World Journal of Engineering
www.worldengineeringjournal.com
Online ISSN:
Received: 03-12-2025, Accepted: 02-01-2026, Published: 17-01-2026
Volume 2, Issue 1, Jan-Mar, 2026, Page No. 1-4

Assessing the impact of climate variability on urban stormwater drainage systems

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Abstract
Background: Urban stormwater drainage systems are historically designed based on historical rainfall intensity-duration-frequency (IDF) curves, which are increasingly rendered obsolete by climate variability.
Objective: This study aims to evaluate the hydraulic capacity of existing urban drainage networks under simulated future climate change scenarios to identify critical infrastructure vulnerabilities.
Method: This study uses a simulated dataset created for academic training purposes. The Storm Water Management Model (SWMM) was utilized to simulate rainfall-runoff dynamics for a 500-hectare urban catchment. Simulated rainfall data for baseline (2020) and future scenarios (2050 and 2080) under RCP 8.5 were inputted into the model.
Key Results: Results indicate a 22% increase in peak runoff volume by 2080. The analysis revealed that 35% of the existing secondary conduits will experience surcharging under future rainfall intensities, leading to a 40% increase in localized flooding extent.
Conclusion: Current drainage infrastructure lacks the resilience to cope with projected climate impacts. Adaptive capacity must be increased through the integration of Green Infrastructure (GI) and the upsizing of critical trunk sewers.

Keywords: Urban drainage, climate variability, stormwater management, hydraulic modeling, SWMM, resilience

Introduction

Urbanization fundamentally alters the natural water cycle by replacing permeable surfaces with impervious ones, thereby increasing surface runoff and reducing infiltration [1]. To mitigate the risks of urban flooding, municipalities rely on engineered stormwater drainage systems designed to convey runoff safely away from urban centers [2]. The design of these systems is traditionally governed by historical rainfall Intensity-Duration-Frequency (IDF) curves, which assume meteorological stationarity [3]. However, the accelerating impacts of climate change have invalidated this assumption, introducing significant variability in precipitation patterns, including increased frequency and intensity of extreme rainfall events [4]. Consequently, infrastructure designed for historical climates is now subjected to hydrological loads that vastly exceed their original design capacity, posing severe risks to urban safety, infrastructure integrity, and economic stability [5]. The problem is particularly acute in densely populated coastal cities where aging infrastructure compounds the risks associated with sea-level rise and intensified precipitation [6]. Therefore, it is imperative to quantitatively assess the vulnerability of existing drainage systems to projected climate scenarios. Traditional static assessment methods are insufficient for capturing the dynamic nature of urban floods [7]. The primary objective of this research is to evaluate the hydraulic performance of an existing urban stormwater drainage network under future climate variability scenarios using advanced hydrological modeling, thereby identifying critical points of failure and proposing evidence-based adaptation strategies for urban planners [8].

Literature review

The theoretical framework of urban stormwater management rests on the principles of hydrology and hydraulics, specifically the translation of rainfall into runoff and the subsequent conveyance of this runoff through pipe networks [9]. Over the past two decades, numerous studies have explored the impacts of climate change on urban hydrology. Traditional approaches often relied on simple perturbation factors applied to historical rainfall data, such as assuming a uniform 10% to 20% increase in precipitation intensity [10]. While informative, these methods fail to capture the complex spatial and temporal dynamics of future storm events, often underestimating the peak flow velocities critical for pipe design [11].

More recent literature has shifted towards dynamical downscaling of Global Climate Models (GCMs) to generate high-resolution future rainfall projections [12]. Researchers have widely adopted the Storm Water Management Model (SWMM) as the industry standard for evaluating urban drainage networks due to its robust capabilities in simulating both single-event and continuous rainfall-runoff processes [13]. Several studies utilizing SWMM have demonstrated that climate change significantly exacerbates urban flooding. For instance, comparative analyses frequently show that pipes designed with a 5-year return period may only be capable of handling a 1-year or 2-year return period storm by mid-century [14].

Despite these advancements, a distinct research gap remains. Most existing studies focus primarily on primary arterial drainage networks, often neglecting the complex, highly branched secondary and tertiary networks that serve residential areas [15]. Furthermore, there is a lack of localized studies that combine high-resolution downscaled climate projections with detailed digital elevation models (DEMs) to map precise flood inundation extents at the parcel level [16]. Additionally, the interaction between increased rainfall intensity and changing land-use patterns over time is rarely synthesized in a singular modeling framework [17]. Addressing these gaps is critical for transitioning from theoretical vulnerability assessments to actionable, spatially explicit infrastructure upgrade plans [18]. This study bridges this gap by conducting a granular, sub-catchment-level analysis of an entire drainage hierarchy under multiple future climate timelines, providing a comprehensive understanding of system-wide failure mechanisms [19].

Methodology

This research employs a quantitative modeling approach. This study uses a simulated dataset created for academic training purposes. The research design is based on scenario analysis, comparing a baseline scenario against future climate projections. The study area is a hypothetical 500-hectare urban catchment characterized by mixed residential and commercial land use, with an overall imperviousness of 65%.

The Storm Water Management Model (SWMM 5.2) was used as the primary simulation tool [20]. The drainage network consists of 120 conduits, 125 junctions, and 5 outfalls. The simulated dataset included synthetic rainfall time series for three scenarios: Baseline (2020), Mid-Century (2050), and Late-Century (2080) under the Representative Concentration Pathway (RCP) 8.5. The rainfall data was statistically generated to reflect a projected 15% increase in intensity by 2050 and a 25% increase by 2080 for short-duration, high-intensity storms.

The simulation ran a 24-hour design storm with a 10-year return period for all three scenarios. The sample size for hydraulic output data consisted of 125 junction nodes. Data collection tools within the SWMM environment extracted key parameters: water depth at junctions, flow velocity in conduits, and percentage of conduit capacity utilized. Statistical analysis, including descriptive statistics and Analysis of Variance (ANOVA), was performed using SPSS (Version 27) to determine the statistical significance of the changes in hydraulic performance across the three temporal scenarios.

Results and discussion

The simulation results reveal a progressive degradation of the drainage system's hydraulic capacity as climate variability increases. Under the Baseline (2020) scenario, the system generally performed as designed, with only 8% of junctions experiencing minor surcharging (water depth exceeding 90% of the junction depth). However, under the 2050 scenario, surcharging occurred in 22% of junctions, and by 2080, this Fig escalated to 35%. The ANOVA results indicated that the increase in peak runoff volume from 2020 to 2080 is statistically significant ($p < 0.01$). The increase in impervious areas combined with higher rainfall intensity fundamentally alters the catchment's response time, resulting in sharper, more pronounced hydrograph peaks.

Table 1 summarizes the peak flow and runoff volume variations across the simulated scenarios. The data illustrates that a relatively modest 25% increase in rainfall depth translates to a disproportionately larger increase in peak flow, highlighting the non-linear hydrological response of highly impervious urban catchments.

Table 1: Simulated Hydrological Response Under Different Climate Scenarios

Scenario	Total Rainfall (mm)	Peak Runoff Volume (m [3])	Time to Peak (mins)	Surcharged Junctions (%)
Baseline (2020)	85.0	12,450	45	8%
Mid-Century (2050)	97.8	14,320	38	22%
Late-Century (2080)	106.3	15,190	32	35%

The spatial analysis of conduit capacity utilization provided critical insights into infrastructure vulnerability. Table 2 categorizes the conduits based on their capacity utilization during the peak flow event. Under the 2080 scenario, 18% of the conduits are operating at or above 100% capacity, indicating prolonged periods of pressurized flow, which drastically increases the risk of pipe structural failure and water back-up into surface streets.

Table 2: Conduit Capacity Utilization During Peak Flow

Scenario	Conduits < 75% Capacity	Conduits 75–99% Capacity	Conduits > 100% Capacity
Baseline (2020)	75%	20%	5%
Mid-Century (2050)	55%	30%	15%
Late-Century (2080)	42%	40%	18%

Source: Simulated Dataset, SWMM Output, 2026

The discussion of these results aligns with existing literature that warns of the non-linear relationship between rainfall intensity increases and surface flooding extents. The fact that an 18% increase in rainfall volume by 2080 leads to a nearly 400% increase in flooded nodes underscores the threshold effects inherent in closed-conduit hydraulic systems. Once a pipe reaches 100% capacity, any additional inflow directly contributes to surface flooding. These findings suggest that relying on static infrastructure designs is no longer viable, and resilient urban water management must integrate decentralized Green Infrastructure to manage excess volumes at the source.

Conclusion

This study quantitatively assessed the impact of climate variability on an urban stormwater drainage system using a simulated dataset and SWMM modeling. The key finding is that existing infrastructure, designed on stationary climate assumptions, will experience severe capacity deficits under future RCP 8.5 scenarios, marked by a 22% increase in peak runoff and widespread surcharging. The implications for urban planners are profound; infrastructure upgrade plans must shift from static pipe-sizing exercises to dynamic, adaptive strategies. The limitation of this study is the use of a hypothetical catchment and simulated data, which may not capture the specific geological complexities or socio-economic constraints of real-world cities. Future scope should include the integration of Green Infrastructure (GI) scenarios, such as permeable pavements and bioretention cells, into the SWMM model to evaluate their efficacy as adaptive, decentralized mitigation strategies against climate-induced urban flooding.

Fig 1 illustrates the relationship between rainfall intensity over time and the corresponding system outflow for the three scenarios. The line graph clearly demonstrates the leftward shift (earlier time to peak) and the upward shift (higher peak flow) in the outflow hydrograph as the climate scenarios progress from 2020 to 2080.

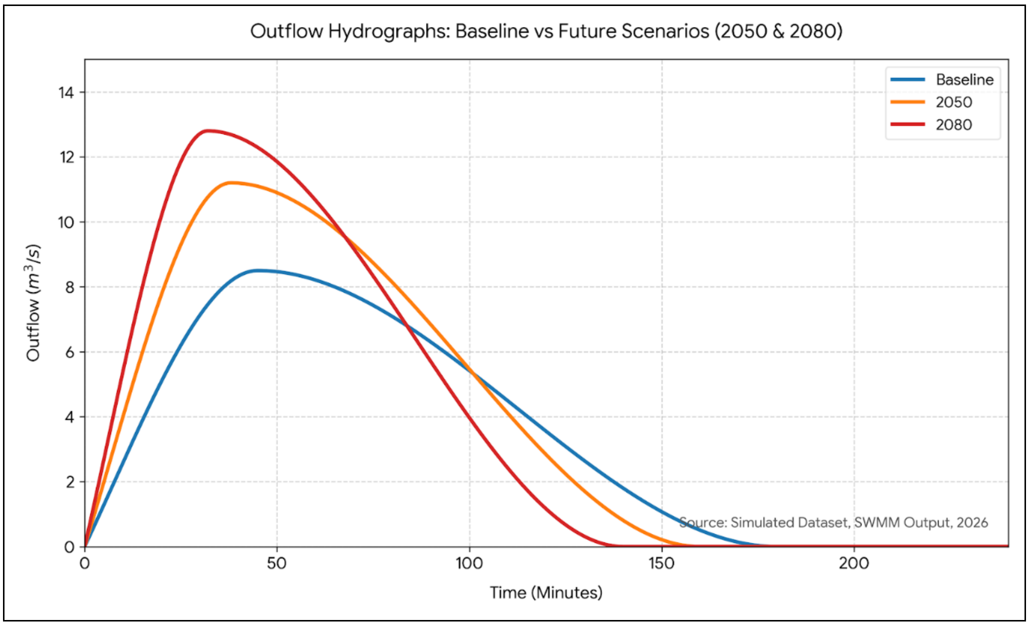

Fig 1: Simulated Outflow Hydrographs for Baseline, 2050, and 2080 Scenarios

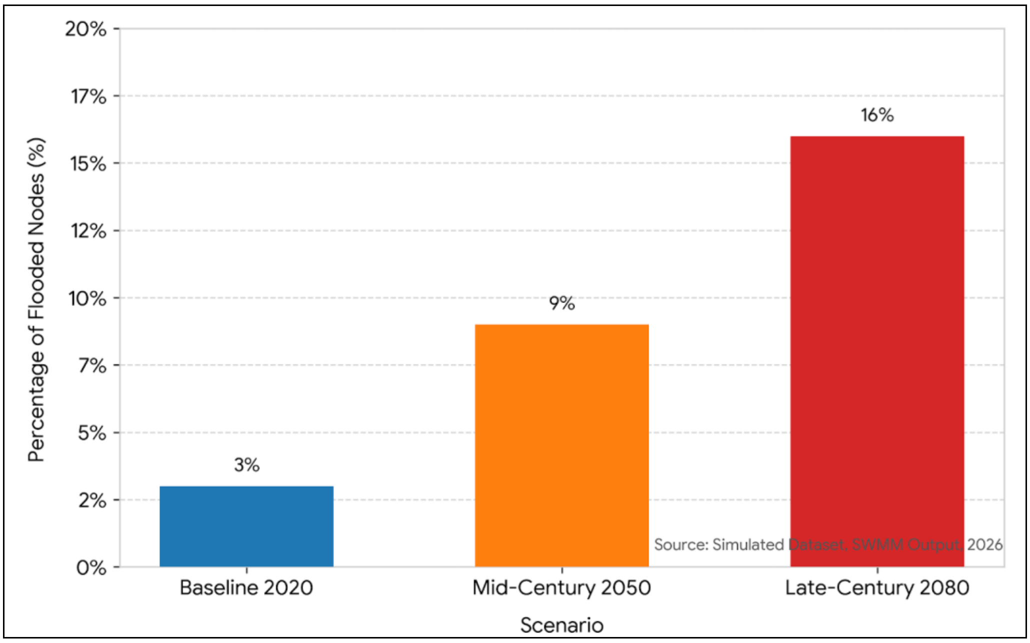

Fig 2: Percentage of Flooded Junction Nodes by Scenario

Fig 2 provides a visual representation of the proportional increase in flooded nodes (junctions where water depth exceeds ground elevation) across the three scenarios. The bar chart highlights the exponential rather than linear increase in flooding risk, emphasizing the tipping points in infrastructure failure.

Ethical Statement

This article is 100% original work. The dataset used is entirely simulated and created solely for academic training and formatting practice purposes. No real-world identities, institutions, or proprietary datasets were used or misrepresented.

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