Assessment of Low-Impact Development Practices on Stormwater Management using SWMM 5.2: A Case Study of Shiraz, Iran

By

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Abstract

As the world's population continues to grow and urban areas expand, climate change has become an increasingly urgent challenge. The change in land use due to urbanization can increase surface runoff volume, resulting in urban flooding. Additionally, climate change increases the likelihood of extreme rainfall and inadequate stormwater drainage systems can worsen flood risk. Therefore, the adoption of innovative stormwater management techniques is imperative. Recently, there has been a move towards some approaches such as Low Impact Development (LID) that aims to reduce the strain on stormwater infrastructure. This study aimed to model stormwater management using EPA SWMM 5.2, focusing on a case study of Shiraz, Iran originating from a semi-arid zone watershed. To mitigate the escalating peak stormwater and address the limitations of existing drainage systems, different LID methods have been employed in the study area under 4 different return periods (5, 25, 50, and 100 years). The results underscore that LID methods have resulted in a decrease in flooding volume within the study area across different return periods, ranging from 13.83% to 54.65%. The findings show that the integration of permeable pavements and bioretention cells was highly effective in managing water flow and it approximately decreased watershed total runoff volume by 42% corresponding to all return periods. This research offers insights into tailored stormwater management for rapidly urbanizing areas. Shiraz's successful LID techniques can serve as a model for cities facing similar challenges, enhancing their resilience to urban floods, and promoting sustainable water management amid urban growth and climate change.

Keywords: Urbanization, Climate Change, Stormwater Management, Flood Risk, Low-Impact Development (LID), SWMM

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Thank you all for your invaluable support and guidance.

Achievements and Contributions

This thesis significantly advances the understanding of urban stormwater dynamics in the context of land-use changes and climate variations. The subject, "Urban Stormwater Modeling in the City of Shiraz Based on Land-Use and Climate Change Using EPA SWMM 5.2," has been presented at the PEOPLE 2023 conference in August 2023. This conference provided an invaluable platform for exchanging ideas and insights with fellow researchers and practitioners in the field. This contribution underscores my dedication to exploring innovative solutions for sustainable urban water management.

Additionally, I have been awarded the esteemed title of "Fellow of the School of Graduate Studies," an acknowledgment of my continued academic excellence throughout the program.

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Nomenclature

AOGCM	Atmospheric-Ocean General Circulation Models
BC	Bioretention Cell
BR	Bioretention
CC	Climate Change
CDF	Cumulative Distribution Function
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
GI	Green Infrastructure
GR	Green Roof
IPCC	The Intergovernmental Panel on Climate Change
IT	Infiltration Trenches
LID	Low Impact Development
PP	Permeable Pavement
RB	Rain Barrel
RCP	Representative Concentration Pathway

RG	Rain Garden
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathways
SWMM	Storm Water Management Model
TFV	Total Flooding Volume
TRV	Total Runoff Volume
VS	Vegetative Swales

Chapter 1: Introduction

1.1 Background

In recent years, the increasing trend of flood risk, especially in urban areas with growing populations, is a serious challenge (Hlodversdottir et al., 2015; Jiang et al., 2018). On the one hand, the change in land use due to population growth can increase surface runoff volume, resulting in urban flooding. On the other hand, climate change increases extreme rainfall and inadequate stormwater drainage system can increase flood risk (BECCIU et al., 2015; Bibi, 2022; Mohammed et al., 2021). In the future, flood risk will increase significantly due to the combination of urbanization, land-use, and climate change (Alves et al., 2018; Cohen, 2006).

More than half the world's population lives in urban areas today, and by 2050, this number is expected to rise to 68% (Heilig, 2012). This rapid urbanization has brought about significant challenges, including the escalating threat of urban flooding, which endangers communities, infrastructure, properties, and the environment. The severity of urban flooding has intensified over time, primarily due to the increased surface runoff resulting from changes in land use patterns (Thieken et al., 2016). Furthermore, the rise in flood risk, even in arid regions with limited annual rainfall, can be attributed to the influence of urbanization, as evidenced by numerous studies highlighting its impact on surface runoff (Mahmoud & Gan, 2018).

Through urbanization, natural surfaces are transformed into impermeable surfaces, disrupting natural hydrological processes. Inadequate stormwater drainage systems compound the problem, as they are ill-equipped to handle peak flow rates (Kundzewicz et al., 2014; Nile et al., 2018). As part of the traditional stormwater management strategy, curbs, gutters, and other gray infrastructures were used as well as sewers to transport stormwater quickly and safely. This approach, however, has resulted in lower infiltration rates, decreased times of concentration, higher peak flows, and a shift in water balance from groundwater recharge and storage to surface water runoff in urban areas as impervious surfaces have increased (Konrad & Booth, 2005).

As a growing population swells and cities across the globe continue to expand, the question of how to mitigate flooding presents a formidable challenge. Therefore, the concepts of Green Infrastructure (GI), Low Impact Development (LID), and Sponge Cities are all overlapping, with the goal of mitigating flooding in urban watersheds by retrofitting or integrating infrastructure into new developments (Damodaram et al., 2010; Hettiarachchi et al., 2022).

With GI, urban planning aims to incorporate as much green space as possible and maximize its benefits (Eckart et al., 2017a). A GI is a network of natural and semi-natural features that provide multiple benefits to people and the environment. By capturing and infiltrating rain, GI can reduce stormwater runoff, facilitate ground water recharge, improve watershed health, and mitigate flood damage (Jia et al., 2012).

LID is an approach to land development that seeks to minimize the impact of land use on the environment. LID emphasizes the conservation and use of natural resources as well as integrating engineered stormwater management systems. LID has been shown to be effective in reducing the volume, peak flow rate, and pollutant load of stormwater runoff from developed land (Chen et al., 2016; Damodaram et al., 2010).

Sponge Cities is an urban development concept that focuses on managing and utilizing rainwater as a valuable resource rather than treating it as a nuisance. Sponge Cities is a term commonly used in China to describe cities that aim to "absorb" and "hold" rainwater like a sponge. This concept is also known as "Water Elastic City", a new concept for managing urban stormwater. It is a response to the challenges of rapid urbanization, increasing urban flooding, and water scarcity. Water resource management is improved through a comprehensive approach to sponge cities by reducing stormwater runoff, enhancing infiltration, and reducing runoff (Cai et al., 2023; Guan et al., 2021; Qiao et al., 2020).

All these methods aim to address the challenges of urbanization and climate change by integrating water management strategies into urban planning and design.

1.2 Problem Statement

Climate change exacerbates the challenges faced by stormwater management systems due to urbanization. The increasing prevalence of impervious surfaces, such as roads, parking lots, and roofs, hampers water infiltration and leads to heightened surface runoff during heavy rainfall events. Inadequate stormwater infrastructure compounds these issues, resulting in flooding and associated risks. Moreover, climate change indicates a rise in extreme rainfall events, intensifying the problem even further.

To address these complex challenges, innovative stormwater management approaches are required. GI has emerged as a promising solution to mitigate stormwater hazards. This approach aims to reduce surface runoff volumes, and enhance infiltration, thereby alleviating flooding problems.

In this context, the research focuses on the case study of Shiraz, Iran, a city grappling with the impacts of urbanization and climate change on its stormwater management system. Shiraz's aging infrastructure, designed for lower intensity rainfall events, struggles to cope with the changing climate patterns that have brought about increased frequency and intensity of extreme weather events, leading to flooding and adverse consequences. Additionally, rapid urbanization has altered land use and increased impervious surfaces, exacerbating runoff and flooding risks.

The research objectives aim to evaluate the effectiveness of LID techniques, specifically bioretention cells and Permeable Pavements, in reducing stormwater hazards in Shiraz. By utilizing Storm Water Management Model (SWMM) software, the study will assess the current stormwater management system's limitations in mitigating the impacts of urbanization and climate change-induced extreme rainfall events. It will also analyze the economic and environmental benefits of LID techniques compared to traditional gray infrastructure practices. The findings will provide recommendations and guidelines for implementing infrastructure in Shiraz and other cities facing similar challenges.

Through this research, a comprehensive understanding of the effectiveness and potential of LID in mitigating the negative impacts of urbanization and climate change on stormwater management will be gained. The study's insights will contribute to the development of more effective stormwater management strategies, enhancing the resilience of urban areas in the face of climate change and urbanization pressures.

1.3 Research Objectives

The objective of this study is to assess the effectiveness of LID techniques in mitigating the peak runoff and flooding volumes in the City of Shiraz, Iran under different return periods. By utilizing SWMM 5.2 software, the current stormwater management system in Shiraz will be evaluated, considering its limitations in addressing the challenges posed by urbanization and climate change-induced extreme rainfall events. The findings will highlight the potential benefits of LID approaches in reducing peak stormwater runoff and mitigating flooding problems in Shiraz, while comparing their performance to traditional gray infrastructure stormwater management practices. This research aims to contribute to the development of sustainable and climate-resilient stormwater management strategies, specifically tailored to the unique conditions and challenges faced in Shiraz.

It is expected that climate change will increase the frequency and severity of extreme rainfall events. This, combined with rapid urbanization and the expansion of impermeable surfaces, is likely to lead to higher volumes of stormwater runoff. This will put additional strain on the already burdened stormwater infrastructure, potentially leading to higher flood risks. By implementing LID techniques, which focus on enhancing infiltration, retention, and natural drainage processes, the existing stormwater system can be better equipped to handle the challenges posed by climate change. By providing recommendations and guidelines for the implementation of LID techniques or green infrastructure, this research intends to assist not only Shiraz but also other cities facing similar challenges in effectively managing stormwater and adapting to climate change impacts.

1.4 Thesis Organization and Layout

The thesis is structured into five chapters to provide a comprehensive examination of the research on urban stormwater management. The organization and layout of the thesis are as follows:

- Chapter 1: Introduction

In this chapter, the background of the research topic is presented, highlighting the significance of urban stormwater management. The problem statement identifies the challenges and issues related to stormwater management in urban areas. The research objectives are outlined, focusing on the evaluation of low-impact development techniques in mitigating stormwater issues.

- Chapter 2: Literature Review

This chapter provides an overview of relevant concepts, including climate change and stormwater management. It reviews previous studies on urban stormwater management, examining existing research and identifying gaps in the literature that necessitate the current study.

- Chapter 3: Materials and Methods

The materials and methods chapter explains the SWMM modeling approach and the assumptions made in the study. It describes the study area and the sources of data used. The development of the stormwater model and the data employed in the analysis are discussed. The implementation of specific low-impact development techniques, such as bioretention cells and permeable pavements, in the SWMM model is explained. Additionally, the incorporation of green infrastructure practices in the stormwater management approach is explored. The simulation of rainfall events using SWMM is also described.

- Chapter 4: Results and Discussion

This chapter presents the simulation results and combines the analysis and discussion of the findings. It compares and analyzes the results in relation to the objectives of the study, explores their implications for urban stormwater management. The performance of different stormwater management techniques, in reducing peak runoff and mitigating flooding problems is assessed. The effectiveness and limitations of these techniques are discussed, providing insights into their performance and potential for broader application.

- Chapter 5: Conclusion and Recommendations

The conclusion and recommendations chapter interprets the results in relation to the research questions and objectives. It draws conclusions from the study and discusses their implications for urban stormwater management in Shiraz or similar cities and highlights the limitations of the study and suggests future research. The chapter summarizes the study and its findings with recommendations for future research and practice in optimizing stormwater management strategies, implementing effective low-impact development approaches, and integrating green infrastructure into urban planning and design.

Chapter 2: Literature Review

2.1 Overview of Relevant Concepts

2.1.1 Climate Change

Since the advent of the Industrial Revolution in the late 1700s and early 1800s, there has been a substantial release of greenhouse gases into the atmosphere, with a significant surge occurring in the past century. From 1970 to 2004, greenhouse gas emissions witnessed a staggering increase of 70%, with carbon dioxide, the primary greenhouse gas, experiencing an approximately 80% rise during this period. Presently, the levels of carbon dioxide in the atmosphere far surpass the natural range observed over the past 650,000 years (IPCC, 2014).

A lot of evidence shows that humans are the main culprit of the ever-increasing CO_2 emissions that can increase the Earth's temperature. The majority of CO_2 emissions released into the atmosphere originate from the combustion of fossil fuels, including oil, coal, and natural gas. Various modes of transportation such as cars, trucks, trains, and planes rely on fossil fuels for energy. Land use change and fossil fuel burning are some human primary activities that can affect this serious problem. According to The Intergovernmental Panel on Climate Change (IPCC)'s 2018 analysis of current emissions rates, global warming is expected to reach 1.5°C sometime between 2030 and 2052 at current emission rates (IPCC, 2022). Carbon cycling is disrupted, and greenhouse effects increase by humans, however, it is possible to restore some sort of balance to the atmosphere in the future by significant increases in the output of carbon from the atmosphere (Burch & Harris, 2021).

Precipitation intensity and frequency can be affected by climate change. Evaporation will increase as temperatures rise, intensifying the Earth's water cycle. Moisture-rich air can move over land or converge in a storm and increase precipitation. Heavy precipitation doesn't necessarily mean that there is more precipitation in each area - it occurs only during extreme weather events. Total precipitation, however, can change as a result of changes in precipitation intensity and the interval between events (USGCRP, 2017).

2.1.1.1 The Effects of Climate Change on Semi-Arid Area

A semi-arid climate is a transitional climate zone between arid (desert) and humid climates. These regions are defined by an average annual rainfall ranging from 200 to 700 mm (Gallart et al., 2002; Kottek et al., 2006). Semiarid landscapes have an aridity index between 0.20 and 0.50, which refers to the ratio of annual precipitation to potential evapotranspiration (Lal, 2004). The precipitation in these areas tends to be sporadic and concentrated within specific seasons, often characterized by intense storms occurring at irregular intervals. Rainfall may be highly variable and unevenly distributed throughout the year, leading to a high degree of variability in precipitation patterns in space and time. The climates generally experience hot summers and mild to cool winters. Daily temperature variations can be significant, with hot days and cooler nights. The temperature range between day and night can sometimes exceed 20°C (36°F). Due to the limited water availability, vegetation in semi-arid regions is typically sparse and adapted to drought conditions (Grimmond, 2007; Petralli et al., 2014). Drought-resistant shrubs, grasses, and xerophytic (drought-tolerant) plants are commonly found (D'Odorico & Porporato, 2006).

Climate change can have significant impacts on semi-arid regions like Shiraz. It is leading to rising global temperatures, which can exacerbate the already hot conditions in semi-arid areas (Figure 1). This can further exacerbate water scarcity and drought conditions. Climate change can also disrupt precipitation patterns, leading to changes in the timing, intensity, and distribution of rainfall. Semi-arid regions may experience reduced overall precipitation or increased variability in rainfall, resulting in more frequent and severe droughts and prolonged dry periods (Azhdari et al., 2018).

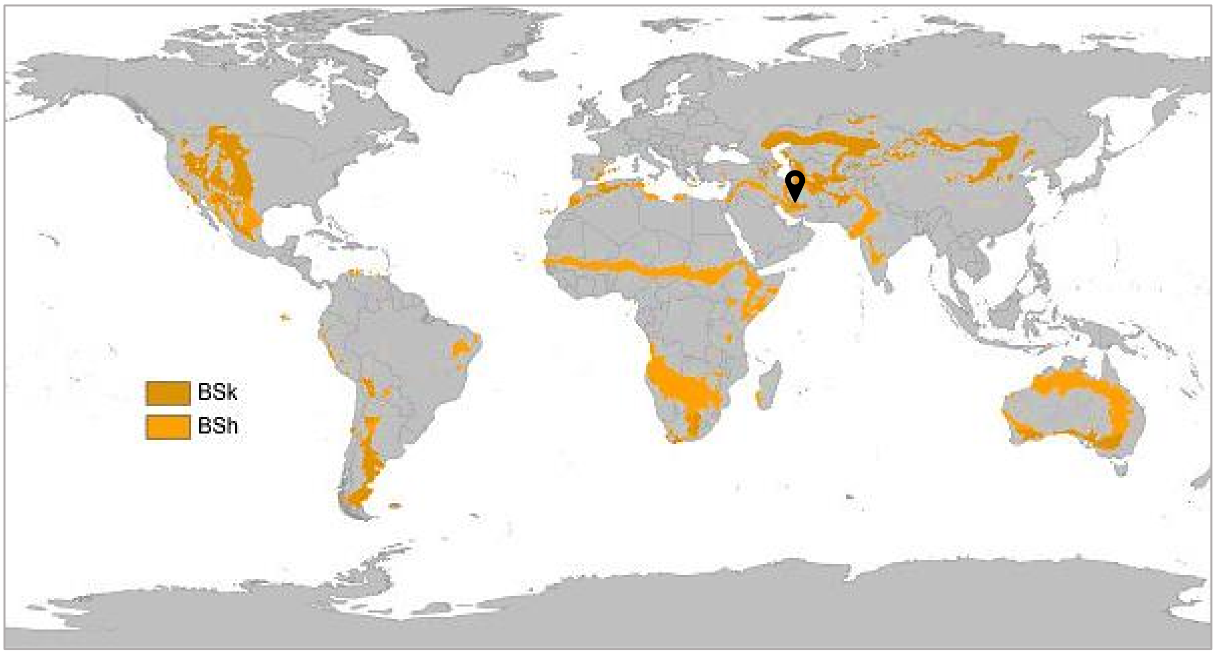

Figure 1. Climate classification of hot (BSh) and cold (BSk) semiarid regions (Kottek et al., 2006).

Climate change has significant implications for groundwater resources, especially in arid regions where surface water is scarce. It directly impacts the global hydrological cycle and the quantity and quality of groundwater by causing rising temperatures, altered precipitation patterns, and more frequent flooding and droughts. These changes affect evaporation rates, rainfall patterns, and water storage in surface and subsurface reservoirs, such as lakes, rivers, and groundwater storage. Furthermore, climate change contributes to issues such as groundwater contamination, seawater intrusion, and water scarcity. Adaptation strategies based on global climate models are essential to addressing the impact of climate change on groundwater resources. A sustainable water management strategy in semi-arid regions requires an understanding of climate change's impact on groundwater resources (Deshmukh et al., 2022).

Moreover, land-use changes in semiarid regions, such as agricultural activities and the abandonment of croplands, can have significant implications for both the natural environment and infrastructure. These changes often contribute to the formation of erosion features like rills, gullies, shallow debris flows, and small landslides, which can pose risks to infrastructure systems. Additionally, coupled with variations in rainfall characteristics, such as an increase in rainfall intensity compared to overall precipitation, the vulnerability of badland landscapes to degradation is heightened. Therefore, effective land-use management practices and infrastructure planning are crucial in semiarid areas to minimize erosion, preserve ecological stability, and ensure the resilience of infrastructure systems in the face of changing conditions (Bagheri & Tousi, 2018; Piccarreta et al., 2006; Poesen et al., 2002).

2.1.2 Stormwater Management

Stormwater refers to rainwater and meltwater from hail and snow that typically runs off streets and other land surfaces. However, it's important to note that snow also acts as a form of water storage within a watershed and can contribute to increased runoff during rainfall events when the snow melts. In contrast to natural landscapes where stormwater can infiltrate the soil, on hard lands such as pavements, sidewalks, or driveways, it cannot be absorbed by the soil. So, it can dramatically affect the environment. The runoff which has not been soaked into the ground can carry harmful pollutants such as oil, pesticide, or bacteria and flow into storm drains, municipal sewers or streams, and rivers. In addition, a high level of runoff, in particular, could result in flooding, altered stream flows, erosion, compromised water quality, and threats to aquatic habitats (Easterling et al., 2012).

Managing stormwater refers to managing the flow of water during and after precipitation events. A stormwater management plan aims to reduce the negative impact of stormwater runoff on the environment and human health by designing and implementing strategies that mitigate those impacts. Stormwater management prevents flooding and erosion by moving stormwater into detention basins, retention ponds, or other types of storage facilities to prevent flooding and erosion. Taking these measures helps protect infrastructure, property, and the environment from damage (Eckart et al., 2017b).

Water quality is also protected by stormwater management. Pollutants like oil, sediment, and chemicals can be carried into local waterways by stormwater runoff, which can harm aquatic ecosystems and humans. Using stormwater management techniques such as low-impact development and green infrastructure can reduce the amount of pollutants entering our waterways (Liu et al., 2015). These approaches increase groundwater recharge, use of rainwater, and improve on-site water balance, while reducing downstream flooding (Chen et al., 2016).

A well-designed drainage system that can efficiently collect and manage stormwater is essential to mitigate the dangers posed by flooding in urban areas. However, as a result of climate change and rapid urbanization, urban areas may face a strain on drainage systems. Several consequences can result from this strain, including flooding, extensive infrastructure damage, reductions in social and economic services, and increased human vulnerability (Afrin et al., 2021; Bibi et al., 2023).

In recent decades, urban areas have experienced significant alterations due to the increase in impervious surfaces such as roads and buildings, leading to a decline in the presence of water bodies and vegetation. The implementation of green infrastructure can provide a sustainable solution to address the strain on drainage systems caused by climate change and rapid urbanization, effectively reducing flooding risks and enhancing urban resilience (Fletcher et al., 2015; Xu et al., 2023).

2.1.3 Stormwater Management Practices

2.1.3.1 Green Infrastructure

GI refers to a network of natural and semi-natural elements, strategically planned and managed, that provide multiple ecological, economic, and social benefits within an urban or built environment. GI utilizes natural processes and ecosystem services to manage stormwater, improve air and water quality, mitigate heat island effects, enhance biodiversity, support wildlife habitats, promote human health and well-being, and enhance the overall resilience and sustainability of urban areas (Benedict et al., 2012; Grabowski et al., 2022; Neighborhood Technology, 2010). In addition to water management, the value of GI depends on the ability of a community to model and measure its additional values beyond its water management effects (Moore, 2011).

In a study commissioned by the City of Toronto, Canada, demonstrated that GI reduces rainwater runoff, energy consumption, urban heat island effect, emissions and improve air quality (Banting et al., 2005). Therefore, human well-being and ecological health can be enhanced by the design and management of natural systems, as GI recognizes (Fletcher et al., 2015).

GI also implemented as a decentralized approach to stormwater management can have positive impacts on social equity by providing equitable access to green spaces, improving public health, creating economic opportunities, fostering community engagement and empowerment, and enhancing climate resilience in historically marginalized neighborhoods. Some of these impacts are summarized in Figure 2, highlighting the multi-dimensional benefits of green infrastructure on social well-being and equity (EPA, 2017).

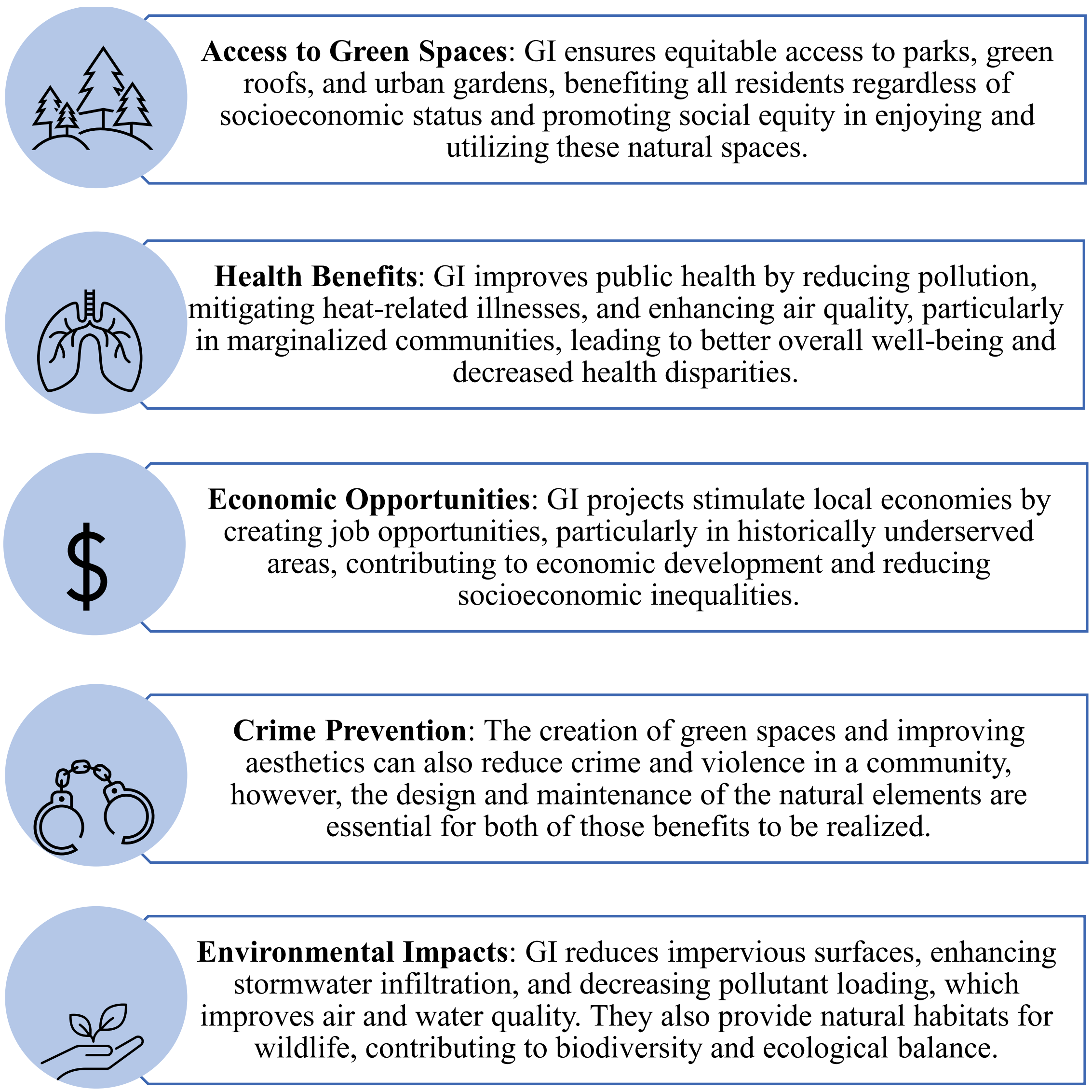

Figure 2. Benefits of Green Infrastructure in Communities

(EPA, 2017)

2.1.3.2 Low Impact Development (LID)

LID is considered a type of GI that refers to a range of innovative and sustainable stormwater management practices and techniques. It is specifically designed to address the adverse impacts of urbanization on the natural hydrological cycle. LID aims to minimize stormwater runoff, improve water quality, and enhance the overall sustainability of urban areas (Guan et al., 2015; Kong et al., 2017; Line et al., 2012).

LID was originally conceived by the Environmental Resources department of Prince George's County in the early 1990s, but the term was first used in a study by Barlow et al. in 1977 to reduce stormwater management costs (Barlow et al., 1977). The main objective of LID is to control stormwater quantity and quality, treat runoff close to its source, promote natural hydrological processes, and provide ecological benefits (Eckart et al., 2017a). Rain barrel (RB) or cistern, green roofs (GR), bioretention cell (BC) or bioretention (BR), rain gardens (RG), permeable pavement (PP), vegetative swales (VS), infiltration trenches (IT), infiltration basins (IB), rooftop downspout disconnection, and tree box filters are examples of LID techniques. These practices aim to manage stormwater runoff in a sustainable and environmentally friendly manner by promoting infiltration, evapotranspiration, and pollutant removal, among other benefits. Specifically, the study will examine bioretention cells and permeable pavement, which offer more advantages for managing stormwater runoff. The following discussion will explore the principles, design, and benefits of these two approaches.

LID practices promote the infiltration and detention of stormwater runoff as a strategy for urban flood control. LID practices, for example, BR and PP, have been used as viable solutions for reclaiming large volumes of runoff. In an impervious area such as a parking lot, a rooftop, or a street, a BC is designed to capture and retain runoff. The runoff is directed to the cell, where it is filtered through a layer of mulch, soil, and vegetation. The vegetation within the cell, such as grasses, shrubs, and trees, absorbs and metabolizes the nutrients and pollutants in the runoff, reducing their concentrations and removing them from the water (Sirova, 2015).

By incorporating climate change considerations, stakeholders gain insight into sustainable urban development. LID alternatives, with a nature-based approach, reduce runoff volumes, peak flow rates, and pollutants, offering a comprehensive and sustainable approach. Utilizing LID as a retrofit in urban stormwater infrastructure can alleviate strain and promote climate change adaptation (Ahiablame et al., 2013; Eckart et al., 2017a).

In many studies, different parameters were considered to evaluate how effective LID is at mitigating flood hazards in urban areas. Ahiablame & Shakya (2016) reported that the implementation of the three LID practices at different levels led to a runoff reduction ranging from 3% to 47% in the study watershed (Ahiablame & Shakya, 2016a). Zahmatkesh et al. (2015) found that by implementing LID controls, a 41% reduction in runoff volume was achieved (Zahmatkesh et al., 2015).

One of the most commonly used LID techniques is the BC. Stormwater runoff from impervious surfaces such as roads, parking lots, and rooftops can be captured and treated by a bioretention cell. A BR system is a purposefully designed depression in the landscape that effectively manages stormwater runoff from impervious surfaces. It is typically composed of multiple layers, including a media layer consisting of sand, soil, and organic matter for runoff treatment, a surface mulch layer, various types of vegetation, and a storage pool with a depth of 15 to 30 cm. The primary objective of bioretention systems is to mimic the natural hydrologic cycle by retaining and treating runoff, thereby reducing flow rates and volumes. Alongside this primary function, bioretention systems offer additional benefits such as enhancing the aesthetic appeal of the surrounding neighborhood, providing habitat for wildlife, preventing soil erosion, and recharging groundwater, which in turn enhances base flows in local streams (Shafique & Kim, 2016; Sirova, 2015).

The process within a bioretention cell involves the infiltration of incoming runoff through the media layers, with excess water discharged through underdrain pipes. Water can also be lost through exfiltration and evapotranspiration. Exfiltration refers to the drainage system losing water as it percolates or gets absorbed into the existing soil. Vegetation present in the bioretention cell plays a role in water and nutrient uptake from the media. If the media becomes saturated, overflow may occur, resulting in temporary ponding until the water level reaches a predetermined control elevation, at which point it begins to discharge (Davis et al., 2009; Eckart et al., 2017a; Garcia-Cuerva et al., 2018; Liu & Fassman-Beck, 2017).

As stormwater flows through each level of the bioretention system, it undergoes sequential filtration, with the media layer playing a crucial role in primary filtration. This process effectively filters and treats debris, particles, sediments, and pollutants present in the runoff, ensuring cleaner water before its discharge into stormwater conveyance systems or receiving waters. The presence of vegetated surface layers helps to slow down the velocity of runoff and trap sediment. Within a bioretention cell, various unit processes leverage the chemical, biological, and physical properties of plants, microbes, and soils to effectively remove pollutants from urban runoff. These systems have demonstrated their ability to reduce peak flows, volume of runoff, and pollutant loads while promoting evapotranspiration through vegetation uptake and increasing lag time. Figure 3 provides an example of a field-scale bioretention cell, showcasing the practical application of these systems (Fassman-Beck & Saleh, 2021; Lisenbee et al., 2022; Liu et al., 2014).

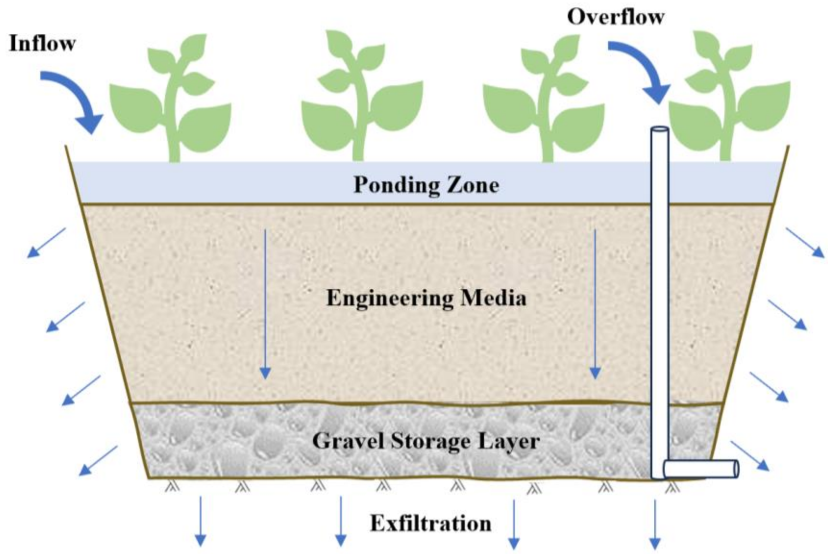

Figure 3. Bioretention facility and its hydraulic pattern
(Fassman-Beck & Saleh, 2021; J. Liu et al., 2014).

PP characterized by its porous surface layer and underlying open-graded aggregate, serves as a type of LID that effectively mitigates the negative impacts of roads and parking lots on urban water systems. By allowing water to infiltrate through its permeable surface, this innovative pavement solution helps alleviate the adverse effects associated with stormwater runoff and the urban water cycle (Brattebo & Booth, 2003). It offers a promising solution to reduce the adverse effects of urbanization on hydrological processes.

The studies have shown the effectiveness of permeable pavement in enhancing infiltration and reducing runoff volumes, thus alleviating the risks of flooding and water pollution. Andersen et al. (1999) investigated the hydrological performance of permeable pavements in the UK. The results highlighted the significant influence of bedding material particle size distribution and water retention in the surface blocks on evaporation, drainage, and retention within the structures. On average, 55% of a one-hour, 15 mm/h rainfall event could be retained by a dry structure, while a wet structure could store 30% of the same rainfall event with a minimum time interval of 72 hours between rainfall applications (Andersen et al., 1999). As a result, permeable pavements significantly reduced peak flows and delayed the time of concentration during storm events.

The PP system exhibits high infiltration rates, effectively capturing and treating stormwater runoff, while also providing an aesthetically pleasing and durable surface. The studies underscore the potential of permeable pavement as an effective LID strategy for managing urban stormwater and highlights its valuable contribution to sustainable urban development (Andersen et al., 1999).

PPs are designed to allow rainwater to infiltrate through the surface and bedding layers. These systems consist of concrete blocks or pavers with open joints that facilitate water infiltrartion. When rain falls on the pavement, it can be trapped on the surface or absorbed by the pavement layer. The remaining water either infiltrates downward into a stone reservoir or flows as surface runoff. The high permeability of the pavement layers reduces surface runoff, while the stone reservoir temporarily stores excess water during heavy rainfall. The stored water eventually infiltrates into the underlying subsoil (Figure 4). PP offer an eco-friendly solution for managing stormwater, promoting infiltration, reducing runoff, and mitigating the risks of urban flooding.

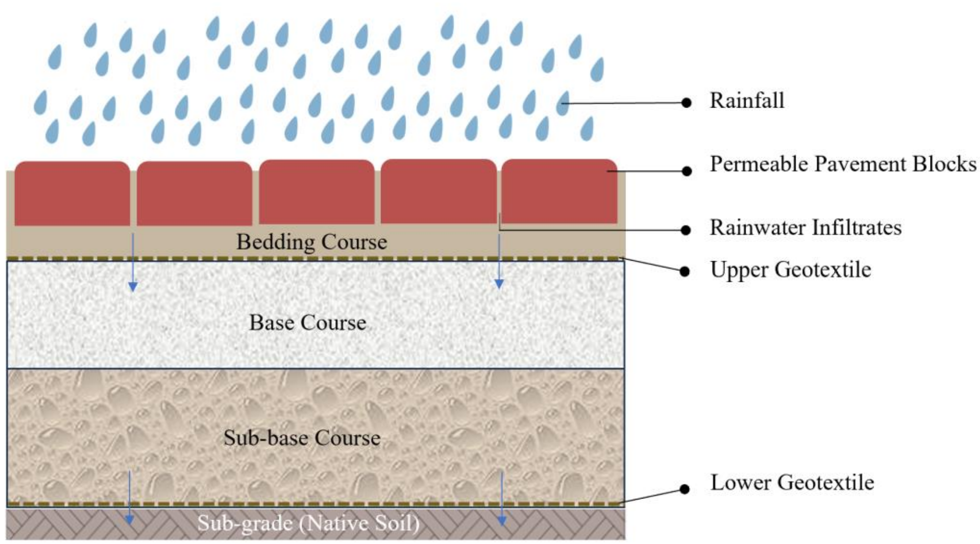

Figure 4. Schematic diagram of a typical permeable pavement
(Shafique et al., 2018)

This thesis assesses LID techniques' efficacy in mitigating urban flooding using SWMM for two-dimensional simulations under different return periods and LID implementations.

2.1.3.3 LIDs in Semi-Arid area

Sustainable drainage systems techniques can manage stormwater runoff in semi-arid areas. This can involve constructing features like PPs or BCs. These features help slow down and infiltrate stormwater, replenishing groundwater and reducing the risk of flash floods while promoting groundwater recharge.

LID methods can be an excellent approach for stormwater management in semi-arid areas like Shiraz. LID focuses on managing stormwater runoff at its source through decentralized, nature-based techniques. Utilize permeable or porous pavement materials for roads, parking lots, and walkways, allow rainwater to infiltrate through the surface, reducing runoff and promoting groundwater recharge. Permeable pavements can help mitigate flooding, improve water quality by filtering pollutants, and conserve water resources. LID techniques significantly reduce the volume of runoff generated during rain events. This helps prevent excessive runoff from overwhelming stormwater drainage systems and downstream water bodies.

These techniques enable rainwater to penetrate the ground, replenishing groundwater reserves. By increasing infiltration, LID methods help maintain higher soil moisture levels, which can mitigate drought conditions and improve water availability for vegetation.

LID techniques help attenuate peak flows during storms. Instead of water rapidly rushing off impervious surfaces and causing flash floods, LID practices slow down the flow of stormwater. By implementing features like Bioretention cells, LID methods allow for the controlled storage and gradual release of excess stormwater during heavy rain events. This helps alleviate the burden on downstream infrastructure, reduces the risk of flooding in low-lying areas, and protects communities and properties from flood damage.

LID techniques contribute to building climate resilience in semi-arid areas. As climate change brings more intense rainfall events and increased variability in precipitation patterns, LID methods help manage the excess water efficiently. By promoting infiltration, reducing runoff, and improving stormwater management, LID practices enhance the adaptability of urban areas to changing climate conditions and minimize the impact of extreme weather events. By incorporating new methods into stormwater management plans, Shiraz can reduce the impact of urbanization, enhance water sustainability, and improve the overall resilience of the city to climate change impacts.

2.2 Review of previous studies on LIDs

Zahmatkesh et.al (2015) examined the impact of climate change on urban stormwater runoff in the Bronx River watershed, New York City, and explore the potential of LID controls to mitigate these effects. Using climate change projections based on the Coupled Model Intercomparison Project Phase 5 (CMIP5), the simulations indicate an increase in the frequency and intensity of extreme storm events under future climate conditions. However, implementing LID controls such as rainwater harvesting, porous pavement, and bioretention significantly reduced annual runoff volume by an average of 41% and decreased peak flow rates by 8 to 13% (Zahmatkesh et al., 2015). Additionally, LID measures resulted in a decrease in watershed runoff for different return periods, showing promise in managing stormwater runoff and addressing the impacts of climate change on urban areas (Zahmatkesh et al., 2015).

Zhou et al. (2019) evaluated the effect of climate change and urban development on flood volume and runoff. Zhou et al. noted that urban drainage systems play an important role in dealing with changing flood risks in cities. According to their study, by developing urban areas and increasing land use, the runoff volume would increase between 208 to 413% (Zhou et al., 2019).

Zhou et al. (2010) showed that due to the excessive expansion of urban areas and weakness in the drainage system, they faced the greatest risk of flooding. Urbanization has been identified as a contributing factor to an increase in annual surface runoff. However, the extent of changes in urban flood volumes can vary significantly depending on the effectiveness of the drainage system implemented during urban development. Notably, the changes in expected annual flood volumes resulting from urbanization far exceed the effects caused by climate change. For effective management and adaptation to urban floods, which are influenced by local and large-scale changes induced by urbanization and climate change, it is crucial to reevaluate both current and future urban drainage systems (Zhou et al., 2019).

Bibi (2022) showed that the impervious areas in the town increased by about 44% from 2010 to 2030 and as a result, the flooding volume experienced an increase of about 67%. The study revealed that climate change and the expansion of impervious surfaces have contributed to a notable rise in runoff and flooding volumes within the investigated region. This indicates that the existing drainage systems were overwhelmed by the volume of water exceeding their design capacity, emphasizing the need for proactive measures to address the combined impacts of land-use changes and climate change. To mitigate the adverse effects, three environmentally sustainable low-impact development strategies, namely BR, PP, and a hybrid approach combining both techniques, were implemented. The results showed that the implementation of these approaches yielded a significant reduction in peak stormwater levels, effectively addressing the challenges posed by increased flooding events (Bibi, 2022).

Comparing the result of two studies in two different locations shows a large increase in total runoff volume during each period (Figure 5). Considering a return period of 10 years, Zhou et al. (2019) & Bibi (2022) experienced about 43% (from 2010 to 2018) and 38% (from 2010 to 2020) increase in the total inflow volume in response to significant changes in land use including urbanization and cover types (Zhou et al., 2019 & Bibi, 2022).

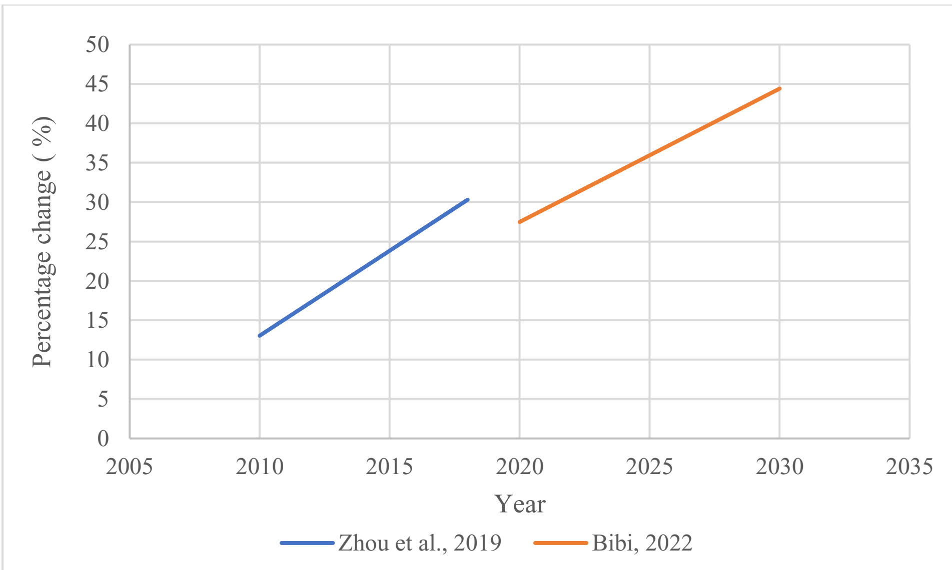

Figure 5. Comparison of total inflow volume for 2 studies with a 10-year return period (Bibi, 2022; Zhou et al., 2019)

Moreover, with increasing urbanization, flooding frequency has also increased at varying return periods. Due to the sensitivity of low-return period floods to urbanization compared to extreme floods at high-return periods (e.g., 50 or 100 years), flood events at low-return periods increased with urbanization more rapidly than at higher return periods (Akhter & Hewa, 2016). The implications for stormwater management in the face of increasing urbanization and the subsequent rise in flooding frequency at varying return periods are significant. As urban areas expand, the vulnerability of low-return period floods to urbanization becomes apparent, with these events showing a more rapid increase compared to extreme floods at higher return periods. The intensified urban development leads to a higher concentration of impervious surfaces, obstructing natural infiltration and amplifying surface runoff during rainfall events. To address these challenges, effective stormwater management strategies are crucial. Integrating sustainable drainage systems and adopting urban planning practices that prioritize natural water retention and the creation of green spaces can enhance resilience in stormwater management, promoting sustainable and adaptive approaches to mitigate flood hazards in urban areas. By embracing these measures, communities can better manage stormwater runoff, reduce flood risks, and foster more sustainable and resilient urban environments.

When the different drivers such as the increase in land use or climate change are combined, they affect runoff volume much more destructively. Marhaento et al. (2018) investigated that combining different climate and land use scenarios can increase the mean annual runoff from +21% to +102%, which is 60% more than acting alone (Marhaento et al., 2018).

Omar Abdul-Aziz et al. (2016) developed a rainfall-runoff model and investigated the sensitivity of stormwater runoff and quality to hydro-climatic and land use. The study developed a rainfall-runoff model using EPA SWMM 5.0 for the Miami River Basin of Florida to investigate the sensitivities of potential stormwater runoff and quality to changes in hydro-climatic and land use/cover. The results showed that potential storm runoff in the complex urban basin exhibited high seasonal sensitivities to rainfall, with stronger responses in the drier early winter months and wetter late summer months. Changes in the number, depth, and duration of precipitation events, as well as soil saturation, resulted in different sensitivities of runoff and pollutant loads in different months (Abdul-Aziz & Al-Amin, 2016).

The study also found that imperviousness and roughness had a more dominant influence on potential basin runoff and pollutant loads than slope, and that sensitivity to land use changes was relatively low compared to hydro-climatic changes. Converting open lands to residential, commercial or industrial areas resulted in greater increases in runoff and pollutants, while conversion among residential, commercial, and industrial land uses led to much less changes. The study emphasizes that quantified sensitivities can be useful for managing stormwater quantity and quality in complex urban basins under a changing climate, land use/cover, and hydrology around the world (Abdul-Aziz & Al-Amin, 2016).

By using an urban storm-water management model to determine the effectiveness of the proposed solution, Nile et al. in 2018 attempted to mitigate flooding in Kerbala, Iraq. The research filled a gap in flood control studies in the Middle East and provides technical support for decision makers. By implementing the proposed solution, sewer hole flooding decreased from 48% to 33% under maximum rainfall conditions, and the duration of flooding was reduced from 72 to 26 hours (Nile et al., 2018).

Neupane et al. in 2021 investigated the impact of land-use and climate change on urban hydrology in Columbia, South Carolina, using the PCSWMM model. A significant increase in mean annual runoff was found for future periods, ranging from 40% to 70%. In the study, LID approaches reduced urban runoff by 10% to 32% depending on the type of LID methodology used. A key finding of the study relates to how LIDs can be integrated with existing storm drainage systems in order to reduce the impact of urbanization and climate change (Neupane et al., 2021).

Ahiablame & Shakya in 2016 evaluated the effectiveness of LID practices in mitigating flood risks in an urban watershed in central Illinois using the PCSWMM model. The study evaluated different land use scenarios and the impacts of urbanization on runoff and flooding. Based on the results of the study, increasing urban land use from 50% to 94% between 1992 and 2030 led to significant increases in runoff and flood events, indicating greater flood risks without proper management. LID practices have reduced runoff by 3-47% and flooding by 0-40% when implemented at various levels, including porous pavement, rain barrels, and rain gardens. As a result, LID practices can effectively mitigate flood risk in urban watersheds (Ahiablame & Shakya, 2016b). It should be determined that reasonable LID implementation levels should be selected and determined based on practical considerations and the specific characteristics of the watershed. Furthermore, the study emphasizes the need for watershed-specific LID scenarios and policies, taking into account local contexts and economic feasibility. The large-scale adoption of LID practices can be achieved through collective efforts involving business owners, homeowners, local governments, and public incentive programs, ensuring a gradual and strategic approach to implementation.

Franciele and Da (2018) focused on the impact of urbanization on runoff and flooding volume in developing countries like Brazil and explores the effectiveness of LID structures and zoning measures in mitigating these issues. The results showed that the expansion of urban occupation increased the volume of surface runoff by 16%. However, the implementation of LID structures and zoning measures reduced the surface runoff volume by 13.8% compared to the future scenario. The study emphasizes the importance of urban planning measures, such as controlling permeability rates and optimizing land use, in reducing runoff volumes. The performance of LID structures was found to be more efficient in areas with lower total rainfall, while nonstructural measures showed efficiency regardless of rainfall intensity (Franciele & da, 2018).

The Table 1 provides a comprehensive summary of data from related research, highlighting the comparative effectiveness of low impact development practices in mitigating environmental impacts.

Table 1. Assessing the Effectiveness of LID Practices: A Comparative Analysis of Case Studies

Case study	Runoff Reduction	Flood Reduction	Source
New York City, USA	14% to 28%	-	(Zahmatkesh et al., 2015)
Karbala, Iraq	-	33% to 48%	(Nile et al., 2018)
Columbia, South Carolina (USA)	10% to 32%	-	(Neupane et al., 2021)
Dodola, Ethiopia	53.4% to 48.5%	-	(Bibi, 2022)
Central Illinois, USA	3% to 47%	0% to 40%	(Ahiablame & Shakya, 2016b)
Central Creek, Brazil	13.8%	-	(Franciele & da, 2018)

2.3Evaluation of Climate Change and Land-use in the Study Area

2.3.1 Climate Change Model in Shiraz

Natural hazards such as flooding are becoming more frequent and serious, causing enormous damage to the economy, society, and people's property and safety. Flooding is more likely to occur in cities due to changes in hydrological and hydrometeorological conditions, as well as urban population concentrations (Huang et al., 2017). According to the Fifth Assessment Report of the IPCC, global mean surface temperatures are expected to continue to rise in the 21st century, and global precipitation is expected to fluctuate based on latitude (IPCC AR5, 2014). Climate change coupled with urbanization has greatly increased the occurrence of urban flood events in the past several decades.

The evaluation of climate change's effects on the efficiency of the drainage system relies on assessing the accuracy of climate models. Climate models are used to simulate various climate variables, with precipitation being a key factor of interest.

Numerous studies have been reviewed to evaluate the impact of climate change in Shiraz. One such study conducted by Roshan et al. (2019) utilized Atmospheric-Ocean General Circulation Models (AOGCM) under different emission scenarios (A1B, A2, B1). The objective was to assess the effects of climate change on Intensity-Duration-Frequency (IDF) curves for the Shiraz by employing downscaled outputs of an appropriate AOGCM and applying the LARSWG-5 model for the period from 2046 to 2065. Intensity-Duration-Frequency (IDF) curves depict the relationship between rainfall intensity and the duration of a storm, considering its frequency of occurrence for a specific location. These curves are essential for engineering and planning, aiding in tasks such as flood risk assessment and designing drainage systems based on historical rainfall data.

AOGCMs, which are complex computer models, are utilized to simulate climate variables and understand the interactions between the atmosphere and the ocean, providing valuable insights into climate patterns and their implications for drainage systems. AOGCMs are complex computer models that simulate the interactions between the atmosphere and the ocean to understand and predict climate patterns. These models incorporate various physical processes, such as solar radiation, atmospheric circulation, heat transfer, and ocean currents, among others. AOGCMs are used to simulate climate conditions under different scenarios, including different levels of greenhouse gas emissions (Emori et al., 2016; IPCC AR5, 2013; Kattsov et al., 2007).

The emission scenarios, such as A1B, A2, and B1, represent different trajectories of future greenhouse gas emissions. These scenarios are based on different assumptions about population growth, economic development, technological advancements, and policy measures. By running

AOGCMs with different emission scenarios, scientists can project future climate conditions and study the potential impacts of different levels of greenhouse gas emissions on temperature, precipitation patterns, sea level rise, and other climate variables. These models are important tools for policymakers, researchers, and climate scientists to understand and plan for potential climate change scenarios (Ahmadzadeh Araji et al., 2018; IPCC-TGICA, 2007).

The Fourth Assessment Report (AR4) of the IPCC published in 2007 incorporated a set of greenhouse gas emission scenarios known as the Special Report on Emissions Scenarios (SRES) for analyzing possible future emissions pathways. These scenarios are marked with different codes, such as A1B, A2, and B1. However, since the publication of AR4, there have been advancements in climate science, and the IPCC's Fifth Assessment Report (AR5) and subsequent reports, including the Sixth Assessment Report (AR6), use different sets of scenarios. To represent various future greenhouse gas concentration levels, AR5 introduced Representative Concentration Pathways (RCPs). In comparison with the older SRES scenarios, these RCPs provided a more detailed representation of various emission pathways (IPCC AR5, 2014; IPCC AR6, 2022).

Similarly, AR6 of the IPCC uses Shared Socioeconomic Pathways (SSPs) in conjunction with RCPs to assess future climate changes. As an addition to RCPs, SSPs provide additional context regarding possible societal developments. As a result, the IPCC's AR5 and AR6 reports have transitioned to using RCPs and SSPs, which represent future greenhouse gas emissions and socioeconomic conditions in a much more comprehensive and advanced manner. It is essential to note that SRES scenarios were valuable for their time, and the introduction of more advanced scenarios does not undermine the significance or validity of earlier studies. However, researchers and policymakers can better understand possible future climate change scenarios and prepare more effectively for climate adaptation and mitigation based on these advancements in scenario development.

Figure 6 shows the IDF curves of base and future period under A1B Scenario for different return periods in the city of Shiraz (Roshan et al., 2019). The study employed the fitted Gumbel distribution to estimate maximum short-term precipitation quantiles during the base period (1968-2000) and verified the empirical Bell type equation for the future period. The findings revealed a decrease in both the mean of maximum daily precipitation and annual precipitation in the future. Additionally, the maximum precipitation intensities for durations up to 60 min were projected to decrease from 0.15 mm to approximately 10.79 mm compared to the observed period across different return periods and scenarios (Roshan et al., 2019).

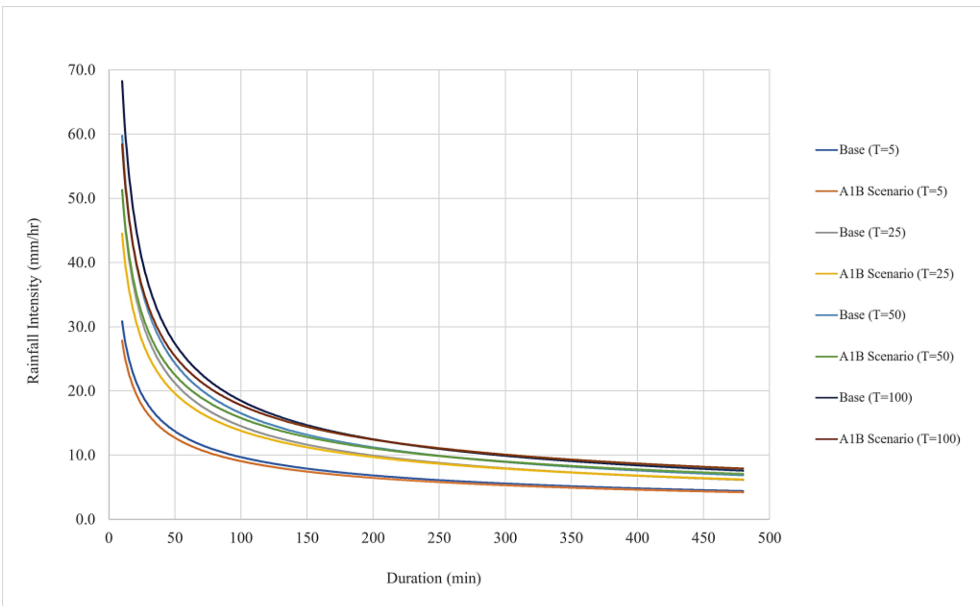

Figure 6. Intensity-duration-frequency (IDF) curves of base and future period under A1B Scenario in Shiraz (Roshan et al., 2019)

Deihamifard et al. (2014) aimed to predict meteorological parameters, calculate drought indices, and assess their spatial distribution under changing climate conditions in Fars province. By employing two climate models (HadCM3 and IPCM4) and considering three scenarios (B1, A1B, and A2), the future climate conditions in nine districts of Fars province were evaluated. The Standardized Precipitation Index (SPI) was calculated at a 12-month time scale to estimate drought probability. SPI time series were generated for a historical base period (1980-1990) and three future periods (2011-2030, 2046-2065, 2080-2099). Results showed that drought severity is projected to increase under climate change, with certain regions classified as experiencing extreme drought. Nevertheless, most areas are expected to remain in the normal drought class in the future (Deihimfard et al., 2014).

Gholampour (2017) evaluated the impact of climate change on precipitation and temperature at the Shiraz synoptic station for a 30-year statistical period (2011-2040). The HadCM3 atmospheric-ocean general circulation model was utilized under the A2 scenario from the Special Report on Emissions Scenarios (SRES) collection. The LARS-WG method was employed to downscale the long-term temperature and precipitation data series for future periods (2030-2050). Overall, the results showed that the annual average temperature is projected to increase by 2.93% in future periods compared to the baseline period. As for precipitation, the results indicated a decrease of 0.1 millimeters in future decades (Gholampour, 2017).

The decreasing trend in precipitation in Shiraz, both in the past and projected for the future, suggests that the occurrence of huge flooding in recent years may not be directly related to an increase in rainfall. Other factors, such as land use changes and urban development, could play a significant role in exacerbating the flooding events.

2.3.2 Land-use change in Shiraz

Urbanization and changes in land use can lead to increased surface runoff and reduced infiltration capacity of the soil, resulting in heightened flood risk. When natural areas, such as forests or grasslands, are replaced by impervious surfaces like concrete or asphalt, rainfall cannot infiltrate into the ground effectively. Instead, it quickly flows over these surfaces and accumulates in urban drainage systems, which may become overwhelmed during heavy rainfall events, leading to flooding.

Rouhani et al. (2021) examined the impacts of urbanization and urban development in Shiraz, specifically focusing on the consequences of rapid urban growth in the region. The findings indicate a significant decrease in agricultural land, with percentages dropping from approximately 11% in 1982 to 3.70% in 1996, 3.30% in 2006, and 2.65% in 2018 (Figure 7). The expansion of urban areas and streets emerged as the most prominent change in land use. The decline in agricultural land by 8.35% and the reduction in tree cover by 2% were primarily attributed to urban development fueled by economic growth and increasing demand. The research reveals that the urban area is expanding on the outskirts of the city, especially in the southern districts (2, 5, and 9) and southeastern district (7). This expansion is primarily driven by the rapid population growth of the city (Rouhani & Elmi, 2021).

Although climate change and reduced water reserves may have some influence, the main driving force behind the conversion of land to residential areas in Shiraz is rapid urban sprawl. Unfortunately, this rapid population increase has led to the loss of vegetation cover, as construction has encroached upon previously vegetated areas. In recent years, residents of Shiraz have extended their presence beyond the city limits, utilizing not just barren lands but also rural and agricultural areas. The combination of extensive urban development and inadequate drainage infrastructure has resulted in issues such as flooding during heavy rainfall events. Therefore, alongside the need to address urban expansion, there is also a necessity to enhance the drainage systems to ensure sustainable urban development (Rouhani & Elmi, 2021). .

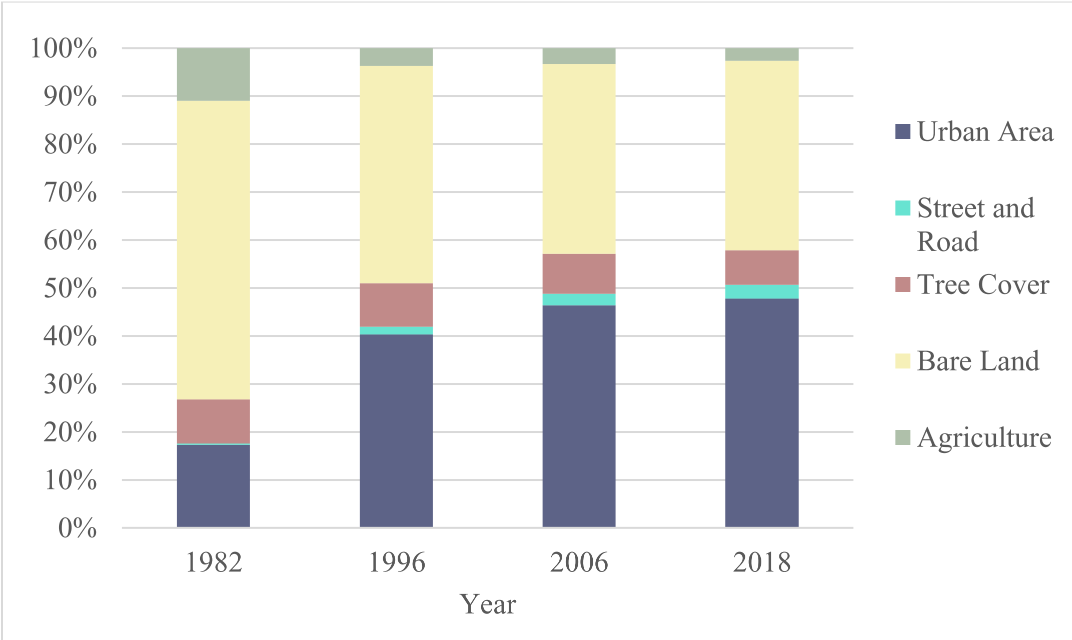

Figure 7. Proportions of land-use types in Shiraz for 1982, 1996, 2006, and 2018 (Rouhani & Elmi, 2021)

Ahani et al. (2009) used maps of Tang-Sorkh watershed in Shiraz by LANDSAT and SPOT 5 (High Resolution Geometry) images by considering geometric and radiometric corrections and seasonal image difference, to classify the land use of the city for the years 1988 and 2005. The percentage changes in land use in Shiraz, including the decrease in green areas, agriculture, and rangeland, along with the slight increase in impervious surface and residential areas, indicate a shift towards urbanization and reduced natural vegetation. These changes can have significant implications for flooding as the loss of green areas and rangeland reduces water absorption capacity, while increased impervious surfaces and urban expansion hinder water infiltration and increase surface runoff (Ahani et al., 2009).

The results of the 20-year study indicate a significant increase in the area of residential land, from 38 square kilometers in 2005 to 142 square kilometers in 2020. This considerable growth in residential areas within the examined timeframe highlights the need for comprehensive planning and improved urban management strategies. It emphasizes the necessity of formulating sound plans to enhance urban governance and address the challenges associated with rapid urbanization effectively (Figure 8).

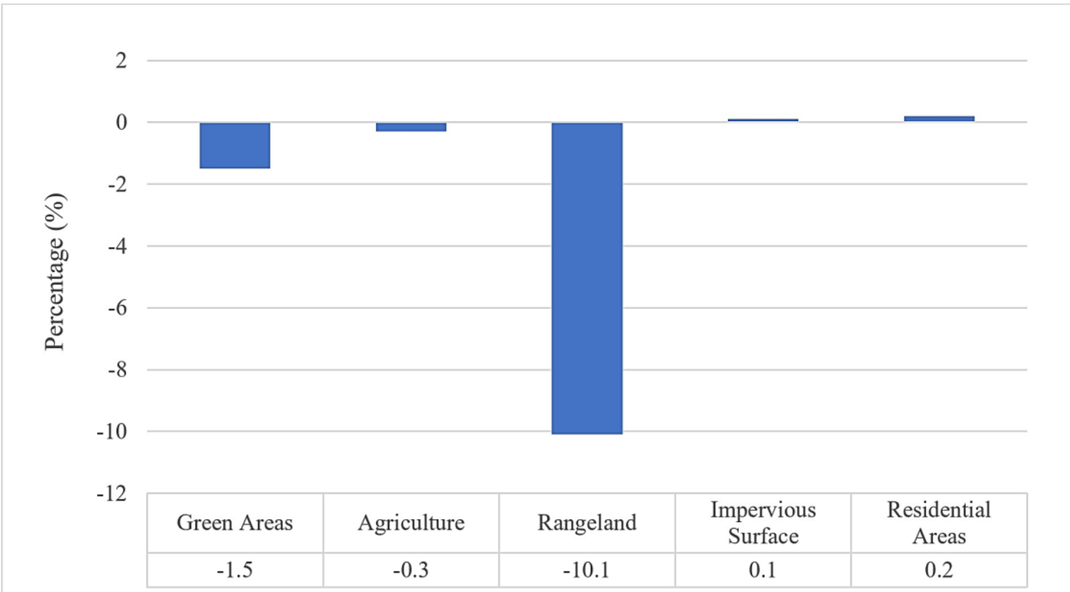

Figure 8. Changes in land-use from 1988 to 2005 in the city of Shiraz
(Ahani et al., 2009)

Nohegar (2010) conducted a simulation approach to enable the isolation of the impact of land use change on runoff volume and flood susceptibility by keeping other influential factors constant, such as vegetation cover or other land uses. By manipulating a single factor while holding rainfall constant, the study aimed to calculate the influence of land use modifications on the volume of runoff and flood-prone conditions. High-resolution satellite imagery and the application of GIS capabilities were proposed for accurate land use mapping, monitoring, and analysis, particularly in areas where statistical data are lacking. The results indicate that flooding in the specified area has increased by 15% over the last 18 years (Nohegar et al., 2012).

Based on object-based image analysis, Ebrahimy et al. (2018) analyzed land use changes in Shiraz over a 15-year period in 2018 (Figure 9). To predict land use changes in the study area in 2020, the cellular automata-Markov (CA-Markov) model was used. Through this modelling approach, future land use patterns can be identified and projected, providing useful insight for urban planning. The results indicated a significant expansion in residential land, increasing from 38 square kilometers in 2005 to 142 km^2 in 2020, underscoring the necessity for comprehensive planning and enhanced urban management strategies (Ebrahimy et al., 2018).

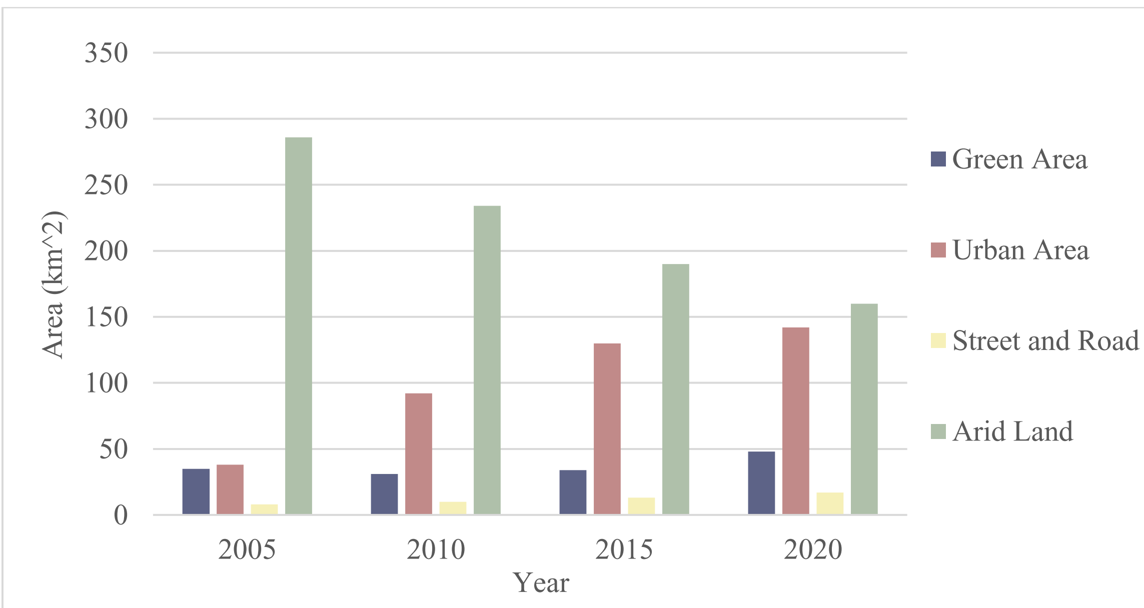

Figure 9. Changes in Land use in the city of Shiraz for 2005, 2010, 2015, and 2020 (Ebrahimy et al., 2018)

Considering the findings, it is evident that the land use changes observed in Shiraz, particularly the conversion of natural areas into urbanized regions, have significantly contributed to the city's heightened vulnerability to flooding. The expansion of impermeable surfaces have collectively diminished the area's natural water absorption capacity and disrupted the hydrological cycle. To address these challenges, the implementation of LID techniques emerges as a potential solution. LID practices promote sustainable land development by emulating natural hydrological processes through the utilization of green infrastructure, permeable pavements, and rainwater harvesting systems. By adopting LID approaches, Shiraz can mitigate the adverse effects of land use changes, enhance its resilience to future flood events, and foster a more sustainable and resilient urban environment.

LID techniques can indeed be a potential solution to mitigate the impacts of urbanization on flooding. LID is an approach that aims to manage stormwater at its source, mimicking natural hydrological processes to reduce runoff and promote infiltration. It involves incorporating sustainable drainage practices, such as green roofs, permeable pavements, rain gardens, and retention ponds, into urban planning and design (Pour et al., 2020).

2.4 Identification of research gaps and the need for this study

The existing literature on the impact of climate change and urbanization on runoff or flooding volume reveals several research gaps and underscores the need for further investigation. Through our discussions, several key findings and knowledge gaps have emerged.

A significant research gap exists regarding the impact of climate change on runoff dynamics and flooding volumes and the need for innovative drainage systems. Understanding the effects of climate change on these aspects and evaluating the effectiveness of mitigation strategies is crucial for effective water management. Urbanization and climate change often occur simultaneously, leading to complex and intertwined impacts on runoff generation. Understanding the synergistic effects of these factors is essential for effective stormwater management and flood mitigation. The literature review highlighted the scarcity of research in some areas regarding flood control and urban hydrology. This indicates a need for more localized studies to understand the unique challenges and opportunities presented by climate change and urbanization in selected regions.

Furthermore, there is a dearth of research examining the effectiveness of low-impact development practices in mitigating runoff or flooding volume. Although some studies have explored the potential of LID controls, further investigation is required to assess their performance. Additionally, the literature suggests the importance of integrating LID measures with existing storm drainage infrastructure to enhance their effectiveness.

One crucial research gap is the limited focus on the current and recent flood events in Shiraz and the urgent need for effective solutions. Recent years have witnessed severe floods in Shiraz, highlighting the vulnerability of the city to climate change impacts. It is essential to address this issue by conducting research that examines the specific effects of climate change on flooding in Shiraz and identifies and evaluates appropriate mitigation strategies to minimize the devastating consequences of future flood events.

Therefore, the proposed thesis aims to bridge these research gaps by focusing on localized studies that consider the impact of land-use and climate change on runoff or flooding volume.

Chapter 3: Materials and methods

3.1 Explanation of SWMM modelling approach and assumptions

Storm Water Management Model (SWMM) simulates the performance of urban stormwater runoff and sewer systems. Stormwater management modelling was developed by the US Environmental Protection Agency (EPA) in the late 1960s for analyzing stormwater runoff quantity and quality. The SWMM distinguishes itself from other urban watershed models by including combined and sanitary sewers in its design and performance considerations for stormwater runoff management. A current version of SWMM allows users to simulate LID that reduce impacts on the environment, such as rain barrels, porous pavement, and infiltration trenches (Niazi et al., 2017). A view of SWMM's core processes and assumptions from which the equations were developed is provided in Figure 10.

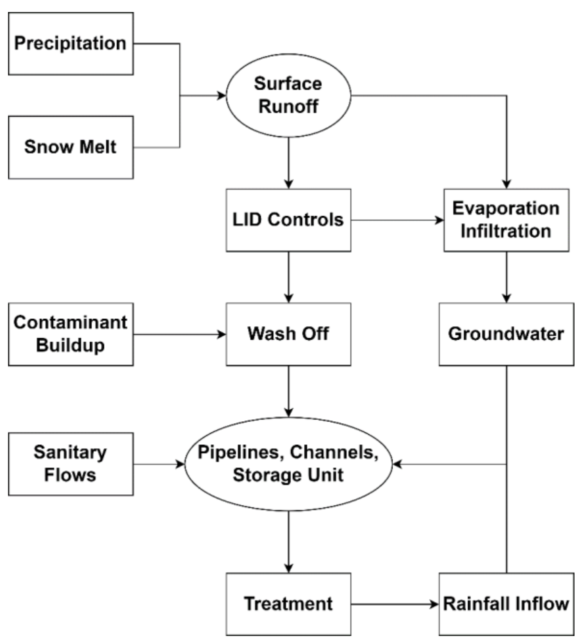

Figure 10. Flowchart diagram of the SWMM model's processes
(Niazi et al., 2017)

Since its development, the SWMM model has been used in numerous studies to collect and analyze surface runoff data. Some of the main uses of this model are:

1. Designing and planning detention basins to control flooding and maintain water quality: Detention basins are designed to temporarily hold and slowly release stormwater runoff. SWMM can be used to simulate how water flows into and out of these basins and help engineers determine the best design to control flooding and maintain water quality.
2. Managing networks of stormwater drainage systems: SWMM can be used to manage and optimize networks of stormwater drainage systems. It can simulate how water flows through pipes and channels and can help engineers determine the most efficient way to manage the system to prevent flooding and maintain water quality.
3. Using various types of standard open and closed natural systems: SWMM can simulate various types of natural systems, including open and closed systems. These simulations can help engineers determine the best design for a given area to prevent flooding and maintain water quality.
4. Modeling various components of the urban water cycle: SWMM can be used to model different components of the urban water cycle, including storage units, pipes, pumps, and various types of inlets and outlets. These simulations can help engineers optimize the system design to prevent flooding and maintain water quality.

The SWMM model uses various operational parameters in the watershed such as:

- Rainfall data such as rainfall intensity, duration, and frequency.
- Characteristics of the watershed such as its size and topography.
- Hydraulic information such as the type, shape and size of pipes and channels.

- Junction Nodes which represent points in the drainage system where pipes, channels, or other features meet.
- Outfalls which represent points where water leaves the system.
- Storage units such as ponds or tanks that temporarily store water.
- Pumps that help move water through the system.
- Regulators that control the flow of water through the system.

The differential equations that govern flow are complex, and the use of these models is essential for designing and studying various flood control structures and their effects on reducing flood damage.

The most complex form of flow equations is the three-dimensional Navier-Stokes equations. However, for practical purposes, one-dimensional models such as the Saint-Venant equations are commonly used. These models solve for the one-dimensional depth-averaged flow in channels and open waterways and are converted to a single partial differential equation in the direction of flow, known as the Saint-Venant equation.

The Saint-Venant equations include the continuity equation (Equation 1) and the momentum equation (Equation 2).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t} \qquad (2)$$

$Q: discharge\ (m^3/s)$

$A: cross\ sectional\ area\ (m^2)$

$g: acceleration\ due\ to\ gravity\ (m^2/s)$

$S_o: bed\ slope$

$t = time\ (s)$

During flood routing, not all terms in the momentum equation are used. There are three methods for solving flood routing problems in channels:

- Kinematic wave method
- Diffusive wave method
- Dynamic wave method

These methods differ in how they model the flow and how they solve the equations. The kinematic wave method assumes that the flow is shallow and uniform, while the diffusive wave method accounts for the gradual changes in flow depth and velocity. The dynamic wave method is the most comprehensive and considers both the inertia and friction effects on the flow. The choice of method depends on the nature of the problem and the accuracy required in the results.

SWMM employs multiple equations to simulate various hydrological processes. The calculation of runoff in SWMM is determined by Equation 3, which represents the difference between the inflow and outflow:

$$Q_{storage} = Q_{input} - Q_{output} \qquad (3)$$

In this equation, $Q_{storage}$ represents the maximum surface storage provided by ponding, surface wetting, and interception, Q_{input} is the total inflow including precipitation and upstream sub-catchment flows, and Q_{output} is the outflow that considers evaporation, infiltration, and surface runoff. Each sub-catchment surface is treated as a nonlinear equation, with the storage of the reservoir being a function of both inflow and outflow.

Surface runoff occurs when the water depth in the reservoir exceeds the maximum depression storage. The calculation of surface runoff for each sub-catchment is based on the continuity of mass, as shown in Equation 4:

$$\frac{dV}{dt} = \frac{d[A*d]}{dt} = A * I_e - Q \qquad (4)$$

In this equation, dV/dt represents the change in volume stored over time for the sub-catchment, V is the volume of water in the sub-catchment (in cubic meters), A is the sub-catchment area (in square meters), d is the water depth in the sub-catchment (depth of storage in the reservoir), I_e is the excess rainfall (difference between rainfall intensity, evaporation, and infiltration rate), and Q is the runoff flow rate from the sub-catchment (in cubic meters per second).

The Manning equation (Equation 5) is used to calculate the surface runoff flow rate (Q) based on the cross-sectional area of flow over the sub-catchment (A_{cs}), hydraulic radius (R), slope (S), width (W), and Manning roughness coefficient (n).

$$Q = \frac{A_{cs} R^{2/3} S^{1/2}}{n} \qquad (5)$$

The hydraulic radius is defined as the ratio of the cross-sectional area to the wetted perimeter, as shown in Equation 6.

$$R = \frac{A}{p} = \frac{\{W*[d-d_p]\}}{W} = d - dp \qquad (6)$$

Thus:

$$Q = \frac{W*(d-d_p)^{\frac{5}{3}} * S^{1/2}}{n} \qquad (7)$$

By substituting Equation 7 (derived from the Manning equation) into Equation 4, the calculation for surface runoff (Q) can be obtained.

$$\frac{dd}{dt} = \frac{d_{i+1}-d_i}{t_{i+1}-t_i} = I_e - \frac{W*(d-d_p)^{\frac{5}{3}} * S^{\frac{1}{2}}}{A*n} \qquad (8)$$

Let i and i+1 denote the subscripts representing the boundary conditions at the end of time step i (or the start of time step i+1) and the end of time step i+1, respectively (for example, d_{i+1} represents the depth at the end of time step i+1). The time step size is denoted as Δt, representing the duration in seconds between t_i and t_{i+1}. Q represents the average runoff flow rate during time step n+1 in cubic meters per second (m^3/s), while I_e denotes the average rainfall intensity throughout time step n+1 in meters per second (m/s). The average depth of flow during time step n+1, represented by d, is calculated as the average of di and d_{i+1}, measured in meters (m).

3.2 Description of the study area and data sources

Shiraz, located in the semi-arid zone of southwestern Iran, is the fifth-most-populous city in the country and the capital of Fars Province. The city covers an area of approximately 240 km^2 (93 ml^2) with the population of 1,995,500 people. Shiraz lies along the course of the Rudkhaneye Khoshk seasonal river. Shiraz lies along the course of the Rudkhaneye Khoshk seasonal river, which originates from the Zagros Mountains. Although the river is typically dry, it can experience flow during periods of heavy rainfall or snowmelt. The river passes through the city, enriching the landscape and contributing to the irrigation and agricultural activities in the region. However, the Rudkhaneye Khoshk River is also susceptible to flash floods, posing risks to the city and its inhabitants. Notable landmarks such as the Tomb of Hafez and the Quran Gate are situated along the river's path. Ultimately, the river reaches its destination at Maharloo Lake, located about 27 km southeast of Shiraz (Figure 11).

Shiraz is located in a region that is susceptible to flooding due to its topography and climate. Several rivers flow through the city which has been prone to flooding during seasons of heavy rainfall.

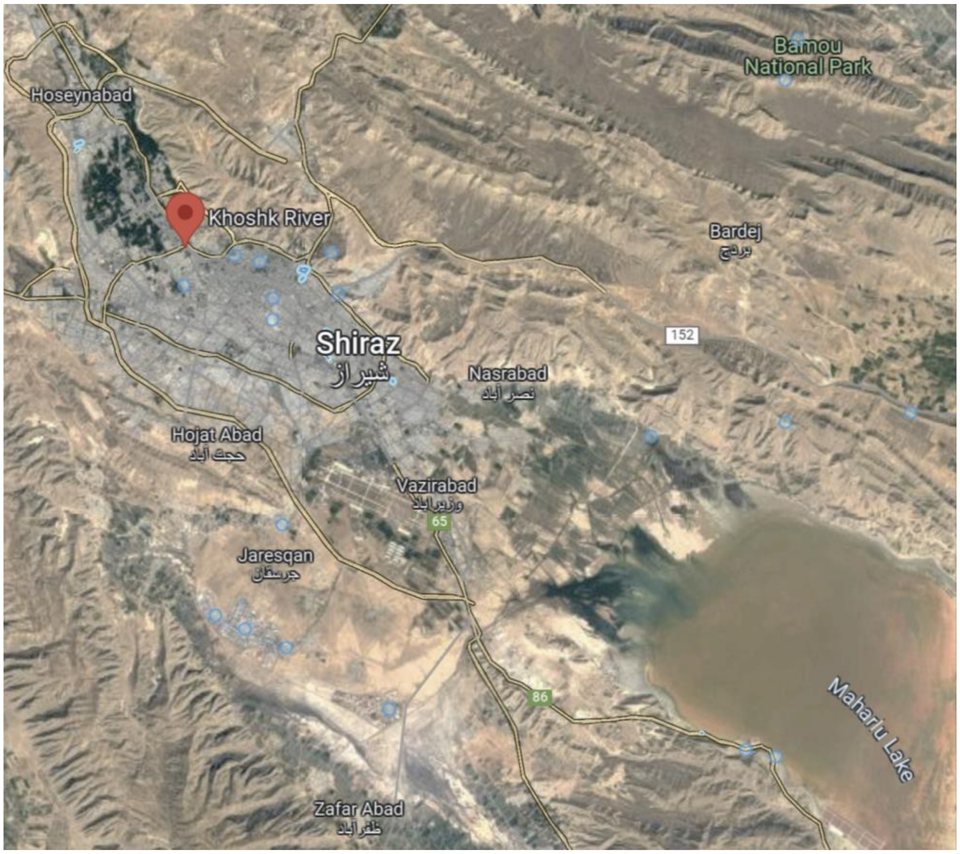

Figure 11. Location of the study area in Shiraz, Iran, depicting Rudkhaneye Khoshk River and Maharloo Lake on Google Maps.

While Iran is suffering from a long drought, floods occur frequently in different regions of the country, indicating mismanagement in controlling the amount of water in rainy years. Significant flooding has occurred in Shiraz, Iran in the past few years. A flash flood in Shiraz on March 25, 2019, before the Iranian New Year, resulted in 21 deaths and 164 injuries and buildings, roadways, and infrastructure in the city were damaged. The flooding affected several areas in and around Shiraz, including the historic Vakil Bazaar and the Arg-e Karim Khan fortress.

There was heavy rainfall and overflowing rivers and streams in the area that caused the floods. It has been reported that 70 mm of rain fell in just a few hours, exceeding the capacity of drainage systems and flooding streets and buildings.

There was flooding in Shiraz again in April 2020, caused by several days of heavy rains that damaged buildings, roads, and bridges, and resulted in several deaths and injuries. Shiraz was flooded in 2020 because of heavy rains that occurred over a short period. Reports indicate that some areas received more than 200 mm of rain in less than 24 h, the most in 70 years. Rainwater accumulated rapidly in the city's drainage systems and overflowed into streets and buildings, causing severe damage and loss of life. As with other natural disasters, Shiraz's flooding in 2019 highlights the need for effective disaster preparedness and response strategies. Likewise, long-term efforts are needed to address the root causes of flooding.

The flooding in Shiraz in 2020 was not an isolated event. Iran has experienced a number of severe floods in recent years, which have been attributed to a combination of factors, including climate change, deforestation, and inadequate infrastructure. These floods have caused significant damage and loss of life, highlighting the need for improved disaster preparedness and management in the region.

The mean annual rainfall from 2013 to 2022 is 1.4–34.97 mm. The mean lowest and highest monthly rainfalls from 2013 to 2022 are 0 mm (in Sep) and 37.97 mm (in Feb), respectively (National Centers for Environmental Information, 2022).

In order to assess the impact of flooding and develop effective mitigation strategies, a study was conducted focusing on four districts in Shiraz, namely districts 2, 3, 7, and 8 (Figure 12). These districts were selected out of 11 districts in the city of Shiraz for modeling using SWMM, encompassing a combined area of approximately 68 km^2. Notably, district 3 and its surrounding areas were of particular interest due to the significant flood event that occurred in 2019. Through this evaluation, the aim was to gain insights into the flood dynamics and identify potential measures to enhance resilience and reduce the vulnerability of these districts to future flooding incidents.

The selection of specific districts (2, 3, 7, and 8) within the city of Shiraz for this study was purposeful and justified based on several considerations:

- Flood Vulnerability: District 3 and its surrounding areas had experienced a significant flood event in 2019. This event made district 3 a focal point of concern due to its vulnerability to flooding. By concentrating on this district, the study aimed to comprehensively analyze the dynamics of flooding in an area that had previously been severely affected. This focus allowed for a detailed examination of factors contributing to flood risks and facilitated the identification of potential mitigation strategies.
- Resource Constraints: Conducting a city-wide study, encompassing all districts, can be resource-intensive and time-consuming. By narrowing the scope to specific districts, the research could allocate resources more efficiently, ensuring a thorough investigation of flood-related issues within a manageable area.
- Strategic Planning: Focusing on particular districts aligns with strategic urban planning approaches. Cities often prioritize vulnerable or high-risk areas for in-depth analysis and the development of targeted mitigation measures. By concentrating efforts on these districts, the study aimed to contribute to strategic urban planning efforts that could be applied more broadly.

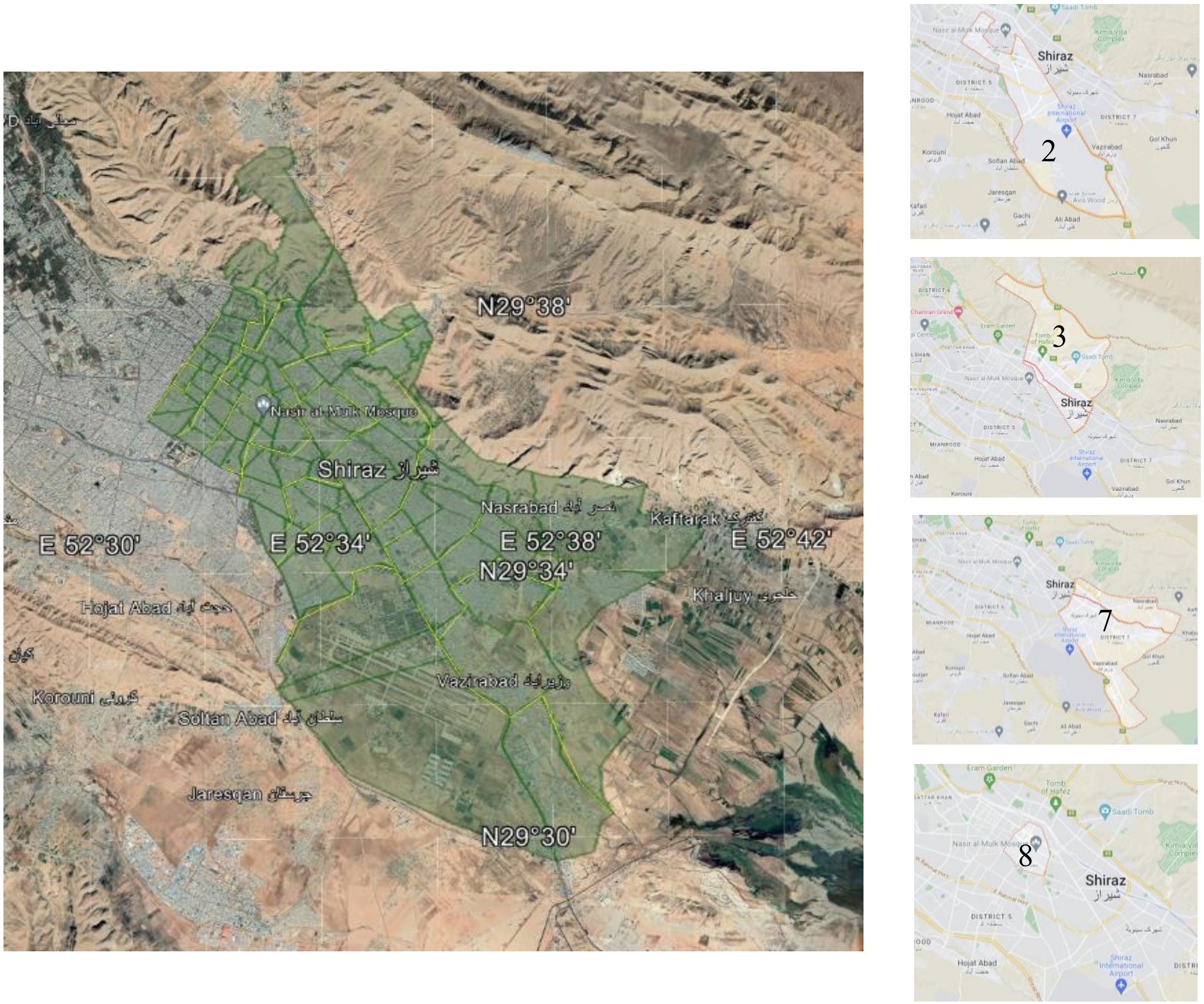

Figure 12. Location of the case study area in Shiraz, Iran, using Google Maps.

It is worth mentioning that the consideration of networking, particularly in the context of urban drainage systems, is crucial for an accurate and comprehensive analysis of stormwater management and flood risk. In many urban areas, drainage networks extend beyond administrative boundaries, creating an intricate web of interconnected pipes, channels, and drainage infrastructure. When studying the impact of stormwater management techniques or assessing flood risk within specific districts, it's imperative to recognize that the behavior of water doesn't adhere strictly to these artificial boundaries.

3.3 Model Development and Data

The initial phase involved data layer preparation and delineation of the study areas utilizing a Digital Elevation Model (DEM). DEM is an essential tool in hydrological and topographic analysis that represents the surface terrain by providing elevation values for each point within a geographic area. It provides information about the elevation, slope, and aspect of the land, which are crucial in hydrological modeling and analysis. DEM-derived slope information is used to simulate water movement, calculate flow accumulation, and estimate runoff patterns.

One thing to note about a DEM is that the quality of the delineated hydrological features is sensitive to the accuracy and resolution of the DEM. The relatively low resolution of the available DEMs contributed to some details being lost and incorrect and required manual manipulation and field surveying. A 12.5m x 12.5 m spatial resolution DEM was acquired from the Alaska Satellite Facility (https://asf.alaska.edu) to analyze the average slope of each sub-catchment.

Comprehensive data regarding the pipelines, manholes, and junctions within the study area were provided by the water and sewer organization in Iran. The dataset included detailed information about the shape, measurements, and connectivity of these components served as a fundamental resource for the development and implementation of the hydraulic modeling of the water and sewer system. The pipelines dataset contained attributes such as pipe location coordinates, elevation, shape, and dimensions, which allowed for an accurate representation of the network in the hydraulic model.

According to the SWMM software structure, in order to initiate and process a hydraulic model, it is necessary to provide all the initial information and parameters required for modeling. To do so, the necessary information for the program was provided based on the available data for the study area's simulation and model execution. Generally, the required hydraulic information for the model includes attributes such as conduits, manholes, outlets, and other network components, especially those for which data is available and accessible. Figure 13 shows a representation of the studied area in SWMM.

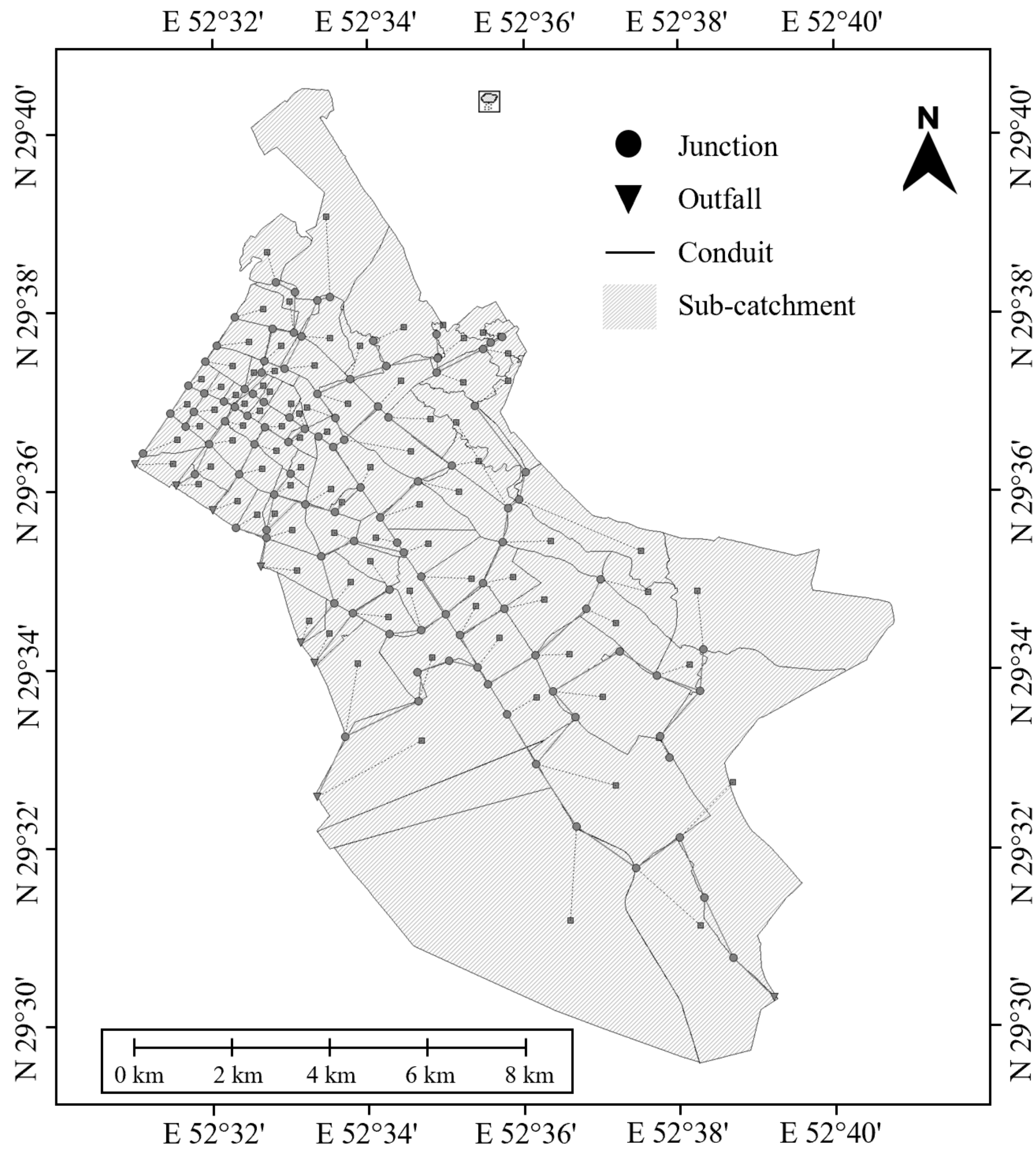

Figure 13. Representation of the study area modeled in SWMM.

In the SWMM software, certain parameters are essential for defining a model, including characteristics such as subcatchment area, width, slope, imperviousness, etc., which have been considered in this modeling. The number of subcatchments, Nodes and links in the study area defined in the SWMM model are given below:

Number of subcatchments: 93

Number of nodes: 113

Number of links: 104

3.4 Implementation of LID Techniques in SWMM

3.4.1 Bioretention Cell

Bioretention modeling in SWMM involved several steps. Firstly, the bioretention cell's location and dimensions were defined within the study area, considering factors such as space availability, proximity to runoff sources, and compatibility with the surroundings. This step ensured that the bioretention cell was strategically placed for optimal performance.

When selecting areas for bioretention cell design, several factors should be considered, including:

- Drainage Area: Identify areas with significant impervious surfaces, such as parking lots, rooftops, or roadways, that generate substantial stormwater runoff. These areas can benefit from bioretention cells to manage and treat the runoff.
- Slope and Topography: Favor areas with gentle slopes and relatively flat terrain, as this promotes proper infiltration and retention of stormwater within the bioretention

cells. Steep slopes may hinder the effectiveness of infiltration and increase erosion risks.

- Soil Conditions: Look for areas with suitable soil characteristics that promote water infiltration and retention. Soils with good permeability and moisture retention capacity, such as loam or sandy loam soils, are ideal for bioretention cell.

  Various characteristic parameters must be defined in SWMM to depict the behavior of the soil media within a bioretention cell, critical for simulating stormwater infiltration and treatment processes. These parameters include:

  1. Thickness (in. or mm)
  2. Porosity (volume fraction)
  3. Field Capacity (volume fraction)
  4. Wilting Point (volume fraction)
  5. Conductivity (in/hr or mm/hr)
  6. Conductivity
  7. Slope
  8. Suction Head (in. or mm)

- Distance from Water Bodies: Consider the proximity of bioretention cell locations to nearby water bodies. It is beneficial to place bioretention cells in close proximity to the source of stormwater runoff to minimize the transport of pollutants to downstream water bodies.
- Vegetation and Landscaping: Assess the potential for incorporating vegetation and landscaping elements into the bioretention cells. Vegetation helps enhance water

absorption, nutrient uptake, and pollutant removal, while also providing aesthetic and ecological benefits.

- Maintenance Accessibility: Ensure that the selected areas for bioretention cells are easily accessible for maintenance activities, such as vegetation pruning, sediment removal, or filter media replacement.

By considering these factors, suitable areas for bioretention cell design can be identified. It is important to evaluate each potential location against these criteria to maximize the effectiveness of bioretention systems in managing stormwater runoff.

Next, the properties and parameters of the bioretention cell were assigned. These included characteristics like surface area, storage capacity, infiltration rates, vegetation type, and soil composition. These values were obtained from design guidelines, literature sources, or field measurements, ensuring that the bioretention cell accurately represented its real-world counterparts. To simulate the behavior of the bioretention cell in SWMM, LID controls were configured specifically for this purpose. The LID control settings were customized to represent a bioretention system, and parameters such as surface roughness, drain coefficient, and vegetation characteristics were inputted accordingly. This allowed for the simulation of the bioretention's performance in managing stormwater (Figure 14).

Assigning the bioretention cell to relevant subcatchments was another crucial step in modeling. By identifying the subcatchments influenced by the bioretention cell, SWMM could simulate the impact of the cell on runoff within those specific areas. This integration ensured that the bioretention cell's effects on the overall hydrological system were accurately captured. The screenshot from SWMM in Figure 15 displays some fields that require attention when assigning bioretention cells to the subcatchments.

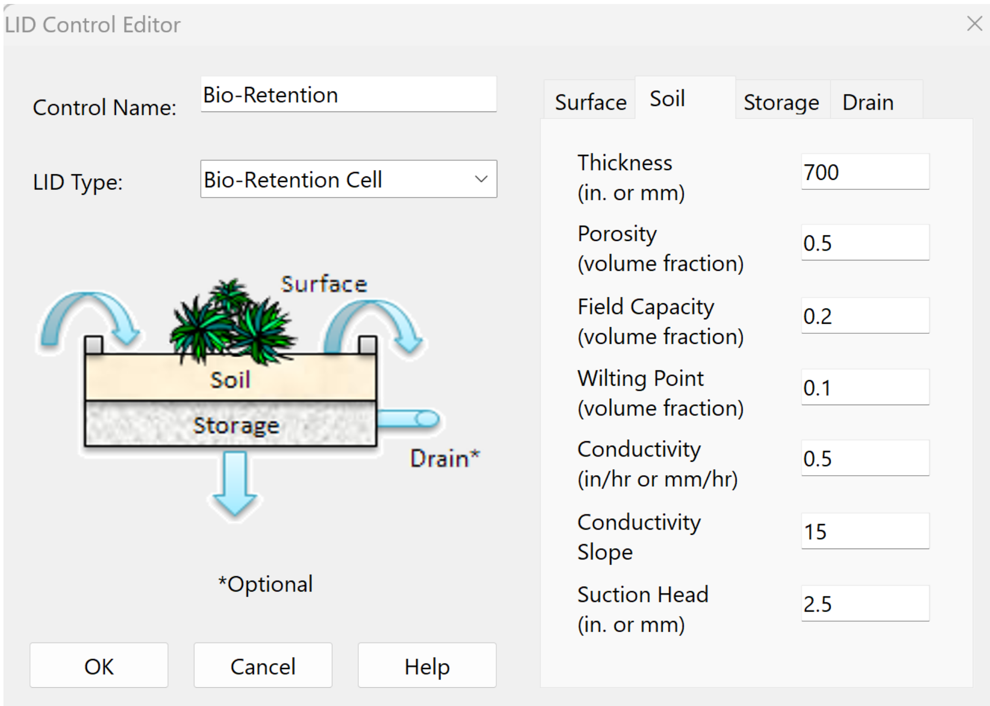

Figure 14. Defining Bioretention Cells in SWMM

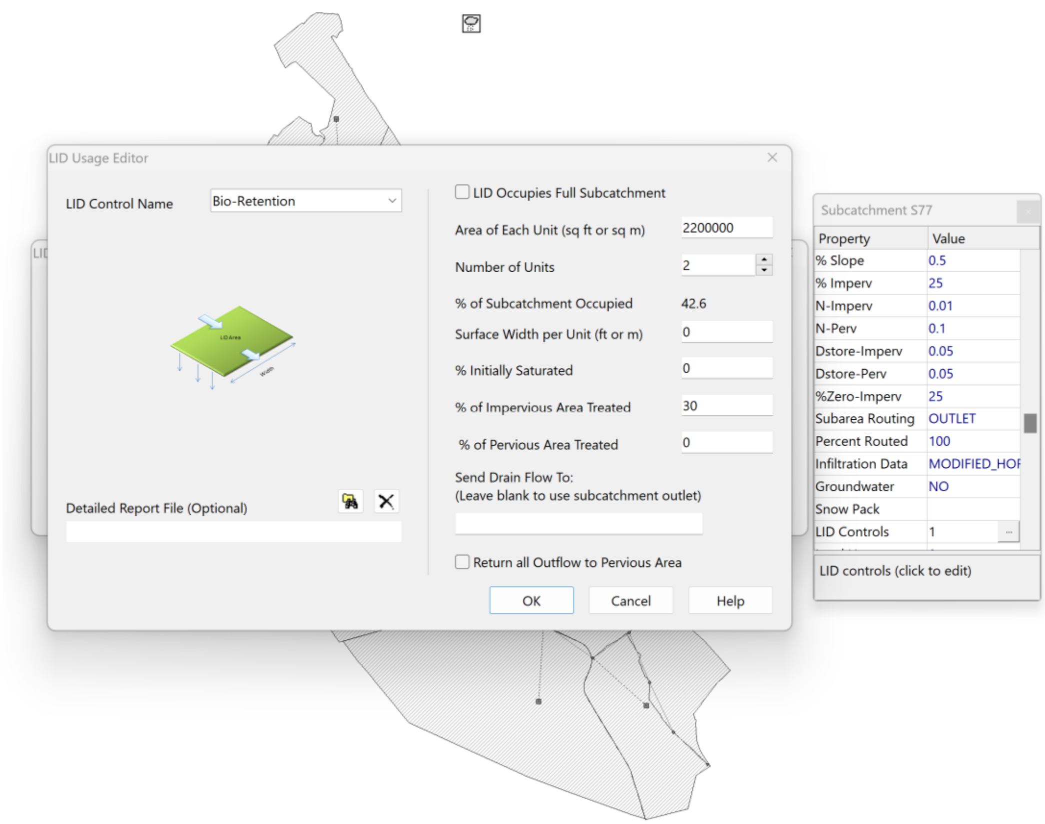

Figure 15. Assigning Bioretention Cells to the subcatchments in SWMM

To summarize the bioretention designs, Table 2 was created to present the key characteristics of each bioretention cell. This consolidated information allows for easy comparison and evaluation of the different bioretention designs implemented within the study area.

Table 2. Details of each bioretention cell designed in SWMM.

Subcatchment	LID Control	No. of Units	Unit Area (m^2)	Area Covered (%)
S6	Biretention	4	140000	63.46
S15	Bioretention	3	25000	42.83
S21	Bioretention	1	220000	44.51
S24	Bioretention	3	250000	45.26
S38	Bioretention	2	140000	46.43
S43	Bioretention	4	140000	48.67
S44	Bioretention	5	35000	44.14
S56	Bioretention	4	100000	34.51
S61	Bioretention	2	250000	54.10
S77	Bioretention	2	2200000	42.62
S80	Bioretention	2	2500000	52.37
S82	Bioretention	5	2500000	61.66
S88	Bioretention	7	170000	38.40
S92	Bioretention	5	150000	49.46

3.4.2 Permeable Pavement

One of the other sustainable stormwater management techniques is PP that allows water to infiltrate through the pavement surface into the underlying soil layers. By allowing water to infiltrate into the ground, PP reduces the amount of stormwater runoff that would typically flow over impervious surfaces like concrete or asphalt. This reduction in runoff helps to mitigate the volume and velocity of water flowing into stormwater systems, thereby minimizing the risk of localized flooding.

The ability of permeable pavement to facilitate water infiltration helps replenish groundwater reserves. As water percolates through the pavement and into the underlying soil, it can replenish underground aquifers and contribute to maintaining sustainable water resources.

Traditional impervious surfaces, such as asphalt and concrete, absorb and retain heat, contributing to the urban heat island effect. Permeable pavement, with its ability to absorb and store water, helps to dissipate heat and lower surface temperatures, contributing to a cooler and more comfortable urban environment.

When designing permeable pavement systems, it is essential to consider the subcatchments and their characteristics to effectively model and simulate their performance in SWMM. Within each subcatchment, specific impervious areas that will be replaced with permeable pavement must be identified. These areas, which can include parking lots, walkways, or driveways, should be precisely delineated to determine the extent of permeable pavement coverage.

Infiltration properties play a vital role in permeable pavement modeling. These properties, such as infiltration rate, hydraulic conductivity, and storage capacity, determine how quickly water infiltrates through the pavement and the volume of water retained within the system. They need to be defined based on the specific characteristics of the permeable pavement material.

Additionally, the layers beneath the permeable pavement, including aggregate base, filter fabric, and underlying soils, should be considered. These layers assist in facilitating the infiltration and storage of stormwater. Their properties, such as porosity, permeability, and storage capacity, need to be defined within the SWMM model to accurately simulate the system's behavior.

By considering these factors and accurately modeling permeable pavement within SWMM, the performance of the system can be assessed, aiding in decision-making for stormwater management strategies. The screenshot from SWMM in Figure 16 displays some fields that require attention when defining permeable pavement.

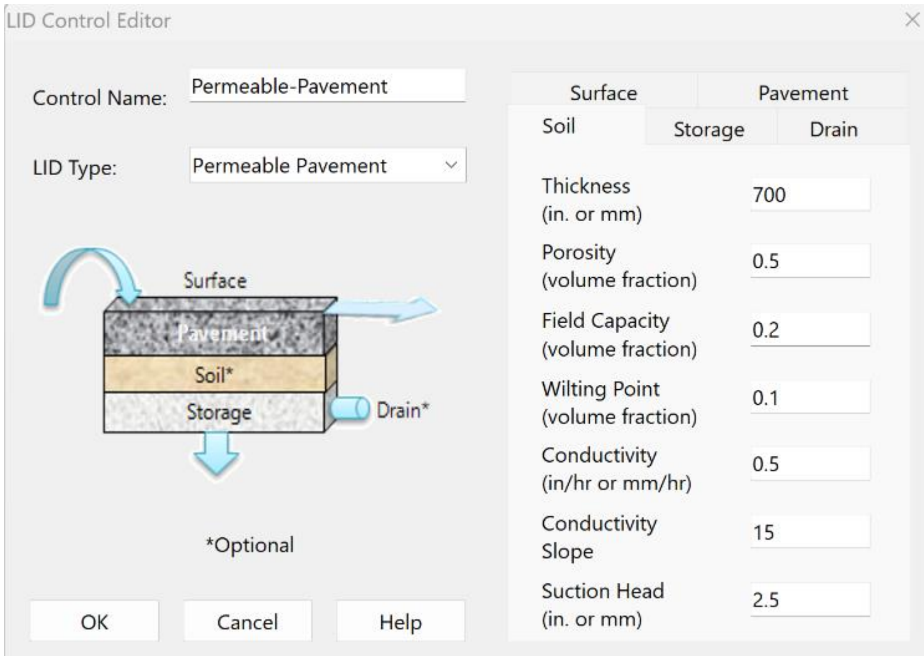

Figure 16. Defining Permeable Pavement in SWMM

In Table 3 the summary of defined permeable pavements in the study area has been shown.

Table 3. Details of permeable pavement designed in SWMM.

Subcatchment	LID Control	No. of Units	Area Covered (%)	Unit Area (m^2)
S5	Permeable Pavement	5	36.45	15000
S17	Permeable Pavement	4	54.61	100000
S20	Permeable Pavement	5	31.34	150000
S21	Permeable Pavement	3	66.76	110000
S22	Permeable Pavement	2	50.04	1500000
S23	Permeable Pavement	4	30.53	250000
S26	Permeable Pavement	2	22.92	150000
S36	Permeable Pavement	2	29.96	50000
S37	Permeable Pavement	3	59.15	150000

Table 3 Cotinued. Details of permeable pavement designed in SWMM.

S39	Permeable Pavement	2	80.68	500000
S41	Permeable Pavement	4	62.04	200000
S42	Permeable Pavement	4	54.01	150000
S48	Permeable Pavement	1	22.04	25000
S51	Permeable Pavement	4	43.8	150000
S54	Permeable Pavement	5	45.66	200000
S69	Permeable Pavement	1	45.23	57000
S77	Permeable Pavement	2	58.12	3000000
S81	Permeable Pavement	2	63.66	2000000
S83	Permeable Pavement	4	69.61	1500000
S88	Permeable Pavement	2	64.54	1000000
S89	Permeable Pavement	2	54.93	1500000
S91	Permeable Pavement	3	68.54	150000

3.4.3 Modified Bioretention

In this thesis, to increase infiltration capacity within the bioretention method, the curve number in some subcatchments was changed in order to increase infiltration and improve bioretention. The "modified bioretention" approach involves adjusting the conventional bioretention cells by modifying the curve number in specific subcatchments to enhance infiltration and improve performance. This adaptation aims to address any limitations or challenges encountered with standard bioretention cells.

To implement the modified bioretention method in the area, the following steps can be taken:

1. Site assessment: Identify suitable subcatchments within the study area where the modified bioretention approach can be implemented effectively. Consider factors such as soil characteristics, land use, and proximity to sources of stormwater runoff.

2. Curve number modification: The curve number in the selected subcatchments is adjusted to promote increased infiltration. The curve number represents the runoff potential based on land cover and soil conditions. By modifying the curve number, greater infiltration of stormwater is encouraged, and the natural drainage system is enhanced.

3. Design considerations: The appropriate modified curve numbers for the specific subcatchments are determined based on the desired infiltration rates and local conditions. Factors such as soil type, vegetation, and anticipated rainfall patterns are considered.

4. Construction and implementation: The modified bioretention cells are constructed in the designated subcatchments. Factors such as drainage area, soil preparation, selection of suitable vegetation, and proper installation of infiltration and drainage layers are taken into account.

The modified bioretention approach can be seen as a favorable option compared to other methods like permeable pavement for several reasons:

1. Flexibility: Modifying the curve number in specific subcatchments allows for a more targeted approach to enhance infiltration. This flexibility enables the addressing of the unique characteristics and challenges of each subcatchment within the study area.

2. Cost-effectiveness: The modified bioretention approach may offer cost advantages compared to permeable pavement, as it may require less extensive construction and maintenance. It can be implemented in areas where permeable pavement may not be feasible or cost-effective.

3. Environmental benefits: The modified bioretention method promotes natural drainage processes and encourages the infiltration of stormwater into the soil. This approach helps reduce runoff volume, minimize erosion, and improve water quality by filtering pollutants and sediments.

4. Adaptability: The modified bioretention approach can be tailored to suit specific site conditions and can be adjusted or expanded as needed. It allows for adaptive management and continuous improvement based on monitoring and evaluation results.

By implementing the modified bioretention approach, the opportunity is provided to enhance the performance of bioretention cells in managing stormwater, improving infiltration, and mitigating flooding risks in a more targeted and efficient manner.

3.5 Simulation of Rainfall Series in SWMM

SWMM requires accurate and representative rainfall data to simulate and analyze stormwater runoff in urban areas. The rainfall data serves as a crucial input parameter for the model, influencing the simulation results and the performance assessment of the stormwater drainage system. The graphs presented in Figure 17 depict the rainfall data utilized for modeling in SWMM in this study.

In this study, rainfall data were collected from reliable sources such as regional weather databases which provide historical records of rainfall measurements, capturing the intensity, duration, and temporal distribution of rainfall events in the study area.

To incorporate the rainfall data into the SWMM model, it was necessary to define the rainfall input based on the desired return periods. Return periods represent the average recurrence intervals of rainfall events, indicating their likelihood of occurrence within a specific time frame. Four different return periods including 5, 25, 50, and 100 years were considered for current modeling and simulating stormwater runoff in SWMM.

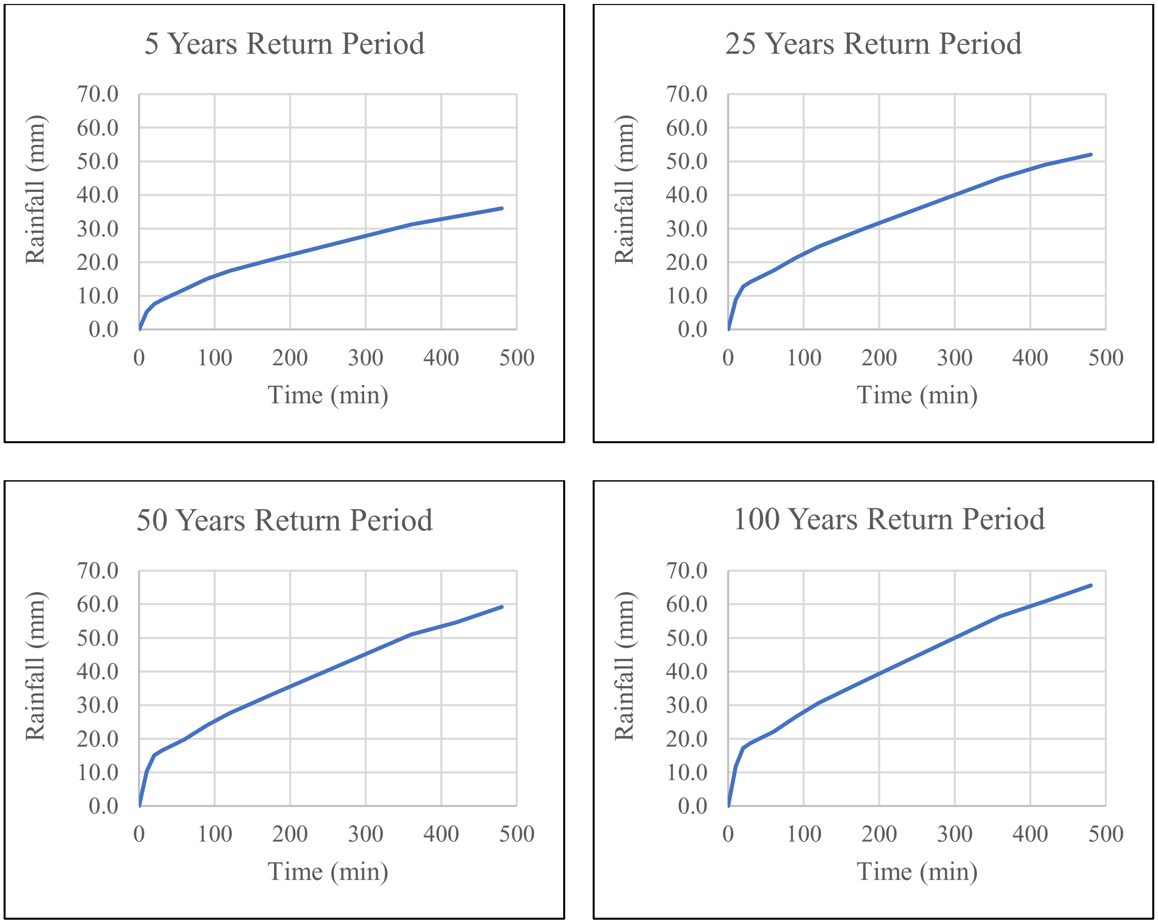

Figure 17. Rainfall time series for the city of Shiraz under 5, 25,50, and 100 years Return Period

Chapter 4: Results and Discussion

This chapter presents the results and analysis of the stormwater management strategies employed in the study area. The chapter aims to provide a comprehensive evaluation of the effectiveness of various LID methods in mitigating runoff and reducing flooding risks.

The chapter begins with an overview of the total runoff mapping for the study area without the implementation of any LID method. This baseline assessment sets the stage for understanding the existing runoff patterns and serves as a reference for evaluating the impact of the applied stormwater management techniques. The absence of LID modeling reflects the existing management system employed in the city of Shiraz.

Following the total runoff mapping, the analysis of node flooding will be presented. This analysis focuses on specific nodes within the stormwater system and evaluates the performance of each LID method in reducing flooding at these critical locations. By comparing the node flooding results between different LID techniques and the No-LID scenario, valuable insights can be gained into the effectiveness of each method in mitigating flood risks.

To further assess the impact of the LID methods on runoff, the chapter presents mapping results that incorporate the application of various LID techniques. These maps depict the spatial distribution of runoff after the implementation of each method, highlighting localized changes in runoff patterns. By visualizing the impact of LID techniques on runoff distribution, valuable information can be obtained regarding the effectiveness of different methods in managing stormwater.

Additionally, assessment of node flooding with LID methods is presented. This analysis focuses on the performance of each specific LID technique in reducing flooding at individual nodes. The findings from this assessment provide valuable insights into the effectiveness of each LID method in mitigating flood risks at critical locations.

To provide a comprehensive understanding of the runoff characteristics and associated risks, also Cumulative Distribution Function (CDF) curves are presented. These curves illustrate the probability of exceeding specific runoff volumes for each LID method and allow for a comparative analysis of their performance. By examining the CDF curves for different return periods, the chapter provides valuable insights into the ability of each LID technique to manage runoff and reduce flood risks.

4.1 Total Runoff Mapping without LID Method

The map of total runoff in the study area reveals valuable insights into the spatial distribution, temporal variations, and management implications of runoff patterns (Figure 18). The diverse spatial distribution of total runoff across the area is immediately noticeable, with certain regions exhibiting higher runoff values, indicating areas that are more susceptible to flooding. These hotspots of runoff concentration require careful attention and targeted flood management strategies to mitigate potential damages. Moreover, variations in runoff intensity can be observed across different parts of the area, suggesting the influence of local topography, land use patterns, and drainage infrastructure.

Temporal variations in total runoff between different return periods provide crucial insights into the hydrological dynamics of the study area. The comparison of runoff patterns for each return period highlights areas that consistently experience high runoff volumes, serving as indicators of flood-prone regions. Comparing total runoff values across different return periods enables the assessment of significant differences and their implications for flood management. Identifying return periods with substantial increases or decreases in runoff aids in making informed decisions regarding the selection of appropriate return periods for design and planning purposes. This understanding helps prioritize investments in infrastructure, land-use planning, and flood control measures to effectively manage flood risks.

One of the important outputs of the SWMM simulation is the total runoff, which represents the total rate of surface runoff during a precipitation event. In this section, the maps of the runoff for the city of Shiraz, without the implementation of low-impact development techniques has been presented. The maps cover the different return periods, including 5, 25, 50, and 100 years.

Figure 18 presents the runoff values for the studied area under different return periods, with Figure 18 corresponding to the 5-year return period, Figure 19 to the 25-year return period, Figure 20 to the 50-year return period, and Figure 21 to the 100-year return period. In these maps, it can be observed that several areas are located within the flood zone and become inundated during flood events. The red color represents areas that are unable to effectively handle the incoming floodwater, leading to accumulation of water and flooding. These regions are considered flood-prone areas where the drainage system is unable to accommodate the volume of water and discharge, often due to inadequate design of urban drainage channels.

The presence of red-colored subcatchments signifies the high risk of flooding in those areas. The accumulation of floodwater can result in various consequences, including financial losses, damage to infrastructure and property, potential transmission of waterborne diseases, and threats to human safety.

On the other hand, the blue color in the map indicates subcatchments that have the capacity and capability to accommodate the incoming floodwater, remaining stable during flood events. These areas demonstrate a more efficient drainage system, with the ability to handle and channel the excess water, thereby minimizing the risk of flooding.

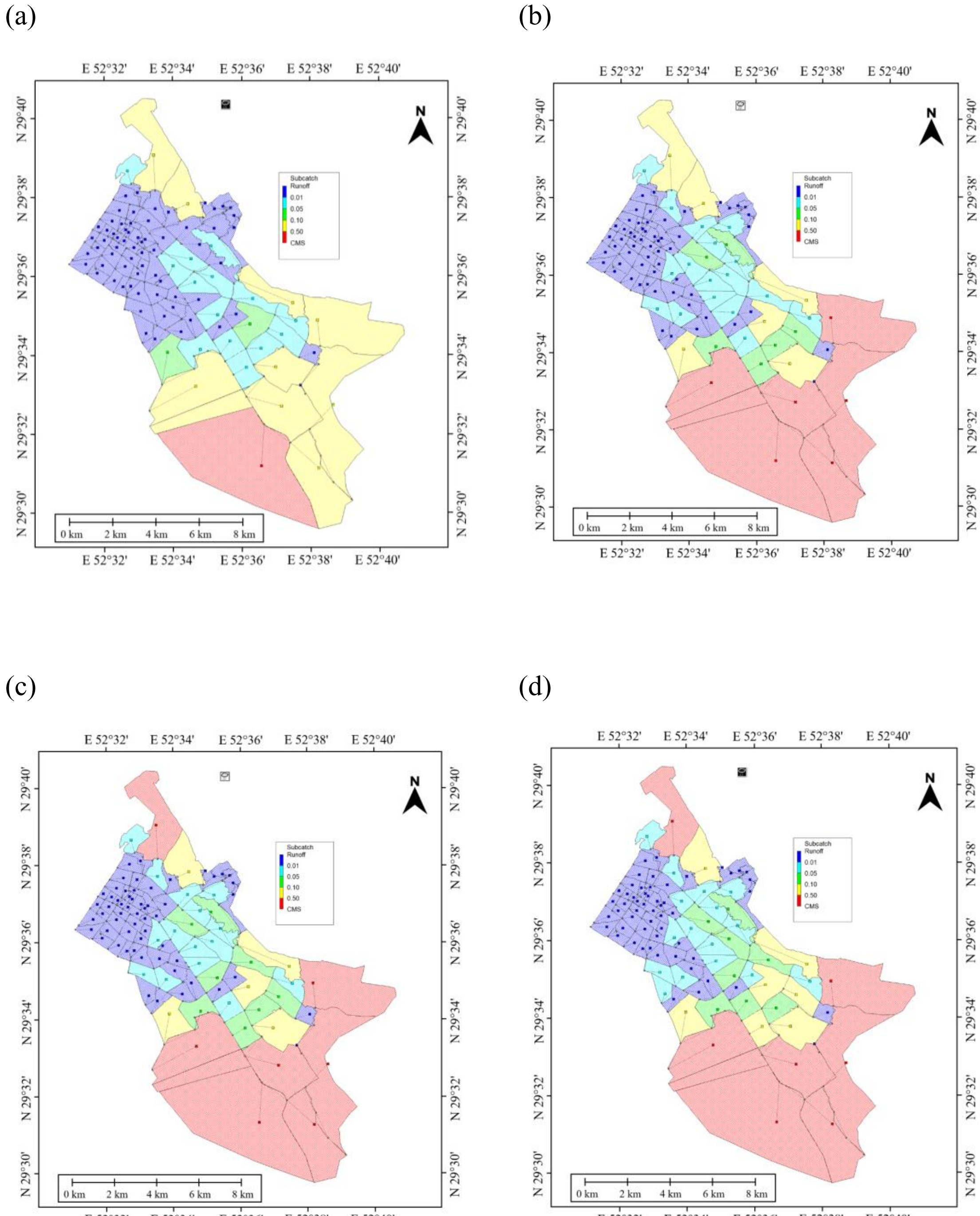

Figure 18. The Map of Total Runoff in the Study Area of Shiraz, Iran, using SWMM without LID under (a) 5-year (b) 25-year (c) 50-year, and (d) 100-yea Return Period

4.2 Node Flooding Analysis without LID Method

The evaluation of node flooding, obtained from SWMM, played a significant role in understanding the implications and importance of flood management in the study area. The results obtained from SWMM provided valuable insights into the behavior and dynamics of water flow within the drainage system.

By examining the node flooding data, it was possible to assess the extent to which individual nodes were prone to flooding under the considered specific return period. By understanding the nodes that are most susceptible to flooding, appropriate measures can be implemented to reduce the impact of floods on the surrounding areas.

Furthermore, the analysis of node flooding data from SWMM allowed for the evaluation of the effectiveness of existing drainage systems and the identification of potential improvements. It helped highlight areas where modifications or upgrades to the drainage infrastructure could enhance the resilience of the system and reduce the risk of flooding.

By focusing on a specific return period (25-year return period) in this section, the severity and extent of flooding at individual nodes were evaluated, providing valuable insights into areas of vulnerability and potential risks. The 25-year return period represents a moderate but significant level of rainfall intensity and recurrence that strikes a balance between shorter and longer return periods. The 25-year return period is often used as a standard benchmark in engineering and urban planning practices to assess and design infrastructure systems, including stormwater management. Although the explanation here is based on the 25-year return period, it is important to note that data for all the other return periods (5, 50, and 100 years) were also collected and analyzed by SWMM. To ensure a comprehensive presentation of the results, the detailed findings for these return periods have been included in the appendix of this thesis.

Continuing with the analysis of the results, in Table 4, the detail of node flooding in the study area for 25-year return periods are presented which indicate hours of maximum flooding and the total flood volume. The table presented in this section provides valuable insights into the nodes within the stormwater drainage system that experience flooding. Similar tables for other return periods have been provided in appendix A.

One of the parameters listed in the tables is "Hours Flooded" which indicates the total number of hours that a particular node experiences water levels above a predetermined flood threshold. It helps identify the nodes that are most susceptible to flooding and provides an understanding of the duration of inundation.

Another parameter included in the table is "Maximum Rate CMS," which represents the peak flow rate of water passing through each flooded node. This parameter is expressed in CMS and reflects the intensity of water flow during the flooding event. Identifying the nodes with the highest flow rates allows for targeted interventions and infrastructure improvements to manage excessive water levels and mitigate potential damages.

The "Hours of Maximum Flooding" parameter provides information on the duration during which each node experiences the highest flooding. This duration indicates the period when the water level or flow rate reaches its peak at each respective node. Understanding the timing of peak flooding is crucial for emergency response planning, as it helps allocate resources and prioritize actions during critical periods.

Lastly, the "Total Flood Volume" parameter quantifies the cumulative volume of floodwater that passes through each flooded node during the specified time period. This parameter, expressed in million liters, provides an overall measure of the amount of water that flows through the node. It helps assess the total impact of flooding on the drainage system and can guide decision-making for infrastructure improvements or the implementation of flood control measures.

Among these junctions, J77, situated downstream of the city, stands out as being heavily impacted by flooding. The total volume of flooding at this junction is estimated to be 305.248*10^3 m^3, which accounts for approximately 12% of the total flooding observed in the study area. The simulation results indicate that 42.5% of all junctions in the area are flooded under the 25-year return period. The result underscore the implications of rapid urbanization and an inadequate drainage system on the increased risk of urban flooding. As urban areas experience growth, the downstream area of the town becomes particularly vulnerable to high levels of flooding.

Table 4. Summary of Node Flooding in the Stormwater Drainage System for a 25-year Return Period.

Node	Hours Flooded	Maximum Rate CMS	Hours of Maximum Flooding	Total Flood Volume (1000 m^3)
J1	4.87	1.635	8:10	8.415
J2	4.25	1.423	8:10	4.303
J3	8.4	2.324	8:10	30.52
J6	5.68	1.527	8:10	6.257
J7	2.01	2.018	8:11	5.163
J11	0.61	1.168	8:11	0.819
J13	0.5	1.1	8:13	0.691
J18	1.63	1.707	8:13	4.635
J19	6.38	2.527	8:10	24.585
J20	3	1.258	8:10	2.909
J22	6.16	2.607	8:11	18.155
J23	0.24	0.743	8:14	0.297
J25	1.62	1.132	8:12	2.454
J27	8.03	2.781	8:10	21.645
J29	8.16	2.058	8:10	12.9
J30	18.07	3.145	8:10	73.753
J31	14.36	2.631	8:10	42.084
J32	2.41	1.12	8:10	2.161
J35	0.59	1.121	8:11	0.749
J36	10.76	3.739	8:10	40.608
J37	10.56	3.128	8:10	43.82
J38	2.3	1.671	8:10	3.63
J39	16.06	2.675	8:10	36.026
J40	0.29	0.893	8:12	0.359
J44	10.52	3.504	8:12	29.332
J46	9.7	2.423	8:10	17.182
J47	1.49	1.594	8:10	2.59
J48	12.91	2.805	8:10	46.985
J49	0.87	1.414	8:10	1.419

Table 4 Continued. Summary of Node Flooding in the Stormwater Drainage System for 25-year Return Period.

J50	5.88	1.945	8:10	8.911
J51	20.62	2.101	8:10	58.313
J54	11.43	2.118	8:10	15.677
J55	12.26	3.126	8:11	30.676
J58	19.01	2.171	8:10	27.815
J60	9.29	2.234	8:10	23.375
J61	22.24	4.363	8:10	106.059
J62	17.6	3.165	8:10	50.242
J63	15.79	3.566	8:10	75.384
J64	4.58	2.316	8:10	9.025
J65	20.75	6.161	8:10	113.629
J66	6.87	2.246	8:10	14.307
J67	11.49	2.781	8:10	26.232
J68	8.21	2.338	8:10	14.353
J69	15.1	2.73	8:10	52.748
J70	0.55	1.145	8:10	0.767
J71	1.68	2.353	8:09	5.396
J72	10.55	3.996	8:10	49.984
J73	13.86	4.432	8:10	53.425
J75	6.24	3.903	8:10	22.458
J76	22.21	6.447	8:10	107.553
J77	22.38	11.018	8:10	305.248
J78	22.47	6.377	8:10	154.366
J80	10.11	3.746	8:10	33.53
J81	3.31	2.458	8:10	8.171
J83	22.55	7.372	8:10	163.884
J85	5.25	3.028	8:10	14.707
J86	1.09	1.909	8:10	2.416
J88	0.93	1.221	8:10	1.16
J89	22.66	3.602	8:11	42.484
J91	22.74	3.411	8:16	90.899
J92	14.94	1.552	8:10	29.001
J93	6.84	0.317	3:06	4.553
J94	0.52	1.159	8:12	0.785
J95	1.17	0.172	9:11	0.396
J96	15.5	2.711	8:10	54.396
J97	17.38	1.705	8:09	50.265
J99	18.91	0.137	2:32	6.773
J103	20.54	0.481	16:38	26.857
J104	0.46	0.252	8:43	0.204
J109	22.79	0.561	23:35	44.729

The Figure 19 displays the distribution of flooded junctions within the study area, indicating the severity of flooding experienced at each location. The probability plot (Figure 20) generated from the analysis of flooding in junctions reveals the presence of five outlier data points (highlighted in Figure 19). These outliers represent junctions that experienced significantly higher flooding volumes compared to the majority of the other junctions in the study area. The flooding volumes associated with these outlier junctions are as follows:

Junction 76: $107.553*10^3$ m^3

Junction 65: $113.629*10^3$ m^3

Junction 78: $154.366*10^3$ m^3

Junction 83: $163.884*10^3$ m^3

Junction 77: $305.248*10^3$ m^3

Which are 4.5, 4.8, 6.5, 6.9 and 12.8 percentage of the node flooding, with the total flooding of 35.5% in all nodes in the study area, respectively.

The presence of these outliers is noteworthy and indicates specific junctions that are highly susceptible to flooding. These junctions may possess unique characteristics or be influenced by specific factors that make them more prone to experiencing extreme flooding events. It is crucial to investigate these outlier junctions further to understand the underlying reasons for their higher flooding volumes.

Identifying and analyzing these results provide valuable insights for urban planning and flood management strategies. It highlights the importance of implementing targeted measures in the identified junctions to mitigate the risks associated with flooding. By focusing on these specific locations, resources and efforts can be directed more efficiently to reduce the potential impact on infrastructure, properties, and the well-being of residents. By addressing the vulnerabilities and implementing appropriate mitigation measures, it is possible to enhance the overall resilience of the drainage system and reduce the overall flood risk in the study area.

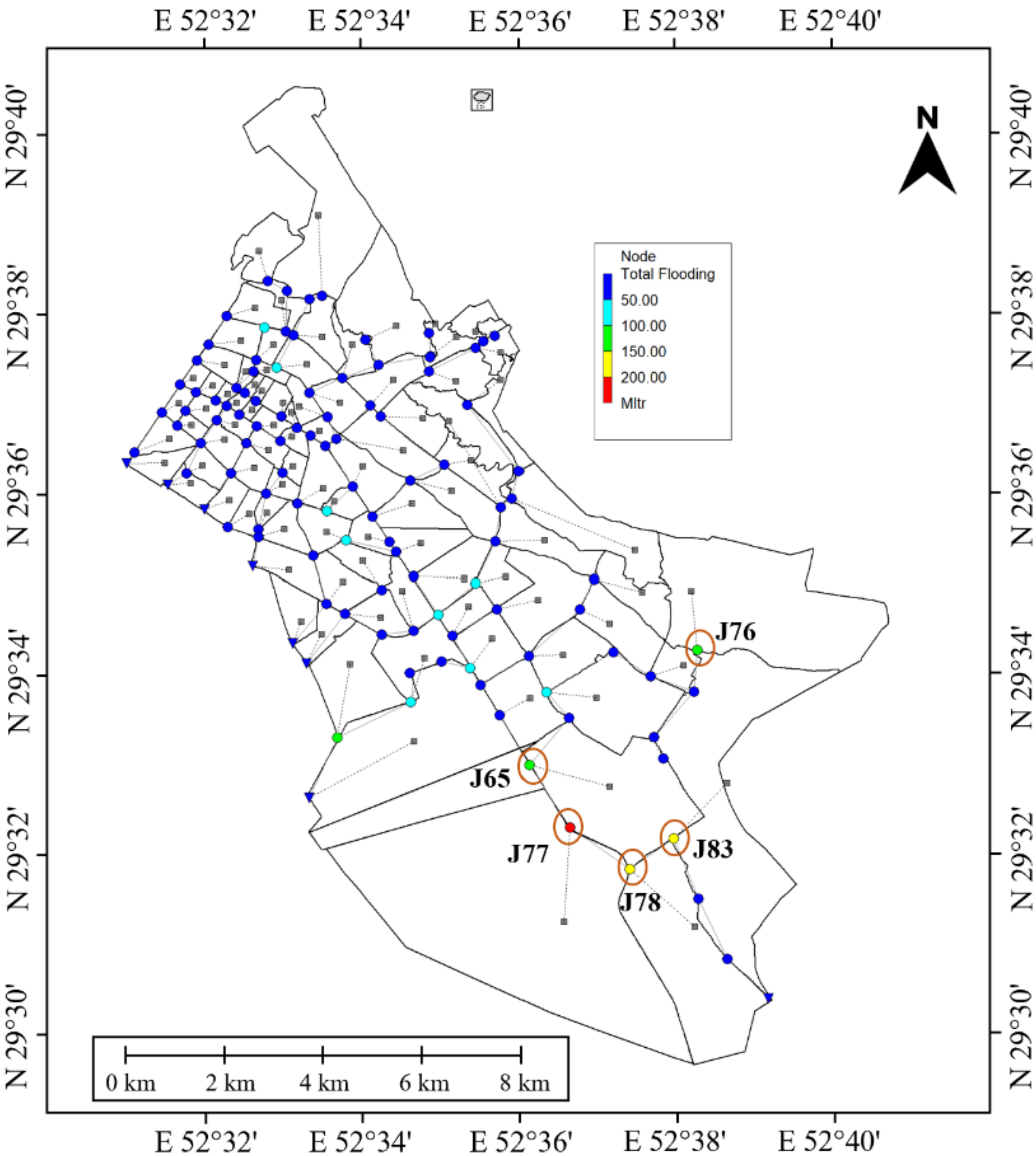

Figure 19. The performance of the stormwater drainage system of Shiraz city under 25-year period.

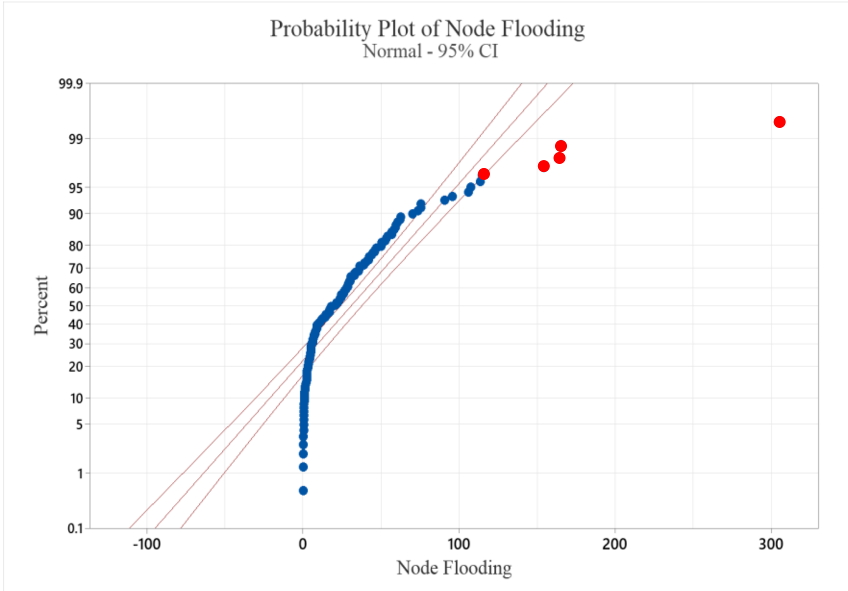

Figure 20. The probability plot of node flooding for study area under 25-year return period using Minitab.

4.3 Mapping Total Runoff with LID Methods

To reduce the total runoff and modify the extent of flooding in the study area the performance of various LID techniques has been evaluated by SWMM. The LID techniques considered include bioretention cells (BR), permeable pavement (PP), modified bioretention (Modified BR), and a combination of bioretention and permeable pavement (BR+PP).

By analyzing the results obtained from the study, it is evident that the application of LID techniques has successfully reduced the total runoff in the study area. This reduction signifies the ability of these techniques to retain, infiltrate, and manage stormwater effectively.

Figure 21 to Figure 24 show that the adoption of BCs, PP, and their combinations has led to a substantial decrease in the overall runoff volumes, indicating their effectiveness in mitigating stormwater runoff. Figure 25 and Figure 26 also provide an overview on a percent reduction and the volume reduction in the total runoff. Areas that were previously classified as "very highly flooded" have transitioned to "highly flooded," while areas categorized as "highly flooded" have transformed into "fairly flooded." This shift indicates that the LID techniques have effectively attenuated the intensity of flooding events in the study area.

The observed modifications in the flooding extent demonstrate the positive impact of LID techniques in reducing the vulnerability of the study area to flood risks. The implementation of bioretention cells, permeable pavement, and their combinations has contributed to the overall resilience of the drainage system and the urban environment. The modified flooding patterns highlight the potential of these techniques to enhance the overall flood management strategies in the study area and mitigate the potential damage associated with excessive stormwater runoff.

Bioretention cells are designed to capture and treat stormwater by allowing it to infiltrate into the soil and undergo natural biological processes. In Figure 21, the map shows the extent of runoff reduction achieved by bioretention cells under various return periods, namely 5-year, 25-year, 50-year, and 100-year. For each return period, the map indicates the areas where bioretention cells effectively reduce the total runoff volume. By doing so, bioretention cells help decrease the volume of stormwater reaching the drainage system, reducing the risk of flooding in the study area.

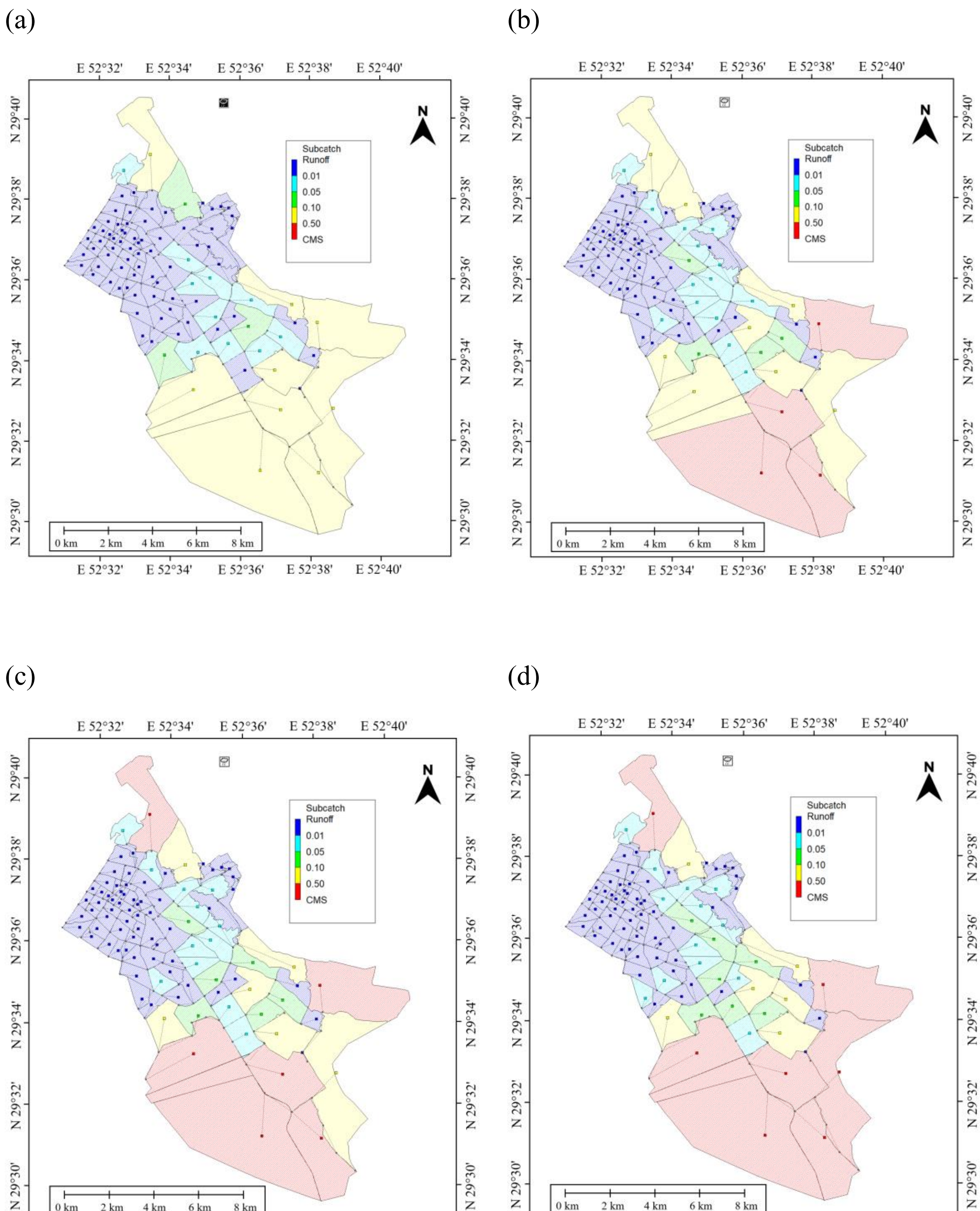

Figure 21. The Map of Total Runoff in the Study Area of Shiraz, Iran, using SWMM with LID (BR) under (a) 5-year (b) 25-year (c) 50-year, and (d) 100-yea Return Period

Permeable pavement is a type of pavement that allows water to pass through it, promoting water infiltration into the ground. When rainwater falls on permeable pavement, it permeates through the surface and infiltrates into the ground below. The pavement's porous structure and underlying layers provide storage capacity for water, allowing it to slowly infiltrate into the soil or be absorbed by vegetation. This infiltration process helps to mimic the natural water cycle, where rainfall is absorbed by the ground, replenishing groundwater reserves and reducing surface runoff.

Figure 22 shows the map of total runoff under 4 return periods which provides a visual representation of the amount of water that would potentially flow over the surface during specific return period events. It considers the combined effects of precipitation, land characteristics, and the implementation of permeable pavement as an LID method.

Figure 25 and Figure 26 show that by incorporating permeable pavement as an LID technique, surface runoff decreases by allowing water to infiltrate through the pavement and into the underlying soil. This infiltration process helps to mitigate the impacts of urbanization and reduce the potential for flooding in the study area. The map provides valuable information for decision-makers and urban planners in Shiraz, as it indicates areas that are more susceptible to runoff and can assist in identifying locations where the implementation of permeable pavement may be most effective in reducing flood risks.

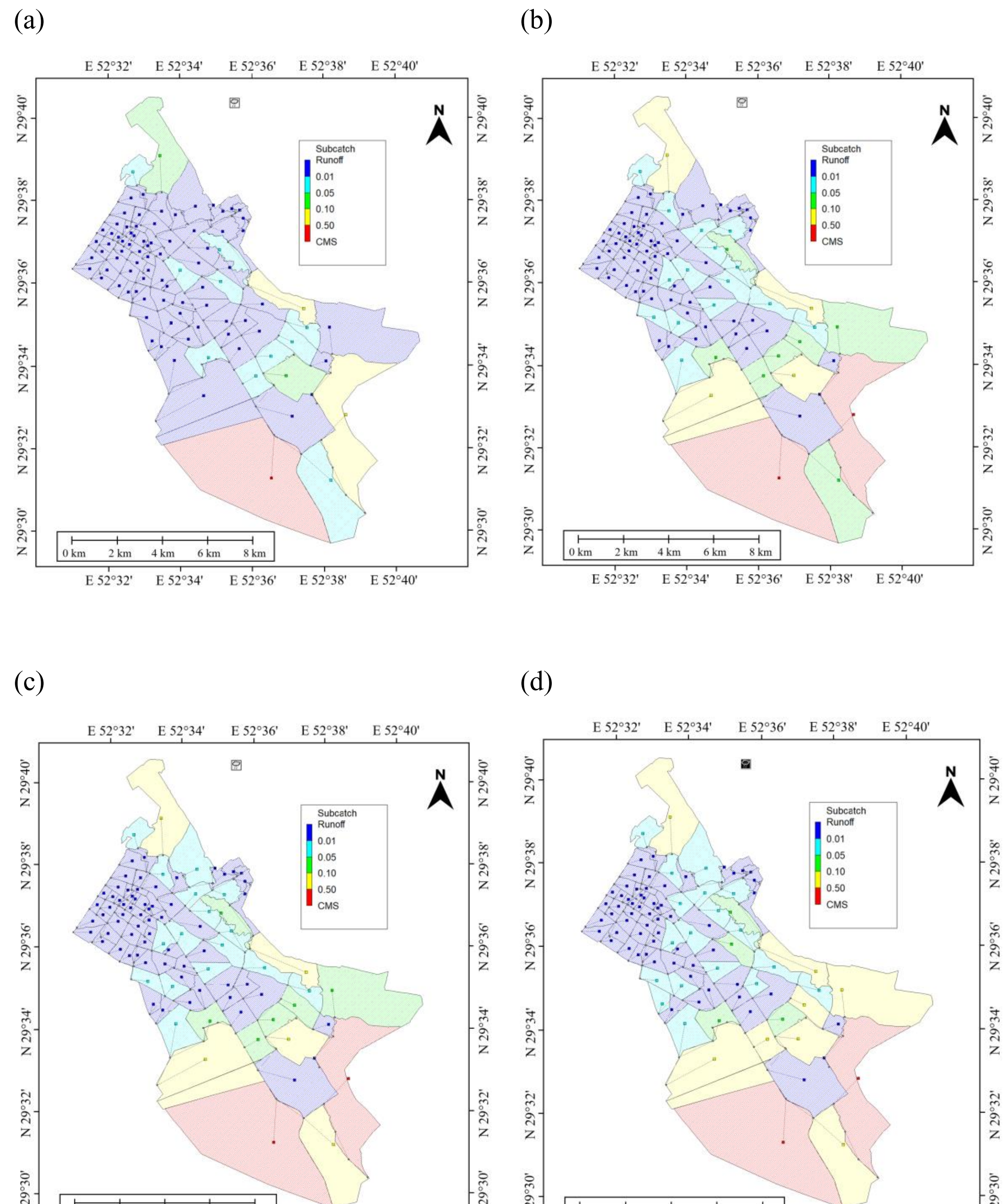

Figure 22. The Map of Total Runoff in the Study Area of Shiraz, Iran, using SWMM with LID (PP) under (a) 5-year (b) 25-year (c) 50-year, and (d) 100-yea Return Period

In pursuit of enhancing the effectiveness and resilience of the stormwater management system, significant advancements have been made to previous methods. One such improvement involves the integration of bioretention cells and permeable pavements, which offers a more robust approach. Additionally, modifications have been made to the bioretention method itself, further optimizing its performance. These innovations aim to enhance the overall efficiency of stormwater management, providing sustainable solutions that effectively address water runoff and contribute to environmental preservation.

By incorporating natural processes and enhancing infiltration, the integrated approach helps manage larger volumes of stormwater and reduces the strain on the drainage system during extreme rainfall events.

Figure 23 and Figure 24 show the distribution and magnitude of total runoff in the study area with combined and modified LIDs under the 4 return periods. The map provides a visual representation of the benefits of combining bioretention cells with permeable pavement for stormwater management in the study area of Shiraz. It highlights the potential for reducing runoff and minimizing flood risks under different return periods. This integrated approach not only helps to manage stormwater effectively but also offers additional environmental benefits, such as improved water quality, enhanced biodiversity, and a more resilient urban landscape.

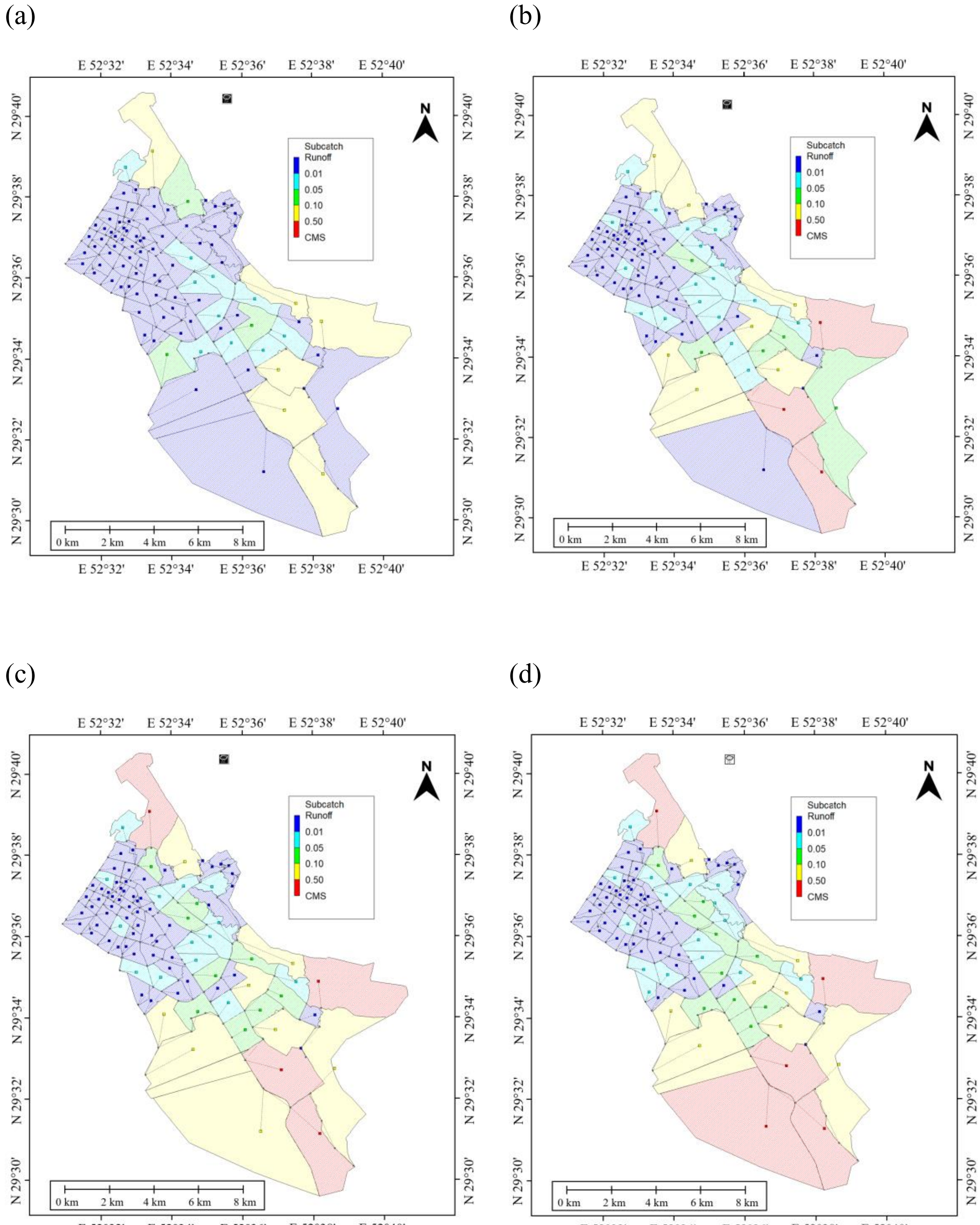

Figure 23. The Map of Total Runoff in the Study Area of Shiraz, Iran, using SWMM with LID (Modified BR) under (a) 5-year (b) 25-year (c) 50-year, and (d) 100-yea Return Period

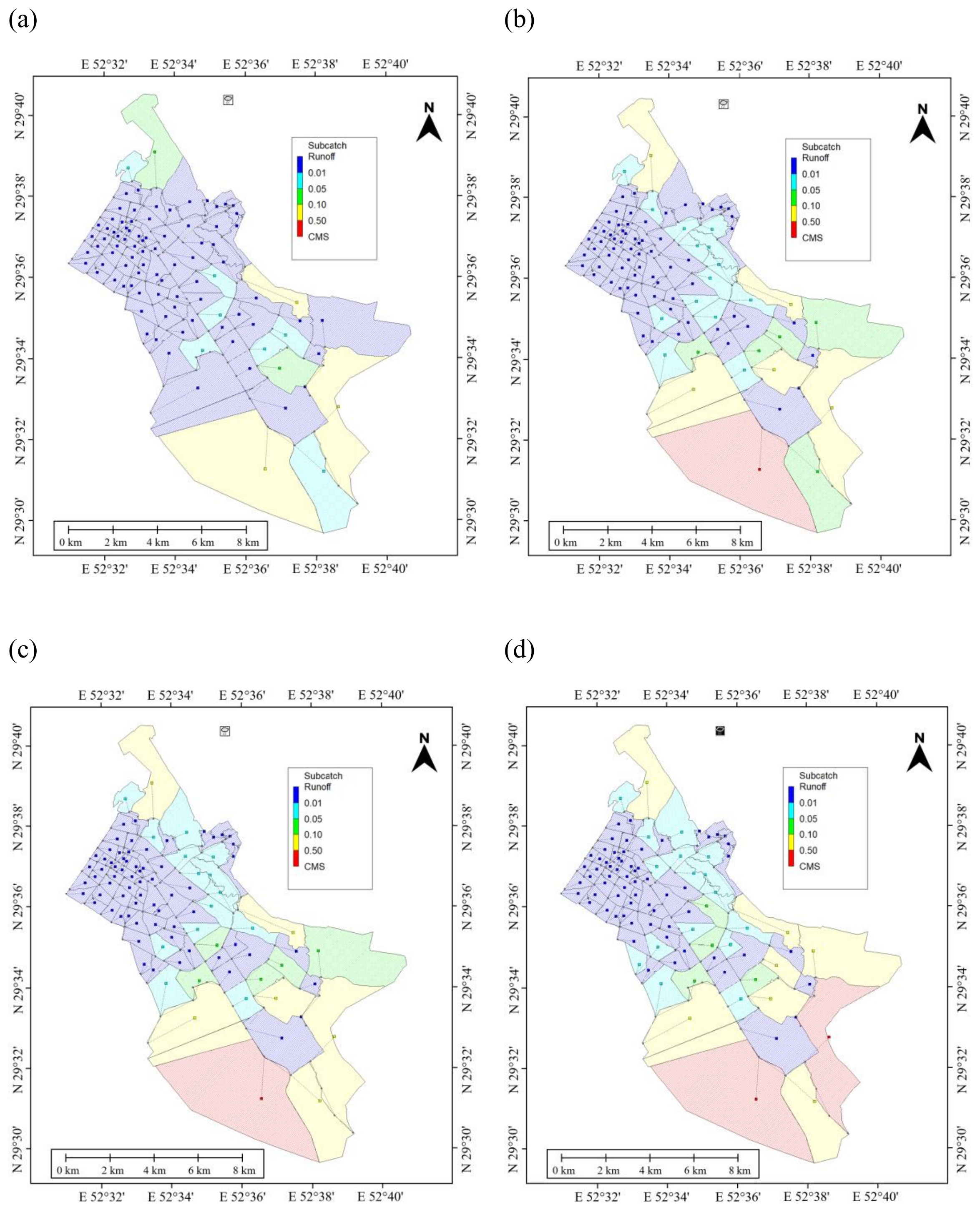

Figure 24. The Map of Total Runoff in the Study Area of Shiraz, Iran, using SWMM with LID (BR+PP) under (a) 5-year (b) 25-year (c) 50-year, and (d) 100-yea Return Period

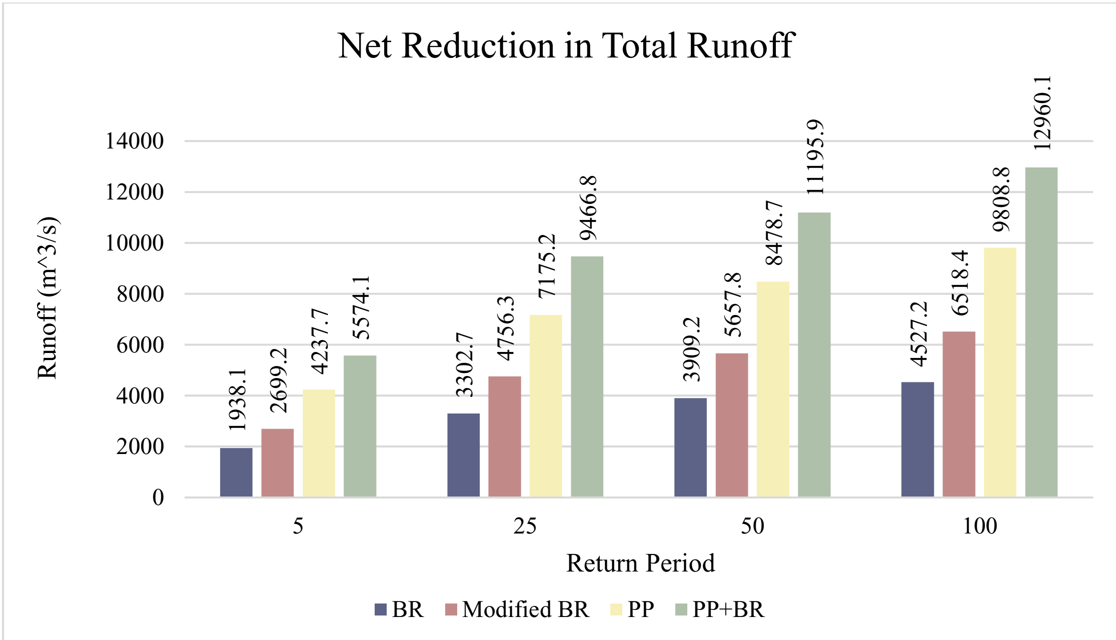

Figure 25. Net Reduction in Total Runoff Volume in the study area by implementing different LIDs under 4 return periods.

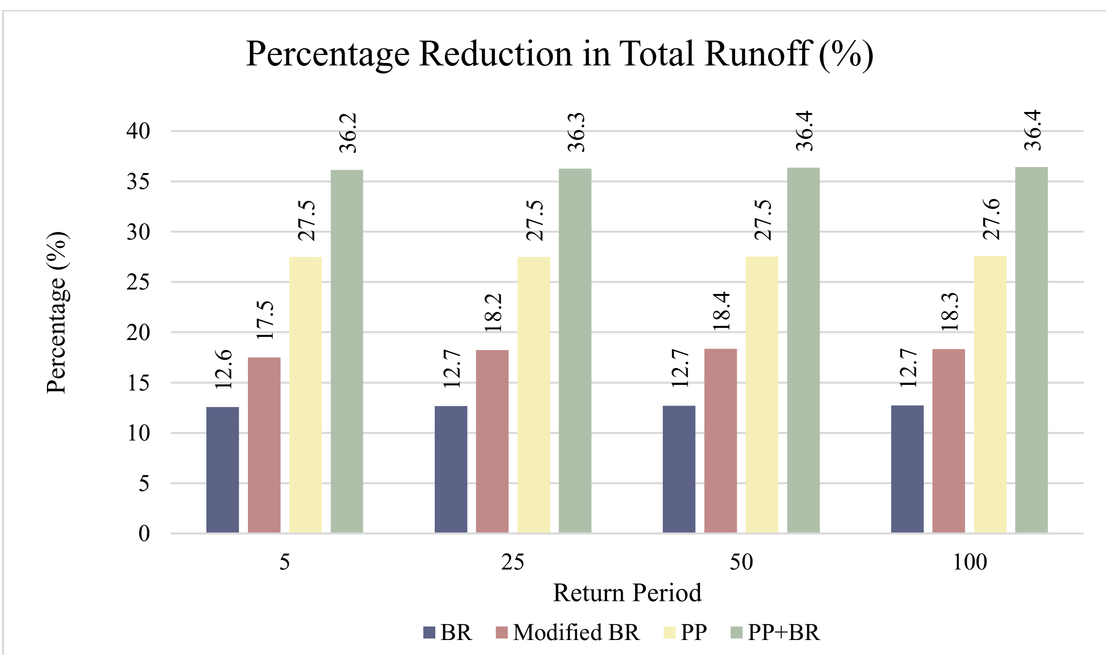

Figure 26. Percentage Reduction in Total Runoff (%) in the study area by implementing different LIDs under 4 return periods.

4.4 Node Flooding Assessment with LID Methods

The analysis of node flooding in SWMM model reveals some important findings. It indicates that the implementation of LID measures has resulted in a decrease in the number of nodes experiencing flooding, as well as a reduction in the amount of flooding and flood volumes across different return periods.

Moreover, when comparing different return periods, it is observed that the flood volume has decreased with LID measures. This reduction in flood volume indicates the ability of LID measures to attenuate and manage stormwater runoff during intense rainfall events. By infiltrating, storing, and slowly releasing stormwater, LID measures help to mitigate the risk of flooding and alleviate the burden on the drainage system.

Table 5 Shows the comparison of node flooding with different LIDs for a 25-year return period. The specific examples further emphasize the effectiveness of LID measures in reducing flood volumes at individual nodes within the system. In the case of node J40, without the implementation of LID measures, it experienced a flood volume of $0.36*10^3$ m^3 during the 25-year return period. However, after designing and incorporating LID measures (Bioretention Cells), this node no longer experiences any flood.

However, it is essential to acknowledge that the effectiveness of LID measures like PP may not be as significant, and it can be influenced by various factors, including the interconnectedness of the drainage network. The lack of improvement observed with PP at node J40 may be attributed to specific conditions unique to that node. It is crucial to recognize that PP's performance may show greater efficacy when assessed within the broader system, where it contributes to reducing runoff and enhancing infiltration over a more extensive area. Furthermore, the effectiveness of PP might become more pronounced when evaluating its impact on the entire drainage network rather than examining individual nodes in isolation.

In summary, the variability in performance between Bioretention Cells and Permeable Pavement (PP) can be attributed to multiple factors. A comprehensive assessment of their effectiveness should encompass their contributions to the entire urban drainage system to derive meaningful conclusions regarding their role in flood mitigation.

Similarly, in the absence of LID measures in node 65, it encountered a flood volume of $113.63*10^3$ m^3 under the 25-year return period. However, after implementing LID measures with PP, the flood volume at this node reduced to $7.85*10^3$ m^3. This significant reduction in flood volume indicates that the LID measures employed in the vicinity of node 65 successfully intercepted and managed a significant portion of the stormwater runoff, thereby mitigating the potential for flooding.

In appendix B, additional tables are provided to illustrate the flood volumes for various return periods in the study area. These tables present the node flooding data for each return period, both with and without the implementation of LID measures. The tables offer a comprehensive overview of the impact of LID measures on flood mitigation.

One of the most vulnerable nodes in the system is node 77. Analyzing the flooding volumes for node J77 under different methods (No LID, BR, PP, Modified BR, and BR+PP) can help evaluate the effectiveness of each technique in mitigating flooding. Comparing the flooding volumes, it is evident that the No LID scenario resulted in the highest flooding volume of 305.25*103 m3. This indicates that without any stormwater management measures in place, node J77 experienced significant flooding during the simulation period.

On the other hand, the scenarios involving stormwater management techniques exhibited reduced flooding volumes. Among these scenarios, Modified BR had the lowest flooding volume of 74.13*103 m3, followed by BR+PP with 108.38*10^3 m^3. This shows that the modified BR and its combination with PP can achieve reductions of 76% and 64% in the total flooding at node J77.

The BR scenario resulted in a flooding volume of 136.81*10^3 m^3, indicating that the bioretention technique alone provided a moderate reduction in flooding. Similarly, the PP method showed a flooding volume of 285.67*10^3 m^3, indicating that PP also contributed to mitigating flooding but to a lesser extent than the combined approaches. Overall, the analysis of the node flooding results provides valuable insights into the effectiveness of different stormwater management techniques in reducing flooding at different nodes. The findings highlight the importance of implementing comprehensive approaches to mitigate flooding and enhance the resilience of the drainage system.

Table 5. Comparison of Node Flooding in the study area with different LID methods for a 25-year Return Period

Node	No LID	BR	PP	Modified BR	BR+PP
J1	8.42	5.87	7.70	2.26	4.62
J2	4.30	2.03	1.04	1.32	0.12
J3	30.52	28.13	29.18	23.55	23.94
J6	6.26	6.09	6.18	5.87	5.89
J7	5.16	2.07	5.16	2.06	0.90
J11	0.82	0.82	0.82	0.82	0.82
J13	0.69	0.69	N/A	0.69	N/A
J18	4.64	4.64	1.84	4.64	1.84
J19	24.59	24.59	17.62	24.57	17.62
J20	2.91	2.91	2.82	2.91	2.82
J22	18.16	18.16	18.15	9.33	18.15
J23	0.30	0.30	0.30	0.18	0.30
J25	2.45	2.45	2.45	0.98	2.45
J27	21.65	8.88	21.58	4.29	8.82
J29	12.90	12.90	5.34	2.64	5.34
J30	73.75	73.75	21.28	69.05	21.28
J31	42.08	38.22	34.40	38.22	33.66
J32	2.16	0.16	2.10	0.16	0.16
J35	0.75	0.75	0.75	0.75	0.75
J36	40.61	37.28	15.95	37.28	13.86
J37	43.82	34.77	21.28	34.77	21.28
J38	3.63	3.63	3.63	N/A	3.63
J39	36.03	19.00	33.59	19.00	18.07

Table 5 Continued. Comparison of Node Flooding in the study area with different LID methods for a 25-year Return Period

J40	0.36	N/A	0.36	N/A	N/A
J44	29.33	27.28	29.29	25.89	27.18
J46	17.18	17.18	20.32	15.51	20.32
J47	2.59	2.59	N/A	2.59	N/A
J48	46.99	46.99	19.56	44.83	19.56
J49	1.42	1.42	N/A	1.42	1.42
J50	8.91	8.91	8.78	8.91	8.78
J51	58.31	55.45	50.13	56.31	49.53
J54	15.68	15.68	15.28	15.68	15.28
J55	30.68	30.66	30.46	30.66	30.62
J58	27.82	27.52	26.94	27.52	27.31
J60	23.38	23.38	1.59	23.38	1.59
J61	106.06	105.20	52.61	105.06	51.39
J62	50.24	49.78	46.11	49.55	45.26
J63	75.38	73.60	27.31	71.28	26.75
J64	9.03	1.47	9.03	84.50	1.41
J65	113.63	99.43	7.85	N/A	3.97
J66	14.31	14.31	14.31	7.57	14.31
J67	26.23	9.80	24.34	9.80	11.01
J68	14.35	14.03	2.06	14.03	2.06
J69	52.75	49.85	47.00	49.85	45.32
J70	0.77	N/A	0.77	N/A	N/A
J71	5.40	2.67	5.40	0.41	2.67
J72	49.98	42.85	49.98	33.63	42.85
J73	53.43	53.42	8.92	53.42	8.92
J75	22.46	22.46	0.32	22.42	0.32
J76	107.55	107.55	2.97	107.55	2.97
J77	305.25	136.81	285.67	74.13	108.38
J78	154.37	153.76	60.78	152.66	60.20
J80	33.53	33.17	33.53	33.17	33.40
J81	8.17	8.17	N/A	8.17	N/A
J83	163.88	78.90	163.26	29.03	78.25
J85	14.71	3.74	N/A	3.74	N/A
J86	2.42	2.36	2.42	2.36	2.42
J88	1.16	1.16	1.16	1.16	1.16
J89	42.48	42.48	42.49	42.48	42.49
J91	90.90	90.90	77.47	90.87	77.47
J92	29.00	28.12	24.28	28.12	22.80
J93	4.55	4.55	0.12	3.25	0.12
J94	0.79	0.79	0.78	0.79	0.78
J95	0.40	0.33	N/A	0.33	N/A
J96	54.40	54.40	33.98	52.89	33.98
J97	50.27	48.88	22.53	48.88	48.03
J99	6.77	6.67	6.55	6.67	6.61
J103	26.86	26.76	14.21	26.75	12.90
J104	0.20	0.20	N/A	0.20	N/A
J109	44.73	44.73	22.31	44.73	22.31

The percentage of differences in total flooding for each method compared to the system without LIDs are shown in Figure 27. The results obtained from comparing the total flooding percentages for different stormwater management methods (BR, PP, Modified BR, and BR+PP) to the NO LID for various return periods (5, 25, 50, and 100 years) reveal important insights regarding the effectiveness of these techniques (Figure 27). Comparison among the stormwater management methods:

- The combined method of BR+PP consistently demonstrates the highest reductions in total flooding percentages across all return periods, highlighting its effectiveness in flood mitigation.
- The PP method, although performing slightly lower than BR+PP, still exhibits substantial reductions in total flooding percentages, making it a reliable choice for flood control.
- The BR method, while providing notable improvements over the NO LID scenario, shows comparatively lower reductions in total flooding.
- The method of Modified BR demonstrates moderate reductions in total flooding percentages, indicating the additional benefits of modifying BRs in flood management strategies.

Comparison across different return periods for each method:

- All stormwater management methods consistently show higher reductions in total flooding percentages as the return period decreases. This suggests that these techniques are more effective in mitigating flood risks associated with less severe rainfall events.

- The percentage reductions tend to decrease as the return period increases, indicating diminishing returns in flood reduction as the magnitude and frequency of rainfall events increase.
- These two observations underscore crucial aspects of flood mitigation strategies. As the Return Period increases, the flood risk becomes more pronounced, highlighting the need for more effective interventions such as LID measures at higher return periods. However, there is a practical limit where even the most advanced interventions may struggle to cope with exceptionally intense rainfall events at very high return periods. In such cases, the primary objective should shift towards minimizing the impacts and destruction caused by these extreme events, rather than entirely preventing them. This nuanced approach recognizes the importance of adaptive and resilient urban planning that not only seeks to reduce flood risk but also prepares communities to respond effectively to the most severe weather events.

Therefore, the results emphasize the significance of employing stormwater management methods to mitigate urban flooding. The results indicate that employing a combined method initially, followed by PP as the secondary option, proves highly efficient in reducing overall flooding. These insights can guide decision-makers in selecting appropriate stormwater management strategies based on return periods and the desired level of flood reduction.

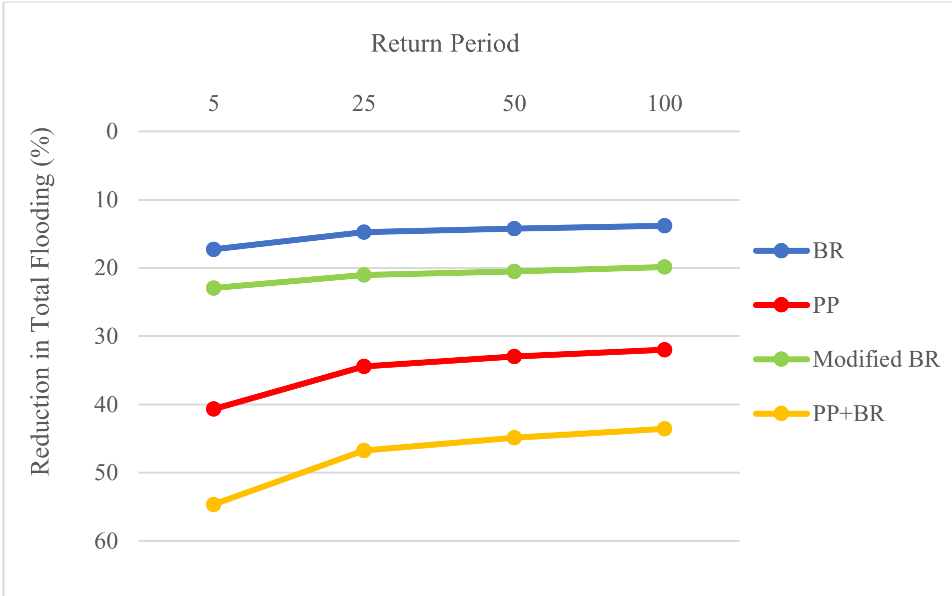

Figure 27. Reduction of total flooding (%) by different LID options: Permeable Pavement (PP), Bioretention (BR), and the combinations (BR+PP, Modified BR).

4.5 Cumulative Distribution Function (CDF) Curves

The cumulative distribution function (CDF) determines the chances that a random variable has a value less than or equal to X. In other words, it sums up the total likelihood up to that point. There is always a range between 0 and 1 in its output. CDFs have the following definition (Equation 9):

$$CDF(x) = P(X \leq x) \qquad (9)$$

The CDF graph generated from the analysis of the LID methods using Minitab (Figure 28 to Figure 31) reveals interesting findings regarding their effectiveness in managing runoff. The figure illustrates the cumulative probabilities of different runoff volumes for each LID method, allowing for a direct comparison of their performance.

For better evaluation a specific amount of total runoff under 25-year return period is considered. For example, consider a runoff volume of $50*10^3$ m^3. Cumulative distribution functions can be used to determine the probability that a runoff volume will be less than $50*10^3$ m^3. The CDF graph shows that without LIDs, the probability that a runoff volume will be $50*10^3$ m^3 or less is approximately 45%. Accordingly, there is a 45% chance of experiencing runoff volumes equal to or below $50*10^3$ m^3 within a given period. The curve representing the "No LID" method is positioned at the lowest level. This indicates that without any LID method, the area experiences the highest runoff volumes and, consequently, higher flood risks.

By implementing the BR method, the statistical output for the normal CDF indicates that runoff volume has a probability of 0.53 for being ≤ 50 which is equivalent to the 53rd percentile., the probability of being equal or less than the same runoff volume increases to approximately 53%. In other words, the BR method has shown to be effective in reducing runoff volumes, as indicated by the higher probability of having lower runoff volumes (≤ $50*10^3$ m^3). This means that with the BR approach, there is a higher likelihood of achieving runoff volumes below the $50*10^3$ m^3 threshold, which is desirable for managing stormwater and reducing flood risk in urban areas.

The CDF graph demonstrates that using PP as a stormwater management method leads to a more substantial reduction in runoff. The probability of being equal or less than 50 million liters change to approximately 67%. This suggests that PP is effective in attenuating runoff and significantly lowering the likelihood of experiencing high runoff volumes.

Combining PP with bioretention enhances the runoff reduction. The higher placement of these curves reflects their ability to achieve significant runoff reduction compared to the other LID methods. The CDF graph shows that the probability of being equal, or less than $50*10^3$ m^3 is approximately 77%. This indicates that the synergistic effect of PP and BR results in a considerable reduction in runoff, significantly lowering the probability of exceeding the specified threshold.

In summary, the CDF graph demonstrates the varying effectiveness of different stormwater management methods in reducing runoff volumes. PP, both individually and in combination with

BR, shows the highest performance in reducing the probability of exceeding the specified threshold. This suggests that PP methods should be given strong consideration when aiming to mitigate runoff in your study area.

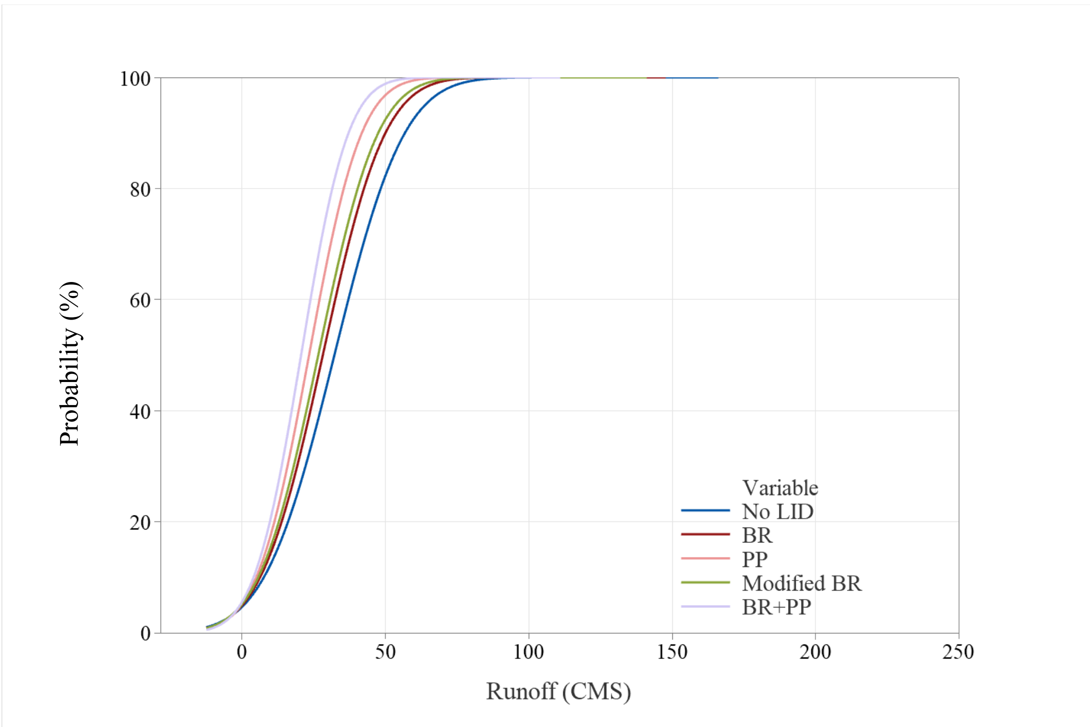

Figure 28. Cumulative distribution function (CDF) of the total runoff under 5-year return period using Minitab

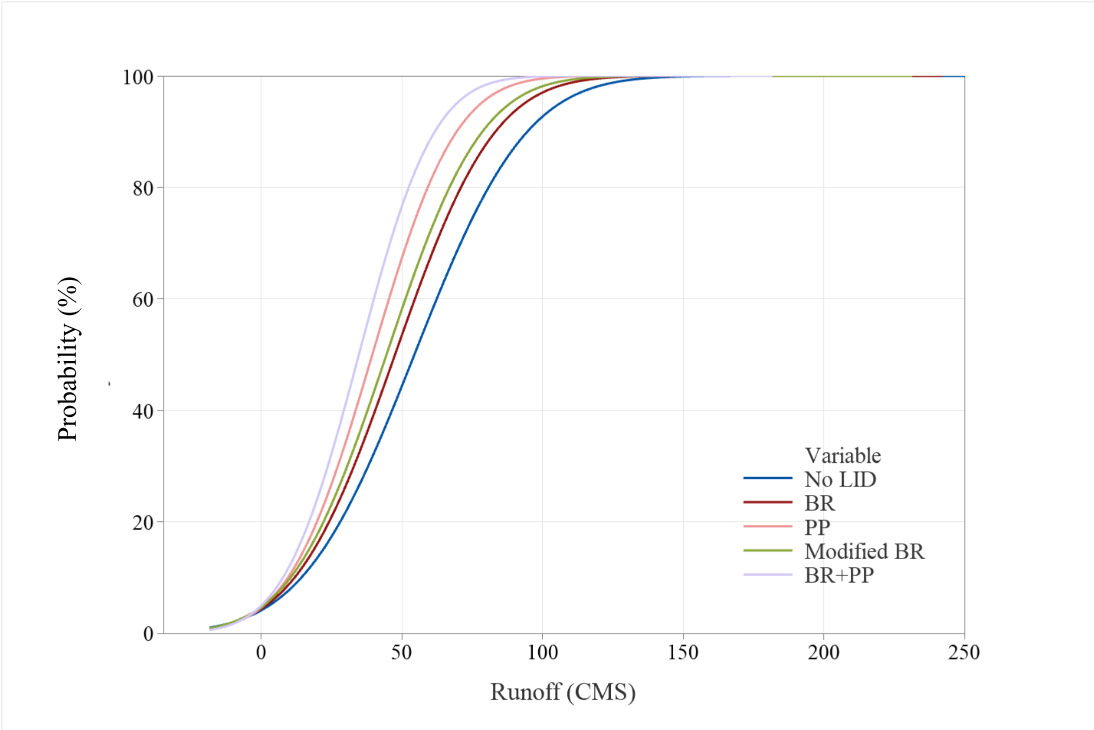

Figure 29. Cumulative distribution function (CDF) of the total runoff under 25-year return period using Minitab

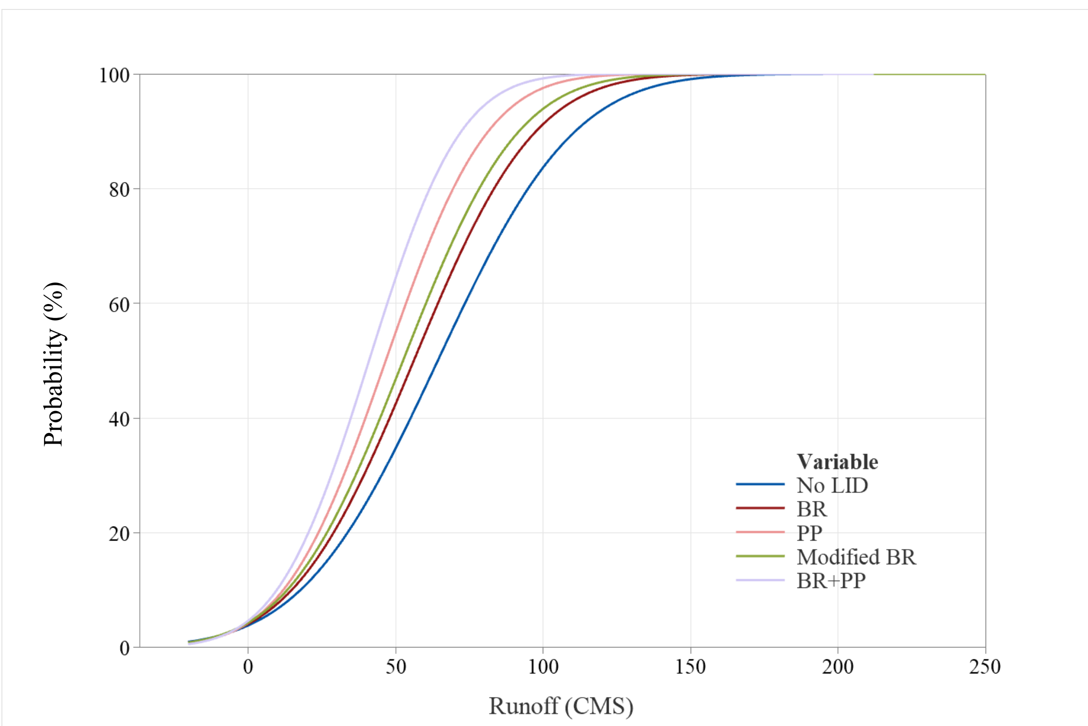

Figure 30. Cumulative distribution function (CDF) of the total runoff under 50-year return period using Minitab

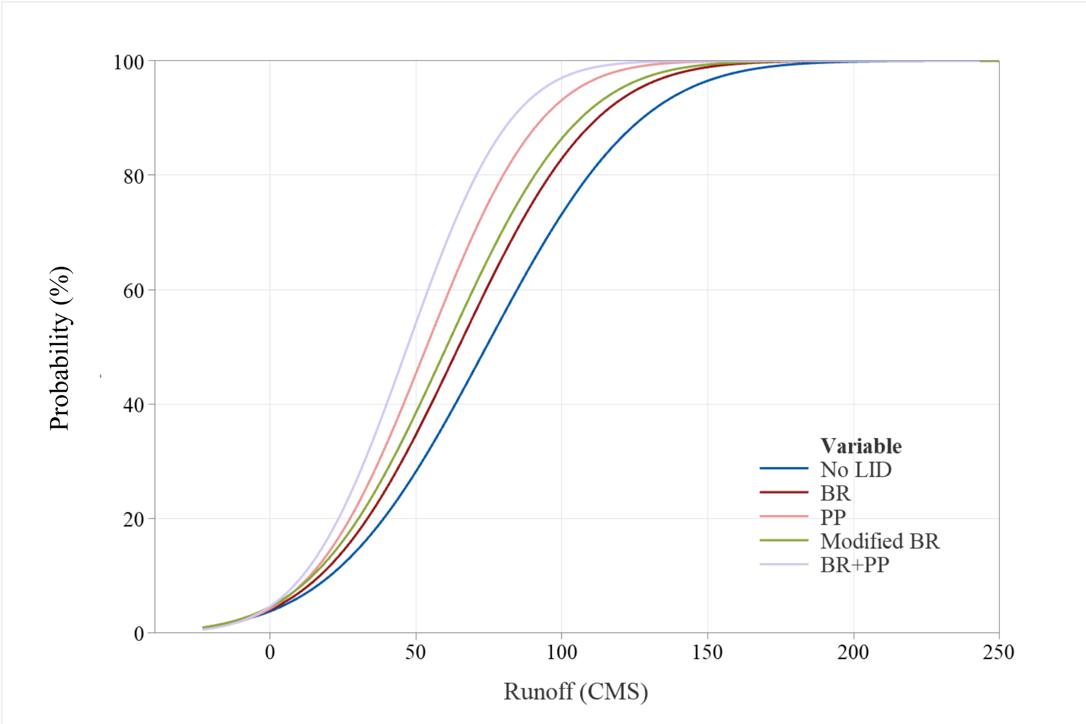

Figure 31. Cumulative distribution function (CDF) of the total runoff under 100-year return period using Minitab

Through the analysis of the CDF curves, the most suitable return period can be determined when designing and implementing LID strategies. This involves evaluating the trade-off between the level of reduction in runoff volumes and the expected lifespan of the LID methods. By selecting an appropriate return period, we can strike a balance between mitigating flood risks and ensuring the long-term effectiveness and viability of the LID solutions. For this reason, the CDF curves for each and return period, are presented in Figure 32 to Figure 36.

For better evaluation a specific amount of total runoff in the study area without LIDs is considered. The probability of non-exceedance a runoff volume of 50 million liters in the study area without any LID methods implemented varies for different return periods. For the 100-year return period, the probability of non-exceedance this runoff volume is 28%. This indicates that in a given storm event with a 100-year return period, there is a 28% chance of the runoff volume being equal or less than 50 million liters.

Similarly, for the 50, 25, and 5-year return period, the probability of non-exceedance the same runoff volume increases to 35%, 45%, and 83%, respectively. This suggests a higher likelihood of experiencing runoff volumes lower 50 million liters with a 50, 25, and 5-year return period.

When considering which return period is better to choose, several factors need to be considered. Firstly, the reduction achieved by the LID methods in each return period can be taken into account. Lower probabilities of exceedance imply a more significant reduction in runoff volume and potentially lower flood risks.

Additionally, the life expectancy of the LID methods should be considered. Some methods may offer better performance in the short term but may require more maintenance or have limited effectiveness over time. Evaluating the long-term effectiveness and durability of the LID methods is crucial in selecting the appropriate return period.

Ultimately, the decision on which return period to choose should be based on a comprehensive assessment that considers both the reduction achieved and the life expectancy of the LID methods. It is essential to strike a balance between the desired level of flood risk reduction and the feasibility and sustainability of the chosen approach.

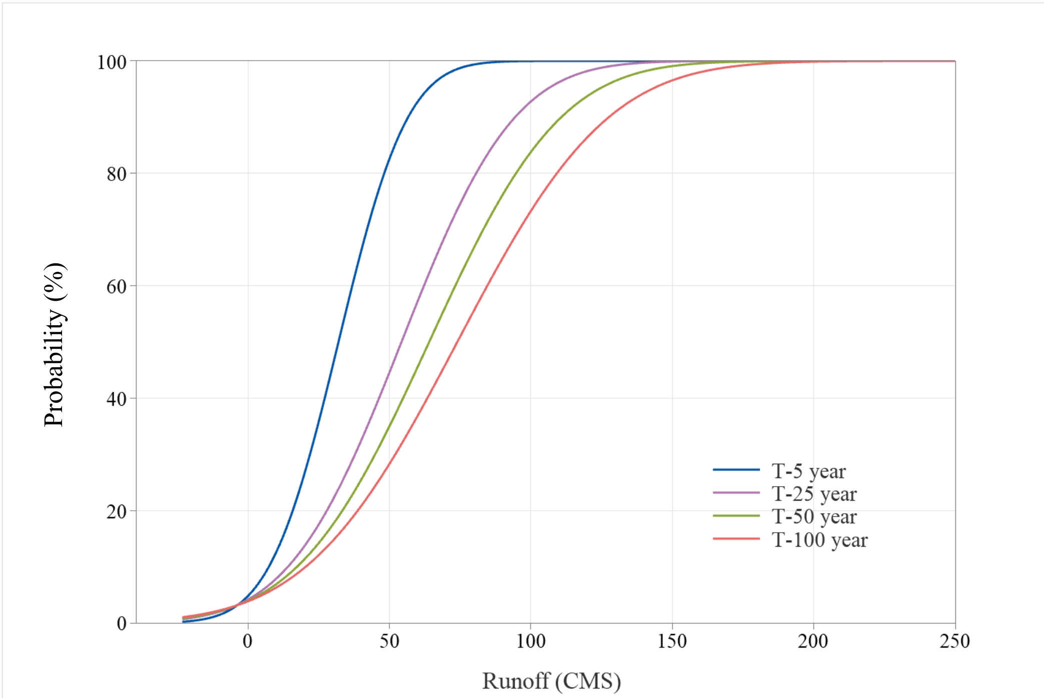

Figure 32. Cumulative distribution function (CDF) of the total runoff for the study area without LIDs under different return periods using Minitab

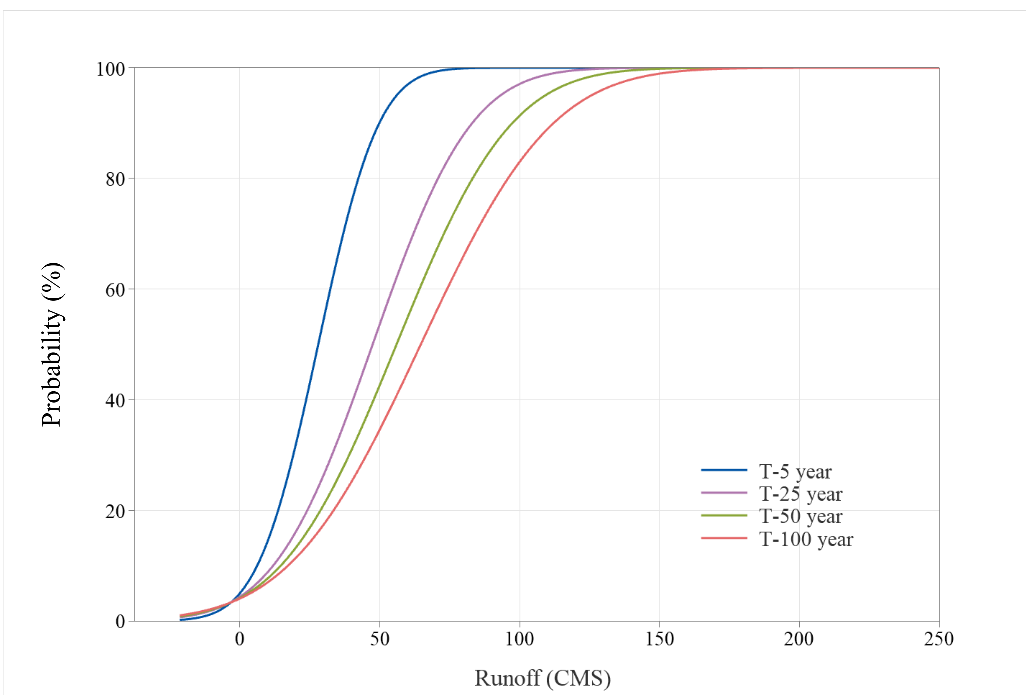

Figure 33. Cumulative distribution function (CDF) of the total runoff for the study area with LID (BR) under different return periods using Minitab

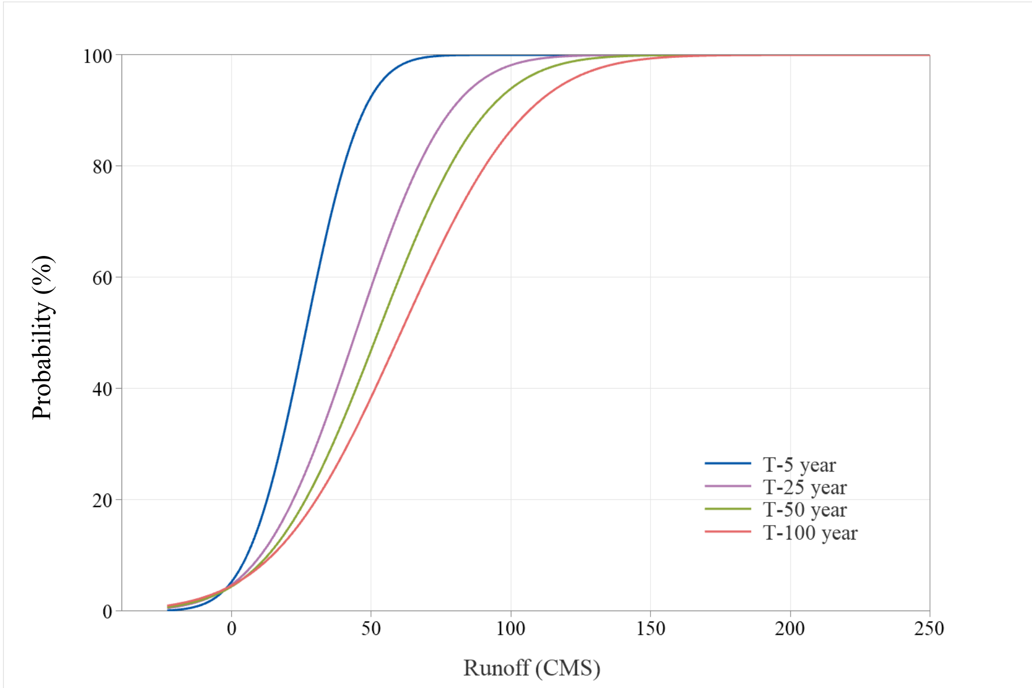

Figure 34. Cumulative distribution function (CDF) of the total runoff for the study area with LID (Modified BR) under different return periods using Minitab

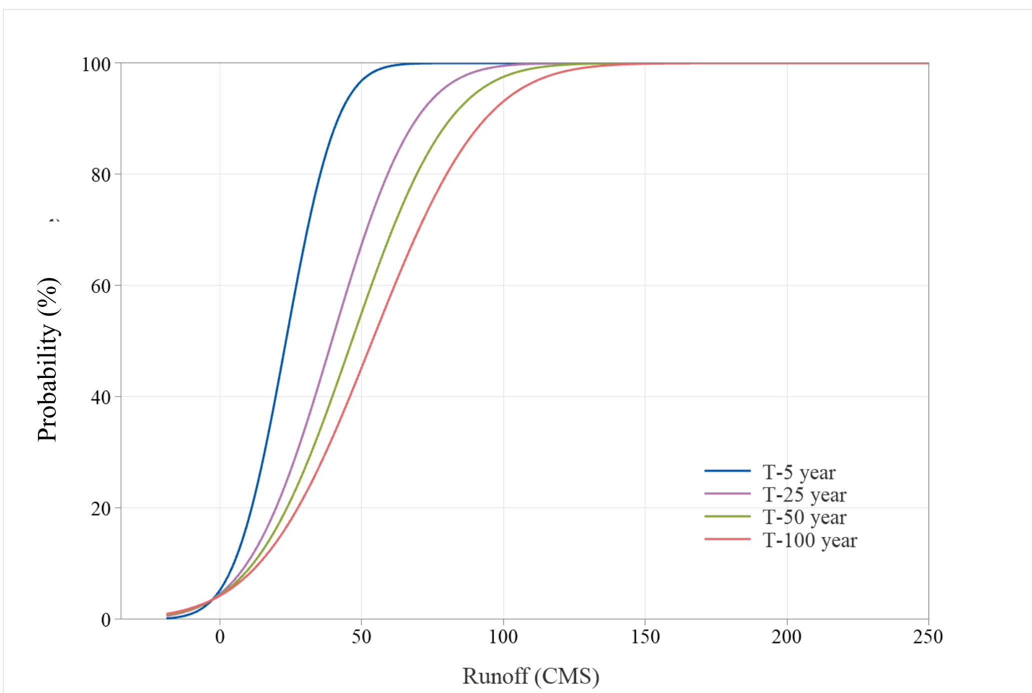

Figure 35. Cumulative distribution function (CDF) of the total runoff for the study area with LID (PP) under different return periods using Minitab

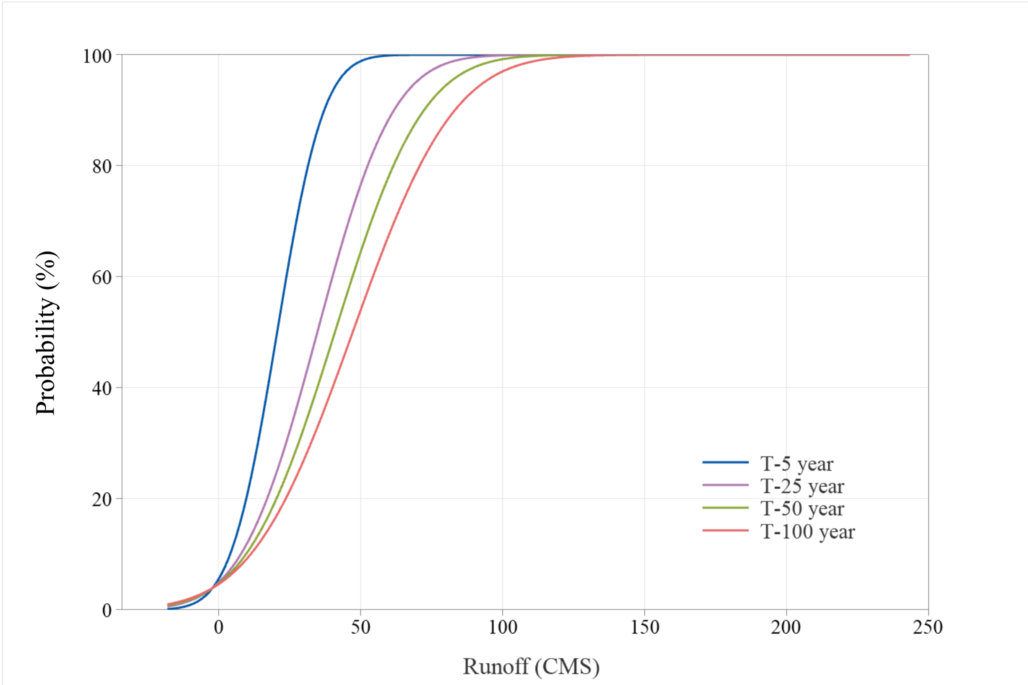

Figure 36. Cumulative distribution function (CDF) of the total runoff for the study area with LID (BR+PP) under different return periods using Minitab

4.6 Comparison of the results

Table 6 provides an overview of the percentage change in Total Flooding Volume (TFV) and Total Runoff Volume (TRV) for different LID techniques compared to the system without LIDs under various return periods. The results indicate that the combination of BR and PP exhibits the most significant reduction in flood and runoff volumes, followed by the standalone use of Permeable Pavement.

The superior performance of the combined BR and PP method can be attributed to several factors. Firstly, Bioretention is effective in capturing and infiltrating stormwater, reducing surface runoff and the potential for flooding. It provides an opportunity for water retention and gradual release, allowing for natural recharge of groundwater. On the other hand, Permeable Pavement facilitates water infiltration directly through its porous structure, reducing surface runoff and promoting groundwater recharge. When these two techniques are combined, their complementary effects enhance the overall effectiveness in reducing flood and runoff volumes.

The implementation of the modified bioretention technique has demonstrated significant reductions in flood and runoff volumes. The modified bioretention method effectively promotes stormwater retention and infiltration, resulting in a notable decrease in overall runoff volume. Through its unique design and functionality, modified bioretention contributes to increased evapotranspiration and improved absorption of water by plants and soil, thereby enhancing the stormwater management system's efficiency and resilience.

Bioretention as a standalone technique still demonstrates a significant reduction in flood and runoff volumes, although it may not be as effective as the combined methods. Bioretention facilities, such as vegetated basins or cells, provide opportunities for stormwater treatment, filtration, and retention, allowing for the removal of pollutants and gradual release of water. However, their limited capacity for infiltration compared to Permeable Pavement may result in a relatively lower reduction in flood and runoff volumes.

The results indicate that the PP method has a more significant effect on reducing total flooding percentages in the study area compared to the BC method. There could be several reasons contributing to this observation:

- Surface Infiltration: PP allows for direct infiltration of rainfall into the ground through its porous structure. This helps to reduce surface runoff and decrease the overall volume of water entering the drainage system. In contrast, bioretention cells rely on the storage and slow release of water through vegetation and soil, which may not provide the same level of infiltration as permeable pavement.

- Runoff Reduction: Permeable pavement effectively captures and retains rainfall within its porous surface, preventing immediate runoff. This helps to alleviate the burden on the drainage system and reduce the likelihood of flooding. Bioretention cells, while capable of storing and slowly releasing water, may not have the same immediate impact in reducing runoff during intense rainfall events.
- Maintenance and Performance: Permeable pavement systems are generally designed with careful consideration of their porosity, base materials, and maintenance requirements. When properly installed and maintained, they can sustain their effectiveness in reducing flooding over the long term. On the other hand, bioretention cells require periodic maintenance to ensure proper functioning, such as vegetation management and sediment removal, which could affect their performance if not adequately addressed.
- Site-specific Factors: The effectiveness of stormwater management methods can vary depending on site-specific characteristics, such as soil conditions, slope, and land use. It is possible that the soil permeability or other site factors in your study area are more favorable for the implementation of permeable pavement, leading to its superior performance compared to bioretention cells.

Table 6 compares TFV and TRV for different LID methods under different return periods. It is important to note that the selection of LID techniques should not solely rely on the percentage of reduction in stormwater runoff. When selecting the most suitable LID techniques for a particular area, several parameters should be considered. These parameters help assess the feasibility, effectiveness, and compatibility of LID techniques with the specific site conditions and project goals. The following parameters are commonly evaluated:

Site Characteristics: Evaluate the physical attributes of the site, such as topography, soil composition, drainage patterns, and available space. These factors influence the suitability of different LID techniques and their ability to function effectively in managing stormwater runoff.

Hydrological Conditions: Consider the local climate, precipitation patterns, and hydrological characteristics of the area. The rainfall intensity, frequency, and volume play a crucial role in determining the appropriate LID techniques for managing stormwater runoff effectively.

Site Constraints and Opportunities: Identify any site limitations or constraints that may affect the implementation of specific LID techniques. This includes factors like available land area, existing infrastructure, utility locations, and any regulatory restrictions. Additionally, explore any opportunities presented by the site, such as natural features or landscape elements that can be integrated into the LID design.

Water Quality Goals: Determine the specific water quality objectives for the project. Different LID techniques have varying capabilities to address water quality concerns, such as pollutant removal and filtration. Consider the required level of treatment and select LID techniques accordingly.

Maintenance Requirements: Assess the long-term maintenance needs of the chosen LID techniques. Some techniques may require regular inspection, cleaning, and vegetation management to ensure optimal performance. Evaluate the available resources, expertise, and capacity for ongoing maintenance and factor them into the decision-making process.

Cost-effectiveness: Consider the economic feasibility of implementing LID techniques. Evaluate the initial costs of construction, installation, and maintenance, as well as the potential long-term savings in stormwater management and infrastructure costs. Compare the cost-effectiveness of different LID techniques to select the most suitable option.

Community Acceptance: Involve stakeholders and consider their perspectives, preferences, and concerns. Engage with the local community, including residents, businesses, and municipal authorities, to ensure that the selected LID techniques align with their needs and aspirations.

By carefully considering these parameters, stakeholders can make informed decisions when selecting the most suitable LID techniques for a particular area. This comprehensive evaluation helps ensure that the chosen LID techniques align with site-specific conditions, project goals, and long-term sustainability.

Table 6. Percentage Change of 4 LID techniques on Total Flooding Volume (TFV) and Total Runoff Volume (TRV) compared to the system without LIDs under different return periods.

	T=5		**T=25**		**T=50**		**T=100**	
	Percentage Change (%)							
	TFV	TRV	TFV	TRV	TFV	TRV	TFV	TRV
BR	-18.54	-15.34	-16.23	-14.98	-15.77	-14.94	-15.43	-14.92
PP	-38.37	-30.44	-35.18	-30.96	-34.51	-31.17	-34.04	-31.37
Modified BR	-27.12	-23.50	-24.65	-23.07	-22.59	-21.52	-24.46	-24.18
PP+BR	-53.95	-41.36	-48.93	-41.59	-47.84	-41.75	-47.07	-41.92

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

This thesis aimed to investigate and analyze the effectiveness of various stormwater management techniques in mitigating urban flooding in four districts of the eastern part of Shiraz. By employing EPA SWMM 5.2 and conducting a thorough examination of stormwater modeling, the study has yielded valuable knowledge regarding the effectiveness of diverse stormwater management techniques. These findings offer essential insights into the implications for urban resilience and the effectiveness of these methods in mitigating urban flooding. The city of Shiraz, which has experienced a significant and devastating flood event in recent years, highlights the urgent need for effective stormwater management strategies. The knowledge gained and information generated from examining flood-prone regions in Shiraz and implementing diverse mitigation approaches can provide valuable guidance for other cities encountering comparable difficulties.

The results and insights gained from this research can inform the development of sustainable and resilient stormwater management practices in urban areas, enabling cities worldwide to better prepare for and mitigate the impacts of extreme rainfall events and climate change.

By examining the influence of urban development and climate change on hydrological runoff and urban flood volumes, this study offers critical insights into flood mitigation solutions. It places particular emphasis on the urban drainage system, employing diverse methods and model simulations across different time frames. This research underscores the overlooked significance of the urban drainage system in effectively managing evolving flood risks, highlighting its pivotal role in achieving the study's objectives.

Moreover, this research introduces LID methods including BR, PP and their combinations a innovative and effective approaches in mitigating urban flooding. These LID techniques provide promising solutions by enhancing stormwater infiltration, reducing runoff volumes, and minimizing the likelihood of high runoff volumes. The integration of BR and PP exhibits synergistic effects, further amplifying their benefits in reducing flooding. The findings underscore the potential of LID methods as valuable tools in urban flood mitigation strategies, offering a sustainable and environmentally friendly alternative to traditional stormwater management approaches. The successful application of BR, PP, and their combination in Shiraz can serve as a model for other cities grappling with urban flood risks.

The results demonstrate that adopting comprehensive and integrated approaches to stormwater management is crucial for effectively mitigating urban flooding and enhancing the city's resilience in the face of a changing climate and evolving land use patterns. Among the studied techniques, combining PP with PR exhibited synergistic effects and further enhanced runoff reduction. This method resulted in approximately a 42% reduction in total runoff in the study area over all return periods.

The analysis of total flooding in the study area without LID measures compared to the weighted average of this parameter incorporating different LID methods revealed a decrease in flooding volume from 8,118 to 4,844*10^3 m^3 (40.33% reduction) under a 5-year return period, 17,093 to 11,202*10^3 m^3 (34.46%) under 25-year return period, 21,181 to 14,171*10^3 m^3 (33.1% reduction) under 50-year, and 25,387 to 17,237*10^3 m^3 (32.1% reduction) under 100-year return period.

The examination of junctions categorized as "very highly flooded" and "highly flooded," experiencing flooding volumes exceeding 150 million liters, revealed significant improvements when comparing the system without LID measures to the weighted average of flooding incorporating LID methods under a 5-year return period. The results demonstrated a remarkable 66.52% reduction in flooding volume in the junctions experiencing flooding volumes exceeding 150 million liters. For return periods of 25, 50, and 100 years, the reduction was found to be 51.13%, 49.46%, and 50.57%, respectively. These findings indicate that the implementation of LID methods effectively mitigated the severity of node flooding in the study area, particularly in junctions prone to high levels of flooding.

Notably, the analysis revealed that stormwater management methods were more effective in mitigating flood risks associated with less severe rainfall events in a shorter return period. As the return period decreased, all techniques consistently demonstrated higher reductions in total flooding percentages. However, the percentage reductions tended to diminish as the return period increased, indicating the need to account for more intense and frequent rainfall events when designing stormwater management strategies for the future. However, it is important to note that the choice of return period should not be solely based on the higher percentage of reduction. Other factors, such as life expectancy and maintenance costs, should also be taken into consideration. While a shorter return period may yield greater reduction percentages, it may not necessarily be the most suitable option in terms of long-term sustainability and cost-effectiveness. Therefore, a comprehensive evaluation considering multiple factors is essential when selecting the appropriate return period for stormwater management strategies in order to ensure optimal urban resilience and efficient use of resources.

In the context of selecting appropriate stormwater management techniques for a city, several factors should be considered, including the reduction achieved by LID methods, their lifespan, and their adaptability to the projected changes in land use and climate conditions. Based on the findings of this study, PP and the combination of BR with PP are effective options, showing superior performance in reducing total flooding percentages. It is important to note that the suitability of specific stormwater management techniques may vary depending on the unique characteristics of each city, and site-specific factors such as soil conditions, land use, and rainfall patterns should be carefully considered when selecting the most appropriate LID techniques.

5.2 Recommendations for the future studies

While this research has provided valuable insights into stormwater management in the context of Shiraz, there are some limitations that should be acknowledged. The analysis focused primarily on the effectiveness of stormwater management techniques in reducing flooding and runoff volumes, without considering other factors such as cost-effectiveness, maintenance requirements, and long-term performance. Future studies should address these aspects to provide a more comprehensive understanding of sustainable stormwater management practices tailored specifically to Shiraz's needs and challenges.

Moreover, it is crucial for Shiraz to incorporate comprehensive loss estimation techniques in its stormwater management strategies. By quantifying the potential economic, social, and environmental losses associated with urban flooding, decision-makers can prioritize investments and allocate resources effectively. Loss estimation provides valuable insights into the true costs of flooding and helps justify the implementation of stormwater management measures. By integrating loss estimation into the decision-making process, Shiraz can assess the cost-effectiveness of different stormwater management techniques and prioritize investments based on their potential to mitigate losses. This approach enables the city to make informed decisions and allocate resources where they will have the most significant impact in reducing damages and improving urban resilience. Furthermore, the results and methodologies developed in this study can serve as a foundation for loss estimation in other similar cities facing urban flooding challenges. By adapting and applying the findings to their specific contexts, these cities can enhance their understanding of the potential losses associated with flooding and make informed decisions regarding stormwater management investments.

In addition to mitigating urban flooding, LID techniques can play a crucial role in improving water quality by reducing the transport of pollutants and contaminants from stormwater runoff. To effectively address water quality concerns, it is recommended to incorporate specific LID practices that focus on pollutant removal and water treatment. By incorporating the water quality-focused LID practices into stormwater management strategies, Shiraz can address not only flooding concerns but also improve the overall health and quality of its water resources.

Furthermore, stormwater management practices should be regularly monitored to assess their performance and adapt to changing conditions. Implementing a monitoring system that tracks the effectiveness of stormwater management techniques, monitors water quality, and measures the impact on flooding can provide valuable data for future decision-making. This data-driven approach enables the city to identify potential shortcomings, refine strategies, and ensure the ongoing effectiveness of stormwater management efforts.

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Appendix A

Table 7. Summary of Node Flooding in the Stormwater Drainage System for a 5-year Return Period

Node	Hours Flooded	Maximum Rate CMS	Hours of Maximum Flooding	Total Flood Volume (1000 m^3)
J1	1.62	0.877	8:12	2.113
J2	0.98	0.761	8:10	0.867
J3	4.73	1.59	8:11	12.413
J6	2.17	0.789	8:10	1.598
J7	0.34	0.562	8:18	0.32
J18	0.31	0.483	8:22	0.306
J19	3.33	1.672	8:18	8.401
J20	0.83	0.6	8:10	0.572
J22	2.29	1.299	8:13	4.747
J25	0.32	0.386	8:15	0.221
J27	4.16	1.551	8:13	7.044
J29	2.81	1.112	8:10	3.429
J30	12.94	2.314	8:10	40.869
J31	10.23	1.666	8:10	23.361
J32	0.57	0.556	8:10	0.299
J36	6.43	2.133	8:10	15.215
J37	5.77	1.905	8:10	16.406
J38	0.22	0.192	8:25	0.069
J39	12.87	1.598	8:10	19.94
J44	7.16	1.981	8:12	12.438
J46	3.82	1.22	8:10	4.573
J48	9.07	2.074	8:11	21.316
J50	1.94	0.952	8:10	1.998
J51	17.07	1.531	8:10	45.089
J54	6.64	1.18	8:10	6.053
J55	9.03	1.745	8:11	13.734
J58	15.44	1.32	8:10	16.715
J60	3.57	1.534	8:10	7.392
J61	19.51	2.807	8:10	69.264
J62	13.9	1.928	8:10	28.736
J63	12.37	2.441	8:10	44.544
J64	1.18	1.015	8:10	1.347
J65	14.09	3.751	8:10	51.753

Table 7 Continued. Summary of Node Flooding in the Stormwater Drainage System for a 5-year Return Period

J66	2.45	1.221	8:10	3.77
J67	6.14	1.54	8:10	8.68
J68	2.82	1.186	8:10	3.541
J69	10.81	1.861	8:10	31.084
J72	5.57	2.447	8:18	17.006
J73	7.48	2.33	8:10	18.118
J75	1.95	1.597	8:10	3.909
J76	14.19	3.566	8:10	45.685
J77	21.82	6.563	8:10	181.29
J78	21.94	3.909	8:10	97.123
J80	3.99	1.815	8:10	8.795
J81	0.64	0.896	8:11	0.841
J83	22.04	4.339	8:10	90.299
J85	1.45	1.248	8:10	2.322
J89	22.08	2.138	8:11	25.279
J91	22.3	2.306	8:21	62.914
J92	11.85	1.104	8:10	19.793
J93	2.25	0.315	8:04	1.514
J96	12.86	1.867	8:10	36.669
J97	13.78	1.505	8:20	31.383
J99	15.28	0.122	5:21	5.621
J103	14.65	0.492	2:59	19.522
J109	22.48	0.545	7:05	39.634

Table 8. Summary of Node Flooding in the Stormwater Drainage System for a 50-year Return Period

Node	Hours Flooded	Maximum Rate CMS	Hours of Maximum Flooding	Total Flood Volume (1000 m^3)
J1	6.35	1.938	8:10	12.446
J2	5.2	1.728	8:10	6.142
J3	9.29	2.547	8:10	36.223
J5	0.22	0.859	8:11	0.293
J6	7.01	1.875	8:10	8.899
J7	3.18	2.561	8:10	8.283
J11	0.88	1.557	8:10	1.593
J13	0.84	1.58	8:11	1.562
J18	3.09	2.2	8:13	7.959
J19	6.98	2.849	8:10	30.406
J20	4	1.568	8:10	4.53
J22	7.03	3.091	8:10	24.365
J23	0.54	1.359	8:11	0.922
J25	2.68	1.469	8:11	4.245
J27	9.1	3.036	8:10	27.896
J29	10.02	2.503	8:10	17.479
J30	19.99	3.538	8:10	85.753
J31	15.49	3.047	8:10	48.681
J32	3.47	1.396	8:10	3.501
J35	1.04	1.671	8:10	1.922
J36	12.23	4.221	8:10	51.736
J37	12.24	3.39	8:10	54.647
J38	2.8	2.13	8:10	5.731
J39	17.06	3.182	8:10	42.86
J40	0.71	1.493	8:10	1.151
J44	11.26	4.201	8:11	36.687
J46	11.15	2.944	8:10	23.33
J47	2.26	2.09	8:10	4.579
J48	13.73	3.121	8:10	55.435
J49	1.36	1.961	8:10	3.015
J50	7.38	2.412	8:10	12.916
J51	21.73	2.426	8:10	63.133
J52	0.15	0.318	8:15	0.084
J54	12.16	2.559	8:10	20.228
J55	12.86	3.76	8:11	38.206
J58	20.05	2.571	8:10	32.378
J60	10.86	2.597	8:10	29.584

Table 8 Continued. Summary of Node Flooding in the Stormwater Drainage System for a 50-year Return Period

J61	22.38	5.09	8:10	120.512
J62	18.66	3.745	8:10	59.271
J63	16.81	4.093	8:10	85.963
J64	6.17	2.925	8:10	14.412
J65	22.3	7.275	8:10	141.487
J66	8.3	2.699	8:10	20.603
J67	13.46	3.364	8:10	34.388
J68	9.64	2.879	8:10	20.073
J69	16.21	3.139	8:10	59.945
J70	0.95	1.685	8:10	1.922
J71	2.4	2.899	8:10	8.959
J72	12.21	4.559	8:10	64.998
J73	15.34	5.381	8:10	69.683
J74	0.23	0.348	8:20	0.143
J75	8.1	4.971	8:10	34.896
J76	22.87	7.77	8:10	138.383
J77	22.55	13.039	8:10	358.162
J78	22.65	7.516	8:10	179.889
J80	11.72	4.553	8:10	46.128
J81	5.27	3.155	8:10	14.007
J83	22.7	8.76	8:10	196.973
J85	7.27	3.905	8:10	23.008
J86	1.68	2.607	8:10	4.692
J88	1.45	1.586	8:10	2.308
J89	22.8	4.281	8:11	49.733
J91	22.84	3.789	8:15	100.619
J92	15.9	1.759	8:10	31.681
J93	8.88	0.316	2:03	5.979
J94	1.72	2.115	8:10	3.891
J95	2.4	0.173	9:46	0.772
J96	16.82	3.485	8:10	66.281
J97	19.33	1.704	8:03	63.1
J99	20.83	0.137	2:17	7.327
J103	21.92	0.481	19:00	30.971
J104	1.93	0.396	8:11	1.787
J109	22.92	0.561	0:00	45.019

Table 9. Summary of Node Flooding in the Stormwater Drainage System for a 100-year Return Period

Node	Hours Flooded	Maximum Rate CMS	Hours of Maximum Flooding	Total Flood Volume (1000 m^3)
J1	7.18	2.222	8:10	15.696
J2	6.01	2.014	8:10	8.163
J3	10.1	2.741	8:10	41.354
J5	0.5	1.382	8:10	0.827
J6	7.87	2.203	8:10	11.605
J7	4.33	2.874	8:10	12.34
J11	1.26	1.913	8:10	2.496
J13	1.08	1.916	8:11	2.43
J18	3.87	2.655	8:12	12.067
J19	7.61	3.151	8:10	35.465
J20	5.09	1.859	8:10	6.396
J22	7.63	3.29	8:10	30.175
J23	0.82	1.79	8:10	1.859
J25	3.7	1.789	8:11	6.4
J27	9.97	3.357	8:10	34.08
J29	10.93	2.927	8:10	22.172
J30	21.7	3.911	8:10	96.888
J31	16.42	3.442	8:10	54.92
J32	4.32	1.654	8:10	5.014
J35	1.47	2.123	8:10	3.34
J36	12.98	4.748	8:10	62.484
J37	13.55	3.727	8:10	64.694
J38	4.65	2.567	8:10	9.023
J39	17.91	3.668	8:10	49.56
J40	1.04	1.891	8:10	2.202
J44	11.82	4.86	8:11	43.918
J46	12.11	3.444	8:10	29.593
J47	3.25	2.567	8:10	7.173
J48	14.38	3.417	8:10	62.672
J49	1.96	2.478	8:10	5.024
J50	8.49	2.858	8:10	17.102
J51	22.63	2.729	8:10	67.448
J52	0.28	0.763	8:12	0.315
J54	12.68	2.98	8:10	24.777
J55	13.41	4.364	8:11	45.706
J58	20.96	2.951	8:10	36.799
J60	12.37	2.94	8:10	35.633

Table 9 Continued. Summary of Node Flooding in the Stormwater Drainage System for a 100-year Return Period

J61	22.54	5.802	8:10	134.254
J63	17.65	4.599	8:10	95.406
J64	7.74	3.515	8:10	20.561
J65	22.44	8.383	8:10	168.898
J66	9.43	3.131	8:10	26.233
J67	14.45	3.928	8:10	42.537
J68	11	3.4	8:10	26.057
J69	17.08	3.527	8:10	66.25
J70	1.34	2.177	8:10	3.361
J71	3.4	3.471	8:10	13.549
J72	13.51	5.103	8:10	79.309
J73	16.55	6.158	8:10	86.062
J74	0.48	1.323	8:12	0.762
J75	9.82	6.03	8:10	49.336
J76	23.03	9.087	8:10	169.619
J77	22.69	15.064	8:10	411.775
J78	22.76	8.649	8:10	205.548
J80	13.45	5.33	8:10	59.59
J81	6.85	3.836	8:10	20.772
J83	22.81	10.145	8:10	230.447
J85	8.89	4.713	8:10	32.581
J86	2.48	3.225	8:10	7.456
J88	1.92	1.935	8:10	3.584
J89	22.9	4.926	8:11	56.839
J91	22.93	4.106	8:14	109.372
J92	16.63	1.952	8:10	34.162
J93	10.46	0.296	13:09	7.07
J94	1.72	2.115	8:10	3.891
J95	2.4	0.173	9:46	0.772
J96	16.82	3.485	8:10	66.281
J97	19.33	1.704	8:03	63.1
J99	20.83	0.137	2:17	7.327
J103	21.92	0.481	19:00	30.971
J104	1.93	0.396	8:11	1.787
J109	22.92	0.561	0:00	45.019

Appendix B

Table 10. Comparison of Node Flooding in the study area with different LID methods for a 5-year Return Period

Node	No LID	BR	PP	Modified BR	BR+PP
J1	2.113	0.904	1.85	N/A	0.303
J2	0.867	0.188	0.035	N/A	N/A
J3	12.413	10.024	11.014	7.667	7.494
J6	1.598	1.469	1.512	1.353	1.356
J7	0.32	N/A	0.32	N/A	N/A
J18	0.306	0.306	N/A	0.306	N/A
J19	8.401	8.401	4.513	8.378	4.513
J20	0.572	0.571	0.43	0.571	0.43
J22	4.747	4.746	4.746	1.778	4.746
J25	0.221	0.221	0.221	N/A	0.221
J27	7.044	2	7.016	0.615	2
J29	3.429	3.432	N/A	0.537	N/A
J30	40.869	40.869	7.382	34.761	7.382
J31	23.361	19.442	14.666	19.442	14.566
J32	0.299	N/A	0.277	N/A	N/A
J36	15.215	12.249	4.469	12.249	3.471
J37	16.406	10.315	5.091	10.315	5.091
J38	0.069	0.069	0.069	N/A	0.069
J39	19.94	10.942	18.038	10.942	9.653
J44	12.438	10.393	12.32	9.016	10.318
J46	4.573	4.573	6.028	3.772	6.028
J48	21.316	21.316	6.966	18.846	6.966
J50	1.998	1.998	1.981	1.997	1.981
J51	45.089	43.214	39.328	43.96	38.767
J54	6.053	6.055	5.85	6.055	5.85
J55	13.734	13.711	13.534	13.711	13.667
J58	16.715	16.416	15.853	16.416	16.182
J60	7.392	7.392	N/A	7.392	N/A
J61	69.264	68.398	37.382	67.407	36.379
J62	28.736	28.338	24.865	27.716	23.857
J63	44.544	42.474	12.611	38.736	11.796
J64	1.347	N/A	1.177	N/A	N/A
J65	51.753	42.225	2.479	32.657	0.085
J66	3.77	3.772	3.772	0.959	3.772

Table 10 Continued. Comparison of Node Flooding in the study area with different LID methods for a 5-year Return Period

J67	8.68	2.642	8.233	2.642	2.754
J69	31.084	27.218	24.501	27.218	22.35
J72	17.006	12.453	17.008	8.3	12.453
J73	18.118	18.118	0.872	18.118	0.872
J75	3.909	3.909	N/A	3.901	N/A
J76	45.685	45.684	0.165	45.684	0.165
J77	181.29	74.722	151.817	43.684	46.986
J78	97.123	96.574	42.803	91.569	36.301
J80	8.795	8.559	8.801	8.559	8.728
J81	0.841	0.841	N/A	0.841	N/A
J83	90.299	38.302	89.615	15.218	37.558
J85	2.322	0.087	N/A	0.087	N/A
J89	25.279	25.279	25.279	25.279	25.279
J91	62.914	62.914	50.79	62.142	50.79
J92	19.793	18.419	13.531	18.419	11.583
J93	1.514	1.514	N/A	0.957	N/A
J96	36.669	36.668	23.155	34.358	23.155
J97	31.383	30.216	15.331	30.216	29.304
J99	5.621	5.526	5.397	5.526	5.465
J103	19.522	19.248	5.493	18.86	4.924
J109	39.634	39.634	14.333	39.634	14.333

Table 11. Comparison of Node Flooding in the study area with different LID methods for a 50-year Return Period

Node	No LID	BR	PP	Modified BR	BR+PP
J1	12.446	9.358	11.577	4.076	7.082
J2	6.142	3.586	1.77	2.025	0.335
J3	36.223	33.896	35.095	31.264	30.594
J5	0.293	0.293	0.293	0.293	0.281
J6	8.899	8.716	8.814	8.492	8.506
J7	8.283	3.624	8.282	3.619	1.989
J11	1.593	1.593	1.592	1.593	1.593
J13	1.562	1.562	0.057	1.562	0.057
J18	7.959	7.959	3.535	7.956	3.535
J19	30.406	30.407	23.921	30.387	23.921
J20	4.53	4.53	4.458	4.53	4.458
J22	24.365	24.365	24.365	15.245	24.365
J23	0.922	0.922	0.922	0.749	0.922
J25	4.245	4.245	4.244	2.153	4.244
J27	27.896	12.809	27.847	7.87	12.758
J29	17.479	17.48	8.312	5.396	8.312
J30	85.753	85.753	27.456	84.327	27.456
J31	48.681	44.813	41.304	44.813	40.345
J32	3.501	0.424	3.451	0.424	0.424
J35	1.922	1.922	1.922	1.922	1.922
J36	51.736	48.38	20.807	48.38	18.692
J37	54.647	45.264	30.238	45.264	30.238
J38	5.731	5.732	5.731	0.675	5.731
J39	42.86	22.389	40.179	22.389	21.418
J40	1.151	N/A	1.15	N/A	N/A
J44	36.687	34.668	36.656	33.691	34.589
J46	23.33	23.33	26.724	21.916	26.724
J47	4.579	4.579	24.185	4.543	N/A
J48	55.435	55.435	N/A	54.508	24.185
J49	3.015	3.015	N/A	3.015	3.015
J50	12.916	12.916	12.677	12.916	12.677
J51	63.133	59.671	54.069	60.323	53.288
J52	0.084	0.084	N/A	0.084	N/A
J54	20.228	20.228	19.821	20.228	19.821
J55	38.206	38.193	38.003	38.193	38.156
J58	32.378	32.098	31.529	32.098	31.899
J60	29.584	29.584	3.308	29.584	3.308

Table 11 Continued. Comparison of Node Flooding in the study area with different LID methods for a 50-year Return Period

J61	120.512	119.777	58.188	120.011	56.921
J62	59.271	58.798	54.965	58.824	54.08
J63	85.963	84.262	31.832	83.481	31.458
J64	14.412	3.011	14.505	N/A	3.01
J65	141.487	126.399	10.401	114.909	5.36
J66	20.603	20.603	20.603	13.435	20.603
J67	34.388	13.484	32.565	13.484	15.68
J68	20.073	19.907	3.406	19.907	3.402
J69	59.945	57.052	54.397	57.052	52.965
J70	1.922	0.047	1.922	N/A	0.047
J71	8.959	6.017	8.959	2.475	6.016
J72	64.998	56.553	64.998	48.091	56.553
J73	69.683	69.683	14.675	69.683	14.66
J74	0.143	0.143	N/A	0.143	N/A
J75	34.896	34.896	1.192	34.887	1.192
J76	138.383	138.383	4.985	138.383	4.985
J77	358.162	161.617	341.951	97.787	137.326
J78	179.889	179.3	68.563	179.126	67.883
J80	46.128	45.666	46.128	45.666	45.955
J81	14.007	14.007	N/A	14.007	N/A
J83	196.973	97.108	196.382	46.753	96.499
J85	23.008	7.033	0.131	7.033	0.131
J86	4.692	4.646	4.447	4.646	4.448
J88	2.308	2.308	2.308	2.308	2.308
J89	49.733	49.733	49.735	49.733	49.735
J91	100.619	100.619	86.915	100.703	86.915
J92	31.681	30.938	27.34	30.938	26.038
J93	5.979	5.979	0.302	4.848	0.302
J94	2.176	2.176	2.176	2.176	2.176
J95	0.668	0.645	N/A	0.645	N/A
J96	60.529	60.529	36.807	59.843	36.807
J97	57.026	55.612	25.256	55.612	54.758
J99	7.08	6.972	6.865	6.972	6.914
J103	29.183	29.171	16.982	29.177	15.514
J104	1.019	1.019	N/A	1.019	N/A
J109	44.898	44.898	25.176	44.898	25.176

Table 12. Comparison of Node Flooding in the study area with different LID methods for a 100-year Return Period

Node	No LID	BR	PP	Modified BR	BR+PP
J1	15.696	13.29	14.722	5.211	10.36
J2	8.163	4.91	2.644	3.125	0.642
J3	41.354	39.164	40.476	36.582	36.265
J5	0.827	0.817	0.827	0.817	0.794
J6	11.605	11.535	11.573	11.275	11.325
J7	12.34	5.242	12.344	5.231	3.07
J11	2.496	2.49	2.495	2.472	2.471
J13	2.43	2.43	0.355	2.43	0.355
J18	12.067	12.067	5.323	12.061	5.323
J19	35.465	35.465	30.1	35.451	30.1
J20	6.396	6.396	6.279	6.396	6.278
J22	30.175	30.175	30.172	19.741	30.172
J23	1.859	1.859	1.859	1.744	1.859
J25	6.4	6.4	6.399	2.881	6.399
J27	34.08	16.882	34.037	10.102	16.83
J29	22.172	22.172	12.156	7.291	12.156
J30	96.888	96.888	32.762	88.066	32.762
J31	54.92	50.7	47.585	50.7	46.404
J32	5.014	0.739	4.956	0.739	0.739
J35	3.34	3.34	3.335	3.34	3.334
J36	62.484	59.423	25.561	59.423	23.64
J37	64.694	55.61	39.259	55.61	39.259
J38	9.023	9.023	9.022	2.115	9.022
J39	49.56	25.651	46.692	25.651	24.701
J40	2.202	N/A	2.202	N/A	N/A
J44	43.918	42.008	43.897	40.288	41.961
J46	29.593	29.593	32.965	27.186	32.965
J47	7.173	7.173	N/A	7.125	N/A
J48	62.672	62.672	28.58	60.566	28.58
J49	5.024	5.024	N/A	5.024	5.024
J50	17.102	17.102	16.898	17.102	16.898
J51	67.448	63.496	57.631	64.503	56.714
J52	0.315	0.315	N/A	0.315	N/A
J54	24.777	24.777	24.403	24.777	24.403
J55	45.706	45.699	45.512	45.699	45.668
J58	36.799	36.529	35.961	36.529	36.341
J60	35.633	35.633	5.111	35.633	5.111

Table 12 Continued. Comparison of Node Flooding in the study area with different LID methods for a 100-year Return Period

J61	134.254	133.644	63.422	133.178	62.116
J62	68.074	67.596	63.584	67.178	62.673
J63	95.406	93.717	36.002	91.467	35.708
J64	20.561	4.708	20.572	0.603	4.696
J65	168.898	154.08	12.991	133.122	7.639
J66	26.233	26.233	26.236	16.797	26.236
J67	42.537	17.212	40.742	17.212	20.545
J68	26.057	26.008	5.289	26.008	5.283
J69	66.25	63.484	60.734	63.484	59.287
J70	3.361	0.351	3.361	N/A	0.351
J71	13.549	9.727	13.549	5.769	9.726
J72	79.309	70.353	79.315	56.615	70.357
J73	86.062	86.061	21.367	86.061	21.367
J74	0.762	0.762	N/A	0.762	N/A
J75	49.336	49.336	2.443	49.332	2.443
J76	169.619	169.619	7.796	169.619	7.796
J77	411.775	187.087	397.775	86.076	165.433
J78	205.548	205.024	76.266	202.156	75.621
J80	59.59	58.902	59.59	58.902	59.357
J81	20.772	20.772	N/A	20.772	N/A
J83	230.447	115.439	229.898	39.395	114.855
J85	32.581	11.125	0.471	11.125	0.471
J86	7.456	7.447	6.994	7.447	6.994
J88	3.584	3.584	3.584	3.584	3.583
J89	56.839	56.839	56.84	56.839	56.84
J91	109.372	109.372	95.522	109.314	95.522
J92	34.162	33.434	29.985	33.434	28.76
J93	7.07	7.07	0.686	5.824	0.686
J94	3.891	3.891	3.891	3.891	3.891
J95	0.772	0.746	N/A	0.746	N/A
J96	66.281	66.281	39.177	64.084	39.177
J97	63.1	61.665	27.782	61.665	60.84
J99	7.327	7.22	7.121	7.22	7.165
J103	30.971	30.967	18.91	30.965	17.61
J104	1.787	1.787	N/A	1.787	N/A
J109	45.019	45.019	27.408	45.019	27.408