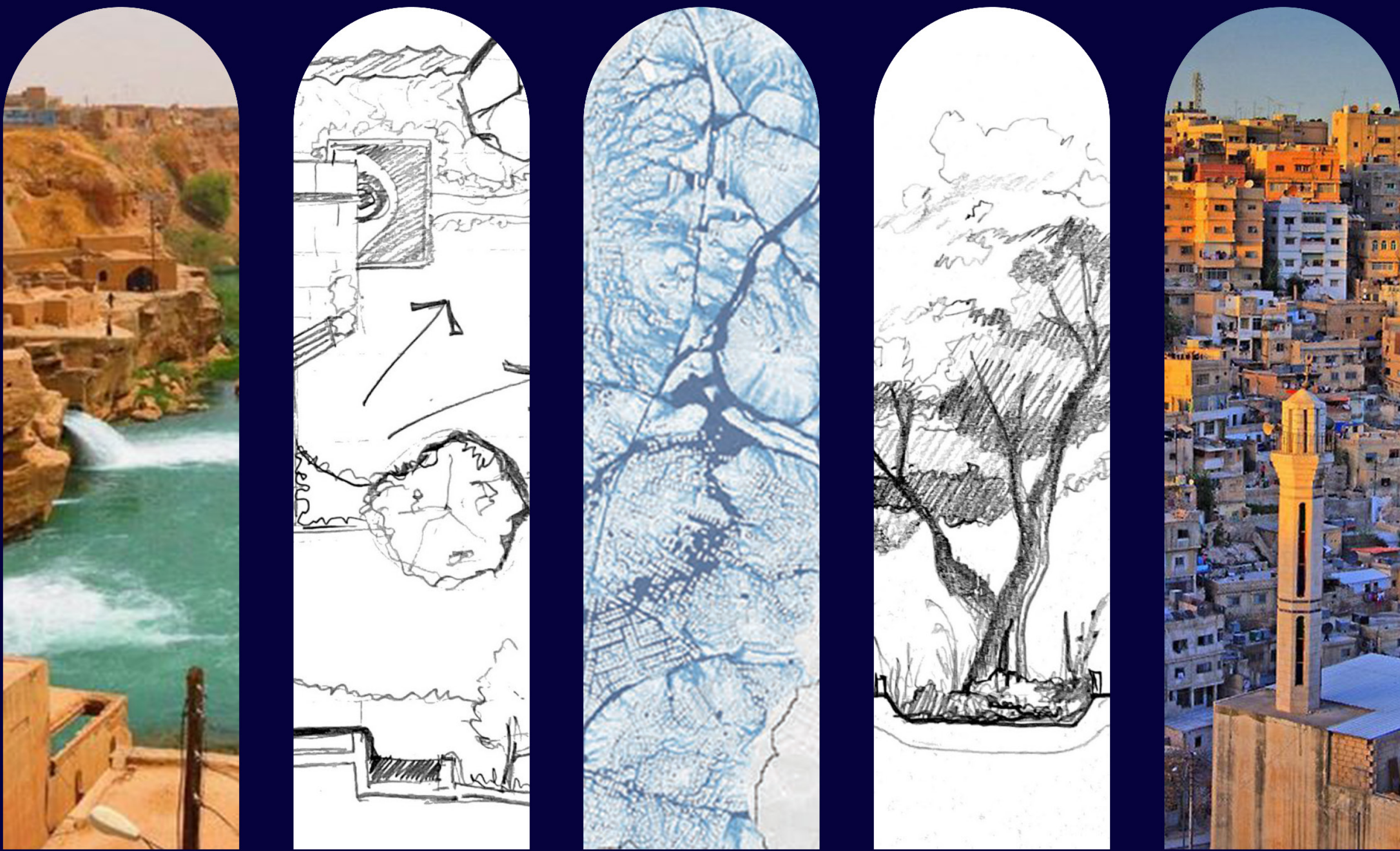

A comparative scenario analysis of WSUD measures for stormwater management in Amman, Jordan

REAP Master Thesis

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A comparative scenario analysis of WSUD measures for stormwater management in Amman, Jordan

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Abstract

Jordan is one of the most water-scarce countries in the world. At the same time, it has faced many flash floods due to the topography and rainfall patterns in the region. However, Jordan's vulnerabilities to these water shocks have been exacerbated due to factors like climate change, rapid urbanization, a huge influx of refugees and the lack of proper management to keep up with these changes. With increased international cooperation, Jordan has committed to achieving various climate goals, however, the implementation of these policies into practice has been a challenge. This Master's thesis aims to analyse the effects of integrating water-sensitive urban design measures into urban areas in arid and semi-arid climates. This is done by conducting an urban analysis of a catchment in Amman, a developing area called Marj Al Hammam. In this catchment, certain hotspots are identified that are at high risk of flooding, and at the same time present a potential to implement WSUD strategies. Further, three scenarios are envisioned - business as usual, interventions in public spaces and the inclusion of private spaces for stormwater management. While these hotspots vary greatly in their typologies, a common inference was that in the current state, maximum damage would incur due to stormwater runoff. The lack of open public space available according to the current land use plan poses a challenge to integrate WSUD, however, even in the minimal spaces available, its impact is quite apparent in terms of reducing and attenuating stormwater runoff volumes and runoff velocities. Further integrating these measures into private areas, especially rainwater harvesting has a huge impact on the overall system hydrology. Moreover, with strategic storage and treatment, stormwater runoff can be a good source of water supply during the dry periods in Amman. Additionally, these measures come with many ecological and social benefits - improving the microclimate, promoting biodiversity by bringing nature into the city and providing dynamic spaces in the city for people to come together, hence improving the overall quality of stay. The planning and implementation of these measures, however, should be done with stakeholder workshops and public participatory programs. Thus this analysis concludes with recommendations for the further development of the catchment and directs the path to further research on the detailed design of measures, to make Amman a resilient, green, just and inclusive city.

Keywords:
water sensitive urban design, resilient city, flash floods, stormwater management, rainwater harvesting, reduction of runoff volumes and discharge rates

Table of Contents

List of Figures

List of Tables

Abbreviations

CityRAP: City Resilience Action Planning Tool
CRF: Cities resilience framework
DWA: German Association for Water, Wastewater and Waste
GAM: Greater Amman Municipality
GCAP: Green City Action Plan
GG-NAP: Green Growth National Action Plan
GIS: Geographic Information System
HW: Hamburg Wasser
INWRDAM: Inter-Islamic Network on Water Resources Development and Management
IPCC: Intergovernmental Panel on Climate Change
LID: Low Impact Development
MGP: Metropolitan Growth Plan
MoEnv: Ministry of Environment, Jordan
MoLA: Ministry of Local Administration
REAP: Resource Efficiency in Architecture and Planning
RCP: Representative Carbon Pathways
RWH: Rainwater harvesting
SuDS: Sustainable Urban Drainage Systems
UN: United Nations
UNDP: United Nations Development Programme
UNESCO: United Nations Educational, Scientific and Cultural Organization
UNFCCC: United Nations Framework Convention on Climate Change
WSUD: Water Sensitive Urban Design
WAJ: Water Authority of Jordan
WWTPs: Waste water treatment plants

UNITS:

%: Per cent
°C: Degree Celsius
ha: hectare
mm: millimetres
m: metres
m^2: square metres
m^3 : cubic metres
l: litres
s: seconds
min: minutes
h: hours

Glossary

Attenuation— a reduction of the volume and discharge rate.

Bioretention cell—the general term for rainwater management facility to capture, treat, and infiltrate runoff organized as a landscaped depressions with vegetative cover and engineered soil medium.

Catchment area — the territory where all accumulated surface runoff flows to the same outlet destination, such as rainwater collector or surface water body.

Droughts — below-average rainfall and diminishing surface and groundwater levels

Evapo-transpiration—the process of water transfer through a plant and its evaporation

Extreme rainfall event — relatively rare cloudburst, generally considered to be an event with a return period of 10 years and more.

Flash floods — A flood caused by heavy or excessive rainfall in a short period of time

Forebay — a small basin or treatment element at the inlet zone trapping sediment.

Geocellular system— below-ground modular plastic units with a high porosity capable of managing high flow events, the alternative to the gravel drainage.

Permeable pavement — a surface type covered with a material that is impervious itself, however, there is void space for water penetration from the surface to sub-base.

Pervious area — an area of ground that allows water to be infiltrated

Ponding capacity—the water volume which can be temporarily held above the ground level of a raingarden.

Resilient city — a city organized in the way to resist physical, economic, social or institutional challenges and shocks.

Runoff —water flow over the ground surface to the drainage system

Chapter 1

Amman's Urban waters: Issues and Opportunities

1.1 Introduction to the project

The location of settlements throughout the history of mankind seems to have depended on the existence of a permanent source of water in the vicinity. Jordan is one of the countries that lies in a region where many kingdoms flourished by creating a near-permanent water supply where surface water was not readily available. However, along with a steady influx of refugees and rapid urbanization, climate change poses a serious threat to the availability, quality and quantity of water which is a basic human right (UNESCO 2020). Jordan is one of the most water-scarce countries in the world(Gammoh and Shamseldin 2019), and at the same time faces flash floods of devastating nature. Jordan's development challenges will be exacerbated by delays in addressing climate realities, but developing in a way that responds to climate change can help bridge inequalities, safeguard livelihoods, and promote social cohesion (The World Bank Group 2022). Water Sensitive Urban Design (WSUD) aims to integrate sustainable stormwater management with urban planning requirements, thereby aligning the urban water cycle to the natural one (Hoyer et al. 2011). An example can be seen in Figure 1 which shows the successful implementation of WSUD in the Azraq basin that is the source of water for Amman. This thesis is based on the research of the currently ongoing project "CapTain Rain: Capture and Retain Heavy Rainfall in Jordan" and aims to understand the contradicting nature of urban stormwater, in the form of flash floods and severe scarcity through the lens of water sensitive urban design (WSUD).

Figure 1: On 5 February 2021, a flash flood in Jordan's Azraq basin filled a newly constructed Managed Aquifer Recharge water harvesting structure with 65,000 m^3 of fresh water in under three hours, equivalent to nearly 800,000 Jordanians' daily consumption, showcasing a pilot initiative using local mud to decentralize drought risk management solutions through national collaborative water management efforts. Source: (Hubendick and Gupta 2021)

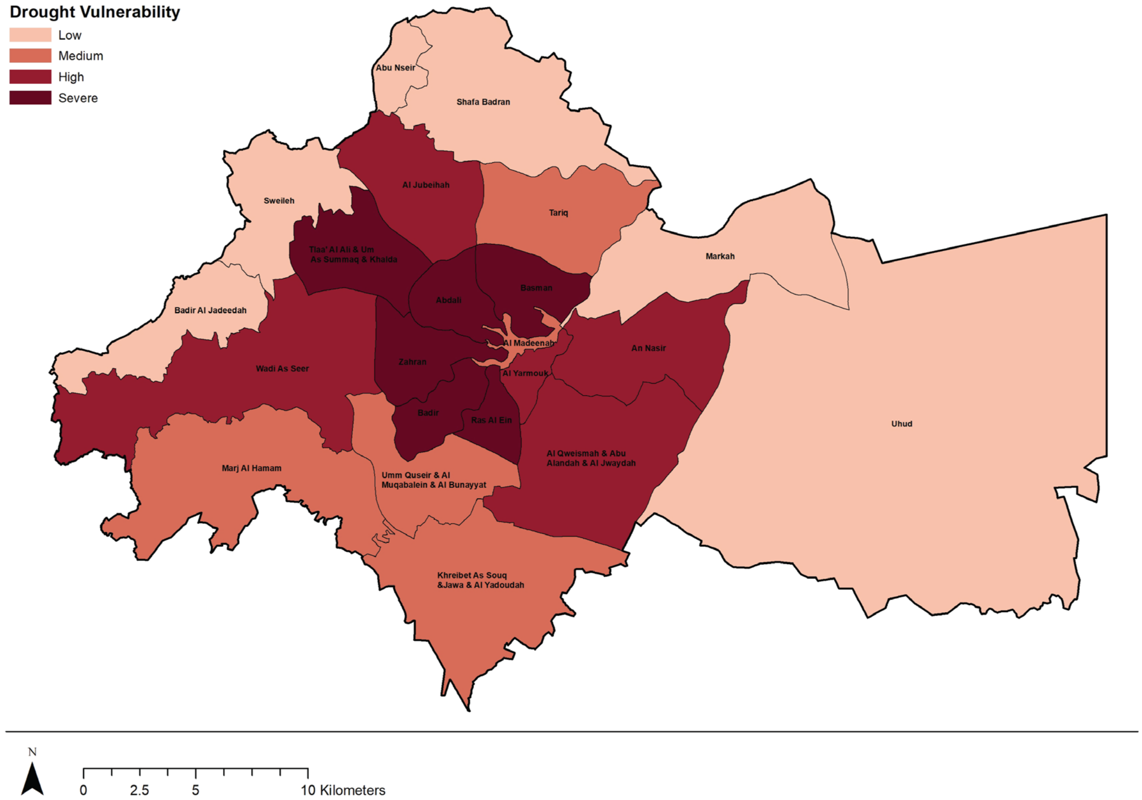


Figure 2: District vulnerability to Drought
Source: Greater Amman Municipality (GAM), "Climate Change Risk Assessment for Amman City", 2024, (Assessing Climate Vulnerabilities in Amman City 2024)

1.2 The contradictions of Amman's Waterscapes

Historically, Jordan has always been prone to water scarcity on one extreme and flash floods on the other. However, these conditions have been exacerbated by climate change and rapid urbanization due to an influx of refugees. Climate hazards pose significant environmental, economic, health, and social risks, heightening the vulnerability of people, urban systems, and assets. Amman's most noTable climate hazards include heatwaves, droughts, flash floods, and air- and vector-borne diseases. The IPCC defines drought as a "prolonged period of unusually dry weather causing a severe hydrological imbalance" (IPCC 2012). According to Jordan's Fourth National Communication Report (the Hashemite Kingdom of Jordan 4th National Communication; United Nations Development Programme 2022), periodic droughts have plagued Jordan throughout its history. Coupled with rising population and economic growth, these droughts have intensified water stress, reaching 104.31 per cent in 2020 (UN Water 2024; FAO AQUASTAT Dissemination System 2024). Droughts in Jordan are marked by below-average rainfall and diminishing surface and groundwater levels.

These events profoundly impact Amman, a rapidly growing and densely populated city, resulting in intermittent water supply, increased water prices, and heightened socioeconomic vulnerabilities. The city's ageing water infrastructure, plagued by leaks and faulty meters, exacerbates water challenges by creating non-revenue water (Assessing Climate Vulnerabilities in Amman City 2024).

Drought significantly impacts water security in Amman, with a vulnerability assessment revealing each district's exposure, sensitivity, and adaptation levels. Factors like population distribution, refugee density, and household numbers highlight exposure, while residential and commercial areas are most sensitive to water scarcity, affecting industries and heritage sites as well. Limited water availability threatens public green spaces, trees, and soil quality in undeveloped areas. Vulnerable groups, including women, people with disabilities, youth, the elderly, and city workers, are particularly affected. Drought leads to more frequent water supply restrictions and increased consumption demands, exacerbated by damaged water networks. While the Greater Amman Municipality (GAM) has implemented projects for water resource management and resilience, such as water harvesting, green infrastructure, and wastewater treatment, Miyahuna, Amman's private water company, focuses on maintaining pumping stations, and networks, and promoting public awareness. As seen in Figure 2, central districts like Basman, Abdali, Badir, Zahran, Ras Al Ein, Tlaa' Al Ali, Um As Summaq, and Khalda are highly

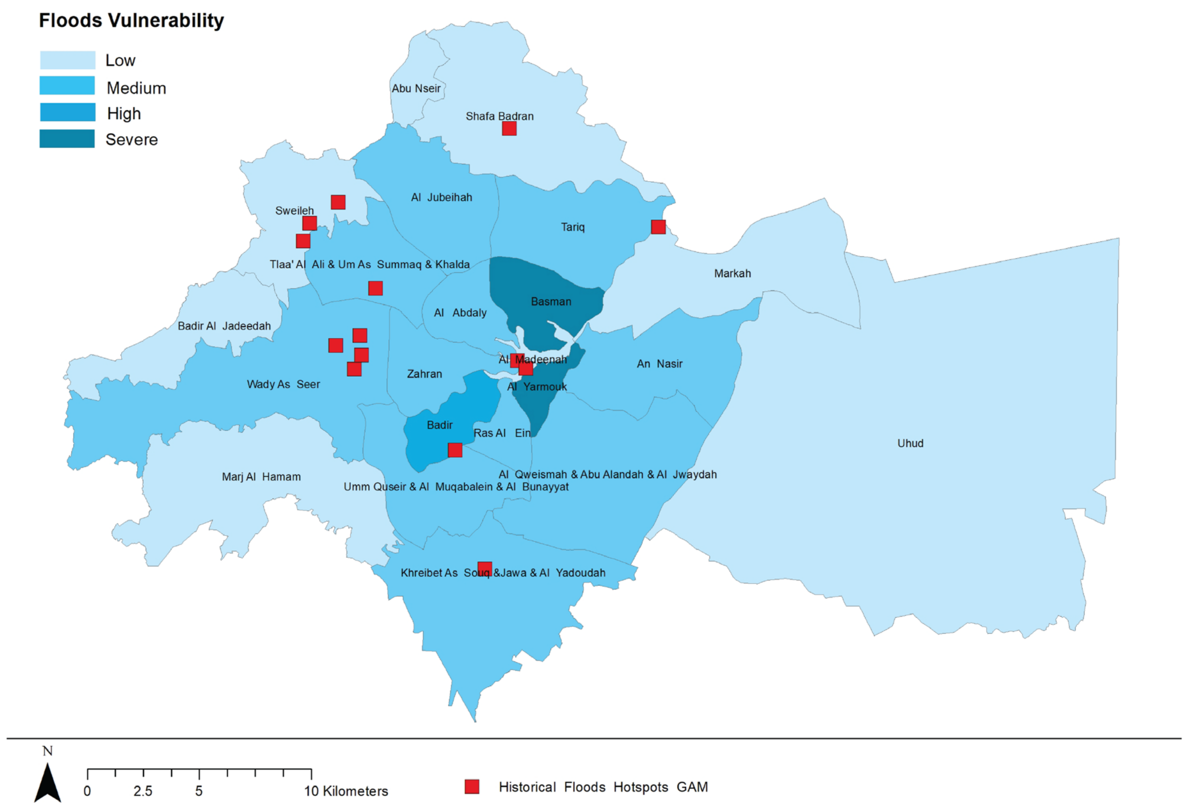


Figure 3: District vulnerability to Floods
Source: Greater Amman Municipality (GAM), "Climate Change Risk Assessment for Amman City", 2024, (Assessing Climate Vulnerabilities in Amman City 2024)

vulnerable to drought. Conversely, northern and western districts with abundant green spaces—such as Abu Nseir, Shafa Badran, Sweileh, and Badir Al Jadeedah—are seen as less susceptible. Areas like Markah, which has groundwater wells, and Uhud, which has a lower population density, exhibit lower vulnerability to drought (Assessing Climate Vulnerabilities in Amman City 2024).

On the other hand, over the past decade, Amman has experienced severe rainfall events leading to flash floods, particularly in low-lying areas like Al Madinah District. Contributing factors include urban sprawl over natural waterways, population growth straining inadequate stormwater infrastructure, lack of green spaces, and extensive impermeable asphalt surfaces preventing groundwater infiltration. From 2013 to 2015, Amman faced severe flash floods annually, causing fatalities and damaging infrastructure. In 2019, a devastating flood not only harmed people and properties but also submerged the Roman theatre archaeological site in downtown Amman, increasing the financial burden on the municipality and damaging the city's heritage (Assessing Climate Vulnerabilities in Amman City 2024).

In addition to the topographical, hydrological, and land use characteristics of Amman's districts, densely populated areas, including underprivileged refugee spaces, are more exposed to flash floods. The residential areas, commercial centres, and schools increase district vulnerability, and heritage sites, particularly in Al Madinah district, are highly susceptible to flood risks. Specific demographics, such as women, people with disabilities, youth, the elderly, and city workers, are particularly vulnerable during these events. Factors like concentrated refugee camps, tunnel infrastructure, and impermeable surfaces such as asphalt significantly contribute to the heightened vulnerability to flash floods. Conversely, green spaces and vacant lands play a crucial role in enhancing districts' adaptive capacities (Assessing Climate Vulnerabilities in Amman City 2024). Assessments reveal Basman and Al Yarmouk as severely vulnerable to floods (see Figure 3). Marj Al Hamam, Al Madeenah, Abu Nseir, Shafa Badran, Sweileh, Badir Al Jadeedah, Markah, and Uhud are the least impacted by flash floods. flood risks.

1.3 Problem statement

Even though arid and semi-arid regions often face water shortages and infrequent low rainfall, recent floods in these areas have demonstrated that flooding can be exceptionally severe and life-threatening. However, flooding still needs to be more adequately understood as a natural hazard in these environments, and its management must confront challenges, some of which are specific to arid and semi-arid zones (Nabinejad and Schüttrumpf 2023).

Urban hydrology is increasingly stressed by urbanization and climate change. Urbanization is proven to affect the hydrological responses of natural catchments. It reduces infiltration, base flow and lag times, and at the same time, stormwater flow volumes, peak discharge, frequency of floods and surface runoff are dramatically increased (Du et al., 2012). In the future, Amman, Irbid, and Zarqa, Jordan's major cities crucial to the economy, will face heightened vulnerability to hazards due to climate change. These cities are expected to become drier while also encountering more intense precipitation events, leading to heightened flood risks. The built-up areas exposed to pluvial flood hazards have expanded and are projected to keep growing across all climate scenarios, particularly impacting low-income households (The World Bank Group, 2022).

"The existing conventional stormwater systems lack the flexibility to accommodate rapid changes in urbanization and climate that have exacerbated droughts and floods in Jordan."

Looking over time and due to climate change impacts and drought events, the extreme events of floods and droughts have been exacerbated recently. Based on the third national report to UNFCCC, Jordan is expected to have a warmer and drier climate with a potential increase in air temperatures from +2.1 degrees Celsius to +4 degrees Celsius and a decrease in the annual rainfall from 15% up to 35 % in 2100 (MoEnv, 2014).

Despite the governmental efforts to manage the country's limited water resources and the ongoing search for alternative sources of supply, the adopted political, financial and technical responses are not able to bridge the supply and demand gap. Several of the inspected adaptation measures include desalination, wastewater and greywater recycling, stormwater collection and efficient water use. However, the existing conventional stormwater systems lack the flexibility to accommodate expanding urbanization and climate change impacts effectively and efficiently (Gammoh & Shamseldin, 2019).

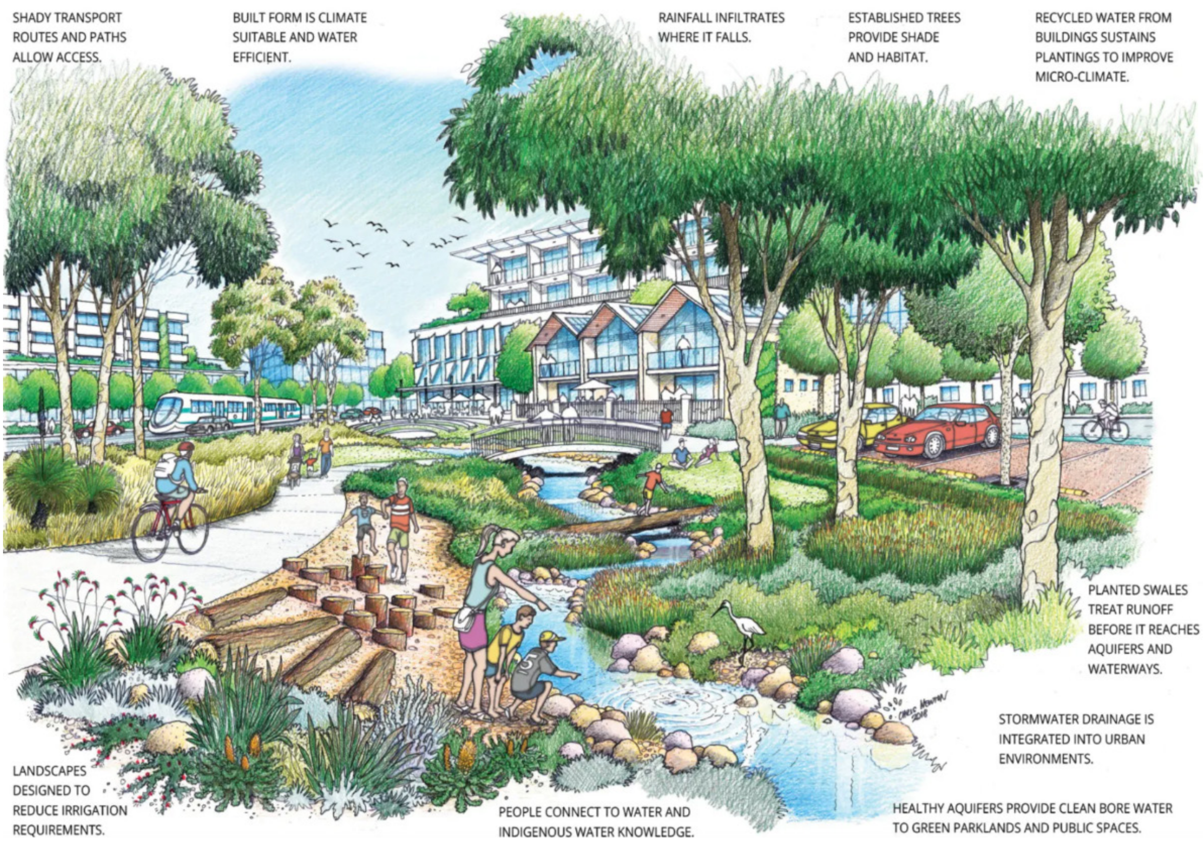


Figure 4: An urban space integrated with WSUD measures
Source: Urban Design Lab , 2024

1.4 Water Sensitive Urban Design

While these issues seem unrelated to each other, a common solution can be found in the circularity of stormwater. Going back to the natural water cycle and managing stormwater as close to the source as possible would not only help with flood relief, but also keep the rainwater from being polluted as it runs over various impermeable surfaces, either by seeping directly into the groundwater or by being collected in storage tanks for reuse (Urban Design Lab 2023). The aim is to keep these solutions as natural as possible, meaning, no major constructions and find a resource-efficient way to achieve these goals. Water Sensitive Urban Design (WSUD) is a holistic approach to urban planning and design that integrates the management of the whole urban water cycle into the process of land use and urban development (Elzein et al., 2022; Sharifian et al., 2022). In WSUD, urban water is managed so that it minimizes the negative urbanization impacts while maximizing the economic, social, and environmental benefits, thus providing more healthy and livable cities (DEWNR, 2013).

Water Sensitive Urban Design (WSUD) integrates water management, urban design, and landscape planning by encompassing the entire urban water cycle and integrating water management functions with urban design principles (Hoyer, J., et.al, 2011). It provides the link between integrative approaches of stormwater management and urban design and comprehensively addresses all facets of the urban water cycle, with a particular emphasis on stormwater management, recognizing its dual role as a valuable resource and as a means to protect receiving waterways (Melbourne Water, 2005). Decentralized stormwater management systems are enhanced when integrated with urban design requirements. Consequently, WSUD is primarily applied in urban stormwater management, aiming to emulate a natural water cycle and enhance urban amenity. As outlined in the "Urban Stormwater: Best Practice Environmental Management Guidelines" by the Victorian Stormwater Committee (1999), the objectives of WSUD in stormwater management and planning are as follows:

- Protection of natural water systems within urban developments.
- Improvement of water quality through filtration and retention methods.
  Reduction of stormwater runoff and peak flows via local detention and retention strategies and minimizing impervious surfaces.
- Decrease in drainage infrastructure and associated development costs, while enhancing sustainability and urban amenity.
- Integration of stormwater management into the landscape by creating multi-use corridors that enhance the visual and recreational appeal of urban areas (Hoyer et al. 2011).

Figure 4 illustrates how an integrative approach and resource management would look in an urban space by reversing biodiversity loss caused by urbanization (Urban Design Lab, 2024).

1.5 CapTain Rain

Several studies have been done on water sensitive urban design, the sponge city concept and low impact development for huge metropolitans around the world. These have led to the development of several pilot projects and international cooperation to make cities resilient to extreme rainfall events. CapTain Rain is a similar project being developed by the German and Jordanian cooperation that aims to capture and retain rainfall for potential reuse in Jordan. Despite their destructive power, heavy rainfall events play a key role in the hydrological cycle of (semi-)arid regions, as they replenish scarce water resources. In the face of increasing drought risk and water scarcity, it is therefore important to capture and retain rainfall (ISOE GmbH 2024). In this context, CapTain Rain is investigating measures for the diversion, retention and utilization of heavy rainfall and for improving heavy rainfall preparedness of the local population. The study is conducted along an urban-rural gradient and includes Amman and Petra. In addition to traditional methods of stormwater retention, storage and utilization, the concept of multifunctional land use for heavy rainfall prevention is explored in urban areas (CapTain Rain 2024).

Within the trans-disciplinary research project CapTain Rain, the German and Jordanian project partners aim to help improve current methods and tools for flash flood prediction and prevention. For this purpose, the driving factors of flash floods in Jordan's wadi systems will be analysed and the complex interactions between climate and land use changes and hydraulic engineering measures will be unraveled. Based on vulnerability analyses and engineering solutions for water collection and drainage during heavy rainfall events, measures to protect the population will be identified. Climate services (e.g., flash flood risk maps, early warning systems, recommendations for heavy rainfall risk prevention) will be developed in close collaboration with Jordanian stakeholders and practice partners, considering scientific as well as local practical knowledge as shown in Figure 5. The study areas include the capital Amman in the metropolitan region and the more rural region Wadi Musa around the UNESCO World Heritage Site Petra. Both regions have been heavily affected by flash flood events in the past (CapTain Rain progress report, 2023).

The trans-disciplinary research methodologies employed by CapTain Rain facilitate a comprehensive analysis of flash flood hazards and prevention strategies, effectively bridging the gap between scientific knowledge and practical climate change adaptation measures. Specifically, CapTain Rain will:

1. Examine the social-ecological drivers of flash floods in Jordan's wadi systems and unravel the complex interactions between climate and land use changes, improving the simulation and prediction of flash flood events.
2. Evaluate the social-ecological risk of flash floods through an integrated vulnerability analysis, considering spatial exposure, sensitivity, and adaptive capacity.
3. Develop climate services to support flood-related decision-making, utilizing stakeholder dialogs and participatory approaches.
4. Identify effective measures to enhance the adaptive capacity of local communities, including technologies and methods for capturing and retaining water from heavy rainfall and preventing damage (CapTain Rain 2024).

This thesis is based on the data retrieved through Hamburg Wasser for the project CapTain Rain, which is one of the partner companies and chief stakeholder in the project. The data is primarily site observations by the Hamburg Wasser teams on site, landuse data from GAM and hydrological analysis done by other stakeholders as part of this research.

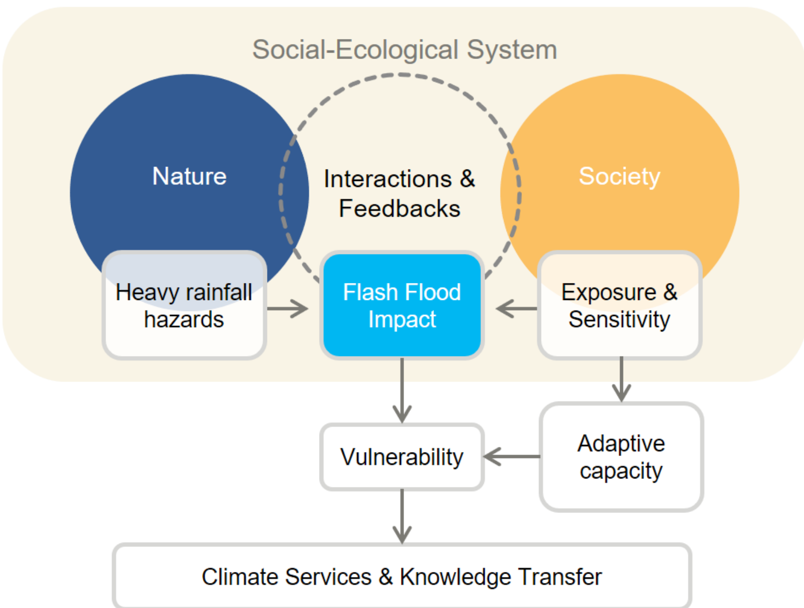


Figure 5: Conceptual framework of the integrated vulnerability analysis of flash floods for CapTain Rain. Source: (CapTain Rain 2024)

1.6 Research question and objectives

In arid and semi-arid regions, adopting Water Sensitive Urban Design (WSUD) is a cost-effective approach to managing scarce water resources. It facilitates efficient water use, creating green open spaces with treated wastewater and native plants, addressing extreme heat, providing urban cooling, and offering ecological, social, and amenity benefits. WSUD practices also enhance stormwater infiltration and groundwater recharge for drought adaptation. Challenges include health risks, public acceptance, limited experience, and the need for substantial spaces in densely populated areas, along with institutional barriers (Costa et al., 2015).

Therefore, this research aims to explore water-sensitive urban design strategies that best suit a dense urban area in Amman, Jordan to tackle stormwater challenges, both in terms of flash floods and water shortages.

While these studies cover the aspects of stormwater management in various climates, contextualisation of these measures to semi-arid and arid regions is a fairly new and emerging concept. On one hand, decentralized methods of stormwater management are being explored at the household level and on the other, mega projects of desalination and wastewater recycling are being given high investments. Therefore, this research aims to explore middle-ground, medium-scale, and low-impact development strategies and to investigate their efficiency. The scope, however, is limited to the implementation of WSUD measures in a dense urban area in Amman. This would be done by creating 3 distinct scenarios, each with defined boundary conditions, and different strategies for stormwater management, and ultimately comparing the results.

"What combination of Water Sensitive Urban Design strategies can be implemented in a dense urban area in Amman, Jordan, to overcome stormwater challenges, both in terms of protection during flash floods and providing an additional source of water during dry periods?"

Therefore, the objectives of this research are:

- To identify the hotspots in a catchment area, or places of high risk and high potential.
- To define the planning goals to be achieved by certain selected WSUD measures.
- To develop strategies for different scenarios and compare their results.
- Finally, to create a list of recommendations for future development in this area.

1.7 Scope and limitations

The scope of this research is limited to the analysis of one catchment in the district of Marj Al Hamam with an area of 1317 hectares. Since access to the site was not possible, most of the data gathered is from satellite imagery and data obtained from the Greater Amman Municipality or GAM through the project CapTain Rain and Hamburg Wasser as well as published reports of previously conducted surveys. This raw GIS data has not been published yet and hence is referenced only as HW 2024, from where it is sourced. However, it has been added to and further improved by Google Maps and ArcGIS satellite imagery. Due to this many assumptions about the types of surfaces have been made, as explained in the further chapters. It should also be noted that the areas taken from GIS for the various scenarios have a slight error margin, therefore the calculated values of areas and volumes are an estimation and should not be considered exact.

To further limit the scope of this project, a detailed analysis will be done of selected hotspots and not of the entire catchment area. These hotspots will be selected based on their typology and keeping in mind that they are representative of the different neighbourhoods of the catchment for future scalability.

The measures and strategies taken into account are designed at a conceptual level according to a study of the area available for implementation. Further analysis of the feasibility of these measures needs to be done with the involvement of the various stakeholders. Additionally, further research needs to be done on the application of these measures in arid climates and the respective native plantations. A guide to native plants has been published (Guide to Species Selection for Amman Public Open Spaces 2021) and referred to in the following chapters.

The volume estimations are done based on German standards from the DWA as the information on Jordanian stormwater management and urban drainage regulations was not available. The idea is to conduct an estimation of the effects of WSUD measures in this particular context, to create further scalable recommendations. The volume estimations also need to be further calculated on software like STORM or SWMM for a more precise design simulation.

Chapter 2

Research Methods and Approaches

The reason for choosing the context of Amman was driven by a curiosity of exploring the flooding patterns in desert climates, something that is not a popular perception or understanding. Even though the annual precipitation in arid regions is low, stormwater management becomes especially vital for the purpose of rejuvenating the ground water Table and maintaining natural water flow cycles even in densely urbanized areas. The research done in this field is limited to South Australia and the USA which may have similar climate contexts but vary widely in urban and demographic contexts. Inspiration and experience were gained during the involvement with Hamburg Wasser, one of the stakeholders of the research project CapTain Rain and subsequent contribution to it.

This chapter elaborates on the various research methodologies used for this thesis. It explains the methods in detail in the following section, outlines the sourcing and quality of data and the approaches of analysing it. It also provides a basic outline of each of the chapters in this thesis and illustrates how they are connected and what is the research flow. Though this was an iterative process, with a lot of back and forth between sections, a linear research flow was managed and followed to create a storyline. The interconnection between chapters and the flow of the master thesis research is illustrated in Figure 6.

2.1 Chapter structure and research flow

Chapter 1 - Amman's Urban Waters, provides an introductory insight into the relevance of WSUD in Amman. It discusses how urbanization and climate change have exacerbated the conditions of flash floods and water scarcity in Amman, thus defining the problem. It further elaborates on the need for WSUD and explains the basic principle of blue-green infrastructure and its positive impacts on the urban water cycle of any place. Further, this chapter also discusses the contribution of the research project CapTain Rain. Finally, it is summarised by a statement of the research question and objectives and the scope and limitations of the project.

Chapter 2 – Research methods and approaches explain the methodology and research flow as well as the details concerning obtained data. It briefly outlines the contents of each chapter and how they are interconnected. Further, the creation of the scenarios is explained here, and the rationale behind them. Finally, this chapter contains the most crucial elements of the comparative analysis – how it is conducted qualitatively and quantitatively, citing the formulas used and the rationale behind them.

The third chapter on Amman's Waterscapes outlines the status quo of Jordan and Amman in terms of background, climate, policies and stakeholders. Here the issues and opportunities of Amman's urban waters are detailed. This forms the basis of finding research gaps and contextualises the site. It is concluded by lessons learnt from case studies that would help in building the recommendations for further development in the area.

Chapter 4 - Designing the WSUD Toolbox summarises the planning goals that set guidelines for selecting and implementing measures. Further, the various selected measures are detailed in a format to better understand the processes and technologies involved. The format is also intended to be used in stakeholder meetings and workshops, essentially simplified to a level of easy understanding. This toolkit will be used for the conceptual design of the scenarios in the next chapter.

Chapter 5 – Scenarios in focus, is where the bulk of the analysis is conducted, beginning from the urban analysis of the site to select the relevant hotspots. These hotspots are then further detailed, and different types of surfaces and their areas are obtained. The next step is to create 3 distinct scenarios with a conceptual design of the measures from the toolkit. Further, these scenarios are compared based on the calculations of peak runoff volumes and peak runoff rates, as well as the planning goals achieved by them.

Lastly, Chapter 6 – Future Horizons outlines the recommendations that are an outcome of the comparative analysis conducted in the previous chapter. The section of the discussion addresses certain challenges and the conclusions drawn from the research and offers the possibilities for further research.

2.2 Literature review

One key methodology used to refine this research is a literature review. To get a deeper understanding of the context, this section delves into summarizing reports and publications that describe the background of Jordan as a country and the challenges it faces in the context of water. It further describes the capital city of Amman, its climate, topography and urban hydrology. It also looks into policies and frameworks for further urban development and the stakeholders responsible for the same. Some stormwater management projects that have been researched are mentioned here as well. Finally, some case studies of implemented stormwater pilot projects by the UN Habitat are observed and lessons learned from applied WSUD in Rotterdam are summarised.

2.3 Urban Analysis

The second methodology used is conducting an urban analysis of a selected catchment area. The mapping of different typologies of surfaces and materials is done based on satellite imagery from Google Maps, Open Street Map and ArcGIS satellite imagery. The data collected is synthesized in QGIS, separating the various layers of the urban area like built and unbuilt, ownership of land, land use based on function, open space and flow of stormwater. The hydrological maps are based on the heavy rainfall event of 2019 and are taken directly from HW, 2024. Separating these layers and then overlapping them with the hydrological data leads to the identification of hotspots or areas that are at high risk and have a good potential for implementing WSUD measures. Further, some hotspots will be selected for an in-depth analysis that best represents the catchment area and represent certain distinct urban typologies.

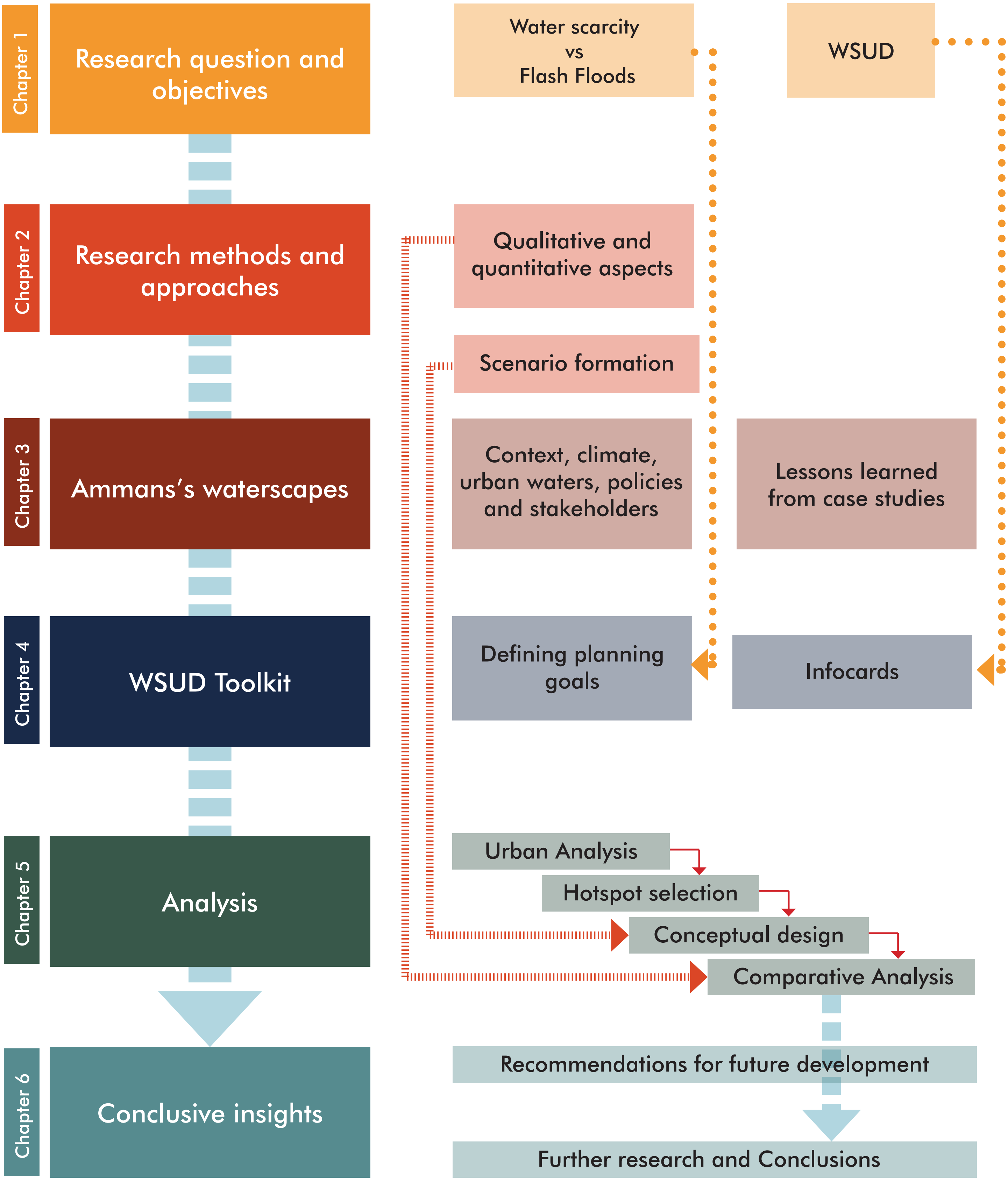


Figure 6: Chapter structure and Research Flow
Source: Author

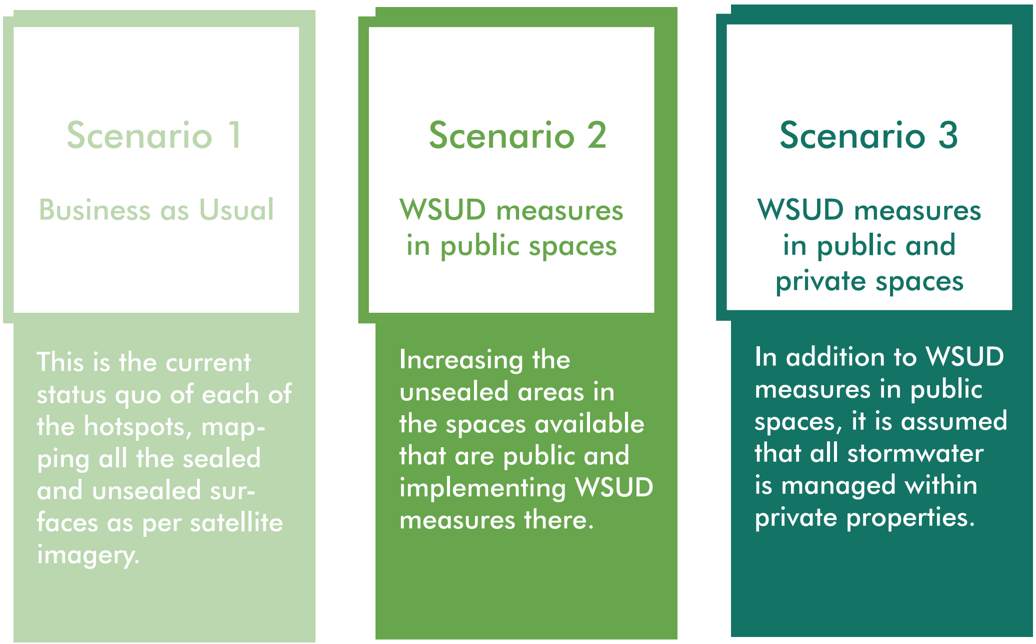


Figure 7: The three scenarios defined.
Source: Author

2.4 Scenario Creation

Iorder to further analyse these hotspots, 3 distinct scenarios are created. This is done to compare the effects of urban development on stormwater runoff, and the impact of implementing blue-green measures to reduce the peak runoff volumes. The scenarios are explained as follows and a summary is illustrated in Figure 7:

Scenario 1: Business as usual
In this scenario, the different surfaces are taken as they exist currently and provide a baseline for implementing measures. It highlights what would it look like if no changes were made and development continued on the current path. This is the current status quo of each of the hotspots, mapping all the sealed and unsealed surfaces as per satellite imagery.

Scenario 2: WSUD in public spaces
Next, focusing only on the public areas available in these hotspots, certain appropriate measures from the toolkit are implemented. This indicates the unsealing of surfaces like streets and pavements and the potential of developing multifunctional spaces, that may be used as water storage in times of a flood but may have other uses during dry periods. Where public space is not available, these measures would only be implemented on streets and the effects would be measured.

Scenario 3: Limiting outflow of stormwater from private properties

In this scenario, in addition to WSUD measures in public spaces as in scenario 2, it is assumed that all stormwater is managed within private properties. This can be done with rooftop RWH, installing water collection tanks or green roofs and retention areas within the private green spaces. For calculations, the surface areas of rooftops are eliminated, assuming the runoff from these surfaces is collected and managed within the private lands and does not add to the cumulative runoff volumes from the rest of the hotspot.

The aim is to use this analysis as a base for recommendations for other similar areas within the catchment that exist or will be developed in the future. This may also be scaled for other areas in Amman. The recommended measures in these scenarios are just a preliminary conceptual design and would need to be developed further and as per the context. Some examples of how these recommendations may be applied are detailed as possibilities, however, are not considered as a detailed design, but only a suggestion.

Return Period	Rainfall Intensity (mm/hour) for Different Durations (minutes)									
	5	10	15	30	60	120	180	360	720	1440
2	44.3	32.3	28.2	21.9	16.5	12.4	10.1	7.25	4.86	2.70
5	60.8	44.3	38.8	30.0	22.7	17.0	13.9	9.96	6.67	3.70
10	71.1	51.7	45.3	35.1	26.5	19.8	16.2	11.6	7.80	4.33
25	83.3	60.6	53.1	41.2	31.1	23.3	19.0	13.6	9.14	5.07
50	91.8	66.9	58.5	45.4	34.2	25.6	20.9	15.0	10.1	5.59
100	100.0	72.8	63.7	49.4	37.3	27.9	22.8	16.4	11.0	6.09

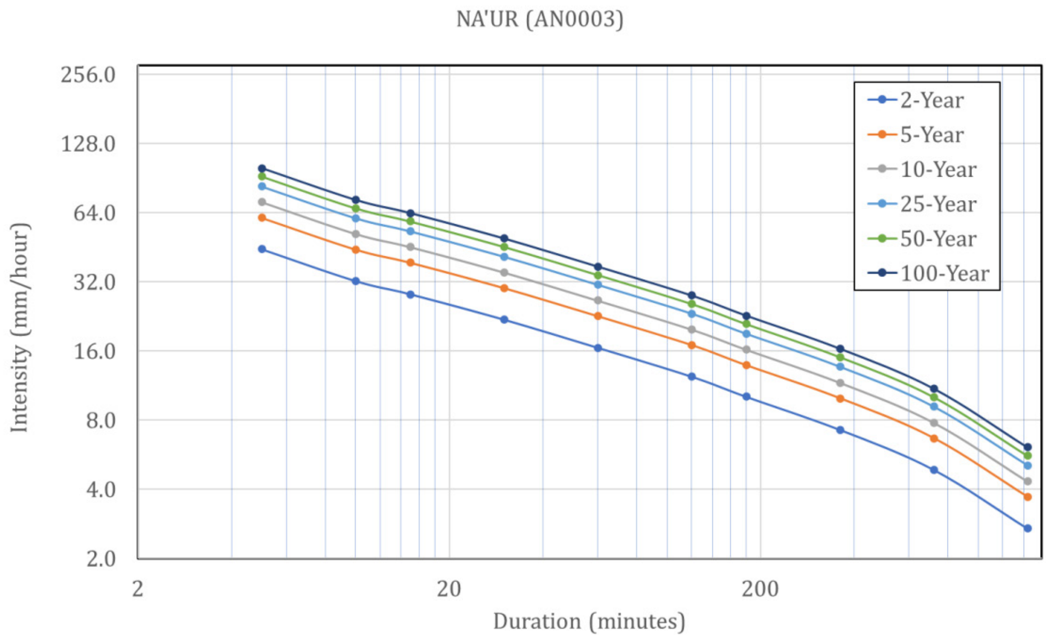


Table 1: Intensity-Duration-Frequency (IDF) values for Na'ur Station. Source: (UN Habitat 2020)

Figure 8: Intensity-Duration-Frequency (IDF) curves for Na'ur Station. Source: (UN Habitat 2020)

2.5 Qualitative and quantitative analysis

For qualitative analysis, a comparison of the different planning goals achieved will be analysed. For example, the hotspots will be ranked based on the fulfilment of different criteria like improvement of urban microclimate or improvement in aesthetics and biodiversity as to have no impact, low, medium or high impact. This assessment is made subjectively, based on understanding of the collective performance of recommended measures. While certain measures may contribute to these factors, others may only help in reducing the flood risk in the area or help in the storage of water like underground tanks. Therefore, these multiple factors are taken into consideration for a holistic comparative analysis of the different hotspots in the three distinct scenarios.

Furthermore, in order to make sure that the surface runoff does not have a detrimental impact on the urban environment, it is important to control

- How fast the runoff is discharged from the site and
- How much runoff needs to be discharged from the site(CIRIA 2015) .

The peak runoff rates and runoff volumes will be calculated for each scenario, comparing the gradual increase in unsealed areas and decentralised stormwater management techniques. This will constitute the quantitative analysis of the three scenarios of different hotspots. The calculations taken into consideration in this research are based on the German standards DWA-A117E, DWA-A 138E and DWA-A 153E as well as the modified rational method suggested in (CIRIA 2015) for the calculation of peak runoff rates. The calculation of peak runoff volumes for each hotspot is done iteratively for the rainfall intensity for different durations respectively with a return period of 5 years. However, the measures are designed to mitigate the peak volumes obtained after 24 hours as recommended by the German standard for large and slightly slopes connection areas (DWA 2006). The first step in developing the different scenarios for the hotspots would be defining the rainfall scenario the proposed measures should respond to. Usually, it would be sufficient to consider the precipitation data of the entire city, however, slight variations are always observed in different stations. For this, the Intensity-Duration-Frequency data of rainfall collected from the Na'ur Station is studied as it is located closest to the selected site area. The IDF data and graphs are shown in Table 1 and Figure 8 respectively.

Type of surface	$\Psi_{m,i}$	Assumption basis	Reference
Existing surfaces			
Building rooftops	0.9	Flat roof, Cement	DWA
Streets	0.9	Asphalt	DWA
Paved	0.75	Pavement with sealed joints	DWA
Existing Greens	0.2	Arable land without connection to drainage system and average slope	Assumed, based on DWA
Undeveloped open space	0.4	Recommended between 0.1 - 0.3, however a higher value is assumed due to soil type, low vegetation and observed low infiltration capacity	Assumed, based on DWA
Private Gardens	0.3	Higher value assumed than recommended due to consideration of partially paved gardens	Assumed, based on DWA
Public Gardens	0.1	As per recommendation	DWA
Sports Grounds	0.8	Sealed surface usually cement	Assumed, based on DWA
Blue Green measures			
Bioswales	0.2	Assumed	Assumed, based on DWA
Green roofs	0.4	Extensive green roofs, average taken between 0.3 - 0.4	DWA
Permeable Pavements	0.3	Assumed	Assumed, based on DWA
Raingardens	0.1	Assumed	Assumed, based on DWA
New green areas	0.2	Assumed equal to existing green areas	Assumed, based on DWA

Table 2: Assumed values of mean runoff coefficient for different surface types
Source: Author based on DWA and (State Water Resources Control Board 2011)

The next step is identifying different types of surfaces in the area, both sealed and unsealed ($A_{c,i}$). A sum of these areas is calculated separately. These areas are then multiplied by the runoff coefficient. The runoff coefficient ($\Psi_{m,i}$) is a dimensionless value that correlates the volume of runoff with the amount of precipitation. It is higher in areas with low infiltration and high runoff, such as paved or steep terrains, and lower in permeable, vegetated areas like forests or flat lands (State Water Resources Control Board 2011). Its value varies between 0 to 1 with 0 being the most permeable and 1 being the least. Based on recommendations of the DWA, the State Water Resources Control Board of California (mentioned in Appendix A, Table A1) and other references mentioned, the following values of the runoff coefficient are assumed for further calculations.

While the values of existing sealed surfaces are easier to assume based on the many guidelines, the values for blue-green measures were assumed based on many other factors. Extensive green roofs typically show runoff coefficients ranging from 33 % to 48 %, influenced by factors such as rain intensity, duration, and plot slope, with a general assumption of a coefficient of 0.4 (Palla et al. 2010). Similarly, green infrastructure elements like bioswales, swales, and rain gardens are designed to significantly reduce runoff through enhanced infiltration and water storage, displaying generally low runoff coefficients. Bioswales, designed to manage stormwater runoff, filter pollutants, and enhance infiltration, are often vegetated and mulched, with runoff coefficients very low, usually between 0.05 and 0.30, dependent on design, soil, and maintenance. Rain gardens are shallow, planted depressions that absorb runoff from impervious areas such as roofs and driveways, with similarly low coefficients, ranging from 0.05 to 0.25, influenced by soil type, size, and plant selection. For volume calculations in this research, the runoff coefficients are assumed to be 0.2 for bioswales and 0.1 for raingardens. For the determination of the required storage volume the inflow and percolation volumes are to be linked via a condition for continuity:

$$A_{imp} = A_{c,i} \cdot \Psi_{m,i} \qquad \text{(Equation 1)}$$

Where
$A_{c,i}$ = Area of surface in the catchment in m^2
$\Psi_{m,i}$ = Mean runoff coefficient
A_{imp} = Impermeable area calculated in m^2

Similarly,

$$A_{p} = A_{c,i} \cdot \Psi_{m,i} \qquad \text{(Equation 2)}$$

Where
$A_{c,i}$ = Area of horizontal percolation surface in the catchment in m^2
$\Psi_{m,i}$ = Mean runoff coefficient

A_p = Permeable area calculated in m^2

Now that we have the reduced permeable and impermeable areas, the next step is to calculate the inflows and outflows of runoff taking into account the rainfall intensity.

$$Q_{in} = A_{imp} \cdot r_{D(n)} \cdot 10^{-7} \quad \text{(Equation 3)}$$

Where
Q_{in} = inflow to the precipitation facility in m^3/s
A_{imp} = Impermeable area calculated in m^2
$r_{D(n)}$ = rainfall intensity for a duration D and a return period n in l/s ha
10^{-7} is taken for the conversion of r from l/s ha to m^3/s.

And

$$Q_{out} = A_p \cdot k_f/2 \quad \text{(Equation 4)}$$

Where
Q_{out} = outflow or percolation rate in m^3/s
A_p = pemeable area in m^2
k_f = coefficient of hydraulic conductivity of the saturated zone in m/s for different types of soils

Therefore,

$$V = (Q_{in} - Q_{out}) \cdot D \cdot 60 \cdot fs \quad \text{(Equation 5)}$$

Where
Q_{in} = (constant) inflow during the rainfall duration D in m^3/s as calculated in Equation 3
Q_{out} = (constant) outflow or percolation rate during the rainfall duration D in m^3/s as calculated in Equation 4
V = (required) storage volume in m^3
D = Rainfall duration in min
fs = Surcharge factor in accordance with DWA-A 117E

The values of all these variables are from the data collected and analyzed. The impermeable and permeable areas are calculated from GIS analysis. The runoff coefficients are taken from Table 2. Rainfall intensity is taken from the UN Habitat report as shown in Table 1 and is further calculated for the conceptual design for a 5-year return period. However, after the measures are designed conceptually, for the sake of comparison, the peak runoff volumes are also calculated for extreme rainfall scenarios. The hydraulic coefficient of the percolation area is 10-5 for silty loam soil (Al-Jaloudy 2015) as per the values given in Appendix A, Table A2 and A3 (StructX 2024; DWA 2006). Hence the assumed values are summarised in Table 3.

Next, to calculate the peak runoff rates, the modified rational method is used (CIRIA 2015).

$$Q = A \cdot i \cdot \Psi_{m,i} \quad \text{(Equation 6)}$$

Where
Q = runoff rate for the corresponding rainfall intensity in l/s
A = Area of the catchment in m^2
i = Rainfall intensity in mm/hr
$\Psi_{m,i}$ = runoff coefficient

However in this project, the area of the catchment taken for this equation is a sum of all reduced permeable and impermeable surfaces, that is, the areas multiplied by their respective runoff coefficients as in Table 2. Therefore,

$$A = \Sigma(A_{imp} + A_p) \quad \text{(Equation 7)}$$

Which makes the equation

$$Q = A \cdot i \quad \text{(Equation 8)}$$

Table 3: Assumed values and their description for the calculation of volume for storage.
Source: Author based on DWA

Symbols	Description	Units	Assumed Values
V	Volume	m^3	to be calculated
$A_{c,i}$	Area of surface	m^2	Calculated from GIS
A_{imp}	Impermeable Areas	m^2	$A_{c,i}$ for impermeable areas multiplied by Runoff coefficient
A_p	Permeable Areas	m^2	$A_{c,i}$ for permeable areas multiplied by Runoff coefficient
$r_{D(n)}$	Rainfall intensity for duration D and return period n	l/s ha	Varies for different durations, return period 5 years
K_f	Hydraulic coefficient of soil		10^{-5} for silty loamy soil
D	Duration of rainfall	min	Varies (15min for design)
fs	Safety Factor		1.2 for 20 %
$\Psi_{m,i}$	Runoff coefficient		Assumed based on DWA

These values are calculated for different durations of rainfall intensity for 24 hours, out of which the peak rate is identified. Hence, a comparison of the three scenarios is done quantitatively for both these variables. Further, to verify if the recommended measures can store the volume calculated for a design rainfall for the peak runoff volume, the areas decided are given depths accordingly and storage volumes are calculated. Depending on the result, further recommendations will be formulated. This concludes the quantitative analysis and gives an estimation for the concept design of the measures. For more precise results, the measures and design rainfall should be modelled in software like STORM or SWMM.

2.6 Formulation of Recommendations

Finally, the recommendations for the further development of the catchment are the culmination of the analysis. It would be a list of measures to be taken for areas that are similar to the hotspots selected and may be applied elsewhere as well. Further discussion and remarks would be the basis for further research as it would also highlight some of the limitations that this research presents.

Chapter 3

Amman’s Waterscape: Policies, Challenges, and Global Lessons

3.1 National context

The Hashemite Kingdom of Jordan, referred to as Jordan, is situated in the rocky desert region of the northern Arabian Peninsula. It shares borders with Syria to the north, Iraq to the northeast, and Saudi Arabia to the east and south, spanning a total area of 89,318 square kilometres as in Figure 9. As of 2019, Jordan has a population of 10.5 million people, with a significant concentration residing in and around the capital city, Amman (UN Habitat 2022). Jordan is renowned for its stability in a turbulent region. Throughout its history and particularly since the onset of the Syrian crisis, it has welcomed large numbers of refugees. Jordan has the second-highest number of refugees per capita globally, with 89 refugees per 1,000 inhabitants (UN Habitat 2022).

Jordan’s population nearly doubled between 2004 and 2015, influenced by the political situations in Iraq and Syria. As one of the youngest countries globally, around 63 % of its population is under 30. This demographic trend necessitates long-term resource planning to meet the future needs of the growing population (UN Habitat 2022).

Figure 9: Map of Jordan with its neighbouring countries and main cities Source: (Vidiani 2011)

3.2 Urbanisation in Jordan

Jordan is among the 50 most urbanized countries globally, with 90.3 % of its population living in urban areas. The country is experiencing rapid urban growth, with an annual population growth rate of 2.3 % (2019) and a population density of 118.9 people per square kilometer. Over the past two decades, Jordan’s built-up area has doubled to 1,500 km^2, with urban areas covering 909 km^2. This expansion, at 1 % per year (15 km^2), threatens agricultural land and infrastructure development (UN Habitat 2022).Nearly three-quarters of Jordan consists of a barren plateau in the east and southeast. The western and northwestern regions are the most fertile, habiTable, and urbanized, where most of the population resides. The southern governorates are sparsely populated, with only 8 % of the population, and have lower infrastructure development, except for Aqaba city, due to the challenging landscape, resource availability, and climate (UN Habitat 2022)..

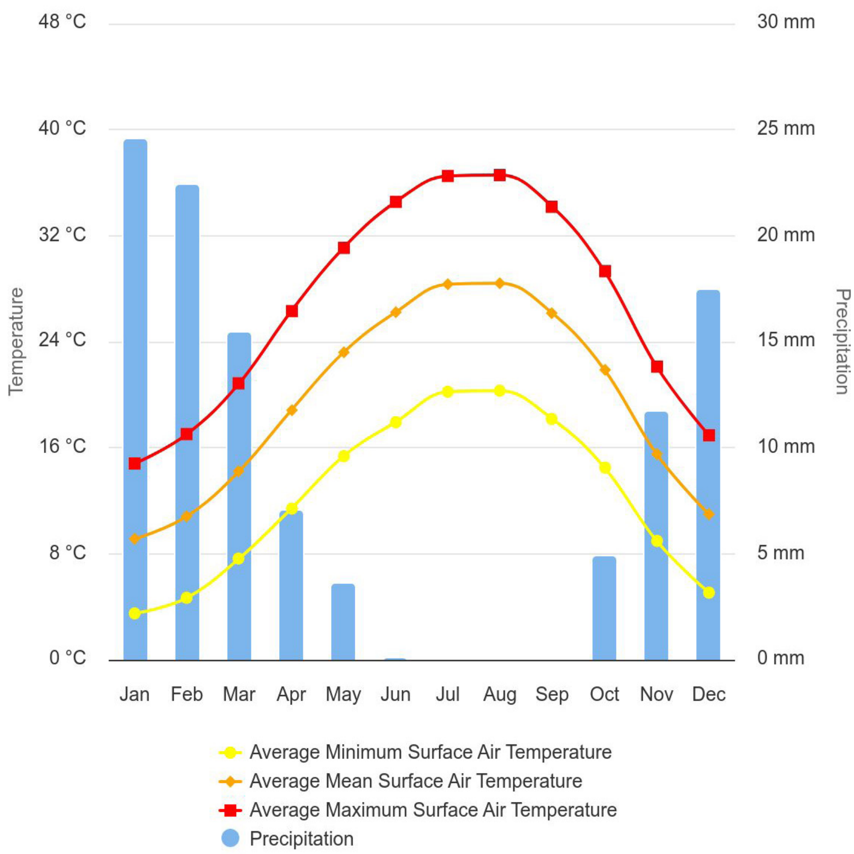


Figure 10: Monhtly climatology of average minimum, mean and maximum surface air temperature and precipitation 1991-2020 in Jordan Source: (World Bank 2021)

3.3 Amman's context

Amman Governorate, home to Jordan's capital city Amman, is the largest in terms of population. Located in the northwestern region of Jordan, it has a central geographical position among the Kingdom's governorates. It borders Zarqa Governorate to the north and northeast, Al Balqaa and Madaba to the west, Karak and Ma'an to the south, and shares an international border with Saudi Arabia to the east. The governorate is about 750 above sea level and covers an area of 7,579 km², accounting for 8.5 % of Jordan's total area (Ministry of Interior Jordan 2024).

As of 2020, Amman Governorate's population constitutes of 42 % of Jordan's total population, which is equal to 4.5 million, and most of this population -around 3.8 million- resides within Greater Amman Municipality (GAM) (UN Habitat, 2022). Amman is the most urbanized governorate, with 97.22 % of its population living in urban areas. It serves as the political, economic, and cultural hub of Jordan, hosting 48 % of the country's economic and commercial institutions, as well as most of the state's institutions, governmental departments, and the Parliament (Ministry of Interior Jordan 2024).

3.4 Climate

Jordan's climate is predominantly arid and semi-arid, with an average surface temperature ranging from 10 °C to 25 °C. Precipitation varies internally due to topography, with the rainy season typically spanning from October to May and peaking in January as seen in Figure 10. Three ecological zones characterize Jordan: the Jordan Valley, experiencing warm winters and hot summers with 100-300mm of rainfall; the Western Highlands, with higher rainfall (300-600mm) and fluctuating temperatures; and the arid Badia region, with annual rainfall below 50mm and wide temperature variations as shown in Figure 12 and 13 (Jordan Red Crescent 2022). The internal Koppen classification of Jordan's climates provides further detail, as illustrated in Figure 11.

Despite its relatively small size, Jordan boasts a diverse terrain and landscape, which is typically associated with larger countries. This diversity is influenced by factors such as geography, history, geopolitics, and the scarcity of natural resources. Although Jordan covers an area of 89,320 km², three-quarters of its territory is desert. However, the landscape exhibits remarkable diversity over short distances. Five main physiographic regions, aligned in a north-south direction, characterize Jordan: the tropical desert in the central Ghor or rift valley, escarpments and mountain highlands east of the Ghor, arid plains, the Badia, and the Azraq and Wadi Sirhan depression. These regions correspond to five major morphological zones (United Nations Development Programme and GEF 2022). Jordan has three distinct ecological zones:

1. Jordan valley which is a narrow strip below the sea level and has warm winters (19-22 °C) and hot summers (38 - 39 °C) with an average rainfall between 100-300mm
2. The western highlands where rainfall is relative-

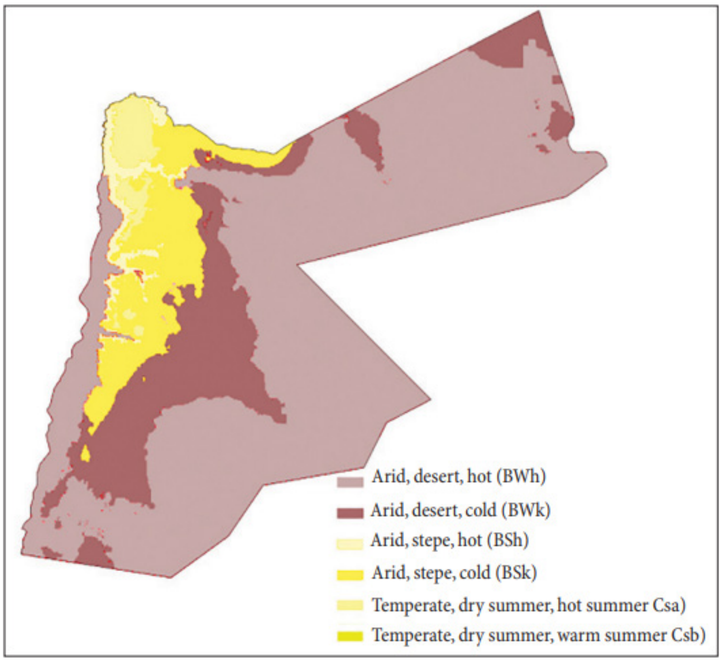
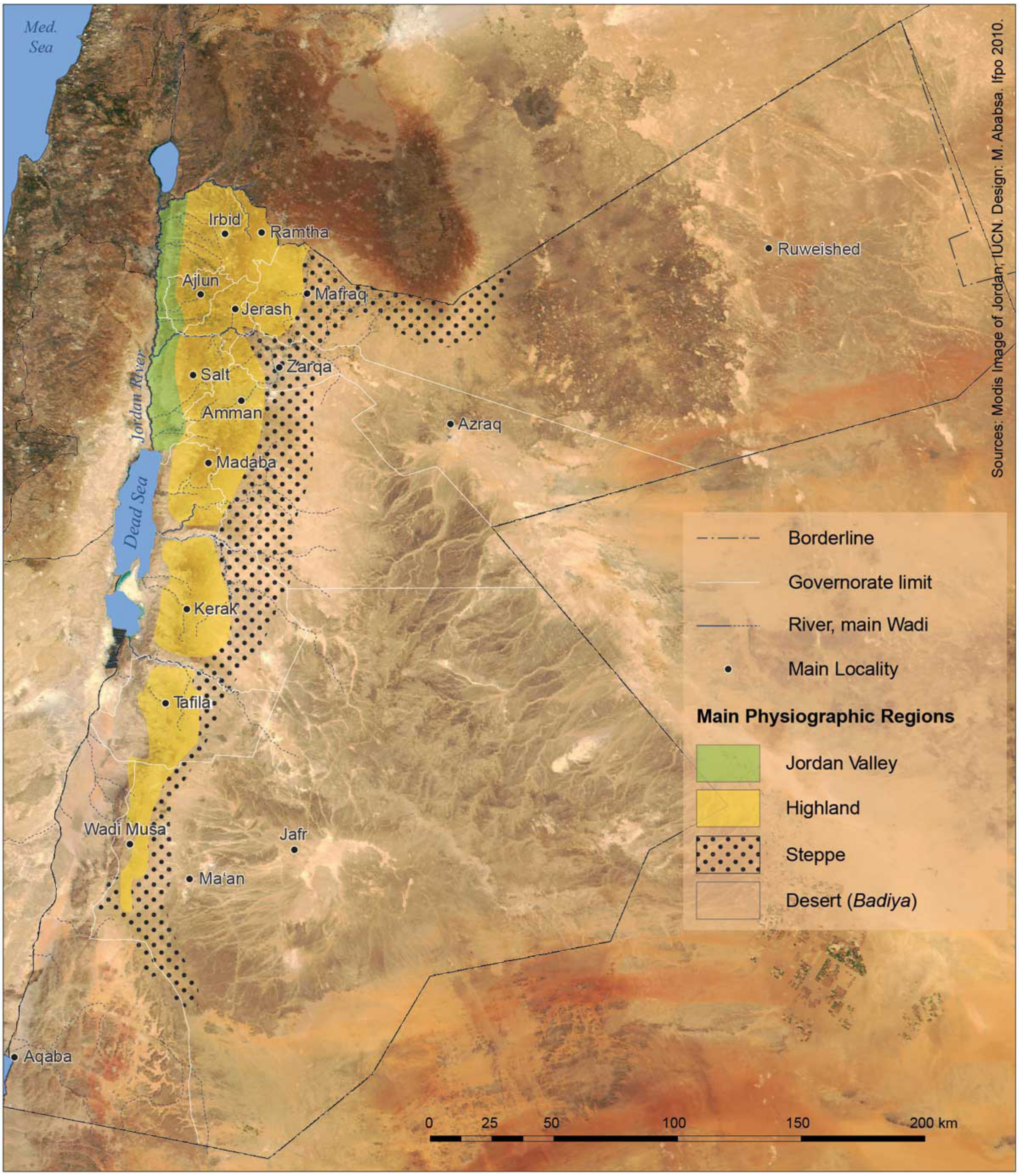


Figure 11: Internal Koppen climate classification in Jordan
Source: (Albadaineh, 2022)

Figure 12: The physio-morphological zones of Jordan
Source: (United Nations Development Programme and GEF 2022)



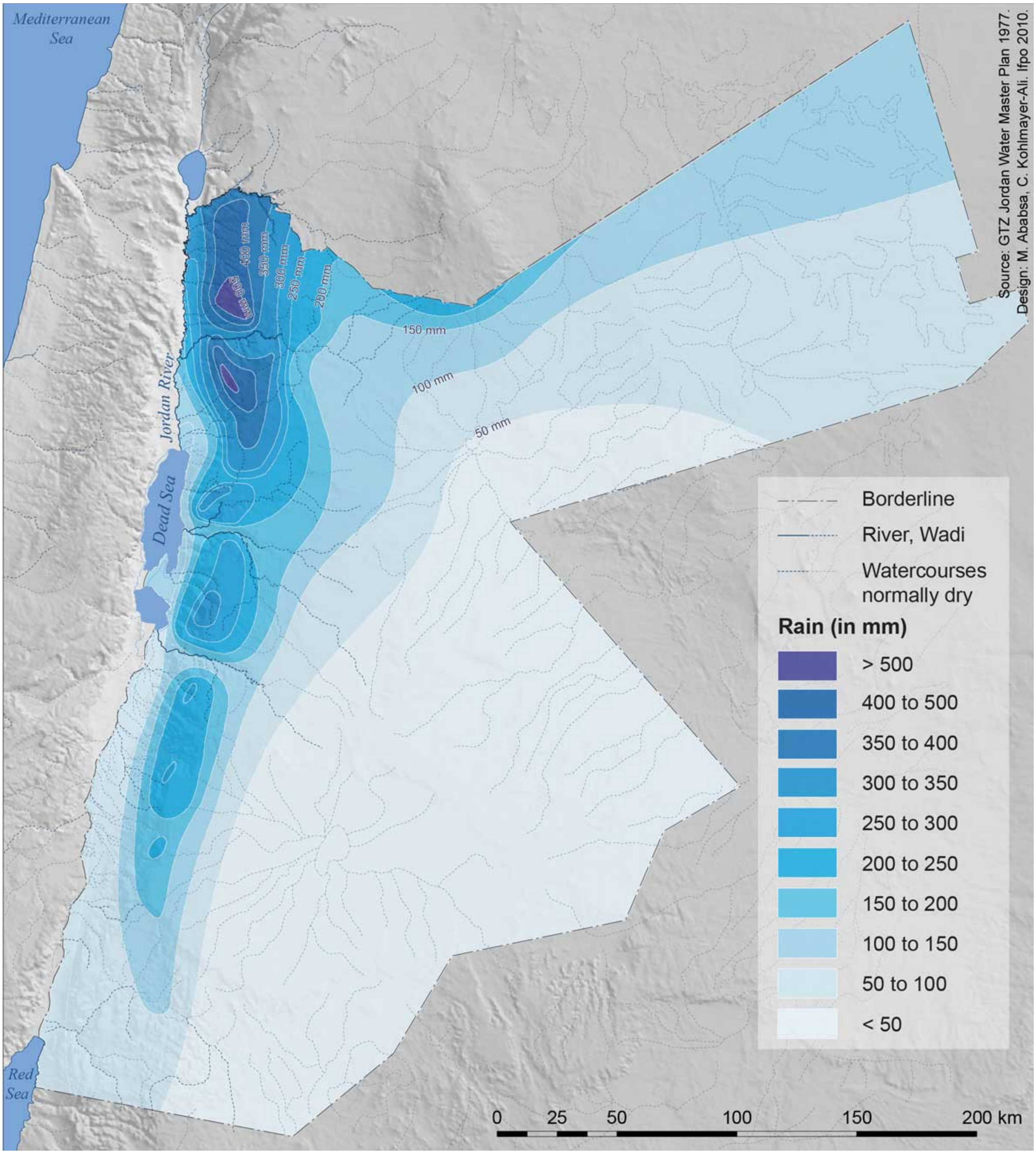


Figure 13: Average rainfall in Jordan
Source: (Ababsa 2013)

ly high (300-600mm) per year and temperatures range between 9 -13 °C in the winter to 26 – 29 °C in the summer

3. The Badia, an arid and semi arid island to the east that covers aout 80 % of the land where the annual rainfall is below 50mm and temperatures range between 14 -16 °C in the winter to 35 -37 °C in the summer (Jordan Red Crescent 2022; GEF 2014).

3.5 Climate change impacts on Jordan

With very limited water sources, Jordan is the second most water-scarce country in the world, with annual renewable water resources of less than 100 m^3 per person (UNICEF 2019). Heavily reliant on external water resources, this scarcity has caused tensions with neighbouring countries. The large influx of refugees has further strained Jordan's ability to meet its domestic water needs (UN Habitat 2022). Though not a major contributor to climate change, Jordan is among the countries most affected by it. The nation is experiencing rising temperatures, erratic rainfall, reduced water availability (both underground and surface), and a higher likelihood of heatwaves, flash floods, droughts, and landslides (LandLinks 2018).Based on future projections and climate forecasts, Jordan is expected to experience significant climate change impacts according to various greenhouse gas concentration pathways. The main insights from the comprehensive climate change projections exercise conducted in the 4NC are summarized in Table 4. These trends outline the anticipated future climate in Jordan through 2100 (United Nations Development Programme and GEF 2022).

3.6 Water

3.6.1 Water supply in Jordan

Due to its arid climate and limited water resources, Jordan is ranked second globally in terms of water scarcity and has the lowest per capita water availability. Political instability in the region has exacerbated the issue, leading to a decrease in trans-boundary surface water resources over time. In the long term, the country is expected to receive approximately 8.2 billion m^3 of rainfall annually, with only 5 % recharging groundwater aquifers and 2-3 % transforming into direct flood flow. The majority of rainfall (92-93 %) is lost to evapo-transpiration. Consequently, developed surface water resources cannot meet water demand, necessitating reliance on groundwater and unconventional sources such as treated wastewater. Main surface water resources include water stored in dams and water from the Yarmouk River and the Tiberia Conveyor (Peace Water). These resources are primarily located in basins with relatively higher rainfall, such as the Yarmouk basin (shared with Syria) and side-branches of the Jordan Valley, where dams have been constructed to supply water for various uses. Some dams receive treated wastewater mixed with rainfall water for irrigation in the Jordan Valley (United Nations Development Programme and GEF 2022).

Water supply for Amman Governorate originates from various sources, with the majority of drinking water traveling distances of 125 to 325 km, leading to increased supply costs (Ministry of Environment Jordan 2020). Unlike other areas relying on groundwater, west Amman City receives water from the King Abdullah Canal, Jordan's largest canal system, serving 40 % of the governorate's water needs post-treatment (Ministry of Environment Jordan 2020; UN Habitat 2022). The completion of the Disi aquifer project in 2013 contributed significantly, providing approximately 107 million m^3 of drinking water annually to Amman Governorate and neighbouring regions (UN Habitat 2022). Despite these efforts, there are challenges in water access through the public network, with non-revenue water accounting for 50 % of total consumption, especially noTable in Amman Governorate (MoWI, 2016). Water utilities in Amman, southern, and northern Jordan have successfully reduced water losses through USAID-backed initiatives, aiming to save 7 million m^3 of water by 2020, equivalent to the needs of 190,000 people yearly (USAID, 2020).

3.6.2 Access to water and its consumption

Miyahuna, a state-owned private company, operates Amman's piped water system under the regulation of the Water Authority of Jordan (WAJ) (Klassert et al. 2015). Despite approximately 98 % of households being connected to this system, a 40 % increase in water demand due to population growth has led to intermittent supply issues (GAM and Rockefeller 2017). As a result, households often store water in rooftop or basement tanks, with capacities varying based on income levels. Additionally, an estimated 37 % of water is lost as non-revenue water (AECOM 2021). Households in Amman pay for piped water and wastewater based on an increasing block tariff, with costs amounting to 1 % to 1.5 % of household incomes. However, due to perceived health risks, many households refrain from using piped water for drinking, opting for alternative sources such as private tanker operators, water stores, or retail bottles (UN Habitat 2022).

Approximately 98 % of households in Amman Governorate are connected to the piped water system, but only 14.2 % of the population uses the public network for drinking water (Klassert et al. 2015). The majority, 85.8 %, either rely on water filters or purchase mineral water due to the perceived low quality of publicly supplied water. Regarding refugees, 99 % of Syrian households in Amman have access to a piped water source (UN Habitat 2022).

Being one of the most water-scarce nations globally, Jordan highly values water as a precious commodity. With only 90 m^3 of water available per person annually in comparison to the global benchmark of absolute water scarcity of 500m^3 (Jordan Red Crescent 2022), projections suggest this allocation may decrease further to 60 m^3 by 2040 (International Trade Administration 2024). Renewable water resources barely meet half of the country's total consumption, resulting in frequent interruptions. Several factors worsen Jordan's already delicate water situation, including low rainfall, rising demand due to population growth and economic development, unsustainable agricultural and groundwater pumping practices, non-revenue water losses, limited water resources, deteriorating water quality, and the impacts of climate change (International Trade Administration 2024).

Trend	Description
A warmer climate	For the 2070-2100 period the minimum air temperature is extremely likely to increase by 1.2 °C [+0.6 °C to +2.9 °C] according to RCP 4.5 and by 2.7°C [+2.1 °C to +4.5 °C] according to RCP 8.5. Similarly, the maximum air temperature is very likely to increase by 1.1 °C [+0.7 °C to +1.7 °C] according to RCP 4.5 and by 3.1 °C [+2.6 °C to +3.7 °C] according to RCP 8.5.
A drier Climate	For the 2070-2100 period the country is likely to become drier, as the precipitation tends to decrease by 15.8 % [-7.1 % to -31.3 %] according to RCP 4.5 and by 47.0 % [-23.3 % to -57.5 %] according to RCP 8.5, taking into account that some zones are predicted to receive more precipitation, with a maximum increase of 19 %, according to RCP 4.5, while the whole country is projected to become drier according to RCP 8.5. The significant precipitation decrease is projected to be most likely at the western part of the country, while predicted potential increases are likely to occur in the southern arid zones.
Insignificant wind changes	Wind speed forecasts didn't indicate significant changes; however, the country is about as likely as not to be subjected to wind bloom events exceeding 12 m/s.
Mild decrease in relative humidity	For the 2070-2100 period the relative humidity is likely to decrease by 3 % [-2.5 % to -3.3 %] according to RCP 4.5 and by 7.2 % [-6.0 % to -7.8 %] according to RCP 8.5. In all scenario cases, the Northern Badia is likely to be subjected to a decrease in relative humidity at a higher rate than other parts or regions.
More drought, a contrasted water balance	Drought SPI indicators reveal an increasing trend of drought in the northern part of the country reaching a maximum of 50 % using RCP 4.5 and 93 % using RCP 8.5. The magnitude of drought events is increasing with time, from normal to severe, while the duration of the droughts is likely to become longer, over 3 consecutive years, using RCP 4.5 and more than 5 years using RCP 8.5.
High crop water demand	For the 2070-2100 period, the potential evapo-transpiration is very likely to increase by 5.8 % [+4.7 % to +6.9 %] according to RCP 4.5 and by 11.1 % [+8.1 % to +15.3 %] according to RCP 8.5. In the worst-case scenario, the evapo-transpiration for the whole country is very likely to increase by 15 % above the baseline scenario, thus setting the systems under pressure of greater water demands.
Intense precipitation and potential floods	The is no significant sign of heavy rain days (more than 20 mm), however future trends indicate the probability of occurrence of potential intense precipitation, that seems to decrease with time, especially at RCP 8.5 as compared to RCP 4.5. On other hand, the severity is variable by location and tends to become more likely than not intense during the mid-21st century and reduces by the end of the 21st century.
More intense heat waves	Future predicted heatwave events are more severe in terms of duration and magnitude, where the probability of occurrence increases to an average of 120 % by 2100 (ranging from 54 % to 398 % based on spatial location) using RCP 4.5, and about a threefold increase (ranging from 1.5 to 9.0 times, based on spatial location) using RCP 8.5. Thus, it is very likely that more severe threats are expected in terms of heatwave exposure intensity and duration, especially in the highlands regions of Madaba, Shoubak and QAI Airport during the months of March, April and May.

Table 4: Trends and their descriptions that indicate the expected future of climate in Jordan until 2100.
Source: Adapted from (United Nations Development Programme and GEF 2022)

3.6.3 Wastewater

As previously mentioned, reclaimed water is highly valued by the Jordanian government for its contribution to the country's water resources, as emphasized in Jordan's Water Strategy 2008-2022. The strategy states that wastewater should not be treated as waste but rather collected and treated to standards that allow for its unrestricted use in agriculture and other non-domestic purposes, including groundwater recharge. Over 70 % of Jordan's population is connected to the sewage system, with raw wastewater directed to 34 wastewater treatment plants (WWTPs). The most common treatment method is the activated sludge process, which accounts for 60 % of wastewater treatment. The As-Samra Wastewater Treatment Plant, a large-scale facility, processes more than 70 % of the country's total wastewater, amounting to 170 million m^3 in 2020 (United Nations Development Programme and GEF 2022).

3.6.4 Stormwater (and the lack of it)

The Hashemite Kingdom of Jordan is facing severe water scarcity, ranking among the top four most arid nations globally. This scarcity poses a significant challenge to growth and development, as available water resources per capita are decreasing while demand is rising. The water deficit is exacerbated by both economic and population growth. To manage water consumption, water is distributed only once a week to citizens and businesses, who then store it in tanks. Currently, municipal water usage, including in the Greater Amman Municipality (GAM), relies primarily on groundwater sources. If the supply remains unchanged, per capita domestic consumption is projected to drop to 90 m^3 per person per year by 2025, categorizing the country as experiencing an absolute water shortage that could hinder economic growth and threaten public health (GAM 2019).

The national government of Jordan, specifically the Ministry of Water and Irrigation, is responsible for water supply, pumping, and delivery, as well as wastewater treatment in Amman. These systems are under significant strain due to the growing refugee crisis and the influx of refugees. Groundwater levels have significantly declined, indicating unsustainable usage. Despite improvements in water-supply infrastructure, a critical imbalance between supply and demand persists. From 2011 to 2015, water demand increased by 40 % (Hashemite Kingdom of Jordan, 2013). Climate change further aggravates these issues, potentially reducing precipitation.

Despite the overall decrease in precipitation, the frequency of severe storms leading to heavy rainfall has increased, causing frequent flash floods in Amman. In 2015, a 30-minute downpour resulted in a severe flash flood, causing fatalities, property damage, flooded streets, and people being trapped in their cars and homes. Events like these have become more frequent like the flash flood in 2018 and 2019 consecutively caused a lot of damage to the city's infrastructure. Therefore, effective stormwater management is a primary focus of the Resilience Strategy (GAM 2019).

3.6.5 WSUD and the Challenges of its implementation in arid and semi-arid areas

Here is a brief explanation of the different terminology used to describe this planning approach:

Sustainable Drainage Systems (SuDS): Used mainly in the UK and Ireland, SuDS manage surface water close to its source by mimicking natural processes. They address water quality, quantity, and amenity through various techniques for attenuation, infiltration, flow control, and water treatment (Stephenson 2013).

Water Sensitive Urban Design (WSUD): A global approach to urban planning that integrates sustainable water management across the entire water cycle, promoting healthy ecosystems in urban environments (Stephenson 2013).

Blue-Green Infrastructure (BGI): The European Commission defines blue green infrastructure as 'strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem service' (Rashetnia et al. 2018)

In arid and semi-arid regions, Water Sensitive Urban Design (WSUD) is a cost-effective strategy for managing scarce water resources and offers numerous benefits. Green open spaces are particularly vital in these areas, as they alleviate extreme heat, provide urban cooling, and enhance thermal comfort. These spaces can serve multiple functions, offering not only water management solutions but also ecological, social, and amenity benefits. WSUD practices can also promote stormwater infiltration and groundwater recharge, aiding in drought adaptation.

However, several challenges hinder the implementation of WSUD in arid and semi-arid regions. These include health risks associated with water reuse in green areas and on water surfaces, public acceptance issues, and a general lack of experience and knowledge. Additionally, in densely populated areas, the need for extensive spaces to implement water-sensitive solutions presents a significant challenge, and institutional barriers further impede widespread adoption (Elzein et al. 2022). Therefore further research needs to be done on this topic and by introducing more pilot projects.

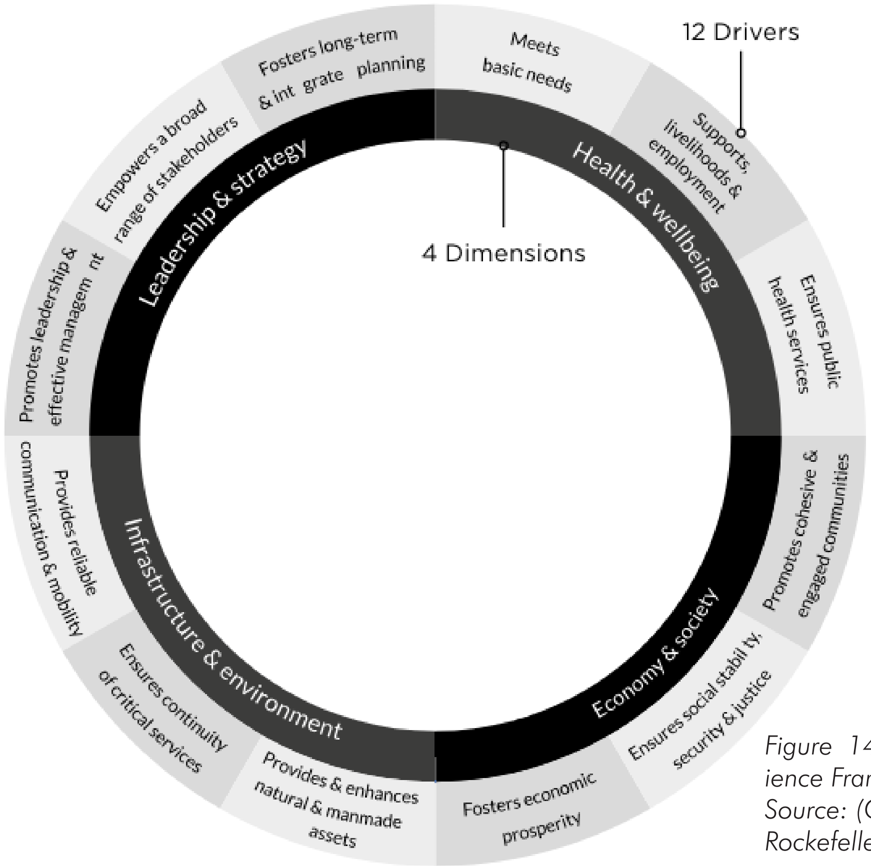


Figure 14:City Resilience Framework Source: (GAM and Rockefeller 2017)

3.7 Planning In Amman: Policies and Stakeholders

Since the governorate is administered by GAM and MoLA, several master plans have been developed for its various municipalities. However, these municipalities are not empowered to create their own master plans and lack the necessary staff, equipment, and training and can legally only update existing land use plans. Some of the major master plans are explained below:

1. The Metropolitan Growth Plan:

The Metropolitan Growth Plan (MGP), created in 2008 for areas within GAM boundaries, serves as the primary framework to coordinate various sub-plans. It aims to integrate land use, transportation, and infrastructure for compact urban development, promoting public transit and pedestrian travel over cars (GAM 2008). It identifies growth areas, including existing urban spaces and future expansion zones, as well as areas for limited or no growth, such as natural and cultural heritage sites. Though developed before the Syrian refugee influx, the MGP lacks specific provisions for refugees. Only 20 % of the plan has been implemented, prompting ongoing updates by GAM with input from the comprehensive planning department and council, aligning with GAM's administrative boundaries and directives (UN Habitat 2022).

2. Amman Resilience Strategy

City resilience refers to the ability of individuals, communities, institutions, businesses, and systems within a city to endure, adapt, and thrive in the face of various challenges, be they chronic stresses or sudden shocks. Amman has adopted the City Resilience Framework (CRF) developed by Arup and The Rockefeller Foundation, as part of the 100 Resilient Cities initiative. This framework assists cities in evaluating their resilience by identifying strengths, weaknesses, and opportunities. Cities are intricate systems composed of overlapping components, and the CRF serves as a tool to comprehend this complexity and the factors that contribute to resilience. The framework consists of four main dimensions and twelve drivers, offering a comprehensive understanding of what constitutes a resilient city as shown in Figure 14.

In 2017, Amman embraced the Amman Resilience Strategy to address urban challenges amplified by refugee influx and climate change. The strategy, built on five pillars—integration, environmental responsibility, innovation, youth empowerment, and unity—proposes an action plan. It aims to align refugee response with the city's long-term goals, emphasizing job creation and improved access to municipal social services for refugees (GAM and Rockefeller 2017).

3. The Amman Green City Action Plan

The Amman Green City Action Plan, launched in May 2021, stems from GAM's efforts to enhance environmental performance and systematically tackle urban environmental issues. It aims to identify, prioritize, and address critical climate change and environmental challenges such as solid waste management, water, wastewater, urban transport, and building energy efficiency. Through extensive stakeholder engagement, the city has devised 37 initiatives slated for implementation by 2025 to meet these objectives (AECOM 2021).

Along with many other goals in the area of efficient buildings, transport and waste management, the GCAP has prioritised the role of integrated water resource management. The proposed actions aim to integrate nature-based solutions with traditional infrastructure to effectively mitigate flood risk and improve water quality. Furthermore, they aim to upgrade and expand essential water infrastructure to ensure residents have access to clean water and are connected to wastewater networks. Finally, these actions seek to enhance water resource management by integrating efficient systems into the built environment (AECOM 2021). Among many planned proposals, some of the planned actions are mentioned below:

1. Develop water conveyance and/or storage to reduce flood risk

GAM plans to map the flow of water in the city and create a conveyance or storage system to redirect floodwaters from two vulnerable areas in downtown Amman, thus averting potential damage to critical infrastructure. This diversion of floodwaters is expected to yield significant economic savings by minimizing impacts on downtown infrastructure. Additionally, it will alleviate strain on sewerage systems, reducing the risk of wastewater pollution incidents and decreasing the energy needed for water processing within these systems.

2. Integrate WSUD and SuDS

It's crucial to integrate WSUD (water-sensitive urban design) and SuDS (sustainable urban drainage system) principles into land use planning and regulations. These principles enhance the integration of the water cycle into urban design. GAM will incorporate WSUD and SuDS principles into new land-use plans and offer guidance documents on these principles for departments revising relevant regulations and codes (e.g., road maintenance). This approach aims to tackle flooding issues and promote efficient and environmentally-friendly water usage.

3. Pilot SuDs implementation on municipal property

The city will integrate Sustainable Drainage Systems (SuDS) principles into all current and future publicly-owned buildings to support the objective of integrating WSUD and SuDS (W4). GAM will pinpoint suiTable sites for pilot SuDS projects within new municipal works and upgrades of existing publicly-owned buildings. With anticipated hydrological changes from climate change, integrating SuDS into city planning will mitigate flood and drought impacts while ensuring a more dependable water supply. The planting aspect of the program will prioritize xeriscaping and drought-resistant vegetation (AECOM 2021).

4. USAID CITIES Programme

Outside of GAM, the Ministry of Local Administration (MoLA) supports eight other municipalities. Within the governorate of Amman, the USAID CITIES Programme has financed strategic plans and local development plans for the years 2020-2023 in six municipalities: Al-Ameriyah, Husban, Na'our, Sahab, Muaqqar, and Umm Al-Rasas. These plans were collaboratively developed involving all relevant stakeholders to enhance municipal performance, services, efficiency, and public-private partnerships. However, these plans do not specifically address the needs or integration of refugees into communities.

5. The Amman Climate Action Plan

The Amman Climate Action Plan marks the initial step towards a sustainable future, aiming to make Amman carbon neutral while expanding services to meet the city's growing demands. The plan sets a 40 % reduction target for greenhouse gas emissions by 2030 and fosters collaboration among the government, private sector, development partners, and residents toward a shared vision of carbon neutrality.

6. The Green Growth National Action Plan

The Green Growth National Action Plan 2021-2025 lays out pathways for sustainable development that will increase resilience, strengthening Jordan's capacity to contain shocks and recover from catastrophic events such as COVID-19. The GG-NAP outlines five national green growth objectives on which the Agriculture Sector GG-NAP was developed:

1. Enhance Natural Capital
2. Sustainable Economic Growth
3. Social Development and Poverty Reduction
4. Resource Efficiency

5. Climate Change Adaptation and Mitigation

From these five national objectives, the Water Sector GG-NAP identifies 16 sector sub-objectives that serve to mainstream the overarching green growth objectives into water sector policies and investments. The green growth approach encourages innovation and market-driven solutions to address challenges such as creating green jobs, enhancing financial sustainability, and building resilience to climate change in the water sector. Improving water sector performance is interconnected with other sectors; for instance, reducing inefficiencies in water pumping can cut energy consumption. Implementing water efficiency technologies and large-scale water harvesting can alleviate pressure on water networks. The Water Sector Green Growth National Action Plan (GG-NAP) aims to achieve several transformative impacts: addressing supply and demand challenges, fostering community stewardship, introducing incentives to reduce costs, improving water access for vulnerable groups, and enhancing the capacity of decision-makers in water management (Ministry of Environment Jordan 2020). Figure 15 shows a timeline of the different plans made by the ministries in Jordan regarding adaptation to climate change over the years.

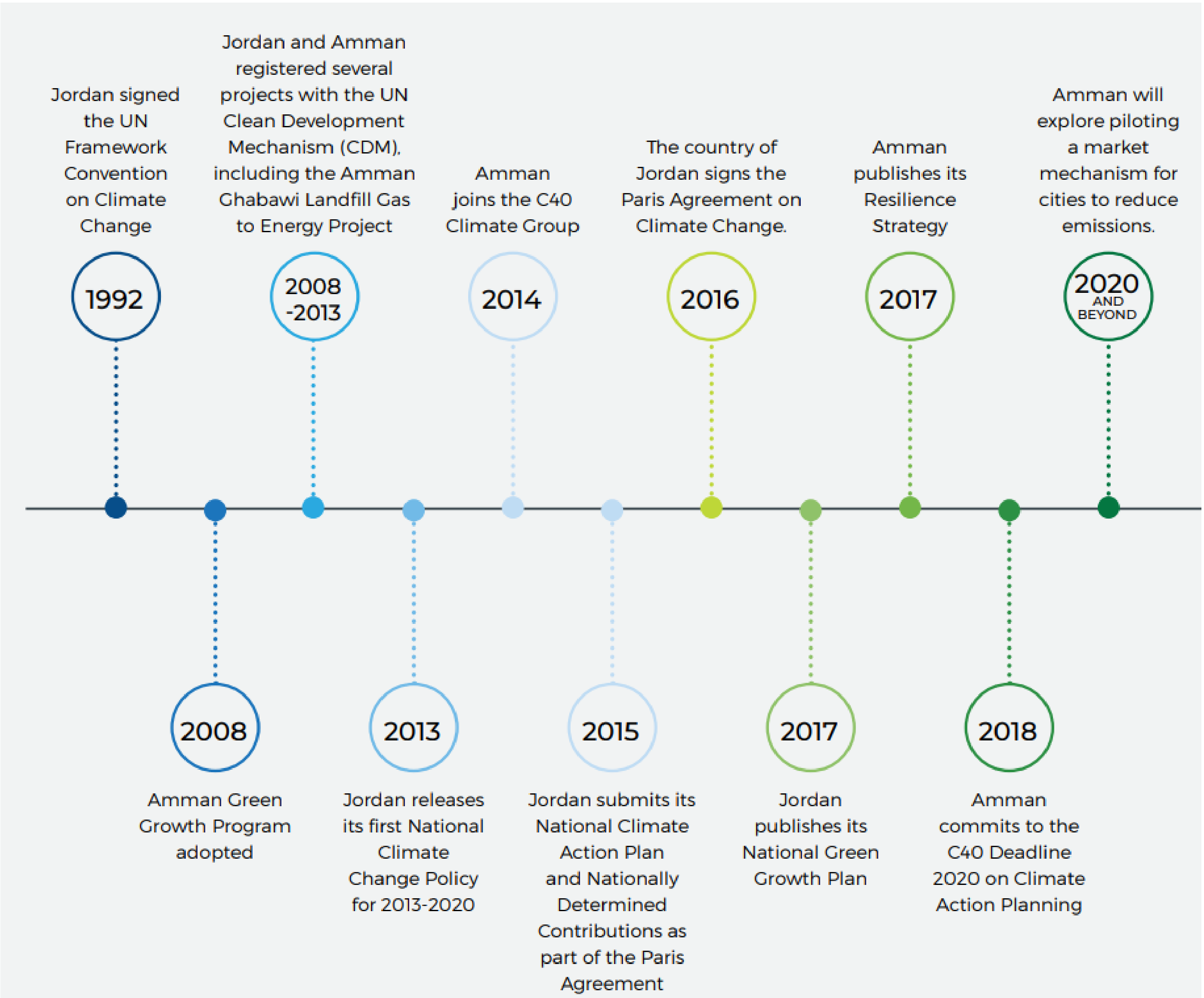


Figure 15: The timeline of different plans for climate change adaptation in Jordan
Source: GAM, 2019

3.8 Lessons learned from Pilot projects in Amman and projects from around the world

CASE STUDY 1: Strengthening the Social Stability and Resilience of Vulnerable Jordanian Communities and Syrian Refugees in Amman Against Flash Floods - UN Habitat

Historically, heavy rainfall has caused significant disruptions in the city, resulting in fatalities and severely impacting schools, transportation, livelihoods, and the electrical grid. These incidents have particularly heightened the vulnerabilities of the poorest Jordanians and Syrian refugees, further restricting their access to essential services. The growing threat of natural disasters presents a substantial risk to lives and infrastructure in Jordan.

In response, UN-Habitat Jordan, in partnership with the Greater Amman Municipality (GAM), has launched the project "Strengthening the Social Stability and Resilience of Vulnerable Jordanian Communities and Syrian Refugees in Amman against Flash Floods." This initiative seeks to bolster the resilience and capacity of both governments and communities to more effectively manage flash floods. It achieves this through community consultations, raising awareness, building capacity, and implementing flood-resilient infrastructure (UN Habitat and GAM 2023).

The project had the following outcomes:
Outcome 1: Improved protection and resilience to flooding in the target location in Amman.
Outcome 2: Reduced vulnerabilities of refugees and local communities to flash floods.
Outcome 3: Strengthened capacities of the government and communities to better manage floods in urban areas in Jordan.

To build the resilience of Amman city to flash floods, and ensure the sustainable and scalable impact, UN-Habitat Jordan followed an integrated approach that specifically focused on the following methods described in Figure 16 and are described in the following section.

1. Flood Risk Assessment

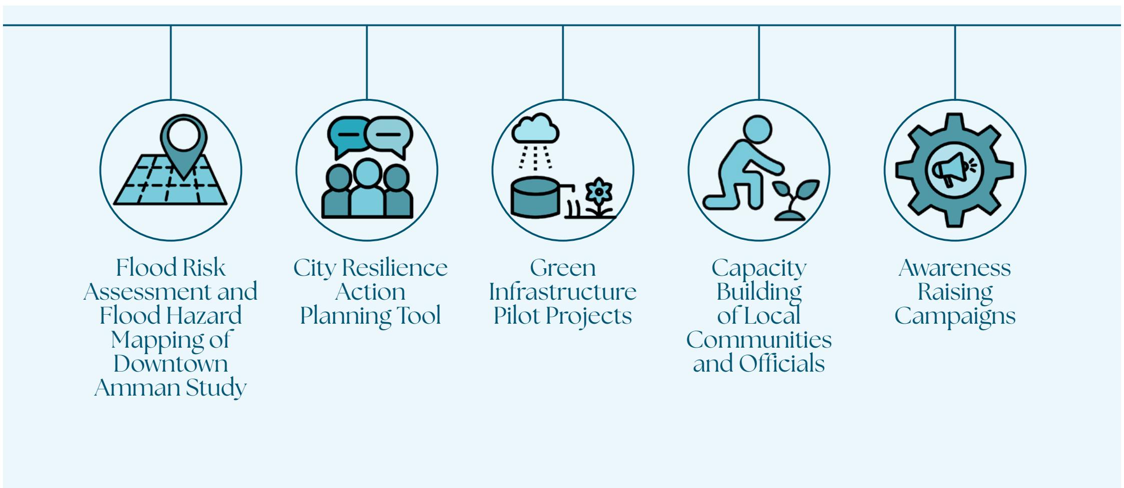
UN-Habitat conducted the first comprehensive city-level study and high-resolution flood risk mapping of Downtown Amman, accurately identifying the most flood-prone zones. This assessment facilitates disaster risk reduction programs and outlines a roadmap for developing a flood-resilient city.

The hydrological and hydraulic modeling study pinpointed flood hotspots in Amman, proposing short-, medium-, and long-term solutions. The recommended strategy is a combination of interventions to control and eliminate flooding risks. Long-term measures include large infrastructure projects, such as diverting stormwater runoff from West Amman. Medium- and short-term solutions involve stormwater retention and detention elements in upstream areas to slow down floodwaters, allowing the downtown drainage system to manage the water without causing damage. This green stormwater infrastructure approach is exemplified by the Al Zohour Green Triangle project (UN Habitat and GAM 2023).

2. CityRAP

To gain insights from the community's perspective, UN-Habitat Jordan employed the City Resilience Action Planning Tool (CityRAP). Developed by UN-Habitat, CityRAP is a participatory resilience planning methodology that guides communities through a step-by-step

Figure 16: Methods of integrated approach to build resilience against flash floods
Source: (UN Habitat and GAM 2023).



process to understand risks and plan actions for building resilience. This approach facilitates the development of a Resilience Framework for Action, empowering communities to reduce risks and enhance their resilience.
The community identified the challenges of uncontrolled surface runoff, unregulated constructions and the need to raise awareness. They further came up with solutions of rainwater harvesting and creating green pockets that then became the pilot projects implemented by the UN Habitat (UN Habitat and GAM 2023).

3. Pilot projects developed:

A) Water Harvesting Systems Installation and Green Pockets Initiative (Rainwater Gardens)

Based on the local community's recommendations during the CityRAP sessions, UN-Habitat installed water harvesting systems at four buildings: two at the University of Jordan, one at the Greater Amman Municipality building in Basman, and one at the Heart of Amman building in Ras El Ain as shown in Figure 17. These installations aim to mitigate the impacts of flash floods in Amman and raise awareness about water harvesting and the crucial role of local communities in enhancing the city's flood resilience.

The systems help alleviate floods, primarily caused by climate change and urban expansion, by introducing new solutions to reduce stormwater runoff. They consist

Figure 17: Water Harvesting Systems Installation
Source: (UN Habitat and GAM 2023)

of gutters that collect rainwater from rooftops and store it in tanks for future use. Additionally, in Ras El Ain, a rain garden was implemented to collect rainwater, which is then slowly drained through layers of plants, mulch, bioretention soil, and gravel into an underground storage system.

B) Al Zohour Green Triangle Pilot Project

The Al Zohour Green Triangle Pilot Project was implemented at one of 120 sites identified for short- and medium-term green stormwater infrastructure interventions. Covering an area of 2300 m^2, it is located at the intersection of Al Quds Street and Bab Al Khalil Street in the Al Zohour District of Amman, an area that channels substantial stormwater runoff from its 8 km^2 watershed into Downtown Amman as shown in Figure 18. The project, with a total cost of $465,000, is based on the concept of Sustainable Urban Drainage Systems (SUDS) and aims to demonstrate two green stormwater management concepts: stormwater bioretention and stormwater detention.

The bioretention concept is showcased through bioretention and bioswale areas designed to allow water to infiltrate the ground and be absorbed by vegetation. The detention concept is demonstrated through a concrete underground tank for stormwater storage.

4. Capacity Building

To enhance the skills of local officials, UN-Habitat organized the 'Climate Change and Resilience Capacity Building Training Workshop.' This workshop significantly improved the capacities of the Greater Amman Municipality (GAM) by providing practical information and global case studies on integrating climate change into their frameworks and plans, translating these into actionable steps to build resilience against various hazards and threats. It also aimed to advance GAM's participatory approaches, making their decision-making processes more transparent, inclusive, and effective.

Additionally, UN-Habitat focused on building the capacities of local communities in sustainable green agriculture methods and implementing small-scale home and community garden projects. With the assistance of a local permaculture expert, the 5-day training titled 'Community Mobilization and Logistical Preparations for the Community Resilience Priority Actions to Flash Floods' aimed to teach communities in Amman how to collect and use rainwater for agricultural purposes and domestic needs, thus minimizing the impact of flash floods on the drainage system. This training provided educational and livelihood opportunities, improved food security, decreased the socioeconomic consequences of COVID-19, and fostered social cohesion among community members.

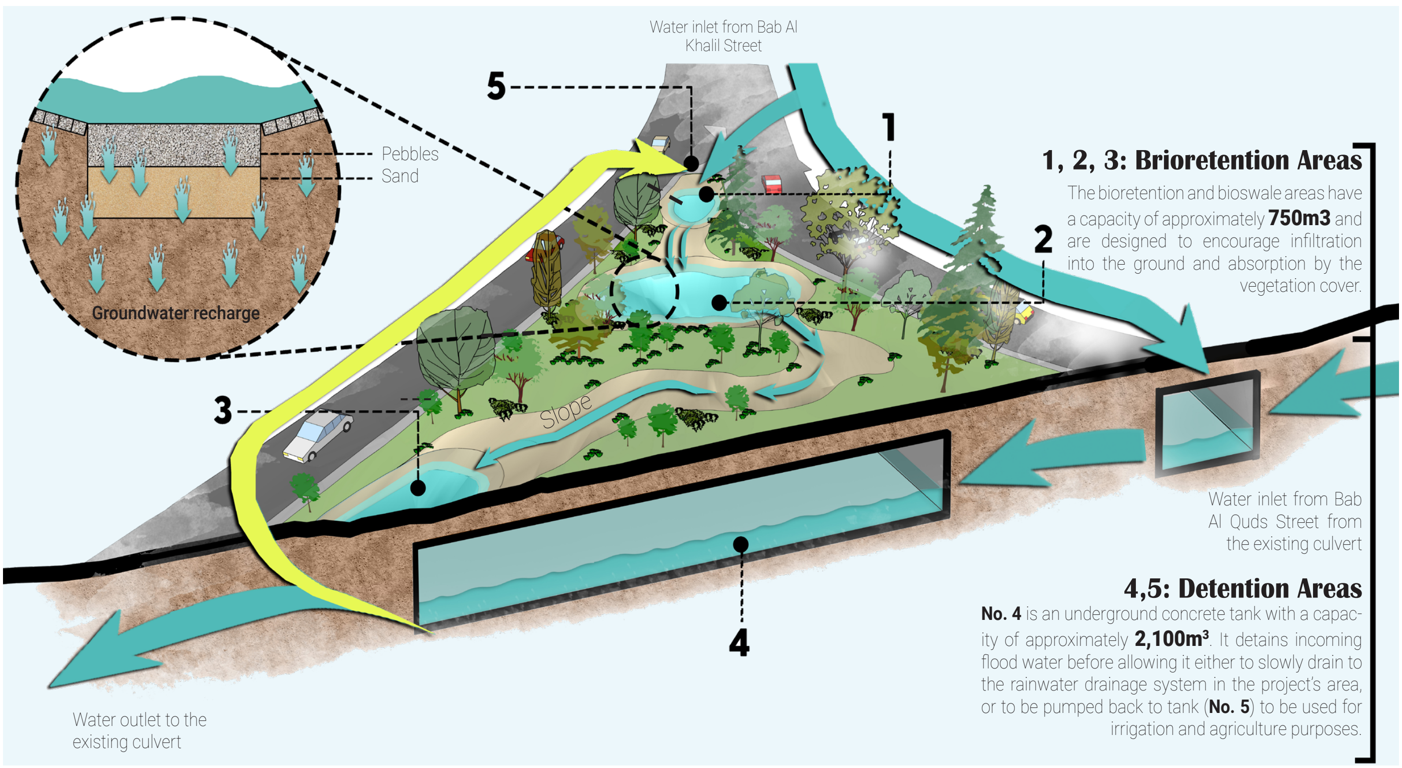
5. Awareness Raising Campaigns

To extend the impact of the project beyond Amman and its projected duration, UN-Habitat and partners also sought to raise awareness about flood risks and encourage community involvement in implementing solutions. These awareness campaigns were distributed via digital platforms to reach different segments of Amman's population, leveraging GAM's social media presence. They included TV appearances and an instructional video on flash floods and resilience measures, aiming to reduce risks in Downtown Amman. Enhanced community knowledge and awareness are crucial for bolstering resilience and improving quality of life for vulnerable populations. Such digital campaigns could be disseminated widely across the country and region, empowering communities to proactively address various climate risks and disasters.
Furthermore, UN-Habitat and its partners developed a Water Harvesting System Installation Manual, disseminated to various households, providing a step-by-step guide for implementing water harvesting solutions at the household level.

Lessons learned:

- Hydraulic mapping and risk assessment is the first step to identifying the hotspots for flash floods and coming up with integrated short, medium and long term solutions.
- The community must be involved in the decision making process since the beginning of the project to include their perspectives of the challenges and their inputs for the solutions.
- Digital tools help in conveying knowledge and raising awareness as well as gathering information.
- Rainwater harvesting is one of the most widely understood and accepted methods of stormwater management, especially in Jordan.
- The use of public spaces such as road intersections is critical in managing stormwater and is quite effective in storing large volumes of surface runoff.
- Plans and policies must be converted into actionable strategies that are easy to implement through capacity building of the different stakeholders.
- Finally, digital and popular media is a good way of raising awareness and is vital to the success of any project.

Figure 18: Al Zohour Green Triangle Pilot Project
Source: (UN Habitat and GAM 2023)



CASE STUDY 2:
Rotterdam: Perspective for the inner dike urban district and the iconic Watersquares

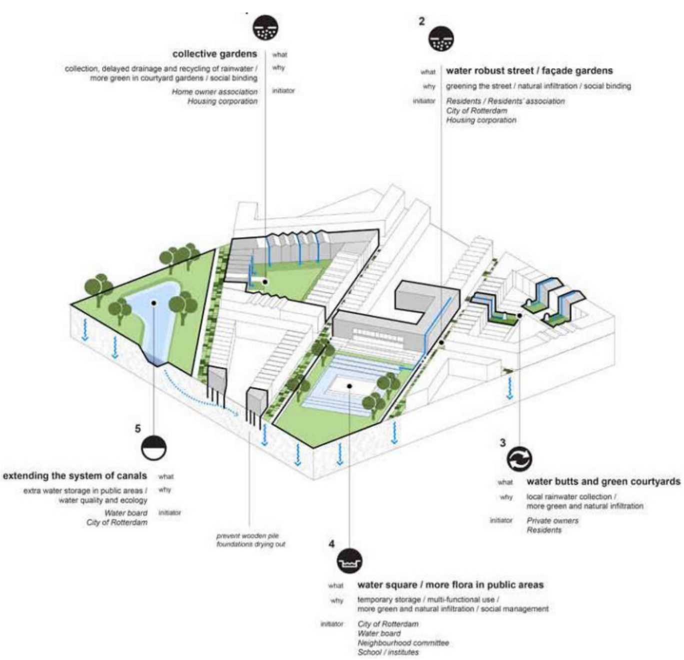
The context of Rotterdam in Netherlands is vastly different from Amman. It varies in topography, demography, climate and development. However it also faces the threats of extreme rainfall events and drought and has a dense urban area. Moreover, the soil in Rotterdam also does not support infiltration easily and hence the city has come up with innovative solutions for climate adaptation, integrated into the urban planning.

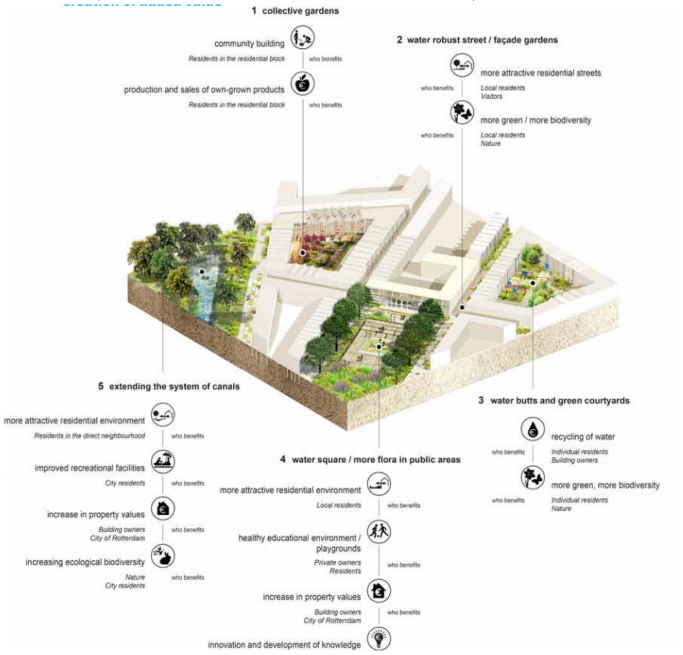
The inner-dike city districts are densely built urban blocks scattered around the city of Rotterdam. Because of their dense structure, only small-scale interventions can be implemented that would also maintain the character of the district. The wooden pile foundations of buildings located in these areas are particularly susceptible to changing groundwater levels and are vulnerable to floods and droughts. These fluctuations can be reduced by increasing infiltration and introducing more plants and water bodies. However, this is not always possible due to the lack of open space. Therefore, the temporary storage of water and delayed infiltration or surface drainage create interesting opportunities for recreation spaces, for example the water squares which are detailed in the next section. Wherever it is possible, the paving is reduced, for example, by creating façade gardens in the streets and increase in planting trees and green spaces in private and public open areas. Measures are taken at various levels from water butts to improving the quality of open water bodies. The aim is to increase the value of the property by making the districts resilient through incorporation of more green spaces. It also has the added benefits of stimulating social interaction, improving the biodiversity and creating a healthy educational and playing environment for children as shown in Figure 19. (Rotterdam Climate Initiative 2013).

The watersquares in Rotterdam, emblematic of the city's water management during extreme rainfall events, have emerged as a leading example in adaptation strategies. These squares function as supplementary water reservoirs during such events, mitigating flooding on surrounding roads. Situated in public spaces, they serve as recreational and social hubs during normal conditions, enhancing the urban environment. However, during periods of heavy and sudden rainfall, they fulfill their primary role by collecting excess rainwater, which is subsequently drained using a slow pumping system. This dual functionality underscores their effectiveness in both enhancing urban quality of life and managing water-related challenges (Bassolino 2019).

The concept of watersquares was conceived by the design group De Urbanisten, who brought the "Water Square Benthemplein" to fruition in 2013. Comprising three basins, the square's two smaller basins collect rainwater during precipitation events, while the deeper basin only activates when the capacity of the others is exceeded, channeling excess water via stainless steel collection channels as shown in Figure 20. Following rainfall, water from the smaller basins is directed to a storage area for groundwater infiltration, while water from the deeper basin is released into the open water system within 36 hours. This system alleviates pressure on the sewer system and segregates black and grey water. Additionally, green roofs, known as polder roofs, are identified as a strategic solution for temporarily retaining water during heavy rains. By absorbing rainwater, green roofs slow down water flow, thus reducing runoff into the sewage system (Bassolino 2019)

Figure 19: Integrated WSUD in inner dike districts
Source: (Rotterdam Climate Initiative 2013)





Lessons learned:

- Innovative solutions like the watersquares of Rotterdam can be implemented in dense urban areas with low infiltration capacity of the soil
- Temporary detention areas vastly decrease the stress on stormwater systems and can act as multifunctional spaces during dry periods
- Aspects of WSUD can be implemented even in areas with very limited open spaces
- Private open spaces should also be incentivised to increase unsealed areas.
- The integration of WSUD in dense urban spaces greatly improves aspects such as social integration, improvement of biodiversity and quality of stay, as well as raises awareness amongst the community.

Figure 20: The Benthemplein water square as temporary water storage facility, artist's impression of the scene during a downpour (top) ; The Benthemplein after a shower (bottom left) and on a sunny day (bottom right) Source: (Rotterdam Climate Initiative 2013)

Chapter 4

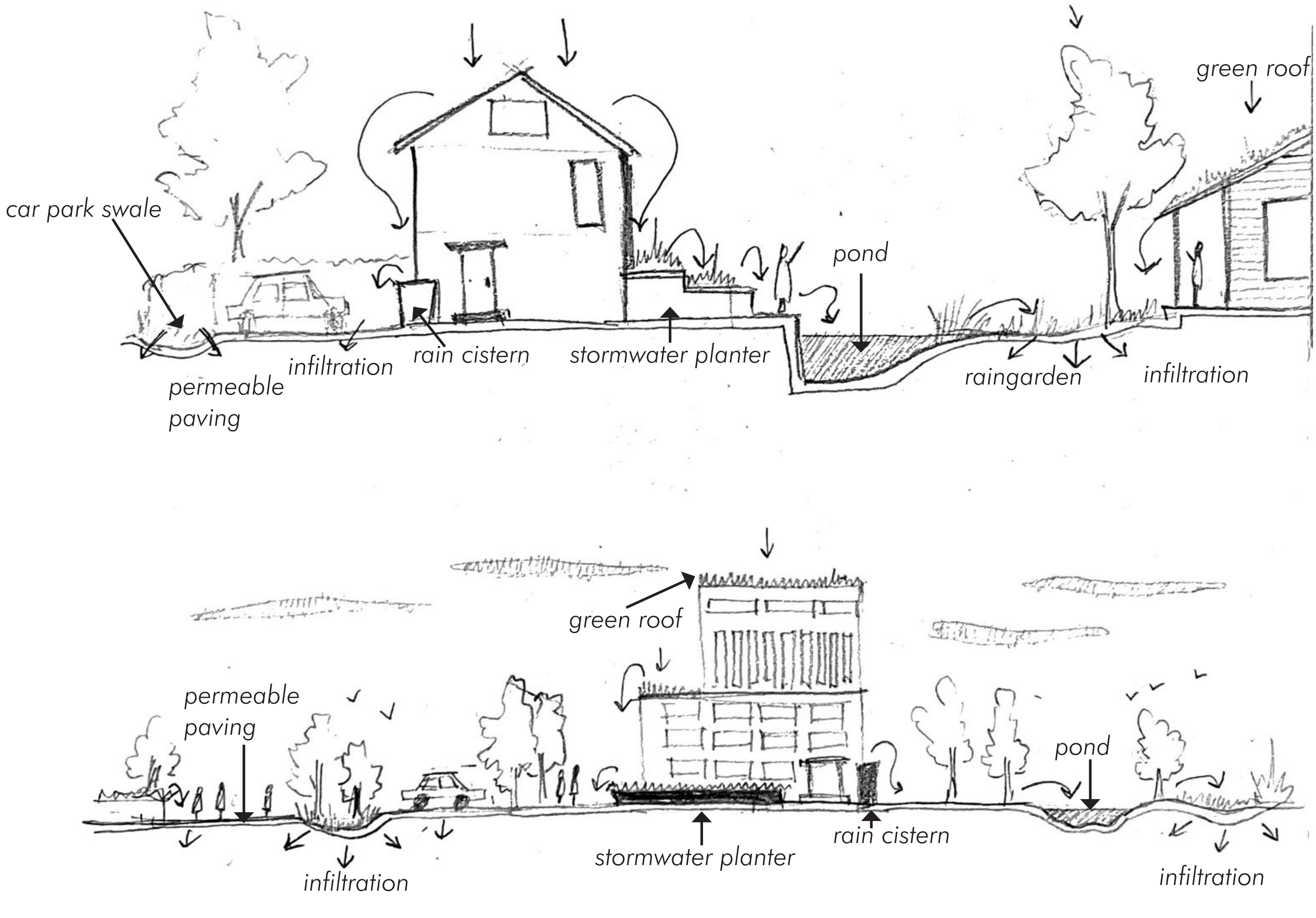
Designing with Nature: Amman's WSUD Toolkit

4.1 Introduction

The general idea of this water sensitive urban design toolkit is to put together a set of planning goals and measures that all stakeholders can easily understand. This toolkit not only outlines what these measures do but could also be used as a tool in a more participatory setting. As mentioned in previous sections and also in the case study of the UN Habitat, the inclusion of participants on various levels during the conception and design phase greatly encourage acceptance of shifts and changes in systems. Citizens are more likely to accept the interventions and are more educated about the positive aspects of WSUD.

This toolbox includes definitions of the planning goals as guides to selection and design of the measures as well as their significance in the stormwater chain. It deals with the sequence and chain of elements that when put together are highly efficient at managing stormwater in a decentralized manner, by creating a cascading effect as shown in Figure 21. It also aims to emphasize the fact that these measures do not only serve a practical purpose but also enhance the environment with their added benefits.

Figure 21: The cascading effect in a stormwater chain in a residential (top) and commercial (bottom) areas. The two diagrams shows how linked sequences of features can capture rainfall and release it back into the landscape. Source: Redrawn and adapted from (Dunnet and Clayden 2007)



4.2 Defining the planning goals

Planning goals provide a guiding principle to selection of measures and recommendations. They also form the base for the measurement of effectiveness of these measures under different scenarios. Hence, they are stated and defined as follows:

1. Flood reduction:

Flash floods are very localised (in space and time), fast-evolving surface water responses to rainfall from intense thunderstorms or a sudden release of water from a reservoir, which results in short lead time and a considerable potential for damage due to high flow velocities and thus high hazard intensities. The goal of reduction of flash flood damage is to direct, capture, or temporarily store large volumes of stormwater as well as reduce the peak runoff rates in order to prevent drastic damage from flooding.

2. Groundwater recharge:

Returning the water balance to near natural state is one of the most important goals of this project, and this means facilitating the natural process of water like evaporation and infiltration. Urbanisation has led to an increase in sealed spaces, therefore stormwater is unable to infiltrate into the soil. Since the public supply of drinking water is under a lot of pressure from the growing population and depleted resources, securing the water supply by replenishing the groundwater becomes one of the foremost tasks.

3. Water collection for reuse:

While groundwater recharge is one way of contributing to the water supply for consumption, an easier and much more decentralised way to do this would be collection of stormwater for reuse. This can be done by diverting water from sealed surfaces to storage tanks that may be built underground or above. However, this may mean that the water also collects all the pollutants from these surfaces, and may have limited usage. Alternatively, bioretention systems have the ability to cleanse some of the pollutants and can be built with storage tanks as well. In either case, shortening the supply chain makes an important aspect of this research and contributes to mitigating the water scarcity in Amman.

4. Promotion of biodiversity:

Replacing paved surfaces, or intensely managed grass areas with mixed native species of plants not only results in overall reduced need for maintenance and inputs of fertilizers, water and energy, but also greatly increases the wildlife and habitat value. The native shrubs and grasses are home to a lot of insects and invertebrates that inhabit the soil, and are the source of nutrition for more visible fauna like butterflies and seed eating birds. Co existing with the variety of flora and fauna increases the appeal of any urban space and hence makes for a good planning goal.

5. Quality of Stay:

As mentioned in the previous points, when planned strategically, blue green measures automatically add to the aesthetic appeal of any place. Additionally, making a space beautiful also enhances its value to live and work in. While in urban environments, water is often seen as a nuisance, something to get rid of, or controlled and contained, if managed through aesthetic infrastructure, the presence of the same water enriches the experience of the city.

6. Balanced Urban Climate:

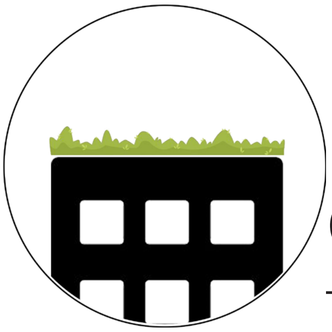
At the basic level, substituting hard paced surfaces with vegetation cools the summer landscape. Hard surfaces store heat from the sun and re radiate it during the night, warming the adjacent air while reflection the same heat during the day. On the other hand, plants provide shade but also cool the air through evapotranspiration. With increased paved areas in the city causing the urban heat island effect, a goal for future development should focus on balancing that urban climate through the introduction of more green spaces.

7. Environmental Education:

Lastly, improving public knowledge on environmental issues should be a priority since it affects their lifestyle. The design of urban spaces has the ability to influence and shape human behaviour. Having an unlimited supply of water through a tap for example, makes a person completely unaware of the source ot comes from and the processes it goes through to be consumed by the user. When the same processes are made visible through measures implemented in the surroundings, streets, parks and backyards, a person is likely to be more conscious of their consumption patterns. It also raises the likelihood of people participating in the design and implementation processes of these measures throughout their neighbourhood.

4.3 Measures and their descriptions

The selected measures are detailed in this section as a set of info cards, that may be distributed at a stakeholder workshop or just to inform the reader of this research about the details of the measure. Therefore, it includes a representative icon, an indication of costs, a description, criteria to implement it, maintenance required and how it ranks for the various planning goals mentioned before. The ranking is about how well a measure may perform for each planning goal based on the expert discussions at HW, 2024. Lastly, it also included a graphic representation of how these measure work and/or an example.



Green roofs

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DESCRIPTION

Green roofs are vegetated areas installed on building rooftops for various purposes, including visual appeal, ecological benefits, improved building performance, and reduced surface water runoff (CIRIA 2015). They can be of two types:

- Extensive: low substrate depth, low load on buildings, inaccessible, simple planting
- Intensive: deeper substrate depth, higher loads, accessible as the variety of plants need more maintenance.

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■■■
Groundwater Recharge	■■□
Biodiversity	■■□
Urban Climate	■■■
Quality of Stay	■■□
Environmental Education	■■□

DESIGN CONSIDERATIONS

- Can be applied to public or private building roofs
- Accessibility requirements
- Imposed loads when saturated, including maintenance loadings
- The need for integration of rooftop equipment, such as vents, air-conditioning systems, solar panels and/or RWH systems
- Management of drainage - outflow to a storage tank, integrated into landscape, connection to the drainage system, etc.
- Suitability of plants

PROCESSES

- Filtration
- Evapo-transpiration
- Purification
- Retention
- Biological absorption
- Micro climate improvement

MAINTENANCE

Intensive roofs need more frequent maintenance like mowing of grass and de-weeding, whereas extensive roofs only need bi annual checks for unwanted plants and cleaning.

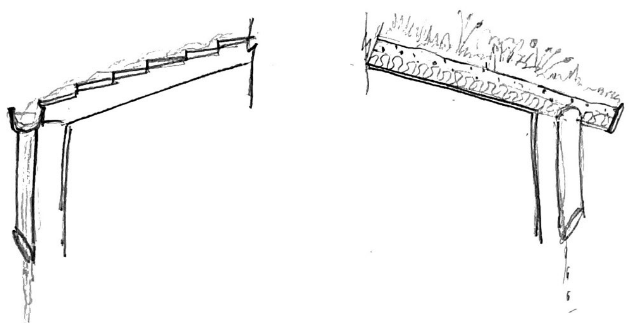
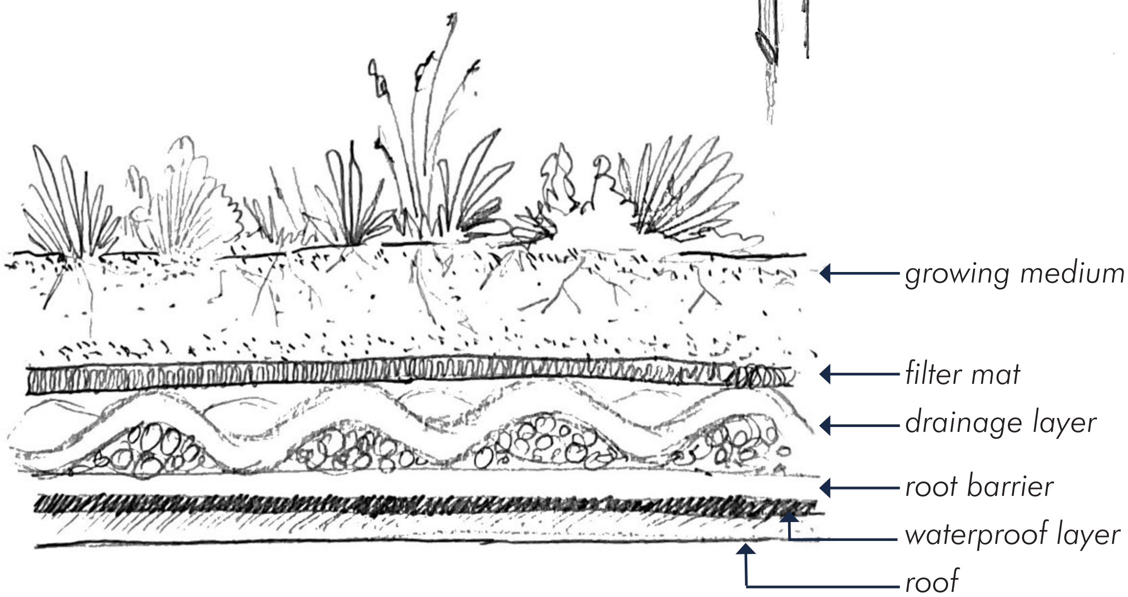
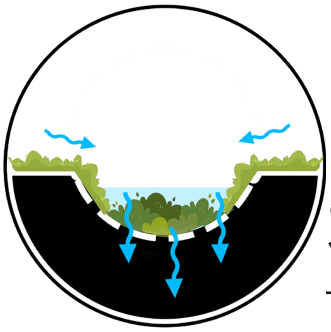


Figure 22: The green roof will absorb and gradually release rainfall - unlike a conventional roof, which rapidly sheds the water into connecting drains. Source: Redrawn and adapted from (Dunnet and Clayden 2007)

Figure 23: Section of a typical green roof buildup Source: Redrawn and adapted from (Dunnet and Clayden 2007)





Swales/ Bioswales

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DESCRIPTION

Swales are linear depressions covered with grass or more dense vegetation designed to convey, treat and often attenuate surface runoff (CIRIA 2015; DWA 2006). Runoff is collected temporarily on the surface and then filters through the vegetation and underlying soils. Bioswales may involve a continuous component of bioretention along the length of the swale, or a portion of bioretention before the outlet of the swale. For heavier rainfall events, water will flow along the swale though the velocity is controlled by vegetation and simultaneous infiltration (CIRIA 2015).

DESIGN CONSIDERATIONS

- Parabolic or trapezoidal cross section, with the base between 0.5-2m.
- The side slopes should be between 25 % to 33 %, to improve pre-filtration of the runoff where space permits.
- When applied along streets, the minimum length should be 5 m for maintenance access and with depths between 400-600 mm and a ponding depth of 300mm.
- The flow velocity and vegetation should be designed so that when water flows along the bioretention swale the filter material is not eroded.
- To achieve effective biofiltration, the base of the swale must be constructed as a series of flat areas that are terraced down the length of the swale.
- SuiTable vegetation should be chosen that can withstand inundation and flow of water.
- An underdrain may be added to provide additional treatment and conveyance capacity beneath the base of the swale and prevent waterlogging.

PLANNING GOALS

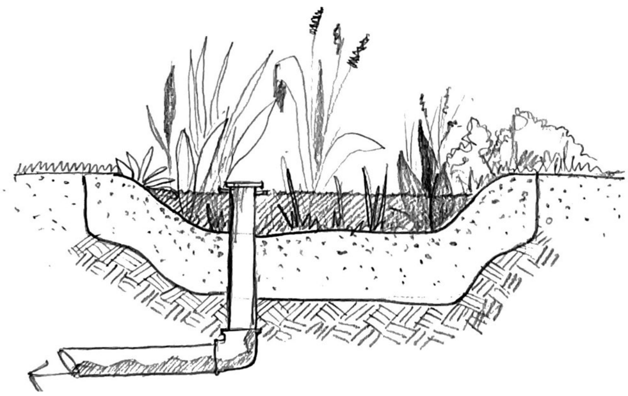
Flood Reduction	■■■
Water collection for reuse	■□□
Groundwater Recharge	■■■
Biodiversity	■■□
Urban Climate	■■■
Quality of Stay	■■■
Environmental Education	■■□

PROCESSES

- Infiltration
- Filtration
- Evapo-transpiration
- Purification
- Retention
- Biological absorption
- Micro climate improvement
- Conveyance

MAINTENANCE

- Litter and debris removal
- Mowing of the grass and maintenance of the vegetation, maintaining the height to at least 75-150mm.
- Occasional sediment removal.



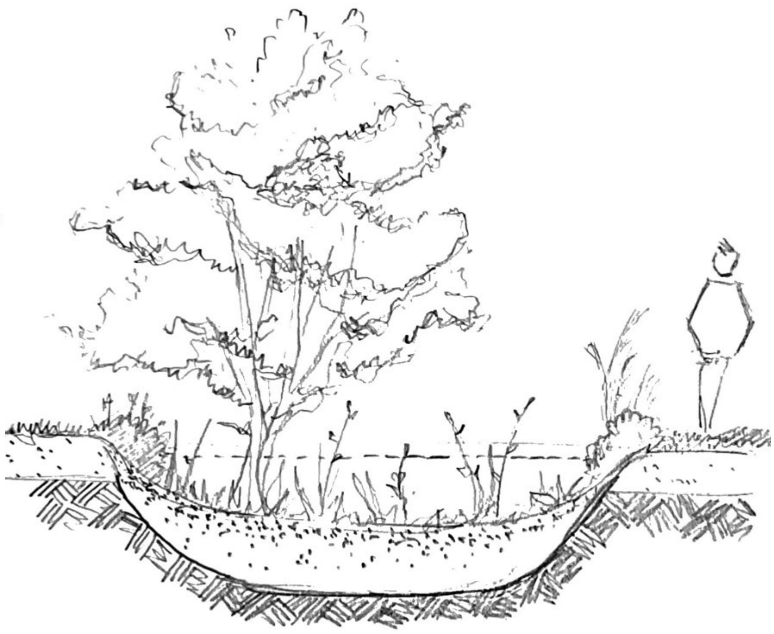


Figure 24: (Above) Section of a typical swale with overflow into the drainage system
Figure 25: (Right) A vegetated swale with geo-textile to permeate as well as convey stormwater runoff
Source: Redrawn and adapted from (Dunnet and Clayden 2007)

Raingardens

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DESCRIPTION

Bioretention systems like raingardens are shallow landscaped depressions and are a cost effective retrofit since they are flexible in terms of shape, materials, plantings and dimensions. They can reduce runoff rates and volumes by improved infiltration through engineered soils and vegetation. The runoff is either collected using an underdrain or is fully or partially infiltrated to the surrounding soils and is further reduced by evapotranspiration and plant transpiration (CIRIA 2015).

DESIGN CONSIDERATIONS

- Can be implemented in most types of developments, along roads, parking spaces, roundabouts, already landscaped lawns, in public or private areas
- Can be creatively shaped according to requirements
- Depths between 150-300mm, can be deeper depending on site conditions
- Filter medium depth 400-1000mm
- Overflow through surface drain or underdrain system
- SuiTable perennial vegetation that promotes biodiversity

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■□□
Groundwater Recharge	■■■
Biodiversity	■■■
Urban Climate	■■■
Quality of Stay	■■■
Environmental Education	■■□

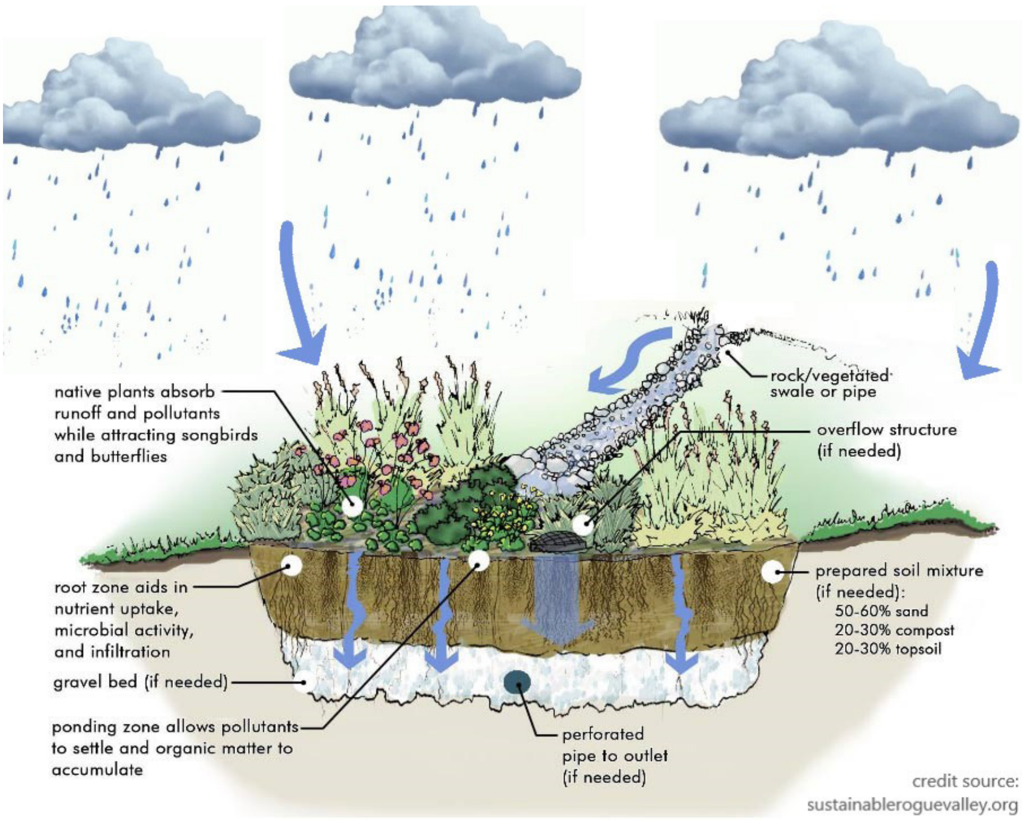
PROCESSES

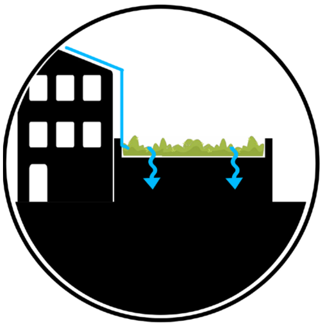
- Infiltration
- Filtration
- Evapo-transpiration
- Purification
- Biological absorption
- Micro climate improvement

MAINTENANCE

- Litter and debris removal
- Regular removal of weeds
- Cleaning access to underdrains where necessary

Figure 26: How a raingarden works
Source: (Berkshire Environmental Action Team 2021)





Stormwater Planters

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DESCRIPTION

These are boxed systems, which can be prefabricated, built above the ground surface with a planted soil mix and an underdrain to collect filtered water. They are commonly used to manage runoff from nearby roofs and are particularly useful for retrofitting in urban areas. They may be built to infiltrate directly in the soil below or can be further connected to the next step in the drainage chain (CIRIA 2015) (Dunnet and Clayden 2007).

DESIGN CONSIDERATIONS

- Minimum depth of 300mm
- Waterproofing when constructed right next to a building
- SuiTable vegetation to promote biodiversity
- Addition of stones or pebbles to moderate the velocity of water from the downspout
- Outflow into a drain or next step in the drainage chain
- Can be integrated creatively into the urban landscape where space is limited.

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■□□
Groundwater Recharge	■■□
Biodiversity	■■□
Urban Climate	■■□
Quality of Stay	■■■
Environmental Education	■■■

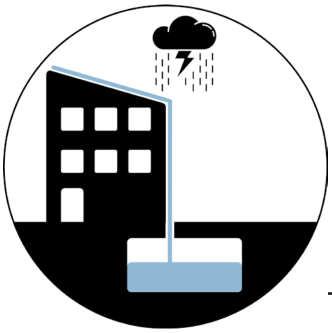
PROCESSES

- Infiltration
- Filtration
- Evapo-transpiration
- Biological absorption
- Micro climate improvement
- Conveyance

MAINTENANCE

- Litter and debris removal
- Weed removal to avoid clogging
- Occasional sediment removal.

Figure 27: A series of stormwater planters collecting water between two structures integrated into the landscape, creating a drainage chain to reduce runoff volumes and rates, Source: (Central Steel Service Inc 2019)



Rainwater Harvesting

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DESCRIPTION

Rainwater harvesting is the collection of runoff from roofs and other impermeable surfaces which can be stored, treated if required and reused for many purposes (CIRIA 2015). Rooftop rainwater harvesting typically requires the construction of a storage tank, either on the surface or underground. The collected water can be used for irrigation, or for non-poTable domestic purposes on site, or can be directed to a treatment plant. The storage tanks can be designed and located to serve individual buildings like residences or can be larger and collect runoff from several buildings.

DESIGN CONSIDERATIONS

- Disconnection of the downspout from roofs from the drainage network and into a storage tank.
- The size of the storage tanks depends on the amount of rainfall collected form the rooftop, the space available for the tank and the purpose for which the water will be reused.
- Accordingly, a pump may need to be installed to extract the stored water.
- An overflow outlet needs to be installed that could connect to the system drainage.

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■■■
Groundwater Recharge	□□□
Biodiversity	□□□
Urban Climate	□□□
Quality of Stay	□□□
Environmental Education	■■□

PROCESSES

- Storage
- Reuse

MAINTENANCE

- Inspection of tanks for debris and cleaning annually

Figure 28: Section of RWH system
Source: (Civil Engineer DK 2021)

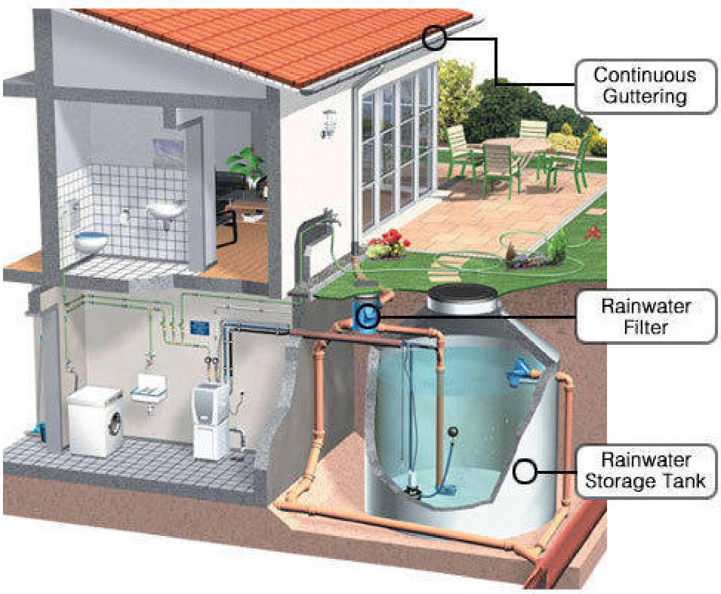
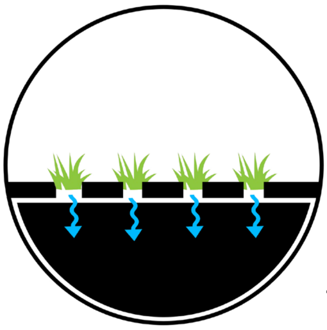


Figure 29: RWH in a garden for irrigation
Source:(UltraTech Cement 2021)



Permeable Pavements

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DESCRIPTION

Pervious pavements support pedestrian and vehicular traffic while allowing rainwater to infiltrate through the surface into the underlying structural layers. The water is temporarily stored beneath the surface before being used, infiltrating into the ground, or being discharged in a controlled manner downstream (CIRIA 2015). They can be made either of porous materials like porous asphalt or concrete in which case water can infiltrate throughout the surface of the material. Or they are commonly blocks of impermeable materials with wide joints filled with grit through which water seeps in.

DESIGN CONSIDERATIONS

- As they are an alternative to impermeable areas, they require no extra space to install.
- The choice of materials whether it is porous asphalt, paver blocks or reinforced grass depends on the traffic loads and visual appearance required.
- The aggregate sub base might be replaced by geo-cellular sub base to improve infiltration and can also aid in storage of the runoff.
- When an adjacent impermeable area or roofs are draining onto the pervious pavement, the recommended ratio impermeable/pervious surface is up to 2:1 (CIRIA, 2015).

PLANNING GOALS

Flood Reduction	■■□
Water collection for reuse	■□□
Groundwater Recharge	■■□
Biodiversity	□□□
Urban Climate	■□□
Quality of Stay	■■□
Environmental Education	■■□

PROCESSES

- Infiltration
- Evapo-transpiration
- Micro climate improvement

MAINTENANCE

- Inspection and repair paving as required
- Regular checks for silt clogging the joints

Figure 30: Typical section of a permeable pavement
Source: Redrawn and adapted from (Dunnet and Clayden 2007)

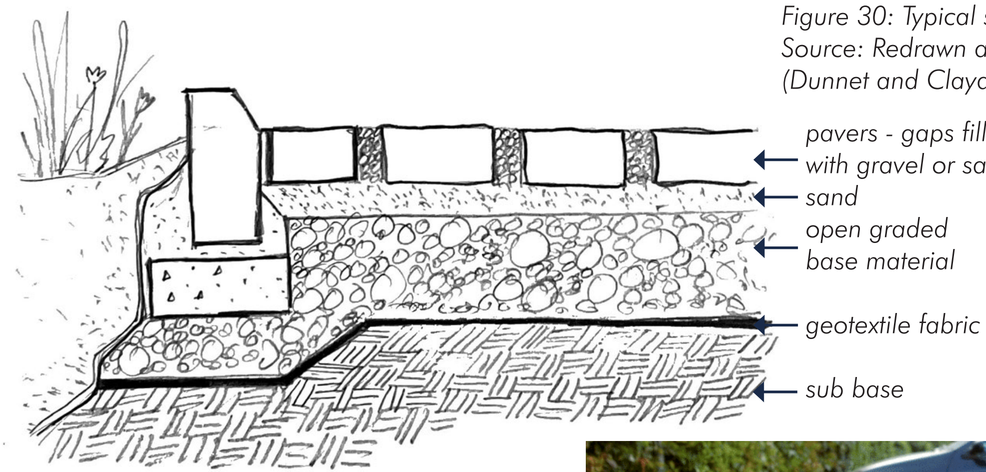

Figure 31: Example of a permeable pavement in a parking lot
Source: (Hardcastle 2022)

New Green Spaces

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DESCRIPTION

Replacing paved surfaces or intensely managed grass areas with mixed, naturalistic and diverse native vegetation is the objective of this measure. Paved areas contribute highly to urban heat island effect and increase runoff rates and volumes. On the other hand, intensely managed landscapes with monoculture vegetation is not effective in soaking up or trapping excess runoff, and are not effective in removal of contaminant as well. These diverse green spaces whether in small pocket gardens or larger parks and gardens not only reduce needs for maintenance, but also greatly increase the wildlife and habitat value and improves the overall quality of stay (Dunnet and Clayden 2007).

DESIGN CONSIDERATIONS

- Disconnection of the downspout from roofs from the drainVery flexible in terms of size, scale, typology and can be implemented in dense urban areas on private or public property.
- The most effective biodiverse landscapes are a combination of grasslands, wetlands, woodlands and scrub. The combination of these promotes biodiversity and creates an "ecotone" – two or more types of vegetated areas that interact with each other and are often dependent.
- They can be combined with play areas for children and pedestrian paths for wandering.
- They can incorporate a wide variety of WSUD measures like wetlands, retention areas and swales, incorporating water into the landscape for visual quality and stormwater management (Dunnet and Clayden 2007).

PLANNING GOALS

Flood Reduction	■■□
Water collection for reuse	■□□
Groundwater Recharge	■■■
Biodiversity	■■■
Urban Climate	■■■
Quality of Stay	■■■
Environmental Education	■■■

PROCESSES

- Infiltration
- Filtration
- Evapo-transpiration
- Biological absorption
- Micro climate improvement
- Retention

MAINTENANCE

- Removal of weeds
- Regular removal of litter and debris.

Figure 32: Spring in the Highline in New York. A corridor of biodiversity in a dense urban setting brings life to this post industrial district. Source: (Sangaku San 2015)

Retention Basins

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DESCRIPTION

Retention basins are one of the final elements in the stormwater chain providing a final resting point for runoff water. Its most important functions are storage and pollutant removal through settling and filtration through plants. The level of water in these ponds usually fluctuate as they mimic natural lakes or wetland dynamics.

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■□□
Groundwater Recharge	■■□
Biodiversity	■■□
Urban Climate	■■□
Quality of Stay	■■■
Environmental Education	■■□

DESIGN CONSIDERATIONS

- The length/width ration of the flow path is between 3:1 and 5:1 (CIRIA, 2015).
- The standard depth of the permanent pond is about 1.2 m, and the maximum one is up to 2 m (CIRIA, 2015).
- The maximum of the storage volume above the permanent pond level is 0.5 m (CIRIA, 2015).
- Side slope is up to 1:3 to provide safe conditions and access to the structural components (CIRIA, 2007).
- The retention time is about 20 days to assure the biological treatment (CIRIA, 2007).
- The space required for the pond depends on the catchment area, about 3-7 % of its size (CIRIA, 2007).
- Retention ponds are typically located at the lowest point of the catchment area.
- The pond construction has to include the overflow control and emergency spillway.

PROCESSES

- Infiltration
- Filtration
- Evapo-transpiration
- Biological absorption
- Micro climate improvement
- Storage

MAINTENANCE

- Litter and debris removal
- Weed removal to avoid clogging
- Occasional sediment removal.

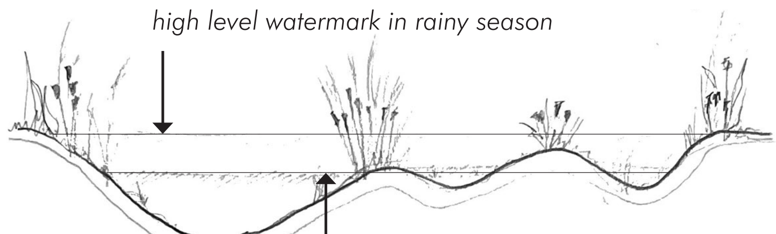

Figure 33: (Top) - The slope of the base of the pond is not even, giving rise to a complex mosain of conditions. Source: Redrawn and adapted from (Dunnet and Clayden 2007)

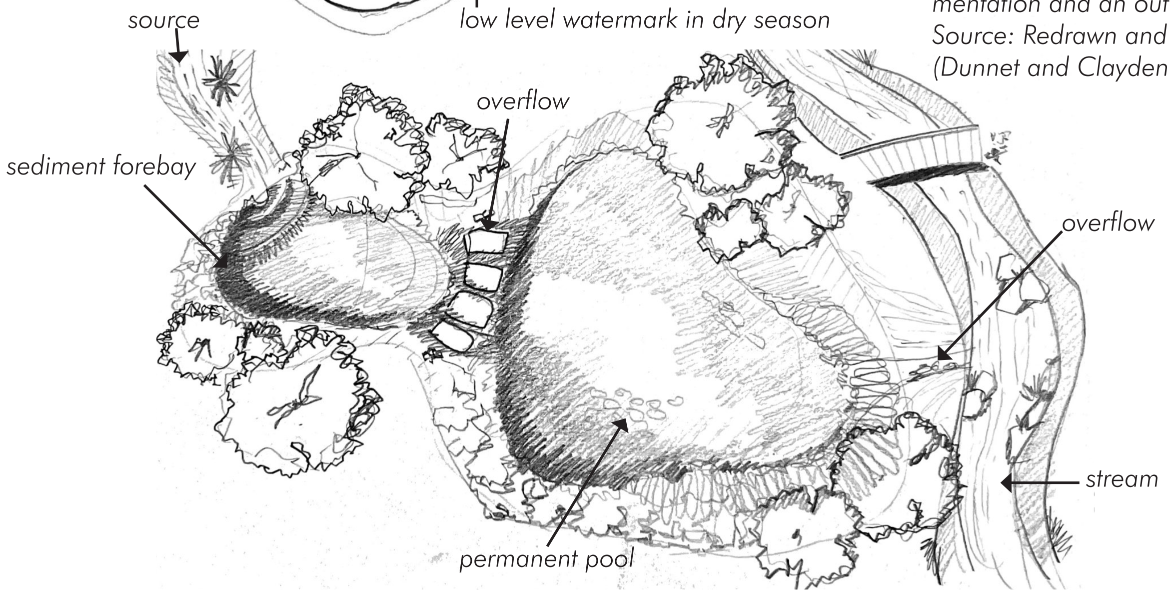

Figure 34: (Bottom) - A retention basin may include a forebay area to encourage sedimentation and an outflow for excess water. Source: Redrawn and adapted from (Dunnet and Clayden 2007)

Detention Basins

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DESCRIPTION

Detention basins are landscaped depressions that remain dry except during and immediately after storm events. They can be vegetated depressions, which can treat runoff when designed to manage regular flows, or hard landscaped storage areas, typically used as off-line components that do not provide treatment (CIRIA 2015). They can either be designed such that regular runoff goes through the basin and due to a restricted outflow, the basin fills up. Alternatively, they can be designed to hold the runoff until it reaches a point of overflow. Infiltration is possible in vegetated detention basins and during dry periods, they can have alternate uses.

DESIGN CONSIDERATIONS

- Detention basins should usually not have geometric shapes, but rather natural curves and undulations in levels for aesthetics, unless required by context.
- A hardscape detention pond may be used as a sports ground, park or amphitheatre during dry periods
- The length/width ration of the flow path is between 3:1 and 5:1 (CIRIA, 2015).
- The maximum depth is 2m (CIRIA, 2015).
- The slope of the vegetated basin bottom is up to 1 % for the direction of the outlet (CIRIA, 2015).

PLANNING GOALS

Flood Reduction
Water collection for reuse
Groundwater Recharge
Biodiversity
Urban Climate
Quality of Stay
Environmental Education

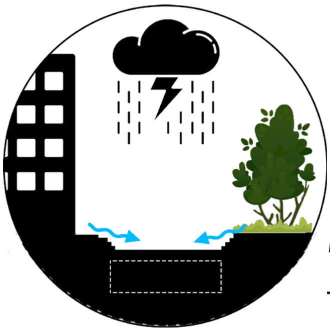
PROCESSES

- Storage
- Infiltration
- Filtration
- Evapo-transpiration
- Biological absorption
- Micro climate improvement

MAINTENANCE

- Removal of litter, debris, and sediment
- Regular inspection and cleaning of structural components especially after heavy rain events
- Maintenance of a healthy vegetation level, planting management, removal of invasive species (Andrukovich, 2019)

Figure 35: (Left) Detention pond (dry), Gelsenkirchen, Germany Source: (J. Eckart).
Figure 36: (Right) Detention pond (wet) in Tanner Springs Park, Portland, Oregon, USA Source: (J. Hoyer, 2011)



Multifunctional Spaces

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DESCRIPTION

A multifunctional public space for stormwater management serves not only as an area for public recreation and entertainment but also plays a vital role in urban water cycle management. These multipurpose spaces enhance city livability by providing social benefits and mitigating water hazards through Water Sensitive Urban Design (WSUD) measures. Planning these spaces involves integrating urban design, landscape planning, and water management. The most noTable example of such a multifunctional space is a water plaza.

DESIGN CONSIDERATIONS

- The sediment forebay has to be organized at the inlet zone.
- The construction may be protected by the waterproof layer from the groundwater.
- The volume calculation is based on the catchment area size.
- Outflow into a drain or next step in the drainage chain
- Can be integrated creatively into the urban landscape even where space is limited.

PLANNING GOALS

Flood Reduction	■■■
Water collection for reuse	■■□
Groundwater Recharge	■■□
Biodiversity	■■□
Urban Climate	■■□
Quality of Stay	■■■
Environmental Education	■■■

PROCESSES

- Infiltration
- Filtration
- Evapo-transpiration
- Biological absorption
- Micro climate improvement
- Conveyance

MAINTENANCE

- Litter and debris removal
- Weed removal to avoid clogging
- Occasional sediment removal.

Figure 37: (top) - The Tåsinge Plads combines the technical requirements of storm water management with the neighbourhood's desire for a green oasis and a local meeting space. Source: (Urban Waters 2024)

Figure 38: (bottom) - Part of the Tåsinge Plads that provides seating around green areas Source: (Urban Waters 2024)

In this project, the various measures when implemented have different processes involved. They are defined as follows:

- Infiltration —water seeping into the soil and aquifer recharge;
- Filtration—sediments separation from water by interposing a medium (filter); Sedimentation—sediments separation from water by setting it out of the fluid;
- Storage — conservation of cleaner water;
- Recycling — cleaner water reuse;
- Evapotranspiration – moisture transferring to the atmosphere by evaporation of water and transpiration from plants;
- Purification — water treatment through biological processes;
- Retention—the reduction of rainwater's peak flow and holding water volume at the source;
- Detention—the reduction of rainwater's peak flow and graduate water infiltration; Conveyance — control and rainwater flow transportation to a destination;
- Biological absorption –nutrients` uptake by plants from water and soil;
- Microclimate — improvement, for example, heat island effect reduction, shading, sun and wind protection.

Certain measures support a wide spectrum of processes. Some measures imply either retention or detention depending on the local conditions regarding groundwater Table and based on the applied system. Thus, collected by the raingarden water can be retained and then directed to the next destination such as urban wetland or canal. The second option is gradual discharge to the soil. A combination of these measures result in a cascading effect of stormwater, slowing down the runoff and managing it close to the site.However, the efficiency of these measures and processes needs to be further investigated in the context of arid climates. The selection of species for the planting in all these measures should be referred to from the research done by (Jaajaa et al. 2021) in their publication "Guide to Species Selection for Amman Public Open Spaces".

Chapter 5

Scenarios in Focus: Analysis of WSUD for Amman

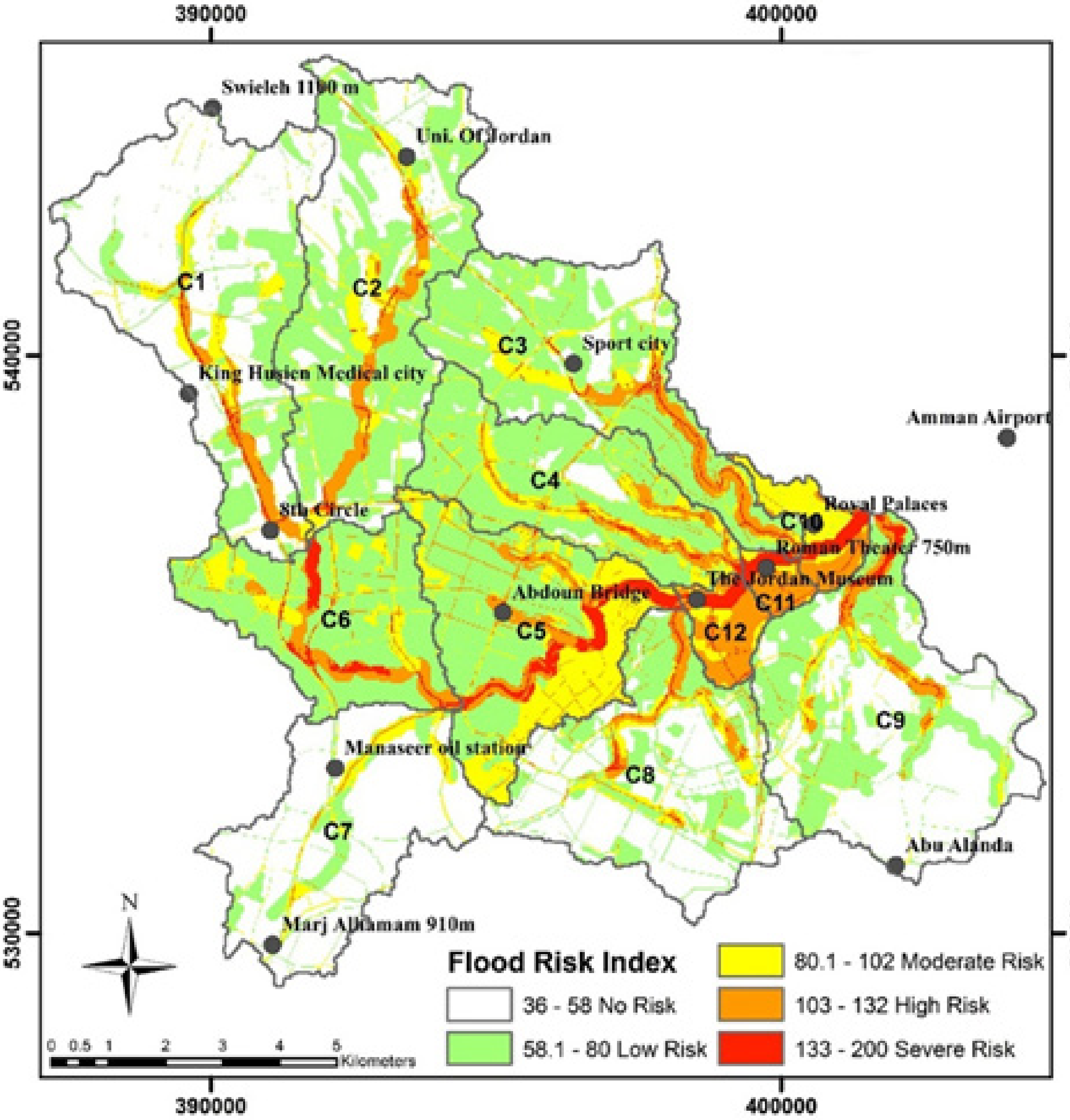


Figure 39: The division of Amman into catchments, flow paths of flood water and flood risk index based on topography. Source: INWR-DAM, 2021

5.1 Urban Analysis

The catchments in Amman as shown in Figure 39, depict a clear picture of flood risk according to topology, with the downtown area of Amman being at the highest risk. However, the surrounding catchments directly feed into the flow stream that leads to the centre, and since these areas are still developing, they have a high potential of implementing WSUD measures to minimize the flood damage closer to the source. Hence as shown in Figure 39, the catchment C7 is considered as the site. This Figure also shows the flow paths and sinks in the sub catchment. A detailed urban analysis of this catchment is carried out in the following pages to further understand the various layers of the area. This is done using GIS and base landuse data provided by Hamburg Wasser (2023). However it is important to note that different assumptions were made to fill in the gaps in the data. This was done by using satellite imagery and the information provided by Google maps. Therefore, due to constant development in the area and the inability to map these changes, the representation in the following maps as well as the area and subsequent volume calculations are estimations and to be used as a baseline or example, to be further developed upon. Based on this analysis, certain hotspots would be identified that are at a higher risk and show good potential for implementing measures.

5.1.1 Figure Ground Map

Figure 40: Figure Ground Map of the catchment
Source: Author, based on HW, 2024

A Figure -ground diagram employs a mapping method to depict the distinction between built and unbuilt spaces within urban settings as shown in Figure 40. It portrays the areas occupied by buildings as solid forms (Figure) and the communal areas such as streets, parks, and plazas as empty spaces (ground). According to Morphocode (n.d.), this map is used to explore built form patterns and the continuity and relation of open space. This map does not include construction sites as built areas. As per area calculations, as shown graphically in Figure 41, the area of the catchment is 1317ha while the built up area is 151ha, which is only 11.48 % of the total catchment area. As shown in the map, the lower part of the catchment is densely built with very less open space, while the upper catchment is yet to be developed.

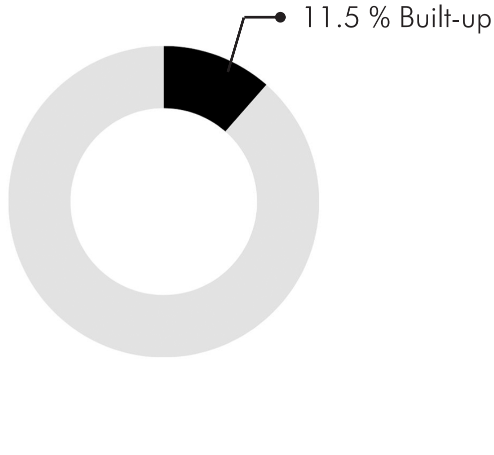


Figure 41: Graph showing the built and unbuilt areas in percentage of the total catchment area.
Source: Author, based on HW, 2024

5.1.2 Building Classification Map

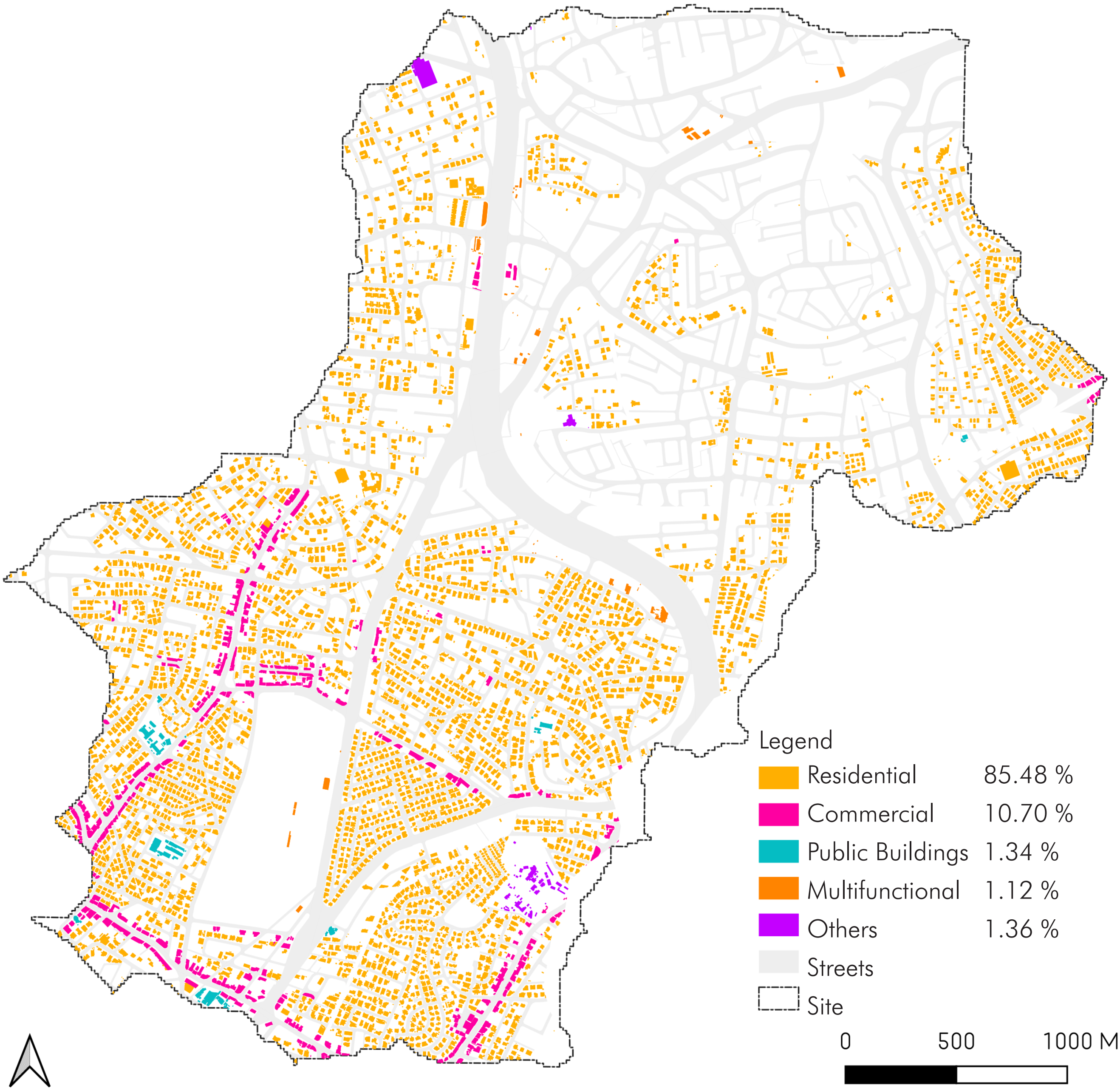


Figure 42: Building classification based on function
Source: Author, based on HW, 2024

The built up area is further classified in this map (Figure 42) based on their function. As shown in the map and in Figure 43, the area is dominated by residential buildings, with relatively few commercial buildings, and only 4 schools and adjoining religious buildings making up less than 2 % of public areas. In this classification, certain buildings had no information about their function and have been classified under "others". There are a few mutlifunctional buildings in the area, which are generally offices or commercial spaces shared with residences above them. From this map, we can gather that most of the built area may not be used for measures, however, a scenario has been designed to include residential buildings as well and their effect on managing the stormwater of a subcatchment.

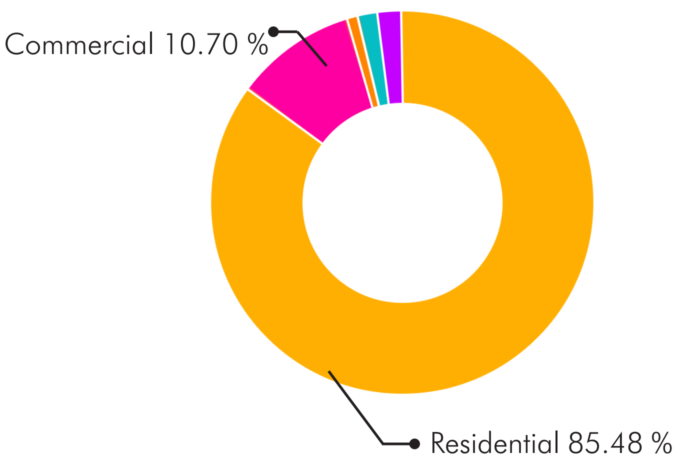


Figure 43: Graph showing the share of different building classifications.
Source: Author, based on HW, 2024

5.1.3 Residential Classification Map

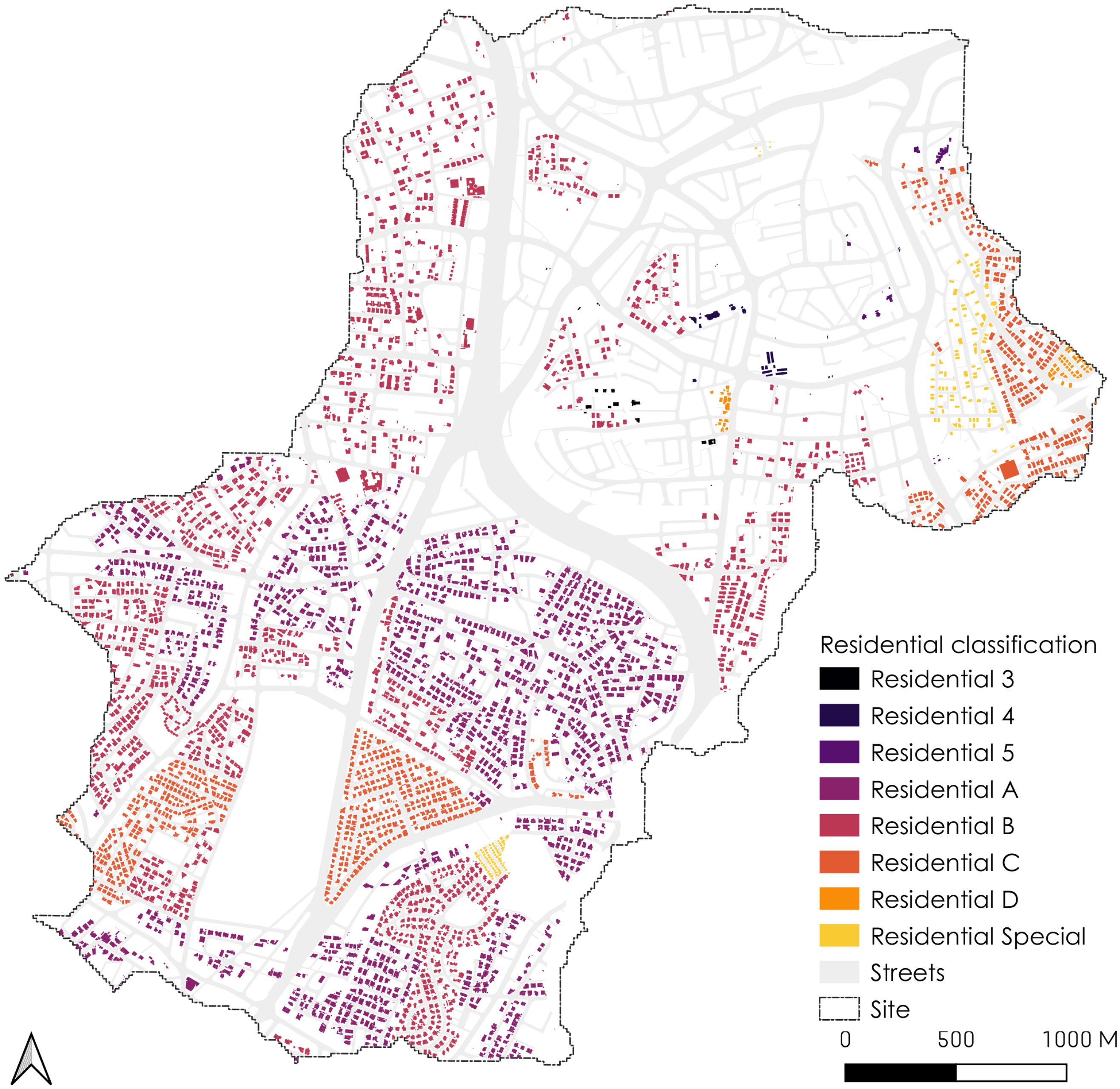


Figure 44: Classification of residential buildings based on typology
Source: Author, based on HW, 2024

Furthermore, the residential buildings are further classified based on data from HW(2024) into different categories based on planning regulations. This shows the potential to use the open spaces surrounding different residences to minimize the outflow of stormwater from their properties. Through this map (Figure 44), residences with more open space may be regulated for the same, while those with lesser open spaces may be compensated by other measures like underground storage tanks or limited outflow of stormwater. Figure 45 is a graphical representation of the share of different residential classes. A detailed description of the different building regulations for the basic 4 types of residential plots is described in Appendix D.

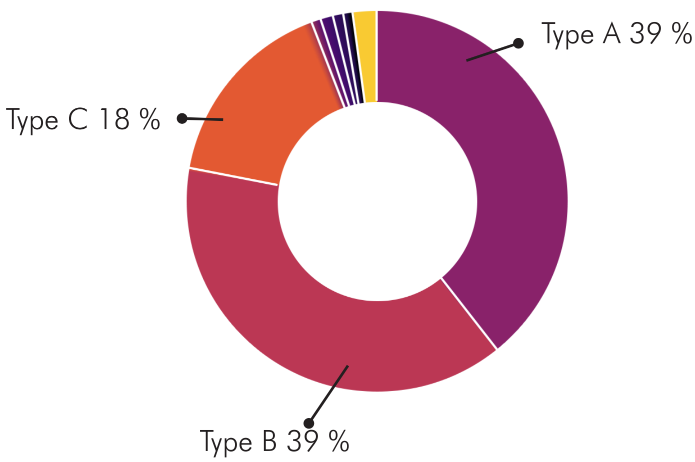


Figure 45: Graph showing the share of different residential classes.
Source: Author, based on HW, 2024

5.1.4 Landuse Map

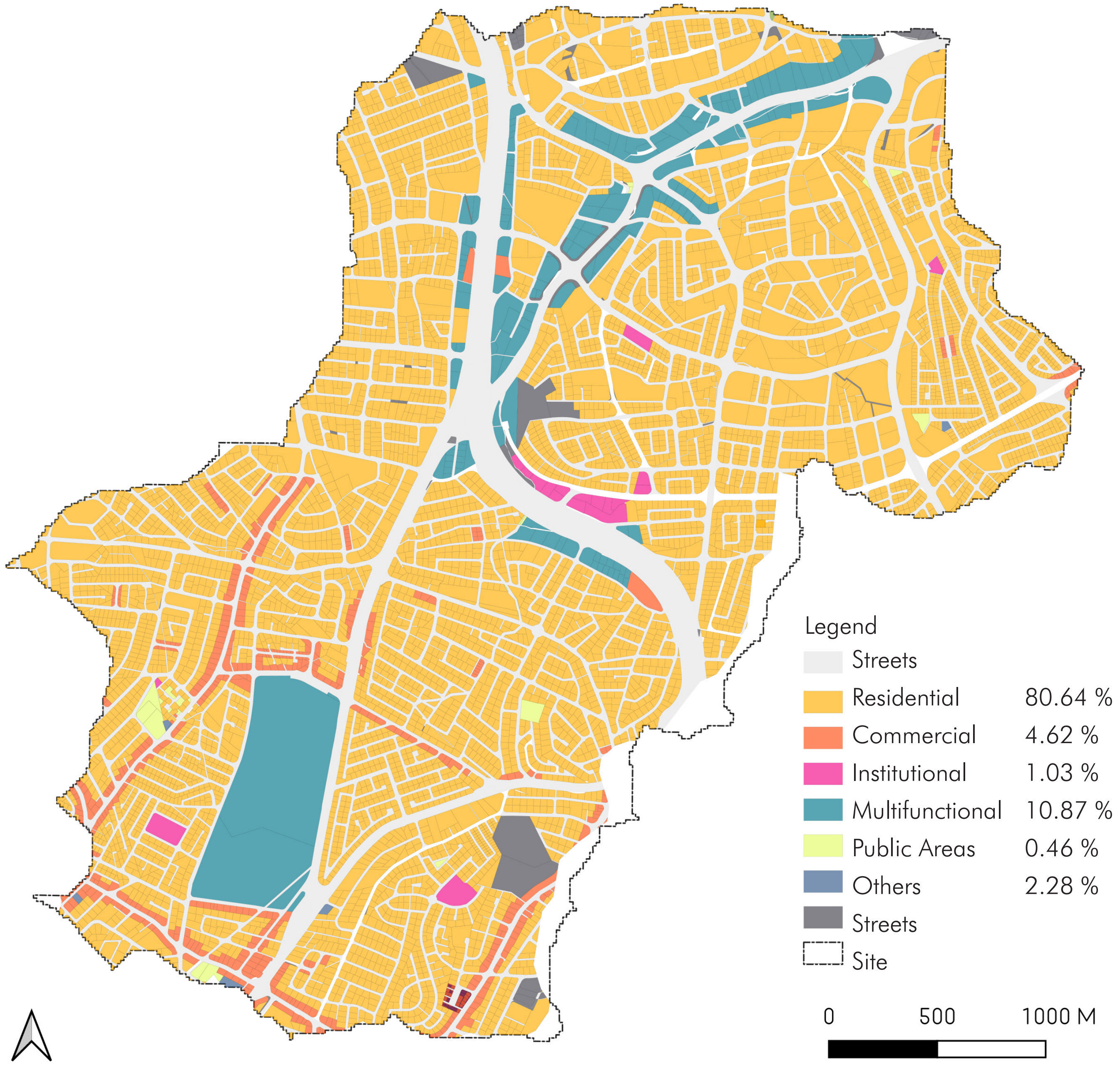


Figure 46: Landuse classification based on function
Source: Author, based on HW, 2024

The Land Use Map in Figure 46 depicts the Planned or Future land use designations that provide general guidance in the density, character and location of land uses and serves as a baseline for analysis. Here, the land use has been categorized into residential, commercial, institutional, multifunctional, religious,and public areas; and spaces that have no assigned function as of now are categorized as "others". This is done based on data from HW (2024), and open spaces assigned by landuse as well as those in schools and religious places are assumed as public space. It is observed in Figure 47 that this public space is less than 3 % of the entire catchment, while residential space is the highest, followed by multifunctional spaces. Most of the assigned multifunctional space is undeveloped at the moment but could have potential for implementing WSUD measures.

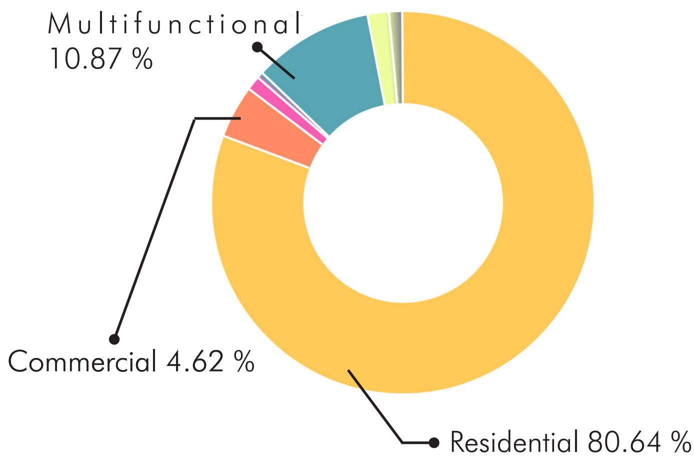


Figure 47: Graph showing the share of Landuse based on function.
Source: Author, based on HW, 2024

5.1.5 Development Map

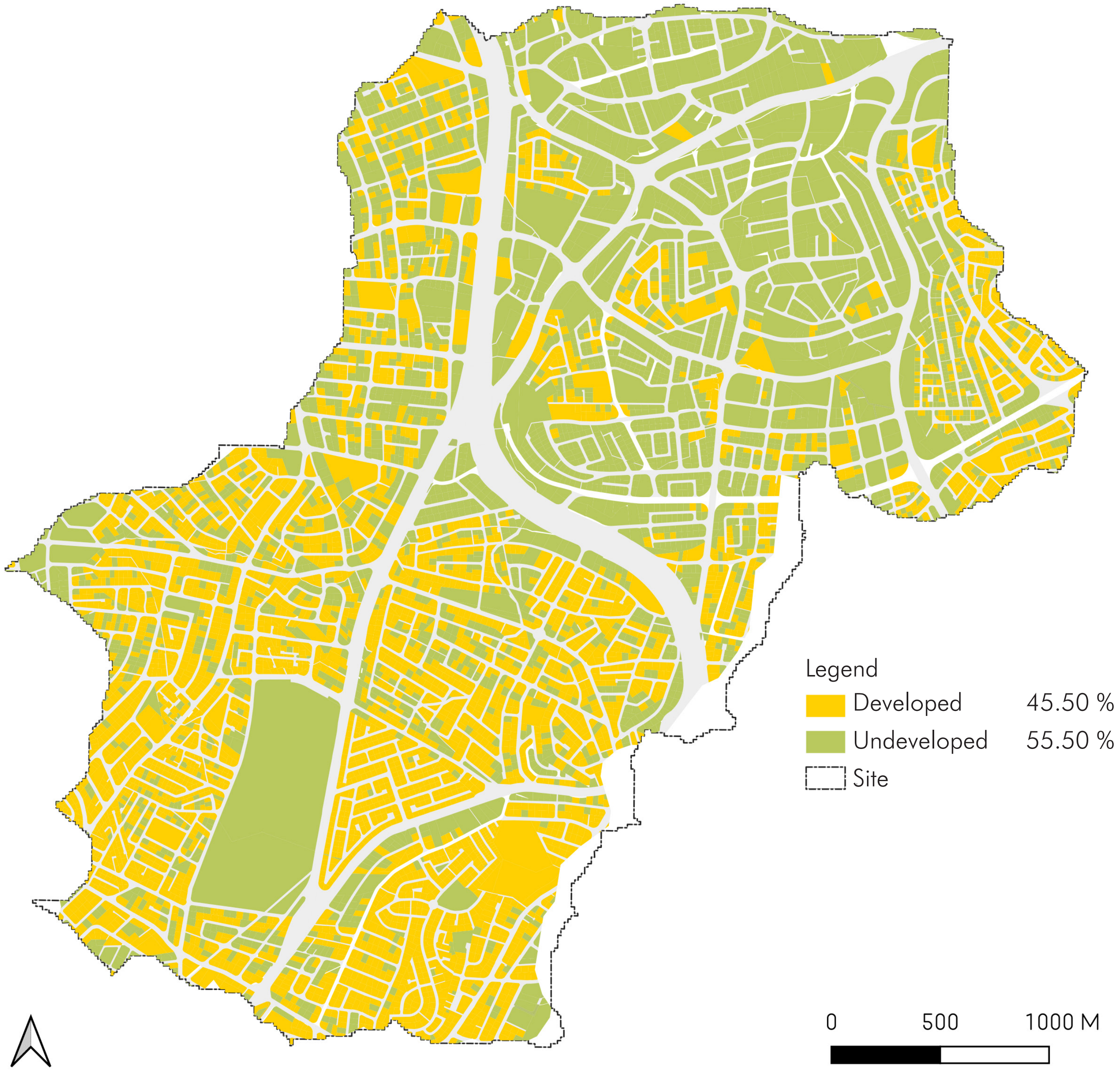


Figure 48: Classification of developed and undeveloped areas. Source: Author, based on HW, 2024

In this map, (Figure 48) the landuse is further categorized into developed or undeveloped areas. Here, construction sites are also considered under developed areas as for the purpose of this analysis, it shows an increase in the sealed areas. It is interesting to observe in the following maps that even though nearly half of the catchment is still undeveloped (see Figure 49), it contributes to the stormwater volumes accumulated at the end of the catchment. This further supports the argument that an increase in sealed areas will lead to an increase in the runoff volumes.

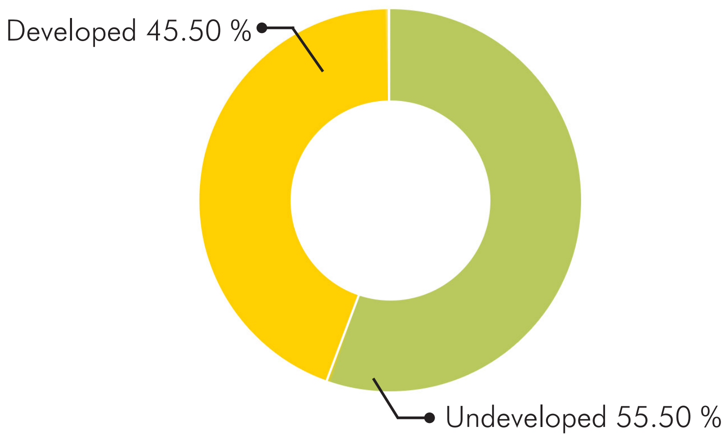


Figure 49: Graph showing the share of developed and undeveloped areas. Source: Author, based on HW, 2024

5.1.6 Public-Private classification Map

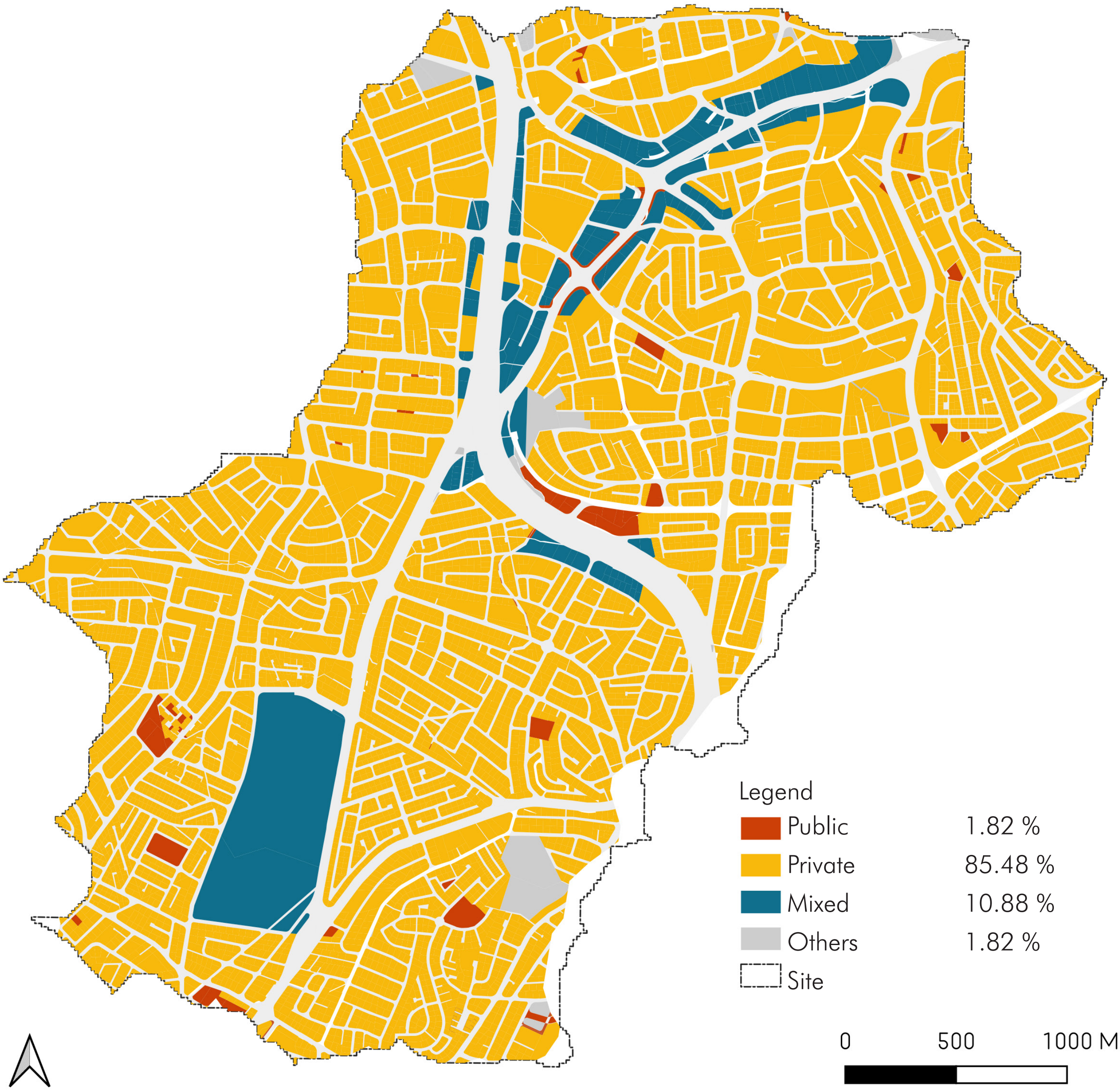


Figure 50: Classification of land based on ownership. Source: Author, based on HW, 2024

This map is classified on the basis of ownership of the land and is divided into public, private and mixed. The largest share of land is privately owned as most of it is residences or commercial spaces. Public land is merely spaces like schools and mosques and some open areas surrounding them. The mixed ownership is of multifunctional spaces as they are assumed to also have some public space along with private spaces. A summary of the shares of landuse ownership is shown in Figure 51 and is geospatially illustrated in Figure 50.

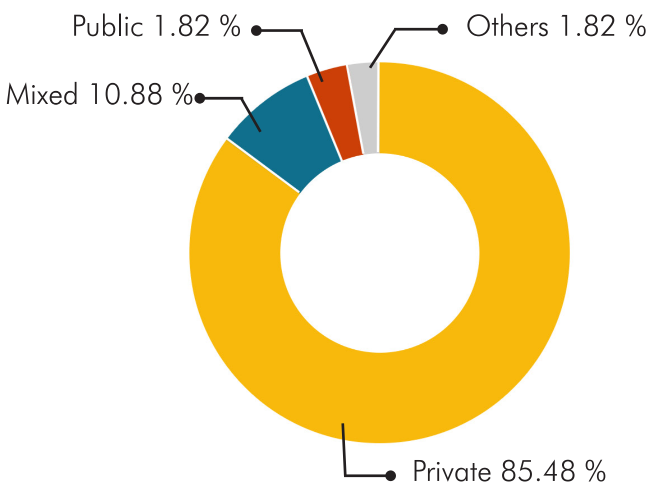


Figure 51: Graph showing the share of Landuse based on ownership. Source: Author, based on HW, 2024

5.1.7 Open Space Classification Map

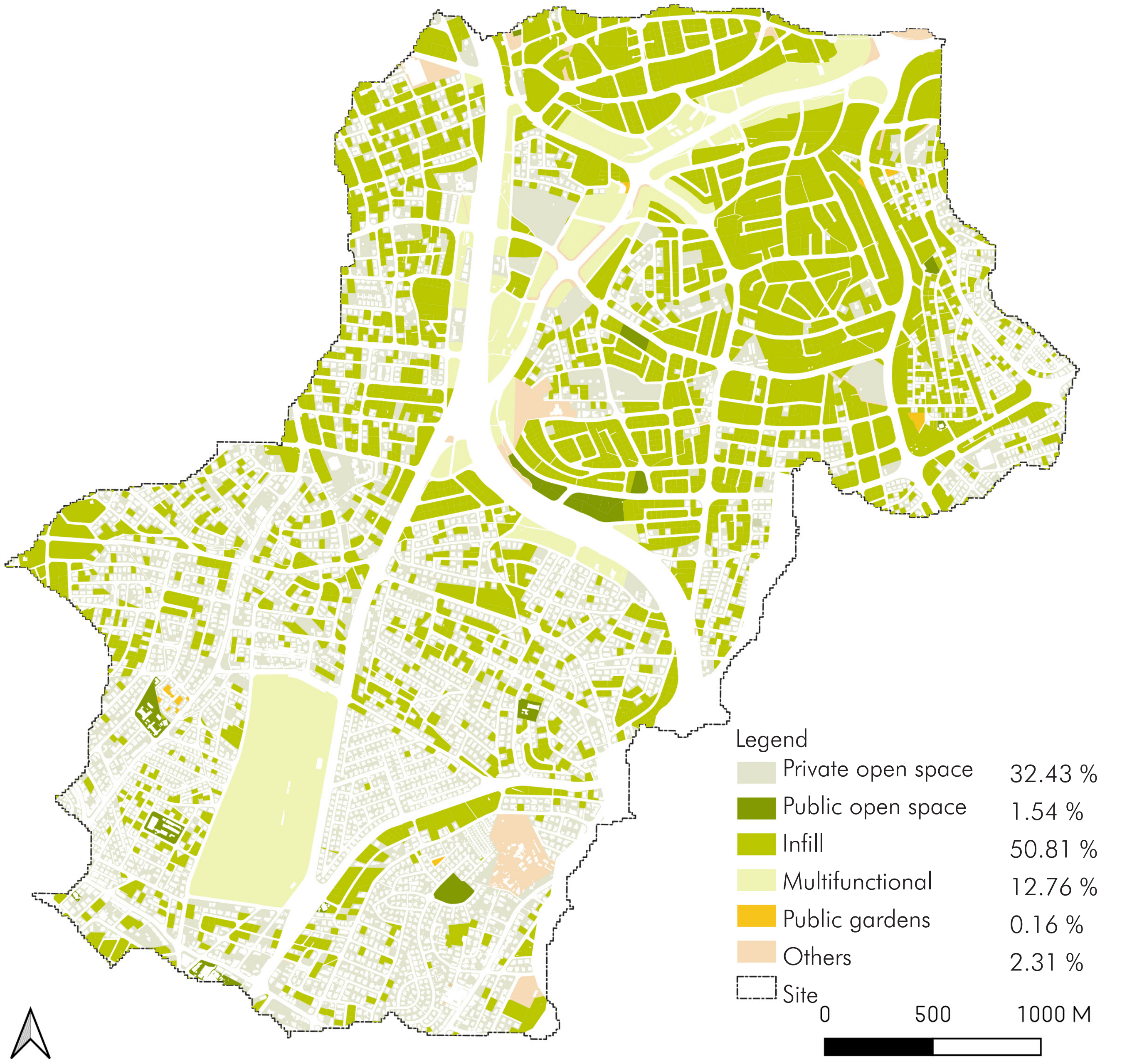


Figure 52: Classification of open spaces based on typology
Source: Author, based on HW, 2024

This map classifies all the available open space in the catchment based on their typologies as shown in Figure 52 and their share in Figure 53. It is interesting to note that most of the undeveloped space is referred to as "infill" instead of just being labeled undeveloped. Infill development refers to the practice of making improvements within existing urban areas, typically on underused or vacant land. This approach is designed to curb urban sprawl by optimizing the use of existing infrastructure and promoting denser, more walkable communities. Such developments can range from residential homes to businesses and public spaces, aiming to enhance neighborhoods and reduce environmental impacts by avoiding the need for new infrastructure (Urban Design Lab, 2023). Therefore, this shows the potential areas that may be repurposed for the inclusion of WSUD strategies.

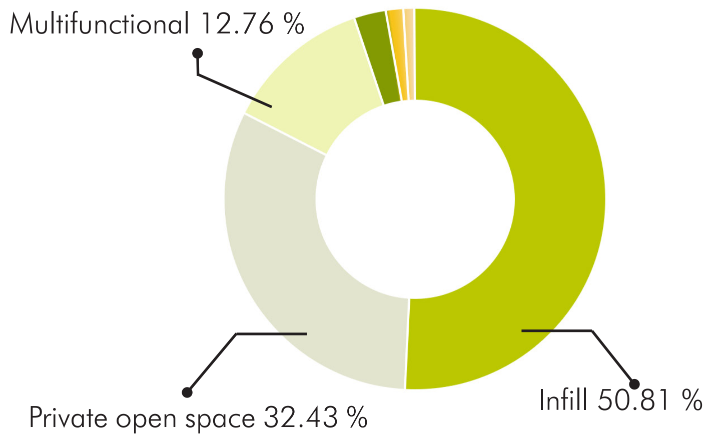


Figure 53: Graph showing the share of open space typologies.
Source: Author, based on HW, 2024

5.1.8 Hydraulic Map

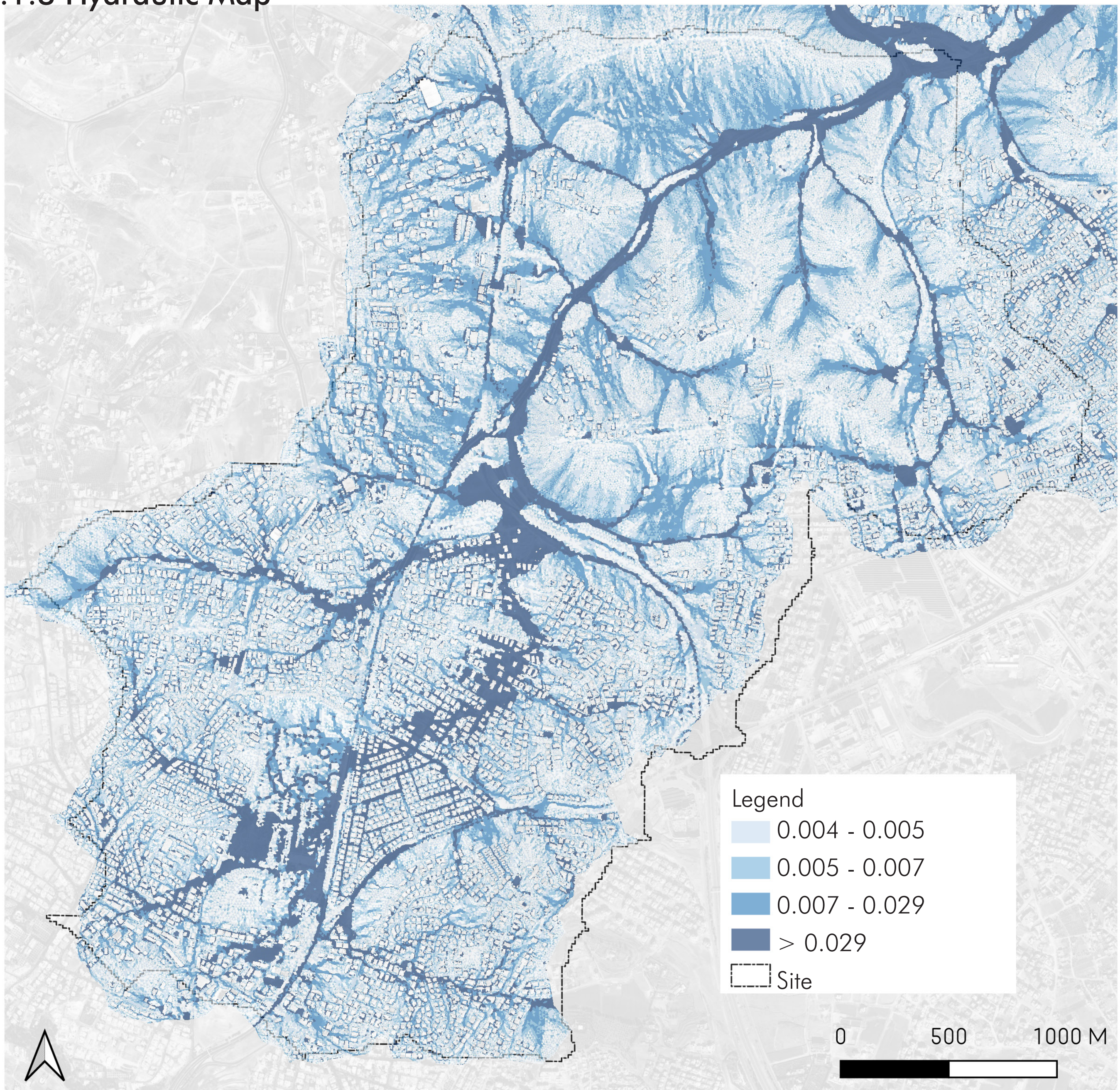


Figure 54: Hydraulic map showing sinks and flow paths
Source: Author, based on HW, 2024

The map in Figure 54 depicts the rainfall data of the 2019 flood event as per HW, 2024. It shows the sinks in the topography and where the water gets collected the most. It can be observed from this map that most of the water flows along streets naturally as they are lower than the built up areas. The runoff flows along the highway towards the north east where lies the lowest outlet of the catchment. It may also be observed that some of the residential areas are highly affected due to the large volumes of water being collected there.

5.1.9 Identification of Hotspots

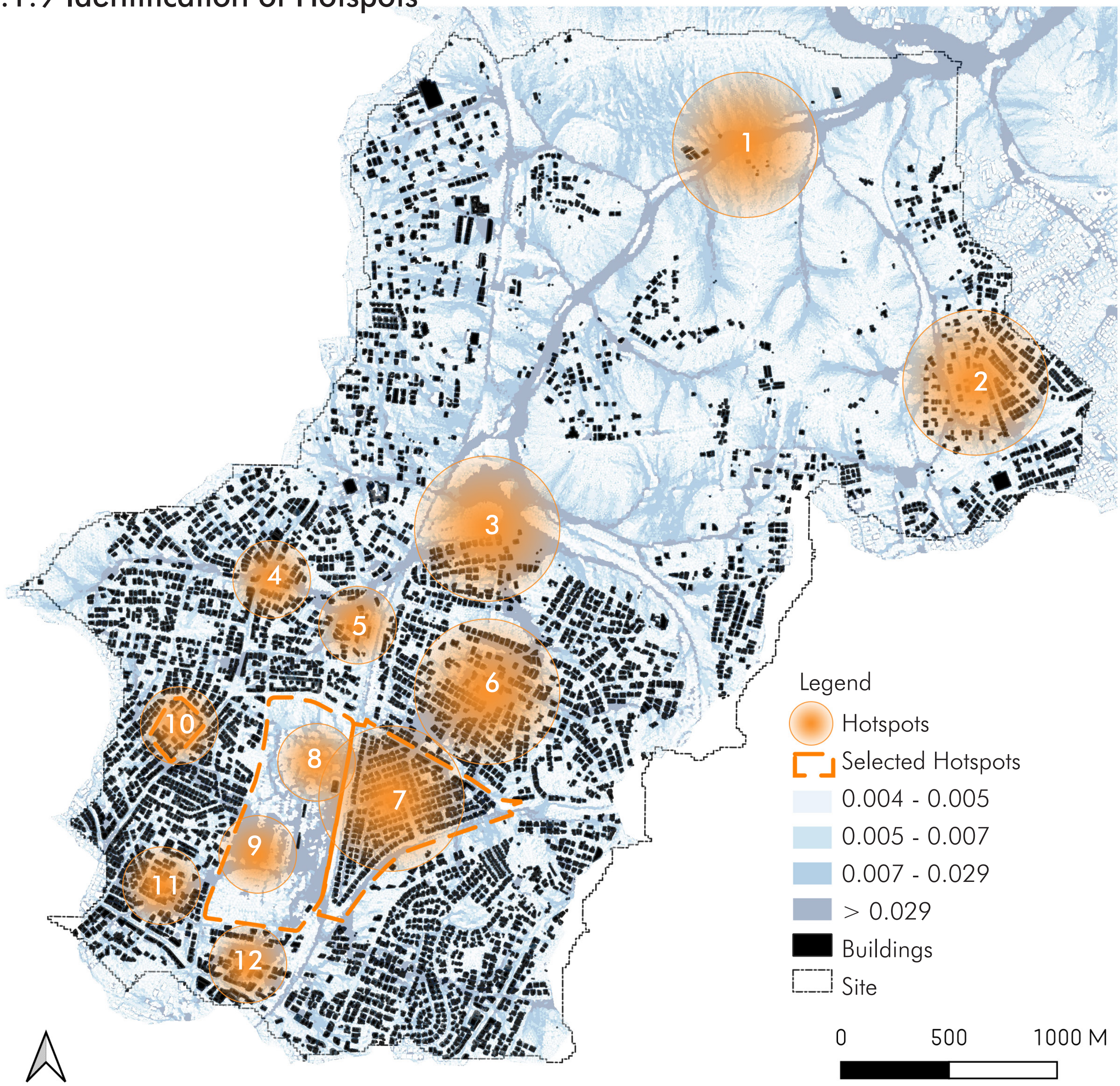


Figure 55: Identification of hotspots
Source: Author, based on HW, 2024

Identification of hotspots has been illustrated in the Figure 55, by overlaying the landuse or satellite image and hydraulic maps, pointing out areas that are at a risk of flooding. This also includes the undeveloped areas. To better understand this, each of the hotspots has been ranked for their level of risk and potential for implementation of WSUD measures as low, medium and high. For example, public spaces and open spaces have high potential for implementation of wsud, and low lying areas and sinks in the hydraulic maps show spots of high risk. The hotspots and their rankings have been described in Table 5. A matrix of these hotspots is depicted in Figure 56, according to their level of risk and potential.

Further, their typologies have been identified and 3 hotspots have been chosen, from each of the typologies. These are, as per the numbers designated:

1. Hotspot 7: The high density residential quarter with high risk and low potential due to lack of public space except for streets, as given the land use, most of the catchment will be developed on the same pattern. This is Hotspot C
2. Hotspot 8+9: The mixed use development of the Royal village project has been combined and analysed as a single hotspot (Hotspot B) as it is at high risk and has high potential of implementing WSUD before construction
3. Hotspot 10: This is a quarter with a school, a mosque and apartment buildings and has a high potential given the availability of open space in the school and public gardens, hence represents public areas, Hotspot A.

An in-depth analysis of these hotspots has been carried out in the next section.

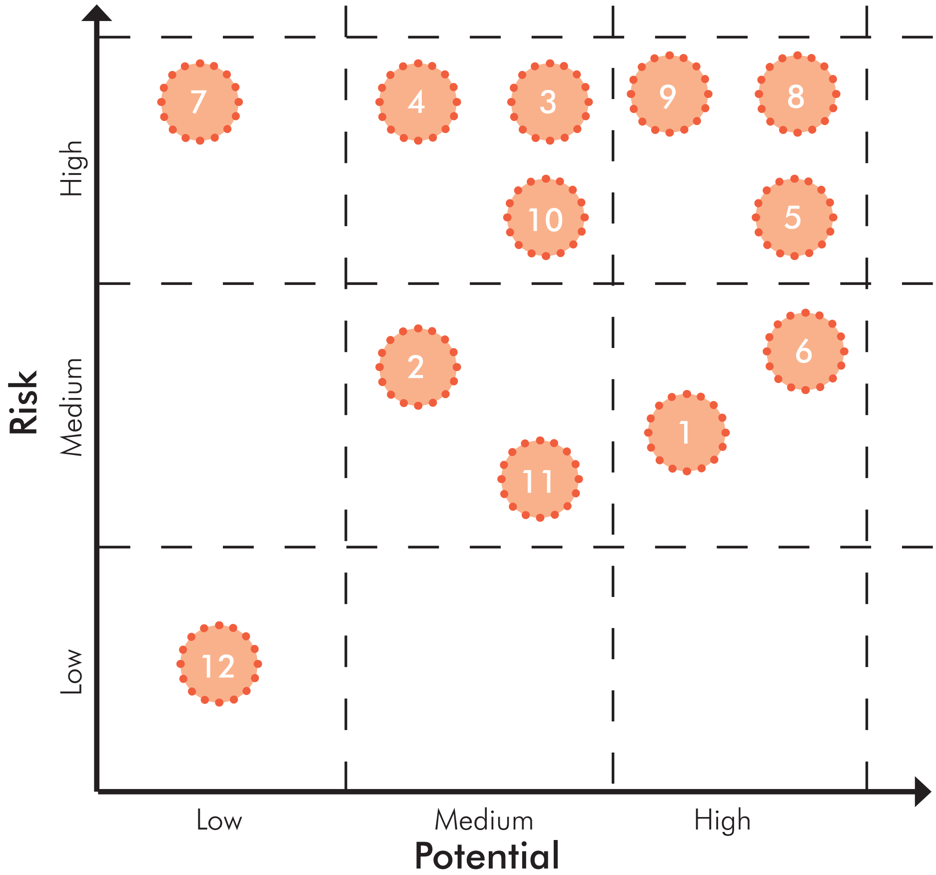


Figure 56: The Risk - Potential matrix for all the hotspots
Source: Author

Table 5: Description of the hotspots. The selected hotspots for further analysis have been highlighted.
Source: Author

Hotspot Number	Typology	Description	Risk	Potential
1	Streets	Highway and surrounding areas towards the north of the catchment	Medium	High
2	Residential	Developing residential neighbourhood with no public space	Medium	Medium
3	Streets	Intersection of 2 major roads and surrounding residential area	High	Medium
4	Residential	Existing semi developed residential area with no public open space	High	Medium
5	Residential	Existing semi developed residential area and street intersec-tions	High	High
6	Residential	Medium density residential area with no public space	High	Medium
7	Residential	High density residential quarter with no public open space	High	Low
8	Mixed Use	North-east part of the Royal Village project (Offices as per proposal)	High	High
9	Residential	South-west part of the Royal Village Project (Residential as per proposal)	High	High
10	Public area/ Mixed use	School, mosque and residential buildings, with unused open space and public gardens	Medium	High
11	Public area	School and surrounding residential area with some open space in the school grounds	Low	Medium
12	Public area	School and surrounding residential and commercial area with limited open space	Low	Low

Figure 57: This map shows an overlap of the hydraulic map showing the flows and sinks on the map showing different functions of buildings and open spaces for the Hotspot A - Public Areas. Source: Author, based on HW, 2024

5.2 Hotspot Analysis

5.2.1 Hotspot A: Public Area

5.2.1.1 Description

This area lies in the southwestern part of the catchment. It is a mixed-use area with multistorey apartment buildings, the Aysheh Bent Abu Bakr Girls Secondary School, a mosque, a few public gardens, and an undeveloped open space that belongs to the school but is currently just being used partially as a parking space and is unpaved (Figure 57). The hydrological maps show a significant volume of stormwater flowing through the school area and the street south of it. While the structures within this hotspot are not at high risk from flooding, the open spaces have a high potential to implement WSUD measures.

5.2.1.2 Identification of types of surfaces and areas

For each of the hotspots, the first step is to identify the different surfaces and materials that are impermeable, such as streets, rooftops, paved areas etc., as well as permeable surfaces like green areas, playgrounds, parks, etc as shown in Figure 58. This is done using GIS and satellite imagery and the areas of the respective polygons are obtained. A detailed analysis of the types of surfaces shows that all building rooftops are flat surfaces and are cemented. The streets are made of asphalt and while calculating the area of the streets, pedestrian sidewalks are not considered as a part of the street due to a change in surface. It must also be noted that the GIS data coupled with satellite imagery does not give us a very accurate picture of the size and material of sidewalks, hence for simplifying the calculations, minor streets are considered to be entirely of asphalt with no sidewalks, unless shown in maps. However, the sidewalks and pavements that are marked are assumed to be made of paving blocks with closed joints. This also includes the pedestrian plazas and pathways around the buildings' open spaces.

Further, the "undeveloped open spaces" are the areas that have not yet been built upon and no vegetation has been intentionally planted. These spaces are visible as patches of dry land on satellite images with sparse

Figure 58: Map of Scenario 1 - The different surfaces within the hotspot as identified by satellite images in the existing conditions. Source: Author, based on GIS analysis, 2024

to no vegetation. On the other hand, "existing green areas" are parcels of land that have been intentionally kept green and are home to local species of bushes and trees. These areas are assumed to be well irrigated and maintained for aesthetic purposes.

Private gardens for this particular hotspot are the green areas surrounding the apartment buildings. Since a very accurate measurement of the sealed and unsealed surfaces within these areas could not be acquired, an assumption of 40 % green area and 60 % paved area is made, to accommodate the parking spaces and pedestrian pathways that dominate this open space. On the other hand, public gardens in this hotspot are the highlight and the spaces with the highest potential. These areas are assumed to be fully vegetated, and though some pedestrian paths may exist, they are considered to be also made of porous surfaces.

A brief summary of these types of surfaces along with their areas and share in the total hotspot area are shown in Table 6.

Type of Surface	Description	Permeable Area	Impermeable Area	Total Area (Ac)	% of total Area
		m²	m²	m²	
Building Roof-tops	Flat and cemented, both residential and public buildings		10628.52	10628.52	22 %
Streets	Asphalt		3857.15	3857.15	8 %
Paved Area	Concrete pavings, and sidewalks with closed joints. 90 % of the area is paved around the school, and 10 % is permeable for the existing trees on site	1495.52	13932.06	15427.58	32 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.	5689.456		5689.46	12 %
Existing Green Areas	Areas with planted vegetation existing on site	744.782		744.78	2 %
Private Gardens	Areas around residential buildings. Based on satellite imagery, 40 % is assumed to be green, while 60 % is paved.	3148.7348	4723.1022	7871.84	16 %
Public Gardens	Areas for public use, with no pavements as per satellite imagery	3513.401		3513.40	7 %
	Total	**14591.89**	**33140.83**	**47732.72**	
		31 %	**69 %**		

Table 6: Description of types of surfaces, their areas in Scenario 1 and share of the total area of the hotspot. Source: Author, based on GIS analysis, 2024

5.2.1.3 Conceptual design of WSUD measures for Scenarios 2 and 3

For the second scenario, measures have been implemented in public spaces in an attempt to increase the unsealed areas within this hotspot. Firstly, focusing on the school, the paved area around the school buildings has been reduced, including the undeveloped space to create new green areas. This area has a huge potential for aesthetically incorporating swales, raingardens, stormwater planters and even retention and detention areas for heavy rainfall events. In the dry periods, it can be used as a huge playground for the students at the school during school hours and may even be open to public after school hours, essentially creating a multifunctional space. For the sake of calculations, these measures are detailed out later as recommendations and for now is simply taken as an increased permeable surface.

Figure 59: Map of Scenario 2 - Conceptual design of measures in public areas
Source: Author

Next, the roofs of the school building and mosque are identified as flat and suiTable to implement green roofs. Swales and infiltration trenches are combined into this area along the streets as shown in Figure 59 and come under the category of bioswales to improve infiltration as well as facilitate conveyance of runoff from streets and surrounding areas towards the open green space created in the school grounds. Additionally, two raingardens have been incorporated into the paved area in front of the school buildings, further unsealing the space and providing intermediate infiltration. Lastly, since the undeveloped space was being used partially as a parking space, a new parking space has been incorporated with permeable paving. This measure has also been suggested for the parking spaces and ends of streets around the residential buildings, decreasing the asphalt street surface. The public gardens are considered the same with no change and just as permeable surfaces for the sake of calculations. However, they can of course be improved in their retention capacities and aesthetic and functional value by implementing measures as recommended in further sections.

For the third scenario, that includes private spaces as well, it is considered that all the water from the rooftops of the apartment buildings is collected and contained within their respective open spaces as depicted in Figure 60. All the areas for the different surfaces and measures are described in detail in Table 7.

Figure 60: Map of Scenario 3 - Conceptual design of measures in public and private areas
Source: Author

5.2.1.4 Quantitative Analysis

As mentioned in section 2.5, the runoff volumes and runoff rates are calculated iteratively for all three scenarios over a duration of 24 hours with the rainfall intensity of a return period of 5 years. For the runoff volume calculation, firstly, the different areas of permeable and impermeable surfaces are multiplied by the assumed mean runoff coefficients as in equations 1 and 2. These change as the surfaces change by implementing WSUD measures in different scenarios and can be observed in Tables 8 and 9. For the third scenario, the building rooftops of the private buildings is simply removed from the calculation as it is assumed that the volume of stormwater runoff is managed within the private property and this change in Figure s can be observed in Table 10. However, it is only the rooftop water that is negated, the reduced outflow from private property is still included in the calculation.

Scenario 2					
Type of Surface	Description	Permeable Area	Impermeable Area	Total Area (Ac)	% of total Area
		m²	m²	m²	
Building Rooftops	Flat and cemented, both residential and public buildings		5109.93	5109.93	12 %
Streets	Asphalt		1352.90	1352.90	3 %
Paved Area	Concrete pavings, sidewalks with closed joints. 90 % of the area is paved around the school, 10 % is permeable for the existing trees on site	603.38	5430.39	6033.76	14 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.		0.00	0.00	0 %
Exisiting Green Areas	Areas with planted vegetation exisitng on site	780.45		780.45	2 %
Private Gardens	Areas around residential buildings. Based on satellite imagery, 40 % is assumed to be green, while 60 % is paved.	2968.30	4452.46	7420.76	17 %
Public Gardens	Areas for public use, with no pavements as per satellite imagery	3513.40		3513.40	8 %
Blue Green Measures					
New Green areas	Permeable area created out of previously sealed or undeveloped open space	7677.53		7677.53	17 %
Green Roofs	Implementing semi intensive or intensive on flat roofs of all public buildings	5506.24		5506.24	12 %
Bioswales	Shallow pits that are vegetated for retention and conveyance of stormwater	928.34		928.34	2 %
Permeable Pavement	Paving blocks with loose joints to increase permeability of the area	5485.27		5485.27	12 %
Raingarden	A landscaped area that captures and filters rainwater runoff	378.18		378.18	1 %
	Total	**27841.09**	**16345.67**	**44186.77**	
		63 %	**37 %**		

Table 7: Description of types of surfaces, their areas in Scenario 2 and share of the total area of the hotspot. Source: Author

Scenario 1				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m^2		m^2	m^2
Building rooftops	10628.52	0.90	9565.66	
Streets	3857.15	0.90	3471.44	
Paved	15427.58	0.75	11570.69	
Existing Green	744.78	0.20		148.96
Public Gardens	3513.40	0.10		351.34
Private Gardens	7871.84	0.30		2361.55
Undeveloped Open Space	5689.46	0.40		2275.78
Total	**47732.72**		**24607.79**	**5137.63**

Table 8: Calculation of reduced areas for Scenario 1
Source: Author

Scenario 2				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m^2		m^2	m^2
Building rooftops	5109.93	0.90	4598.94	
Streets	1352.90	0.90	1217.61	
Paved	6033.76	0.75	4525.32	
Existing Green	780.45	0.20		156.09
Public Gardens	6419.96	0.10		642.00
Private Gardens	7420.76	0.30		2226.23
Undeveloped Open Space		0.40		0.00
New Green	7677.53	0.10		767.75
Green Roofs	5506.24	0.40		2202.50
Bioswale	928.34	0.20		185.67
Permeable Pavement	5485.27	0.30		1645.58
Raingarden	378.18	0.10		37.82
Total	**47093.33**		**10341.87**	**7863.63**

Table 9: Calculation of reduced areas for Scenario 2
Source: Author

Scenario 3				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m^2		m^2	m^2
Building rooftops	0.00	0.90	0.00	
Streets	1352.90	0.90	1217.61	
Paved	6033.76	0.75	4525.32	
Existing Green	780.45	0.20		156.09
Public Gardens	6419.96	0.10		642.00
Private Gardens	7420.76	0.30		2226.23
Undeveloped Open Space		0.40		0.00
New Green	7677.53	0.10		767.75
Green Roofs	5506.24	0.40		2202.50
Bioswale	928.34	0.20		185.67
Permeable Pavement	5485.27	0.30		1645.58
Raingarden	378.18	0.10		37.82
Total	**41983.40**		**5742.93**	**7863.63**

Table 10: Calculation of reduced areas for Scenario 3
Source: Author

In the next step, the runoff volumes are calculated as per equations 3, 4 and 5 in section 2.5 for the three scenarios and the results are described in Table 11. It is observed that for scenario 1, that is the current status quo, a maximum runoff volume of 1528 m^3 is collected after 12 hours of rainfall. On the other hand, by implementing measures in public areas in scenario 2, the peak runoff volume is reduced to 404 m^3 and after around 9 hours, all the water is managed on site. This is reduced further in scenario 3, where the maximum runoff is 216 m^3 after 2 hours of rainfall and is completely managed on site after 3 hours. The comparison can be seen graphically in Figure 61.

Duration	Rainfall intensity	Volume S1	Volume S2	Volume S3
min	l/s ha	m^3	m^3	m^3
5	169.02	172	97	69
10	123.15	245	133	92
15	107.86	319	170	116
30	83.4	480	243	160
60	63.11	700	326	201
120	47.26	993	404	216
180	38.64	1157	402	172
360	27.69	1469	287	-43
720	18.54	1528	-288.26	-730
1440	10.29	509	-2135	-2625

Table 11: Runoff volumes for the three scenarios
Source: Author

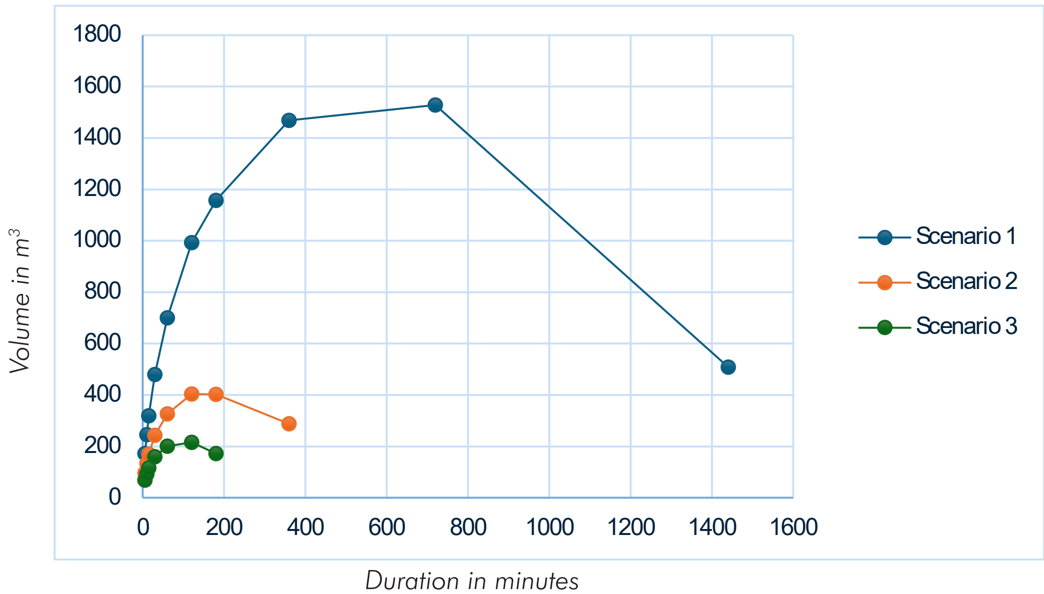


Figure 61: Runoff volumes for the three scenarios
Source: Author

Further, a calculation of the peak runoff rates is also done following the described method in section 2.5. The peak flow describes the maximum discharge during the period of runoff caused by a storm over an area (Sen 2015). In order to calculate it for the three scenarios as per equation 6, the areas of different sealed and unsealed surfaces are taken, multiplied by their respective runoff coefficients as in Tables 8 and 9, and then cumulated to form area (A). This value is then multiplied by the different rainfall intensities in mm/hr for different times of concentration as in equation 8. The values are shown in Table 12 and are graphically depicted in Figure 62.

The calculations show that the discharge rate peaks in the first 5 minutes of rainfall and is the highest in scenario 1 which has the highest percentage of sealed surfaces. Lowering the sealed surfaces in scenario 2 and 3 by introducing WSUD measures lowers the peak runoff rates as well. While a major difference can be seen between Scenario 1 and 2, disconnecting the building rooftops in scenario 3 does not create a major difference in comparison to scenario 2.

		Scenario 1	Scenario 2	Scenario 3
Area (A)		29745.42	18205.50	13606.56
Duration	Rainfall Intensity	Runoff Rate (Q)		
min	*mm/h*	*l/s*		
5	60.80	502.77	307.72	229.98
10	44.30	366.33	224.21	167.57
15	38.80	320.85	196.37	146.77
30	30.00	248.08	151.83	113.48
60	22.70	187.71	114.89	85.87
120	17.00	140.58	86.04	64.30
180	13.90	114.94	70.35	52.58
360	9.96	82.36	50.41	37.67
720	6.67	55.16	33.76	25.23
1440	3.70	30.60	18.73	14.00

Table 12: Runoff rates for the three scenarios
Source: Author

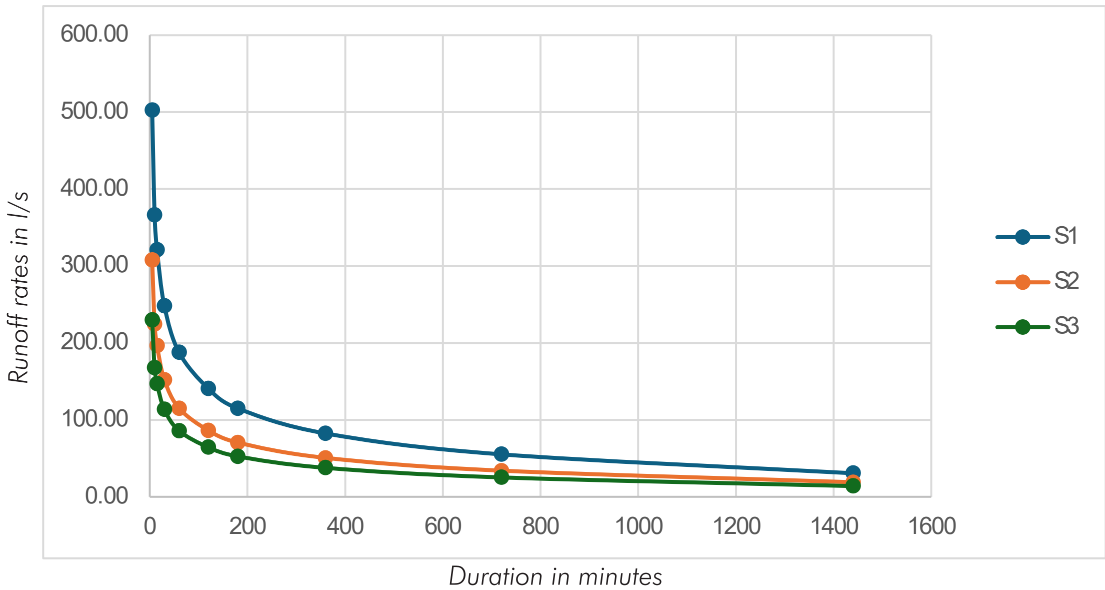


Figure 62: Runoff rates for the three scenarios
Source: Author

5.2.1.5 Further design recommendations

To accurately calculate the water holding capacity of the measures mentioned before, several factors need to be considered.

1. Soil Type and Porosity: Different soil types have varying water retention capacities. Sandy soils drain quickly, while clay soils retain more water. As mentioned before and used in the calculations, this area has sandy loamy soil with a good infiltration capacity.

2. Depth of the measure: The depth of the measure such as a rain garden or swale determines how much water it can store. For example with a depth of 0.3m, that's the maximum amount of water it can hold vertically.

3. Vegetation and Mulch: Plants and mulch within the rain garden can affect its water holding capacity by absorbing and slowing down the movement of water. This factor needs to be considered based on the types of plants and amount of mulch present.

4. Slope and Drainage: The slope of the land and drainage patterns surrounding the measure can affect how much water it receives and retains during rainfall events.

To estimate the volumes of stormwater that can be collected in the measures designed for this project, only the dimensions of the measures are considered, that is, the area calculated before multiplied by the design depth. For more accurate volumes, the conceptual designs can be detailed further and simulated in softwares such as STORM or SWMM.

1. Green roofs:

Green roofs are considered to be semi intensive to intensive so an average depth of substrate varies between 0.15 - 0.6m and is assumed to be 0.5 for this scenario. Further depending on different types of substrates a green roof can hold between 30 % - 60 % of its volume in water. Here it is assumed that it can hold 50 % of its volume. Therefore, with an area of 5506.24 m^2 and a depth of 0.5m, the actual volume of the green roofs would be 2,753.12 m^3. But since its capacity is only 50 %, the volume of water it can actually hold is 1,376.56 m^3.

2. Bioswales:

Bioswales are introduced in this hotspot to convey the runoff from the surrounding streets, especially the one to the south of the hotspot that is vulnerable to flooding, towards the open space of the school. With an area of 928.33 m^2 and depth of 0.3m, it has the capacity to hold 278.5 m^3 of runoff. Bioswales have also the capacity of increased infiltration, therefore slowing down the discharge rates as well as the runoff volumes. However this factor is not taken into account here while calculating the volume.

3. Raingardens:

Raingardens are shallow landscaped depressions that not only reduce the runoff rates and volumes but also treat for water quality through engineered soils and plantation. Therefore, with an area of 378.182m^2 and a depth of 0.3m, the capacity of the raingardens depicted in Figure 58 is 113.45 m^3.

4. Rooftop RWH:

Rooftop rainwater harvesting is the measure assumed for the third scenario, where the runoff from the roofs is assumed to be managed within the private plots, utilising the open space. In this scenario, the disconnection of rooftop reduces the runoff volume from 404 m^3 to 216m^3. Which means that tanks of the capacity 118 m^3 needs to be installed in the private properties. This can be done simply by diverting the drain outlet from the roof into a tank for collection and reuse within the household. However, this water may also be diverted into a raingarden within the open space of a private property, through swales, hence slowing down the runoff, and creating an aesthetic flow and use of the stormwater as depicted in Figure s 85 and 86 in section 5.2.3.5. The excess or overflow from the raingarden may then still be collected in an underground tank, but it would go through layers of infiltration, hence yielding a better quality of water stored.

In this hotspot, the private buildings are multistoreyed apartment buildings, that have common access to public parks. Therefore, instead of merely installing tanks, this rooftop runoff can be used in more dynamic ways and can be creatively integrated in to the landscape as shown in Figure 63. This Figure depicts a case example of 10th@Hoyt Apartments complex in Portland, Oregon where a system of concrete channels and cascades routes the water from the roof into the courtyard, where it visibly flows over back lit and coloured glass dotted Cor-Ten steel weirs into rectangular river stone filled detention basins and a cistern.

Figure 63: 10@Hoyt Apartments is focused on the activation of water in the landscape. Water flows through Cor-Ten steel channels from the rooftops into detention beds filled with river stones. The area, though not entirely unsealed, has green elements combined with open seating and integrates stormwater into the landscape in an artistic manner. Source: (Koch Landscape Architecture 2019; Paragon Corporate Housing 2023)

The Table 14 shows a comparison of the runoff volumes for heavier rainfall scenarios, with a return period of 25 years and 100 years, for all 3 design scenarios to get an idea of whether the conceptual measures would have the capacity to attenuate these volumes.

The total attenuation capacity for the measures in scenario 2 is 1769 m^3 which hugely surpasses the requirements even in a 100 year rainfall event (1132 m^3) as shown in Table 13. This indicates that the measures recommended can be decreased. For example, the green roofs on the school and mosque buildings need not be implemented on 100 % of the roof area for stormwater management purposes. Even if it was to be decreased by 50 %, the runoff can be managed on site with other measures. Additionally, the integration of rooftop RWH decreases the system runoff volume by attenuating a volume of 118 m^3, which might be even reused as per the feasibility on site. For a 5 year rainfall event, after scenario 3, only a volume of 216 m^3 needs to be attenuated which can easily be done with the help of bioswales alone, that have the capacity of 278 m^3. These decisions of which measures to keep and what can be reduced and how should be taken after an active stakeholder meeting and further detailed assessment of the site and detailed stormwater simulations.

Type of surface	Ac,i	Depths	Calculated Volume	Volume capacity	Actual Volume
	m^2	m	m^3		m^3
Permeable Pavement	5485.27		0.00		0.00
New Green	7677.53				
Green Roofs	5506.24	0.50	2753.12	0.50	1376.56
Bioswale	928.34	0.30	278.50		278.50
Raingarden	378.18	0.30	113.45		113.45
Total volume attenuated in scenario 2			**3145**		**1769**
Rooftop RWH			118		118.00
Total volume attenuated in scenario 3			**3263**		**1887**

Table 13: Summary of the attenuation cpapcity of recommended measures
Source: Author

	Runoff Volumes								
Duration	Scenario 1			Scenario 2			Scenario 3		
	5 years	25 years	100 years	5 years	25 years	100 years	5 years	25 years	100 years
min	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*
5	172	239	288	97	138	168	69	99	122
10	245	342	415	133	193	237	92	137	170
15	319	446	541	170	248	306	116	174	218
30	480	680	827	243	365	455	160	252	319
60	700	1000	1221	326	510	646	201	338	440
120	993	1443	1771	404	679	880	216	422	572
180	1157	1703	2110	402	737	986	172	422	608
360	1469	2249	2849	287	765	1132	-43	314	589
720	1528	2586	3384	-288	360	848	-730	-246	119
1440	509	1683	2558	-2135	-1416	-881	-2625	-2088	-1688

Table 14: Comparison of runoff volumes for the three scenarios for return periods of 5, 25 and 100 years.
ource: Author

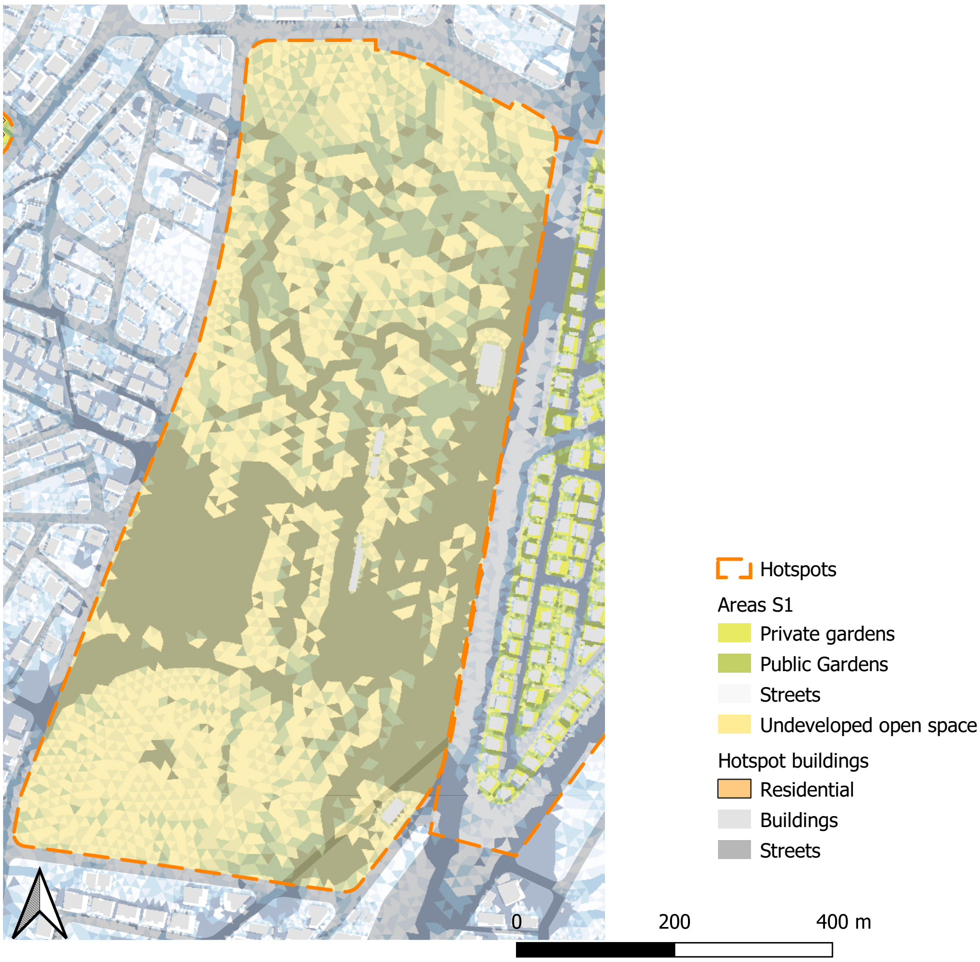


Figure 64: The royal village project in its current "greenfield" state, overlayedby a layer of hydraulics showing sinks within the hotspot
Source: Author, based on GIS analysis

5.2.2 Hotspot B: Royal Village Project

5.2.2.1 Description

The Royal Village Project is situated in a strategic area in Amman on the road leading to the Dead Sea and provides an excellent area to analyse as it is currently not developed but has a proposed masterplan. This allowed the creation of an additional scenario of pre-development or "greenfield" scenario as shown in Figure 64, where the runoffs volumes and discharge rates can be compared with the proposed masterplan and with the results, further integration of WSUD measures can be recommended and even implemented easily.

However, the proposed masterplan of the area describes a mixed-use development as shown in Figure 65. As per the architects and planners of the project Alnasser and partners (2024), the location allows for a main pathway connecting a new retail center to a major hospital, lined with commercial outlets to attract residents and visitors. The remaining areas are residential, each with a distinct character: apartments near the main road with central parks, and villas on higher ground offering city views, including both single and semi-detached options to suit different family needs. As observed from the overlay of the hydraulic map in Figure 64, it can be observed that the residential area in the south and the offices in the north are at high risk of flooding. Also, the majority of public space is paved and only a small percentage of green area is accessible to the public. A detailed analysis of the areas is done in further sections.

5.2.2.2 Identification of types of surfaces and areas

As per the pre-development state or in Scenario 1A, the site lies in the southern half of the catchment and is surrounded by residential areas. It is prone to flooding in the north east and south west parts as shown in Figure 64. For the sake of simplified calculation, the runoff coefficient of this area is taken to be 0.4 and a small construction as observed by satellite imagery is included as a building, as described in Table B1 in Appendix B. On the other hand, as per scenario 1B, or the proposed masterplan, 50 % of the area gets paved by streets and pavements. Further only a mere 22 % of the site remains unsealed with a major portion being private property. A detailed description with areas is shown in Table B2 in appendix B.

Figure 65: The royal village project masterplan as proposed by the architects Alnasser + Partners
Source: Alnasser + Partners, 2024

5.2.2.3 Conceptual design of WSUD measures for Scenarios 2 and 3

For the scenario 2, as before, measures have been conceptualised only for the public spaces as shown in Figure 68. Taking the masterplan as the base, an attempt is made to unseal most paved areas. Permeable pavements have been implemented in all parking lots. All public buildings including the offices, commercial spaces and hospital have a semi-intensive green roof. The streets that are 15m wide in the commercial areas and 12m wide in the residential areas could include swales that convey the stormwater runoff and slow down the discharge rates. These street sections are described in Figure s 66 and 67, integrating landscape elements and showing the basic profile of the streets.

Additionally, the most potential was observed in the paved area between the commercial space that is a plaza according to the masterplan. This could be converted into a “green corridor”, a multifunctional open space that connects the various buildings around but also provides a space for potentially treating and retaining stormwater in this hotspot. Depending on the feasibility of the site conditions, some areas might have public furniture, playgrounds, open gyms or merely green spaces, with differences in levels to accommodate the retention of stormwater. This could also integrate the public park that is included in the masterplan through creative landscape design. The water from the swales could be conveyed towards this green corridor, hence reducing the risk from the residential areas. This would greatly improve the aesthetics and biodiversity in the area, hence adding value and promoting awareness of urban waters.

Alternatively, as per the feasibility, since the infiltration potential of the site is observed to be low (HW, 2024), this plaza could be designed for detention. That is, by lowering the level of the plaza or by creating a multifunctional space that could also hold water and slowly discharge it as shown in Figure 19 and as discussed in the case study of Rotterdam in section 3.8. While the percentage of sealed or unsealed area may be determined on a closer inspection of site conditions, cost benefits and other factors, a combination of all these elements can be designed in detail in further approaches. A summary of the changes made in permeable and impermeable areas is shown in Table B3 in appendix B.

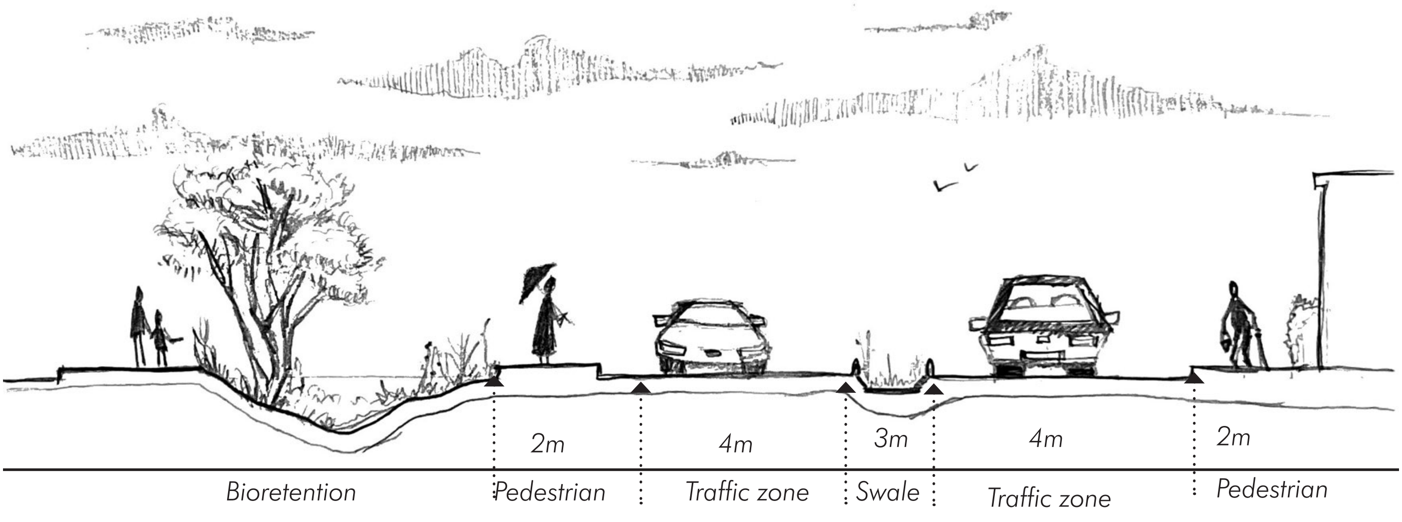


Figure 66: Street E section of a 15m wide road with a bioretention area acting as a buffer between the main street and the Royal village project residential area
Source: Author

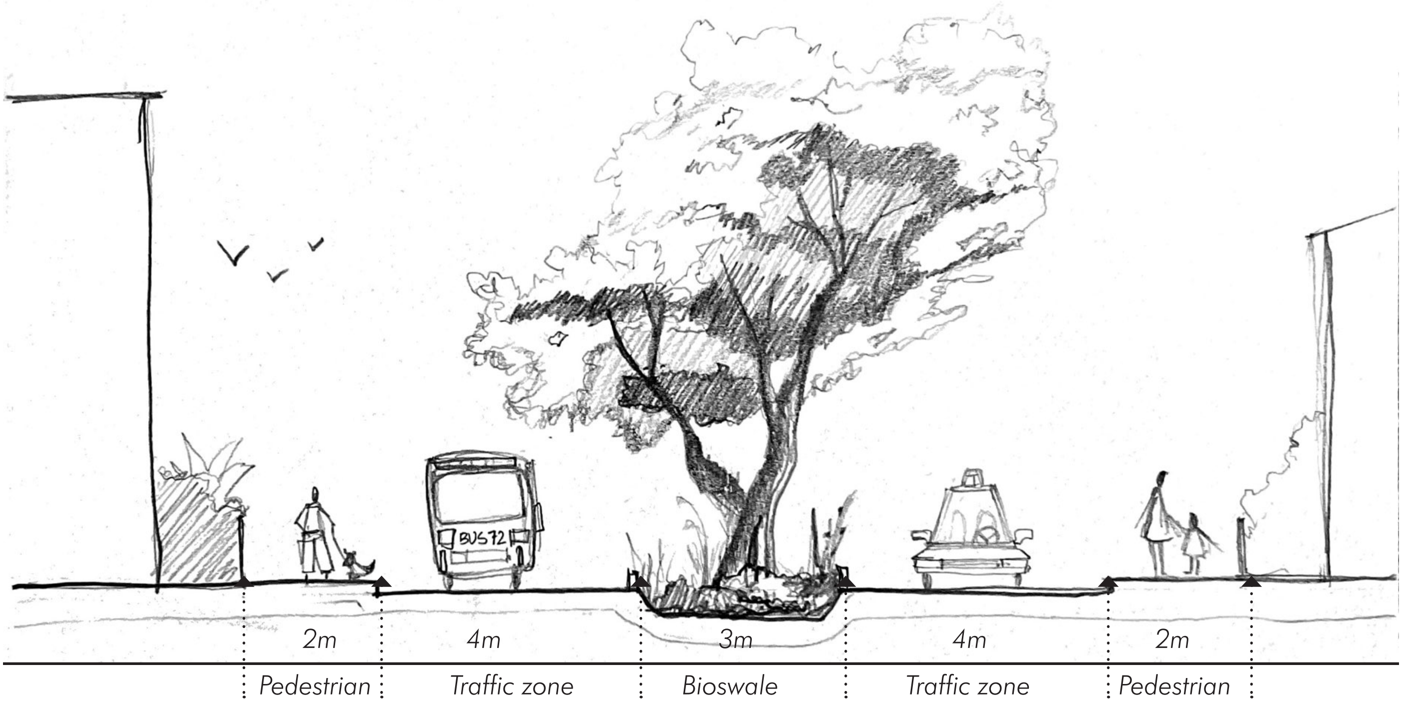
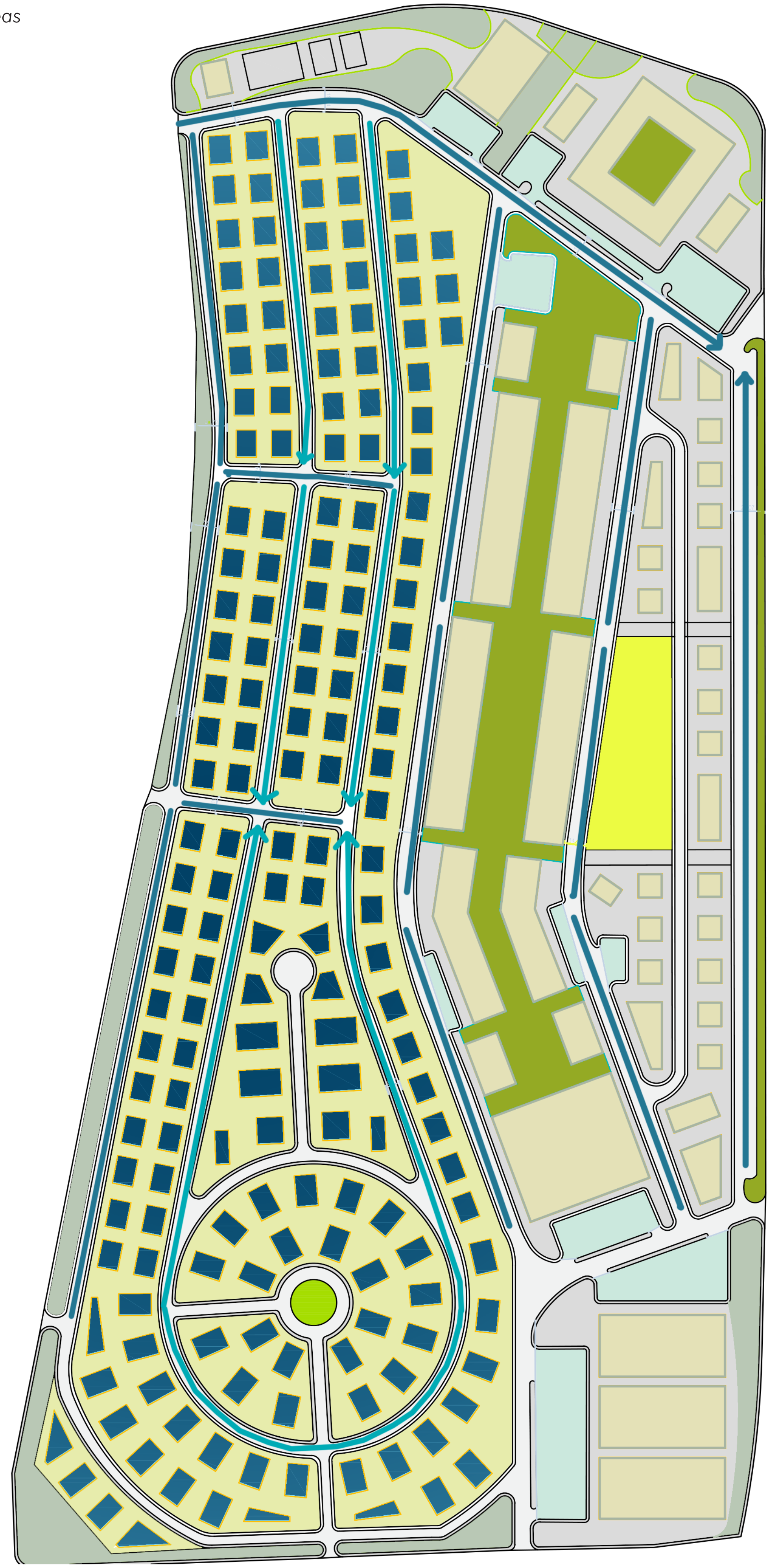


Figure 67: Street F section of a typical 12m wide road with a bio-retention area acting as a median between two lanes of traffic. Source: Author

In scenario 3, the rooftops of the private buildings are disconnected from the system with the assumption that the runoff from the rooftops is managed within the private open space as shown in Figure 69. This site has both villas and multistoreyed apartment buildings that go upto 8 storeys and are surrounded by some open space. The total number of private plots is 177 with an average rooftop area of 275m². Since the typology of the houses differ, the ways to manage stormwater on site may also differ. The villas would probably have more open space and might consider integrating WSUD elements within their gardens or choose to recycle the stormwater for reuse and store in tanks. On the other hand, the apartment buildings might have to simply install tanks underground or opt to also integrate the elements as shown in the section 5.2.3.5.

Figure 68: Recommended measures for scenario 2
Source: Author

Figure 69: Recommended measures for scenario 3 including residential areas
Source: Author



Legend

- Buildings with RWH
- Paved
- Streets
- Private gardens
- Exisitng greens
- Public Gardens
- New green area
- Green roof
- Permeable pavement
- Street E
- Street F

5.2.2.4 Quantitative Analysis

In order to further design these recommended measures, it is necessary to estimate the runoff volumes to be mitigated and the peak runoff rates. This is done similar to the previous section and is described in detail in Appendix B. However, a summary of the results is shown in Table 15 and graphically represented in Figure 70.

Here, it is interesting to observe the stark difference between the pre-development scenario and how the runoff volumes shoot up post development. In the greenfield scenario, a peak runoff volume of 1345 m^3 is accumulated after 30 minutes of rainfall. Whereas as per the proposed masterplan in scenario 1B, that volume is increased by around 16 times to 22562 m^3. This shows the huge difference in runoff volumes when the sealed area is increased by 78 % (see Appendix B). In further scenarios, even with the integration of WSUD measures in the site, while of course the runoff volumes are lower than the masterplan, they are still nowhere close to the natural water cycle. Scenario 2 has 45 % of unsealed areas and 55 % sealed areas which is also quite a high percentage, but the runoff volumes decrease slightly up to 10619 m^3. Whereas further in scenario 3, with the disconnection of residential rooftops from the system, the runoff volume goes down to 7489 m^3. Hence it can be concluded that the integration of WSUD measures in the royal village project will be able to lower the runoff volumes, though these measures need to be designed for attenuation of huge amounts of runoff. This is further explained in the next section.

Duration	Rainfall intensity	Volume S1A	Volume S1B	Volume S2	Volume S3
min	*l/s ha*	*m^3*	*m^3*	*m^3*	*m^3*
5	169.024	787	1894	1480	1214
10	123.154	971	2729	2095	1708
15	107.864	1155	3564	2710	2201
30	83.4	1345	5434	4036	3250
60	63.106	1087	8055	5776	4587
120	47.26	-328	11719	7967	6186
180	38.642	-2533	13996	9026	6842
360	27.6888	-10254	18885	10619	7489
720	18.5426	-29174.5	22562	8824	4631
1440	10.286	-73995	17665	-4766	-9417

Table 15: Runoff volumes for the four scenarios
Source: Author

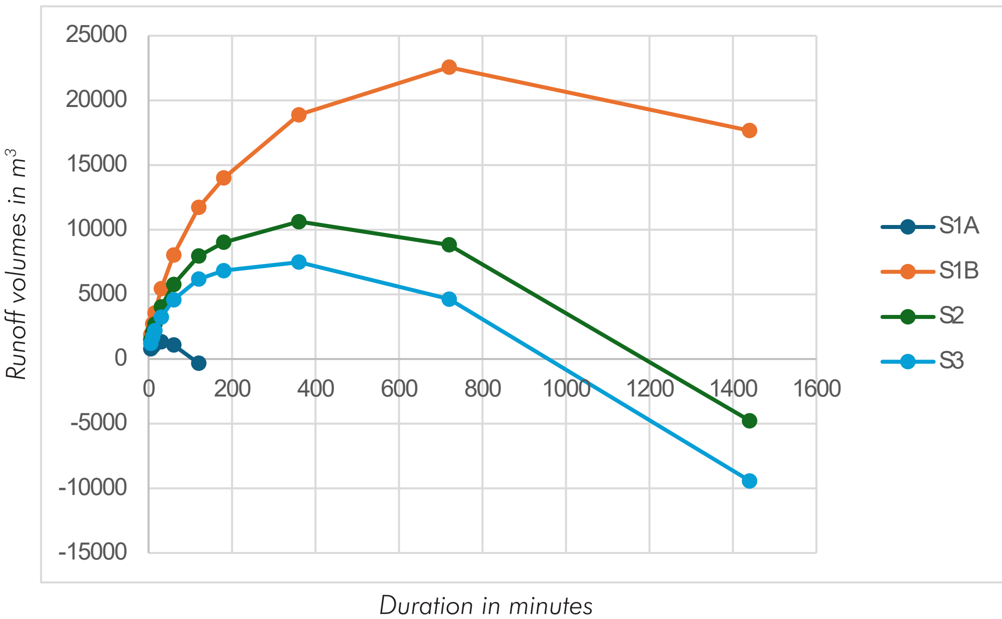


Figure 70: Runoff volumes for the four scenarios
Source: Author

Additionally, a calculation of peak runoff rates is also done similar to the previous hotspot and as described in section 3.8. The results are shown in Table 16 and Figure 71.

The runoff rates however are observed to be reduced almost close to the pre development state, especially in scenario 3. This shows that while the runoff volumes need to be attenuated at various levels in the stormwater chain, the runoff rates can be reduced through unsealing of surfaces and the recommended decentralised measures. It is also noted that the rooftop runoff from the residential buildings have a huge contribution to both these quantitative aspects and the management of this water can prove to be very beneficial, both in terms of flood protection and reuse of the stormwater in dry periods.

		Scenario 1A	Scenario 1B	Scenario 2	Scenario 3
Area (A)		182765.25	320762.73	261819.44	218205.82
Duration	Rainfall Intensity	Runoff Rate (Q)			
min	*mm/h*	*l/s*			
5	60.80	3089.17	5421.66	4425.38	3688.20
10	44.30	2250.83	3950.32	3224.41	2687.29
15	38.80	1971.38	3459.88	2824.09	2353.66
30	30.00	1524.26	2675.16	2183.57	1819.84
60	22.70	1153.36	2024.21	1652.24	1377.01
120	17.00	863.75	1515.92	1237.36	1031.24
180	13.90	706.24	1239.49	1011.72	843.19
360	9.96	506.06	888.15	724.95	604.19
720	6.67	338.89	594.78	485.48	404.61
1440	3.70	187.99	329.94	269.31	224.45

Table 16: Runoff rates for the four scenarios
Source: Author

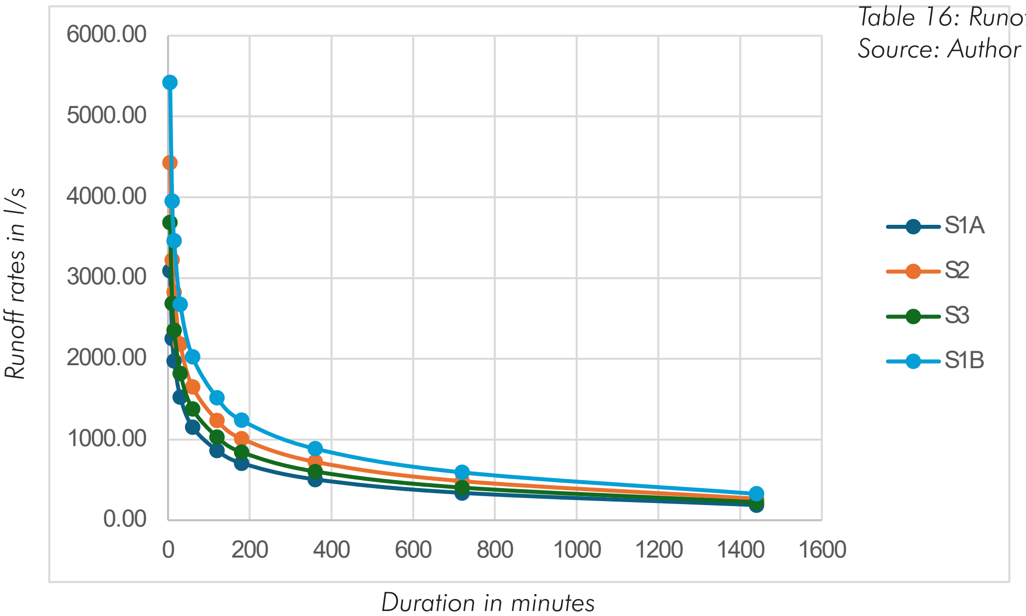


Figure 71: Runoff rates for the four scenarios
Source: Author

5.2.2.5 Further design recommendations

The results show a stark difference in the predevelopment and post development scenarios in terms of runoff volumes. While in the greenfield state, only 1345m³ of runoff volume is reached, it increases to a staggering 22562m³, almost 16 times more. However, the introduction of WSUD measures, and just unsealing surfaces brings that volume down to 10619m³, which shows that there is still a need for the retention of this amount of runoff as it will not be able to simply infiltrate at a fast rate. To mitigate this amount of runoff, the following measures can be designed in detail for retention:

1. Green roofs: With an area of 55884m² of rooftops of all public buildings covered with semi intensive or intensive green roofs of depth 0.5m, and a retention capacity of 50 %, a volume of 13971m³ can be retained. This however is not very realistic and would further be reduced in area as per the feasibility conditions of the site.
2. Bioswales: The bioswales implemented along the streets with an average depth of 0.3m and a total area of 10163m² have a capacity to retain 3049m³ of runoff.

As observed from the summary in Table 17, since the sum of simply the green roofs and bioswales amount to 17020m³ of capacity, the areas can be reduced or the measures can be designed more efficiently to suit the needs. However, as observed from Table 18, the scenario 3 runoff volumes (7489 m³) are quite low as compared to scenario 2 (10619 m³). In this case, the green roofs could be made extensive, with lesser depths, and more focus could be given to elements like raingardens and swales integrated into the streets and paved areas to

Type of surface	Ac,i	Depths	Calculated Volume	Volume capacity	Actual Volume
	m²	m	m³		m³
Permeable Pavement	14464.75		0.00		0.00
New Green	4118.48				
Green Roofs	55884.08	0.50	27942.04	0.50	13971.02
Bioswale	10162.85	0.30	3048.86		3048.86
Raingarden		0.30			
Total volume attenuated in scenario 2			**30991**		**17020**
Rooftop RWH			3130		3130
Total volume attenuated in scenario 3					**20150**

Table 17: Summary of the attenuation capacity of recommended measures
Source: Author

Runoff Volumes												
Duration	Scenario 1A			Scenario 1B			Scenario 2			Scenario 3		
	5 years	25 years	100 years	5 years	25 years	100 years	5 years	25 years	100 years	5 years	25 years	100 years
min	m³	m³	m³	m³	m³	m³	m³	m³	m³	m³	m³	m³
5	787	1199	1505	1894	2617	3153	1480	2069	2507	1214	1706	2070
10	971	1568	2014	2729	3776	4559	2095	2949	3588	1708	2420	2953
15	1155	1940	2522	3564	4942	5962	2710	3834	4667	2201	3138	3833
30	1345	2574	3474	5434	7591	9170	4036	5796	7085	3250	4717	5792
60	1087	2931	4292	8055	11291	13679	5776	8417	10366	4587	6788	8412
120	-328	2438	4457	11719	16573	20116	7967	11929	14821	6186	9488	11898
180	-2533	825	3327	13996	19890	24280	9026	13837	17420	6842	10851	13838
360	-10254	-5461	-1774	18885	27299	33769	10619	17486	22767	7489	13212	17613
720	-29175	-22669	-17770	22562	33980	42578	8824	18143	25162	4631	12398	18248
1440	-73995	-66779	-61405	17665	30329	39761	-4766	5571	13270	-9417	-802	5614

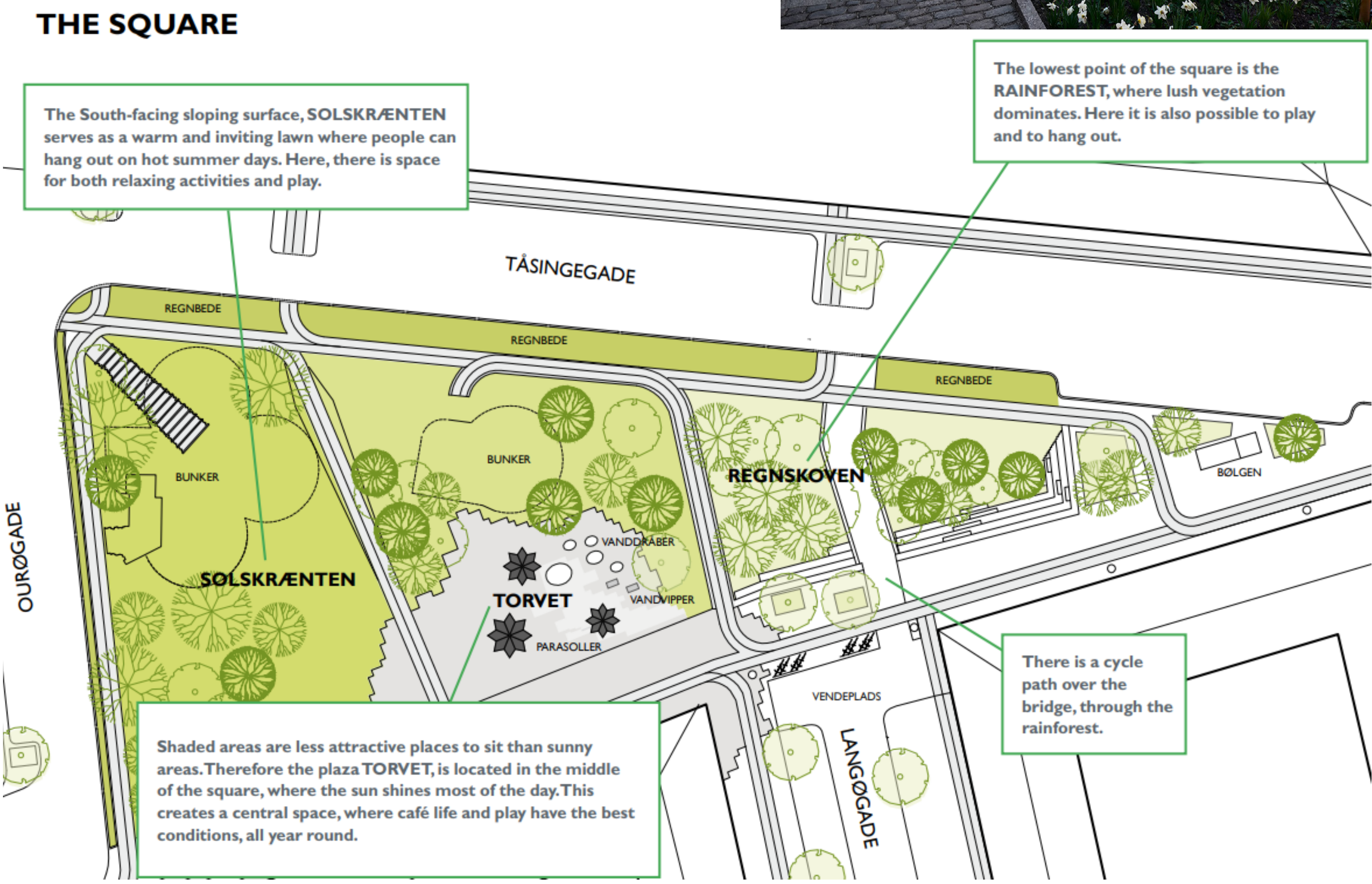
Table 18: Comparison of runoff volumes for the three scenarios for return periods of 5, 25 and 100 years.
ource: Author

retain a runoff volume of 7489m³. In scenario 3, 3130 m³ of runoff is collected in RWH and can be reused. The storage of this volume can be divided among the 177 residential buildings proposed in the masterplan. Where space is not available above ground, underground storage tanks are also possible to implement depending on site feasibility. This leaves 4359 m³ of runoff to be attenuated. While the proposed swales themselves have the capacity to attenuate 3048 m³, they also convey the runoff towards the proposed retention area in the green corridor or the plaza.

However, for a 25 year event, more retention measures may be needed, and can easily be integrated into the landscape, especially in the green corridor. An example of this can be seen in Figure 72 which depicts the Tasinge Plads, which is a multifunctional space implemented in a neighbourhood in Copenhagen. The Tasinge Plads was created as a space to integrate measures for stormwater management with a local meeting space for the residents to interact. It also integrates storagetanks underground into which the water infiltrates and is treated for reuse within the plaza for aesthetic and play purposes (Urban Waters 2024) .
Another example is the Tanner Springs Park in Portland, Oregon, USA. Rainwater runoff from the surrounding impervious surfaces is allowed to attenuate in the retention pond that mimics a wetland, providing aesthetic benefits, improving the local biodiversity and micro climate while managing the stormwater runoff as shown in Figure 73. It also provides space for art and recreation, engaging the public and creating an inviting space for people to interact as shown in Figure 74 (Land8 2015).

The plaza proposed for the royal village project already seems to attract people to meet between office buildings, commercial centres and other attractions. This plaza could be multifunctional in its purpose, serving as an aesthetically planned detention basin, as it has the space to attenuate the stormwater runoff during a rainfall event, and during the dry periods could be used as a gathering space for residents. In conclusion, unsealing paved areas, integrating retention measures into the landscape and capturing rooftop runoff close to the building is the best recommendation for the royal village project as it shows great potential for their implementation.

Figure 72: A layout of Tasinge Plads depicting the various zones and multifunctionality and a view of one of the detention basins Source: (Urban Waters 2024)



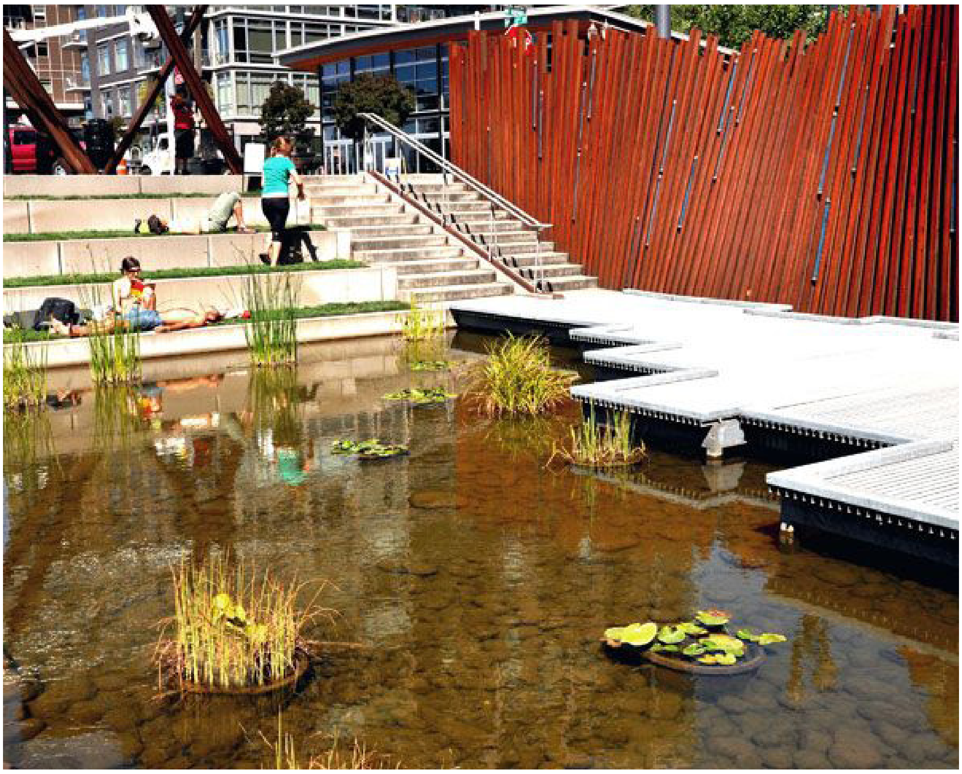


Figure 73: (Top) A view of the Tanner Springs Park in Portland, Oregon, USA. Source: (DREISEITLconsulting 2024)

Figure 74: (Left) Interaction between the stormwater runoff and recreational space in the Tanner Springs Park. Source: (Dreiseitl and Land8 2015)

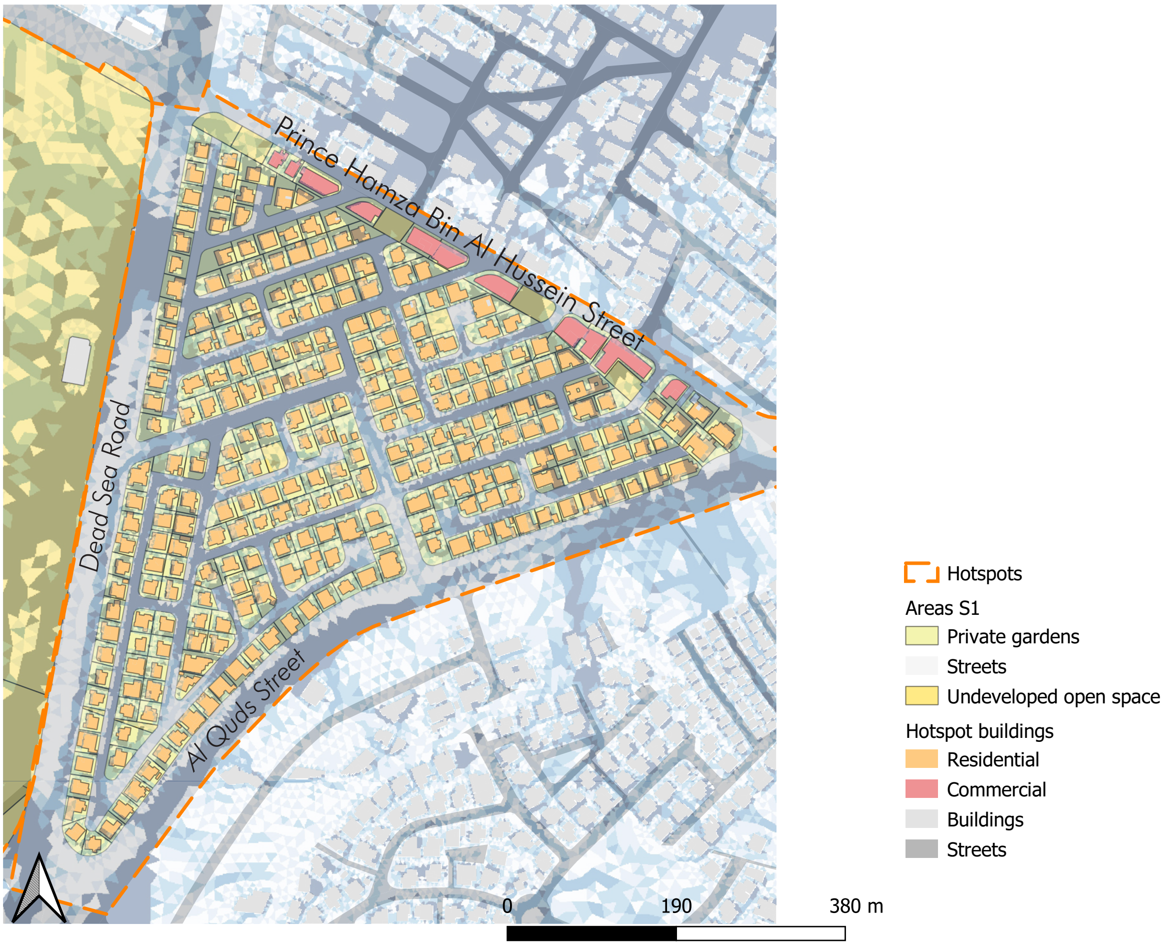


Figure 75: This map shows an overlap of the hydraulic map showing the flows and sinks on the map and showing different functions of buildings and open spaces for the Hotspot C - Residential areas. Source: Author, based on HW, 2024

5.2.3 Hotspot C: Residential Area

5.2.3.1 Description

This hotspot is a very common typology in this catchment and as observed, in other parts of Amman. A dense residential block, with no public areas, no public greens and no other function is a tricky site to work with for WSUD interventions. This particular site is at high risk of flooding as seen in Figure 75. To the west is the highway that leads to the Dead Sea, called the Dead Sea Road and has the royal village project on the other side of it. To the south is another main street called the Al-Quds Street of the same width of 50m with some undeveloped land below it. To the north is an 18m wide street called the Prince Hamza Bin Al Hussein Street with commercial buildings on both sides of it. A 24m wide street connects the two highways to the centre of the residential quarter with. The streets within this neighbourhood range between 11m wide to 18m wide, with a lot of dead ends and cul- de-sacs. All streets are vehicle oriented with little or no pedestrian paths and barely any green space except for the odd tree planted outside houses. The houses in this neighbourhood are classified as type C, which according to (Homes-Jordon 2024), a real estate website, has the following regulations:

- Setbacks: front 4m, side 3m, rear 4m
- Building percentage: 51 %
- Minimum plot area: 500 m^2
- The minimum length of the façade located on the front street: 18 m^2
- Number of floors: 4 floors
- Height: 16 m.

With an open space requirement of 49 %, it is possible to implement raingardens, RWH tanks and so on within the private property, however with only 15 % green space mandatory (Homes-Jordon 2024) , the rest could be paved according to the owner's interest. There are some undeveloped plots of land but are assigned the landuse of either residential or commercial. For the scenario analysis, the only public space hence available are the streets.

5.2.3.2 Identification of types of surfaces and areas

As summarized in Table C1 in appendix C, there are no public green areas or existing greens that are taken into account for the calculations. Since most of the residential plots have gardens, they are considered as private open space out of which 40 % is considered green space and 60 % paved as per satellite imagery and the building regulations. The building rooftops are flat and cemented. And the streets are considered entirely to be made of asphalt, as even with pedestrian path, the difference in pavement makes little difference to the calculations. The different types of surfaces can be observed in Figure 76.

Figure 76: Map of Scenario 1 - The different surfaces within the hotspot as identified by satellite images in the exisiting conditions. Source: Author, based on GIS analysis, 2024

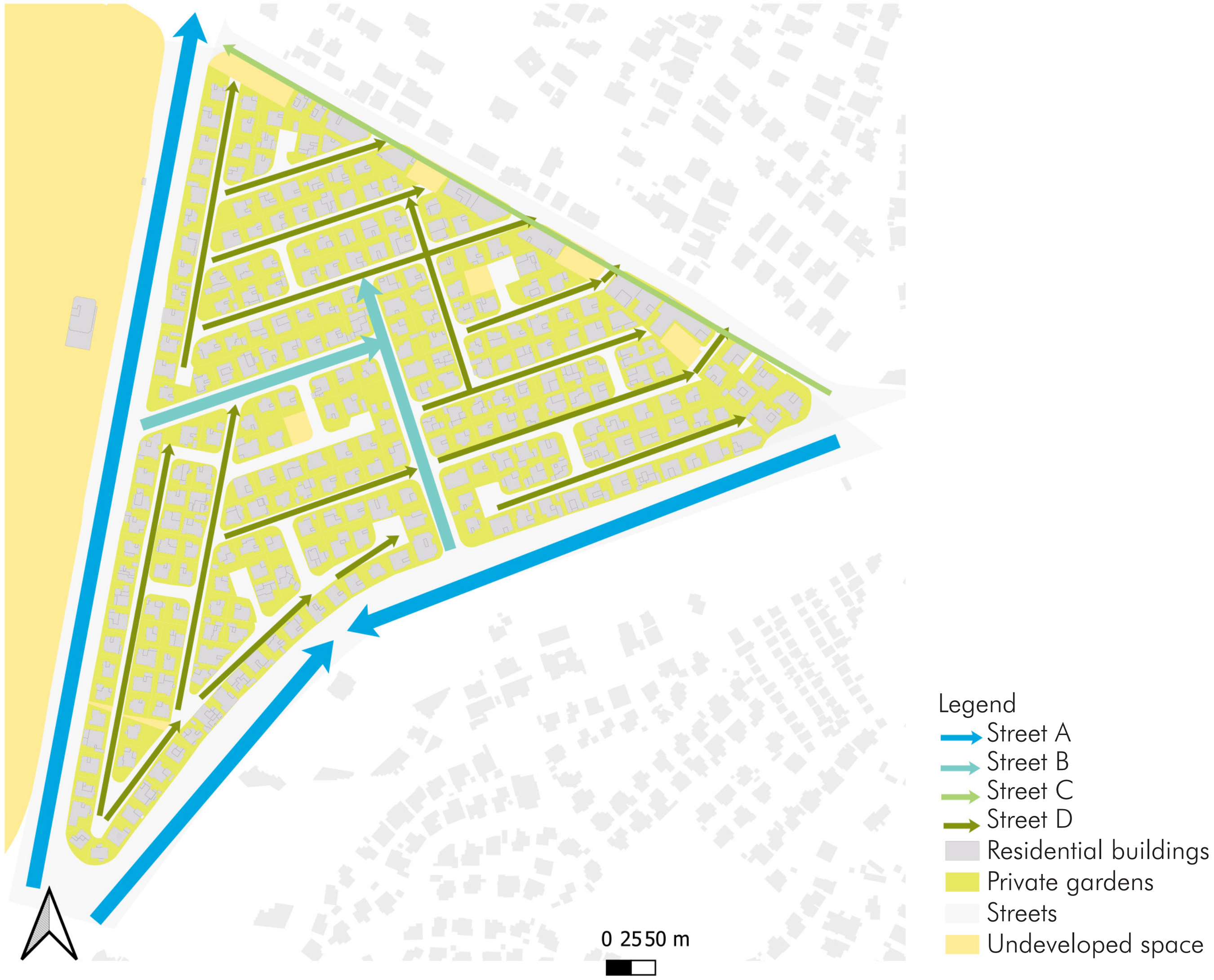


Figure 77: Map showing the layout of different street types and surfaces as per the conceptual design for scenario 2. Source: Author

5.2.3.3 Conceptual design of WSUD measures for Scenarios 2 and 3

Since the only public area in this neighbourhood is the streets that also are the most affected in floods and naturally convey and contribute to the runoff, the streets are where all the interventions are planned for this hotspot. Figure 78 describes a recommended street section for the 50m wide streets for the Dead Sea Road and the Al-Quds Street, annotated as street type A, as located in Figure 77. Here, a 9m wide bioswale with varying depths divides the two directions of traffic and has a huge retention capacity, while smaller swales on the two ends divide the inner lanes of traffic from the main 3 lane road. The increase in green space enhances the quality of the street while separating different traffic speeds and does not compromise on the heavy traffic loads.

For the Prince Hamza Bin Al Hussein Street (street type C) to the north which narrows down to 18m but has a commercial area on either side of it, can integrate raingardens interspersed in the sidewalks and act as separators of parking spaces as shown in Figure 80.

Two streets connect to the inside of the neighbourhood from the main streets and are 24m wide and are designated the street type B. These streets as shown in Figure 79, have a 2m wide swale on either side, separating the pedestrian pathways and the vehicular street. In addition to this, a 4m wide bioswale in the centre separates the two directions of traffic as shown in Figure 78.

Lastly, the inner lanes of this neighbourhood range from 11m to 18m (Street type D), so an average of 15m was taken to create the next street section as shown in Figure 81. Since these streets do not have a lot of traffic and have only houses on both sides, in an effort to increase the shade and improve the microclimate of these spaces, green strips have been placed on both ends of the street, which are to be planted with shady trees and local bushes to increase the infiltration. The detailed description of the areas for scenario 2 and 3 are described in Appendix C Tables C1 and 2.

For the third scenario depicted in Figure 82, the rooftop runoff needs to be managed within the private properties and should not add to the runoff on the streets. This can be done by installing tanks underground or on the surface of the open space, connected to a diverted spout from the roof.

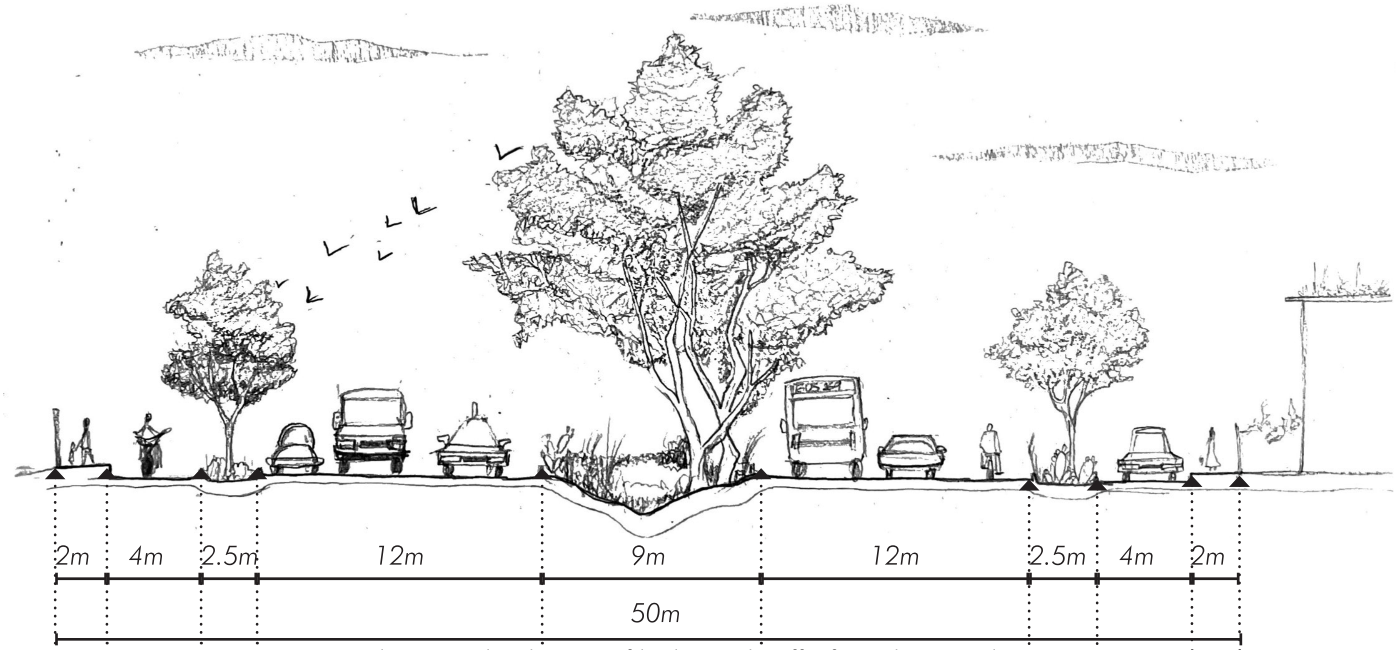


Figure 78: Street type A - section depicting the division of highspeed traffic from the inner lanes through the integration of swales, and a bigger bioretention area in the median of the road. Source: Author

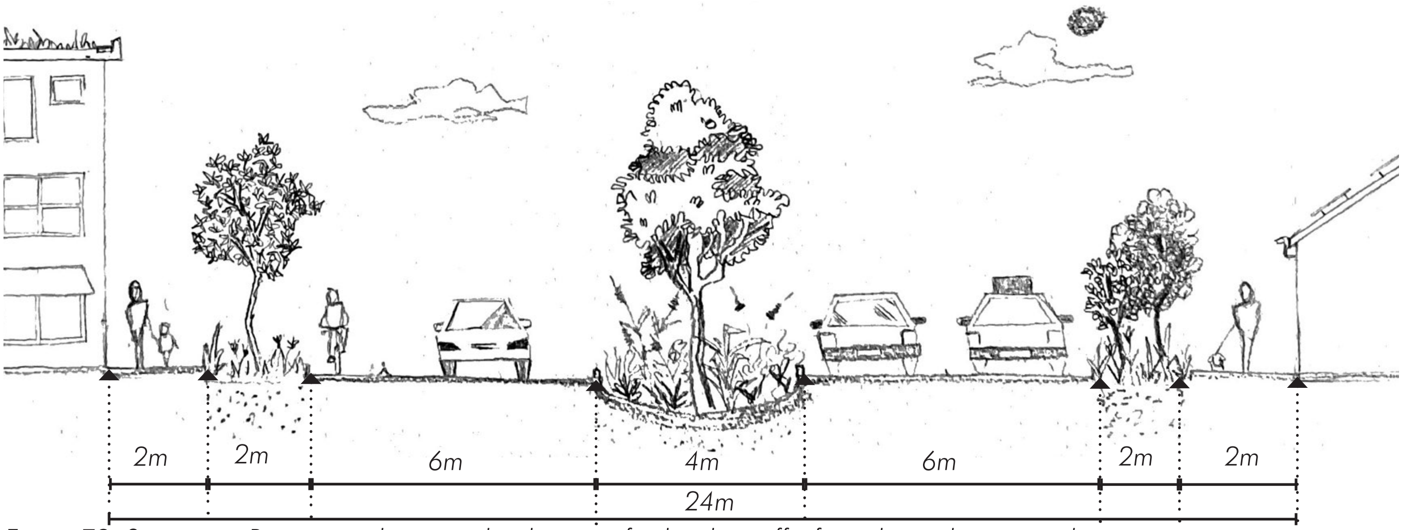


Figure 79: Street type B - section depicting the division of vehicular traffic from the pedestrian paths through the integration of swales, and a bigger bioretention area in the median of the road. Source: Author and Gabriela Lugones Guzman

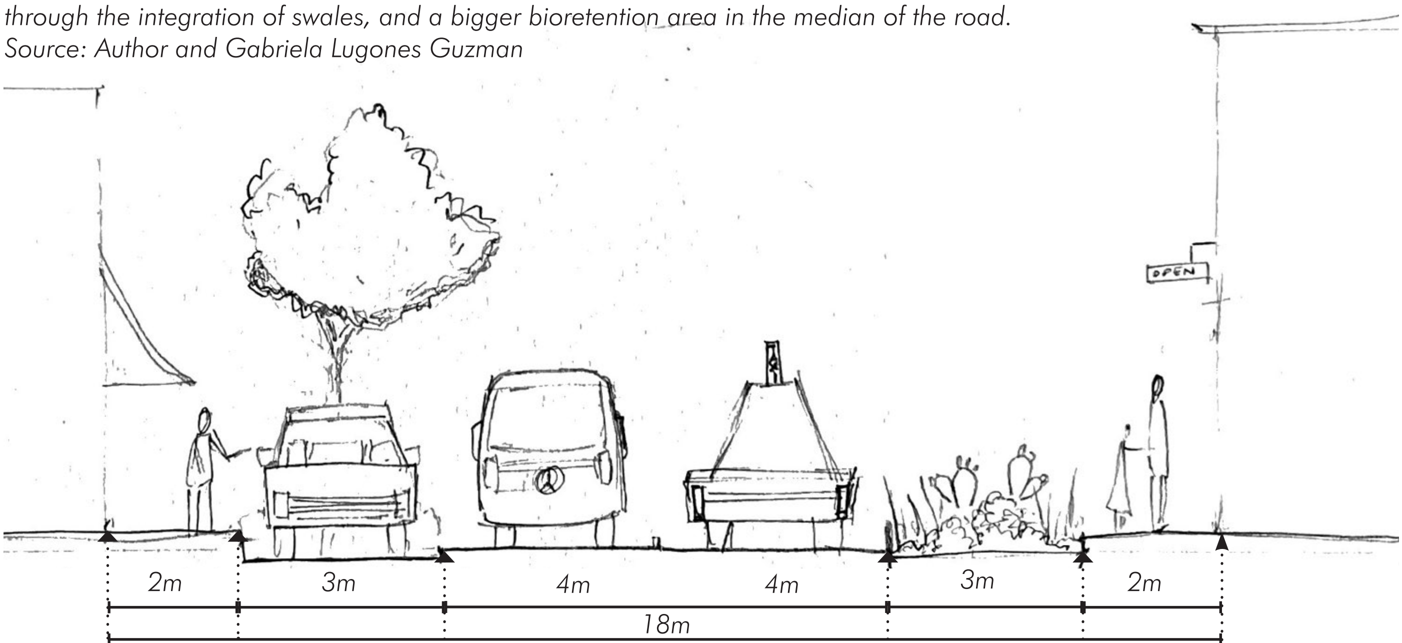


Figure 80: Street type C - This commercial street has a two way traffic lane in the middle and 3m wide parking spaces to the sides interspersed with raingardens that separate the pedestrian pathways in front of the shops. Source: Author

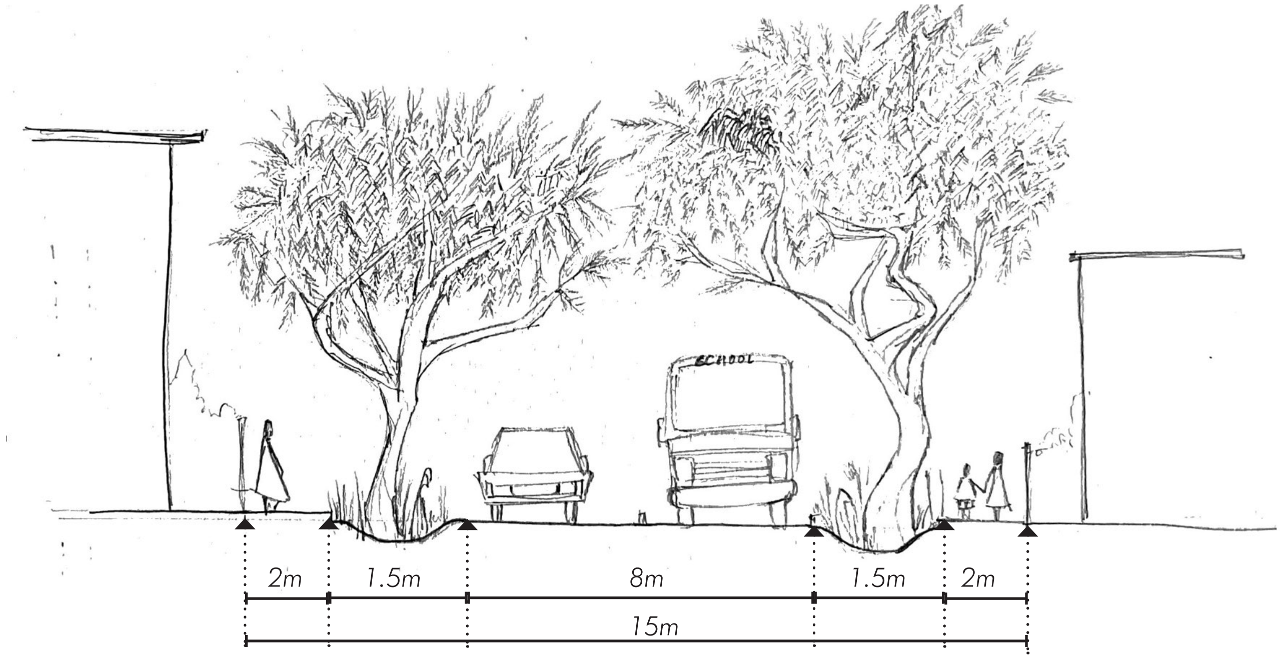


Figure 81: Street type D - section of the inner residential lanes where the traffic is separated from the pedestrian zones though swales that have shady trees to provide a canopy and buffer noise.
Source: Author

Figure 82: Map showing the layout of rooftops with RWH as per scenario 3.
Source: Author

5.2.3.4 Quantitative Analysis

As done for the previous two hotspots, the runoff volumes are calculated for the three scenarios iteratively for rainfall intensity for a period of 24 hours with a 5 year return period. This is done after obtaining the sealed and unsealed areas as shown in Tables C3, 4 and 5 in appendix C. A summary of the results are shown in Table 19 and the comparison is depicted graphically in Figure 83.

Here it can be observed that in the current state, a runoff volume of 15635 m³ is accumulated from the neighbourhood. This volume flows towards the Dead Sea Road and to the north of the catchment, ultimately contributing negatively to the flooding of Downtown Amman. However, with the implementation of bioswales in the streets, simply unsealing the area leads to improved infiltration and a reduction of runoff volume to 10045 m³ in the second scenario. But the most significant difference was observed with scenario 3, with the assumption that all the runoff from the roofs is collected in RWH tanks on site, hence causing a reduced outflow from the private properties. The calculated runoff is reduced to 4580 m³ which is less than a third of the volume in scenario 1.

Additionally, the runoff rates have also been calculated and summarized in Table 20. As observed from the graph in Figure 84, the runoff rates in scenario 1 are the highest, however, the implementation of WSUD measures in the very limited public space does not quite decrease the rate significantly. Further reduction is observed in scenario 3, hence highlighting the significance of the contribution of rooftop runoff in this hotspot.

Duration	Rainfall intensity	Volume S1	Volume S2	Volume S3
min	l/s ha	m³	m³	m³
5	169.02	1515	1274	811
10	123.15	2172	1812	1137
15	107.86	2829	2349	1462
30	83.4	4287	3520	2149
60	63.11	6299	5086	3010
120	47.26	9045	7118.91	4010
180	38.64	10669	8188	4374
360	27.69	13970	10045	4580
720	18.54	15635	9517	2198
1440	10.29	9053	-54	-8175

Table 19: Runoff volumes for the three scenarios
Source: Author

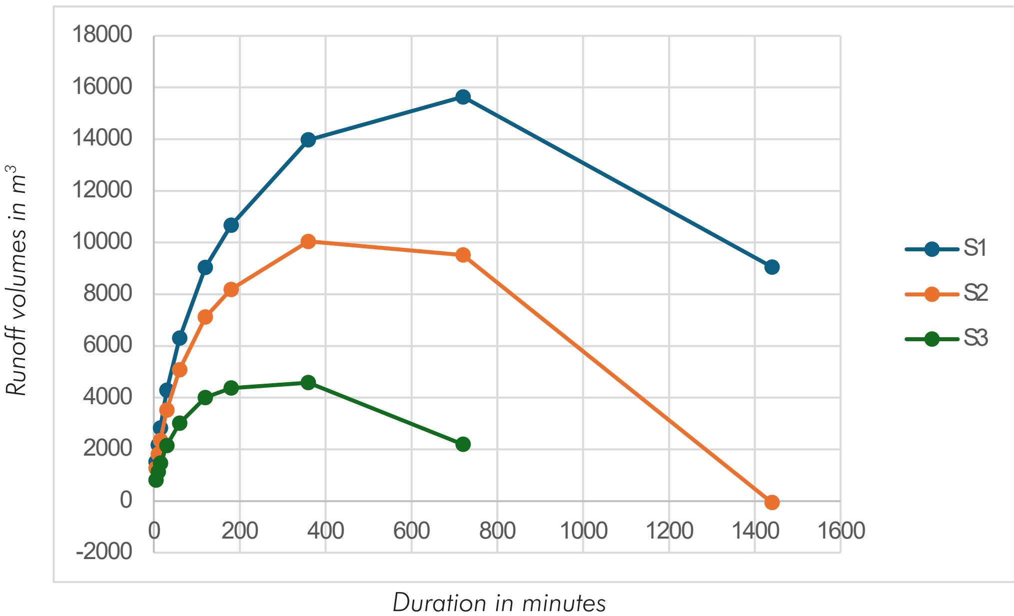


Table 83: Runoff volumes for the three scenarios
Source: Author

		Scenario 1	Scenario 2	Scenario 3
Area (A)		259532.41	222986.96	146841.16
Duration	Rainfall Intensity	Runoff Rate (Q)		
min	mm/h	l/s		
5	60.80	4386.72	3769.01	2481.97
10	44.30	3196.25	2746.17	1808.41
15	38.80	2799.42	2405.23	1583.89
30	30.00	2164.50	1859.71	1224.66
60	22.70	1637.81	1407.18	926.66
120	17.00	1226.55	1053.84	693.97
180	13.90	1002.89	861.67	567.42
360	9.96	718.61	617.42	406.59
720	6.67	481.24	413.48	272.28
1440	3.70	266.96	229.36	151.04

Table 20: Runoff rates for the three scenarios
Source: Author

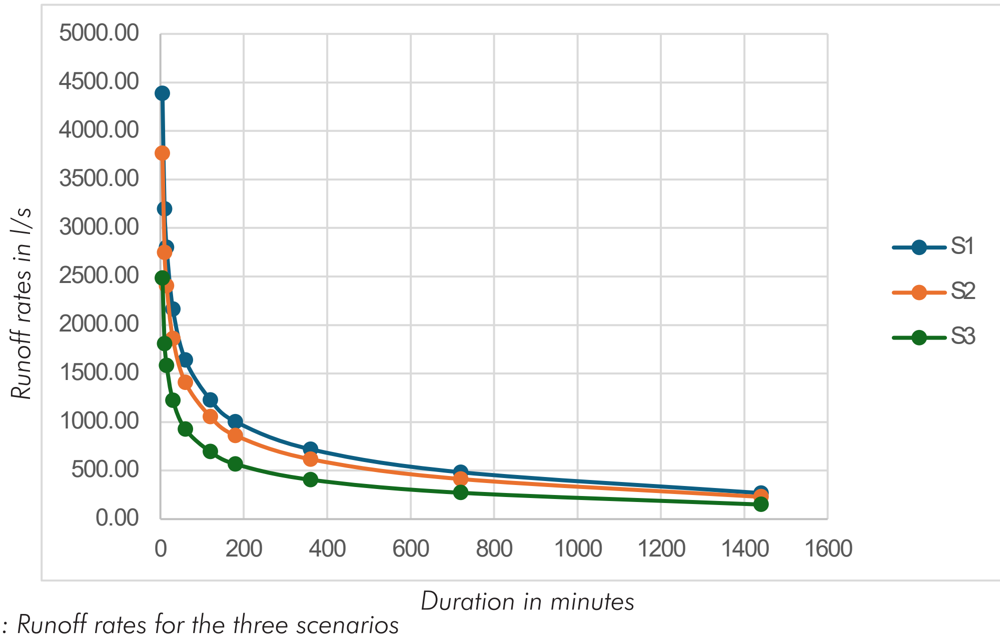


Table 84: Runoff rates for the three scenarios
Source: Author

5.2.3.5 Further design recommendations

Since the only measures applied in scenario 2 in this case are bioswales and raingardens of similar characteristics, they are clubbed together under the term bio-retention, and an average ponding depth of 0.3 has been taken for an estimation of the capacity. With an area of 50250 m², they have a capacity of 15075 m³ in total which is more than the required 10045 m³ for a 5 year event. However, the detailed design of these swales should be done according to the needs and character of the different streets after a more detailed feasibility study. Simply by increasing the unsealed area in a quarter may have the desired effect and adding depths to these measures may not be necessary. It is also observed that after managing the rooftop runoff on site, the runoff volume that needs to be mitigated decreases drastically to 4580m³. These Figure s are summarized in Table 21 which also further shows that the rooftop runoff collected is 5465 m³, which means that for the approximately 300 buildings in this area, around 18 m³ of storage tanks are required for each structure. These storages might be on individual properties or can also be implemented collectively at the end of streets in the cul-de-sacs. However, this is assuming that 100 % of all rooftop runoff is managed within private property, and while this may be a suggestion, making it mandatory by law and introducing building regulations to be implemented may not be fully feasible. Hence, the measures in public areas should be further designed keeping in mind some overflows from private properties as well.

In this hotspot, it can be concluded that due to the minimal public space available, it is necessary for the private spaces to take responsibility for their contribution in stormwater runoff. As observed from the summary of the attenuation capacities of the measures implemented in this hotspot from Table 21, the bioretention systems in the streets will be able to attenuate only the runoff volumes for a 5 year rainfall event. For heavier rainfall events with a return period of 25 years or more, these systems may be able to convey the runoff to an outlet from the neighbourhood, possibly a retention pond. However, if there is not one, the excess runoff that is not attenuated would add to the flooding problem in the catchment. On the other hand, if the rooftop rainwater harvesting systems are installed in the private properties, this vastly reduces the runoff volumes, and even in a 100 year rainfall scenario, the suggested measures have more than enough capacity to attenuate the stormwater, actively helping in infiltration and storage.

To incentivise the installation of RWH systems in residential plots, residents need to be made aware of the various benefits of these systems. In a place where people face such a shortage of water, treatment and reuse of stormwater should become the priority and responsibility of everyone. Further, it may be beneficial to also reinstate the additional benefits of integrated WSUD within private properties, like aesthetics and improvement of biodiversity and microclimate. Figure s 85 and 86 show different ways in which rooftop runoff can be managed within the open space of a residence while improving the aesthetics and getting integrated into the landscape.

Type of surface	Ac,i	Depths	Calculated Volume	Volume capacity	Actual Volume
	m^2	m	m^3		m^3
Bioretention	50250.53	0.30	15075.16		15075.16
Total volume attenuated in scenario 2			**15075**		**15075**
Rooftop RWH			5465		5465
Total volume attenuated in scenario 3					**20540**

Table 21: Summary of the attenuation capacity of recommended measures
Source: Author

	Runoff Volumes								
Duration	Scenario 1			Scenario 2			Scenario 3		
	5 years	25 years	100 years	5 years	25 years	100 years	5 years	25 years	100 years
min	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*	*m^3*
5	1515	2099	2533	1274	1776	2149	811	1141	1387
10	2172	3019	3652	1812	2539	3084	1137	1616	1974
15	2829	3944	4769	2349	3307	4016	1462	2093	2560
30	4287	6033	7311	3520	5020	6118	2149	3136	3859
60	6299	8917	10849	5086	7335	8995	3010	4491	5584
120	9045	12973	15840	7119	10493	12957	4010	6232	7854
180	10669	15438	18990	8188	12285	15337	4374	7073	9082
360	13970	20778	26013	10045	15894	20391	4580	8431	11393
720	15635	24873	31830	9517	17454	23432	2198	7425	11361
1440	9053	19300	26931	-54	8749	15306	-8175	-2377	1940

Table 22: Comparison of runoff volumes for the three scenarios for return periods of 5, 25 and 100 years.
ource: Author

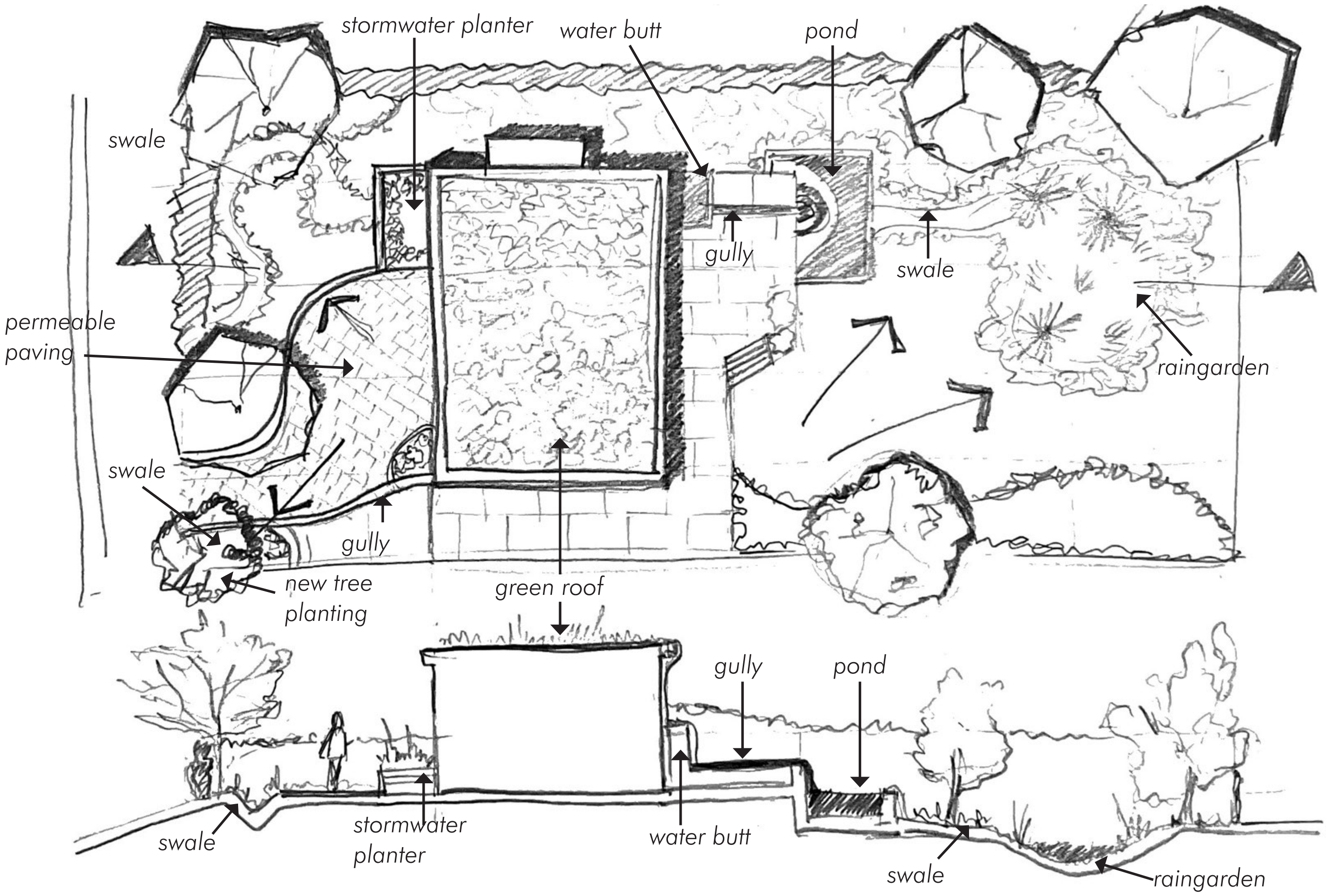


Figure 85: This design aims to create more opportunities for capturing rainwater and then slowly releasing it or using it within the garden. Source: Redrawn and adapted from (Dunnet and Clayden 2007)

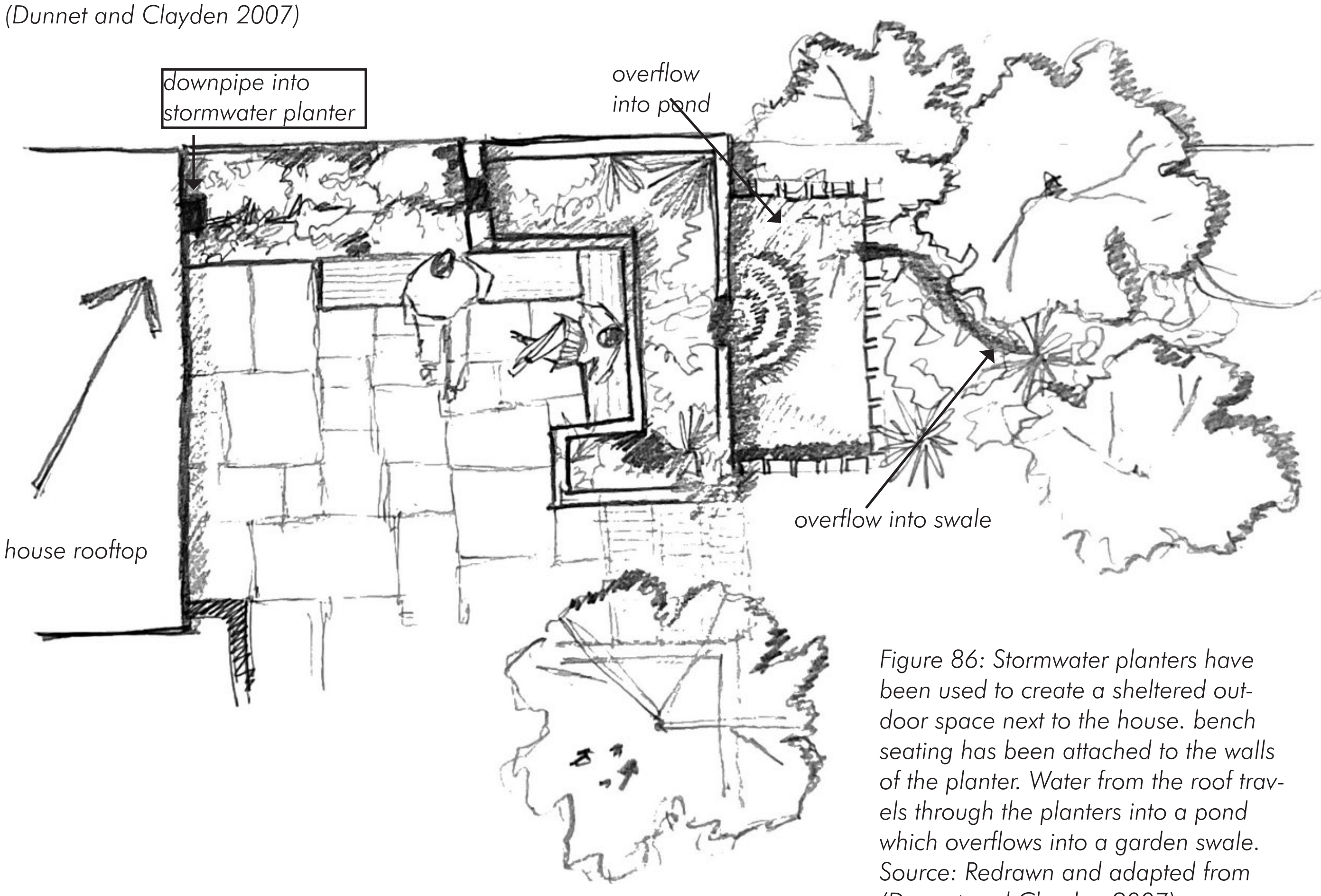


Figure 86: Stormwater planters have been used to create a sheltered outdoor space next to the house. bench seating has been attached to the walls of the planter. Water from the roof travels through the planters into a pond which overflows into a garden swale. Source: Redrawn and adapted from (Dunnet and Clayden 2007)

Chapter 6

Future Horizons: Concluding Insights for Amman’s Stormwater

6.1 Summary of results

Water is a precious resource, not only for Jordan but all around the world. Callous urbanization, whether planned or unplanned has led to depletion of natural resources including water at dangerous rates. While for centuries stormwater has been treated as godsend, to be collected, treated and reused wisely, with the advent of technology to extract groundwater, treating it as limitless, the value of stormwater reduced to only something to be discarded. Now as a consequence of poor planning and a changing climate, the same stormwater has become devastating to modern infrastructure.

However, the integration of WSUD in the urban fabric has proved to bring the water cycle to the near natural state. With many successful projects in Europe, USA and Australia among others, many other countries are also trying to adopt these practices into the planning of their urban areas. While the integration of WSUD in arid and semi-arid areas is not as well known as the ones in regions of frequent flooding events, many small pilot projects are making their way into these regions as well. Among other projects implemented in Jordan to deal with the water issue, the project of CapTain Rain aims at advising the policy makers into bringing these natural solutions to the developing areas of Jordan.

This thesis, attempts to analyse the integration of these WSUD measures and strategies for the different typologies of hotspots and draws comparisons between different hypothetical scenarios. The conceptual design of measures made in the previous chapter shows that this catchment of Amman has great potential for the implementation of WSUD measures and can significantly contribute to dealing with stormwater effectively. A summary of the results of the analysis are presented in the next section.

Hotspot A: Public Areas			
Quantitative Analysis			
Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
Sealed area (% of total area)	69 %	37 %	37 %
Unsealed area (% of total area)	31 %	63 %	63 %
Peak runoff volume (m^3)	1528	404	216
Reduction in percentage (As compared to Scenario 1)		74 %	86 %
Peak runoff rate (l/s)	503	308	230
Reduction in percentage (As compared to Scenario 1)		39 %	54 %
Qualitative Analysis			
Flood reduction	none	high	high
Groundwater recharge	low	high	high
Water collection for reuse	none	none	high
Promotion of Biodiversity	low	high	high
Aesthetics	low	high	high
Balanced Urban Climate	low	high	high
Environmental Education	low	medium	high

Table 23: A comparative analysis of the three scenarios for the hotspot - public areas
Source: Author

6.1.1 Comparative analysis of Hotspot A: Public Areas

The Table 23 depicts a clear comparative analysis of the selected hotspot of public area. There is a correlation of decrease in runoff volumes and rates with an increase in unsealed areas as per the conceptual design in scenario 2. Quantitative aspects like peak runoff volume show a huge decline of 74 % in scenario 2 and an even further reduction by 86 % in scenario 3. Further, the peak runoff rates are also reduced by 39 % and 54 % in scenario 2 and 3 respectively. This clearly shows the contribution of unsealing paved areas and making use of public open spaces. While the runoff rates and volumes were clearly managed on site for a 5 year rainfall event, this space further has the capacity to also integrate more measures like a retention pond or a detention basin within the school grounds for heavier rainfall events or to divert and retain water from the surrounding areas.

Qualitatively, as seen in Table 23, the current scenario offers little to none in terms of added benefits like biodiversity, aesthetics and balancing the urban climate. However, by increasing the green cover and integrating bioswales that contain native plants and grasses, raingardens that can be used to not only retain runoff but also have productive trees and bushes, and green roofs that significantly help in lowering the temperature of the buildings, scenario 2 has many advantages of integrating WSUD measures. However, while the second scenario only focuses on public places, the third scenario offers residents to also be involved in contributing to implement these strategies by integrating rainwater harvesting into their rooftops and private properties. The integration of the runoff from rooftops into visible cisterns or gulleys and gardens makes people more aware about conserving this water and promotes environmental education.

Hotspot B: Royal Village Project				
Quantitative Analysis				
Parameters	**Scenario 1A**	**Scenario 1B**	**Scenario 2**	**Scenario 3**
Sealed area (% of total area)	1 %	78 %	55 %	55 %
Unsealed area (% of total area)	99 %	22 %	45 %	45 %
Peak runoff volume (m^3)	1345	22562	10619	7489
Reduction in percentage (As compared to Scenario 1)	94 %		53 %	67 %
Peak runoff rate (l/s)	3089	5421.66	4425	3688
Reduction in percentage (As compared to Scenario 1)	43 %		18 %	32 %
Qualitative Analysis				
Flood reduction	high	none	medium	high
Groundwater recharge	high	none	high	high
Water collection for reuse	none	none	none	medium
Promotion of Biodiversity	none	low	high	high
Aesthetics	none	medium	high	high
Balanced Urban Climate	high	low	high	high
Environmental Education	none	none	medium	high

Table 24: A comparative analysis of the three scenarios for the hotspot - Royal Village Project
Source: Author

6.1.2 Comparative analysis of Hotspot B: Royal Village Project

For the royal village project, the greenfield state or scenario 1A presents as the best scenario when it comes to managing runoff volumes and peak discharge rates. However, it does not offer much to the aspects of water collection for reuse and environmental education, being just a barren land with unmaintained vegetation. Furthermore, the proposed masterplan while catering to some of the future residents' needs, escalates the issue of flooding drastically and relies entirely on the drainage network to manage the outflow of vast volume of runoff and high velocities. The measures implemented in order to mitigate these effects in scenario 2 have a small effect in reducing the peak volumes and the peak runoff rates. It is also observed that additionally reducing the rooftop runoff in scenario 3 has a bigger improvement over the runoff volumes and brings the runoff rates to near natural state as shown in Table 24.

However many additional benefits can be seen after the implementation of scenario 2 and 3, after unsealing almost half of the hotspot. They both show high potential of improvement of biodiversity and urban climate, promoting environmental education, while improving the aesthetic quality of the neighbourhood. The integration of the suggested methods will also help improve the real estate value and help this project in becoming a very attractive place for future residents. Further detailed design of the green corridor might also improve the quality of stay while acting as a retention area, not only for this sub-catchment but also for the surrounding neighbourhoods. This multifunctional space could become the baseline or key example for future development of similar projects in the catchment.

Hotspot C: Residential Areas			
Quantitative Analysis			
Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
Sealed area (% of total area)	74 %	60 %	60 %
Unsealed area (% of total area)	26 %	40 %	40 %
Peak runoff volume (m^3)	15635	10045	4580
Reduction in percentage (As compared to Scenario 1)		36 %	71 %
Peak runoff rate (l/s)	4387	3769	2482
Reduction in percentage (As compared to Scenario 1)		14 %	43 %
Qualitative Analysis			
Flood reduction	none	high	high
Groundwater recharge	low	medium	high
Water collection for reuse	none	none	high
Promotion of Biodiversity	low	high	medium
Aesthetics	low	high	high
Balanced Urban Climate	low	high	high
Environmental Education	low	medium	high

Table 25: A comparative analysis of the three scenarios for the hotspot - residential areas
Source: Author

6.1.3 Comparative analysis of Hotspot C: Residential Areas

Being the most common and repeated typology in the catchment, the residential area shows the lowest potential of applying WSUD in public areas. The unsealing of streets however, showed a slight improvement in the quantitative aspects, lowering the runoff volumes and rates, but shows a huge impact in the added benefits. A shaded street with unsealed areas acting as buffers between traffic and pedestrian zones not only brings aesthetic quality to the space but significantly impacts the microclimate. It helps buffer the residential areas from the noise, dust and pollution that is caused by vehicular traffic. Streets act as natural conveyors of stormwater and due to the sealed nature of the surface contribute also greatly to high runoff velocities, often causing damage to adjoining infrastructure and posing great risk to human life. The integration of these measures in streets decreases the volumes by 36 % and velocities by 13 % in scenario 2 as shown in Table 25.

However, due to the large portion of this hotspot being privately owned, the runoff contribution from the rooftops of buildings is also very high. With better awareness and proper use if available technology and as per the recommendations, this volume of stormwater runoff can be reused. With various levels of treatment, the stored water can be used a source of supply during dry periods for various uses within the household, or for irrigation. Where storage is not possible due to lack of feasibility, the recommended measures can also be implemented within these private open spaces to increase infiltration and reduce the outflow into the drainage system. Being the key stakeholders in this area, the residents need to be involved in the process for better management of stormwater in dense residential areas like these within the catchment and in other areas of Amman.

6.2 Recommended measures for the catchment

- While the drainage pipes of stormwater and wastewater is separated, the wastewater is directed to treatment plants, whereas stormwater is let out of the catchment into natural outlet streams. Therefore, the treatment of stormwater maybe possible in the treatment plants – which have large capacities, however, pre-storage of this stormwater before treatment might be required.
- Multifunctional spaces need to be integrated, especially in mixed use developments to facilitate on site treatment through bioretention and reuse of treated water for surrounding structures like for flushing, washing and irrigation.
- Use of smart water technologies, water saving technologies and on site reuse of water should be promoted actively.
- Protection of groundwater from pollution should be a priority and can be managed through the integration of various WSUD measures and careful selection of plant species.
- Xeriscapes are dry landscape features that integrate the natural biospheres in urban areas. These kind of vegetated areas are drought tolerant and require minimal maintenance, making them especially viable for Amman.
- Institutions, especially schools among other public buildings, offices and commercial spaces have a huge potential to integrate green roofs and other WSUD measures, because of their public nature. They also promote environmental eduction among the users of these spaces, creating awareness especially among the young generation.
- Street design in developing areas need to be inclusive of WSUD strategies. The streets that are already built also have the potential to be retrofitted with 30 % of cross sectional area for green space/ WSUD measures, as they are the biggest conveyors of stormwater. Lower traffic loads and improve the air quality, act as noise buffers, provide shade to pedestrians, improve overall quality of stay.
- Increase in public open space needs to be integrated into the landuse and zoning maps at the planning stages. In areas where this planning has already taken place, this can be achieved perhaps by reassigning the landuse function of undeveloped spaces.
- Raising awareness through popular media like TV, Radio and public advertisements about water saving through natural solutions should be promoted.
- Integrating community in decision making and design and implementation of WSUD not only increases the transparency of the process but hugely contributes to the acceptance of these changes made in the vicinity of residents.
- On site or community level recycling and treatment of grey water and stormwater for reuse should be promoted.
- Wetland treatment of stormwater might lead to losses through evapo-transpiration, and may remain dry during non rainy seasons, but could in these times be used to treat grey water, instead of big scale treatment plants. This might be subjective to availability of space, but should be considered in the planning of new areas.
- Retention ponds should be integrated in the natural sinks in the catchment in the landscape – part of parks and recreation spaces which are very necessary in the urban areas. Given the rainfall patterns, they may not always have even the minimum water level, but still promote biodiversity in the area and enhance the quality of stay and micro climate. During a flooding event, the stormwater would not cause any damage in these sinks, where otherwise, damage could be caused to infrastructure.
- Guides to plant species that are drought tolerant but also are sustained with a few hours of inundation should be made publicly available for residents to implement in their own backyards, along with their implementation in public areas.
- Subsidies and incentives for integrating RWH on private properties should make their way into Amman's policies. Storage tanks are already installed in most homes as the water supply is not very reliable, therefore, an additional tank for stormwater collection or small ponds for infiltration on site is just a matter of raising awareness and environmental education and are not too expensive.
- On major flooding streets, outlets should be provided to raingardens, retention and detention areas for overflows and special areas should be zoned out in the planning phase of these areas.

6.3 Further Research

Jordan is one of the leading countries in research and development around the issues of water vulnerabilities. With many small pilot projects being implemented for stormwater management and initiatives for international cooperation regarding the same are being made. While this thesis is limited to an overarching analysis of limited areas, a detailed insight is required for further steps in planning. This thesis has suggested that there is enough space available in area of this catchment to implement WSUD measures and even attenuate the runoff volumes with decentralised measures. However, a further study needs to be done to simulate these measures using software like STORM or SWMM that are better at estimating the quantitative aspect of urban hydrology. Furthermore, feasibility studies need to be conducted with on site investigation of built and unbuilt areas, cost benefit analysis and more. Stakeholder meetings and workshops need to be conducted for a proper transference of knowledge and experience from academics to policy makers to the residents of the area. Further research is also suggested to initially create pilot projects to be implemented in this catchment and monitor their performance. With the help of landscape architects, engineers and urban planners, the suggested measures need to be designed in detail, keeping in mind aesthetic, functional, technical and environmental aspects. A revised landuse map needs to be developed for this catchment, integrating the hydrological aspects along with social and environmental aspects.

6.4 Conclusion

The analysis of this thesis outlines the need for integration of WSUD into the policy framework, urban planning and retrofitting of built spaces in Amman. It shows that these strategies not only help mitigate the hydrological vulnerabilities of the city, but also add great value to the urban landscape by improving the microclimate, promoting biodiversity, creating public space for dynamic engagement of the residents and holistically brings nature into the city. The comparison of the different scenarios indicates the high cost of doing nothing, versus the benefits of integrating WSUD into the public and private realms. It shows that even the most impossibly dense areas with minimal potential have the space to integrate these strategies and have great value to be further analyzed. It also shows that while the stakeholders creating policies for climate adaptation realise the need for sustainable drainage systems and have been actively suggesting them in reports for climate resilience and the Green City Action Plan, there is a gap in its implementation, even in the planning document of the urban areas. This gap needs to be covered with the help of capacity building of those responsible for these tasks and involving the community to participate in seeing these tasks through. Prioritizing climate resilience is crucial for Amman, necessitating alignment of its adaptation plan with the national strategy. Enhancing social infrastructure, adopting nature-based solutions, and upgrading critical physical infrastructure are essential for bolstering the city's capacity to withstand climate-related hazards. With the upcoming challenges such as urbanization, inefficient land use, and zoning, along with the threat of exacerbated inequalities due to uneven resource distribution, and an increased instability in the migration trends, underscore the need for integrated urban planning to create a resilient, green, just, and inclusive city.

Appendix

Appendix A: Information on quantitative analysis

Area type	**Type of fastening**	**Average runoff coefficient ÿ m**
Pitched roof	• Metal, glass, slate, fibre cement, • bricks, roofing felt	0.9 – 1.0 0.8 – 1.0
Flat roof (Inclination up to 3° or approx. 5%)	• Metal, glass, fibre cement • Roofing felt • Gravel	0.9 – 1.0 0.9 0.7
Green roof (Inclination up to 15° or approx. 25%)	• humus < 10 cm structure • humus ÿ 10 cm structure	0.5 0.3
Streets, paths, squares (flat)	• Asphalt, seamless concrete • Paving with tight joints • Solid gravel surface • Paving with open joints • Loose gravel surface, gravel lawn • Interlocking stones with joints, Drainage stones • Grass pavers	0.9 0.75 0.6 0.5 0.3 0.25 0.15
Embankments, verges and ditches with rainwater runoff into the drainage system	• clayey soil • loamy sandy soil • gravel and sandy soil	0.5 0.4 0.3
Gardens, meadows and cultivated land with possible rainwater runoff into the Drainage system	• flat terrain • steep terrain	0.0 – 0.1 0.1 – 0.3

Table A1: Runoff coefficients of different surfaces
Source: DWA-117 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2013)

Description	k (ft/s) [m/s]
Sand	(5.77E-04) [1.76E-04]
Loamy	(5.13E-04) [1.56E-04]
Sandy Loam	(1.13E-04) [3.45E-05]
Silty Loam	(2.36E-05) [7.19E-06]
Loamy	(2.28E-05) [6.94E-06]
Sandy Clayey Loam	(2.07E-05) [6.31E-06]
Silty Clayey Loam	(5.57E-06) [1.70E-06]
Clay Loam	(8.04E-06) [2.45E-06]
Sandy Clayey Loam	(7.11E-06) [2.17E-06]
Silty Clay	(3.34E-06) [1.02E-06]
Clay	(4.21E-06) [1.28E-06]

Table A2: Representative Values for Hydraulic Conductivity of Soils
Source: (StructX 2024)

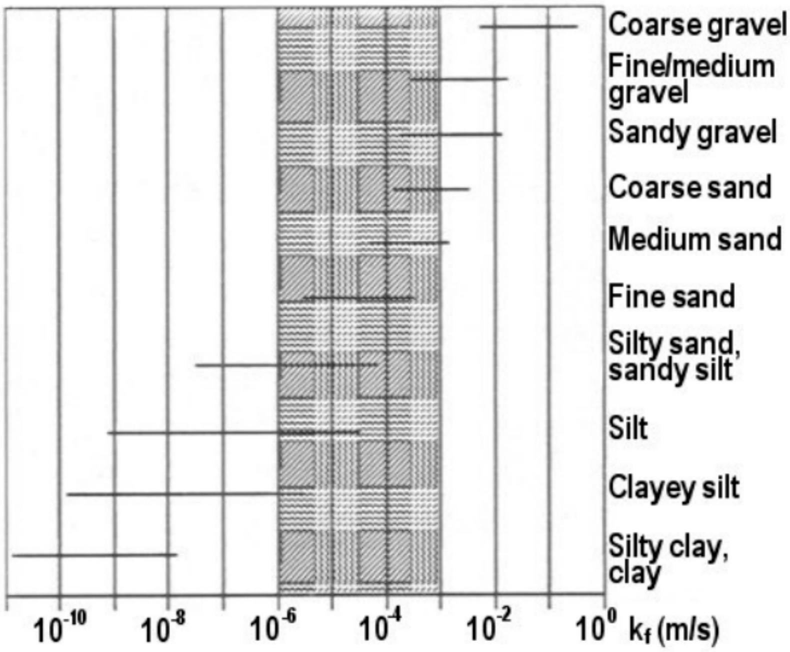


Table A3: Water permeability coefficients of loose rock and percolation range for technical drainage
Source: (DWA 2006)

Appendix B: Additional information for the Royal Village Project

Scenario 1A					
Type of Surface	Description	Permeable Area	Impermeable Area	Total Area (Ac)	% of total Area
		m^2	*m^2*	*m^2*	
Building Roof-tops	Flat and cemented		2700.47	2700.47	1 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.	450837.052		450837.05	99 %
	Total	**450837.05**	**2700.47**	**453537.52**	
		99 %	1 %		

Table B1: Description of areas in scenario 1A or pre-development scenario of the royal village project.
Source: Author

Scenario 1B					
Type of Surface	**Description**	**Permeable Area**	**Impermeable Area**	**Total Area (Ac)**	**% of total Area**
		m^2	m^2	m^2	
Building Roof-tops	Flat and cemented, both residential and public buildings		104343.65	104343.65	23 %
Streets	Asphalt		137938.84	137938.84	30 %
Paved Area	Concrete pavings, side-walks with closed joints.		92864.37	92864.37	20 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.				0 %
Existing Green Areas					
Private Gar-dens	Areas around residen-tial buildings. Based on satellite imagery, 80 % is assumed to be green, while 20 % is paved for driveways	68159.40424	17039.85106	85199.26	19 %
Public Gardens	Areas with planted veg-etation as per the land-scaping masterplan	31754.49		31754.49	7 %
Sports grounds	Paved grounds with ar-tificial turf		1436.9142	1436.91	0 %
	Total	**99913.90**	**353623.63**	**453537.52**	
		22 %	**78 %**		

Table B2: Description of areas in scenario 1B or the proposed masterplan of the royal village project.
Source: Author

Scenario 2					
Type of Surface	Description	Permeable Area	Impermeable Area	Total Area (Ac)	% of total Area
		m^2	m^2	m^2	
Building Rooftops	Flat and cemented, both residential and public buildings		48460	48460	11 %
Streets	Asphalt		113311	113311	25 %
Paved Area	Concrete pavings, sidewalks with closed joints. 90 % of the area is paved around the school, 10 % is permeable for the existing trees on site		70895	70895	16 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.			0	0 %
Exisiting Green Areas	Areas with planted vegetation exisitng on site	31754		31754	7 %
Private Gardens	Areas around residential buildings. Based on satellite imagery, 40 % is assumed to be green, while 60 % is paved.	20062		20062	4 %
Public Gardens	Areas for public use, with no pavements as per satellite imagery	68159	17040	85200	19 %
Blue Green Measures					
New Green areas	Permeable area created out of previously sealed or undeveloped open space	4118		4118	1 %
Green Roofs	Implementing semi intensive or intensive on flat roofs of all public buildings	55884		55884	12 %
Bioswales	Shallow pits that are vegetated for retention and conveyeance of stormwater	10163		10163	2 %
Permeable Pavement	Paving blocks with loose joints to increase permeability of the area	14465		14465	3 %
Raingarden	A landscaped area that captures and filters rainwater runoff				0 %
	Total	**204606**	**249706**	**454312**	
		45 %	55 %		

Table B3: Description of areas in scenario 2 for the Royal Village project
Source: Author

Scenario 1A				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m²		*m²*	*m²*
Building rooftops	2700.47	0.90	2430.42	
Undeveloped Open Space	450837.05	0.40		180334.82
Total	**453537.52**		**2430.42**	**180334.82**

Table B4: Calculation of reduced areas for Scenario 1A Source: Author

Scenario 1B				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m²		*m²*	*m²*
Building rooftops	104343.65	0.90	93909.28	
Streets	137938.84	0.90	124144.96	
Paved	92864.37	0.75	69648.28	
Existing Green	31754.49	0.20		6350.90
Public Gardens		0.10		0.00
Private Gardens	85199.26	0.30		25559.78
Undeveloped Open Space	0.00	0.40		0.00
Sports Grounds (Paved)	1436.91	0.80	1149.53	
Total	**453537.52**		**288852.05**	**31910.67**

Table B5: Calculation of reduced areas for Scenario 1B Source: Author

Scenario 2				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m²		*m²*	*m²*
Building rooftops	48459.57	0.90	43613.61	
Streets	113311.25	0.90	101980.12	
Paved	70895.16	0.75	53171.37	
Existing Green	31754.49	0.20		6350.90
Public Gardens	20061.80	0.10		2006.18
Private Gardens	85199.26	0.30		25559.78
Undeveloped Open Space		0.40		0.00
New Green	4118.48	0.10		411.85
Green Roofs	55884.08	0.40		22353.63
Bioswale	10162.85	0.20		2032.57
Permeable Pavement	14464.75	0.30		4339.42
Raingarden		0.10		0.00
Total	**454311.68**		**198765.11**	**63054.33**

Table B6: Calculation of reduced areas for Scenario 2 Source: Author

Scenario 3				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m^2		m^2	m^2
Building rooftops	0.00	0.90	0.00	
Streets	113311.25	0.90	101980.12	
Paved	70895.16	0.75	53171.37	
Existing Green	31754.49	0.20		6350.90
Public Gardens	20061.80	0.10		2006.18
Private Gardens	85199.26	0.30		25559.78
Undeveloped Open Space		0.40		0.00
New Green	4118.48	0.10		411.85
Green Roofs	55884.08	0.40		22353.63
Bioswale	10162.85	0.20		2032.57
Permeable Pavement	14464.75	0.30		4339.42
Raingarden		0.10		0.00
Total	**405852.11**		**155151.50**	**63054.33**

Table B7: Calculation of reduced areas for Scenario 3
Source: Author

Appendix C: Additional information for Residential Area

Scenario 1					
Type of Surface	Description	Permeable Area	Impermeable Area	Total Area (Ac)	% of total Area
		m^2	m^2	m^2	
Building Roof-tops	Flat and cemented, both residential and public buildings		84,606.44	84,606.44	23 %
Streets	Asphalt		1,63,843.34	1,63,843.34	45 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.	7,138.09		7,138.09	2 %
Private Gar-dens	Areas around residen-tial buildings. Based on satellite imagery, 40 % is assumed to be green, while 60 % is paved.	88,192.96	22,048.24	1,10,241.20	30 %
	Total	**95,331.05**	**2,70,498.03**	**3,65,829.08**	
		26 %	**74 %**		

Table C1: Description of types of surfaces for the residential area for scenario 1
Source: Author

Scenario 2					
Type of Surface	**Description**	**Permeable Area**	**Impermeable Area**	**Total Area (Ac)**	**% of total Area**
		m^2	m^2	m^2	
Building Rooftops	Flat and cemented, both residential and public buildings		84606.44	84606.44	23 %
Streets	Asphalt		112070.51	112070.51	31 %
Undeveloped Open Space	Space with low or no vegetation and natural soil that has not been developed yet.	7138.09		7138.09	2 %
Private Gardens	Areas around residential buildings. Based on satellite imagery, 40 % is assumed to be green, while 60 % is paved.	88192.96	22048.24	110241.20	30 %
Blue Green Measures					
Bioswales	Shallow pits that are vegetated for retention and conveyance of stormwater	50250.53		50250.53	14 %
	Total	**145581.58**	**218725.19**	**364306.77**	
		40 %	**60 %**		

Table C2: Description of types of surfaces for the residential area for scenario 2
Source: Author

Table C3: Calculation of reduced areas for Scenario 1
Source: Author

Scenario 1				
Type of surface	**Ac,i**	**$\Psi_{m,i}$**	**Aimp**	**Ap**
	m^2		m^2	m^2
Building rooftops	84606.44	0.90	76145.80	
Streets	163843.34	0.90	147459.01	
Paved		0.75		
Existing Green		0.20		
Public Gardens		0.10		
Private Gardens	110241.20	0.30		33072.36
Undeveloped Open Space	7138.09	0.40		2855.24
Total	**365829.08**		**223604.81**	**35927.60**

Table C4: Calculation of reduced areas for Scenario 2
Source: Author

Scenario 2				
Type of surface	**Ac,i**	**$\Psi_{m,i}$**	**Aimp**	**Ap**
	m^2		m^2	m^2
Building rooftops	84606.44	0.90	76145.80	
Streets	112070.51	0.90	100863.46	
Private Gardens	110241.20	0.30		33072.36
Undeveloped Open Space	7138.09	0.40		2855.24
New Green		0.10		0.00
Bioswale	50250.53	0.20		10050.11
Total	**364306.77**		**177009.26**	**45977.70**

Scenario 3				
Type of surface	Ac,i	$\Psi_{m,i}$	Aimp	Ap
	m^2		m^2	m^2
Building rooftops	0	0.90	0	
Streets	112070.51	0.90	100863.46	
Private Gardens	110241.20	0.30		33072.36
Undeveloped Open Space	7138.09	0.40		2855.24
New Green		0.10		0.00
Bioswale	50250.53	0.20		10050.11
Total	**279700.33**		**100863.46**	**45977.70**

Table C5: Calculation of reduced areas for Scenario 3
Source: Author

Appendix D: Miscellaneous

Residential land regulation - Provisions for regulating housing areas.

All residential groups share similar provisions, but the difference between them is in proportions and numbers, and these provisions are as follows:

- Setbacks: It is the space separating the building from the border of the land in which building is prohibited. It includes the front, side, and back directions.
- Building Percentage: It is the area on which the landowner is entitled to build in relation to the total land area.
- The number of turns
- The minimum length of the façade located on the front street
- Height: From the ground floor tiling
- Parking

Provisions of categories of housing areas A, B, C, D

1. Residential area A

- Setbacks: front 5m, side 5m, rear 7m
- Building percentage: 39 %
- Minimum plot area: 1000 m^2
- The minimum length of the façade located on the front street: 25 m^2
- Number of floors: 4 floors
- Height: 16 m

2. Residential area B

- Setbacks: (front 4m, side 4m, rear 6m)
- Building percentage: 45 %
- Minimum plot area: 750 m^2
- The minimum length of the façade located on the front street: 20 m^2
- Number of floors: 4 floors
- Height: 16 m

3. Residential area C

- Setbacks: front 4m, side 3m, rear 4m
- Building percentage: 51 %
- Minimum plot area: 500 m^2

- The minimum length of the façade located on the front street: 18 m^2
- Number of floors: 4 floors
- Height: 16 m

4. Residential area D

- Setbacks: front 3m, side 2.5m, rear 3m
- Building percentage: 55 %
- Minimum plot area: 300 m^2
- The minimum length of the façade located on the front street: 12 m^2
- Number of floors: 4 floors
- Height: 16 m

Provisions of the private housing category:

The provisions of this category depend on the residential area on which the building will be built as follows:

- It is characterized by vertical construction, as the number of floors allowed for the building is only two floors and a roof.
- It is located within residential areas (A), (B), and (C), and their regulatory provisions apply to it.
- The maximum height of the two floors is 9 m from the height of the ground tiling.
- When building a roof, it is required that it be in the middle of the floor on which it is built so that it does not exceed 50 % of its area.

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