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Impacts of Climate Change on the Operation of Storm Sewer Networks

Ph.D. Thesis Booklet

By

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1 Introduction

1.1 Background

Climate change has emerged as one of the foremost global issues of the 21st century, influencing a range of environmental and infrastructural systems. Cities play a crucial role in addressing climate change. Currently, around 55% of the global population resides in urban areas, a figure projected to rise to 70% by 2050. Sustainability is becoming a primary focus in urban planning and water management globally, especially in developed nations. In contrast, developing countries continue to struggle with significant challenges such as flooding and water pollution. Rapid land use changes and climate variations are complicating the sustainable planning and management of stormwater systems. The increasing threat posed by climate change has become a major obstacle to the durability and effectiveness of urban infrastructure, particularly in stormwater and wastewater management systems. Beyond the worldwide recognition of drastic climate shifts affecting human life, multiple studies have documented the adverse effects resulting from inadequate storm sewer networks (Bibi & Kara, 2023; Johnson et al., 2022; Peleg et al., 2022). The most recent report from the Intergovernmental Panel on Climate Change IPCC (2021) highlights that future climate changes will have profound impacts across various sectors, particularly in developing nations that lack sufficient adaptive capacities. The unique characteristics of climate change involve altered precipitation patterns and an increased occurrence of extreme weather events like flooding, which pose substantial obstacles for urban infrastructure, notably stormwater management systems. This is mainly because they are traditionally designed based on past hydrological data that may no longer apply in the context of a shifting climate. Urban drainage systems, therefore, are becoming more susceptible to the combined impacts of urbanization and climate change (Zhou et al. 2019), particularly due to the escalating frequency and intensity of extreme rainfall occurrences.

1.2 Research Objectives

The present research focuses on evaluating the performance of storm sewer systems under two developmental scenarios: the "Middle-of-the-Road" development scenario (SSP2-4.5) and the "Fossil-fueled" development scenario (SSP5-8.5) in the designated case study area. Additionally, it integrates temporal aspects by projecting potential climate change effects at

"Middle-of-Century" (2041-2060) and "End-of-Century" (2081-2100) for each development scenario, ultimately proposing a suitable strategy to enhance resilience against these impacts. The outcomes of this research will serve as a valuable resource for policymakers, engineers, and urban planners who are looking to address the challenges posed by climate change on urban infrastructure. By utilizing the Storm Water Management Model (SWMM), the study aims to deepen the understanding of forthcoming challenges and formulate effective strategies to maintain the functionality and safety of stormwater systems in an evolving climate.

Furthermore, the study assesses the effectiveness of green infrastructure solutions within the Bole-Arabsa stormwater management system, considering projected climate scenarios based on CMIP6 models. With a focus on climate resilience, the study explores how green infrastructure can mitigate stormwater impacts, reduce flooding risks, and support sustainable urban development. The results provide essential insights into the role of green infrastructure in climate adaptation, offering significant direction for policymakers and urban planners working towards the establishment of resilient water management systems.

The dissertation is designed to analyze and evaluate storm sewer networks' performance in the context of climate change while assessing the efficacy of green infrastructure in enhancing urban drainage resilience. The primary objectives of this research are:

1. To Analyze climate change trends at basin level and develop custom local climate change scenarios.
2. Modeling Rainfall-runoff to study catchment response sensitivity under changing climate scenarios
3. To investigate how changing climate affects the performance of storm sewer networks.
4. To assess the effectiveness of green infrastructure in enhancing urban resilience under climate change scenarios.

1.3 Significance of the Study

Understanding the impact of climate change on urban drainage systems is essential for ensuring the resilience of urban infrastructure and reducing the risks related to severe weather events.

The results of this research will aid in formulating climate-resilient urban planning policies, sustainable drainage solutions, and innovative flood management approaches. Additionally, this study will offer important insights for engineers, urban planners, and policymakers focused on climate adaptation in cities around the globe. Moreover, our understanding of the capacity for Green Infrastructure (GI) to alleviate flooding in future climates remains insufficient; typically, performance assessments focus on individual GI components within fixed implementation zones under historical conditions or limited future scenarios (Cavadini et al., 2024).

It is also important to acknowledge that the effects of climate change are neither uniform across different regions nor consistent over time (Archer et al., 2024; Mpandeli et al., 2019; Tang et al., 2021). The severity and trends of climate change are significantly influenced by specific local conditions as well as seasonal variations. The impacts of climate change vary significantly across different regions. Factors such as rainfall intensity, duration, and frequency (IDF curves) exhibit distinct variations based on geographic location. When local weather data is aggregated into wider spatial frameworks, specific local trends may be obscured or inadequately represented (M. D. Miller, 2025). Thus, it is vital to conduct localized analyses of past trends and make accurate projections of future climate change to inform sustainable infrastructure planning. This approach is essential for developing effective adaptive and mitigation strategies aimed at achieving sustainable development goals.

A major impact of climate change that is currently threatening the world is urban flooding. The city of Addis Ababa frequently faces flood disasters, resulting in substantial damage to property and loss of life. Several studies conducted in Ethiopia, particularly within Addis Ababa, have documented significant alterations in climatic variables due to land use and climate changes (Alemu & Dioha, 2020; Degefu & Kifle, 2024; Diress & Beshu Bedada, 2021; Mekonnen et al., 2024). Moreover, research by Birhanu et al. (2016), on the city, has indicated that climate change and urbanization have led to increases in peak flow by 10% and 25%, respectively. Similarly, the findings of Bekele et al. (2023) suggest that a large portion of the city is at high risk of flooding. In a recent study Garcia Rubio et al. (2023), highlighted that rapid urbanization and climate change are primarily responsible for the flooding issues faced by the city.

Climate change effects differ significantly depending on geographical context, with their most pronounced impacts occurring at the local level (Braunschweiger & Ingold, 2023). This creates a necessity for solutions tailored to local conditions. Consequently, the local level is crucial for

adapting to climate change. Research by Zhou et al. (2018) emphasizes the significance of considering local adaptations in strategies to manage future urban flooding. Studying climate change at a localized level is, therefore, essential for creating urban drainage systems that are both resilient and adaptive to its effects. This localized research enables cities to develop tailored, data-informed solutions for urban drainage. It also improves flood resilience, infrastructure planning, and sustainability under a shifting climate and contributes to achieve sustainable development goals.

2 Methodology

2.1 Data Collection

The present research relies primarily on a variety of meteorological, hydrological, spatial, and climatic data sourced from multiple origins. Daily meteorological data spanning from 1990 to 2022 was gathered from the National Meteorological Agency of Ethiopia. In addition, 15-minute rainfall records for an 11-year period (2011-2022) were also sourced from the same agency and utilized to disaggregate the daily climate data for better application in SWMM. Daily instantaneous flow hydrological information was obtained from the Ministry of Water and Energy in Ethiopia for the Akaki hydrological station covering the years 1980 to 2004. Comparable spatial datasets including Digital Elevation Model (DEM), land use, soil types, and Ethiopian river basins were likewise obtained from this Ministry. Data related to urban planning, land use within urban areas, as well as information concerning Addis Ababa city and its various sub-cities were acquired from the Addis Ababa City Planning and Development office. Moreover, details regarding storm sewer network design and planning were compiled from the Addis Ababa City Road Authority. The various data sources, main data processing methods, and major models involved to achieve the objectives are shown by the conceptual framework (refer to Figure 1).

Projections regarding climate change were sourced from NEX GDDP dataset. Four CMIP6 models – CESM2, GFDL-CM4, GFDL-ESM4, and NorESM2-MM – were chosen based on their effectiveness in replicating observed data for the region according to prior research (Berhanu et al., 2023). These models offered a comprehensive spectrum of potential future climate scenarios characterized by high-resolution and bias-corrected data along with enhanced simulations of climatic extremes (Kim et al., 2020; Thrasher et al., 2022). This includes both historical climatic data (1950 to 2014) and projected data (2015 to 2100), which was derived

from NASA NEX GDDP dataset corresponding to these four selected CMIP6 models. The climatic information was subsequently extracted for the study area utilizing ONCF-V1.1 application within AgriMetSoft from downscaled NetCDF files. Overall, the dataset has been organized into three categories: baseline data (2001-2020), mid-century projections (2041-2060), and late-century projections (2081-2100), organized under two Shared Socioeconomic Pathways (SSP) namely SSP2-4.5 and SSP5-8.5.

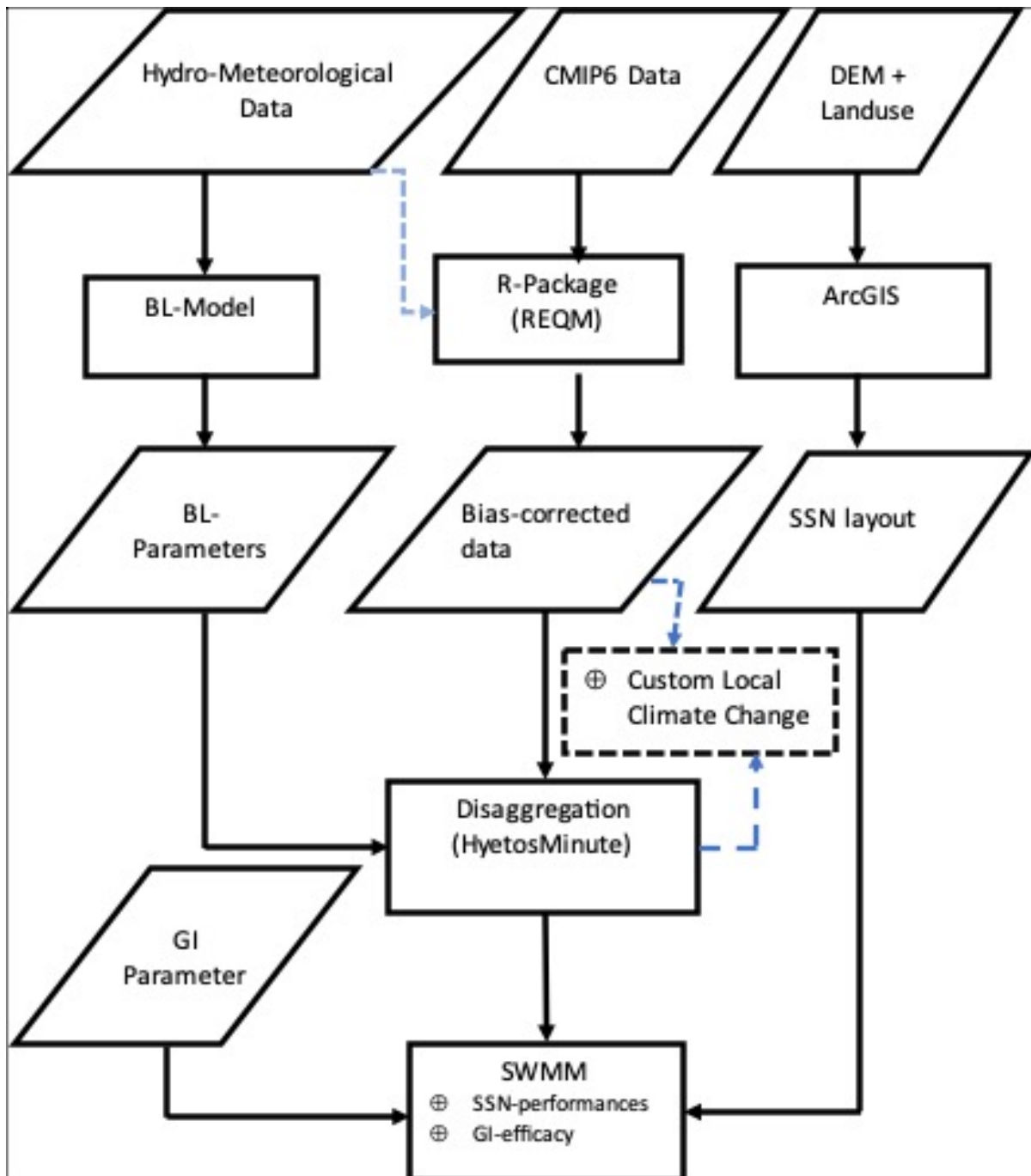


Figure 1: Conceptual framework for the study

2.2 Data Processing

The application of further bias correction and disaggregation methods enhances the dependability of climate data, while the SWMM model provides comprehensive insights into system performance across diverse future scenarios.

Bias Correction:

To improve the precision of climate forecasts, further bias correction was applied to the outputs from the CMIP6 model. This process involved analyzing 31 years of historical model results (1991-2021) against observed data and adjusting future projections to eliminate systematic biases. The performance of models varies over time, exhibiting notable discrepancies in their capacity to replicate observed data across different seasons. Therefore, prior to implementing bias correction, the effectiveness of the four selected models was reassessed for each month using the root mean square error (RMSE) method. Subsequently, the output data from the model with relatively better performance were utilized for projection purposes for each respective month.

Studies conducted earlier in the same basin by Tadese et al. (2020); and Worku et al. (2020) demonstrated the effectiveness of distribution mapping (DM) methods in aligning the statistical characteristics of model outputs with observed data. Several researchers, including Holthuijzen et al. (2022); Katiraie-Boroujerdy et al. (2020); Robertson et al. (2023); Seo & Ahn (2023); and Tong et al. (2021), have utilized the Quantile Mapping (QM) technique for bias correction, yielding reliable outcomes particularly in refining distributions based on observed data. Consequently, this study employed the robust empirical quantile mapping (REQM) package within R programming to correct biases in the CMIP6 downscaled dataset derived from the selected models prior to its application in SWMM model simulations.

Disaggregation:

The time interval of rainfall is crucial for SWMM when it comes to reading and interpreting the input rainfall time series, typically ranging from 1 minute to 1 day. In common SWMM applications, 5-minute intervals are preferred, while 15-minute intervals are deemed acceptable. Hourly data is often considered a compromise, as the response time of smaller sub-catchments is generally much quicker. For long-term rainfall data used in continuous simulation, 15-minute or hourly intervals are standard.

Climate model data is typically provided at a daily temporal resolution; however, urban drainage system simulations using SWMM require a finer temporal resolution, ideally at sub-hourly intervals. This research utilized HyetosMinute software in the R programming to disaggregate daily rainfall data into 15-minute intervals. Various techniques exist for temporally disaggregating daily or monthly projections into hourly or sub-hourly rainfall data while preserving the original statistical properties and variability. Numerous studies – such as those by Dodangeh et al. (2017); Engida & Esteves (2011); Harisaweni et al. (2016); Islam et al. (2023); Kossieris et al. (2018); and Yusop et al. (2014) – have indicated that disaggregation employing the Bartlett-Lewis (BL) process effectively replicates the statistical behaviors of such variables.

Thus, this study applied the BL process from HyetosMinute within R programming to convert downscaled daily rainfall data into 15-minute intervals suitable for SWMM's stormwater drainage system simulations. To achieve this, a series of 11 years of 15-minute observed rainfall data from 2011 to 2022 was analyzed alongside corresponding observed daily data to determine BL parameters, which were optimized monthly to mitigate seasonal variation effects.

GI Configuration

The SWMM integrates Low Impact Development (LID) controls based on conceptual model to simulate Green Infrastructure (GI) elements. This study focuses on two specific GI practices: bio-retention cells and rain gardens. Both systems include vegetation, soil and engineered layers to slow, absorb and filter stormwater from impervious surfaces, such as roads, rooftops and driveways. Essential data for these systems includes characteristics related to the surface, soil, storage, and drainage layers. Information about surface attributes – such as roughness and slope along with soil characteristics like porosity, conductivity, and suction head were obtained from the spatial data of the study area that aligns with suggested engineering soil. Furthermore, design considerations and strategic placement data were adopted from guidelines found in various user manuals and academic literature. The site suitability analysis was conducted using GIS based on landuse, urban planning, and drainage system. Finally, simulation based SWMM framework was applied for optimum design and positioning of GI in view of critical spots and targeted goal of GI integration.

3 New Scientific Contributions

3.1 Theses

Thesis 1

I developed a customized climate change scenario to enhance the local relevance of CMIP6 global climate model outputs for impact assessments. Recognizing the limitations of raw model projections, I applied advanced bias correction using Robust Empirical Quantile Mapping (REQM) and employed HyetosMinute and Bartlett-Lewis disaggregation techniques to generate high-resolution rainfall data at 15-minute intervals from daily time series. This work represents a novel contribution by producing locally adapted, bias-corrected, and temporally disaggregated climate data tailored for urban infrastructure simulations, thereby bridging a critical gap in conventional climate projections. [1, 4, 9]

Thesis 2

Based on a resilient criterion, I developed an innovative, scenario-based simulation framework to assess the increasing vulnerability of storm sewer networks in Addis Ababa under mid- and end-century climate change scenarios, using high-resolution localized rainfall data. Departing from conventional single-event approaches, my framework employs continuous simulation to better capture the cumulative effects of sequential storms and antecedent moisture, offering a more realistic picture of urban flood risks. Moreover, I integrated a hybrid of developmental and radiative forcing scenarios to reflect both emission trajectories and socio-economic uncertainties. This dual-timeline analysis enables urban planners to formulate phased, adaptive strategies that enhance the climate resilience of critical drainage infrastructure. [3,4, 6, 9]

Applications of the developed framework:

Projection of Climate Change Impacts on Network Capacity:

I applied and validated the developed model to evaluate the future impacts of climate change on the Bole-Arabsa storm sewer network, Addis Ababa. The simulation outcomes indicated elongated conduit surcharging hours, an increase in node flooding frequency, heightening of

flooding volume, and a decline in the hydraulic efficiency of the storm sewer networks, corresponding to projected future precipitation patterns (refer to Figure 2).

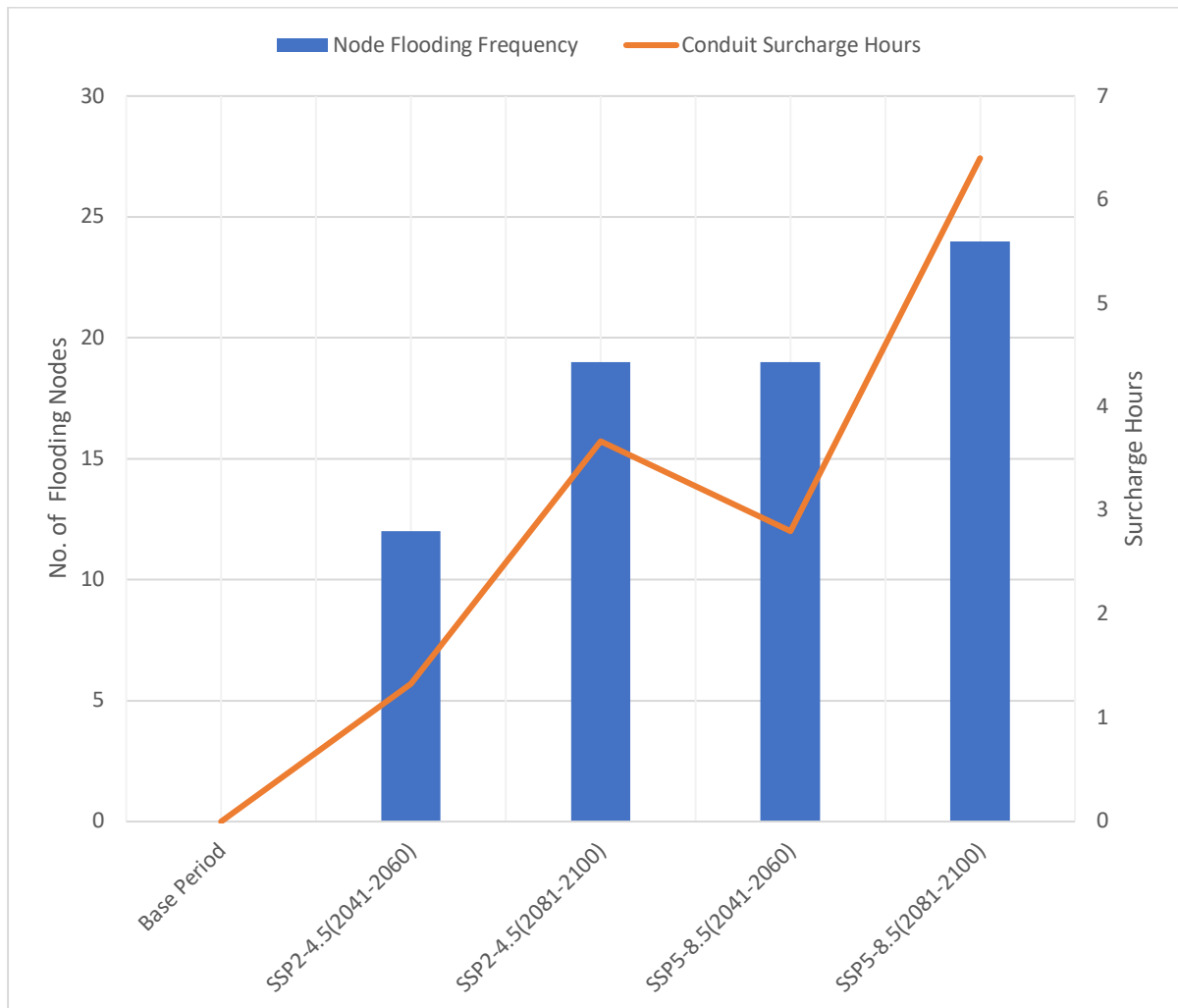


Figure 2: Scaling up of climate change impacts on storm system performance under different projection scenarios in terms of node flooding & conduit surcharge.

Identification of Critical Nodes and Vulnerable Areas:

The model was used to pinpoint particular nodes, pipes, and drainage regions likely to surpass design capacity in light of future climate scenarios for Bole-Arabsa Storm Sewer Network. The identified nodes and conduits are shown with color map output (refer to Figure 3). This gives a valuable information for urban planners and decision makers for prioritizing their phased actions of adaptive strategy implementation.

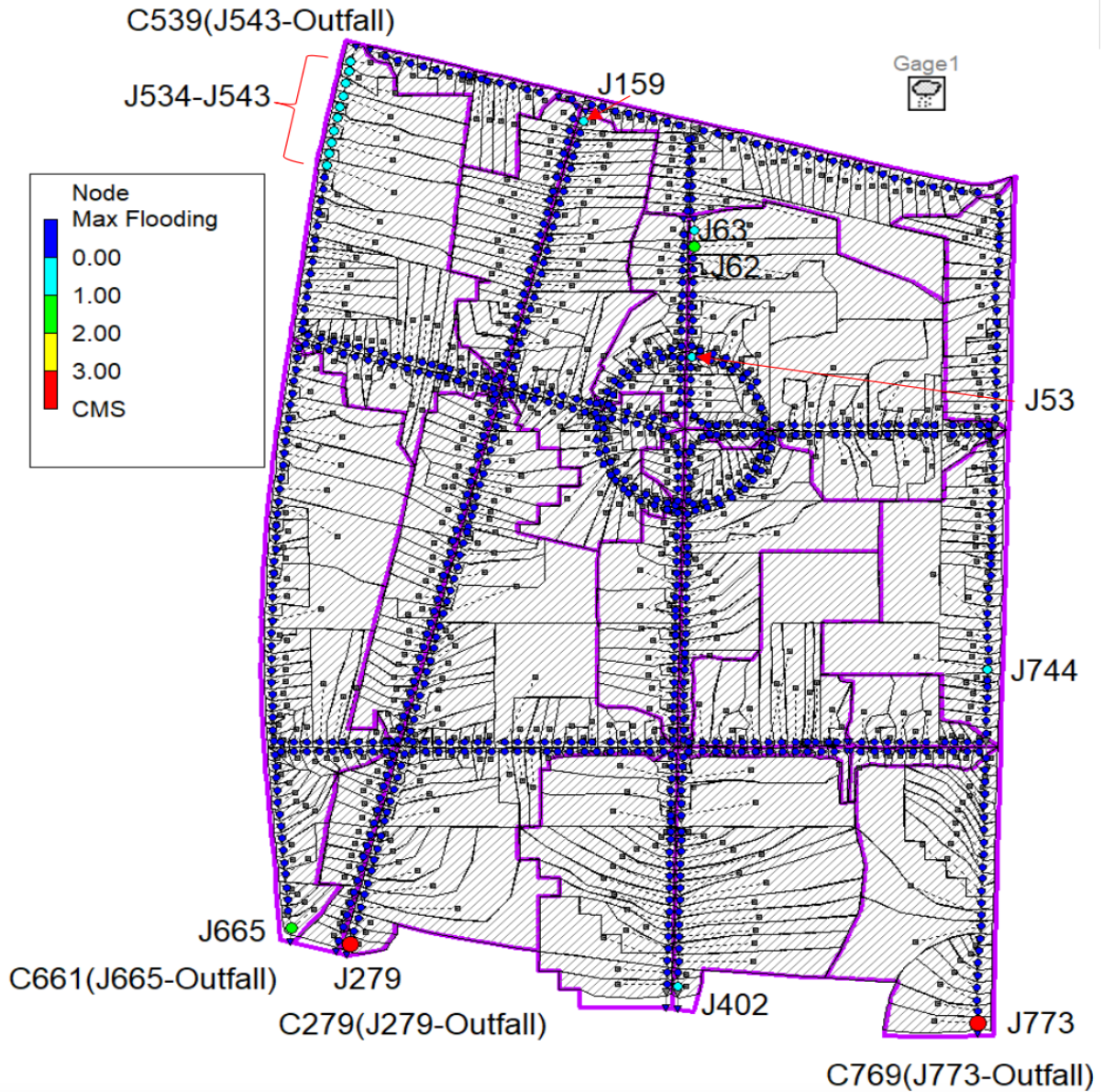


Figure 3: SWMM output map showing critical nodes and pipe spatial locations under SSP2-4.5 Scenario at (2081-2100)

Quantification of Performance Degradation:

The framework was also applied to measure the vulnerability level of the Storm Sewer Network based on the performance indicators: overflow volume, flood duration, and number of flooding nodes. It revealed considerable future challenges, predicting a flooding volume of $19.7 \times 10^3 \text{m}^3$ and number of spots under system stress to rise to 24-spots during high-emission scenarios (see Figure 4). This comprehensive methodological framework offers important insights into the challenges that forthcoming climate conditions will pose to current urban stormwater infrastructure, thereby aiding in proactive urban water management and planning.

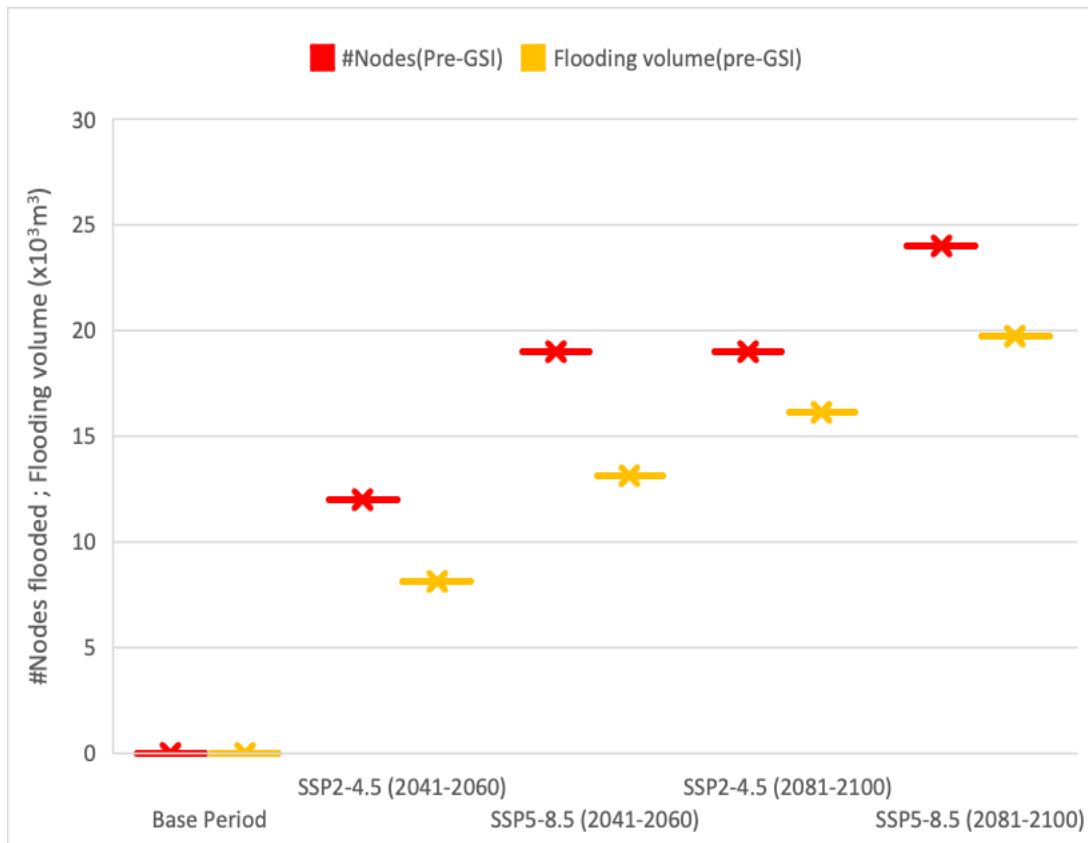


Figure 4: Summary of number of nodes under flooding and flooding volumes across all scenarios.

Thesis 3

I presented and validated a novel decision-support tool that facilitates the integration of green infrastructure (GI) into stormwater planning under the uncertainties of future climate extremes. By employing continuous hydrologic simulation, the tool captures the temporal variability of extreme weather events and allows for scenario-based evaluation of adaptive strategies, including the comparative analysis of with and without GI. The tool could specifically assess and optimize the combined performance of bioretention systems and rain gardens based on land-use suitability, demonstrating their potential to enhance urban stormwater resilience. This research equips planners and decision-makers with a scientifically grounded, forward-looking tool to support sustainable, climate-resilient infrastructure design and optimization. [1, 4, 5, 8]

Application areas of the tool: *Comparative performance analysis like with and without GI or against targeted goal of adaptive strategy under future climate scenarios:*

The tool was employed at Bole-Arabsa storm sewer network to evaluate the improvement in the system operation after integration of bioretention systems and rain gardens in the storm sewer systems. The simulation results have shown a decrease in the number of nodes under flooding by 75% to 90% and total flooding volumes reduction by as much as 86% to 95% across the study case, under late-century, compared to pre-GI scenario (refer to Figure 5). The tool has clearly shown that both bioretention systems and rain gardens exhibited significant capability in mitigating runoff peaks and volumes in response to the heightened rainfall intensities projected for future climate scenarios.

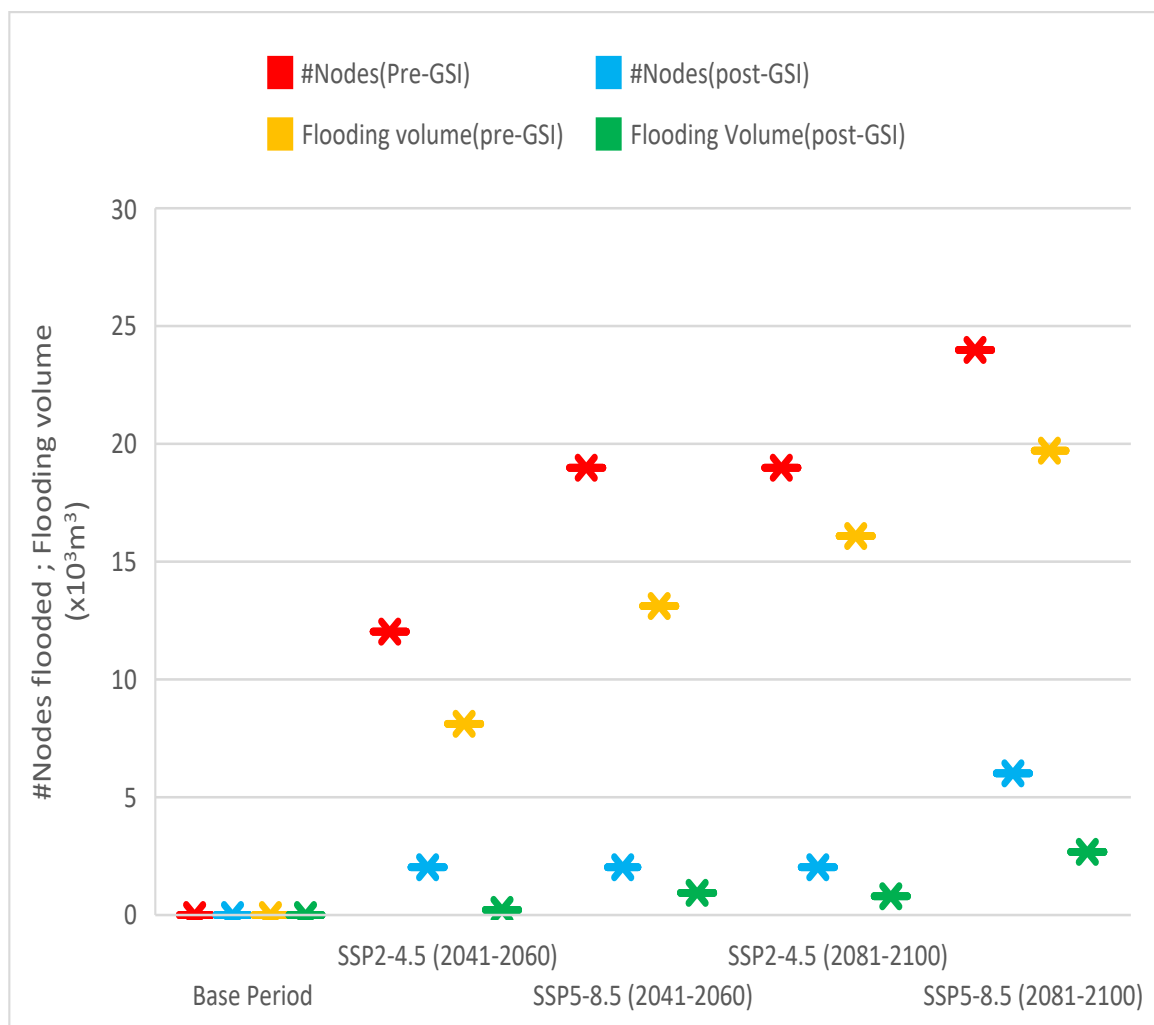


Figure 5: Comparison of number of nodes under flooding and flooding volumes across all scenarios; Pre-GI versus post-GI

Thesis 4

I developed a hydrological modeling framework using the HEC-HMS platform, calibrated and validated with observed rainfall and streamflow data, to simulate runoff dynamics under changing climate conditions. This model was designed to assess the sensitivity of basin hydrological response to future changes in rainfall intensity and to generate reliable runoff estimates at development sites of basins. By incorporating future climate scenarios, the framework provides critical input for climate-resilient infrastructure design, and adaptive water resource planning. The model also quantifies external inflow from rural catchments to urban areas, offering a practical tool for enhancing urban resilience and guiding integrated flood preparedness and water management strategies. [1, 2, 7]

Main Application areas: *Prediction of future flow pattern and sensitivity to climate change*

The model can be applied to analyze alterations in runoff volumes and peak discharges across various projected climate scenarios, emphasizing the risk of potential hydrological extremes. Using the case study, this research examined the seasonal pattern and how hydrological responses of the basin potentially varies in the future scenarios of climatic changes (refer to Figures 6 & 7). The results of the model can serve as input for developing climate-resilient flood mitigation strategies, updating infrastructure designs, and formulating adaptive water resource management plans. The rainfall-runoff model developed can also be utilized for addressing the challenges posed by ungauged sites and the lack of future flow information in light of climate change. This offers valuable insights for future flood preparedness and the planning and management of basin water resources.

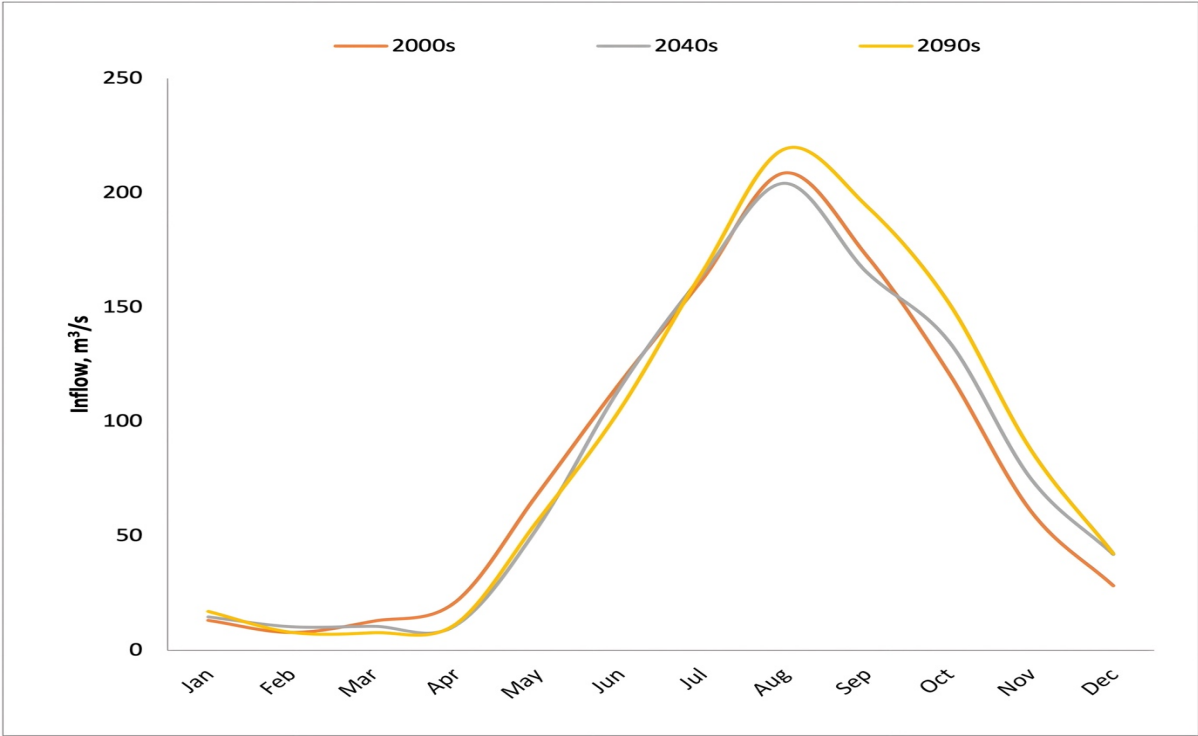


Figure 6: Comparison of flow pattern in the future decades of the 2040s and 2090s against the baseline period.

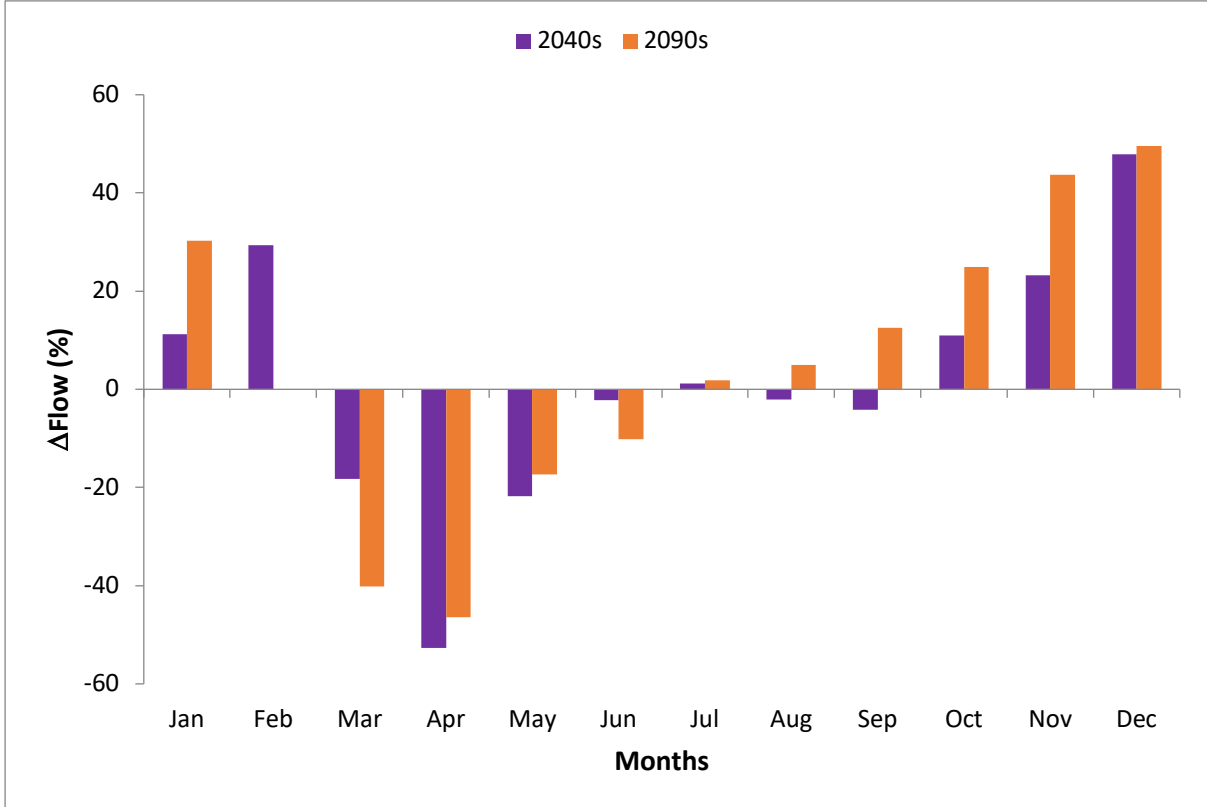


Figure 7: Change in the percentage of flow for future periods compared to the base period.

Thesis 5

To promote locally grounded climate adaptation, I developed a novel methodological framework that integrates a context-sensitive conceptual model for the design, optimization, and strategic placement of bioretention cells and rain gardens. This approach enhances the climate resilience of stormwater sewer systems by offering a flexible, location-specific green infrastructure (GI) framework. I complemented this with a step-by-step guidance tool and design considerations to support planners in aligning GI interventions with local hydrological, spatial, and socio-environmental conditions. Designed for scalability and adaptability, the method can be applied across diverse urban settings and directly contributes to achieving Sustainable Development Goals – particularly SDG 11 (Sustainable Cities) and SDG 13 (Climate Action) – through the advancement of practical, locally tailored resilience strategies. [3, 4, 5, 8]

Application of the Methodological tool:

The framework incorporates different capabilities: site suitability analysis, design optimization and identification of hot spots for GI positioning. The analysis for site suitability was conducted utilizing Geographic Information Systems (GIS), based on factors such as land use, urban planning, and drainage system data. The optimization of GI design and locations was supported by a simulation-based framework of SWMM established in this research. This framework facilitates the strategic placement of GI by identifying flood-prone areas and assessing the efficiency of various sizing scenarios. The primary steps involved in designing bio-retention systems and rain gardens are shown using a methodological flowchart (see Figure 8).

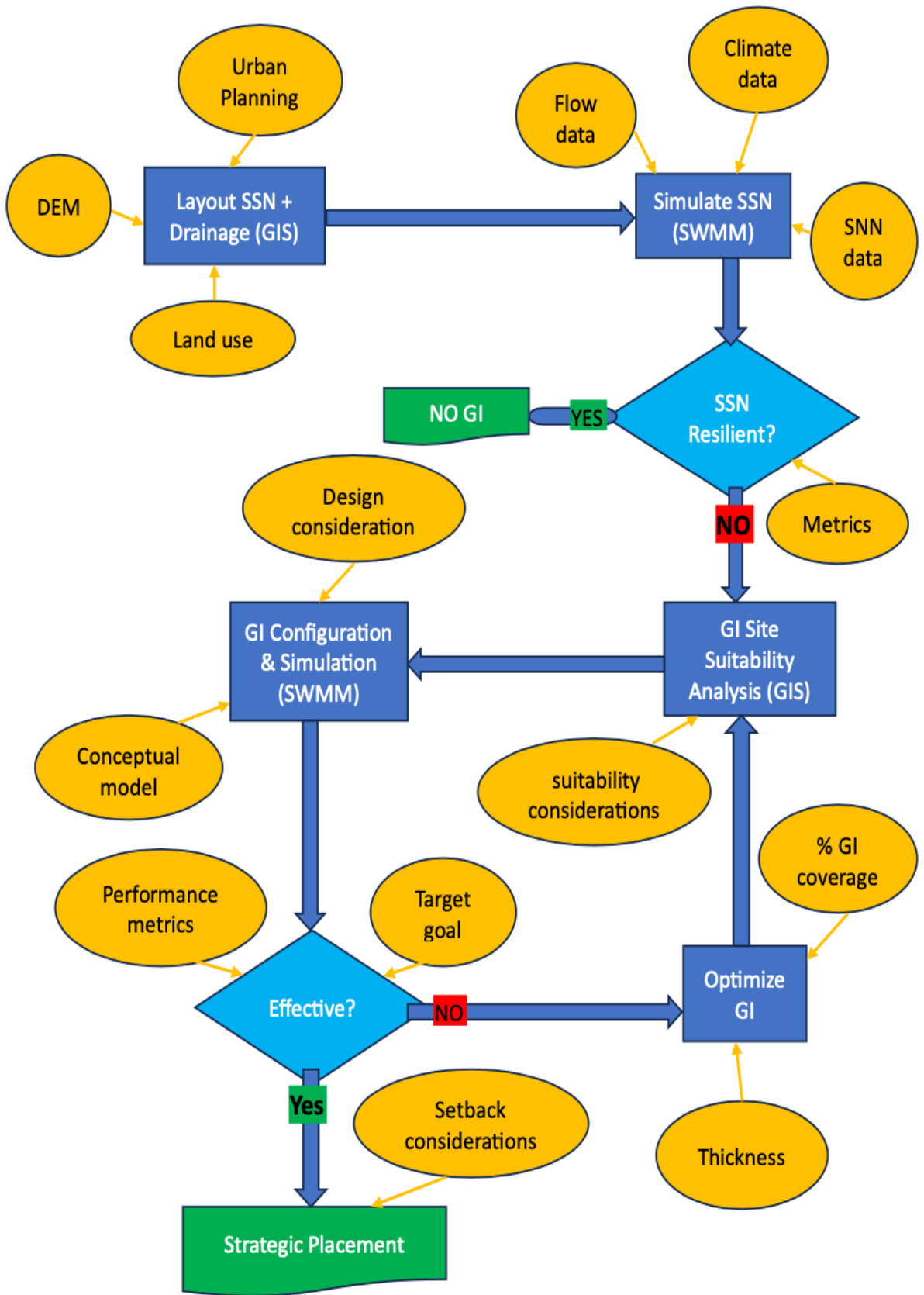


Figure 8: Design flow chart showing the methodological framework.

Conclusions and Future Research Direction:

This research offers significant insights into the potential effects of climate change on urban stormwater systems. The findings demonstrate that climate change, as reflected in expected rainfall trends under shared socioeconomic pathways (SSP), exacerbates the challenges associated with storm sewer flooding and pipe surcharge performance. Simulations using the Storm Water Management Model (SWMM) suggest that current urban stormwater infrastructure is progressively incapable of handling the anticipated increase in precipitation events. The growing number of flooding incidents and pipe surcharging occurrences underscores the vulnerability of urban areas to stormwater-related issues. These insights highlight an urgent need for cities to reassess their stormwater management strategies to enhance resilience against forthcoming climatic challenges.

To mitigate these impacts, it is crucial for urban planners and engineers to adopt the step-by-step methodological tool developed by this research for design and strategic implementation of GI, for effective localized strategies that strengthen the resilience of stormwater systems. By proactively incorporating GI into infrastructure development standards and aligning it with the Sustainable Development Goals (SDGs), cities can improve their defenses against the adverse effects of climate change while ensuring the operational effectiveness of stormwater systems.

The strategic integration of bio-retention systems and rain gardens into stormwater management frameworks has demonstrated notable improvements in both flood control and drainage efficiency. The simulation showed that integration of GI could reduce flooding volume and node flooding by 86% and 75%, respectively, even under the SSP5-8.5 scenario, highlighting the potential of bioretention cells and rain gardens, in enhancing the resilience of urban storm sewer systems to climate change impacts. These results emphasize the promise of locally customized nature-based approaches in fostering sustainable development goals.

However, successful implementation of GI necessitates supportive policies, collaboration across various disciplines, and engagement from stakeholders. This underscores the necessity of incorporating GI solutions into a holistic stormwater management strategy that encompasses hydraulic modeling and community involvement. Therefore, future research should focus on the long-term effectiveness of GI across diverse climate and urbanization scenarios, while integrating policy and socio-economic dimensions of GI.

3.2 Publications connected to thesis

Peer-reviewed journal articles

[1] Muleta, T. N. (2021). Climate change scenario analysis for Baro-Akobo River basin, Southwestern Ethiopia. *Environmental Systems Research*, 10(1). <https://doi.org/10.1186/s40068-021-00225-5>

[2] Muleta, T. N., & Knolmar, M. (2023). Rainfall-Runoff Modeling and Hydrological Responses to the Projected Climate Change for Upper Baro Basin, Ethiopia. *American Journal of Climate Change*, 12(02). <https://doi.org/10.4236/ajcc.2023.122011>

[3] Muleta, T. N., & Knolmar, M. (2025). Ecological impacts of combined sewer overflows on receiving waters. *Discover Water*, 5(1), 24. <https://doi.org/10.1007/s43832-025-00212-2>

Journal articles (Under Peer Review)

[4] Muleta, T. N., & Knolmar, M. (2025). Assessment of Climate Change Impact on the Performance of Storm Sewer Network using SWMM. Submitted to *Journal of Water Resources Management*.

[5] Muleta, T. N., & Knolmar, M. (2025). Green Infrastructure (GI) Performance Assessment for Climate Change Resilience in Storm Sewer Network. Submitted to *Journal of Environmental Management* (2nd revision).

[6] Knolmar, M., & Muleta, T. N. (2025). Vulnerability Assessment of Sewer Networks. Preprint available at DOI: <https://doi.org/10.21203/rs.3.rs-6315652/v1>.

Conference abstracts/Book of Abstracts

[7] Muleta, T. N., & Knolmar, M. (2023). Rainfall-Runoff Modeling and Hydrological Responses to the Projected Climate Change for Upper Baro Basin, Ethiopia. *BOOK OF ABSTRACTS: 1st European GREEN Conference*. ISSN: 2991-5171.

[8] Muleta, T. N., & Knolmar, M. (2025). Green Infrastructure (GI) Performance Assessment for Climate Change Resilience in Stormwater Network. 5th International Conference on Applied Science and Engineering, Netherlands, Amsterdam (accepted).

[9] Muleta, T. N., & Knolmar, M. (2025). Impact of Climate Change on Storm Sewer Performance: A SWMM-Based Assessment. 3rd European GREEN Conference, Vodice, Croatia (accepted).

3.3 Other Publications

[10] Zigale, T. T., Muleta, T. N., & Mohammed, M. J. (2019). Assessment of cause of Huluka micro hydro power scheme failure and estimation of its potential. International journal of research -Granthaalayah, 7(8). <https://doi.org/10.29121/granthaalayah.v7.i8.2019.672>

[11] Babitharani, H., Bharath, A.L., Muleta, T.N., & Pradeep, S. (2019). Use of High-Performance Glass as: A Sustainable Building Material. International Journal of Innovative Research In Technology, 6(2). <https://www.researchgate.net/publication/358461148>