A Computational Approach to Integrating Non-Structural Flood Risk Mitigation Strategies into the Urban Planning Process

Case Study: Addis Ababa, Ethiopia

Master Thesis

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A Computational Approach to Integrating Non-Structural Flood Risk Mitigation Strategies into the Urban Planning Process

Case Study: Addis Ababa, Ethiopia

A Thesis Submitted by

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Abstract

Urban flooding is a growing concern against a background of rapid urbanization and climate change. As both of the fields of urban planning and flood risk management have become increasingly complex over recent decades, interdisciplinary research is crucial for enabling a more comprehensive understanding of such complexities. This research work aims to bring hydraulic knowledge into the urban planning field in order to mitigate flooding impacts caused by storm-water runoff driven by increasing imperviousness. Elaborately, an integrated computational model is proposed, as an early design stage tool, to asses certain urban form aspects against their impacts on runoff volume and surface infiltration in a selected development site in Addis Ababa, Ethiopia, where flood hazards are often poorly understood and understudied. The ultimate goal of the model is to offer a flexible tool to be utilized by urban practitioners with limited knowledge in hydrology. Therefore, it is built on a familiar and accessible platform with an uncomplicated work-flow along a parametric planning process. Namely, the impact of street network layout, land use configuration, and sustainable infiltration tools is evaluated. The orientation of street layouts which align with rainwater flow direction are found to have a significant effect on storm-water storage and subsequent drainage management than those with a perpendicular orientation. The land use configurations which are based on block infiltration capacity contribute significantly more to runoff volume reduction than other distribution strategies based on street hierarchy and random allocation. The integration of different infiltration tools with predefined retention capacities are noticeably found to reduce further runoff volume. Together with the proposed computational model and its application, this research work offers valuable design guidelines, tools, and concepts for adopting a more sensitive planning approach towards flood risk reduction. The work positions itself at the intersection of two rather often disciplines, in order to serve as a hub where joint discussions and knowledge exchange between both urban planners and hydrologists can take place.

Keywords:
flood risk management, urban planning, low impact development, parametric modeling.

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List of Abbreviations

DRR	Disaster Risk Reduction
UNDRR	United Nations Office for Disaster Risk Reduction
UNISDR	United Nations International Strategy for Disaster Reduction
SUDS	Sustainable Urban Drainage Systems
LID	Low Impact Development
WSUD	Water Sensitive Urban Design
EM-DAT	Emergency Events Database
LULC	Land Use and Land Cover
FRA	Flood Risk Assessment
GIS	Geographic Information Systems
CEC	City of El Centro
MDEP	Massachusetts Department of Environmental Protection
EPANET	Environmental Protection Agency Network
HECRAS	Hydrologic Engineering Center River Analysis System
SRTF	Spatial Resilience Toolbox – Flooding
SWMM	Storm Water Management Model
CAD	Computer-Aided Design
SCS	Soil Conservation Services
CN	Curve Number
RGB	Red Green Blue
WPR	World Population Review
CLUVA	Climate Change and Vulnerability of African Cities
AACPPO	Addis Ababa City Structure Plan. Draft Final Summary Report
GA	Growth Angle
HCC	Hertfordshire County Council
UNESCO	United Nations Educational, Scientific and Cultural Organization
FISRWG	Federal Interagency Stream Restoration Working Group

1

Introduction to Flood Risk Modeling in Urban Planning

The First Chapter provides an overview of the relationship between the fields of flood risk management and urban planning along with their associated challenges that lead to the formulation of the problem statement, assumptions, objectives and overall structure of the presented research work.

Chapter One
Introduction to Flood Risk Modeling in Urban Planning

1.1 Overview

“By 2050, 70% of the world’s population will live in urban areas. As cities continue to grow, disaster exposure of lives, livelihoods, economic, social and environmental assets is set to increase exponentially. The local level is the frontline of addressing disaster risk and is where significant gains can be made.” [UNISDR, 2014].

The United Nations pointed out that 43% of natural disasters worldwide, in the period between 1995 and 2015 were related to floods. These events affected more than half (56%) of all people who suffered from any type of natural disaster, killing about a quarter of them (26%). This high number of casualties and associated economic losses can negatively affect the capability of a community ‘s sustainability. As a result, inhabitants, properties and the built environment are expected to be under constant risk in the future.

Flood risk is mainly a combination of three components: Hazard, Exposure and Vulnerability, which must be present simultaneously for a risk to be defined. Exposure is defined by the [UNISDR, 2017] as what may be affected by a flood event such as buildings, land use and population. A hazard refers to the potential threat posed by the natural phenomenon inherent in the event itself [Schanze, 2006], which in the context of this thesis would be flooding events. Vulnerability can be defined as a characteristic of a person or group and their situation that affects their ability to anticipate, cope with, resist and recover from the effects of physical events [Cardona, et al., 2012]. In other words, the less vulnerable an area is to risks, the more resilient it is. Therefore, Flood Risk Management aims to minimize the overall impact of flooding rather than improving existing flood defenses. This can be achieved by viewing a hazard as a resource rather than a threat, with the resilience of an area or system representing its ability to withstand and absorb change and disturbance. This paradigm shift is critical to designing a more sustainable flood risk reduction policy that brings together a variety of factors, sectors, and actions.

Spatial planning is increasingly playing a key role in flood risk reduction. One of the main reasons for this is the capability of urban planning to regulate the use of space over a long period of time [Sutanta et al., 2010]. Multiple planning concepts and approaches have been introduced to mitigate the impacts of different types of floods based on their scale, duration, and frequency. Among these types, urban pluvial flooding, i.e., the saturation of drainage systems resulting in floods, appears to be widespread in recent times especially in developing contexts where its impacts are increasingly posing a major source of concern for urban residents and policy makers [Nkwunonwo, 2018]. Along rapid urbanization, the main causes of pluvial flooding were abrupt land use changes, drainage failures, and poor urban planning [Adeloye & Rustum, 2011]. In addition, the growing complexity of flood risk management models and tools has made them more inaccessible to urban practitioners with limited hydraulic knowledge. As a result, the evaluation of flood risk and its associated mitigation strategies is often not adequately considered into the urban planning and decision making processes.

1.2 Problem Statement

As discussed above, rapid urbanization significantly contributes to the occurrence of floods, where it increases the ratio of impervious surfaces which in turn reduce infiltration and resistance to water flow. Consequently, the volume and flow rate of storm-water runoff increases to levels beyond local drainage capacities leading to flood risks [Chen, 2017]. Such phenomenon impacts developing countries the most, where unplanned urban growth is the common scenario.

Moreover, one of the major problems facing flood risk mitigation measures in such developing contexts is the limitations of structural strategies such as dams, flood walls, and barriers against sudden flooding events as well as the lack of adaptation of non-structural strategies such as land use distribution and low impact development (LID) approaches [Huapeng, 2013]. These non-structural strategies do not often require extensive investments as the structural ones typically do, but rely instead on a good understanding of flood hazard and proper planning schemes [Kang et al., 2009]. Another major problem is that existing scientific models and engineering formulas related to flood risk management are not easily accessible within the urban design field. This is because they are not yet integrated into a suitable design interface which would allow for rapid testing of different planning scenarios against any systematic performance criteria within the early stages of the design process. This raises the necessity to equip urban practitioners with suitable tools so that they can take appropriate measures aimed at reducing flood risk in an effective and sustainable manner.

1.3 Research Questions, Assumptions & Objectives

To address the aforementioned problems, the goal of this thesis is to identify and evaluate certain urban design elements that can positively contribute to flood risk reduction. The selected elements to be evaluated are: site terrain topography, street network layout, land use configuration in addition to the associated impact of specific sustainable storm-water management tools. It is assumed that each of these elements can have a significant impact on storm-water runoff reduction. The orientation of a street layout can enhance drainage performance when aligned with water runoff flow direction. Land use distribution strategies can increase rainwater infiltration when configured according to runoff volume and urban blocks catchment potential. Lastly, the allocation of sustainable storm-water management tools can provide further reduction in runoff volume. These assumptions can be reformulated into the following research question to be pursued:

How can urban form contribute to the mitigation of flood risk through the adaptation of non structural design strategies?

In order to answer this questions, this thesis proposes a computational model which:

- Generates water flow direction through numerical based simulation.
- Evaluates multiple street network layouts according to terrain slope direction and steepness.
- Calculates the storm-water runoff volume for given urban blocks and maps their catchment potential.
- Optimizes land use configurations according to soil type and maximum cumulative infiltration.
- Evaluates the impact of sustainable infiltration tools on runoff volume reduction.

Furthermore, the developed model, which serves as an early design stage tool, is to be applied to a selected site in a developing country in order to scrutinize the effectiveness of its potentials and capability in addressing the problems in question.

Ultimately, this research work, as most works conducted in the field of urban planning, attempts to bridge external disciplines, a circumstance that poses multiple challenges and opportunities. As both disciplines of urban planning and flood risk management are growing in complexity, they require constant and dynamic adaptation in order to maintain relevancy. Therefore, this thesis aims to bring certain elements of each discipline closer together in order to fill existing research gaps and provide a platform for a constructive dialogue between professionals and academics of each side. Accordingly, the illustration below outlines the general research scheme:

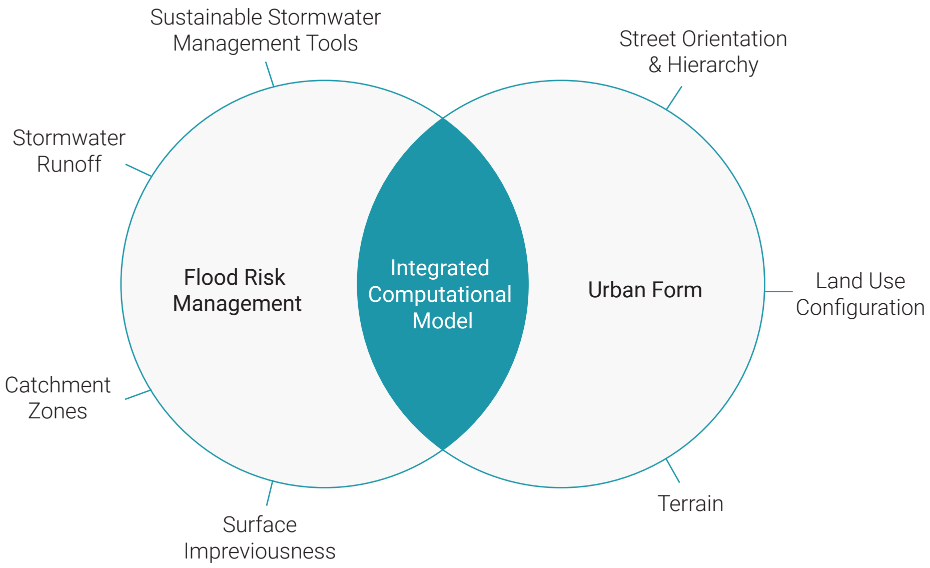

Fig. 1.1 Interdisciplinary Research Scheme

1.4 Thesis Structure

Including this introductory chapter, the thesis is divided into five chapters. Due to the interdisciplinary approach to this research, the Second Chapter outlines concepts and tools of flood risk management. It starts with describing general components of disaster risk management and reduction. It then goes into defining different types of floods, their causes and implications, to enable the reader to become aware of the significance of those topics. Following, it outlines the role of multiple spatial planning approaches and tools in mitigating these impacts. The chapter concludes with a focused review of existing hydrological and parametric design models in both the urban planning and flood management fields as to identify research gaps and opportunities.

The Third Chapter is dedicated to introducing an integrated computational model which incorporates the discussed urban design parameters, flood management tools, and calculation methods. The chapter illustrates the proposed model work flow along with an evaluation process of a couple planning scenarios and approaches based on their potential of mitigating storm-water runoff and promoting surface infiltration.

The Fourth Chapter defines the case study where effectiveness of the computational model is evaluated. The chapter starts with describing the relevancy of the selected location and study site. Following, it introduces a wider variety of planning scenarios and parameters to be evaluated by the proposed model within a large scale context. Lastly, it concludes with the obtained results, discussion and technical limitations.

The thesis concludes with Chapter Five, which discuses conclusions, suggestions, and outlooks of the proposed research work. This chapter emphasizes the significance of incorporating flood risk management approaches in the urban planning process, explains the contribution of this thesis in filling potential research gaps, and explores the possibilities of further relevant approaches for reducing flood risks through more effective planning.

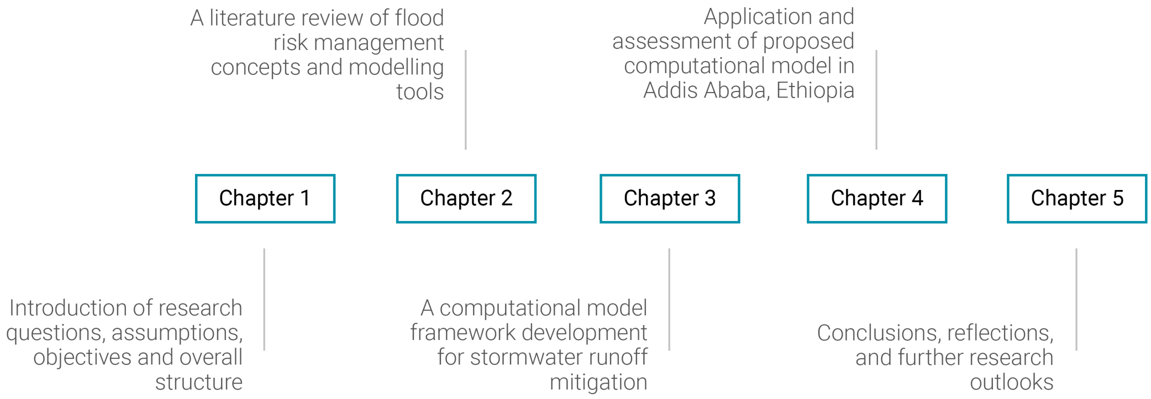

Fig. 1.2 Thesis Structure

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Flood Risk Management Concepts & Modelling Tools

The Second Chapter outlines concepts and tools of flood risk management. It starts with describing general components of disaster risk management and reduction. It then goes into defining different types of floods, their causes and implications to enable the reader to become aware of the significance of those topics. Following, it outlines the role of multiple spatial planning approaches and tools in mitigating these impacts. The chapter concludes with a focused review of existing hydrological and parametric design models in both the urban planning and flood management fields as to identify research gaps and opportunities.

Chapter Two
Flood Risk Management Concepts & Modeling Tools

2.1 Natural Disasters

Historically considered as "Acts of God" or inherent natural phenomena, disasters are now understood as a disruption of the functioning of a community or a society due to hazardous events interacting with conditions of vulnerability and exposure, leading to widespread human, material, economic and environmental losses and impacts [UNDRR, 2015]. Since the 1950s, strategies for dealing with disasters have evolved from civil defense–based response and relief approaches, to risk reduction strategies [UNISDR, 2004].

Currently, general terms, such as Disaster Risk Reduction (DRR) are used to define standard and organized efforts for reducing harm to life, property, and environment due to disasters [Coppola, 2011]. These efforts can significantly increase a community's resilience. Resilience is understood as an ability to cope with various disasters by surviving them, reducing their impacts, and recovery with little social disruption. Additionally, as the type of resilience that planning deals with relates mainly to the urban and built environment, it is also worth to consider resilience as stated by [Meerow, 2016]:

> "The ability of an urban system and all its constituent socio-ecological and socio-technological networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change and to quickly transform systems that limit current or future adaptive capacity."

Rapid urbanization, population growth and economic development, are significantly contributing to increasing urban areas exposed to natural disasters. In many cases this urbanization is unplanned and unrestricted and leads to many physical, social and economic vulnerabilities [Malalgoda et al., 2013]. As a result, densely populated urban areas suffer overwhelming impacts even with small scale naturally occurring disasters. Between 2000 and 2019, over 4 billion people worldwide were affected by disasters and over 1.2 million people lost their lives [UNDRR, 2020]. These numbers not only demonstrate the large-scale impact disasters have across the world, but also the importance of promoting a greater understanding of disaster risk so that appropriate measures can be taken to protect lives and livelihoods.

According to the International Disaster Database (EM-DAT), the major subgroups of natural disasters are classified into Geophysical, Hydrological, Meteorological, and Climatological. Each subgroup poses different social and economic impacts. Globally, floods are the most common type of disaster, accounting for 44% of total events . Floods are hydrological events, a disaster sub group which makes up the bulk of total events (49%) and people affected (41%). However, they are only responsible for 10% of total deaths. On the other hand, geophysical events account for only 9% of total disaster events, but 59% of all disaster related deaths, making them the deadliest type of disaster. In addition, meteorological disasters stand out as the costliest type of disaster, accounting for 49% of overall economic damage. [Figure 2.2]

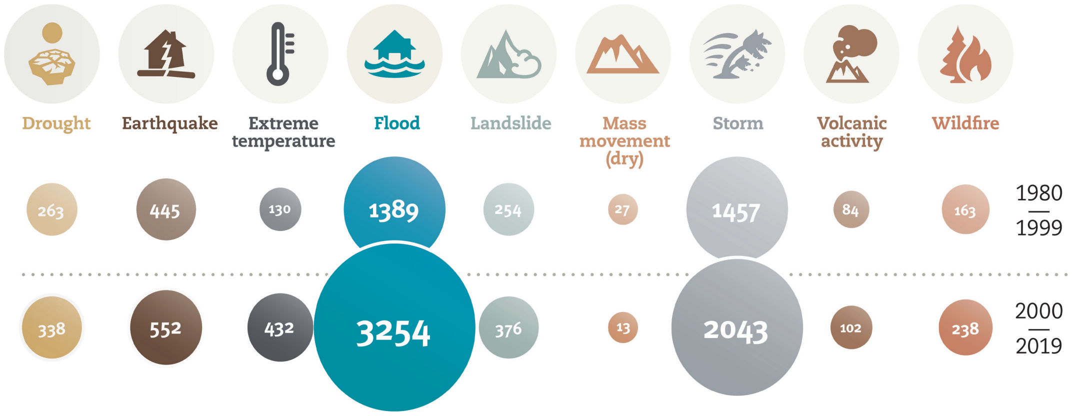


Fig. 2.1 Total Disaster Events by Type: 1980-1999 vs. 2000-2019 [UNDRR, 2020]

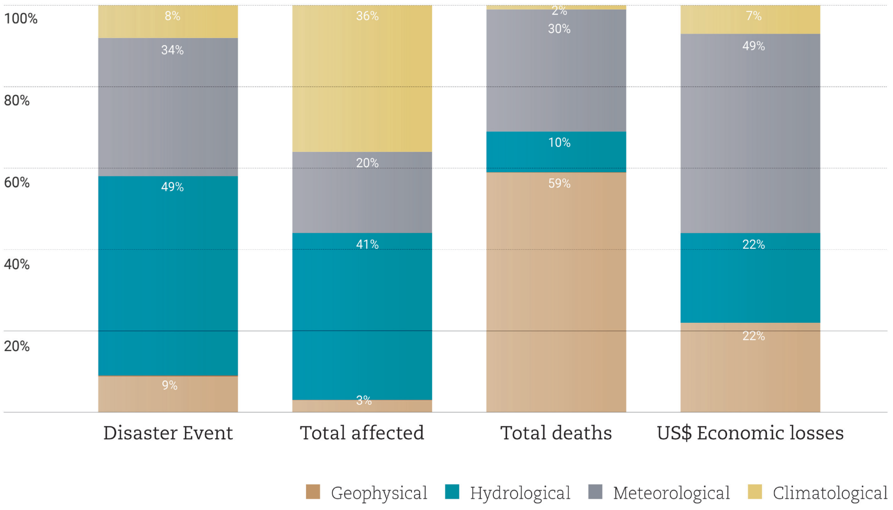


Fig. 2.2 Proportion of Types of Impacts by Disaster Sub-Group (2000-2019) [UNDRR, 2020]

2.1.1 Disaster Risk Management

Disaster management is a key concept in international efforts and capacity development. According to [UNDRR, 2016], Disaster Risk Management is the application of disaster risk reduction strategies, processes and measures to prevent new risks, reduce existing disaster risks and manage residual risks, which contributes to resilience building. Using the disaster management cycle, a heuristic that establishes different phases related to disasters, practical and actionable steps are often collected for local or regional implementation. In principle, disasters can be divided into pre-disaster and post-disaster phases. More specifically, all phases can be represented as 1) mitigation, 2) prevention, 3) preparedness, 4) response, and 5) recovery [Hegger et al, 2014]. Mitigation, prevention, and preparation include actions such as vulnerability assessment, mitigation measures to reduce the impact of a disaster, and preparation of natural vegetation buffers in advance. Preparedness measures typically aim to optimize and coordinate the preparedness of communities, organizations, governments, and institutions. Response activities aim to alleviate the most urgent and pressing problems that arise after a disaster. Finally, reconstruction is a broader and longer process to restore the livelihoods and capacities of people and communities affected by a disaster.

2.1.2 Disaster Risk Reduction

As defined by [UNISDR, 2009], Disaster Risk Reduction (DRR) is the concept and practice of reducing disaster risks through systematic efforts to analyze and manage the causal factors of disasters, including reduced exposure to hazards, reduced vulnerability of people and property, wise management of land and environment, and improved preparedness for adverse impacts. Disaster risk reduction strategies primarily include vulnerability and risk assessment and a range of institutional capacities and operational capabilities. Vulnerability assessment of critical facilities, social and economic infrastructures, the use of effective early warning systems and the application of many different types of scientific, technical and other capabilities are essential features of DRR. There is a clear interaction between disaster risk reduction and disaster risk management. While disaster risk reduction involves activities that focus more on the strategic level of management, disaster risk management is the tactical and operational implementation of disaster risk reduction.

2.2 Flooding

"Great floods have flown from simple sources." - *William Shakespeare*

Floods are usually the result of a combination of meteorological and hydrological phenomena as well as human activities that can cause loss of life, injury or other health consequences, property damage, loss of livelihoods and services, social and economic disruption or environmental damage [UNISDR, 2009]. Statistics show that flood disasters, in particular, are among the most damaging and costly. From 2000 to 2019, floods accounted for 44% of all disaster events and affected 1.6 billion people worldwide [UNDRR, 2020].

2.2.1 Flood Sources & Types

In order to take appropriate action to reduce flood risk, it is important to understand both the nature and the source of the flood. Floods can be classified into the following four categories depending on their occurrence [Sen Z., 2018]:

1. Active water collector floods: Streams and rivers
2. Dry water collector floods; Mountain sides and slopes
3. City floods: Creeks or streets in the urban areas
4. Coastal floods: Open pressure effect on the sea surface.

They can also be classified according to their causes and duration (Table 1). In particular, urban flooding is becoming increasingly costly and difficult to manage as low- and middle-income countries develop into larger urban societies where people and assets are more concentrated in urban centers. In addition to direct economic damage, floods also have long-term consequences such as loss of educational opportunities, disease and poorer overall nutrition.

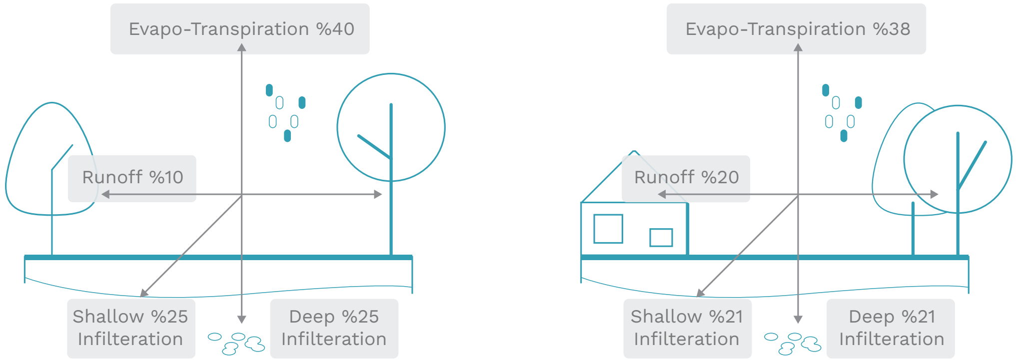
Flood Type	Naturally Occurring	Human Induced	Duration
Urban flood	Fluvial Coastal Flash Pluvial Groundwater	Saturation of drainage and sewage capacity. Lack of permeability due to increased concretization. Faulty drainage system and lack of management.	From few hours to days
Pluvial & Overland Flood	Convective, thunderstorms, severe rainfall, breakage of ice jam, glacial lake burst, earthquakes resulting in landslides	Land used changes; urbanization Increase in surface runoff.	Varies depending upon prior conditions.
Coastal Flooding	Earthquakes Submarine Volcanic Eruptions Subsidence Coastal erosion	Development of coastal zones. Destruction of coastal natural flora.	Usually a short time however sometimes takes along time to recede.
Groundwater	High water table levelcombined with heavy rainfall.	Development in low-lying areas; interference with natural aquifers.	Longer duration.
Flash Flood	Can be caused by river, pluvial or coastal systems; convective thunderstorms.	Catastrophic failure of water retaining structures. Inadequate drainage infrastructure.	Usually short often just a few hours.

Table 2.1 Types of Floods, Causes and Duration [Jha et al.. 2012]

2.2.2 Flood Causes

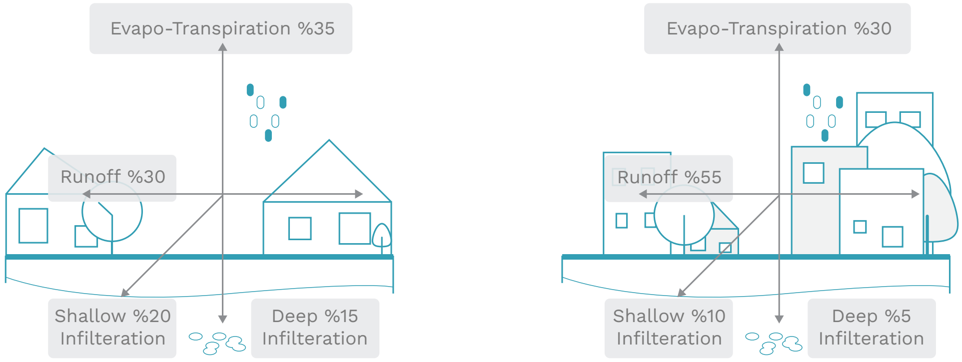
Urban areas can be flooded by rivers, coastal flooding, pluvial flooding, groundwater flooding, and malfunctioning man-made systems. Urban floods are usually due to a complex combination of causes resulting from a combination of meteorological and hydrological extremes, such as extreme rainfall and runoff [Jha et al., 2012]. However, they are also often the result of human activities, such as unplanned growth and development in floodplains or the breach of a dam or levee that does not protect planned development [Min et al., 2011]. In urban areas, the areas of open ground that can be used for water storage are very limited. Heavy rainfall can cause flooding if drainage systems do not have the capacity to handle the runoff. The continuous expansion of cities has reduced the permeability of the soil in groundwater recharge areas and increased runoff, which increases the risk of flooding [Li et al., 2018]. Urban flooding is also caused by the effects of poor or improper land use planning. Many urban areas are facing the challenge of increasing urbanization with rising population and high demand for land. Although there are laws and regulations that control the construction of new infrastructure and diversity of building types, they are often not properly enforced due to economic or political factors or capacity or resource constraints [Jha et al., 2012]. This leads to obstruction of natural water flow pathways resulting in flooding. Urbanization is accompanied by ever-increasing spatial expansion of cities, which alters the natural landscape, Land Use and Land Cover

(LULC), increases impervious surfaces and runoff, reduces infiltration, and changes the frequency of flooding (Figure 3) in the mid-1970s, when urbanization was just beginning to accelerate, a study by [Hollis, 1975] showed that the occurrence of minor floods could increase tenfold with rapid urbanization, while more severe floods with return periods of 100 years or more could double if 30 percent of roads were paved [Wheater & Evans, 2009].



Natural Ground Cover

Impervious Surface 10%-20%



Impervious Surface 35%-50%

Impervious Surface 75%-100%

Fig. 2.3 Impact of Urbanization on the Natural Water Balance [FISRWG, 1998]

In general, communities that move from rural to urban areas or locate in urban areas are at high risk of flooding. Lack of or inadequate flood protection measures can make them very vulnerable. In addition, land changes can increase the risk of flooding by reducing the permeability of soils, which increases surface runoff and overloads drainage systems [Jha et al., 2012]. The causes of flooding are changing and their impacts are increasing. This evolving challenge needs to be better understood and more effectively managed by policy makers.

2.2.3 Flood Implications

Floods have far-reaching effects on the physical and social spheres in the urban environment, which often lead to great economic losses. Most literature has found that economically marginalized people are at greater risk of being affected by natural disasters. For example, slum dwellers, the poor and migrants living in vulnerable areas such as riverbanks, underdeveloped residential areas and coastal regions are more prone to disasters. The following is an overview of the physical and social impacts of flooding:

1. Physical

The physical impact of urban flooding refers to material damage caused by flooding to homes, cars, roads, and other assets in urban areas. In general, the degree of vulnerability of houses or buildings to urban flooding depends on the height of the ground floor. The frequency and depth of flooding are largely influenced by a small change in elevation. The more settlements spread in flood-prone areas, the more they are exposed to a physical threat. As a result of increased living standards, people acquire more assets, which increases the risk of vulnerability [Parker, 1995]. Factors such as the building material, location of the building in relation to the ground, adjacency to other buildings, orientation to the river and other geometric features, number of floors, basements and age of buildings should be considered in urban planning. Other influential attributes for the physical vulnerability of buildings include below grade windows, soil conditions, condition of repairs, and the presence of ventilation shafts and ducts. Street flooding is an increasingly important issue that depends on rainfall, timing and intensity of flooding, runoff situation, and topographic conditions [Yin et al., 2016]. When streets are disrupted due to flooding, the entrapment or rising of open water in cars and other vehicles leads to flood victims [Dorbot & Parkar, 2007]. Overall, it is observed that street mobility hazards during floods are much greater than residential hazards in urban areas [Debionne et al., 2016].

2. Social

While floods can result in direct visible losses such as destroyed infrastructure and damaged property, they also have indirect negative social impacts on affected communities. A common approach to distinguishing the types of indirect negative social impacts of flooding is to distinguish between tangible and intangible flood impacts [Smith & Ward, 1998]. Indirect impacts are those that occur both spatially and temporally outside of the flood event, such as a loss of productivity due to a disruption in supply chains. For those indirect impacts, a distinction is made between tangible and intangible impacts. Tangible impacts are those that can be easily expressed in monetary terms and thus relate to goods for which a market price exists [Meyer et al., 2013]. Examples of tangible impacts include lost sales or traffic disruption. On the other hand, impacts that are difficult to express in monetary terms because there is no market price, such as long-term health and psychological impacts or the destruction of social life and cultural heritage, are referred to as intangible impacts.

2.3 Flood Risk Management & Mitigation Strategies

As outlined by [Sayers et al., 2012], the flood risk management cycle is consisting of five main steps: 1) Risk Assessment 2) Risk Treatment 3) Strategy Implementation 4) Monitoring and Evaluation 5) Risk Goals and Policy Development and Adjustment. In addition to risk communication participation thought out the cycle. Among these five phases, the two main steps that are facing many challenges are Flood Risk Assessment and Flood Risk Reduction.

2.3.1 Flood Risk Assessment

Flood Risk Assessment (FRA) is essential for identifying flood-prone areas in urban environments to mitigate flood risks and support the associated decision-making process. A number of research papers have developed several concepts to understand what flood risk is and how the flood risk system works. Below are the most commonly accepted definitions:

Risk is the probability of a loss, which depends on three elements: hazard, exposure, and vulnerability [Crichton, 1999] [Fig. 2.4]. When any of these three elements of risk increases or decreases, the risk increases or decreases respectively. Accordingly, flood risk can be expressed as follows [Schanze, 2006]:

Flood risk = Flood hazard * Flood vulnerability * Flood exposure

Hazard is a physical event, phenomenon, or human activity that can lead to harm [Schanze, 2011]. [Tywissen, 2005] compared different definitions of hazard and concluded that an important characteristic of hazard is that it is a probability, that is, the likelihood of occurrence. It is a threat that has the potential to cause severe adverse impacts. Flood hazard is defined as the probability of exceedance of potentially damaging flood conditions in a given area and within a given time period. It depends on flood variables such as flood depth, velocity and duration [Tingsanchali, 2011].

Exposure is defined as the presence of people, infrastructure, housing, production capacities, species or ecosystems, and other tangible human assets in places and settings that could be adversely affected by one or multiple hazards [UNISDR, 2017]. Exposure may vary in space and time, for example, as people commute between their work place and their home. Measures of exposure can include the number of people or types of assets in an area.

Vulnerability is a measure of the potential loss of physical, economic and social value of a particular place. It is a product of the interaction of susceptibility and resilience within the system [McFadden, 2001]. It can be expressed in terms of functional relationships between expected losses in relation to all elements at risk and the vulnerability and exposure characteristics of the affected system [Messner & Meyer, 2006]. Flood vulnerability refers to the characteristic of a system that describes its potential to be harmed in terms of social, economic, environmental and institutional aspects. It can be considered as a combination of value or function, susceptibility and coping capacity [Schanze 2011].

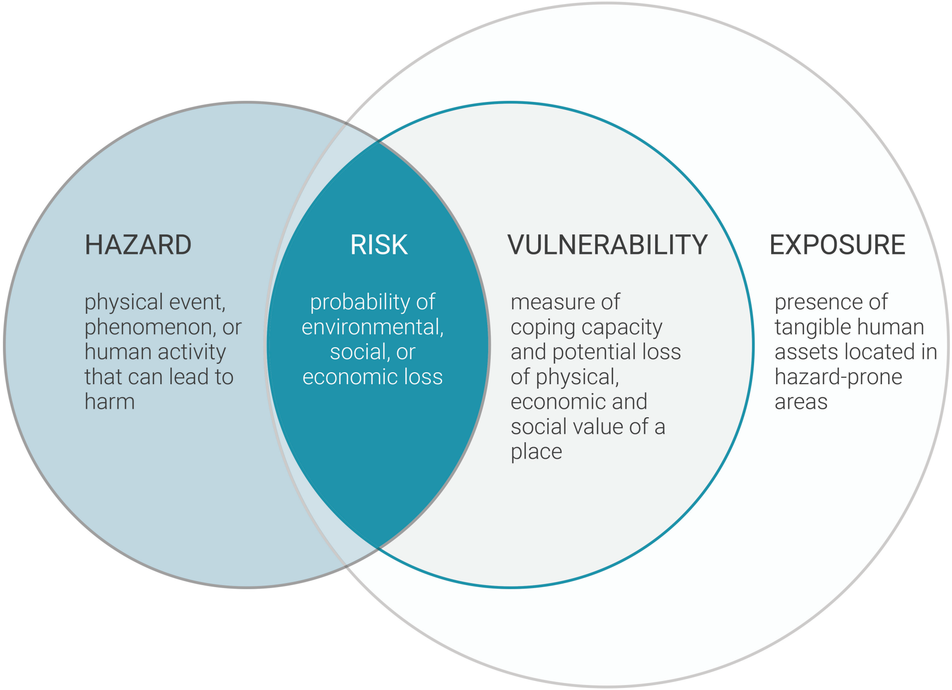


Fig. 2.4 Components of Disaster Risk [Pinelli et al, 2020]

First and foremost, flood risk management attempts to focus protection efforts on areas with a high expected loss by adapting flood protection to the risk situation [Messner & Meyer, 2006]. To achieve the best management results, a risk-based approach using available budget and resources is appropriate, where a hazard is viewed as a resource rather than a threat, with the resilience of an area or system representing its ability to withstand and absorb change and disturbance. However, one of the main problems faced by FRA is the insufficient analysis and mapping of vulnerability [de Brito et al., 2017]. Although there are many studies in this regard, most of the previous studies have focused only on FRA at the regional level. There is a notable limitation in FRA studies at the local level.

2.3.2 Flood Risk Reduction

Flood Risk Reduction strategies have been mainly divided into structural and non-structural mitigation approaches [Lindell et al., 2006].

Structural measures are usually large public works projects that require a medium to large amount of planning and design. Some examples of structural measures used primarily to control the volume of urban surface water include detention or retention facilities, channel improvements to reduce the impact of flooding in flood hazard areas, construction of levees or dams, upstream storage and diversion works, channel modifications or encasements, levees and floodwalls, bridges, and culvert reconstruction or replacement [Abdrabo et al, 2020]. Structural measures used primarily to control urban surface water quality include sedimentation basins, artificial or restored wetlands, and infiltration systems [Lindell et al., 2006].

On the other hand, non-structural measures usually involve little or no construction and can often be implemented quickly by individuals, businesses, and other private entities. They usually require small to medium investments [Kang et al., 2009]. Examples of non-structural measures include institutional control, land use regulation, land acquisition and relocation, elevation of buildings, flood proofing, flood forecasting and warning systems and emergency plans, and a flood insurance program [Abdrabo et al, 2020]. Non-structural measures aim to protect people from flooding through better planning and management of urban development.

In comparison, structural measures tend to be protective measures, while non-structural measures tend to be reduction measures [Table 2.2]. Experience shows that a comprehensive integrated strategy should be linked to existing urban planning and management policies and practices, combining both structural and non-structural flood mitigation measures.

At the same time, the last decade has seen a shift away from traditional approaches to flood management, which aim only to reduce the direct consequences of a flood disaster. This is partly due to the growing realization that structural measures are not sufficient to deal with the multiple consequences of flood events and that they do not provide a solution to the increasing frequency and magnitude of modern flooding [Kang et al., 2009]. Thus, this flood trend reflects a broader movement away from the traditional assumption that disasters are manageable as single events.

	Structural	Non-Structural
Concept	Control over hazard Protection of human settlement	Hazard reduction or avoidance Adjustment of human activities
Measures	Dams, floodwalls, storage reservoirs, dikes and pumps Flood protection Building shelters Detention ponds Floodways and wetlands	Land use control Flood proofing Sustainable infrastructure policy Building code and local legislation Awareness and partnership Financing and recovery Risk reduction and preparedness policies

Table 2.2 Structural and non-structural flood mitigation strategies [Peacock & Husein, 2011]

2.4 Role of Spatial Planning in Flood Risk Reduction

Spatial planning is increasingly regarded as one of the most important tools for disaster risk reduction. In the field of flood risk management, spatial planning has the capacity to regulate land use in flood prone areas and ensure that the development of new settlements and industrial development is kept away from key flood risk areas [Boehm et al. 2004]. As described by [Abdrabo et al. 2020], some of the key urban planning measures that can contribute to greater flood risk reduction and prevention fall into the following categories: 1) land use control, 2) building codes, 3) flood protection and building elevation, and 4) sustainable storm-water management.

2.4.1 Land Use Control

“The need to integrate flood risk in land use planning is immense, given the frequency, severity, and impacts of floods in recent decades.” – World Bank, 2017

One of the most effective strategies for reducing the risk of flood damage in urban areas is to regulate floodplain development through land use planning. Such a strategy requires the cooperation of multiple stakeholders [Sen, 2018]. Poor, ill-informed or non-existent land use planning has consistently contributed to the vulnerability of communities exposed to natural hazards [UNISDR, 2004]. Although urban areas are usually the most vulnerable to flood disasters, there are still inadequate measures to reduce the impact of flooding on local communities. As spatial planning is responsible for deciding the long-term use of land, it can play a fundamental role in reducing flood risk. As the [World Bank, 2017] notes, controlling land use can have a significant impact on reducing flood risk:

- Zoning Plans & Development Controls: classifying different land use setting for flood prone areas by identifying sensitive societal or environmental features. According to degree of flood risk, a link is established for appropriate, safe, and permissible land uses [Fig. 2.5, Fig. 2.6]
- Flood Zoning: prohibiting and restricting future development by determining what risks are associated with specific land uses in highly prone areas, especially with history of disaster occurrences.

Many factors and data sets play a role in spatial and land use planning. First, cadastral data is incorporated into topographic and natural area maps. This map is then built upon incrementally to provide a spatial understanding of all other features such as buildings, infrastructure locations, open space, coastal areas, green belts, nature reserves and watercourses. This approach enables policy makers to properly consider the needs of the community and manage potential flood hazards and risks. Technology is also now supporting land use planning and management. In particular, the use of Geographic Information Systems (GIS) provides agencies with the ability to spatially capture relevant urban data

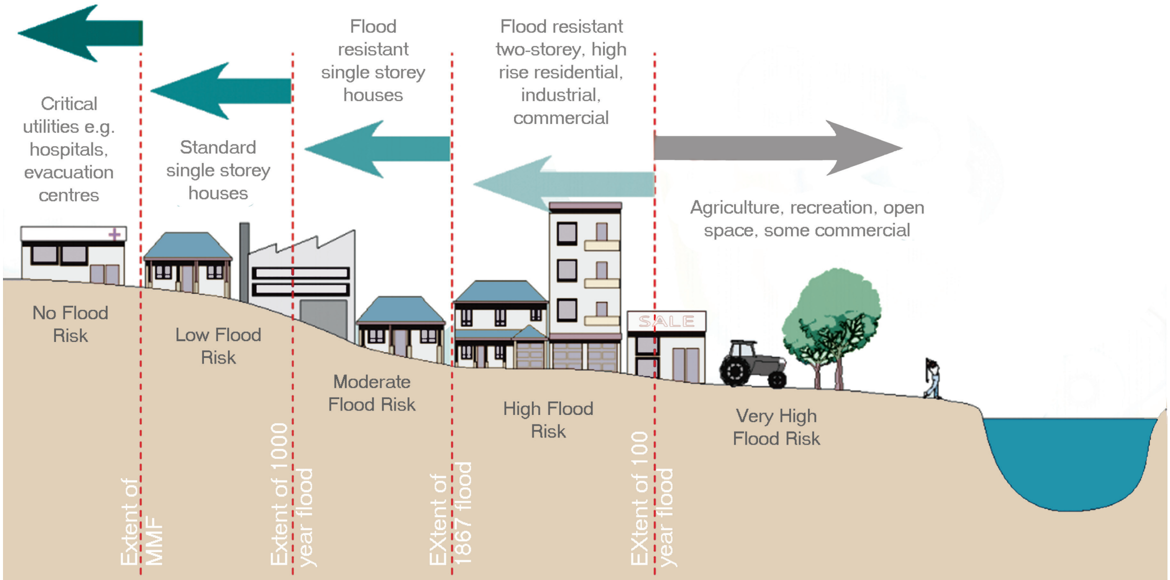


Fig. 2.5 Distribution of the Land Uses on the Floodplain to Reduce Risk [Bewsher et al., 2013]

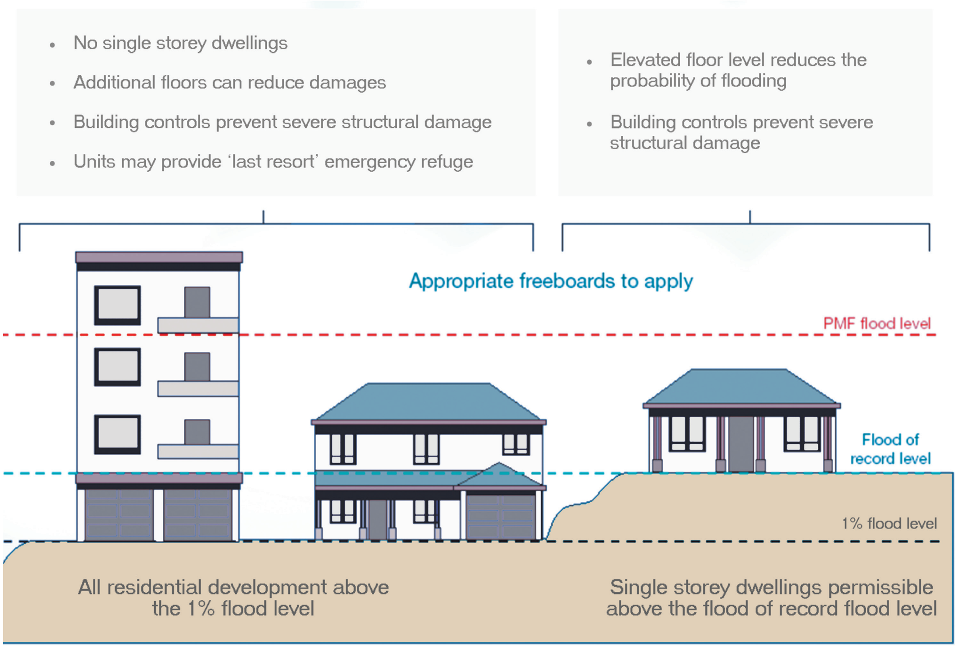


Fig. 2.6 Increased Property Protection through Development Controls [Bewsher et al., 2013]

2.4.2 Street Layout

As discussed in Section 2.2.3, street flooding is an increasingly important issue that depends on rainfall, timing and intensity of flooding, runoff situation, and topographic conditions [Yin et al., 2016]. The hazards to street mobility during flooding are much greater than the hazards to residential areas in urban areas [Debionne et al., 2016]. In addition, the layout of the street network can have a major impact on the hydraulic cycle of an urban area due to its relationship with the water drainage network and infrastructure. Defining a water distribution network as a subset of the street network has been shown to be a robust modeling approach for both newly planned and existing water distribution systems [Zischg et al., 2017]. Accordingly, the layout of a street network can be optimized for water distribution efficiency early in the planning process. As discussed by [Dennemark et al, 2018], a street network growth scenario that follows the slope direction allows for the integration of shortest possible flow paths into the underlying pipe network resulting in improved water distribution. In other words, designing street networks that allow for minimal disruption of the natural drainage pattern can better inform subsequent design and planning of drainage networks.

2.4.3 Building Codes

While land use plans can help incorporate flood risk management through the creation of floodplains and development strategies that identify appropriate land uses and development patterns, such a framework can be of little use unless it is accompanied by appropriate building codes and regulations. Generally, building codes establish minimum standards for materials, access, and floor heights for development within a given urban zone. More specifically, building codes can address flooding events and reduce flood damage by requiring elevated sites and streets, mandatory retrofitting of flood protection measures, flood proofing for critical buildings such as hospitals and emergency shelters, and planning and design for redundancy. In addition, building codes can mandate building orientation to minimize disruption of flood flows and require emergency exits in an elevated area such as the roof [WMO, 2016].

2.4.4 Flood Proofing and Building Elevation

Flood damage to infrastructure elements and houses can be caused by direct water forces, by erosion, or by a combination of both [Santato et al., 2013]. As stated by [UNESCO, 1995], the main flood protection techniques include: 1) Elevation, i.e., raising the building or infrastructure elements above the flood level to ensure continuity of operation of these systems. In particular, the use of elevated walkways greatly improves accessibility between homes and important public buildings, such as flood control

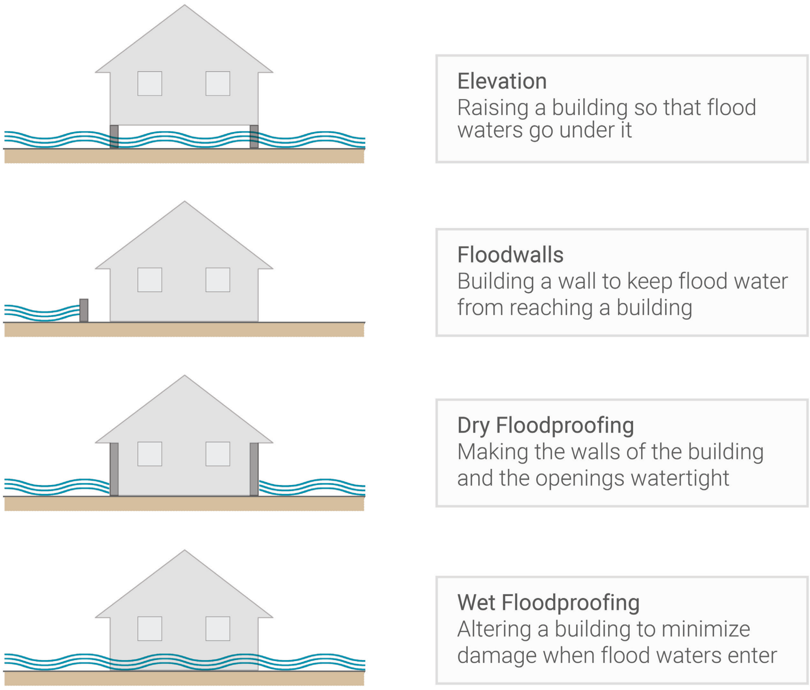


Fig. 2.7 Examples of Flood Proofing [UNESCO, 1995]

structures. 2) Dry flood-proofing, which is divided into i) waterproofing, where building exterior walls are used to retain floodwaters, and ii) shielding, where floodwaters do not reach the building itself because physical barriers are erected at a buffer distance from the building. And 3) Wet flood-proofing: where flood damage is reduced by using waterproof materials when the lower parts of the building are partially flooded and not used for habitation. At the same time, the ground floor can be dry flood-proofed [Fig. 2.7].

2.4.5 Sustainable Storm-water Management

Storm-water management has become increasingly complex in recent decades. This is because both parts of the problem and potential solutions are in the hands of a variety of stakeholders, from water utilities, regulators, planners, and property owners, resulting in complex and often fragmented responsibilities [Fenner, 2019]. Various concepts, approaches, and tools have been used in urban storm-water management and other related fields. Some of these approaches are Sustainable Urban Drainage Systems (SUDS) in the UK, Low Impact Development (LID) in the US, Water Sensitive Urban Design (WSUD) in Australia and the Sponge City in China. All of these approaches have relatively similar principles and often use vegetative surfaces that can provide numerous benefits to the urban environment. However, not all adopt these approaches and in many cases they are met with resistance from developers. The following is an overview of each approach:

Sustainable Urban Drainage Systems (SUDS)

Originally, the term Sustainable Urban Drainage Systems (SUDS) described the UK approach to sustainable urban drainage systems. The concept of SUDS is often implemented in cities that are particularly prone to flash flooding due to high rainfall. In such urban areas, the built environment is usually impervious to water due to the common use of building materials such as concrete and asphalt. As a result, storm-water discharged directly into drainage systems can become overwhelmed. The main goal of sustainable drainage infrastructure is to use multiple landscape elements to manage the movement of storm-water more efficiently [Abdrabo et al, 2020].

Low Impact Development (LID)

The term “low impact development” (LID), most commonly used on North America, was first introduced by [Barlow et al, 1977]. The concept seeks to minimize storm-water management costs by adopting a “design with nature” approach [McHarg, 1971]. The main goal of LID is to achieve natural hydrology by using the design of a site along with integrated control measures. Natural hydrology refers to the balance of storm-water runoff, infiltration, and evapotranspiration prior to development on a site

[Fenner, 2020]. By applying a cascading drainage system, LID aims to minimize direct connectivity between adjacent impervious zones. Thus, LID is primarily concerned with distributing storm-water runoff from upper impervious surfaces to lower pervious zones, such as absorbent landscape areas like permeable pavement and rain gardens, to promote infiltration and improve water quality [Fletcher, 2015].

Water Sensitive Urban Design (WSUD)

The term WSUD was first used in Australia in the 1990s. It is described by (Lloyd et al, 2002) as a "philosophical approach to urban planning and design that aims to minimize the hydrological impacts of urban development on the surrounding environment". Storm-water management is a subset of WSUD that focuses on flood control, runoff management, water quality improvement, and the ability to use storm-water to supplement tap water for non-potable uses. As stated by [Donofrio et al, 2009], WSUD cannot be strictly defined. Rather, it can be viewed as a framework with a number of objectives, some of which include:

- Protecting and enhancing creeks, rivers and wetlands within urban environments.
- Restoring the urban water balance by maximizing the reuse of storm-water, recycled water, and grey water.
- Conserving water resources through reuse and system efficiency.
- Integrating storm-water treatment into the landscape so that it offers multiple beneficial uses such as water quality treatment, wildlife habitat, recreation and open public space.
- Reducing peak flows and runoff from the urban environment simultaneously providing for infiltration and groundwater recharge.

The WSUD approach explicitly works across scales and seeks to engage different disciplines such as architects, planners, social scientists and ecologists in integrated urban storm-water management [Mouritz et al., 2006]. The term WSUD has also inspired a number of related concepts, such as climate-sensitive urban design [Coutts et al., 2013].

Sponge Cities

The term ‘sponge city’ describes cities that are able to adapt flexibly to changes in the environment, like sponges, so that they can absorb, store,infiltrate and purify rainwater, and are able to use the stored water when needed. Building a sponge city is a complex systems engineering task that involves numerous aspects of hydrology, meteorology, river systems, land use, pipeline networks, urban development, and ecosystems [Shao et al., 2016]. China has particularly excelled in its efforts to embrace the concept Sponge City. The country plans for 80 percent of its cities to capture and reuse 70 percent of rainwater [Harris, 2015].

The sponge city concept follows similar guidelines to the LID and WSUD approaches. As described by [Chan, et al, 2018], the sponge city concept has three main objectives:

1. Adopt and develop LID concepts which improve effective control of urban peak runoff, and to temporarily store, recycle and purify storm-water.
2. Upgrade the traditional drainage systems using more flood-resilient infrastructure, e.g. construction of underground water-storage tanks and tunnels, and to increase current drainage protection standards using LID systems to offset peak discharges and reduce excess storm-water.
3. Integrate natural water-bodies, such as wetlands and lakes, and encourage multi-functional objectives within drainage design, such as enhancing ecosystem services, whilst providing additional artificial water bodies and green spaces to provide higher amenity value.

Tools for Sustainable Stormwater Management

Based on the previous review of SUDS, LID, WSUD and the Sponge City strategies, it can be concluded that the four approaches discussed can be broadly described as forms of adaptation measures designed to drive sustainable urban design. As a result, there is considerable convergence between these strategies, and in some cases one approach can be discussed as a subset of another. In addition, all four approaches appear to address strategies that allow storm-water infiltration in urban areas to reduce surface runoff and prevent flooding or to improve groundwater recharge. Basically, the common goal is to make the hydrological design of cities sustainable [Arahuetes, 2019; Hoban, 2019]. Accordingly, the approaches discussed seem to advocate reducing the hydrological impacts of permeable surfaces. That is, SUDS employs strategies to promote groundwater recharge and reduce flooding, LID and Sponge City approaches to mimic the natural environment by attempting to preserve the watercourse from development, and WSUDS encompasses a range of strategies, including LID and sometimes SUDS, that aim to preserve natural systems, restore the hydrological balance, and reduce hydromodification, among other measures [Abbondati & Cozzolino, 2020].

Moreover, the above approaches seem to use similar practices and tools as part of their respective principles of sustainable storm-water adaptation. These tools can be divided into three main categories: Infiltration, Detention, and Retention. An overview of each tool is provided overleaf.

A. Infiltration Tools

Infiltration tools are used to infiltrate storm-water into the ground to reduce the volume of storm-water on the surface. The amount of rainfall that infiltrates into the ground is largely dependent on soil type, land use, degree of soil saturation, and a number of other variables. The main infiltration techniques include:

1. Storm-water Planters

   Storm-water planters are small rain gardens usually housed in structures made of durable material such as wood, stone, brick, or concrete with plastic liners. Storm-water planters are primarily designed to capture runoff and filter out sediment and pollutants [Cahill et al., 2018]. They can be placed on public or private properties where space available for storm-water management is limited. Potential areas for planters include residential front and back yards, parking lots, and streets [Barr, 2001].

2. Permeable Pavements

   Permeable pavements are pavements designed to promote infiltration of storm-water runoff. They can replace traditional impervious pavements without the need for additional storm-water management measures such as a detention basin or rain garden [Cahill et al., 2018]. Pervious pavement typically consists of a porous material through which storm-water can flow, or non-porous tiles arranged to allow water to flow between voids. Storm-water flows through the voids in the pavement and eventually infiltrates into the underlying soil, where it can be stored and used for a variety of purposes. Permeable pavements are commonly used on streets, roads, and parking lots with light vehicle traffic, such as bike paths, service or emergency routes, and sidewalks and driveways in residential areas. This is mainly because roads and areas with high traffic tend to be more polluted, which negatively affects the quality of storm-water infiltration [Yu et al., 2017]. Therefore, permeability requirements vary depending on the type of road and surface material, and the permeability of road surfaces can vary accordingly, ranging from 40% to 70% [Yu et al., 2017].

3. Bioretention Cells

   Bioretention cells, or Rain Gardens, consist of a sunken area with vegetation, an engineered soil mix, and an optional drainage bed of sand or gravel used to treat polluted storm-water. As runoff flows through a bioretention cell, plants and natural soil substrates act as buffers to retain storm-water and reduce its peak velocity while promoting the removal of entrained pollutants [Yu et al., 2001]. Bioretention cells can be installed in lawns, along roadsides, or in the medians of parking lots. The size and design of the bioretention cell depends on the area it drains and the type of soil in which the cell is placed [Jarrett, 2016]. The reduction in runoff volume by bioretention systems has been well documented in a variety of contexts, ranging from 23% to 97% [Zhang et al., 2020].

B. Detention Tools

Detention tools are used to slow down the storm-water runoff before subsequent transfer downstream. Main detentions structures include:

1. Detention Ponds

   Detention ponds are relatively large, sunken areas where excess storm-water is temporarily stored or retained and then slowly drains away as water levels in the receiving channel recede [CEC, 2018]. Their primary purpose is to slow the flow of water and hold it back for a short period of time so that the volume is available for the next flood event. Detention basins can be located in parking lots, parks, roadside slopes, depressed areas, and drainage channels. The choice of location for detention basins depends on cost, public safety, and maintenance [Guo, 2007].

2. Subsurface Storage

   Subsurface storage systems are underground structures designed to temporarily retain and drain storm-water. They typically consist of a pretreatment process at the point of entry and a storage bed under surfaces such as parking lots, lawns, and playgrounds [MDEP, 2008].

C. Retention Tools

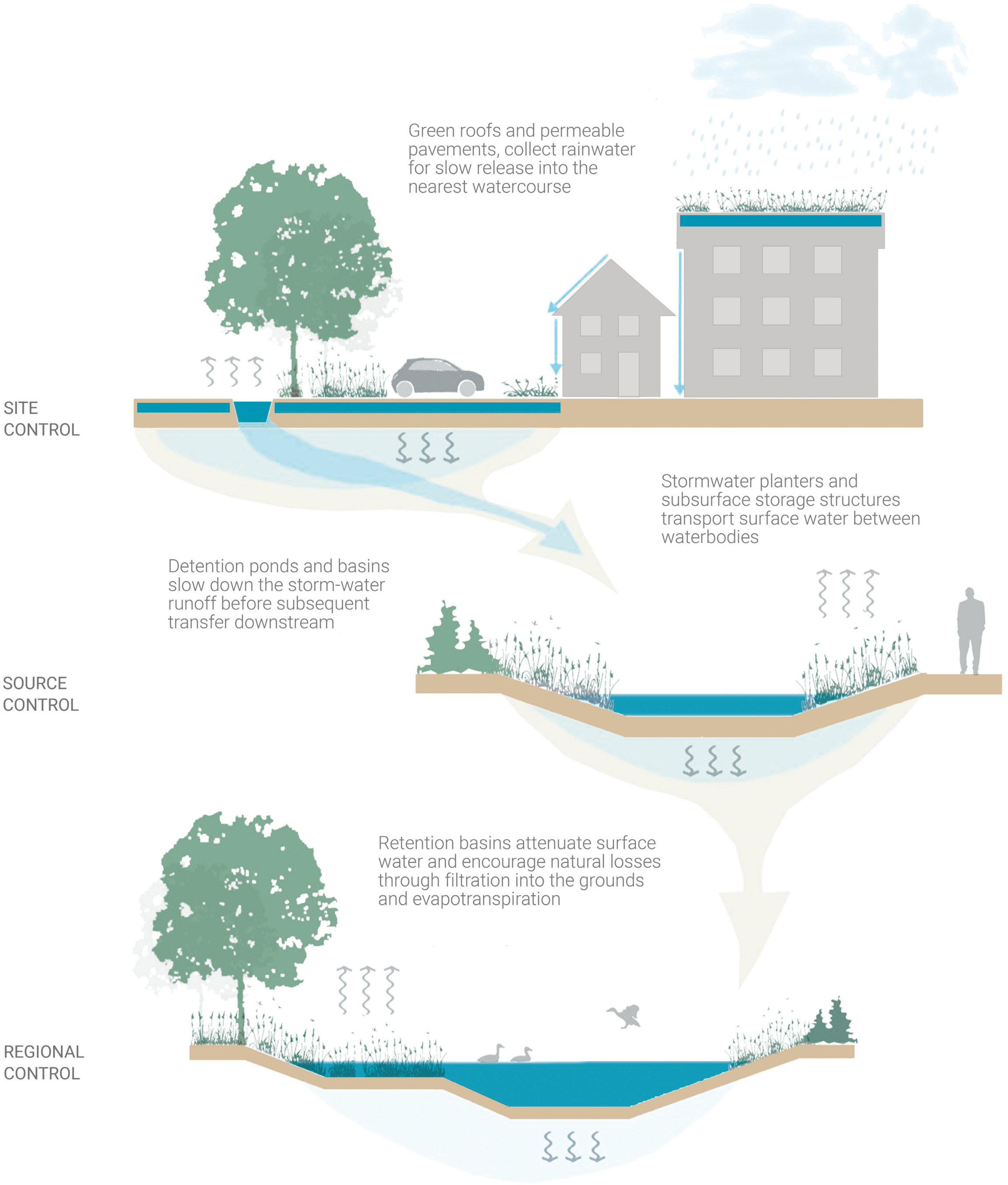
The retention of storm-water runoff to protect receiving watercourses in the event of flooding if long-term storage and additional infiltration are not feasible on site. Some retention structures include:

1. Retention ponds

   Similar to detention ponds, retention ponds also store storm-water, but the storage of storm-water would be on a more permanent basis. In fact, water often remains in a detention basin indefinitely, except for the volume that is lost to evaporation and the volume that is absorbed by soils [CEC, 2018]. Generally, a retention pond is constructed due to a high water table, which means that the groundwater is close to the ground surface and the bottom of the pond is excavated below the water table to create a permanent pond [Abdrabo et al, 2020]. Essentially, retention ponds provide both water quality by removing pollutants from storm-water and quantity control by reducing urban runoff. They are ideal partners for residential areas near rivers, streams, or watersheds [Chuxiong et al., 2014].

2. Green Roofs

   Green roofs are roofs covered with light growth media and vegetation that allow infiltration of precipitation and recover evapotranspiration. Green roofs essentially consist of a vegetation layer, a substrate layer that retains water and anchors the vegetation, and a drainage layer that drains excess water. [Mentens et al, 2003]. Based on the depth of the substrate layer and the vegetation support, two main types of green roofs are usually distinguished: extensive and intensive [Kolb, 1999]. According to a comprehensive study by [Mentens et al, 2005], the annual rainfall retention capacity can be up to 75% for intensive green roofs and up to 45% for extensive green roofs, with the extent of retention capacity depending on the structure of the green roof, climatic conditions and rainfall.



Green roofs and permeable pavements, collect rainwater for slow release into the nearest watercourse

Stormwater planters and subsurface storage structures transport surface water between waterbodies

Detention ponds and basins slow down the storm-water runoff before subsequent transfer downstream

Retention basins attenuate surface water and encourage natural losses through filtration into the grounds and evapotranspiration

Fig. 2.8 Tools for Sustainable Urban Drainage Systems (SuDS) {HCC, 2015]

2.5 Flood Risk Management Modeling

2.5.1 Hydrological Models

Hydrological models have been shown to be very important for a variety of applications, including water resources planning, development, and management; flood prediction and planning; and modeling of coupled systems, including water quality, hydroecology, and climate [Ilias, et al, 2011]. Previous studies have shown various ways of classifying hydrological models [Singh & Frevert, 2006]. Based on the classification system outlined by [Wheater et al., 1993], hydrological models can be classified based on their model structure, spatial distribution and spatio-temporal application. Accordingly, three main categories of models are distinguished. The first category is empirical models, which are primarily based on observations and attempt to characterize the response of a system using available rainfall-runoff data [Wheater et al., 1993]. These data are used to create simple equations via regression relationships that relate the factors responsible for the runoff response to the runoff at the outlet of the watershed [Vaze,, et al, 2011]. The second category includes conceptual rainfall-runoff models that represent the conversion of precipitation to runoff, evapotranspiration, movement of water into and out of groundwater systems, and the change in water volume within the watershed through a series of mathematical relationships. Not all parameters of the conceptual model have a direct physical interpretation. Therefore, at least some model parameters need to be estimated by calibration from observational data [Vaze et al., 2011]. The third category is physics-based hydrological models, which are based on an understanding of the physics of the hydrological processes that govern watershed response and use physics-based equations to describe these processes. Because of this model structure, physically based hydrological models are the most realistic approach for predicting flood scenarios in an urban context [Ilias et al., 2011]. These models can provide a continuous simulation of runoff response when accurate data are available and the physical properties of hydrological processes are applied [Beven, 2001]. Physical models are therefore site specific. Most of them represent a three-dimensional system of water exchange in the soil, surface and air [Morschek et al., 2019]. Consequently, physical models might require extensive calibrations of various individual parameters to function properly. As a result, the performance, versatility, and accuracy of physical models available on the market may require thorough technical knowledge, detailed data entry, and often considerable computational time [Henonin, et al., 2013]. Such limitations can make them impractical in the ideation phase of the urban planning process, where rapid evaluation of multiple design scenarios is required.

Leading physics-based water runoff software packages on the market today include SWMM5, MIKE FLOOD, SUSTAIN, and HECRAS. There are many others, but they do not have a visual enough interface or fast enough editing capabilities to be particularly effective in a fluid design process. SUSTAIN is a powerful software, but it primarily optimizes the placement and use of green infrastructure to modify existing water systems [Cupkova et al., 2015]. HECRAS is a numerical model that uses an integrated 1D model to represent flows and provides interactive solutions for environmental management [Brunner, 2016], but does not perform well in environments that require multidimensional modeling. The SWMM5 is flexible and can provide robust information about pipelines and drainage networks. However, it is based on a simple 2D representation and a data import workflow based on GIS [Cupkova et al., 2015]. Also Mike Flood is a unique software that provides coupled 1D-2D hydrodynamic models suitable for modeling and multi-scale flood assessment and analysis. However, it requires advanced data input and relatively long computation time [Patro et al. 2009].

Overall, the nature of the above tools demonstrates an engineering approach to storm-water management that lacks the integration of a broader design thinking approach. This makes such tools not easily accessible to urban planners, designers and developers in the field of urban planning. To address this gap, better integration of hydrological models into exploratory design tools is needed to help average urban planners and non-hydrologists incorporate relevant storm-water runoff implications into the early planning process of their design proposals. Such an interface can enable more adaptive testing of different design scenarios in relation to storm-water behavior, and provide more comprehensive feedback through interactive visualizations and associated spatial metrics.

2.5.2 Parametric Design Models

The main objective of computational design in urban planning is to develop urban designs according to a specific set of requirements and to provide feedback on spatial performance and configuration by highlighting the associated benefits and problems. To achieve this, the integration of certain software packages is required to perform simulations for multiple design variants. In addition, continuous evaluation and testing of criteria is required to achieve an optimal design scenario. Among the numerous software packages for Computer-Aided Design (CAD), the software environment of Rhinoceros3D and its plug-in for visual programming, Grasshopper, are used for such purposes due to their high modeling flexibility in different disciplines. In particular, the use of Grasshopper can enable the assessment and evaluation of multiple design scenarios through its interactive simulation capabilities and built-in optimization algorithms.

A series of parametric models have been proposed to evaluate water performance and storm-water runoff in the urban design process and the associated geometric and spatial impacts. The aim of these models is to incorporate knowledge from water management into the urban planning process, using tools familiar to urban planners and designers to assist them in developing and formulating realistic recommendations for water-sensitive planning proposals. For example, [Dennmark et al, 2018] has integrated existing hydrological analysis tools, i.e. EPANET [Rossmann, 2000], into Grasshopper for the analysis of pressurized water pipeline networks. The developed parametric model extends the features of EPANET and allows the calculation of hydrological network characteristics based on water demand and topographic location of network nodes for different growth scenarios. Through Grasshopper's user interface, predefined parameters such as pipe diameters or water tank locations can be easily adjusted to provide quick visual feedback on water network performance. Similarly, [Morschek, 2019] has developed a Spatial Resilience Toolbox for flooding (SRTF) to integrate flooding-related aspects into the urban planning process. The toolbox performs physics-based simulations using a built-in interactive physics solver, Kangaroo, to simulate and assess the current state of flood resilience in a selected urban context. The built-in storm-water runoff simulation represents a rainfall event through a weighted particle representation that provides visual feedback for evaluating proposed street and building layouts for potential flooding risks. In addition, the toolbox includes simulation of tidal or fluvial flooding, assessing the risk of different water levels to roads and buildings in a given area.

In addition, several standalone plug-ins and components for storm-water flow simulations and terrain analysis have been developed in Grasshopper. Groundhog, eVe, and Quelea provide vector-based applications for particle flow paths on predefined geometries that ultimately provide similar visualizations of storm-water runoff paths. Epiflow [Cupkova et al., 2015] and Rainwater+ [Chen et al, 2016] contain similar functionality but provide additional components for rainfall and storm-water runoff analysis. Since the latter two plug-ins are not open source, further evaluation of these plug-ins was not possible. Consequently, a more comprehensive approach is needed to adequately assist planners in integrating storm-water performance into their decision-making process.

2.5.3 Calculation Methods

As mentioned earlier, sustainable storm-water management tools aim to reduce flood risk by maximizing the infiltration time and storage capacity of storm-water runoff. This depends on a number of variables, including land use, soil type, and the hydraulic network of an urban area. Increasing urbanization has a variety of impacts on the hydrologic cycle. One of the crucial aspects that accelerates these impacts is the imperviousness of the surface of an area, as it directly affects the infiltration rate of the area. As described by [Johnson, 1973], even a small increase in impervious surfaces leads to increased hydraulic efficiency in urban catchments and can significantly reduce the capacity of a given area to infiltrate rainfall. This leads to a concomitant increase in the production of storm-water runoff [Hey, 2001].

In urban practice, surface imperviousness measurements are usually made using maps, aerial photographs or satellite images [Castelluccio et al., 2015], which can then be incorporated into a GIS database. Otherwise, surface imperviousness calculations can be quite tedious given the complexity of the parameters required. An alternative indicator of surface density is the cumulative infiltration (F) of storm-water runoff from an area. This can be calculated by subtracting the depth of runoff (P_e) of an area from its given depth of precipitation (P), where:

$$F = P_e - P \qquad (1)$$

The SCS-CN method developed by Soil Conservation Services (SCS) in the USA can be used to calculate the depth of runoff (P_e). This simple method is commonly used by hydrologists to estimate direct runoff depth based on precipitation depth. It relies on only one parameter, the curve number (CN). It is expressed as:

$$P_e = \frac{(P-I_a)^2}{(P-I_a)+S} \qquad (2)$$

Where:

P_e = depth of runoff

P = total rainfall depth

I_a = equivalent depth of initial abstractions

S = maximum possible water retention

On the basis of extensive measurements in small size catchments SCS (1985) has adopted I_a = 0.2S as a standard value, thus the equation above becomes:

$$P_e = \frac{(P-0,2S)^2}{(P-0.2S)+S} \qquad (3)$$

The maximum possible retention S is related to the curve number (CN):

$$S = \frac{1000}{CN} - 10 \qquad (4)$$

Where: CN = runoff curve number

For determining the Curve Number (CN), the hydrological soil classification can be adopted in which soils are classified into four classes A, B, C and D based on infiltration and other characteristics. The main soil characteristics that affect thehydrologic classification of soils are effective soil depth, average clay content, infiltration properties, and permeability. Runoff potential for each soil group is lowest for soil group A and highest for soil group D. The variation of the Curve Number (CN) value for different land use conditions and the respective soil types commonly used in practice are shown in [Table 2.3].Once the runoff depth (P_e) is obtained for each catchment zone and its respective land use, the runoff volume (R_v) can be calculated through multiplying the runoff depth (P_e) by the total area (A) of each zone to estimate its runoff potential.

Land Use Description	Curve Number for Hydrologic Soil Group			
	A	B	C	D
Agricultural	64	75	82	85
Commercial	89	92	94	95
Forest	30	55	70	77
Gravel	76	85	89	91
Industrial	81	88	91	93
Institutional	62	76	84	88
Parks	49	69	76	80
Paved Areas	98	98	98	98
Permeable Pavement	71	79	82	85
Residential: High Density	77	85	90	92
Residential: Medium Density	57	72	81	86
Residential: Low Density	54	70	80	84

Table 2.3 Runoff Curve Numbers [Rossman & Huber, 2015]

Once the runoff depth (P_e) is obtained for each catchment zone and its respective land use, the runoff volume (R_v) can be calculated through multiplying the runoff depth (P_e) by the total area (A) of each zone to estimate its runoff potential.

$$R_v = P_e \times A \qquad (5)$$

In the next section, a framework of an integrated computational model is proposed. The model is developed in the Rhinoceros/Grasshopper environment, and aims to integrated the aforementioned parameters in order to estimate the runoff volume and cumulative infiltration amounts for predefined land uses and additional factors.

3

Computational Model Framework

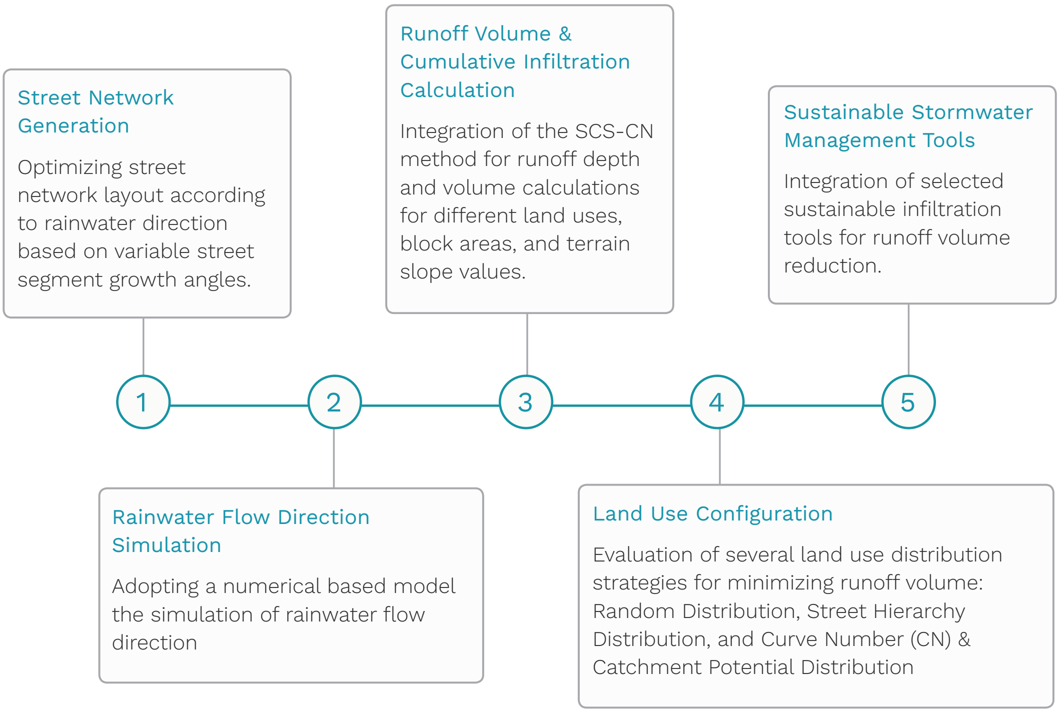
The Third Chapter is dedicated to introducing an integrated computational model which incorporates discussed urban design parameters, flood management tools, and calculation methods. The following chapter illustrates the proposed model work flow along with an evaluation process of a couple planning scenarios and approaches based on their potential of mitigating storm-water runoff and promoting surface infiltration.

Chapter Three
Computational Model Framework

3.1 Objectives

As mentioned earlier, various factors can affect the amount of resulting the storm-water runoff and infiltration rate in urban settings. Among these, the most significant ones were found to be a region's topographic nature, its streets network layout, and its land use configuration. In this section, a hypothetical computational model is proposed to evaluate those factors in order to support a more sensitive decision making for storm-water runoff in the early design stage of the urban planning process. The model aims to incorporate physical based simulations, slope analysis, and runoff calculations to provide estimates of storm-water runoff volumes and infiltration rates for predefined soil groups and land uses. In addition, the impact of selected infiltration tools, i.e. permeable pavements, bioretention cells, green roofs, and storm-water planters, are evaluated.

3.2 Framework



Street Network Generation

Optimizing street network layout according to rainwater direction based on variable street segment growth angles.

Rainwater Flow Direction Simulation

Adopting a numerical based model the simulation of rainwater flow direction

Runoff Volume & Cumulative Infiltration Calculation

Integration of the SCS-CN method for runoff depth and volume calculations for different land uses, block areas, and terrain slope values.

Land Use Configuration

Evaluation of several land use distribution strategies for minimizing runoff volume: Random Distribution, Street Hierarchy Distribution, and Curve Number (CN) & Catchment Potential Distribution

Sustainable Stormwater Management Tools

Integration of selected sustainable infiltration tools for runoff volume reduction.

Fig 3.1 Components of Computational Model Framework

The computational model framework consists of five main components [Fig. 3.1]. Those components are interrelated and aim to minimize total storm-water runoff, and thus mitigate urban flood risks. The entire model is developed within Rhinoceros and its visual programming plugin, Grasshopper due the their high technical flexibility and familiarity in the urban planning field. Following is a detailed description of the model's work flow and its components

3.2.1 Street Network Generation

The first component of the computational framework is the generation of water sensitive street networks and evaluating them for flood risk. For this purpose, the water-based-street-growth model was utilized [Dennemark et al., 2017]. The model allows for the generation of multiple street network layouts on a predefined terrain according to the rainwater flow direction. This is determined through the manipulation of a street segment Growth Angle (GA). The maximum growth angle of each street segment per iteration can be set before the start of the simulation. This allows for the testing of multiple street networks with different growth angles.

With a predefined growth angle of (1), the model generates more perpendicular street layouts, since segment growth per iteration is more constrained [Fig. 3.2]. On the other hand, a higher growth angle of (10) generates a more organic street layout as segment growth per iteration has a higher freedom to grow in more directions [Fig. 3.3]. Both of the generated street network layouts share relatively similar total streets length and are set to generate similar block sizes.

Total Street Length: 2177m

Fig. 3.2 Street Network Segment Growth Angle (GA1)

Total Street Length: 2254m

Fig. 3.3 Street Network Segment Growth Angle (GA10)

Following that, the generated street network segments are evaluated according to their alignment with water flow direction and terrain steepness values. Based on these parameters, each segment is given a remapped color (RGB) value within a domain of 0 to 1. The closer the color value to 1, the warmer (red) the correspondent street segment appears. This indicates both a higher terrain steepness value and a higher water flow direction alignment of that segment. Therefore, the higher the overall warm values of a particular street network layout, the more aligned are its segments with water flow direction, and thus the better it performs when it comes to storm-water subsurface drainage and runoff management.

As illustrated below, the street layout with a higher segment growth angle [Fig. 3.5a] scores a higher color value [Fig. 3.5b] than the street layout with lower segment growth angle [Fig 3.4a, Fig. 3.4b]. This indicates that street layouts with a higher segment Growth Angle (GA) can have a higher potential of mitigating storm-water runoff, increasing drainage efficiency, and ultimately reducing associated flooding risks.

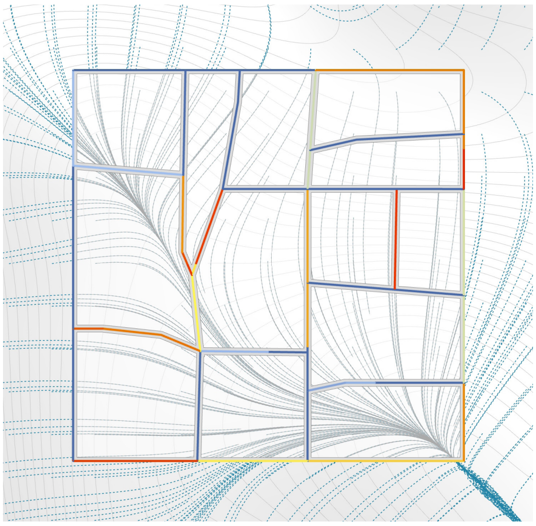


Fig. 3.4a Street Network Alignment with Rainwater Flow Direction (GA1)

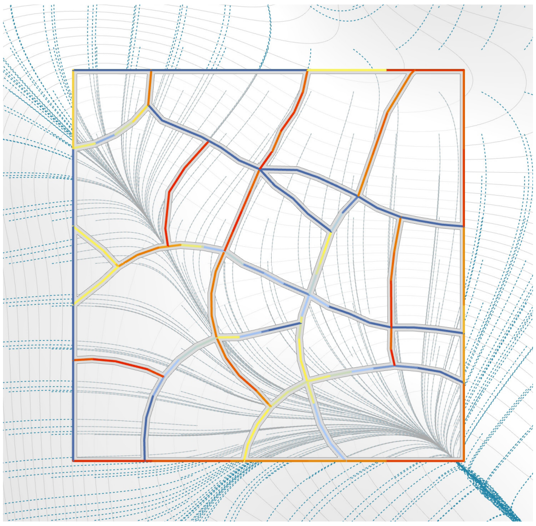


Fig. 3.5a Street Network Alignment with Rainwater Flow Direction (GA10)

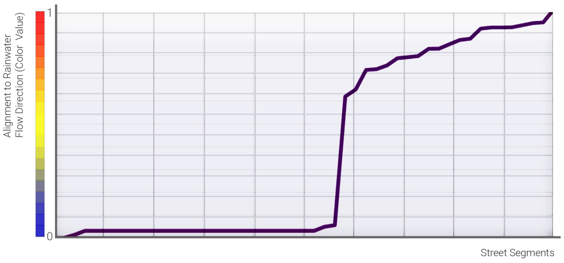


Fig. 3.4b Street Segment Alignment Graph (GA0)

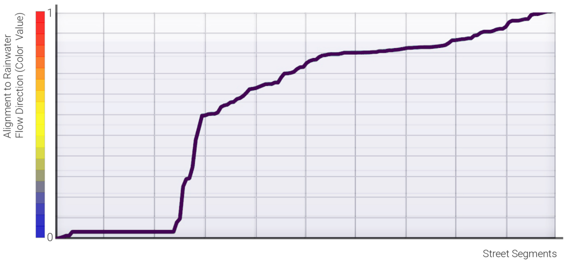


Fig. 3.5b Street Segment Alignment Graph (GA10)

3.2.2 Rainwater Flow Direction Simulation

As discussed in section 2.5.2, numerous Grasshopper plug-ins were developed to simulate water flow direction on a given terrain. Most of these plug-ins adopt physics based models which provide real-time particle like simulations that come with various control parameters such as adjusting surface friction and collision force between particles. Such models have proven to be quite popular due to their high flexibility and interactivity with fed geometries. However, they can require a relatively long computation time and can be tedious to work with when it comes to larger scale applications, which is often the case in the urban planning field. Additionally, generating flow direction maps out of such models requires particle tracking and recording for each simulation session which can be impractical for the work-flow during the design process.

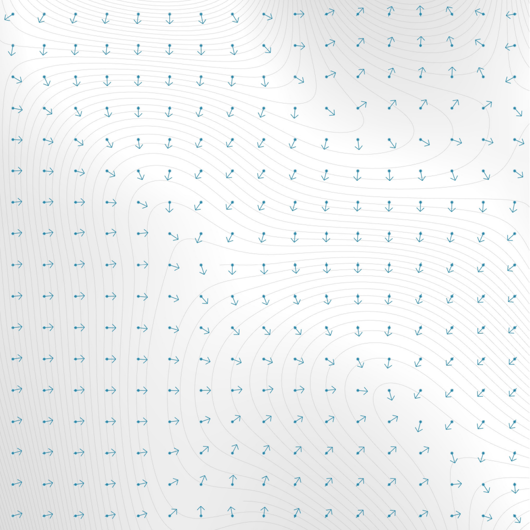


Fig. 3.6a Rainwater Flow Direction Network iteration 01

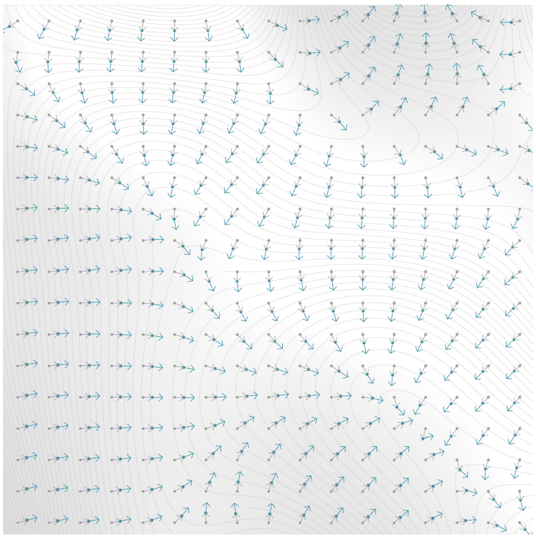


Fig. 3.6b Rainwater Flow Direction Network iteration 02

For this reason, the second component of the computational framework is the development of an alternative model for the generation of water flow direction networks. Unlike particle based models, this numerical model requires no additional recording or simulation time after its first run. A given grid of points is evaluated against a given three dimensional surface whereby the surface normal value for each point along the grid is calculated. Following, the perpendicular direction to each point's correspondent normal value is determined. Along that direction, a line segment is drawn within a given circle radius [Fig 3.6a]. The same process is repeated starting at the end point of the last generated line segment [Fig 3.6b]. A looping logic is constructed where the number of total iterations can be set to control the maximum reach of the network. Therefore, the accuracy of the generated network is dependent on the length of the line segments for each iteration, which is equivalent to the predefined circle radius. The smaller the radius, the smaller the line segment, the higher the accuracy. Once all line segments are generated, they are joined and each line stream is rebuilt into a singular polyline [Fig 3.7]. For comparison, a similar network was generated with a particle based model; Kangaroo [Fig 3.8]. In terms of computing time, the physical based network took 43 seconds to run while the numerical based network took only 6 seconds. And in terms of quality and accuracy, the numerical based network shows more accurate flow lines due to the absence of particle collision and additional friction effects. Moreover, unless the resulted geometry is internalized, physical based models would have to be run every time an evaluation is studied, while the numerical based model is fixed throughout the entire evaluation session. While this offers a more efficient work-flow, particle based models still have the advantage of predicting water flow behavior in real time when certain obstacles are present.

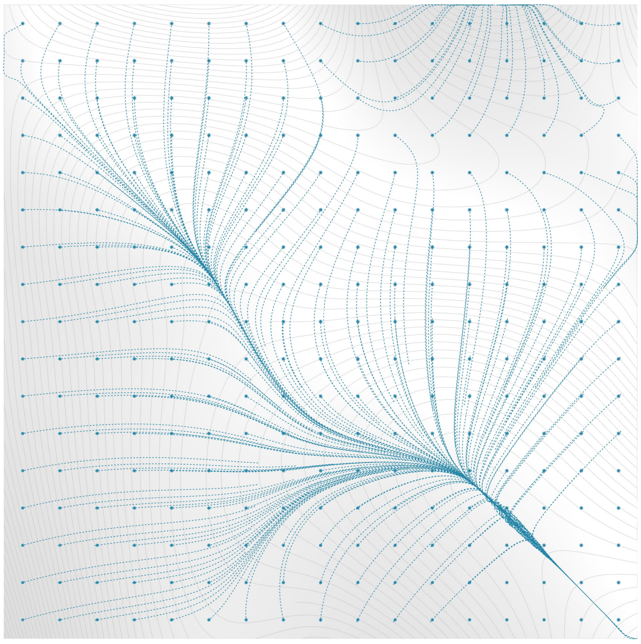


Fig. 3.7 Numerical Based Rainwater Flow Direction Network

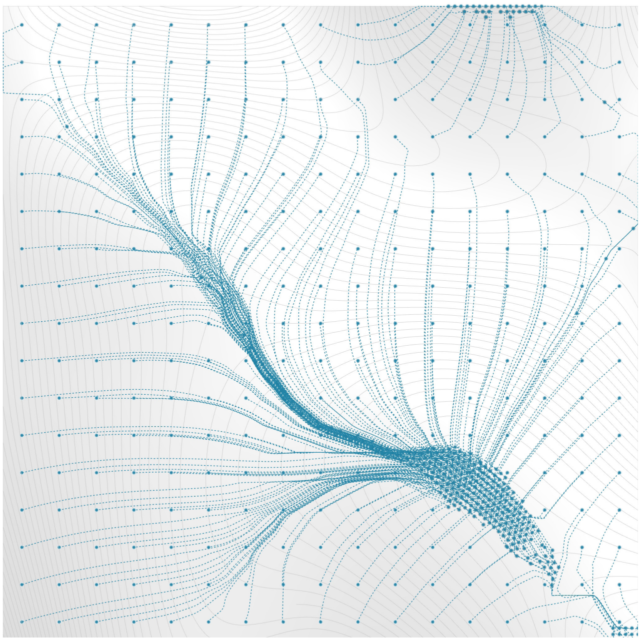


Fig. 3.8 Particle Based Rainwater Flow Direction Network

3.2.3 Runoff Volume & Infiltration Calculation

The third component of the computational model framework is the calculation of total runoff volume and cumulative infiltration for urban blocks or zones. To achieve that, the SCS-CN method (see section 2.5.3) was integrated within Grasshopper to obtain the Runoff Depth for each urban block assuming that all blocks are paved areas. Following, the Runoff Volume is calculated by multiplying the Runoff Depth by its correspondent block Area and terrain Slope Coefficient. The Slope Coefficient is calculated for each urban block based on the quantity of water streams passing through it. This is done by intersecting the water based street network with the rainwater flow direction network where the resulting segment count for each urban block is displayed [Fig. 3.9a, Fig. 3.10a]. The segment count provides an indicator for each urban block's water catchment potential [Fig. 3.9b, Fig. 3.10b], and its slope coefficient which is ultimately included in estimating the Runoff Volume for that particular block.

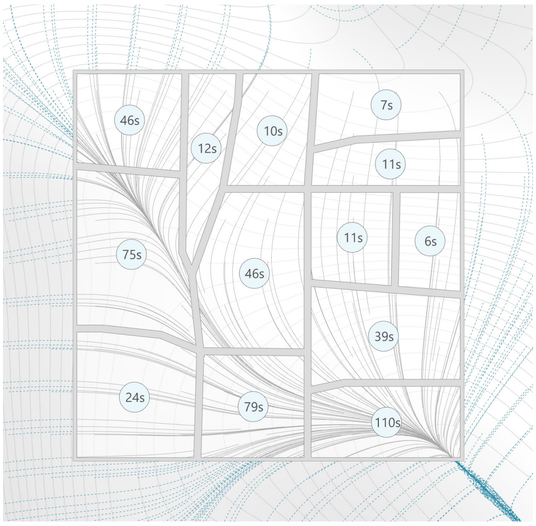


Fig. 3.9a Block Segment Count for Rainwater Flow Direction Network

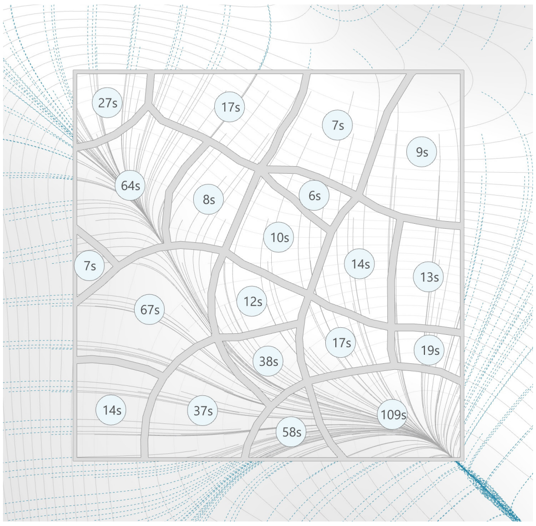


Fig. 3.10a Block Segment Count for Rainwater Flow Direction Network

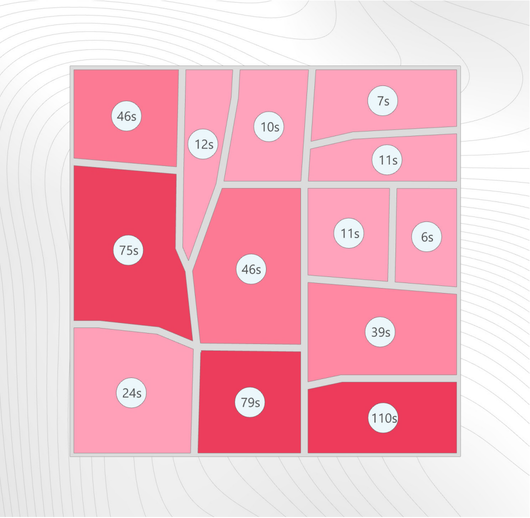


Fig. 3.9b Block Segment Count Map

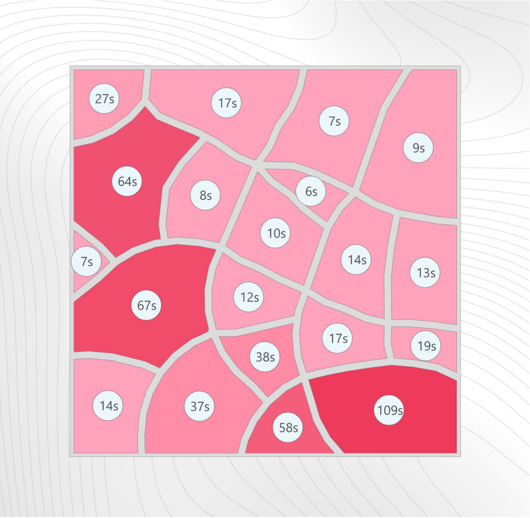


Fig. 3.10b Block Segment Count Map

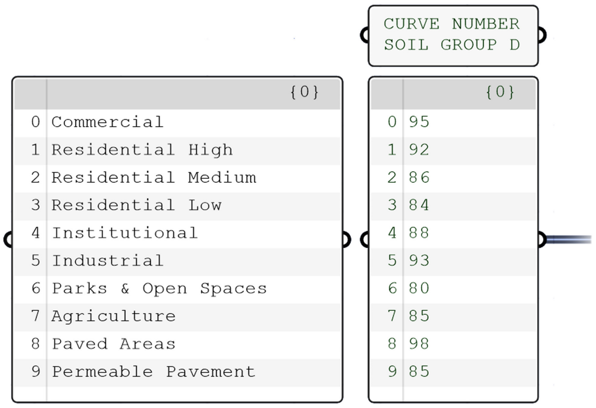
Once the Runoff Volume value is obtained, a correspondent color value for each block is assigned along a predefined domain in order to visualize the blocks with highest and lowest runoff volumes. The Cumulative Infiltration for each block can then be calculated by subtracting the resulting Runoff Volume from the initial Rainfall Volume. Hence, the runoff volume and cumulative infiltration values for each block share a direct correlation. The Total Runoff Volume and the Total Cumulative Infiltration are then calculated for all the blocks of each street layout. The street network layout with a higher segment growth angle [Fig. 3.10c] scored 11 percent less total runoff volume and more cumulative infiltration values than the street network layout with lower segment growth angle [Fig. 3.9c].

Fig. 3.9c Runoff Volume & Cumulative Infiltration Calculation Map

Fig. 3.10c Runoff Volume & Cumulative Infiltration Calculation Map

3.2.4 Land Use Configuration

As discussed in section 2.4.1, land use planning is considered one of the most efficient ways in regulating storm-water in urban areas and reducing flood risk. The fourth component of the computational model framework is the evaluation of the impact of land use configuration on runoff volume and infiltration values. The goal of this component is to allow for rapid testing of different land use configuration strategies to minimize the total runoff volume per design scenario. This is achieved by integrating the associated CN values for various land use categories along their respective soil group [Fig. 3.11].


CURVE NUMBER
SOIL GROUP D

	{0}		{0}
0	Commercial	0	95
1	Residential High	1	92
2	Residential Medium	2	86
3	Residential Low	3	84
4	Institutional	4	88
5	Industrial	5	93
6	Parks & Open Spaces	6	80
7	Agriculture	7	85
8	Paved Areas	8	98
9	Permeable Pavement	9	85

Fig. 3.11 Built-in Land Use Curve Number Values

Land use distribution strategies vary widely depending on site conditions and design criteria. To minimize total travel distances and thus traffic, land uses can be distributed according to the hierarchy of a street network. This is achieved by computing the Betweeness Centrality for a street network, where most and least frequented segments can be identified by calculating the distances traveled from each street segment to all other segments throughout the network. This way, street segments can be classified into groups with predefined weights, i.e. primary, secondary, and tertiary streets. Afterwards, different land uses can be allocated according to their adjacency to those street segment groups. For instance, commercial zones are allocated close to primary streets, high density residential zones and institutional zones close to secondary streets, and low density residential zones and parks close to tertiary streets [Fig. 3.12a, Fig. 3.14a]. Alternatively, land uses can be distributed based on their CN values and catchment potential [Fig. 3.13a, Fig. 3.15a].

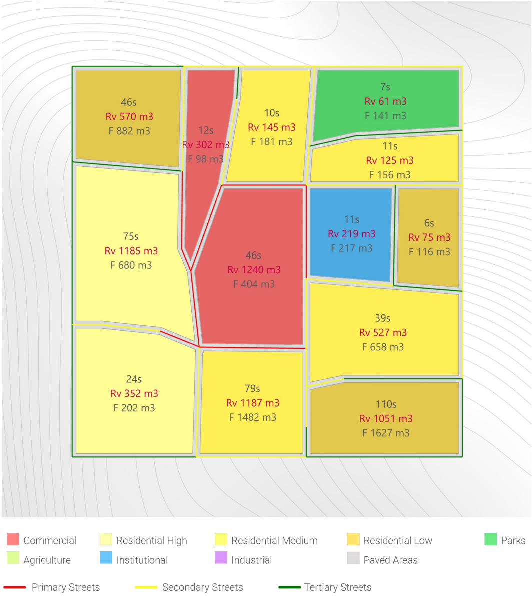


Fig. 3.12a Land Use Distribution based on Street Hierarchy

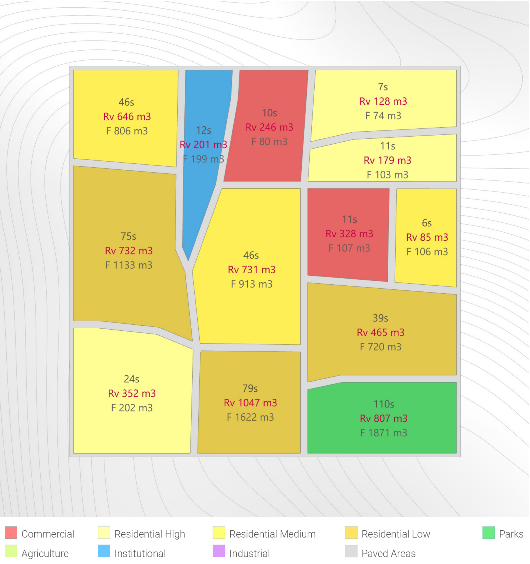


Fig. 3.13a Land Use Distribution based on CN values and Catchment Potential

Fig. 3.12b Runoff Volume & Cumulative Infiltration Map

Fig. 3.13b Runoff Volume & Cumulative Infiltration Values

For instance, land uses with higher CN values have a higher runoff impact, and are therefore matched with blocks or zones which have lower runoff volume potentials. As a result, allocated land uses contribute to further minimizing the total runoff volume and maximizing cumulative infiltration values. A comparison was carried out to evaluate the impact of both land use configuration approaches for both street network layouts. Overall, land use configurations based on CN values and catchment potential [Fig. 3.13a, Fig. 3.15a] have scored less total runoff volumes than configurations based on street hierarchy [Fig. 3.12a, Fig. 3.14a] for both street network layouts, where the amount of decrease in total runoff volume was 20% for the street network with a higher street segment growth angle [Fig. 3.14b, Fig. 3.15b], and 15% for that with lower street segment growth angle [Fig. 3.12b, Fig. 3.13b]. Moreover, regardless of the land use configuration approach, the street layout with a higher segment growth angle scored less total runoff volume for both scenarios.

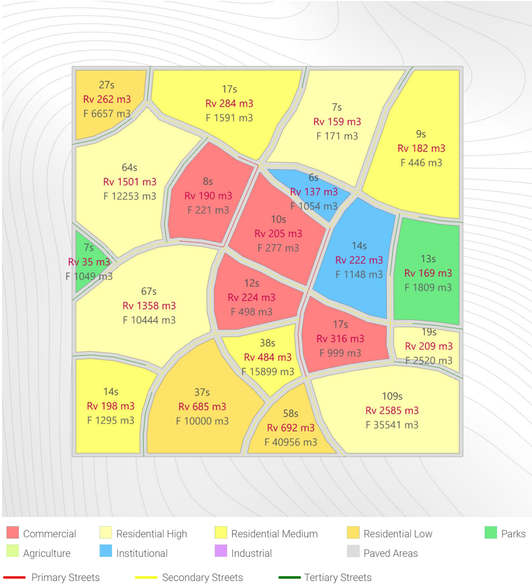


Fig. 3.14a Land Use Distribution based on Street Hierarchy

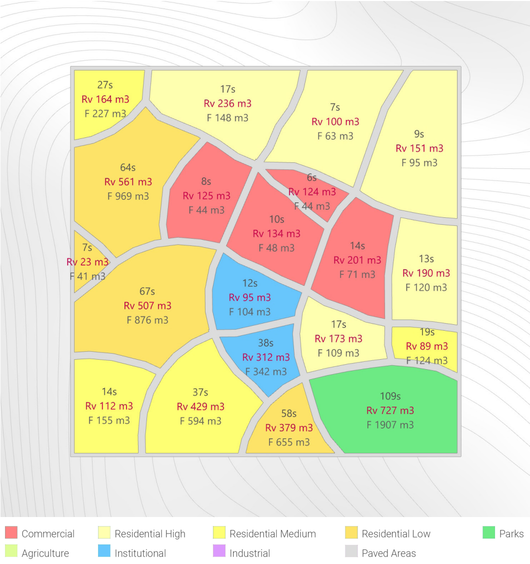


Fig. 3.15a Land Use Distribution based on CN values and Catchment Potential

Fig. 3.14b Runoff Volume & Cumulative Infiltration Map

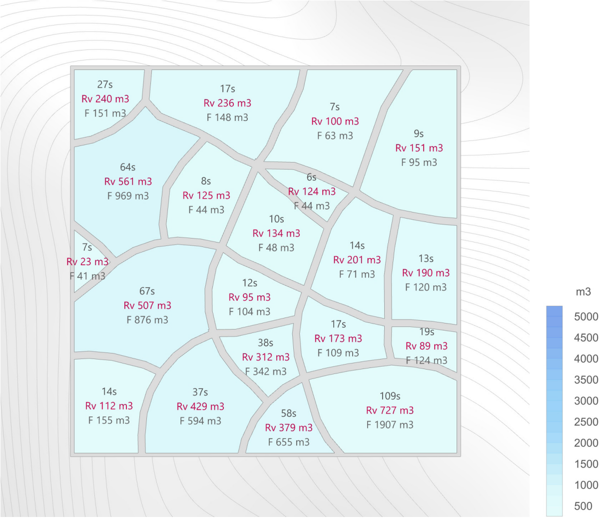


Fig. 3.15b Runoff Volume & Cumulative Infiltration Map

3.2.5 Sustainable Storm-water Management Tools

As outlined in section 2.4.5, tools for sustainable storm-water management, i.e. infiltration, retention, and detention tools, can further contribute to minimizing storm-water runoff. The fifth component of the computational framework is the integration of a combination of these tools in the calculation process of runoff volume. The tools selected were permeable pavements, stormwater planters, bioretention cells, and green roof, where each of which have a predefined range of retention capacity. Similar to blocks evaluation, street segments can be evaluated for runoff volume and catchment potential assuming they are paved zones [Fig. 3.16a]. Accordingly, allocation of permeable pavements or zones to minimize runoff volume can take a place with the parallel consideration of the street hierarchy. This is done to make sure that permeable pavements are not placed on primary roads with high traffic levels, but rather on secondary and tertiary roads, as to minimize the infiltration levels of associated runoff pollutants [Fig 3.16b]. Addition of permeable pavements have resulted in a 46% decrease in the total runoff volume along street segments, and a correspondent increase in total cumulative infiltration.

Based on the final selected land use configuration, additional infiltration tools can be placed within desired blocks to evaluate their impact on runoff reduction [Fig. 3.15b, Fig. 3.17]. The number, area, and retention capacity for each of these tools can be adjusted depending on the allocated land use and runoff reduction targets for each zone. This last component offers a

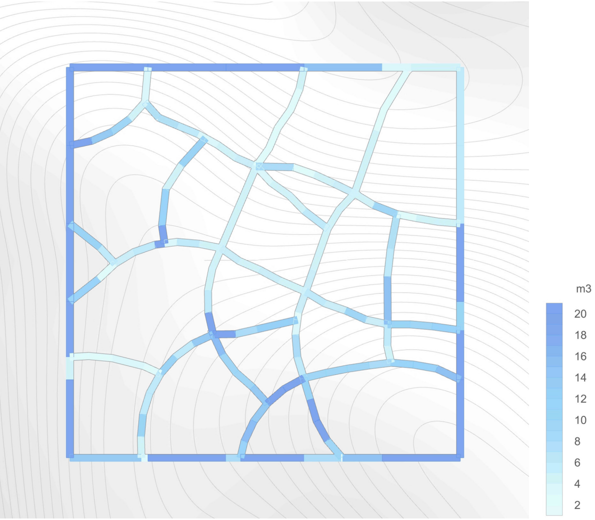


Fig. 3.16a Street Segment Runoff Evaluation

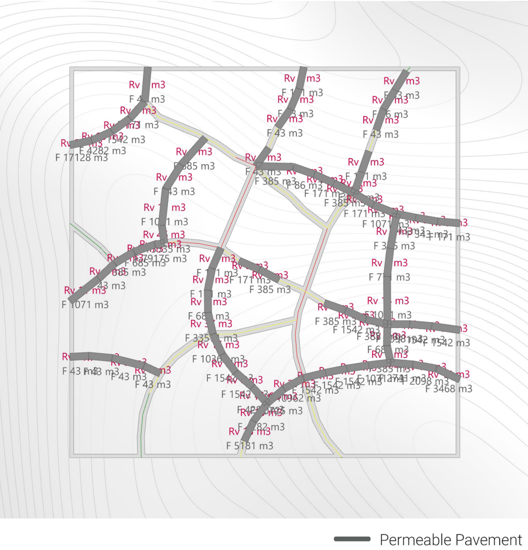


Fig. 3.16b Permeable Pavement Allocation

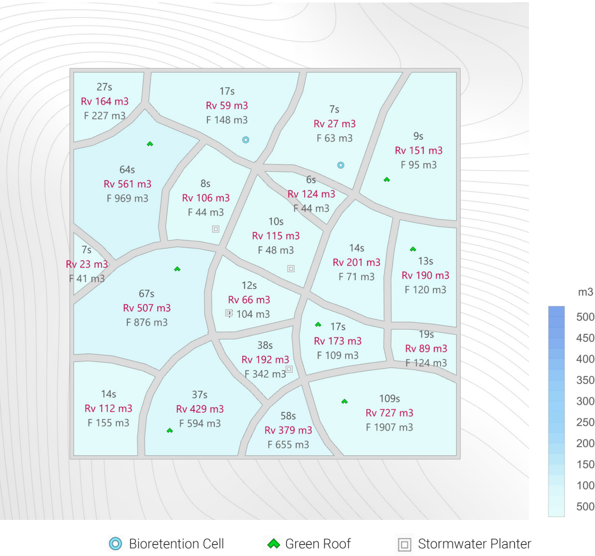


Fig. 3.17 Sustainable infiltration Tools Allocation

flexible and rather schematic approach to integrating Low Impact Development (LID) practices within the design process in order to examine the impact of supplementary measures on runoff volume reduction.

3.3 Model Limitations

The developed computational model offers an integrated framework to minimizing storm-water runoff volume along different stages in the urban design process. The impact of street network layout, land use configuration, and sustainable infiltration tools was evaluated. Firstly, the analysis found that street network layouts which align with rainwater flow direction produce less total runoff volume than layouts which have a perpendicular orientation to rainwater flow direction. Secondly, land use configurations which are based on CN value and catchment potential contribute significantly more to runoff volume reduction than configurations based on street hierarchy. Lastly, allocation of different infiltration tools can further reduce runoff volumes depending on their selected quantity, area, and retention capacities. Overall, the offered components of the computational model provide a straightforward and interactive work flow to assist urban designers with less knowledge in hydrological processes. This enables the evaluation of storm-water runoff in the early design stage of the planning process in order to avoid lost storm-water management opportunities in later stages.

The developed model has some minor limitations. To start with, the model assumes that streets have no influence on rain water behavior as channels or obstacles. This assumption can affect the accuracy of street layout evaluation and subsequent runoff volume calculation. A particle based model for rainwater flow direction can be adopted to resolve this issue. However, this could require considerable input geometry processing and preparation, as well as longer simulation time. Furthermore, depending on the computation power, the evaluation of runoff volume for street segments in particular can cause technical malfunctions when there is a large number of segments to evaluate. Therefore, the scalability of the model is compromised when it comes to evaluating street segments in large scale contexts. To avoid this, it is recommended to rebuild street networks to the lowest possible number of segments prior to starting with the simulation process. Another limitation of the model deals with the allocation process of the predefined infiltration and retention tools, where the specific location of these tools within a particular urban block is merely representational, as to evaluate their impact on the runoff volume of the entire block. This would require the prejudgment of the designer in selecting appropriate quantities and application areas of these tools according to specific design criteria.

Additionally, while the developed model optimizes runoff reduction among several design stages, the evaluation process does not consider the impact of alternative urban aspects such as spatial connectivity and accessibility which can inform other important design elements from transportation networks to building densities.

4

Case Study: Addis Ababa, Ethiopia

The Fourth Chapter defines the case study where effectiveness of the computational model is evaluated. This chapter starts with describing the relevancy of the selected location and study site. Following, it introduces a wider variety of planning scenarios and parameters to be evaluated by the proposed model within a large scale context. Lastly, it concludes with the obtained results, discussion and technical limitations.

Chapter Four
Case Study: Addis Ababa, Ethiopia

4.1 Background

Over the last 50 years, flood-related disasters have shown an increasing trend in Africa [EM -DAT, 2016]. Since 1981, floods account for about 50% of the catastrophic events recorded on Sub-Saharan Africa [Macchi et al., 2014]. Addis Ababa , the capital of Ethiopia and Africa, is the habitat for a quarter of the urban population and contributes to about half of the country's national Gross Domestic Product (GDP) [World Bank, 2015]. In 2021, the population of Addis Ababa is 5.1 million and it is expected to increase to over 7.5 million in the next decade at an annual growth rate of 4.4%. (WPR, 2021)

Many African urban centers suffer from poverty, unemployment, and a rise in informal markets as the rate of urbanization exceeds the required level of economic and social change. Addis Ababa, while also experiencing these problems, is at the same time uniquely positioned to promote inclusive growth and reap the benefits of urbanization due to the rapid pace of its urban development [Tsega, 2021]. In other words, the potential for incorporating sustainable planning practices is greater in developing countries than in developed countries. This gives cities like Addis Ababa a head start in promoting their current and future economic and urban growth.

4.1.1 Urban Flooding

As urbanization increases, flooding is a major challenge for urban development. Urban flooding is exacerbated by rapid changes in impervious surfaces in addition to heavy rainfall [Douglas, 2008]. In particular, Addis Ababa is vulnerable to fluvial and flash flooding due to extreme climatic events and activities in the upper catchment. This vulnerability to flooding is exacerbated by a poor drainage system, rapid development along riverbanks, and the use of inappropriate building materials [World Bank, 2015]. As a result, low-income communities are forced to settle in flood-prone areas [CLUVA, 2013]. The reduction in green structures and increase in impervious surfaces in urban areas leads to more storm-water runoff even during regular storms [Douglas, 2008]. If policy makers do not take appropriate adaptation measures to reduce the negative impacts, the flood risk and vulnerability of urban dwellers living in hazardous and highly impervious areas of the city are expected to increase significantly in the coming years [Birhanu et al., 2016].

At the same time, the lack of comprehensive urban planning and proper land use policies in Addis Ababa has led to further uncontrolled urban growth, environmental degradation, and subsequently urban flooding risks [Asfaw, 2020]. Therefore, greater efforts must be made to integrate sustainable practices into the urban planning process as they would have a significant impact on reducing potential economic and environmental losses that could otherwise be irreversible in the future.

4.1.2 Strategic Development Plan

In order to address the development challenges previously discussed, a strategic plan has been prepared for the City of Addis Ababa to serve as a long-term development framework. The plan consists of two medium-term (five-year) phases that span the period of 2017-2027 [AACPPO, 2017] [Fig. 4.1].

The main objective of this strategic plan is to build consensus and facilitate a planned and coordinated approach among implementing agencies. It was developed with the aim of achieving the national vision and addressing the current and potential challenges of the city. Based on five criteria, i.e. poverty and unemployment, revenue, cityscape, urban quality, and spillover effects and linkages, five themes were selected to prepare the long-term implementation framework. Each of these themes is weighed in terms of its contribution to reducing poverty and unemployment, encouraging investment, improving the standard of living of residents and revenues of City Government, improving the image of the city as African Capital, reducing pollution, keeping the city clean and green, and boosting the urban economy and economic linkages. These criteria were developed to achieve the overarching national vision of attaining middle-income status by 2023 (AACPPO, 2017).

Addis Ababa's environmental framework focuses on adapting sustainable measures to reduce the city's vulnerability to floods, landslides and earthquakes. In particular, the framework points out that conventional flood management practices that merely seek to mitigate floods and/or protect adjacent properties through engineering measures are not sustainable. This is because such approaches merely shift the problem from upstream areas to downstream areas. Therefore, sustainable urban flood management that combines various engineering and land use planning strategies is preferred and recommended. This emphasizes the role of urban planning in reducing environmental risks and coordinating with the city's future urban development plan.

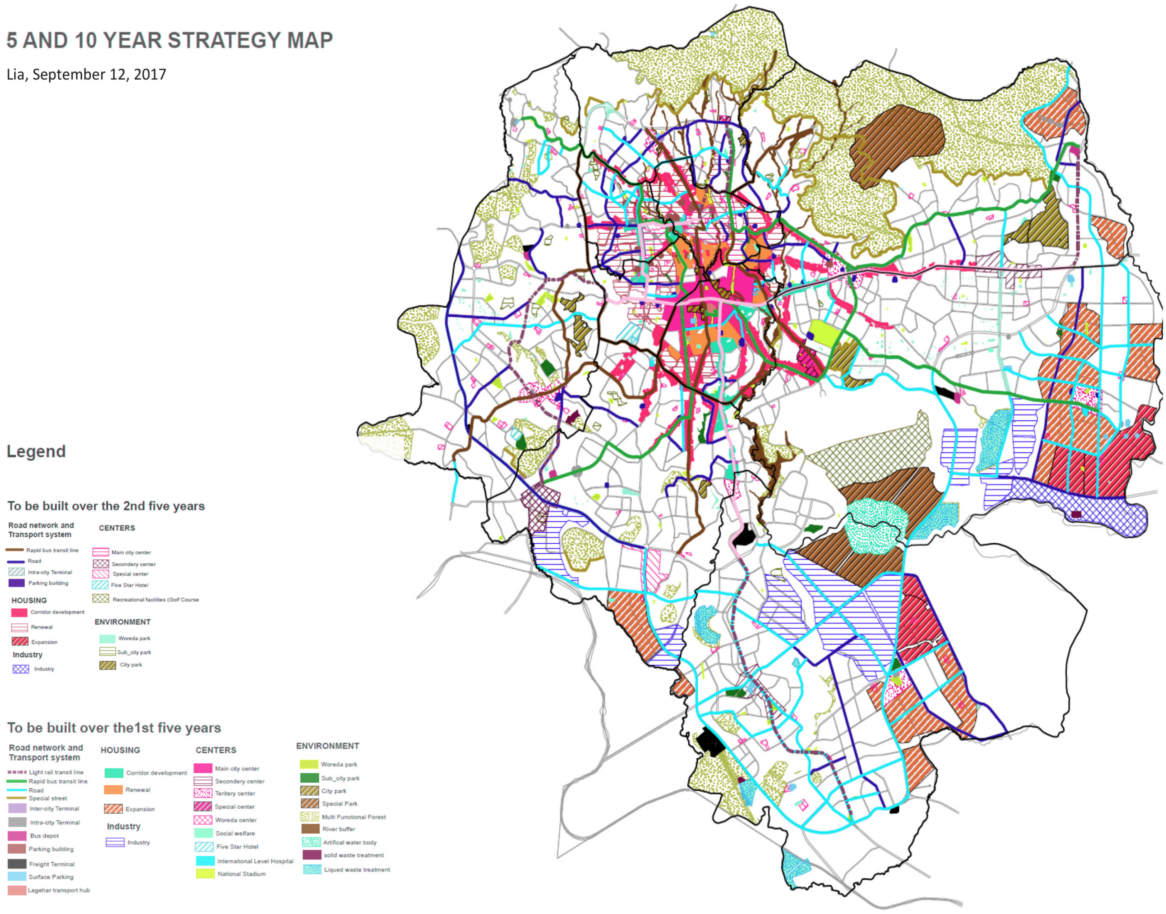


Fig. 4.1 Addis Ababa City Structure Plan 2017-2027 [AACPPO, 2017]

4.2 Site Description

The site selected for the case study is located within a large-scale residential expansion plan on the eastern edge of the City. As shown on the city's strategic map, the selected region is divided into a 5-year and a 10-year expansion zone. While the first zone with the 5-year plan is still in progress, the second zone with the 10-year plan has yet to be realized [Fig. 4.2]. Similar to the first zone, the second zone is also planned to be a medium density residential area consisting mainly of multi-family dwellings, and the total area planned for this expansion is about 2.85 km2. The natural topography of the second zone slopes gradually towards the south, where a river course is located. In addition, the entire expansion area has low vegetation and biodiversity, and has a Type D hydraulic soil group, through which water movement is normally very restricted. These factors make this expansion zone more susceptible to higher flood risks and subsequent surface runoff. Therefore, it is critical to integrate sustainable storm-water management tools and strategies early in the planning process.

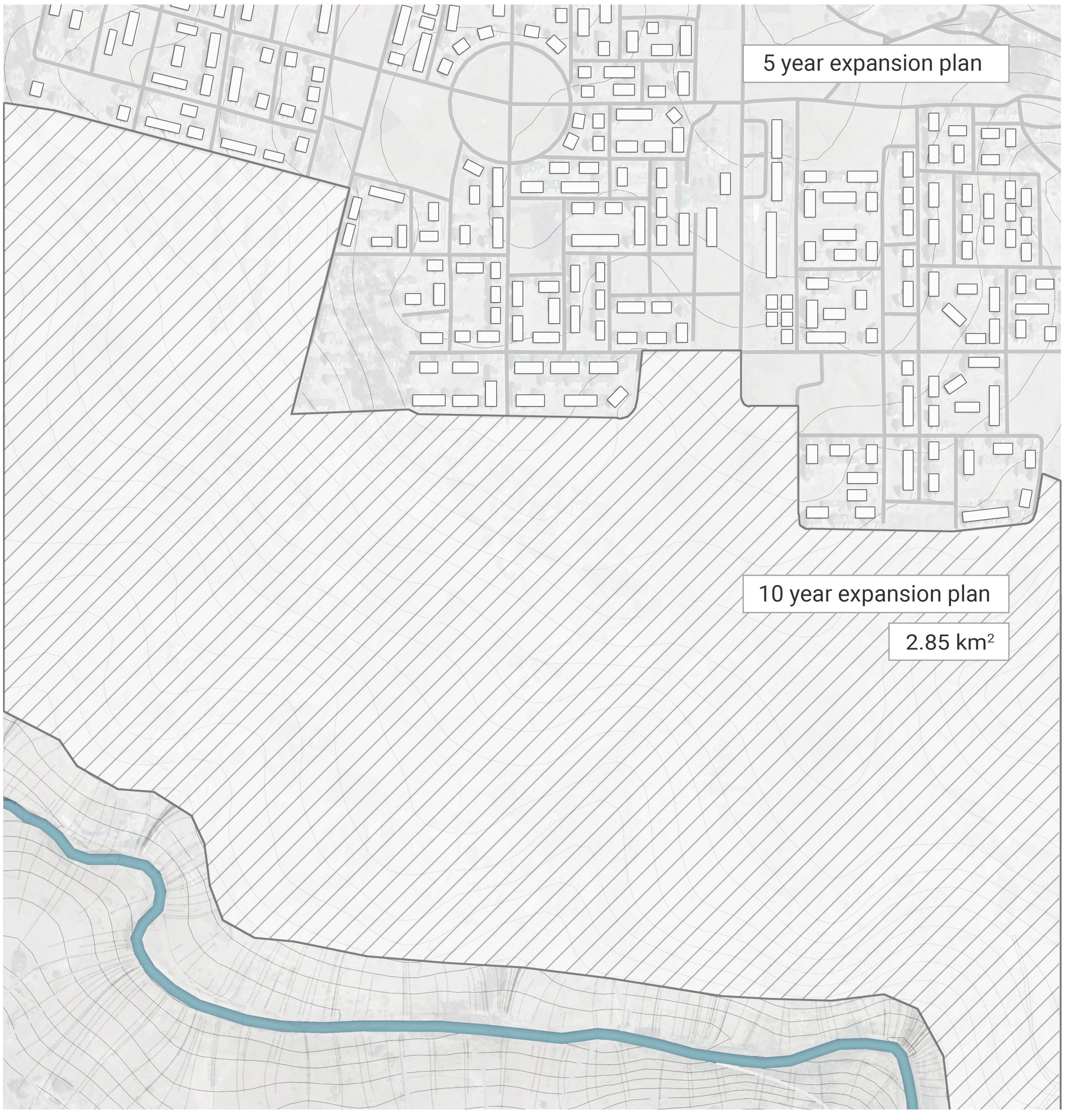


Fig. 4.2 Selected Site Development Plan

4.3 Computational Model Application

The aim of the case study is to evaluate multiple urban growth scenarios and their impacts on storm-water runoff. The evaluation process involves the application of the previously outlined computational model framework and its associated components. The goal of this application is to test the model's feasibility and work flow in large scale contexts for minimizing storm-water runoff and identifying technical gaps and opportunities. Firstly, a site boundary was established within the terrain of the study area and was fed into the model. Following that, multiple street layouts were generated within this boundary and evaluated based on their segments alignment to rainwater flow direction. Afterwards, runoff volume calculations were conducted and compared among each street layout. Finally, different land use configuration strategies and sustainable storm-water management tools were tested on a selected street layout for their impact on total runoff volume and cumulative infiltration values.

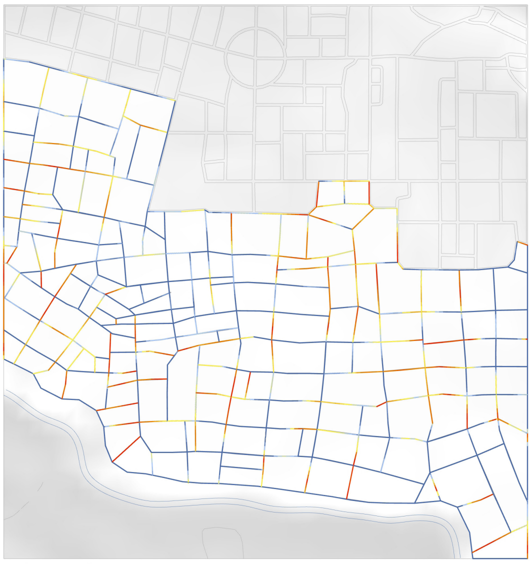
4.3.1 Rainwater Flow Direction Network

The developed numerical based model was utilized on the terrain of the site boundary in order to generate the rainwater flow direction network where multiple rainwater streams can be observed. The generated network gives an initial indication of overall terrain steepness as well as potential rainwater catchment zones. In addition, the network serves as a base map for subsequent runoff simulations and calculation.

Fig. 4.3 Numerical Based Rainwater Flow Direction Network

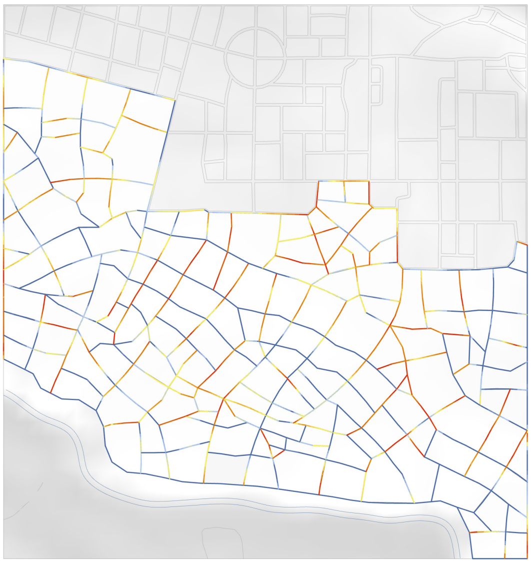
4.3.2 Segment Growth Angle Analysis

Five street network layouts of equivalent total lengths were generated with different segment growth angles (GA); GA1, GA3, GA5, GA7, GA10 [Fig 4.4a - Fig. 4.4e]. The selected domain of input growth angles provides a wide spectrum of street network layouts for the testing of the gradual change of street segment alignment against the rainwater flow direction. An alignment graph for each street network layout was plotted to compare the number of aligned segments within each network based on the segments remapped color values [Fig. 4.5]. The street network with the highest segment growth angle (GA10) scored the maximum aligned segment count [Fig 4.4e].



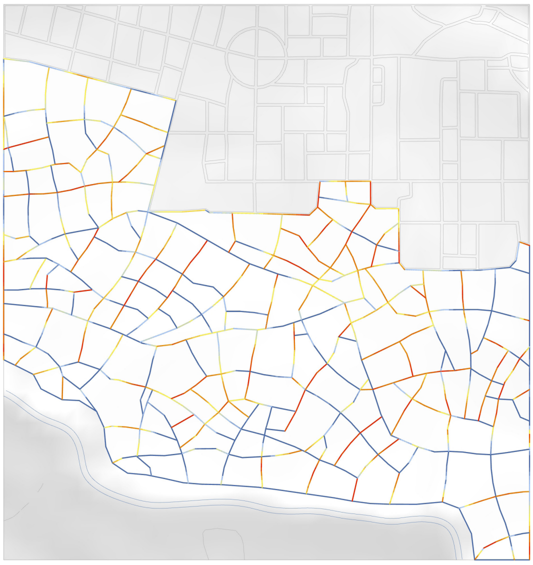
Total Street Length = 50399 m

Fig. 4.4a Street Network Alignment with Rainwater Flow Direction (GA1)



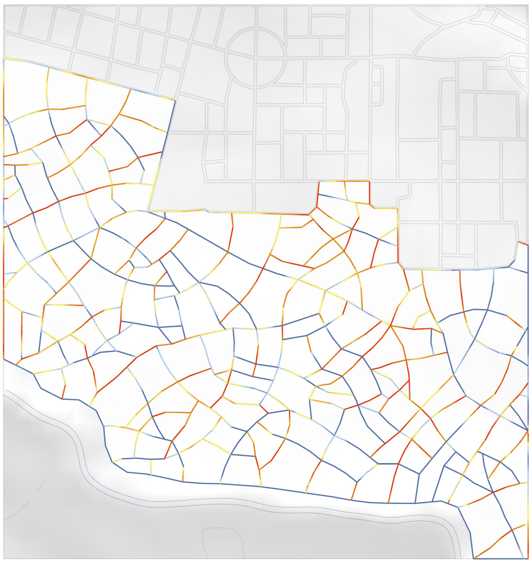
Total Street Length = 48627 m

Fig. 4.4b Street Network Alignment with Rainwater Flow Direction (GA3)



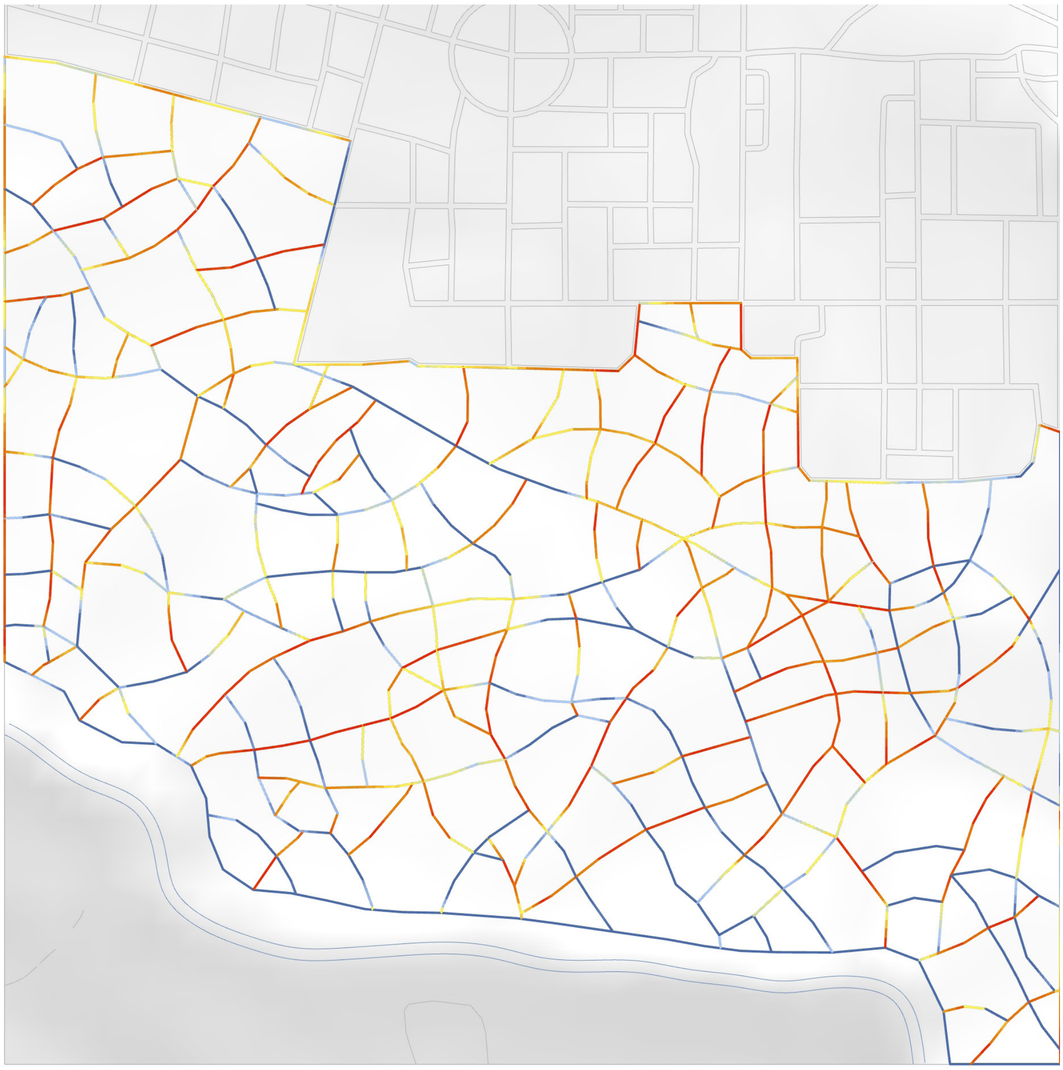
Total Street Length = 49649 m

Fig. 4.4c Street Network Alignment with Rainwater Flow Direction (GA5)



Total Street Length = 50576 m

Fig. 4.4d Street Network Alignment with Rainwater Flow Direction (GA7)



Total Street Length = 50305 m

Fig. 4.4e Street Network Alignment with Rainwater Flow Direction (GA10)

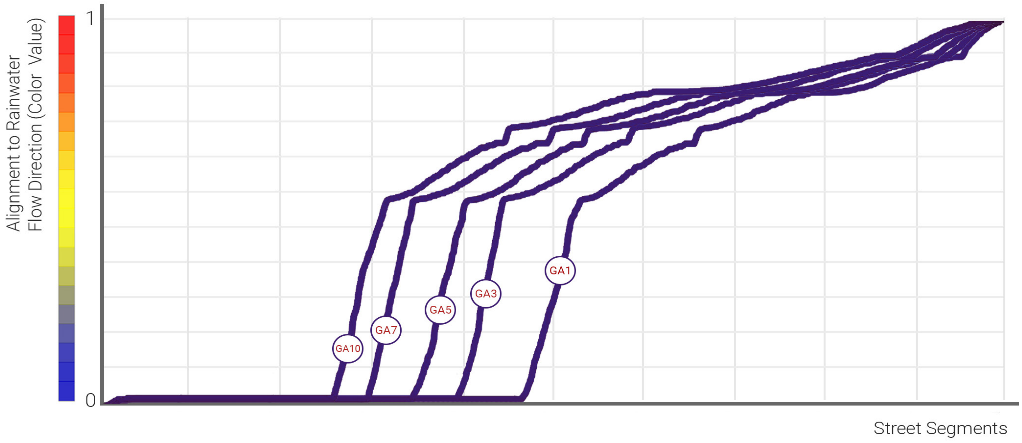
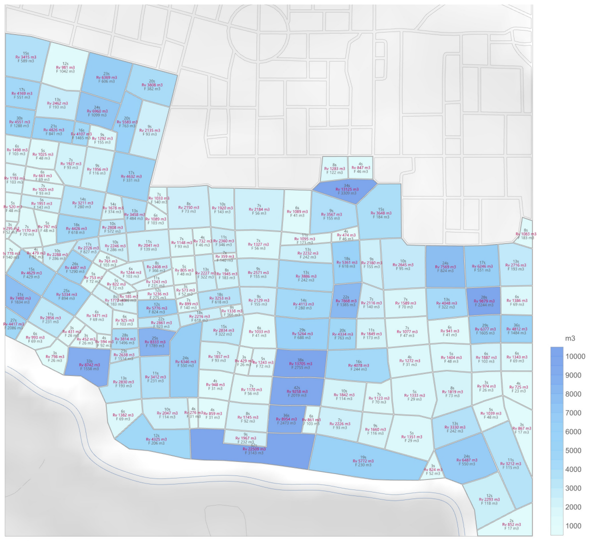


Fig. 4.5 Street Segment Alignment Graphs (GA1 - GA10)

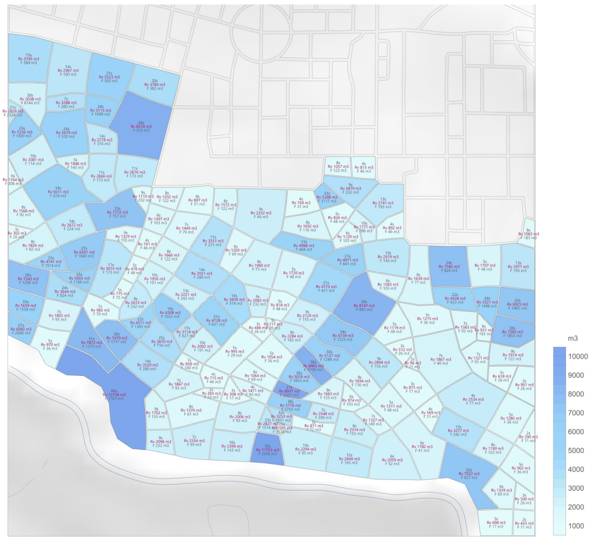
4.3.3 Runoff Volume & Cumulative Infiltration Calculation

For each generated street network layout, runoff volume calculations were carried out within their correspondent urban blocks based on a 100mm rainfall depth input and a fixed Curve Number (CN) value for paved areas [Fig. 4.4a - Fig. 4.4e]. The segment count, area, and slope coefficient for each block was utilized in the calculation process. While street network layouts with higher segment growth angles scored slightly less runoff volumes, it can be observed that all five evaluated layouts share relatively similar total runoff volume values. The same can be concluded for the associated total cumulative infiltration values.



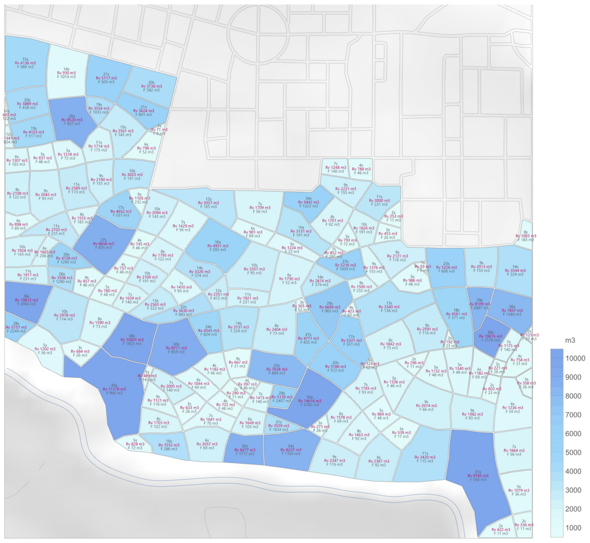
Total Runoff Volume = 459266 m3
Total Cumulative Infiltration = 66929 m3

Fig. 4.6a Runoff Volume & Cumulative Infiltration Calculation Values (GA1)



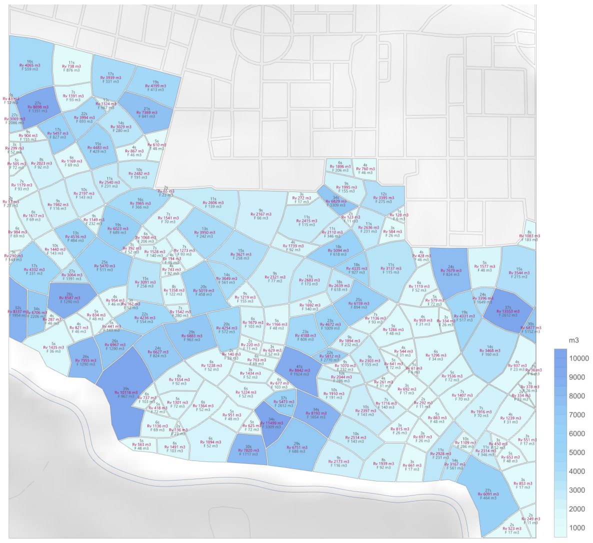
Total Runoff Volume = 454487 m3
Total Cumulative Infiltration = 89382 m3

Fig. 4.6b Runoff Volume & Cumulative Infiltration Calculation Values (GA3)



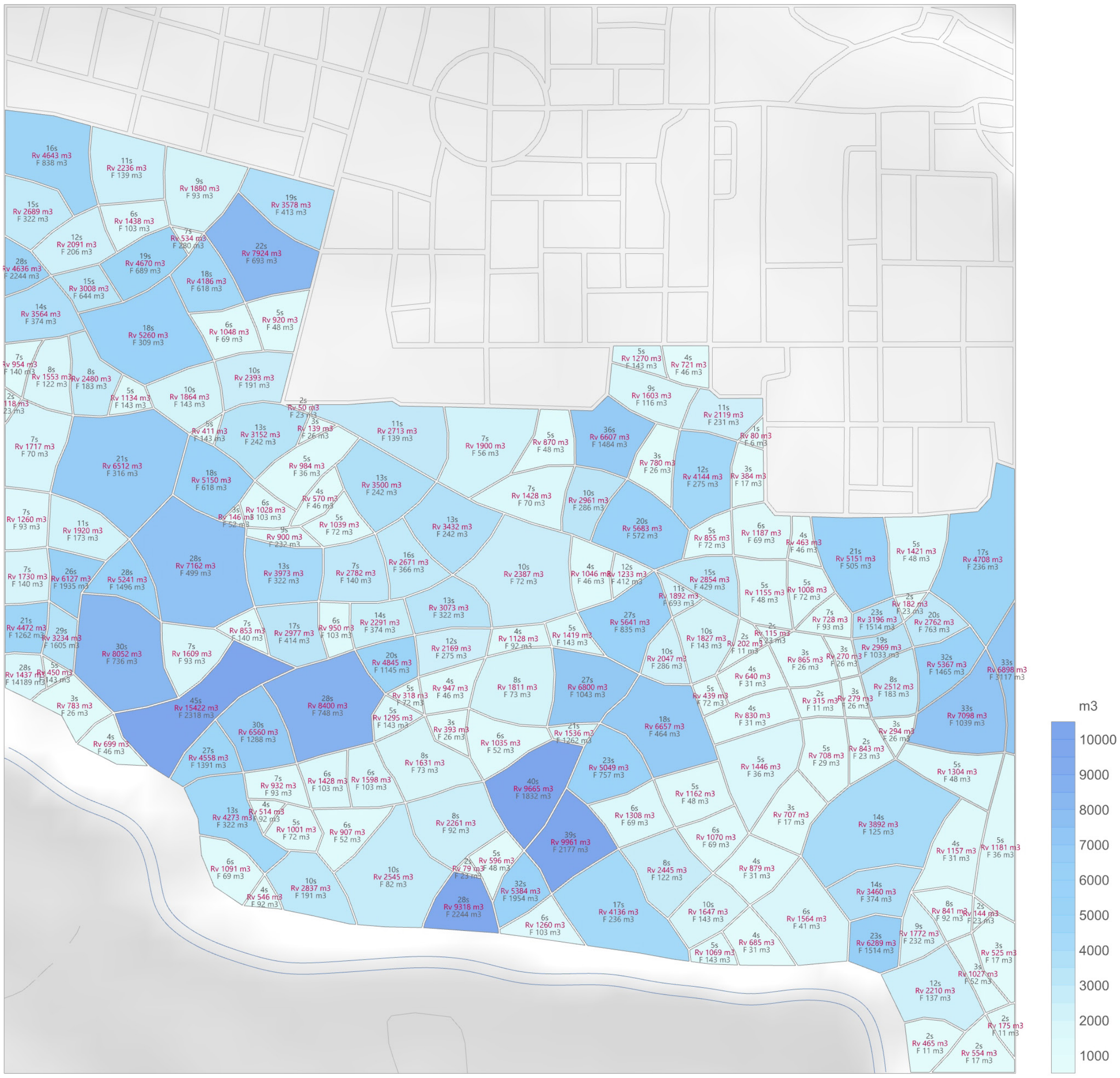
Total Runoff Volume = 424190 m3
Total Cumulative Infiltration = 58251 m3

Fig. 4.6c Runoff Volume & Cumulative Infiltration Calculation Values (GA5)



Total Runoff Volume = 455613 m3
Total Cumulative Infiltration = 73424 m3

Fig. 4.6d Runoff Volume & Cumulative Infiltration Calculation Values (GA7)



Total Runoff Volume = 448006 m3
Total Cumulative Infiltration = 84294 m3

Fig. 4.6b Runoff Volume & Cumulative Infiltration Map

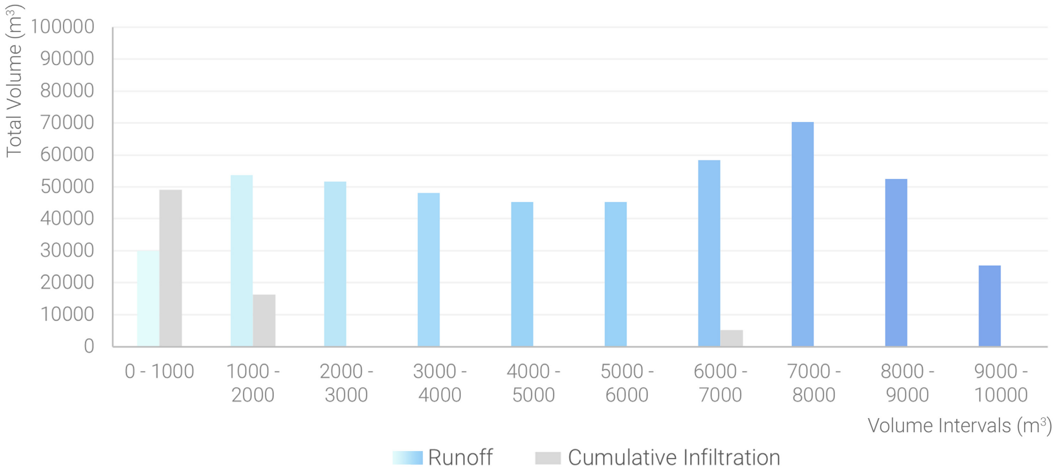


Fig. 4.6c Runoff Volume & Cumulative Infiltration Chart

4.3.4 Land Use Configuration

Three land use configuration strategies were evaluated within the study area in order to examine their impact on runoff volume reduction. For an even comparison, an equal percentage area for each allocated land use category was predefined for all the three strategies. The first strategy tested was a random distribution of land uses to all existing urban blocks of the network. [Fig 4.7a]. The correspondent runoff volume and cumulative infiltration values for each block were calculated and mapped out [Fig 4.7b, Fig. 4.7c].

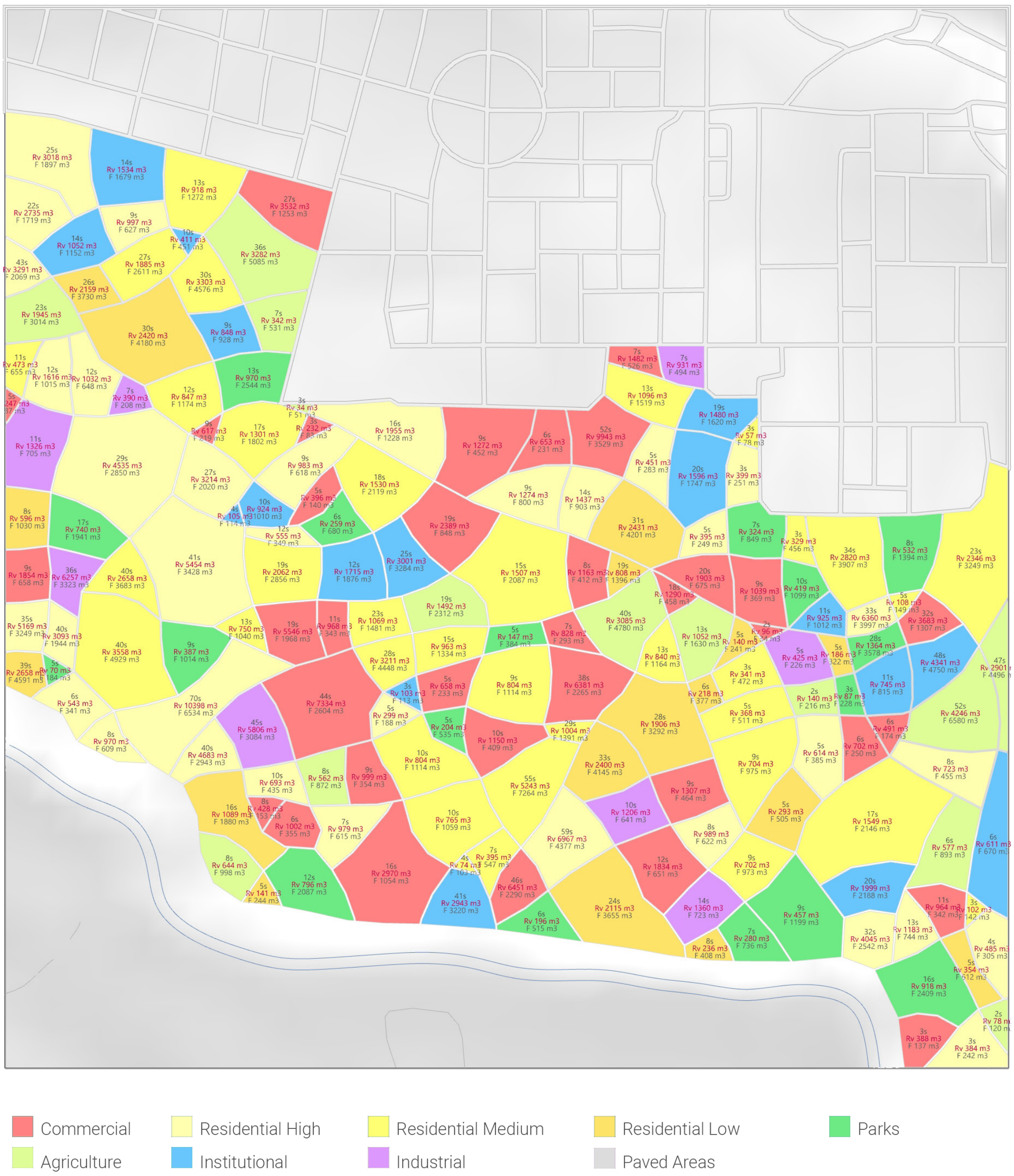
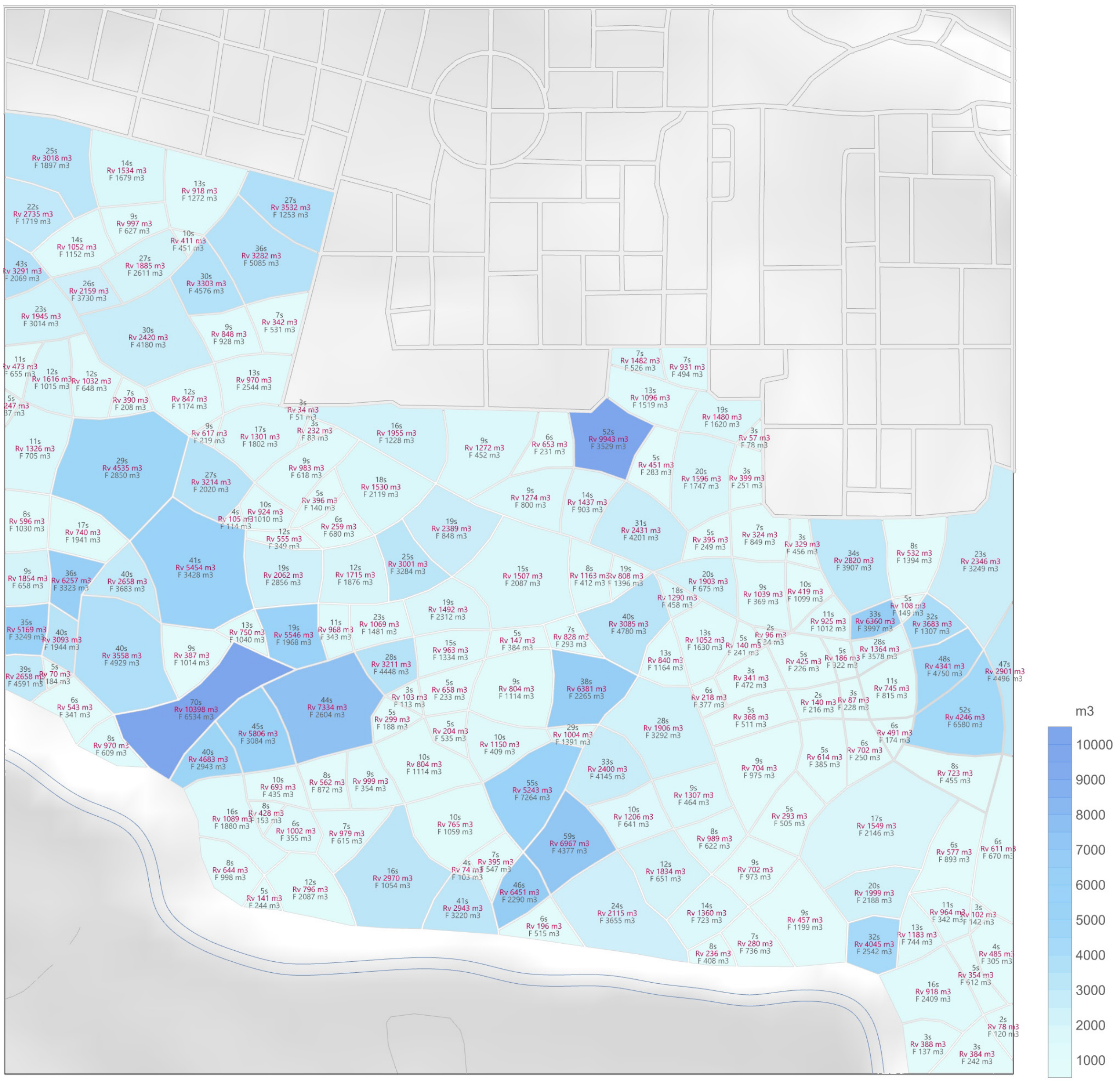


Fig. 4.7a Random Land Use Distribution



Total Runoff Volume = 291321 m3
Total Cumulative Infiltration = 265298 m3

Fig. 4.7b Runoff Volume & Cumulative Infiltration Map

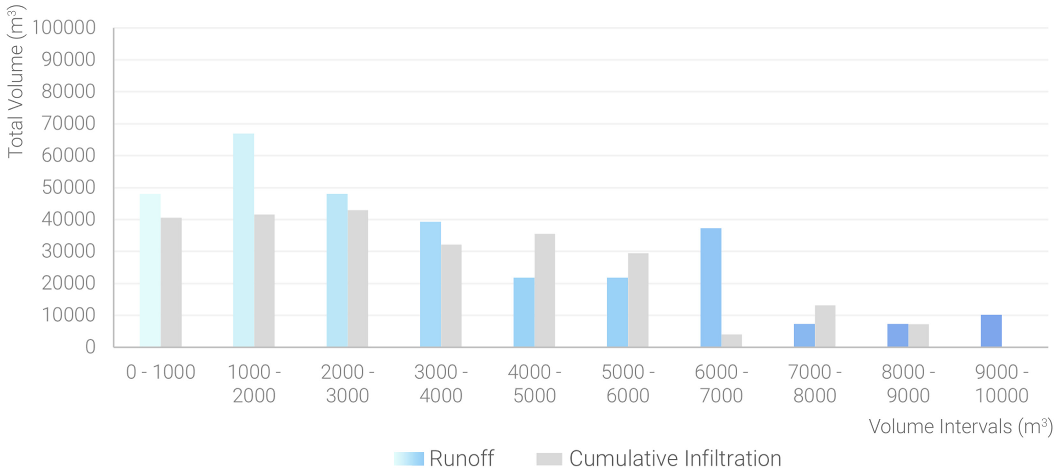


Fig. 4.7c Runoff Volume & Cumulative Infiltration Chart

The second configuration strategy was the allocation of the same land use categories according to a the hierarchy of the street network [4.8a], where land use categories with higher CN values were allocated closer to most the central or frequented segments within the network, and land use categories with lowest CN values closer to least frequented segments. Once again, the runoff volume and cumulative infiltration values for each block were instantly calculated and mapped for this configuration [Fig. 4.8b, Fig. 4.8c]. In a similar manner, equivalent values of runoff volume and cumulative infiltration were calculated and mapped for the third land use configuration strategy.

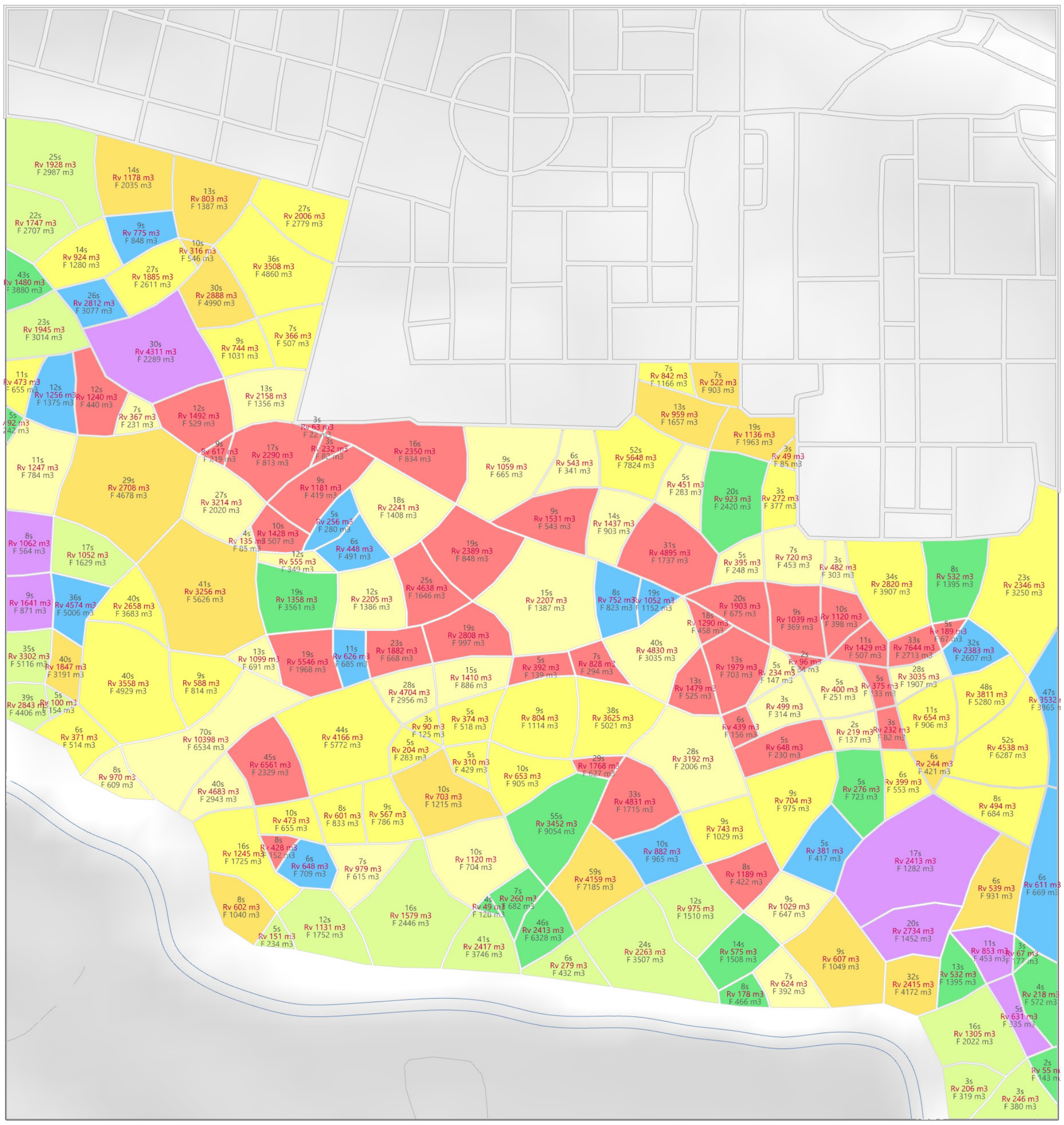
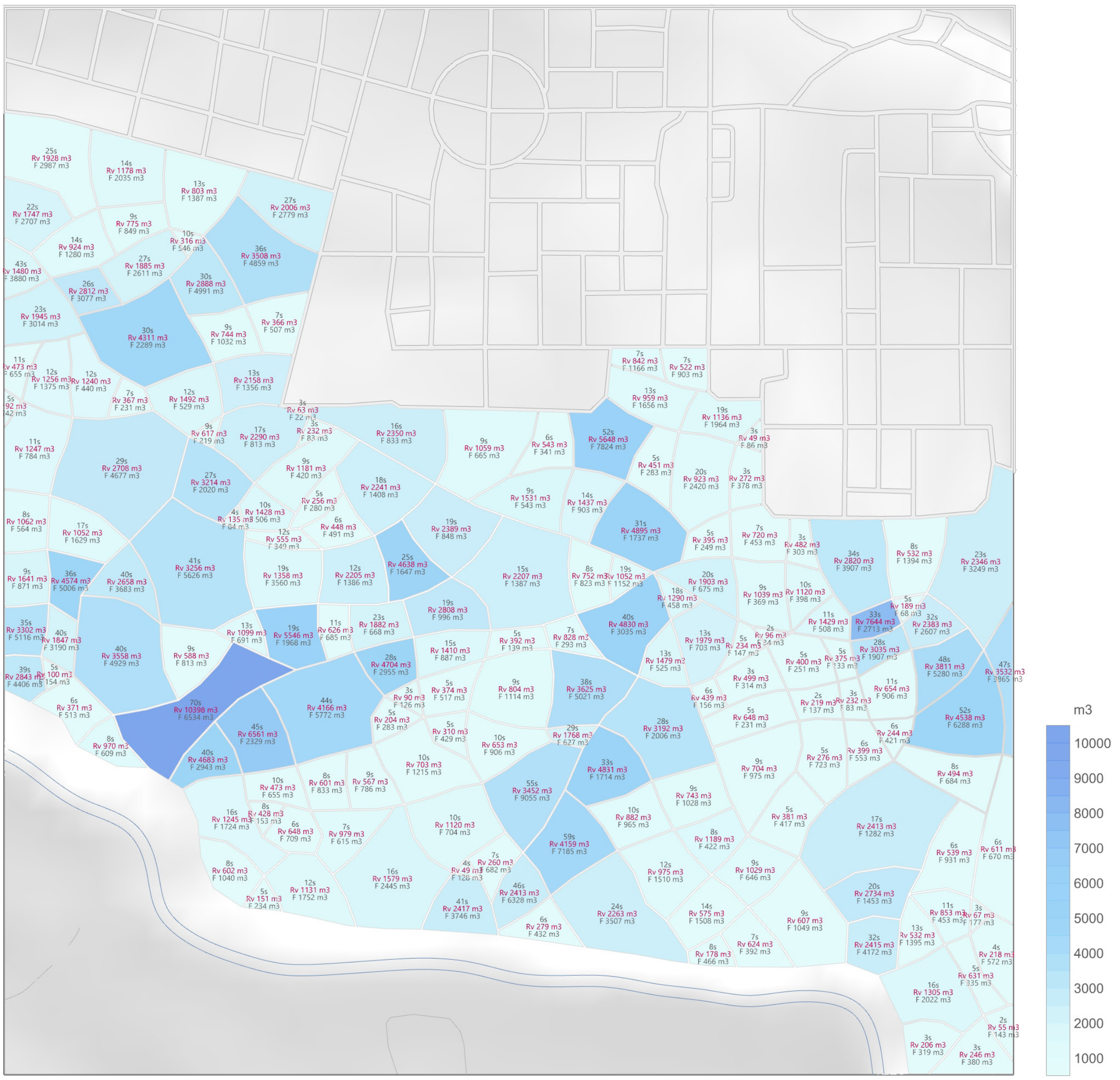


Fig. 4.8a Land Use Distribution based on Street Hierarchy



Total Runoff Volume = 278416 m3
Total Cumulative Infiltration = 278368 m3

Fig. 4.8b Runoff Volume & Cumulative Infiltration Map

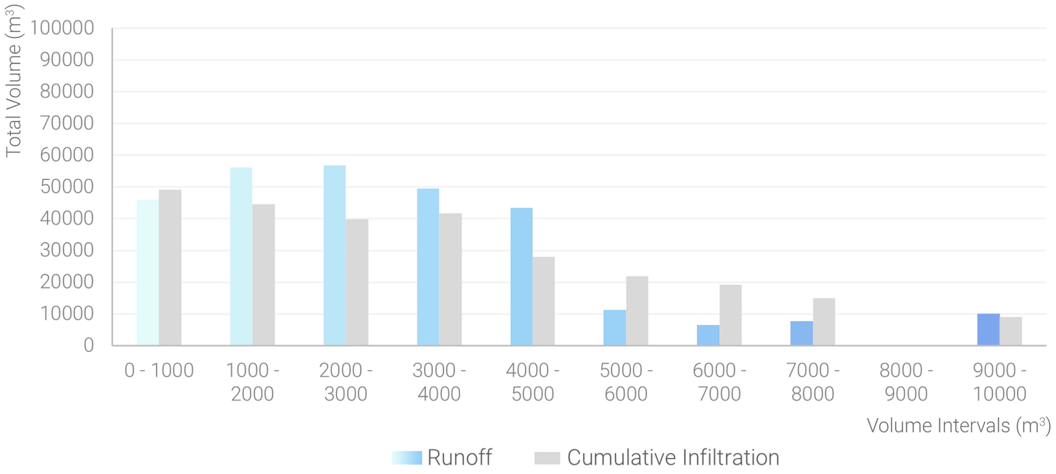


Fig. 4.8c Runoff Volume & Cumulative Infiltration Chart

This last strategy allocated land use categories according to their built in CN values and catchment potential based on the previously calculated runoff values of each block [Fig. 4.9a, Fig. 4.9b]. In other words, land use categories with lowest CN values were matched to urban blocks with highest runoff volume values and vice versa. As a result, the total calculated runoff volume is minimized and the total cumulative infiltration is maximized for this configuration [Fig. 4.7c]. Overall, the total runoff volume scored 18% decrease for the land use configuration based on CN values and block catchment potential when compared to configurations based on random allocation and street network hierarchy.

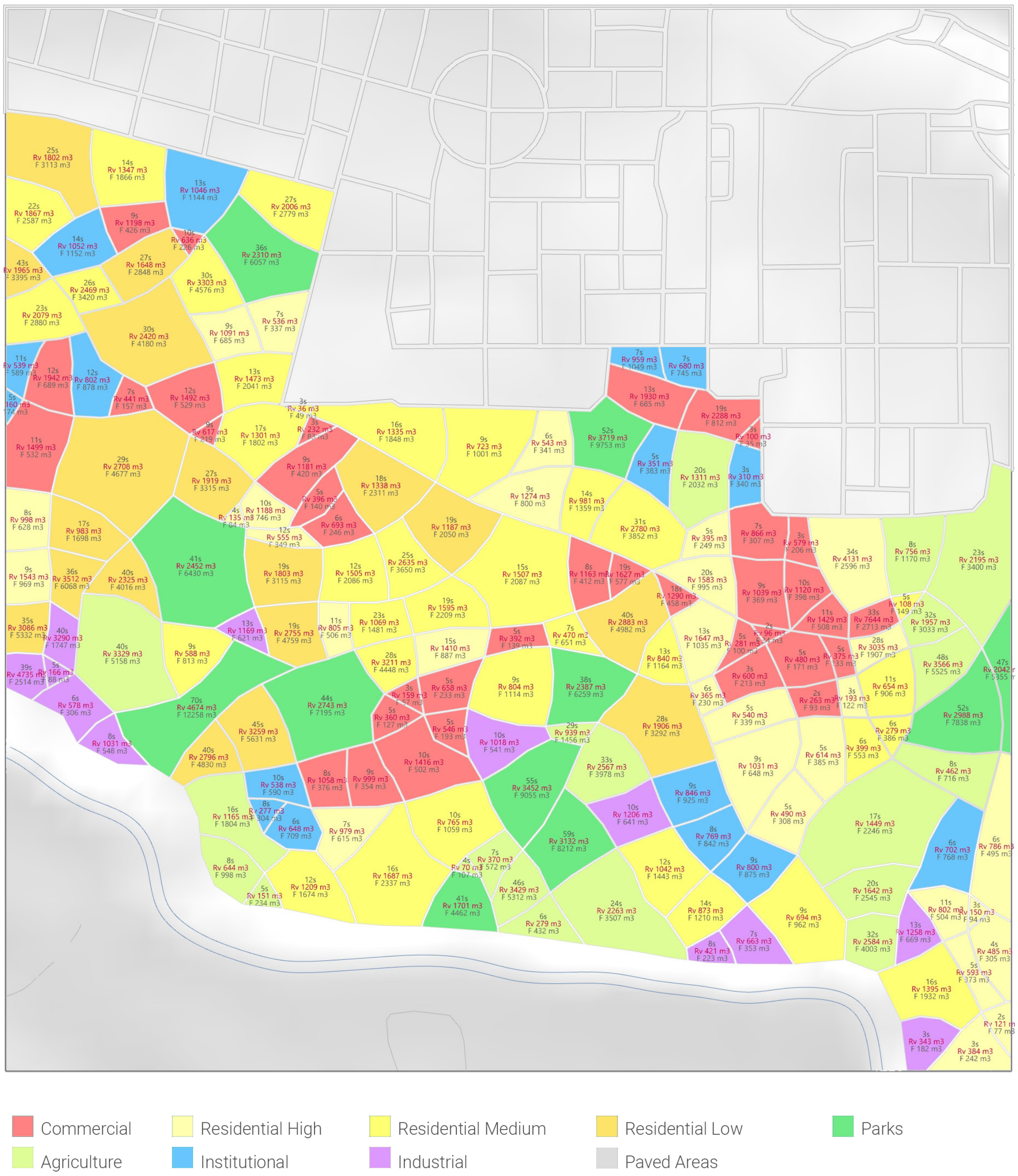
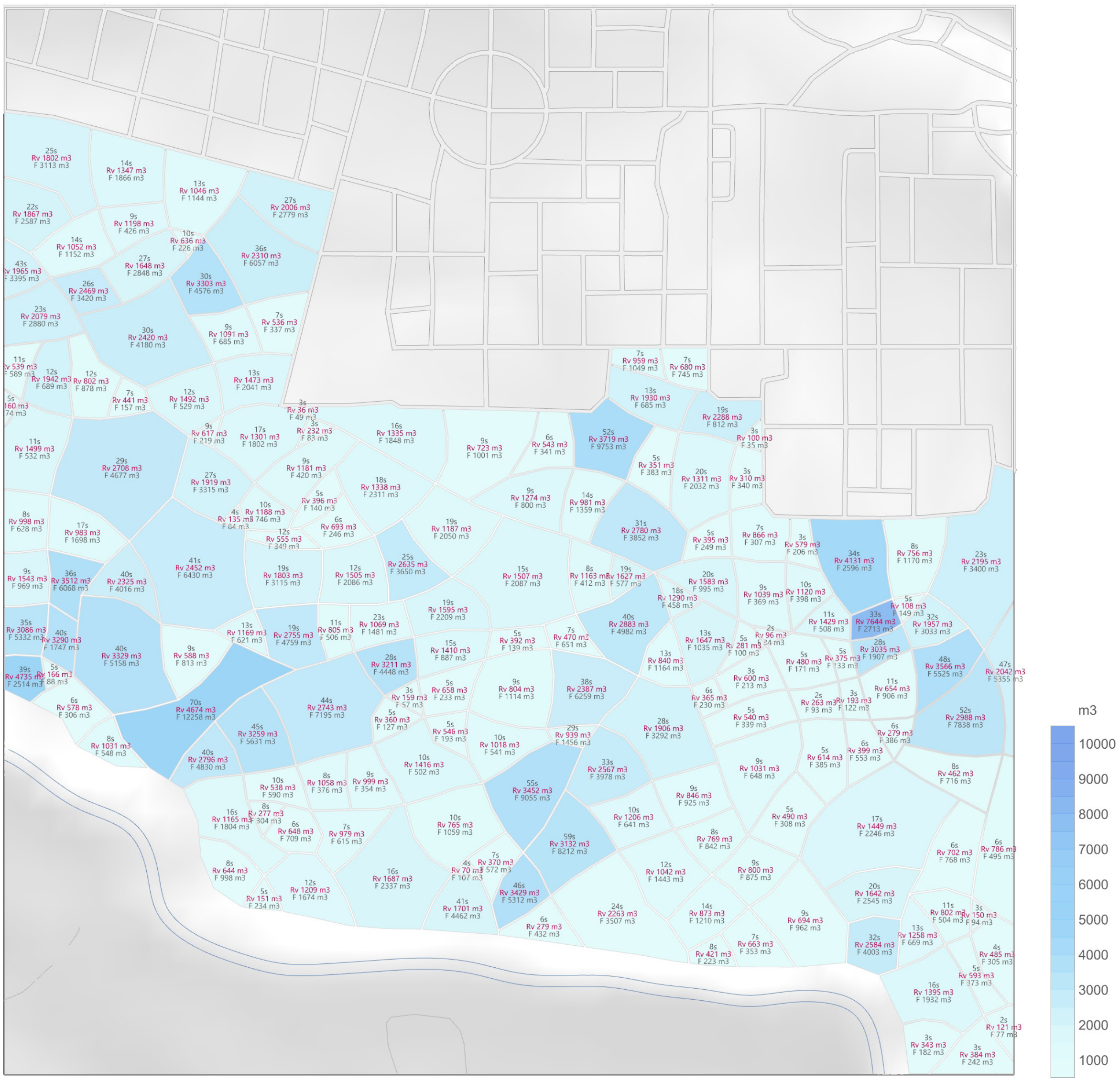


Fig. 4.9a Land Use Distribution based on CN value and Catchment Potential



Total Runoff Volume = 242070 m3
Total Cumulative Infiltration = 314715 m3

Fig. 4.9b Runoff Volume & Cumulative Infiltration Map

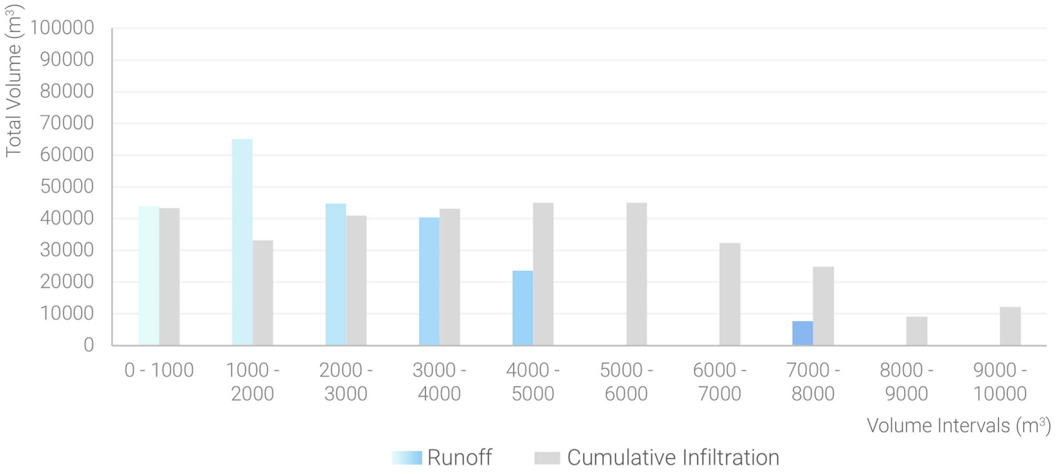


Fig. 4.9c Runoff Volume & Cumulative Infiltration Chart

4.3.5 Sustainable Storm-water Management Tools

Green roofs, bioretention cells, and storm-water planters with adjustable retention capacities and areas were distributed among various blocks with the consideration of the blocks' predefined land uses and boundary areas [Fig. 4.10a]. The impact of these tools on the total runoff volume was calculated and mapped out accordingly. There was a further 13% decrease in total runoff volume and equivalent increase in total cumulative infiltration. Consequently, the overall percentage decrease in total runoff volume summed up to 31%.

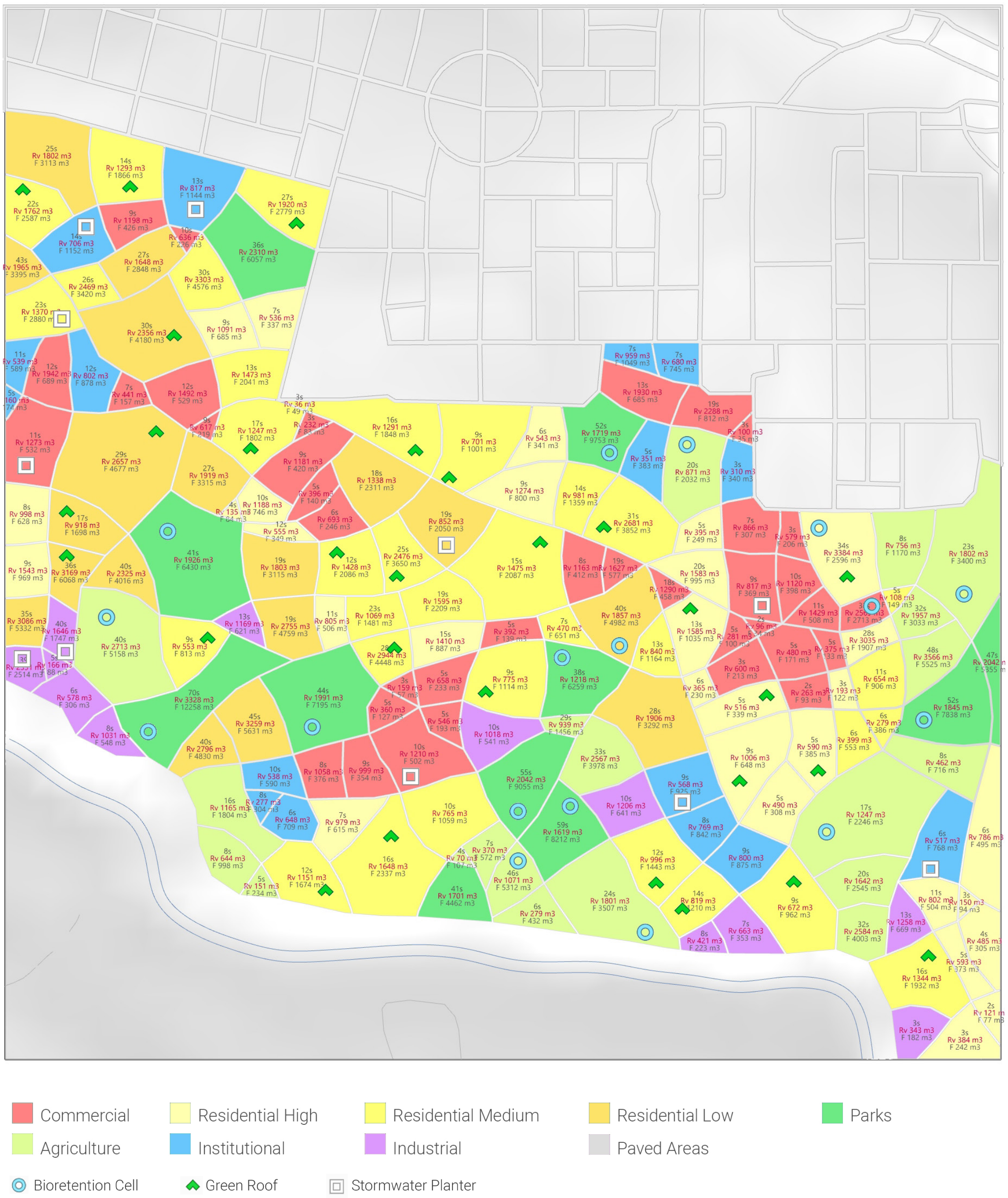
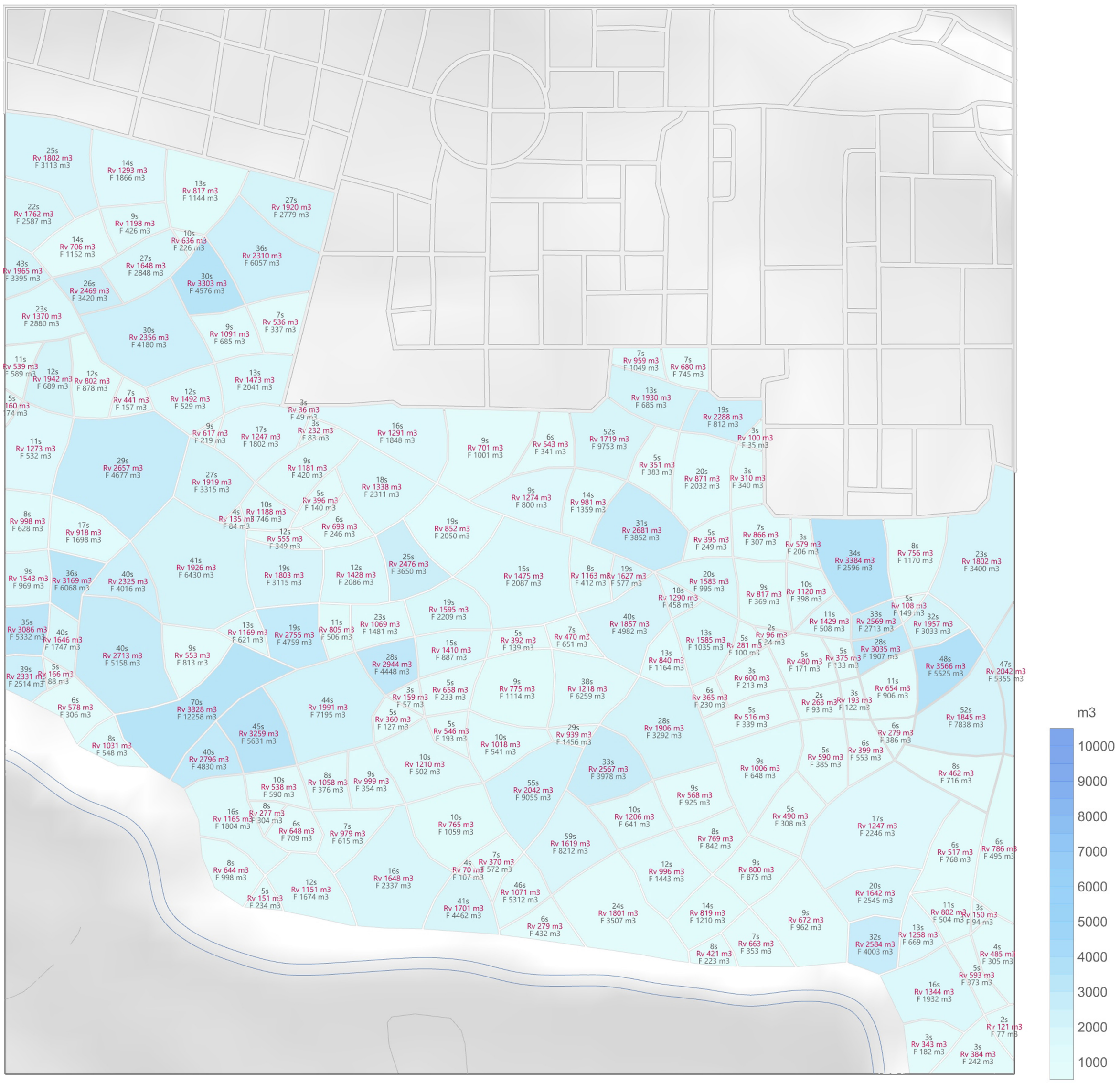


Fig. 4.10a Sustainable Infiltration Tools Allocation



Total Runoff Volume = 212117 m3
Total Cumulative Infiltration = 344715 m3

Fig. 4.10b Runoff Volume & Cumulative Infiltration Map

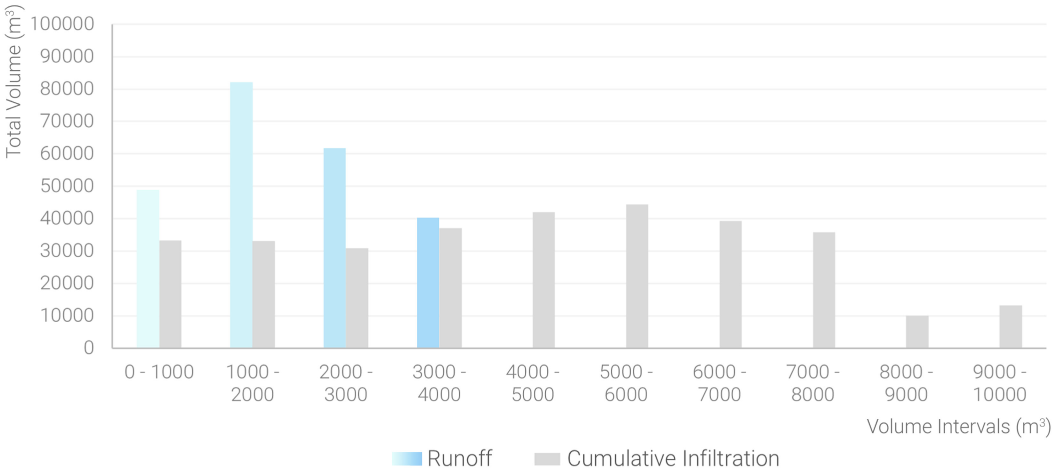


Fig. 4.10c Runoff Volume & Cumulative Infiltration Chart

4.4 Summary & Discussion

In this chapter, the proposed computational model framework was applied to a large scale context in the city of Addis Ababa, Ethiopia. The number of scenarios tested along each component of the model were expanded in order to evaluate more variations.

The numerical based model for rainwater flow direction network generation displayed a better performance in large scale areas with less computation time when compared to physical based models. Different street network layouts with different segment growth angles were then evaluated based their alignment to the slope of the site. Street layouts with higher segment growth angles displayed higher alignment scores for equivalent total street lengths and block sizes. Afterwards, the total runoff volume and cumulative infiltration values for each scenario were calculated and mapped out. The impact of the street layout on runoff volume calculation alone was minimal in the study area as it depended mainly on the total blocks area tested for a particular layout which was relatively similar for all layouts. However the orientation of the street layout has a significant effect on storm-water storage and subsequent drainage management. For this reason, the street layout with the highest alignment score to the site's terrain slope was adopted. In the next evaluation, different land use configuration strategies showed different impacts on runoff volume reduction with the highest recorded impact for strategies based on land use CN values and block catchment potential. Lastly, the addition of different sustainable management tools recorded further noticeable runoff volume reduction and cumulative infiltration increase.

Overall, the computational model performed effectively in a real life large scale case study with a relatively quick simulation feedback. One of the main observed advantages of the framework, was its minimal requirement of input data or preparation. A simple terrain surface and a street network are the only required input geometry for the model to operate. In addition, points can be used when needed to assign a storm-water infiltration tool or modify a land use category for a specific block. This is done by placing a point inside the block for the intended modification through Rhino's layer panel. Additional parameters of the model can be controlled for each evaluation phase within the Grasshopper canvas through predefined number sliders. Altogether, such setup offers a simple work flow for an urban designer to utilize and integrate into their design and decision making process with little to no hydraulic knowledge.

While the calculated outcomes of the model reflect reasonable results, the magnitude of the values themselves needs to be validated against more realistic rainfall precipitation data. For this reason, the resulted amounts of runoff volumes and cumulative infiltration in this case study do not reflect actual contextual values, since they are based on an assumed rainfall depth input (100mm). Therefore, the percentage of difference in values was instead used between the different evaluated scenarios for their impact assessment. For the presented case study, the developed model found that up to 30% of runoff volume can be reduced through alternative configurations of street network and land use layouts, as well as better integration of sustainable storm-water management tools.

5

Conclusion & Outlook

The Fifth and final chapter discuses conclusions, suggestions, and outlooks of the proposed research work. This chapter emphasizes the significance of incorporating flood risk management approaches in the urban planning process, explains the contribution of this thesis in filling potential research gaps, and explores the possibilities of further relevant approaches for reducing flood risks through more comprehensive planning.

Chapter Five
Conclusion & Outlook

5.1 Conclusions

The aim of the research presented was to assess the impact of urban form on flood risk reduction. To achieve this, an interdisciplinary approach was adopted to import relevant knowledge from flood risk management into the field of urban planning. Accordingly, existing definitions and concepts of disaster risk reduction were reviewed. It was found that the resilience of a system is inversely proportional to its vulnerability to a potential hazard and that the magnitude of this relationship is linearly related to the level of measured risk. Sustainable flood risk management therefore prioritizes mitigation strategies (non-structural) over protection strategies (structural) because they are more effective in coping with the increasing frequency and magnitude of modern floods. This view has proven particularly valuable in developing countries with rapid urbanization and resulting flood risks. Accordingly, spatial planning plays an increasingly important role in reducing flood risk because of its ability to regulate the use of space over a long period of time. Several aspects of urban planning and design have been investigated for their effectiveness in reducing flood risk. It was found that the configuration of land use, the design of the road network and certain infiltration tools have the greatest impact and importance. In addition, existing scientific models, formulas and corresponding software packages for flood risk management were examined and compared. It was found that most of these tools are not easily accessible to the urban planning field due to various technical limitations. Therefore, a computational model was developed to evaluate the above planning and design aspects in a single integrated framework that is more familiar and accessible to the urban planning field. The proposed model concluded the following:

- Street network layouts following the direction of storm-water flow have little impact on runoff volume values. Nevertheless, they have better impact on storm-water storage and subsequent drainage management than perpendicularly aligned street networks
- Land use configurations based on CN values and catchment potential contribute significantly more to runoff volume reduction than other distribution strategies which are based on street hierarchy and random distribution.
- The allocation of the integrated infiltration tools with predefined retention capacities showed further positive impact on total runoff volume reduction.

The model was then applied to a new development site in Addis Ababa, in Ethiopia, to investigate its effectiveness in a large-scale context. The analysis was conducted for a larger number of scenarios where a 30% reduction in total runoff volume was achieved during the evaluation process. The main observed advantages of the model were the minimal input data or preparation requirements and the interactive workflow and relatively quick feedback. On the other hand, minor technical limitations of the developed model were documented and discussed in detail throughout chapters three and four.

5.2 Suggestions

In today's world, science and research must find better and more effective solutions to various challenges and analyze complex systems that often require crossing disciplinary boundaries to generate new knowledge and foster innovation. This is because complex problems are often no longer suitable for research in a single discipline. Moreover, discoveries and advances in research and development often occur at the boundaries between different scientific fields. And most importantly, interaction between researchers from different disciplines benefits all those involved and widens their horizons. At the same time, advances in technology have enabled a better understanding of complex phenomena through the development of computational simulations and models which are often at the heart of many interdisciplinary research efforts and are almost mandatory in the development and deployment of new advanced systems. The fields of urban planning and flood risk management are a prime example of the need for overlapping disciplines due to their increasing complexity. The research presented aims to show how such overlaps can lead to valuable aspects to be considered along the urban planning process. It also encourages such research approaches as well as greater integration of computational tools and parametric modeling in the field of urban planning.

5.3 Research Outlook

As mentioned earlier, this research adopted an interdisciplinary approach to propose an integrated computational model framework which evaluates selected urban form aspects for flood risk reduction. Although the proposed model has made valuable contributions in this regard, there are still several directions in which it could be improved as outlined as follows:

- Since the model assumes that streets, as channels or obstructions, have no effect on the behavior of storm-water, the accuracy of the evaluation of street orientation and the subsequent calculation of runoff volume is affected. To address this issue, a particle-based model for rainwater flow direction simulation can be investigated.
- The evaluation of individual street segments and their dimensions for runoff volume reduction proved to be a challenging task due to the large quantity of segments to be evaluated with the available computing power. Considering the significance of such analysis, further exploration is recommended.
- While the model aims to minimize runoff reduction, the evaluation process does not take into account the impact on other urban aspects such as spatial connectivity and accessibility. Therefore, a trade-off assessment between different planning objectives can be explored to determine the overall efficiency of the proposed planning scenario as a whole. Moreover, additional urban form aspects can be incorporated into the model for further evaluation of runoff reduction. Some of these can include a block's building typology and vegetation capacity.

Overall, the depth and breadth of both urban planning and flood risk management fields provide valuable research opportunities for urban researchers and practitioners to explore and integrate into their decision-making process. Accordingly, more efforts are needed to overcome existing gaps and barriers in urban flood modeling, which will be of great value for the role of urban planning in flood resilience.

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Statutory Declaration

I hereby affirm that the Master thesis at hand is my own written work and that I have used no other sources and aids other than those indicated. All passages, which are quoted from publications or paraphrased from these sources, are indicated as such, i.e. cited, attributed.

This thesis was not submitted in the same or in a substantially similar version, not even partially, to another examination board and was not published elsewhere.

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