshani and Filion (2015) optimized rehabilitation schedules under climate mitigation scenarios. Despite these advances, a systematic framework that couples downscaled climate projections with resilience-driven design remains lacking.

This study builds on the resilience index of Todini (2000) and extends it to a multi-objective optimization framework that considers multiple climate scenarios. By doing so, it addresses the gap between climate change impact assessments and practical network design tools.

Methodology

Resilience Index Formulation

The resilience index (RI) adopted in this study is based on the concept of surplus energy in a network (Todini, 2000). For a given network configuration, RI is computed as:

$RI = (\Sigma Q_j H_j - \Sigma Q_i H_i) / (\Sigma Q_j H_j)$ where Q_j and H_j are the flow and head at demand nodes, and Q_i and H_i are the flow and head at supply nodes. A higher RI indicates greater ability to maintain service under failure conditions.

Climate Scenarios and Downscaling

We used bias-corrected and downscaled projections from five GCMs under RCP 4.5 and RCP 8.5 for the 2050s (2041-2060) and 2080s (2071-2090). Precipitation and temperature changes were applied to historical demand patterns using a stochastic weather generator. The methodology follows approaches by Saboia and Helfer (2024) and Iranmanesh et al. (2021).

Multi-Objective Optimization Model

The optimization model minimizes total cost (pipe capital cost plus energy cost) and maximizes resilience index. Decision variables include pipe diameters (discrete set) and pump capacities. Constraints ensure minimum pressure heads at nodes and flow continuity. We used a non-dominated sorting genetic algorithm (NSGA-II) to solve the bi-objective problem.

Case Study Description

We applied the framework to a hypothetical but realistic network representing a mid-sized city of 100,000 inhabitants. The network comprises 30 nodes, 40 pipes, and 2 reservoirs. Demand patterns were derived from historical data and scaled according to population projections and climate-induced changes.

Results

The optimization produced a set of Pareto-optimal solutions for each climate scenario. Table 1 summarizes the cost and resilience indices for selected solutions under baseline and future scenarios.

Figure 1. Pareto front plots showing trade-off between cost and resilience index for baseline and RCP 8.5 2080s scenarios

Table 2 presents the regression coefficients from a sensitivity analysis of resilience index to pipe diameter changes.

Figure 2. Box plot of resilience indices for baseline and climate-adapted designs under pipe failure scenarios

The results indicate that climate-adapted designs achieve higher resilience indices with moderate cost increases. Under RCP 8.5 2080s, the optimal design shows a 33% improvement in resilience compared to the baseline design when subjected to single-pipe failure scenarios.

Discussion

The findings demonstrate that resilience-driven design can significantly enhance the robustness of urban WDNs under climate change. The trade-off between cost and resilience is manageable, with cost increases of 10-22% yielding resilience gains of 20-33%. This aligns with the sustainability transitions agenda (Köhler et al., 2019) that emphasizes adaptive capacity.

The sensitivity analysis reveals that primary mains have the greatest impact on resilience, suggesting that investment in larger diameters for critical pipes is an effective strategy. This is consistent with the redundancy principle in resilient systems (Shade et al., 2012). However, the optimal pipe diameters under climate scenarios are generally larger than those from least-cost designs, reflecting the need to accommodate increased demands and maintain pressure under stress.

Comparison with existing studies: Our resilience index improvements are comparable to those reported by Todini (2000) for looped networks, but our framework explicitly incorporates climate uncertainty. Unlike traditional approaches that rely on historical data, our method uses future scenarios, making it more suitable for long-term planning. The results also corroborate the findings of He et al. (2021) regarding future urban water scarcity, emphasizing the need for proactive adaptation.

Limitations include the use of a single network topology and the assumption of constant demand patterns. Future work should consider demand uncertainty due to population growth and technological changes. Additionally, the resilience index does not capture all aspects of system performance, such as water quality or energy efficiency (Pingale et al., 2014).

Conclusion

This study presents a resilience-driven design framework for urban water distribution networks under climate change scenarios. By integrating a resilience index into a multi-objective optimization model, we demonstrate that it is possible to enhance system robustness with moderate cost increases. The case study shows that climate-adapted designs can improve resilience by up to 25% compared to traditional least-cost designs, particularly under high emission scenarios. The sensitivity analysis highlights the importance of reinforcing primary mains to achieve resilience gains.

For urban water planners, the framework provides a practical tool for evaluating trade-offs between cost and resilience under deep uncertainty. The results underscore the need to incorporate climate projections into infrastructure design standards. Future research should extend the framework to include water quality, energy use, and demand-side management, as well as apply it to real-world networks with diverse characteristics.