Too little, Too much

HafenCity Universität Hamburg

Water Sensitive Urban Design in Hot Dry Climates

A Framework and Transition Strategy for the MENA Region – A Case Study of Alexandria, Egypt

Mahmoud Moursy

Hamburg, 2025

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Kurzfassung

Diese Dissertation befasst sich mit den kritischen Herausforderungen der urbanen Resilienz im heißen, trockenen Klima der MENA-Region, insbesondere im Hinblick auf die zunehmenden Belastungen durch den Klimawandel und die Urbanisierung. Globale Veränderungen in Trockenheit und Niederschlagsmustern beeinflussen nicht nur die Wasserverfügbarkeit, sondern erhöhen auch die Häufigkeit und Intensität extremer Wetterereignisse. Diese kumulierten Probleme von Dürre, Hitzewellen und schweren, aber sporadischen Überschwemmungen werden durch eine unzureichende Infrastruktur verschärft, die sich nicht ohne Weiteres an die sich schnell ändernden Bedingungen anpassen lässt. Solche Umweltdynamiken unterstreichen die dringende Notwendigkeit eines Paradigmenwechsels hin zur Übernahme des Wasserempfindlichen Städtebaus (WSUD) in diesen Gebieten, um die negativen Auswirkungen dieser Extreme zu mildern und sie auszugleichen. Allerdings konzentrierten sich viele der Forschungen und praktischen Anwendungen von WSUD überwiegend auf feuchte Regionen, wobei Pionierbeispiele aus Australien stammen.

Da WSUD-Strategien und -Technologien nicht direkt zwischen verschiedenen Regionen und Klimazonen übertragen werden können, ohne Anpassungen vorzunehmen, zielt diese Dissertation darauf ab, diese Wissenslücke zu schließen, indem ein neuartiger räumliches Planungsrahmen für die Übernahme von WSUD-Praktiken entwickelt und empirisch getestet wird, der auf den einzigartigen urbanen Kontext der trockenen MENA-Region zugeschnitten ist. Dieser Rahmen bietet Entscheidungsträgern und Praktikern Methoden und Werkzeuge zur Integration von Wassermanagementpraktiken in städtische Entwicklungsprozesse.

In dieser Dissertation wird ein induktiver Analyseansatz verwendet, dessen Erkenntnisse die Grundlage für die Entwicklung der Konzepte und Strategien des Planungsrahmens bildet. Zunächst werden die Besonderheiten der trockenen bebauten Umwelt untersucht, wobei häufige städtische morphologische Muster und hydrologische Eigenschaften identifiziert werden. Die Forschung zeigt eine signifikante Wechselwirkung zwischen urbanen physischen Merkmalen und urbaner Entwässerung, die städtische Überschwemmungen in der Region erheblich beeinflusst. Diese Beziehung ist zentral für die Entwicklung eines innovativen WSUD-Planungsansatzes, der urbane Gebiete als eigenständige hydrologische Regionen, sogenannte Mikro-becken und Barrieren, verwaltet. Parallel dazu konzentriert sich diese Dissertation auf das Best-Practice-Beispiel der Stadt Adelaide im Süden Australiens, aus welchem Lehren gezogen sowie wertvolle Erkenntnisse gewonnen werden, die zur Übertragung dieser Erfahrungen auf eine andere trockene Region nützlich sind. Diese Erkenntnisse, unter Berücksichtigung des kontrastierenden städtischen Kontexts, prägen eine Reihe von Prinzipien und Kriterien, die die Übernahme von WSUD-Strategien beeinflussen. Die Ergebnisse zeigen, dass alle WSUD-Technologien auf trockene Klimazonen angepasst werden können, jede in unterschiedlichem Ausmaß. Die Untersuchung identifiziert spezifische Designanpassungen und legt nahe, dass die effektivste Strategie darin besteht, diese Technologien kollaborativ zu nutzen, um die Leistung zu optimieren. Darüber hinaus enthält der entwickelte Rahmen ein konzeptionelles Datenmanagementmodell, welches diese Komponenten in ein umfassendes Entscheidungshilfesystem integriert.

Der Planungsrahmen wird dann in einer empirischen Untersuchung dazu verwendet, herauszufinden, in welcher Weise WSUD-Prinzipien und -Strategien angepasst werden können, um in der Stadt Alexandria die lokale urbane Resilienz gegen Extreme zu verbessern. Primärdaten wurden durch halbstrukturierte Interviews mit Experten, direkte Beobachtungen und Analysen gesammelt, während Sekundärdaten eine detaillierte Überprüfung der verfügbaren Literatur und Dokumente umfassten.

Die wichtigsten Ergebnisse bestätigen die Anwendbarkeit des eingeführten WSUD-Planungsansatzes auf den typischen urbanen Kontext der Stadt, wobei die Vorteile einer mehrschichtigen urbanen Raumanalyse hervorgehoben werden. Diese Analyse liefert wichtige städtische Parameter, die die WSUD-Implementierung, Entscheidungsfindung und Festlegung von Richtlinien beeinflussen. Allerdings sind Verbesserungen in der Qualität und Zugänglichkeit dieser Metriken erforderlich. Die Forschung zeigt auch das Potenzial von linearen Infrastrukturen wie Eisenbahnschienen und Hauptstraßen bei der Verwaltung und Wiederverwendung von Regen- und Grauwasser. In den Vorschlägen für die Stadtentwicklung wird die Notwendigkeit eines Mindestanteils an Grünflächen betont, um die Wirksamkeit von WSUD zu verbessern.

Die dichte und vielfältige urbane Umgebung der Stadt erfordert einen strategischen Ansatz für die Nutzung von Land und Technologien. Die Maximierung der Landnutzungseffizienz durch die multifunktionale Flächennutzung und die Förderung der Baulückenschließung ist unerlässlich. Daher ist eine mikrobeckenbasierte Landnutzungsplanung von entscheidender Bedeutung für die Integration von WSUD, da sie lokal angepasste Wassermanagementlösungen für spezifische Teile der Stadt ermöglicht. Flexibilität und Skalierbarkeit der WSUD-Technologien sind ebenfalls entscheidend und erfordern anpassungsfähige Lösungen, die auf verschiedenen städtischen Ebenen angewendet werden können. Eine optimale Kombination von WSUD-Technologien ist notwendig, um die geplanten Ziele effektiv zu erreichen. Darüber hinaus unterstreicht die Forschung die Bedeutung von Grünflächen und bepflanzten Systemen in WSUD-Strategien und zeigt das transformative Potenzial der Integration von Grünflächen in städtische Umgebungen, wobei konventionelle Ansichten über ihre Umsetzbarkeit in trockenen Klimazonen infrage gestellt werden.

Abschließend trägt die Dissertation zum Bereich des urbanen Wassermanagements und der Klimaanpassung bei, indem sie das Potenzial von WSUD zur Minderung der Klimawandelauswirkungen in heißen, trockenen Regionen aufzeigt. Sie bietet eine methodologische Grundlage und praktisch umsetzbare Erkenntnisse für die Anwendung von WSUD in ähnlichen urbanen Umgebungen weltweit. Die Forschung unterstreicht die Notwendigkeit kontextspezifischer Anpassungen in städtischen Wasserstrategien und hebt die dringende Notwendigkeit einer breiteren Anwendung hervor, um städtische Gebiete vor zunehmenden klimatischen Herausforderungen zu schützen.

Abstract

This dissertation addresses the critical challenges of urban resilience in the hot, dry climate of the MENA region, particularly in view of escalating climate change and urbanization pressures. Global changes in aridity and precipitation patterns are not only affecting water availability but also increasing the frequency and intensity of extreme weather events. These compounded issues of drought, heatwaves, and sporadic yet severe flooding are exacerbated by inadequate infrastructure that struggles to adapt to rapidly changing conditions. Such environmental dynamics underscore the urgent need for a paradigm shift towards adopting Water Sensitive Urban Design (WSUD) in these settings to mitigate the adverse impacts of these extremes and achieve equilibrium. However, most of the research and practice in WSUD has predominantly focused on humid regions, with limited coverage in dry regions.

Given that WSUD strategies and technologies cannot be directly transferred between differing regions and climates without adjustment, this dissertation aims to bridge this knowledge gap by developing and empirically testing a novel spatial framework for adopting WSUD practices tailored to the unique urban context of the dry MENA region. The framework will provide decision-makers and practitioners with methods and tools to integrate water management practices into urban development processes.

This dissertation employs an inductive analysis approach to provide the foundational knowledge for developing the framework's concepts and strategies. Initially, it examines the peculiarities of the dry built environment, identifying common urban morphological patterns and hydrological characteristics. The research reveals a significant interplay between urban physical features and urban drainage, which profoundly influences urban flooding in the region. This relationship is central to developing an innovative WSUD planning approach that manages urban areas as discrete urban hydrological regions, referred to as micro-basins and barriers. In parallel, the dissertation focuses on the best practices reference case of Adelaide City in South Australia, drawing lessons and valuable insights for transferring their experience to another dry region. These insights, considering the contrasting urban context, inform a set of principles and criteria that guide the adoption of WSUD strategies. The findings indicate that all WSUD technologies can be adapted to dry climates, each to a different extent. The investigation identifies specific design adjustments and suggests that the most effective strategy involves using these technologies collaboratively to optimize performance. Additionally, the developed framework features a conceptual data management model that integrates these components into a comprehensive decision support system.

The framework is then employed in an empirical investigation of how adopting WSUD principles and strategies in Alexandria City can enhance local urban resilience against extremes. Primary data was collected through semi-structured interviews with experts, direct observations, and analysis, while secondary data included a detailed review of available literature and documents.

The key findings confirm the applicability of the introduced WSUD planning approach to the city's typical urban context, underscoring the benefits of a multi-layered urban spatial analysis. This analysis produces critical urban metrics that inform WSUD implementation, decision-making, and policy formulation. However, enhancements in the quality and accessibility of these metrics are necessary. The research also demonstrates the potential of linear infrastructures such as railroad tracks and major roads in managing and reusing stormwater and greywater. Urban development proposals recommend maintaining a threshold ratio of green spaces to enhance the effectiveness of WSUD applications.

The city's dense and varied urban setting necessitates a strategic approach to land and technology utilization. Maximizing land use efficiency by leveraging multifunctional spaces and pursuing infill development is essential. Therefore, micro-basin-based land use planning is vital for integrating WSUD by allowing for localized water management solutions tailored to specific parts of the city. Flexibility and scalability in WSUD technologies are also important, demanding adaptable solutions that can be applied at various urban scales. An optimal combination of WSUD technologies is necessary to achieve the planned goals effectively. Furthermore, the research highlights the importance of green spaces and vegetated systems in WSUD strategies. It demonstrates the transformative potential of integrating green spaces within urban environments, challenging conventional views on their feasibility in dry climates.

This dissertation contributes to the field of urban water management and climate adaptation by showcasing the potential of WSUD in mitigating climate change impacts in hot, dry regions. It provides a methodological foundation and actionable insights for applying WSUD broadly in similar urban settings globally. The research underscores the necessity for context-specific adaptations in urban water strategies and highlights the urgent need for broader adoption to protect urban areas from escalating climate challenges.

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Acronyms

ASDCO	Alexandria Sanitation and Drainage Company
ARI	Average Recurrence Interval
ASR	Aquifer Storage and Recovery
CSO	Combined Sewer Overflow
CFW	Constructed floating wetlands
CRC	Cooperative Research Centre for Water Sensitive Cities
CBD	Central Business District
DEM	Digital Elevation Model
ET	Evapotranspiration
GI	Green Infrastructure
GIS	Geographic Information Systems
GPT	Gross Pollutant Traps
IPM	Infiltration Potential Map
IDF	intensity–duration–frequency
IDW	Inverse Distance Weighted
IPSS	Integrated Planning Support System
MAR	Managed Aquifer Recharge
MCDA	Multi-criteria Decision Analysis
MENA	Middle East and North Africa
NbS	Nature-Based Solutions
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NUCA	New Urban Communities Authority
PICP	Permeable Interlocking Concrete Pavement
UGF	Urban Green Factor
UGS	Urban Green Space
UHI	Urban Heat Island Effect
WTP	Water treatment plant
WWTP	Wastewater treatment plant
WSUD	Water Sensitive urban Design
WUE	Water Use Efficiency

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1 INTRODUCTION

1.1 The Context: Macro and Micro

Cities worldwide grapple with the escalating impacts of climate change extremes. Dry regions are paradoxically characterized by their vulnerability to both frequent droughts and flash flooding. Rapid population growth and increasing pressure on water availability, coupled with inadequate infrastructure unable to adapt to these changes, pose significant challenges to urban resilience. The phenomena of increasing extreme conditions can be examined from both macroscopic and microscopic perspectives, encompassing broader global trends and localized challenges. These circumstances underpin the necessity for this research and emphasize the need for innovative urban design strategies that integrate water management and environmental sustainability has never been more urgent.

1.1.1 Change of Aridity and Precipitation Patterns

At the macro level, the overview entails the assessment of large-scale climatic shifts, alterations in long-term trends, and the manifestation of anomalies within a global context. From this perspective, climate extremes are observable through the lens of global climate models, which simulate the complex interactions between the atmosphere, oceans, and land.

The nature of aridity originates from the persistence of limited precipitation and high rates of evaporation conditions over extended periods, leading to water scarcity and desertification. Climate change has further intensified these challenges, leading to changes in aridity patterns. An observed change in aridity identifies shifts of humid and sub-humid regions to drier conditions over the last century. The change indicates an increase of global drylands by about 0.35 %, attributed primarily to the rise of 3.4 % of semi-arid regions (Fig. 1-1), from 13.11 % to 13.56 % (Cherlet et al., 2018).

The expansion of drylands is expected to continue in the future. In a study by Feng and Fu (2013), according to the ensemble average of 27 CMIP5 climate models under a business-as-usual (RCP 8.5) scenario, a consensus among more than 80% of the 27 ensemble models indicates major projected expansions of drylands, particularly towards increased aridity. It is estimated that by the end of this century, global dryland will expand by about 10 % to 23 %

Notably, a substantial proportion, encompassing 80% of the expansion will take place in global south nations. Illustrated in Figure 1-2 are the anticipated alterations in the Aridity Index (AI) for the immediate, near, and far future. It is noteworthy that decreases in the AI reflect heightened aridity, while conversely, increased AI values signify more wetter conditions (Cherlet et al., 2018). These expansions are notable in several regions, including North America, the Mediterranean, southern Africa, Australia, the Middle East, Central Asia, and South America

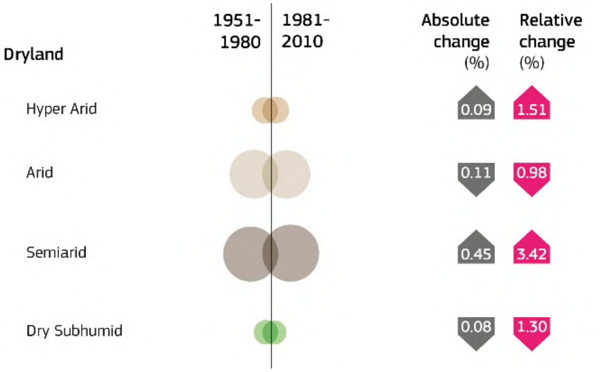
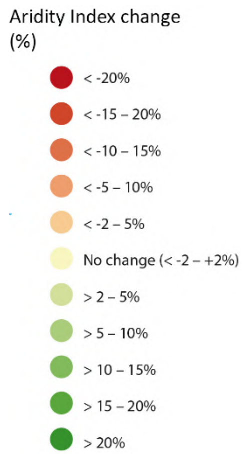


Fig. 1-1: Change in dryland subtypes based on the Aridity Index, from the World Atlas of Desertification (Cherlet et al., 2018)

(especially eastern Brazil, southern Argentina, and coastal Chile). Furthermore, substantial expansion of semi-arid regions is expected over the northern Mediterranean, southern Africa, and North and South America (Feng & Fu, 2013).

While aridity is regarded as a chronic environmental condition, it is mostly accompanied by other episodic climate-induced phenomena such as droughts and floods. Alterations in precipitation patterns represent a primary driver behind the increased frequency and severity of extreme weather events. These changes can disrupt the balance of water supply and demand, leading to regional water scarcity and affecting communities, ecosystems, and economies in drylands.

Observations and global climate models show robust increases in extreme daily precipitation over the past decades, while climate projections for the rest of the century show continued intensification of this phenomenon (Tabari, 2020). Contrary to the common misperception that dry regions will become drier and wet regions wetter, climate projections for the world's drylands reveal substantial ensemble-mean increases in total precipitation and annual extremes, particularly in arid areas (Fig. 1-3) (Donat et al., 2017). The increase in rainfall intensity and frequency will raise the risk of flash flooding at regional levels in dry urban areas, not just as an average across the globe. However,



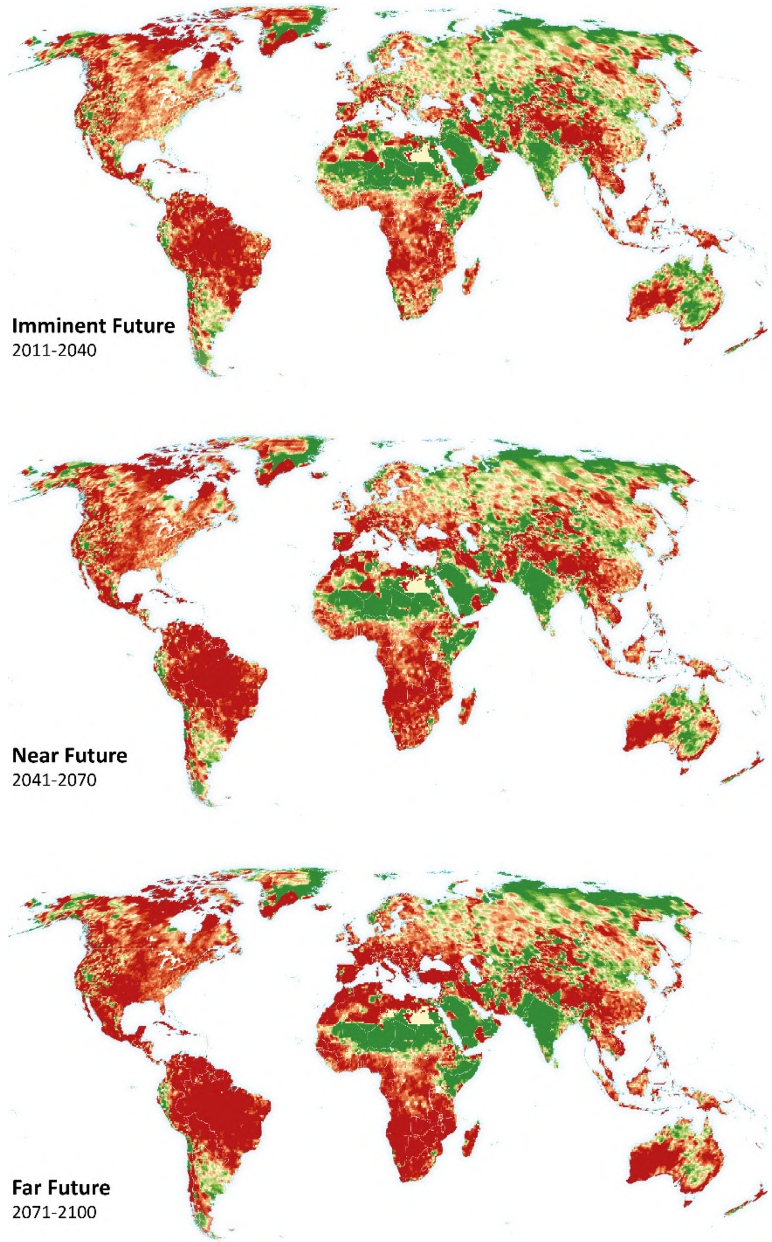


Fig. 1-2: Projected future changes in the Aridity Index (AI), from the World Atlas of Desertification (Cherlet et al., 2018)

this may not necessarily lead to an increase in water availability due to the increase in evaporation caused by a warmer atmosphere which will not change the water storage rate. In addition, global warming causes shifts in temperature, and weather patterns influence the distribution and behavior of waterborne diseases, impacting public health. Altered precipitation patterns causing flooding can affect water quality by increasing the risk of contamination in water sources (IPCC, 2023).

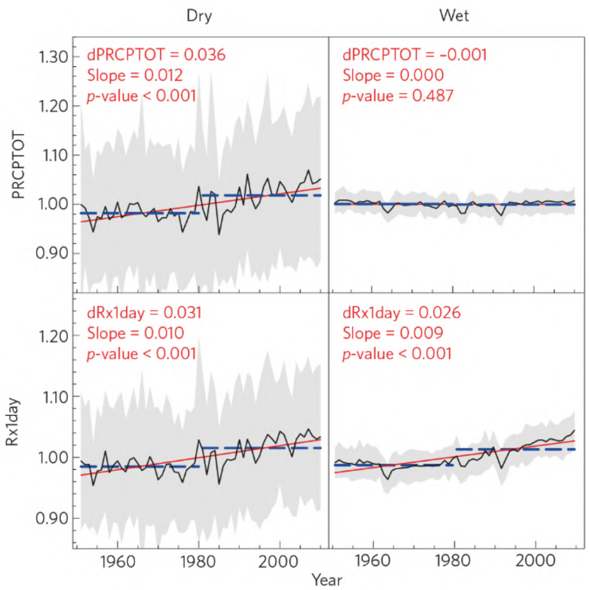


Fig. 1-3: Total precipitation amounts and annual extremes changes in the dry and wet regions identified from GCMs (Donat et al., 2017)

Despite the inherent uncertainties associated with climate projection models, there exists a high degree of confidence in the ongoing global expansion of aridity and changes in extreme weather patterns in drylands. This underscores the urgency of addressing these issues and implementing adaptive measures to mitigate their consequences.

1.1.2 The Drought and Flooding Predicament

At the micro level, localized impacts and specific mechanisms come into focus, Shedding the light on the implication of increased intensity of climate extremes within dry urban environments.

Currently, nearly 38% of the global population resides in dryland regions. Within these regions, approximately 35% of the world's major cities are situated, including megacities like New Delhi, Mexico City, and Cairo. In total, these cities are home to nearly 2 billion people, with 90% of them residing in the global south nations (Cherlet et al., 2018). Projections indicate that these percentages are poised to increase in the future due to compelling evidence of changing aridity patterns, resulting in more cities experiencing heightened drought. Cities in dry environments are currently facing seasonal water imbalance characterized by alternating periods of extended droughts and intense rainfall events causing flooding. Simultaneously, population growth and increased pressure on water resources are accelerating. Those cities are confronted with an alarming resilience challenge due to the interplay of urbanization and climate change. These typical challenges are detailed as follows:

Population growth and urbanization: Growing cities and the sprawling of urban areas have a profound impact on the very sensitive natural hydrological cycles in drylands. Population growth in urban areas drives up water demand which puts additional stress on already scarce water resources, exacerbating water scarcity issues. Stress on water resources causes decreased groundwater levels, reduced surface water flow, and increased competition for limited water resources. In addition, urbanization is typically involved in the alteration of runoff patterns by sealing the natural ground with impervious surfaces such as roads, buildings, and pavements. As a result, the natural flow of water is disturbed, leading to reduced infiltration into the soil and more surface runoff, increasing the risk of flooding during intense rainfall events (Qian et al., 2022).

Heat stress and urban drought: urban areas within this climate are particularly susceptible to heat stress and water scarcity. Heat waves in these regions tend to be more prolonged and intense, with daytime temperatures often reaching extreme levels. Global warming exacerbates the urban heat island effect (UHI), leading to discomfort, health issues, and most critically, an increased demand for water resources. This heightened demand further intensifies the impacts of drought in an already water-scarce region.

Urban drought represents a tangible manifestation of water scarcity within the cityscape in drylands. In such climates, the presence of green spaces and vegetation cover is often limited. However, the establishment and maintaining urban green spaces pose substantial challenges, including the need for reliable and sustainable water supply, efficient irrigation methods, and high maintenance costs. Elevated temperatures and frequent extreme weather events can strain green infrastructure, contributing not only to aesthetic degradation but also reducing the capacity for natural water regulation and temperature moderation. (FAO, 2022; Zhang et al., 2019)

Fig. 1-4: Water tankers sprinkling water on streets of Amman, Jordan in a hot summer day (Photo: Ameer Khalifeh, 2023)

Extreme rainfall and flash flooding:

Paradoxically, alongside water scarcity, urban areas in dryland face the risk of extreme rainfall events leading to rapid urban flash flooding. This inundation of streets and spaces damages infrastructure and poses risks to public safety. These consequences include power outages, road and bridge and building destruction, all of which disrupt daily life and economic activities. One critical issue is that infrastructure in these conditions often is not designed to withstand even minor increases in the intensity of extreme weather events, making them particularly vulnerable to flooding. Intense rainfall can easily exceed the capacity of the urban drainage systems, including sewers and treatment facilities, especially given the aging infrastructure and increased hydraulic stress from a growing population (Arnbjerg-Nielsen et al., 2013; Auld, 2008).

The magnitude of flooding impact is proportional to the expected precipitation in such climates and the design and condition of the existing water infrastructure. As depicted in Figure 1-5, a straightforward comparison of a typical flooding event in humid and dry cities shows a similar impact, despite the substantial difference between average annual rainfall and one-day extreme rainfall events. In cities like Cairo, Jeddah, and many others in the region, the intensity of extreme events can match or exceed the total average annual precipitation, which is considerably less than typical events in more humid locations.

Additionally, during floods, sewage and wastewater systems may overflow, resulting in the discharge of untreated or partially treated wastewater into the environment. This leads to water source contamination and poses significant health risks to the population.

> "Our general water infrastructure was built in the 1950s and 60s, and so it was built for a different population and a different climate,"
>
> *Said Laura Ramos, a water management expert commenting on series of storms floods and droughts hit California, USA (DW, 2023)*

To conclude, cities in dry environments are currently facing seasonal and regional water shortages, frequent drought and flash flooding. Population and pressure on water availability are rapidly growing while a changing climate and inadequate infrastructure are posing a significant challenge to the resilience of those cities. Climate observations and models indicate robust increases in extreme daily, with projections suggesting continued intensification. The increase of rainfall intensity and frequency will raise the risk of flash flooding at regional levels. However, increased rainfall does not necessarily

Fig. 1-5: Comparison between humid and dry cities showing the proportional magnitude of precipitation to flooding impact in two cities from each climates

Mumbai (Photo: Rajanish Kakade, 2017)
Sydney (Photo: Matthew Abbott, 2021)
Cairo (Photo: Getty Images, 2022)
Jeddah (Photo: Salman Marzouki, 2017)

lead to improved water availability. The increase of evaporation caused by a warmer atmosphere will not change the water storage rate. In addition, there may not be infrastructure in place to cope with the increased intensity of precipitation events in dry areas.

This convergence of global macro-level and micro-level challenges inherent to dry urban environments underscores the complex interplay between water excess and scarcity, posing a fundamental challenge to cities. This draws attention to the need for a shift in thinking in water management and urban development that can contribute to healthy and resilient communities.

The research interest falls in the area of Water Sensitive Urban Design (WSUD) planning instruments and approach that apply to urban areas subject to hot dry climates, which can alleviate the risk of urban flash flooding and drought while taking advantage of new opportunities to conserve water and improve quality of public and private urban spaces.

WSUD is an integrated design and planning approach for sustainable urban development that incorporates water management, urban design, landscape, and environmental protection while improving aesthetic and recreational aspects. WSUD incorporates all water aspects, including water supply, wastewater, stormwater, groundwater, and flowing water. It represents a fundamental shift in urban planning and design that considers the urban water cycle (Hoyer et al., 2011; Lloyd et al., 2002). However, much of the research in the field of WSUD has been developed for humid regions. The majority of the literature available reflects the experiences of those regions, with little reference to the arid and semi-arid climates (Cleveland, 2013; Coutts et al., 2013). The fact is, WSUD planning principles and practices required for cities in dry regions cannot plainly be imported from humid ones, and research related to dry regions is limited to experiences in Australia and the Southwestern United States.

1.2 Significance of The Research

There is a research need to address this knowledge gap of adopting WSUD practices in dry environments that limits the ability of planners and designers to opt for the right decisions for city development while providing less guidance to jurisdictions and policymakers. The uncertainty and drastic resistance to adopting rainwater harvesting and urban water management concepts in dry climates need to be further elucidated. Uncertainty includes the fact that; rainfall regimes vary significantly in frequency and quantity, the daily temperature extremes cause higher evapotranspiration, the higher concentration of pollution due to the infrequency of rainfall events, and soil texture and its properties are different in humid regions.

The case study area of Alexandria is a major contribution since there is a need to consider integrated urban water management in the city and others in the region. The development and quality of living in many cities in dry environments are under threat. During the rainy season, many cities in the region including Alexandria have recently experienced flash flooding after intense rainfall events. The inadequate capacity of the drainage system has been identified as the main cause, due to the extended process of densification over many years that has contributed to a rising demand on infrastructure. The vulnerability and consequences of the drainage system's failure were not fully considered (Saud, 2010; Zevenbergen et al., 2017).

Current projects concerning flash flooding in the city are confined to anticipatory measures or reactive measures responding to events after they have occurred, lacking a comprehensive adaptation strategy that reduces the severity while taking advantage of new opportunities that may be presented (Bhattacharya et al., 2018). Although flooding risk is widely discussed across various media platforms (newspapers, TV, social media) (Al Jazeera, 2016; Angwin, 2015) but has not been formally researched. Therefore, this work here has the potential to drive change and contribute toward a better understanding of the Problem. The City of Alexandria could be a model of climate resilience and adaptation for dry cities in the region and others worldwide.

1.3 Aim of Research and Questions

Against this background, the primary objective of this dissertation is to alleviate the repercussions of the flooding and drought dilemma, striving to establish an equilibrium between interchangeable water excess and scarcity conditions, to foster sustainable urban development, and to enhance the resilience of cities affected by hot and dry climates. This goal is chiefly pursued by clarifying the uncertainties and radical resistance to applying the Water Sensitive Urban Design (WSUD) concept while broadening the understanding of the intricacies of urban structure and water cycle.

Applying WSUD principles in dry climates can face resistance due to established urban norms, infrastructural limitations, and challenging environments that might not align with the required changes. This dissertation seeks to explore how this concept can be effectively implemented and adapted to specific challenges and investigate and shed light on the limitations that can hinder the adoption of WSUD in such a climate. The work also aims to examine the distinctive fabric of urban structures in these regions where the urban landscape interacts with the challenges posed by both water scarcity and abundance. This underpins the importance of deepening the understanding of urban contexts concerning water-sensitive urban development. Shifting the focus to the perspective of flooding risk from this standpoint has the potential to inspire further investigations, revealing insights into the nature of this intricate interrelationship. The research attempts to contribute knowledge into how the WSUD paradigm can synergize with these dynamics to foster urban resilience and adaptability to dryland regions.

The dissertation focuses on a reference case as an international best practice of adapting WSUD to dry city with the intention of transferring these practices to other dry cities with different urban contexts. In Addition, it tests the validity of a general hypothesis that WSUD planning instruments and strategies can have a role in the adaption to climate change and can be a feasible approach to stormwater management and water conservation in different dry regions. The showcase study in the City of Alexandria will demonstrate the applications and validate the investigated concept and strategies of WSUD.

With the central aim in focus, this dissertation examines the following three main areas and their sub-questions:

Q1- Understanding water in dry built environment

- What are the primary characteristics of water and urban drainage in a dry environment?
- How does the urban form of cities in hot dry climates influence surface runoff and consequently flooding?
- What is the appropriate planning approach to adopt WSUD practices that address urban settings in this climate?

Q2- Prior experiences and strategies for the adoption of WSUD in dry climates:

- How has the city of Adelaide effectively adapted the WSUD concept to its dry environment?
- What specific measures, tools, and strategies have been implemented in Adelaide to facilitate the integration of WSUD practices?
- How can WSUD technologies be customized to function within hot and dry climatic conditions?
- In what ways can the lessons learned from Adelaide's WSUD implementation be extended to benefit other regions in dry climates?

Q3- Transition framework and the applications of WSUD in the dry MENA region:

- How can a comprehensive transition framework guide the adaptation of WSUD in dry urban environments?
- How can the WSUD approach be efficiently and feasibly adopted in Alexandria and other cities in the MENA region in general?

The outcomes result in answering these questions could provide additional knowledge and insight, which is necessary for urban planners and decision-makers to ensure stronger linkages between sustainable urban development, the planning system and water management in a dry built environment.

1.4 Research Design and Methods

The research design constitutes the basic plan aimed at addressing the research questions, and the arrangement of research methods was employed to implement this plan. The primary methodological framework revolves around a mixed inductive-to-deductive reasoning approach. This approach, as outlined by Proudfoot (2023), involves inductive thematic analysis to gather data and observations, identify patterns or trends, and subsequently formulate hypotheses or general principles grounded in the identified patterns. Then, deductive reasoning is applied to employ these general principles to specific cases, thereby validating their validity and leading to the formulation of specific conclusions and predictions.

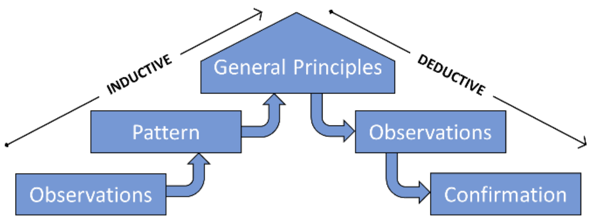


Fig. 1-6: Research inductive-to-deductive approach

The empirical foundation of this research is rooted in both reference and showcase studies, involving a comprehensive exploration of particular city cases within hot dry climates:

The “Showcase Study” (or Case Study) represents an in-depth investigation into the setting of Alexandria City. This involves detailed research, analysis, and documentation to provide insights, lessons, and potential solutions that lead to a successful transition strategy for a water-sensitive city. This case study aims to illustrate real-world scenarios, underscore challenges and adaptation strategies, and offer valuable information for planning and decision-making practices that are transferable to other cities in a broader context of the region.

Besides, the "Reference Case" involves a descriptive narrative detailing the well-established practices and planning strategies associated with WSUD in Adelaide City, South Australia. Given Australia's status as the driest continent and the country's extensive experience in implementing WSUD strategies across both its humid and dry cities, the choice of Adelaide serves as a typical example where the research topic is thought to be strongly addressed. It functions as a benchmark or standard for comparative analysis in the context of dry climates. The purpose of the reference case is to highlight exemplary practices, planning methodologies, policies, and successful implementations, all of which provide valuable insights for the formulation of a transition framework model tailored for water-sensitive cities in dry environments, but with different urban contexts. The primary methodological approach in the reference case of Adelaide entails a qualitative method. In contrast, the case study of Alexandria incorporates a mixed method, encompassing both qualitative and quantitative dimensions. This deliberate approach is intended to construct a holistic perspective regarding the application of WSUD strategies in hot dry climates and to facilitate the validation of the formulated general principle.

Methods of data collection in this dissertation entail the utilization of both primary and secondary sources. Primary data collection involves the acquisition of original data through semi-structured expert interviews and direct observations. Secondary data encompasses information available from a variety of sources such as books, journal articles, reports, satellite images, and websites. Secondary data collection methods encompass literature review and document analysis. A supplementary analysis of various documents and observations would be necessary for data source triangulation. In addition, technical methodologies deployed within this dissertation encompass the utilization of Multiple Criteria Decision Analysis (MCDA) and simplified Delphi Technique.

The research design framework (Fig. 1-7) structures the research phases and groups them into working blocks, which resemble the dissertation chapters. It illustrates the flow of work and the interconnections among the different phases. The research design can be described as follows:

After the general overview of the research topic and its significance in the context of dry built environment, **Chapter 1** outlines the objective of the dissertation and research questions.

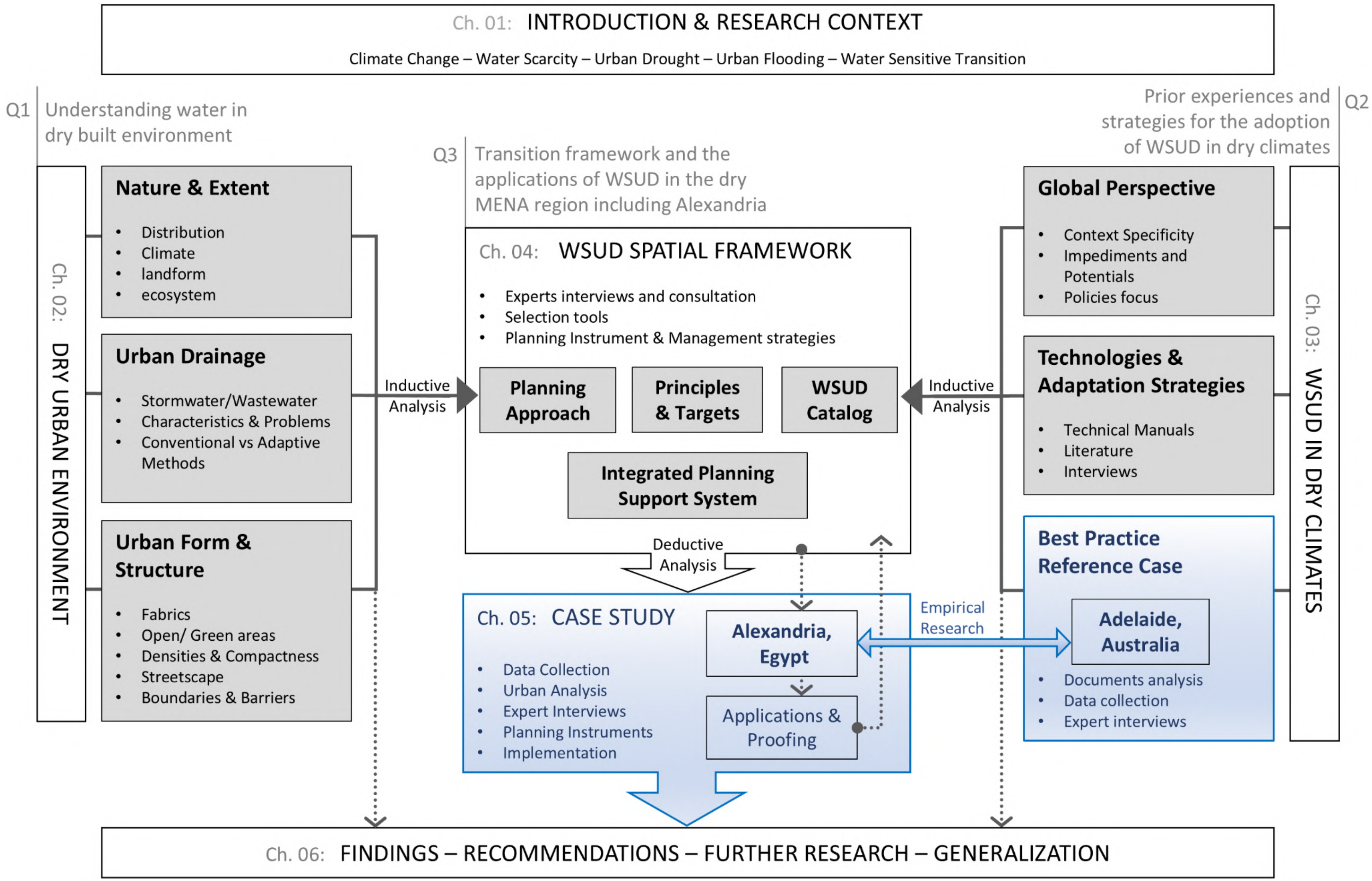


Fig. 1-7: Research structure and processes

The first research question aims to examine dry urban environments in dry climates. Thus, in **Chapter 2**, a comprehensive approach is employed that includes comparative analysis, literature review, observational methods, and logical reasoning. This chapter investigates the unique characteristics of urban drainage and structure in dry climates and analyze how various urban elements, such as urban fabric, green spaces, open spaces, and streetscapes, interact with stormwater and wastewater flows under these specific conditions.

This inductive analysis helps deepen the understanding of the urban context, illuminating how these elements either align with or challenge the implementation of Water Sensitive Urban Design (WSUD) strategies. Through this process, valuable insights and apparent patterns are identified. These patterns form the basis for developing a central planning concept, termed 'grounded theory' as per Glaser and Strauss (2017). This theory then informs the creation of the Transition Framework.

The Transition Framework is applied and validated through a case study focusing on Alexandria and its surrounding region. This holistic approach aims to provide a comprehensive and practical model for urban planning, grounded in both theoretical and empirical observations.

Chapter 3 addresses the second research question, which revolves around the existing practices and knowledge related to WSUD implementation in dry urban environments. This investigation predominantly relies on a qualitative examination of a reference case as a best practice example, namely the evolution of Integrated urban water management and recycling in Australia with a focus on the experience of the City of Adelaide. Various dimensions are analyzed, including challenges and drivers for implementing WSUD strategies, policies and guiding principles and goals, the utilization of tools for planning and decision-making processes, and the central role of capacity building in promoting this approach.

The analysis of the reference city of Adelaide is largely based on available online sources such as journal articles, books, reports, and websites. Additionally, a series of open-ended interviews were conducted with experts representing diverse viewpoints from both public and private organizations actively engaged in different WSUD planning and implementation facets within the city. These interviews were conducted following the guidelines provided in Appendix A. Some of these experts became known to me and directly contacted during the participation in the online 5th Water Sensitive Cities Conference (South Australia) on March 15–18, 2021 (CRC, 2021), an event organized by the Cooperative Research Centre for Water Sensitive Cities (CRCWSC).

The detailed adaptation and adjustments required for each WSUD element in dry climate are systematically examined. This is accomplished by carefully reviewing resources, particularly the Water Sensitive Urban Design Technical Manual for Greater Adelaide Region (SA Govt, 2010). In addition, various guidelines, insights extracted from local expert interviews, and a comprehensive literature review focused on the suitability of individual elements within dry climates.

Ultimately, the results of this analysis and their potential transferability are analogized closely to the context of the Alexandria case study. This process aims to determine the extent to which these findings can be extended to other dry urban contexts. The knowledge gained from the Adelaide experience forms a foundational pillar for the development of the transition framework, which is detailed in Chapter 4.

Chapter 4 presents a comprehensive framework designed to facilitate the transformation of Alexandria into a water-sensitive city within its dry climate context. This framework offers a structured and strategic methodology to guide the transition from conventional approaches to adaptive measures. It has been meticulously developed, drawing upon insights gleaned from the preceding chapters.

The essential components of this transition framework encompass several key aspects:

Performance principles and criteria: are mainly drawn from the understanding of water dynamics within dry urban environments in the MENA region, including Alexandria, in addition to the experience learned from the City of Adelaide

Planning approach: a meticulous planning approach is incorporated, focusing on urban hydrological regions at the micro-basin level and the identification of barriers. This approach is informed by the analyses of urban contexts, pattern identification in Alexandria, and the broader context of the MENA region, as explored in Chapter 2.

WSUD Catalog: The Catalog is developed to aid in the selection process of WSUD elements within the decision support system. This Catalog benefits from insights from Adelaide and an extensive examination of the adaptation of WSUD technologies to the dry urban environment. The Catalog also offers evaluation and prioritization of each element based on performance parameters and predefined criteria for specific zones applying Multiple Criteria Decision Analysis. The evaluation process relies on assessments drawn from seven guidelines and manuals from various cities and institutes and inputs from four Experts in the field of WSUD elements (Annex B), in addition to the researcher's own evaluation.

Planning instrument and management strategies: To support decision-making, a decision support system serves as a tool to facilitate the selection of WSUD strategies and elements according to the urban and microclimatic variables. Various systems were examined to develop one that integrates the other framework aspects of criteria, planning approach and Catalog.

This comprehensive framework is aimed to be applied to the case of Alexandria, thus initiating a feedback loop. Such systematic evaluation of the process and outcomes ensures the detection of weaknesses and modify actions and plans through control mechanisms that allow for refinement and adaptation based on real-world application. Through this iterative process, the framework aims to pave the way for a successful transition towards a water-sensitive Alexandria and ultimately, the broader MENA region.

Chapter 5 covers the City of Alexandria as the selected empirical case study for in-depth analysis and proof of implementation in hot and dry regions.

First, the background of the problem and context is introduced thoroughly in a spatial hydrological analysis of the city. The knowledge gained and presented throughout the dissertation was adapted to the city, guided by the developed 'Spatial Framework'. Primarily, through the planning approach, a detailed micro-basin and barriers-based mapping and analysis were conducted, which evolved around three dimensions: the urban context, infrastructure, and geomorphology. Research methods used in this section involve the collection and processing of land surveying, remote sensing, and geotechnical data. Then, comprehensive concepts were developed for building water-sensitive micro-basins and barriers as well. Finally, an example taking one of the micro-basins presents the implementation of a development-scale WSUD with quantification of the space requirements to apply measures able to manage different extreme events of 5 and 10-year return periods.

The qualitative and quantitative approaches implemented in this chapter are supported by secondary data sources acquired through available books, reports, journal articles, websites, maps and drawings. Primary data was collected from the site during a field research stay in Alexandria in September 2022, including direct observation and expert interviews. The network of selected organizations for data collection and interviews is meant to cover various public and private sectors involved in the urban development and water management aspects, including Local administrations, water company, academics in universities, and public users, in addition to consultants and experts in the fields of geotechnical, landscaping and public green space management. Interviews were conducted in accordance with the guidelines provided in Appendix A. WSUD Cards were used as a communication method for a general overview of the different technologies and their functions while trying to get the interviewee's feedback.

In the **final chapter**, research key findings are summarized as well as an explanation of how they respond to the research question. An outlook on the future of WSUD in hot and dry climates is provided as well as the generalizability of research results to other cities in the MENA region. Finally, the chapter identifies areas for further research and provides recommendations for future studies.

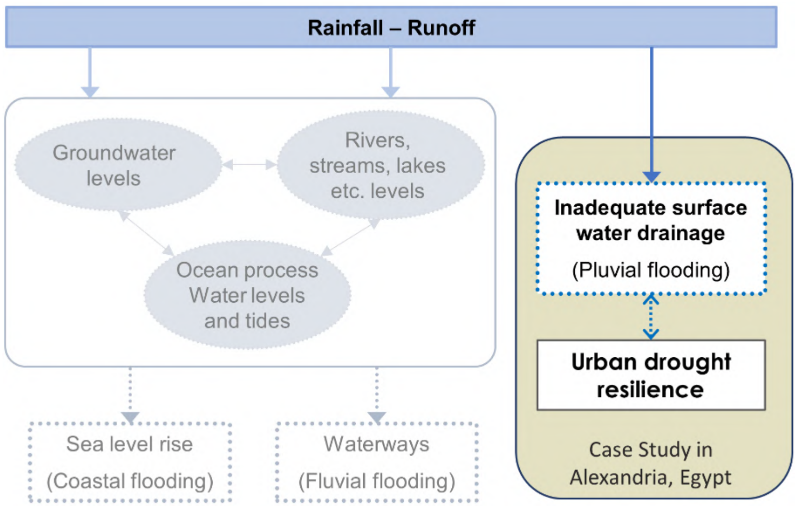


Fig. 1-8: Flooding systems in urban areas and focus of the dissertation, by author based on a diagram by (Salinas Rodriguez et al., 2014)

1.5 Scope and Limitations

Urban flash floods can arise from multiple sources, including sea-level rise (coastal flooding), watercourses (rivers, streams, or fluvial flooding), and direct inundation of areas with insufficient drainage capacity during intense rainfall events (surface water runoff or pluvial flooding). The scope of the dissertation is confined to the imbalance stemming from inadequate surface drainage and urban drought in hot dry climates. The research seeks to develop insight into how the physical built environment can optimally contribute to the evolution of more resilient and water-sensitive cities. This investigation centers on the city of Alexandria and the broader MENA region, utilizing Adelaide, Australia, as a reference for best practices.

The research's primary focus lies in decentralized stormwater management and water conservation solutions, aligning with the principles of the WSUD approach. The dissertation exclusively examines the adaptation considerations of WSUD practices, coupled with a planning approach tailored to the climate and urban context of the hot and dry MENA region. Implicitly addressed but not fully covered within the research scope are aspects such as biodiversity, habitats, plant selection, and institutional frameworks.

However, the empirical results reported herein should be considered in the light of some limitations. The research omits consideration of local social aspects and typical behavior norms that could influence the adoption of the WSUD approach in the region. Challenges include the scarcity of available data, limited access to reliable geospatial data and precipitation information, and a lack of research studies on the topic within the various dry regions. Data collection methods, particularly expert interviews in Alexandria, rely on individuals' perspectives, which may be limited due to the novelty of the WSUD approach to the region.

To overcome this limitation, the research employs triangulation through multiple methods, data sources, and theories to enhance the validity and credibility of the findings. Recommendations for future research advocate a systematic analysis and evaluation of flooding phenomena on a broader scale across different urban settings in the MENA region.

1.6 Definition of Terms

In the domain of Water Sensitive Urban Design (WSUD), particularly when addressing different climates, precision in language is critical for effectively conveying complex concepts and methodologies. This section establishes clear definitions for key terms foundational to the discussions and analyses presented in this dissertation. Clarifying these terms is intended to eliminate ambiguity and make the discourse accessible not only to specialists but also to various disciplines involved in WSUD practices.

This dissertation specifically addresses 'Dry' climates within the context of hot zones, distinguishing these from colder dry zones. This distinction is vital as it highlights the unique challenges that hot dry environments pose to urban design and city development. The word 'Dry' describes climates predominantly characterized by low annual precipitation, insufficient to sustain extensive vegetation. In this dissertation, 'Dry' encompasses all hot and dry sub-climates, ranging from hyper-arid, where almost no rainfall occurs, to dry subhumid, where seasonal droughts are common. This classification follows the Köppen-Geiger climate classification system (Peel et al., 2007). Cold dry zones, such as those, for instance, in the Gobi Desert in Central Asia and the Patagonian Desert in Latin America, are excluded from this definition as they are marked by cold air temperatures and low precipitation, which may pose different challenges and require different adaptation measures.

An example of a hot hyper-arid zone is the Sahara Desert, which experiences extremely minimal rainfall making sustainable water management a significant challenge. In contrast, a hot dry subhumid area like the Texas High Plains in the United States, while also classified as 'Dry', receives relatively more rainfall, allowing for more diverse agricultural practices but still requiring careful water management strategies to combat seasonal variability and drought conditions. In addition, the term 'drylands' is used in this dissertation to describe the geographical extent and physical characteristics of these environments, referring to their various landforms and landscape features.

Throughout the text, definitions of certain technical terms are provided as necessary. This method supports comprehension and ensures clarity of specific terminology that emerges into the discourse at relevant points, directly addressing the context in which these terms are discussed. Finally, a comprehensive glossary is included at the end of this dissertation to provide definitions for a broader array of terms and concepts relevant to WSUD in hot dry climates. This glossary is intended as a quick reference tool to offer concise definitions and contextual explanations, facilitating a deeper understanding of the terminology used throughout this dissertation.

1.7 The Transition to Water-Sensitive City

The increasing recognition of the pressing challenges posed by urbanization, population growth, and climate change on water resources and urban ecosystems, as discussed earlier in this chapter, leads urban communities to demand actions to ensure resilience to extremes and protect natural resources. It is acknowledged that there is a need for a shift to sustainable urban water management where the conventional approach alone is unqualified to address the requirements to adapt to the current and future challenges (Butler et al., 2018; Wong & Brown, 2009). This transformation to Water Sensitive City, as termed by Wong and Brown (2009), pertains to the process of moving urban areas towards sustainable water management practices. This transition involves adopting approaches that integrate water conservation, efficient infrastructure, and environmentally conscious urban design.

The transition to a water-sensitive city involves a comprehensive approach that integrates urban planning, engineering, social sciences, and environmental management, aiming for equilibrium between water supply, quality, flood mitigation, and urban well-being. These methods utilize innovative technologies, policies, and governance for a harmonious built-natural environment relationship. The approach constitutes an emerging water sector paradigm, based on integrated concept of water management, hybrid centralized and decentralized technologies, diverse ecosystem services, adaptive urban planning, and engaged water-conscious communities (Brown et al., 2018)

Central to this transition is the concept of WSUD which merges two vital domains: 'Integrated Urban Water Management' (IUWM) and 'Urban Design and Planning' (Wong & Brown, 2009). Traditionally, these sectors remained separate; designers and planners conceptualized cities and urban spaces, while engineers focused on efficiently draining these areas using centralized solutions. WSUD introduces the notion of integrating water awareness into urban design. Its primary aim is to elevate water's significance within the urban design process. This is by

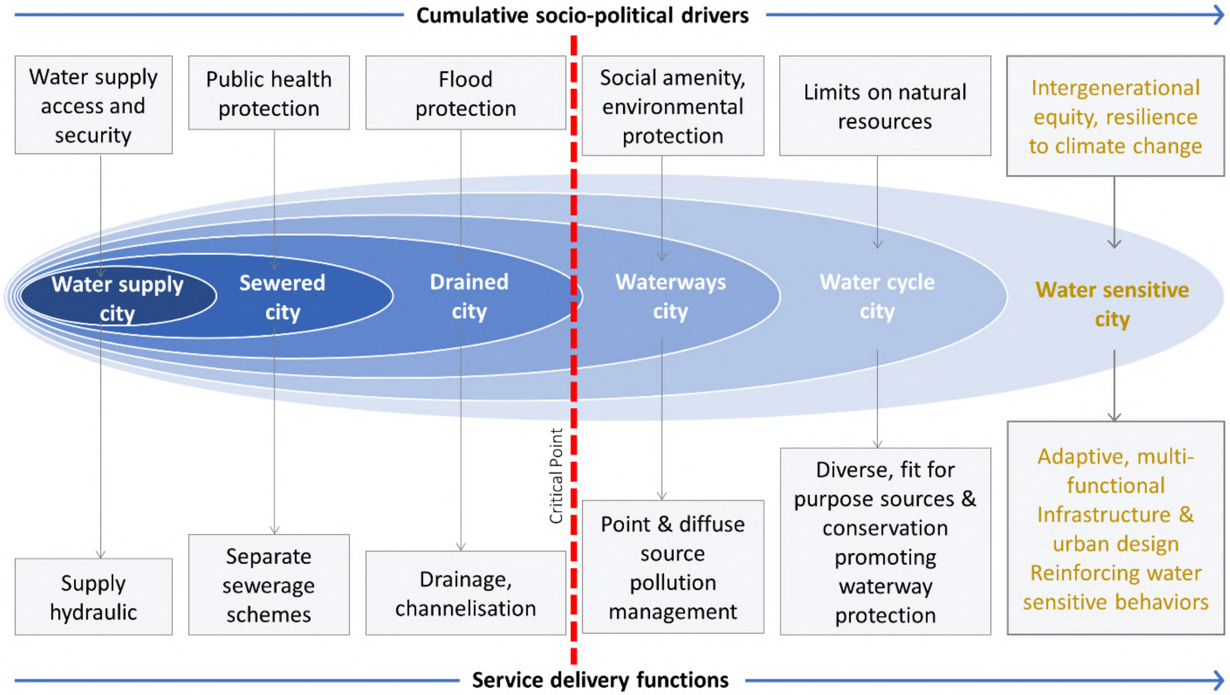


Fig. 1-9: Urban water management transition states, based on (Brown et al., 2009)

integrating urban design with diverse engineering and environmental disciplines related to water services, encompassing the protection of aquatic ecosystems within urban contexts. Inherent to the decision-making process of urban design are community values and the aspirations of urban spaces. This dynamic guides both urban design choices and water management approaches.

1.7.1 Transition States

(Brown et al., 2009) outlines in Figure 1-9 six different development states of urban water management that cities can move through to locate themselves on this nested continuum in response to the evolving socio-political drivers and its attributes of service delivery functions. This process is based on the 'hydro-social contract' concept proposed by Lundqvist et al. (2001) which refers to an implicit agreement between society and governing entities concerning water management. This contract entails responsibilities for providing clean water, managing water resources and sanitation.

Over time, growing environmental and urban challenges, and societal transitions seeking more resilience and livability have prompted shifts in this contract. As cities progress in this way, previous states are impeded in the current one while shaping and influencing it. A pivotal stage in the progression towards a Water Sensitive City is tackling the main obstacle of transitioning beyond a Drained City paradigm. Historically, the water requirements of the cities located on the left side have been fulfilled through extensive centralized infrastructure. However, moving forward towards waterways, cycles, and sensitive cities presents notable challenges, which require a substantial realignment of existing infrastructural, institutional, and water management strategies to an interdisciplinary approach, advocating for adaptable and synergistic infrastructures and institutions at both centralized and decentralized scales (Brown et al., 2018).

1.7.2 Pillars of the Water-Sensitive City

(Wong & Brown, 2009) articulate three guiding principles that serve as the foundational pillars for realizing the vision of the Water Sensitive City. These principles must be adeptly integrated within the urban context to achieve its objectives.

Multi-scale water sources and supply catchments: The initial pillar encompasses the role of the Water Sensitive City as an adaptable water supply catchment. This involves the provision of diverse water sources across different scales and for varied purposes. By offering a spectrum of water sources, the city ensures greater resilience and flexibility in meeting its water demands.

Ecosystem services and well-being: The second pillar emphasizes the value of the Water Sensitive City's natural environment. It serves as a generator of ecosystem services that extend to social, ecological, and economic advantages. This pillar highlights the importance of a thriving environment in fostering holistic well-being for both the urban populace and the ecological systems that coexist.

Water-conscious communities: The third pillar centers on cultivating water-conscious communities within the Water Sensitive City. These communities are characterized by informed individuals who actively engage in water-related decision-making. This pillar emphasizes the significance of citizen participation and responsible actions for achieving water sustainability.

Nonetheless, it is important to note that the Water Sensitive City vision, as a socio-technical resiliency, is sophisticatedly tied to its specific context. The interpretation of "water sensitive" within a particular city context and the feasibility of transitioning towards more sustainable urban water management are shaped by a range of factors. These encompass elements such as the natural environment, ecological aspects, climatic conditions, historical background, geographic characteristics, population dynamics, as well as the pre-existing technologies and institutional frameworks. Therefore, the main question that persists as to how this paradigm shift can be effectively realized within each distinct urban setting accounting for the diversity in physical and cultural attributes and the influence of varying climatic conditions. It is thought to be an interesting field of inquiry to explore the possibility of knowledge exchange from humid to dry climates and in another view from the Global North to the Global South.

2 DRY URBAN ENVIRONMENT

> “If this is a desert, what are all these people doing here?”
>
> *Reyner Banham (1983), Scenes in America Deserta.*

Dry environments can be distinguished from humid landscapes by their characteristic low precipitation and high evaporation, which cause moisture deficits and water scarcity (aridity) (Goudie, 2013). They are commonly described using terms such as ‘dryland’, ‘desert’, ‘arid zones’, and others. The term "desert" might be too restrictive to describe all dry environments. As a collective term to describe areas with a moisture shortage, "dryland" is likely more appropriate than "desert" (Thomas, 2011). Therefore, in the context of this section, I refer to these geographical zones as drylands, which comprise deserts at their core and extend to their margins.

There have been several attempts to categorize and define the drylands of the world using climate parameters (Cooke et al., 1982). A map of the world distribution of dry regions was developed by the UNSECO (1979) based on Meigs (1953), and later the World Atlas of Desertification, a more precise map by UN Environment Program (UNEP, 1997). These maps classify drylands into subtypes based on an Aridity Index (AI), following the Thornthwaite method (Thornthwaite, 1948), which represents the annual total moisture balance as the ratio between precipitation (P) and potential evapotranspiration (PET). The UNEP map defines overall drylands as areas with an aridity index value of less than 0.65. Four subtypes of drylands were delineated by their AI values: hyper-arid, arid, semi-arid, and dry-subhumid. According to this classification, drylands cover almost 41% of the Earth's terrestrial surface and accommodate around a third of the world’s population (Thomas, 2011).

Table 1: Classification of drylands, based on the UNEP Aridity Index (1997)

Description	Aridity Index	Approximate average annual precipitation
Hyper-arid	<0.05	<50 mm
Arid	0.05-<0.2	50-250 mm
Semi-arid	0.2-<0.5	250-500 mm
Dry sub-humid	0.5-<0.65	-

This classification identifies each type by water availability as the moisture deficit experienced in certain zones. However, another climate classification by Köppen-Geiger (Peel et al., 2007) identifies group B (Arid) as one of four main climate groups, which is subsequently divided into two sub-climates: BW (desert) and BS (steppe or semi-arid) based on threshold values and seasonality of monthly air temperature and precipitation. Each sub-climate is further distinguished by either h (signifying hot drylands with an average mean annual air temperature above 18°C) or k (signifying cold drylands with an average mean annual air temperature below 18°C) (Fig. 2-1).

It is important to point out in this context that this classification draws a distinction between hot and cold drylands. Cold drylands (types BWk and BSk) tend to be found in elevated plateaus or mountainous areas at higher latitudes (temperate zones) than drylands situated in tropical and subtropical climates. They are also typically located in continental interiors at a distance from any large bodies of water. Cold dryland climates feature very little precipitation (rain or snow), while seasonal temperatures can drop down to -40°C. Examples of cold drylands

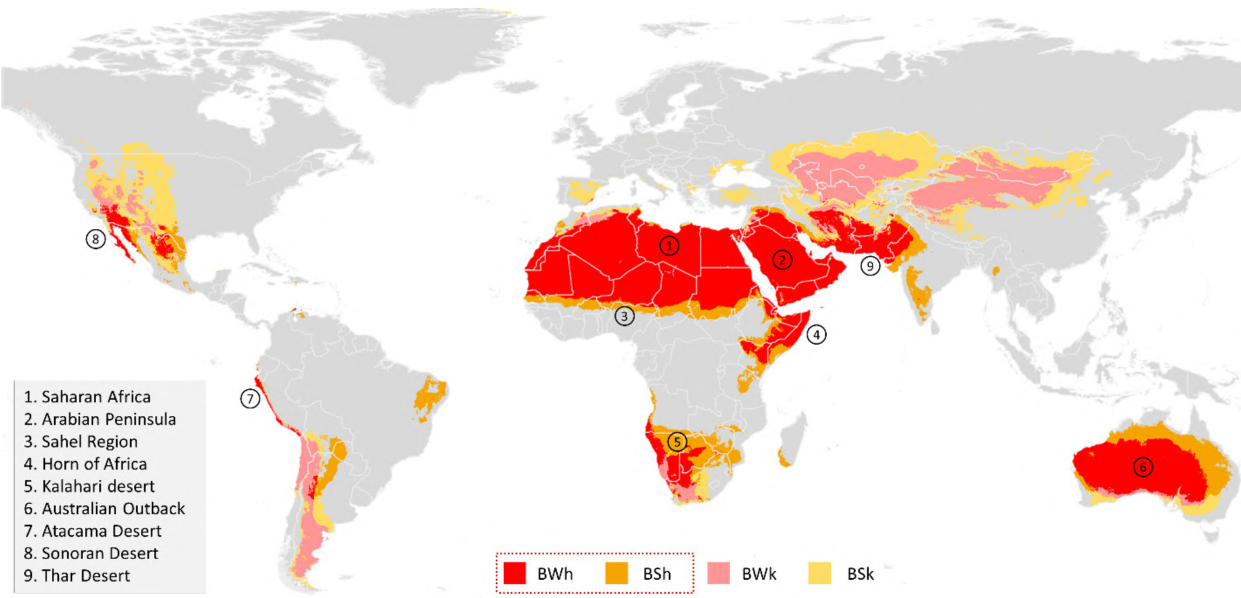


Fig. 2-1: Hot-Dry climate distribution according to Köppen-Geiger Classification, based on (Peel et al., 2007)

include the Great Basin Desert in the United States, the Patagonia Desert in the southern region of South America, and the Central Asian Deserts and their semi-arid margins. Additionally, various scientists consider Antarctica the coldest desert on Earth, although it is not sandy and is exclusively classified as a polar climate.

Thus far, hot and cold dry climates share the common characteristics of low rainfall and limited water availability, but they differ in temperature extremes. This fundamental difference means that we cannot analyze and generalize findings for both types of drylands together. According to Meigs (1953), cold drylands make up 24% of the total dryland climates, while hot drylands constitute 76%. As the subject of this research falls under the hot climate category, the focus is exclusively on hot dryland regions.

2.1 Nature and Extent

Drylands are complex, dynamic formations whose features and dynamic qualities depend on a variety of interconnected interactions between the climate, soil, and plant.

2.1.1 Climate

Hot dry regions are areas that receive relatively low precipitation, usually less than 250 mm per year in arid regions and up to 500 mm in semi-arid regions. Both arid and semi-arid regions are characterized by water scarcity, which can limit vegetation growth and wildlife abundance.

An important aspect of dry climates is the variability and irregular patterns of precipitation that occur over time. Rainfall can be highly erratic and unpredictable, with the timing, intensity, and duration of rainfall varying significantly over the seasons and also from year to year. Rainfall occurs in short bursts or as individual thunderstorms. This seasonal and irregular pattern is a major feature associated with frequent droughts and flash floods (Morales, 1977). The phenomenon in dry regions is discussed in more detail in the next section on urban drainage.

High solar radiation and evaporation are two other important factors contributing to the typically high temperatures and low humidity in hot drylands. Low cloud cover coupled with direct sun rays allows more solar radiation to reach the surface unimpeded, resulting in a sharp rise in temperature, especially during the day. This also increases the potential for evaporation from surfaces. In addition, low humidity favors rapid evaporation because dry air can absorb more moisture.

Dry urban environments often experience the urban heat island effect, where built-up urban areas are significantly warmer than surrounding rural areas due to human activities, building materials, and lack of vegetation.

Wind plays a significant role in the formation of the landform in dry regions, either through depositional or erosional processes. As a typical phenomenon in dry climates that transport sediments, winds can also increase the rate of evaporation by carrying moisture away from surfaces and further drying out the surrounding area. Thus, strong desert winds and frequent sandstorms are the main aspects that influenced the development of the built environment in drylands.

In drylands, however, cities can disrupt the natural movement of sand by wind. Additionally, when people build settlements in the desert and rely on local water and limited farmland, it puts pressure on the land around these settlements. As a result, the desert ecosystem is most affected near urban areas, leading to the destruction of vegetation and soil damage. This disruption causes more sand and dust to move, resulting in larger sedimentation issues (Cooke et al., 1982). This dynamic landscape formation is thought to be ultimately defining the nature of existential concurrence between built and natural environments in dryland.

Fig. 2-2: Road stretches across the dunes of Dubai City (Photo: Alex Meliss, 2018)

2.1.2 Landscapes and Landforms

Dry environments are influenced by a variety of geomorphological processes, resulting in varied landforms in drylands. According to L. Mays in (IRTCUD, 2001), the main types of dryland geomorphology are defined under the following categories:

Alluvial Fans – These are fan-shaped landforms that form where sediments are deposited by a river or stream flowing from a steep slope to a flat area, such as a plain or valley floor. They are prone to flash floods but may still be suitable for urbanization, especially at their outer edges.

Dunes – Mounds of sand formed by the wind, usually in deserts or coastal areas. They can range in size from small ripples just a few centimeters high to sand mountains hundreds of meters tall. Dunes are dynamic landforms that are constantly changing by the wind, causing them to move slowly across the landscape.

Bedrock Fields – Areas where the topsoil and superficial deposits have been removed, exposing the underlying bedrock with little or no vegetation. They may not be suitable for large-scale urban development due to their rough terrain and limited soil coverage.

Desert Flats – Mainly flat plains covered in sand, gravel, or rock, and may also feature sand dunes. They may offer more potential for urbanization. Some examples include the Atacama Desert in South America and the Sahara Desert in North Africa.

Desert Mountains – Mountain ranges or individual peaks. Some examples include the Atlas Mountains in Morocco and the Andes Mountains in South America. Their steep slopes and limited access present challenges for urban development.

Badlands – Extensive barren tracts of heavily eroded land, characterized by steep hills, gullies, and layered rock with sparse vegetation. They are unsuitable for urbanization. Examples include the Badlands National Park in South Dakota, USA, and the Bardenas Reales Natural Park in Navarra, Spain.

In dry climates, surface features and terrain can present significant challenges for urbanization. Some landforms may not be suitable for large-scale urban development. However, major cities in dry environments are often located on desert plains, alluvial fans, or limited to the shallow valleys of desert mountains. In particular cases, cities such as Cairo and Baghdad are situated in river valleys that run through deserts.

Fig. 2-3: Types of landforms in drylands

From top:
alluvial fan in Southern Iran (NASA earth observatory, 2022)
Sand dunes in Abu Dhabi (Achim Thomea, 2013)
Bedrock in Yant Flat in Utah, USA (Shelby Bernal, 2011)
Desert mountains in Morocco (Simon, 2018)
Badlands national park in south Dakota, USA (Taylor Brooks, 20110)

2.1.3 Ecosystem

Urban ecosystems in drylands are unique and face specific challenges due to the limited availability of water and the high evaporation rates, which lead to limited vegetation growth and challenging living conditions for both natural and built ecosystems.

Dry environments typically have large expanses of deserts or other barren landscapes. Semi-arid regions often have a mix of barren deserts and more fertile grasslands, and they can support limited agriculture. Vegetation in these regions mainly consists of water-conserving xerophytes, ephemeral grasses, and small leafy plants, each adapted differently for survival. The density of vegetation can vary significantly between wet and prolonged dry periods at a given location, affecting soil water demand and disposal. Evapotranspiration is the primary water loss mechanism, with groundwater recharge occurring mainly during extreme events. Vegetation growth is limited to areas with higher infiltration capacity (PILGRIM et al., 1988).

2.1.4 Geographical Distribution

Despite the harsh environment and the limitations to establish human settlements, cities in drylands have developed well in every way from the early period of history until today. Scarce resources and climatic extremes have tended to encourage inhabitants to be resourceful and adaptable. Drylands are typically situated in subtropical convergence zones, between latitudes 10-35° N and S (Simmers, 2003). Drylands are present in all inhabitable continents, including regions of southwest USA, south-central South America, South Africa, North Africa extending into central and southern Asia, and most of western Australia. About a third of the total drylands are concentrated in Africa and Asia, while Australia stands out as the most arid continent, with approximately 75% of its land area classified as arid or semi-arid, as depicted in Figure 2-1 (Thomas, 2011).

Table 2: Share of drylands by continent (UNEP, 1997)

Africa	31.9%
Asia	31.7%
Australia	10.8%
North America	12.0%
South America	8.8%
Europe	8.8%

The distribution of drylands in the world can be described as follows:

Saharan Africa: The Sahara is the largest hot desert in the world, covering much of North Africa. It spans across several countries, including Algeria, Chad, Egypt, Libya, Mali, Mauritania, Morocco, Niger, Sudan, Tunisia, and Western Sahara.

Arabian Peninsula: The Arabian Desert covers most of the Arabian Peninsula, including parts of Saudi Arabia, Yemen, Oman, the United Arab Emirates, Qatar, Kuwait, and Bahrain.

Sahel Region and Horn of Africa: The Sahel is a transitional zone between the Sahara Desert to the north and the more humid savannas and forests to the south. It spans across several countries in West Africa and countries in the Horn of Africa

Kalahari Desert: Located in Southern Africa, the Kalahari spans across Botswana, Namibia, and South Africa.

Australian Outback: Large portions of Australia are classified as arid or semi-arid. Key regions include the Great Victoria Desert, Simpson Desert, and Tanami Desert.

Atacama Desert: Located in South America, the Atacama Desert is one of the driest places on Earth. It stretches along the western coast of Chile and parts of Peru.

Sonoran Desert: Covers parts of southwestern United States and northwestern Mexico.

Thar Desert: Situated in the northwestern part of the Indian subcontinent, covering parts of India and Pakistan.

The distribution of drylands is influenced by various factors, including latitude, topography, ocean currents, and prevailing wind patterns. It is also important to note that the distribution of these zones may vary over time due to climate change and other factors.

According to the World Atlas of Desertification (Cherlet et al., 2018), a map in Figure 2-5 highlights the distribution of big cities in drylands with populations of more than 300,000. Currently, 30% of the world's population, or 2.2 billion people, live in 33% of these major metropolises. Nearly half of these are in the semiarid zone, while fewer cities are likely to thrive in the harsh arid and hyper-arid regions, but they tend to have higher populations. Mega cities in drylands with over ten million inhabitants are intensively located in the Middle East region and the Indian subcontinent.

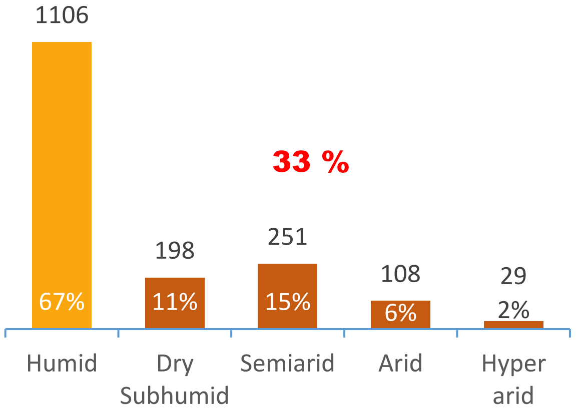


Fig. 2-4: Big Cities in different climates (Cherlet et al., 2018)

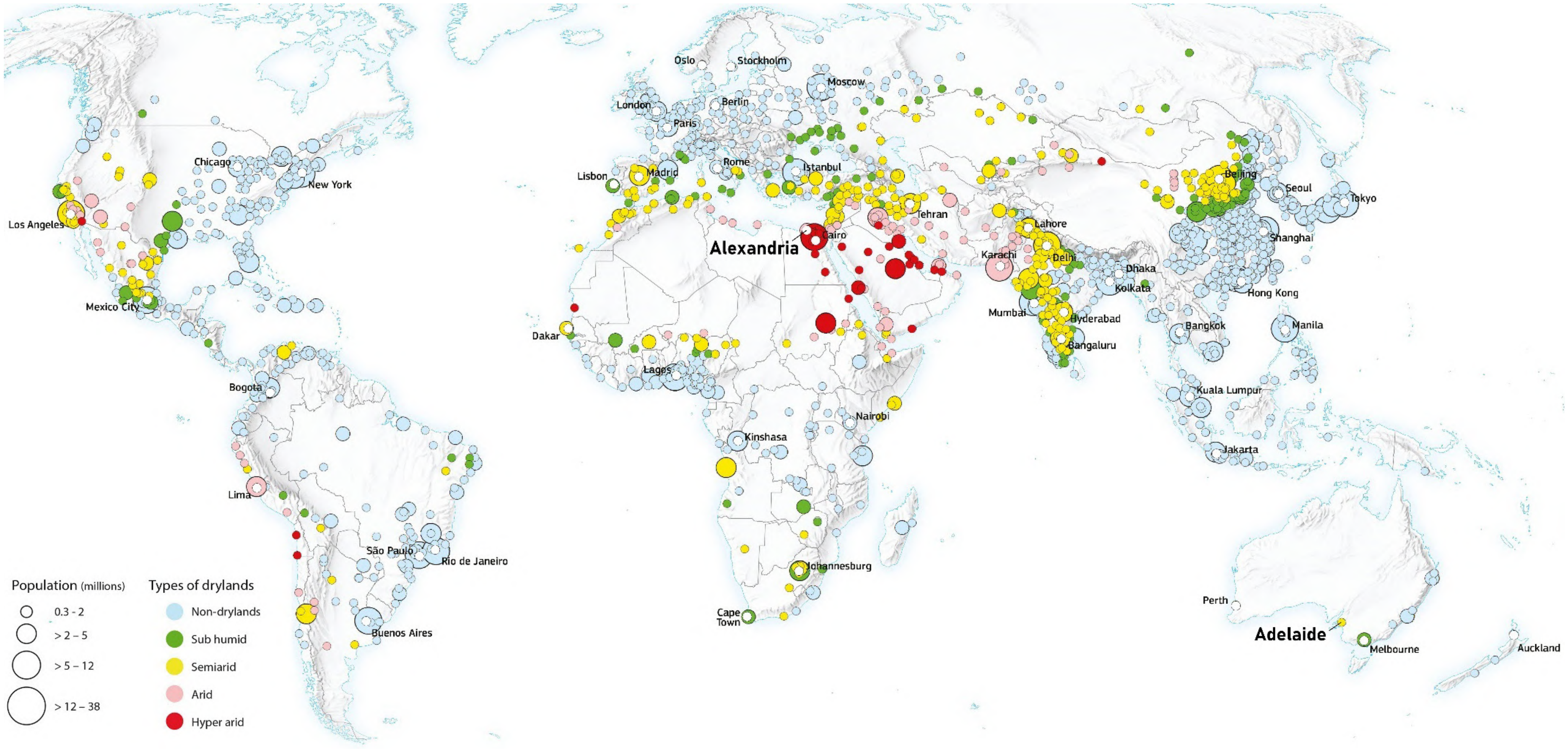


Fig. 2-5: Highlighting both Alexandria and Adelaide among global locations of big cities in drylands with populations over 300,000 (Cherlet et al., 2018)

Another categorization should refer to the global distribution of drylands according to socio-economic aspects. It is noteworthy that most drylands are found within the Global South (developing countries), around 72%, while the Global North only accounts for 28%, including parts of the United States and Australia.

Moreover, the share of drylands in Global South countries rises as the aridity of the regions increases, reaching 100% in the hyper-arid zone. Therefore, the majority of people living in drylands reside in developing countries, comprising 87% to 93% of the population, with only 7% to 15% residing in industrialized nations (Millennium Ecosystem Assessment, 2005).

In summary, drylands are all characterized by limited water availability, which poses challenges for human settlement and ecosystem functioning, but they vary in the temperature extremes experienced throughout the year. A variety of settlement sizes on the urban hierarchies, including several mega cities, spread across the vast expanse of drylands. The way the landscape forms and changes over time in drylands is crucial in determining the coexistence and interaction between human-built environments (such as cities and settlements) and the surrounding natural environments. The dynamic nature of these landscapes, shaped by factors like sand movement, vegetation, and soil structure, plays a significant role in influencing how human settlements can thrive in drylands with a changing climate.

As previously pointed out in this section, hot drylands are the major concern of this dissertation rather than colder counterparts. Hot drylands still spread over all continents. However, to narrow down the scope of the research to relate to the geographical and cultural context of the showcase study in Alexandria City, the focus will be on drylands in the Middle East and North Africa region (MENA).

2.2 Urban Drainage

Human activity in urban settlements involves an interaction with the natural water cycle, which leads to the need for manmade drainage systems. This interaction takes the form of extracting water from the natural cycle to provide a fresh water supply for human life and altering land cover imperviousness by developments in urban areas where sealed surfaces increase runoff and change the local natural drainage cycle (Butler et al., 2018). These interactions in cities result in two types of water: wastewater and stormwater, which require an incorporated drainage system in cities. Despite differences in local climate and urban context, cities worldwide experience these water-related phenomena. However, the provision of adequate urban drainage infrastructure varies significantly in modern societies, depending on the level of development and awareness of the interaction with the natural water cycle.

Describing the major two urban water-based flows that require drainage system as follow:

Wastewater is the discharged water generated from the consumption/use of freshwater or raw water within domestic, industrial, and commercial uses. It is considered used water that contains contaminants, including organic matter, microorganisms, and dissolved material. Treatment of wastewater is essential before it is released into water bodies; otherwise, it could highly pollute those receiving bodies and cause health risk (Butler et al., 2018). The level of pollution in water is based on the usage resulting from it. Domestic (households) or commercial wastewater could be the least polluted and the easiest to treat. Industrial and agricultural wastewater, on the contrary, requires a much more elaborate treatment process.

Stormwater, or surface runoff, is generated by precipitation and is best described in urban or built-up environments as rain that runs off surfaces like roofs and streets where water cannot infiltrate into the soil. Thus, it is captured by either a separate or combined sewer system and then transmitted to the receiving water body or treatment facility. The quality and quantity of stormwater are interdependent on both rainfall itself and the characteristics of the catchment.

Urbanization in this regard significantly impacts the natural water cycle within built environments, particularly when considering urban drainage as an artificial system that replaces parts of the natural water cycle. Understanding this relationship is crucial in drylands.

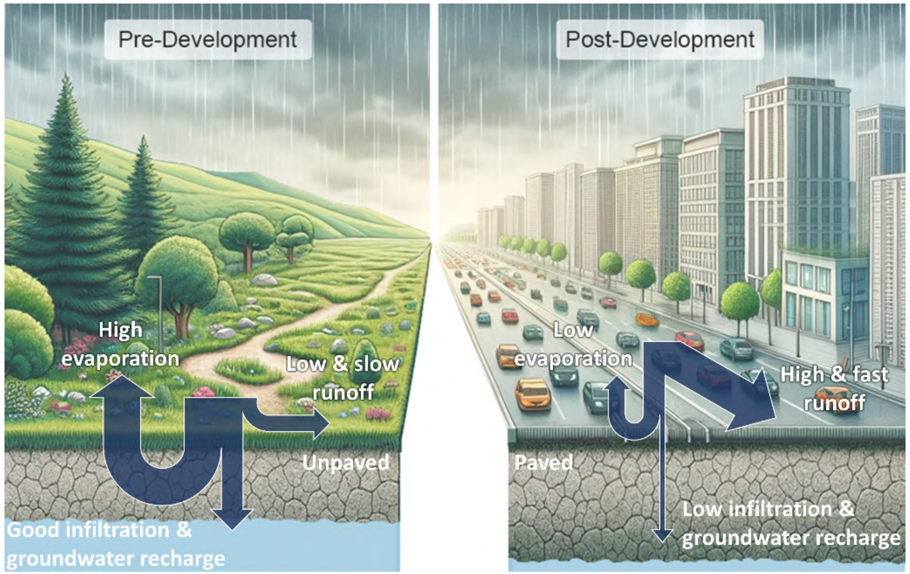
As rainwater falls on surfaces, it can take three forms: it may return to the atmosphere through plant transpiration or surface evaporation, infiltrate the soil and replenish groundwater, or become surface runoff, eventually finding its way into receiving waters. The proportions of these rainwater fragments vary depending on the type of surface and the level of urbanization where the rain falls. In natural, pre-urbanized conditions, the surfaces are generally less sealed and unpaved, favoring infiltration and evapotranspiration while minimizing the impact of runoff on the environment. However, in urbanized areas, the presence of impermeable paved surfaces like asphalt streets, parking lots, and roofs significantly limits evaporation and infiltration. Consequently, runoff becomes the dominant proportion of rainwater, leading to increased risks of flooding and the washing off pollutants into nearby streams and water bodies. Moreover, drainage systems that combine stormwater and wastewater may facilitate the transport of pollutants from untreated wastewater into waterways, further contaminating the receiving water bodies.

2.2.1 Characteristics and Problems

Rainfall

Rainfall, snowfall, hail, and sleet constitute various forms of precipitation that impact land surfaces, with rainfall being the predominant contributor to urban stormwater. Accurate forecasting and analysis of rainfall patterns are crucial for the design and operation of urban drainage systems. Longitudinal historical records of rainfall enable the analysis of the intensity, duration, and frequency (IDF) of rainfall events, which are vital for calibrating models that simulate drainage system performance (Butler et al., 2018).

In dry regions, precipitation is characterized by significant spatial and temporal variability. Most arid areas experience this variability, where the spatial extent of individual storms rarely exceeds 100 km², often ranging between 30–60 km² (Simmers, 2003). Coupled with the fact that rain gauge density is relatively low, Pilgrim et al. (1988) points out two main problems emerging in this case: the potential for data to be unrepresentative of the average rainfall across a drainage basin, resulting in substantial sampling



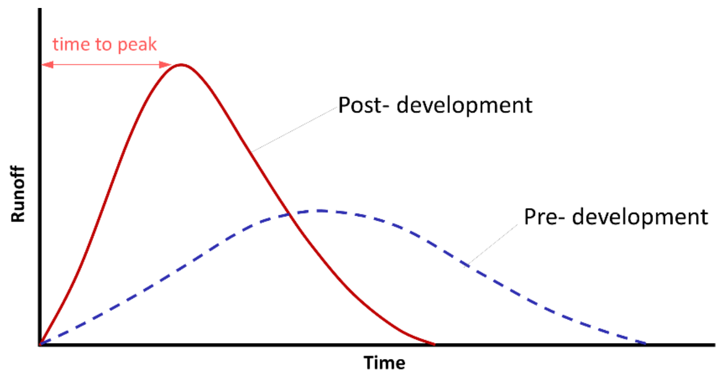


Fig. 2-6: Change in runoff characteristics with urbanization

Illustration by author based on AI generated image (DALL.E, 2023) errors, and questions about the adequacy of using models with lumped inputs for such variable conditions. An example of spatial variability can be seen in Alexandria City, where unofficial rainfall measurements from two districts approximately 12.5 km apart recorded vastly different amounts on the same day – one district noted 50 mm, accumulating to 116 mm to the date, while another recorded only 4 mm, with a total of 152 mm (*Alexandria Rain*, 2023).

Variability in the timing of rainfall in dry areas is more likely than in humid regions. In typical cloudbursts in the most extreme desert regions, the change from complete dryness to full-blast rain occurs instantly. Convective mechanisms are responsible for the extreme intensities in hyper-arid regions since they are linked to elevated temperatures (IRTCUD, 2001). The rainfall measured over four consecutive years at a site in Australia with an average annual rainfall of 250 mm serves as an extreme example of temporal variability. The annual totals were 570, 70, 680, and 55 mm, respectively (Pilgrim et al., 1988).

It is critical to comprehend how precipitation patterns are changing in dry regions to be ready for any future changes. According to a study, the future climate projections in dry regions show a continuous increase in both total precipitation amounts and annual daily extremes over the twenty-first century. This increase in annual precipitation may raise the risk of flooding in areas where high-intensity rainfall events are uncommon, and the infrastructure is less well adapted to more intense rainfall events (Donat et al., 2017).

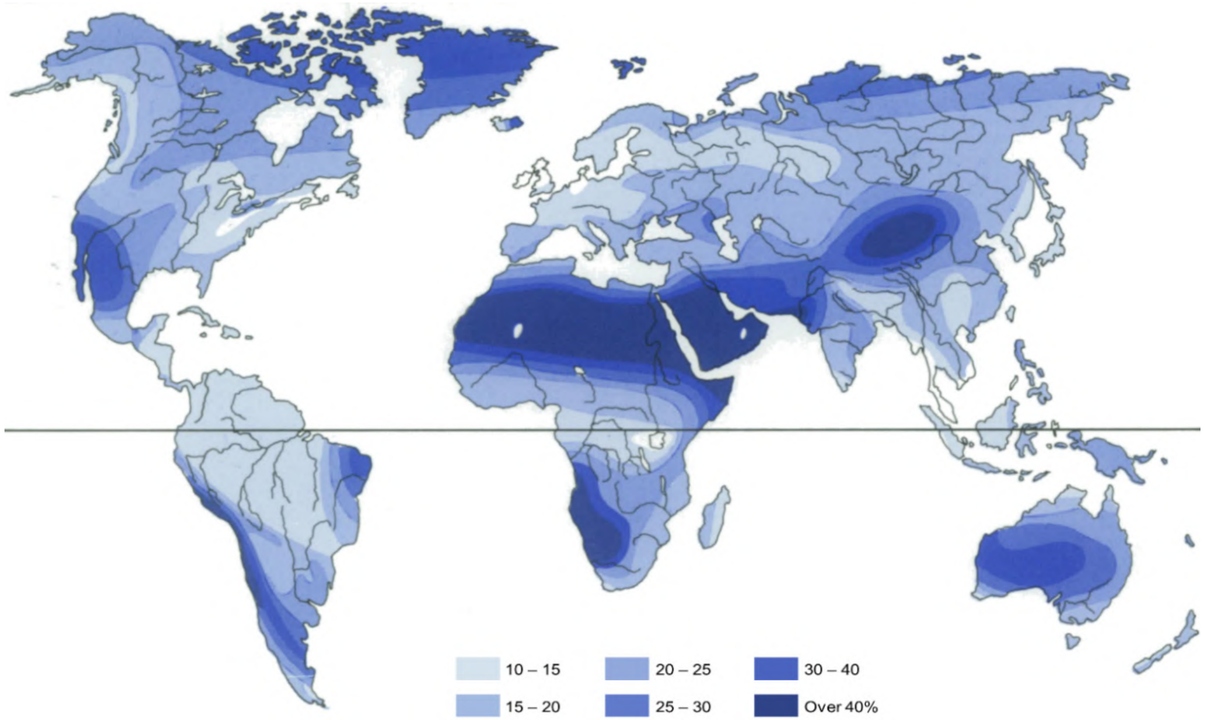


Fig. 2-7: Average deviation in annual rainfall in percent of long-term average (Morales, 1977)

"It is strikingly evident that the areas with high variability coincide with arid areas and that areas with low variability generally coincide with humid areas."

(Morales, 1977) Rainfall Variability: A natural Phenomenon

Evapotranspiration

Evapotranspiration refers to the combination of two separate processes by which water is lost from the soil and open water surfaces by evaporation and from the plants through transpiration, and hence its removal from surface runoff. Despite being a continuous, steady loss, its impact during brief periods of rainfall is insignificant. As a result, in humid regions, it is typically ignored in most models (Butler et al., 2018). However, in dry climates, evaporation is considerable and represents a major rainfall abstraction even during rainstorms extending less than 30 minutes. As a result, ignoring this evaporation amount may result in a significant overestimation of runoff (IRTCUD, 2001).

In dry climates, the high evaporation rate is influenced by radiation and soil temperature. Evaporation from bare soil is more important than transpiration from plants. The reason is the increased area of bare soil over vegetation and the less frequent rainfall events, which enable bare soil to return water to the atmosphere with minimal pathway impedance. Gradients in soil temperature have a substantial impact on the daily rate of evaporation, which increases in importance as soils dry up (Pilgrim et al., 1988).

Dew

Dew, or 'surface moisture,' is the converse process of evaporation and has been well known as a surface-atmospheric phenomenon in dry regions, especially areas located on the coasts and characterized by high relative humidity. Dew forms as water vapor from the air comes in contact with a surface and condenses into liquid. The key condition in this case is that the surface temperature is lower than or equal to the dew-point temperature (Agam & Berliner, 2006).

Richards (2004) notes that studies seldomly address the role of such water resource in complex urban landscapes. Observation and quantification of the phenomenon are mostly limited to agricultural and rural contexts where dew is a considerable source of water for plants and animals. He also gives an overview of dew in urban environments and presents an argument that urban contexts can provide the least suitable conditions for dew formation in comparison to the countryside. This is based on the unproved claim that the heat island effect in cities might contribute to this reduction by increasing temperature. In addition, materials that retain heat overnight like buildings and pavement are much more dominant in cities, while other materials with less thermal mass and more suitable for generating dew have less presence. However, the author still believes that further studies of dew in cities are required to provide a better understanding of the phenomenon and explain the potential and limitations.

There have been only a few attempts to quantify urban dew deposition on both plants and artificial surfaces. According to Richards (2004), it is theoretically possible to collect per night ~0.5–1 mm (0.5–1 l m^{-2}) of dew condensed on a thin plastic sheet. An experiment done in Jerusalem to collect dew from a 1m^2 thin foil sheet installed on a rooftop has shown the potential to collect 33 liters (33 mm) of dew per year. The maximum yield of condensed water (6 liters/m^2) was harvested in the driest month of August and a minimum of (1 liter/m^2) in December (Berkowicz et al., 2004). There has been no evidence of actual deliberate practices of harvesting dew in the MENA region, at least. However, there are some individual projects from the Alexandria Library, which will be presented in a later section to showcase the possibilities to collect dew from building facades and rooftops.

> The phenomenon of dew formation is an underexplored resource in urban environments, particularly in dry climates, where it could provide supplemental moisture in combating drought.

Infiltration

Infiltration is the process by which rainwater seeps into the soil pores through the ground surface. The rate at which water infiltrates into the soil is referred to as its infiltration capacity. The magnitude is influenced by a variety of elements, including soil type, structure, compaction, initial moisture content, surface cover, and the depth of water in the soil (Butler et al., 2018).

As a result of the physical process of soil formation being active in dry regions, heterogeneous soil types with properties that do not significantly differ from the parent material and soil profiles that preserve their heterogeneous characteristics are produced. According to the cementing agent used, such as gypseous, calcareous, iron, and other substances, soils in drylands may have hardened or cemented horizons known as soil pans. The thickness and depth of creation of the horizons, which act as a barrier to water and root penetration, determine how much they influence infiltration and salinization. Under some circumstances, salt crusts can develop at the surface of salt media. Clay particles coagulate in the presence of large amounts of soluble salts. Due to the sodic clays' natural swelling and dispersion characteristics, soils that have been enriched with sodium salts change in structure and become impermeable. The behavior of soil during irrigation and drainage is significantly influenced by changes in soil structure brought on by the action of various salts. Soils that have been damaged by salt and are sodic have a highly loose surface structure, rendering them vulnerable to wind and water erosion (IRTCUD, 2001). Furthermore, long dry periods may affect the soil structure, especially at the surface by forming a soil crust, which can have a significant impact on infiltration and runoff generation (Pilgrim et al., 1988).

Infiltration is a focal point regarding how it is affected by soil composition and structure. In dry environments, soils dominated by sandy textures may enhance infiltration rates, whereas the formation of soil crusts can significantly impede water absorption capabilities.

Sedimentation

Local climatic conditions in dry regions influence sediment accumulation in runoff. The considerable fluctuation of temperature and humidity decomposes the soil into loose materials that flash stormwater carries to the drainage system. Additionally, in urban areas, dirt and other sediments build up on impermeable surfaces during the long dry seasons either by sandstorms or human activities. These pollutants are eventually swept away by surface runoff during rainstorms. Large amounts of sediment are carried to the various drainage system components, and a subsequent major problem occurs as a result of these mechanisms: sewer blockages may be partial or complete as a result of settlement and the subsequent consolidation of significant amounts of silt during the prolonged dry interval between rainstorms. This drainage system obstruction increases the hazard of urban flooding in urban areas (IRTCUD, 2001).

Stormwater Quality

A pollutant is a material present in a concentration greater than that which naturally occurs in the water, air, or soil. Stormwater pollution loads in urban areas are much higher than in unimpaired areas because urban activities generate more pollutants (IRTCUD, 2001). Generally, urban drainage systems' handling of stormwater must consider its quality for a number of reasons. First, drainage systems are susceptible to significant variations in water quality. Second, receiving water can become seriously polluted as a result of direct discharges from drainage systems such as combined sewer overflows and stormwater outfalls. Also, the performance of wastewater treatment plants (WTP) is significantly impacted by stormwater quality (Butler et al., 2018).

It is typically thought of as accumulation and wash-off being the two phases of the stormwater pollution process. The buildup is the accumulation of pollutants over dry periods on catchment surfaces, whereas the removal of surface pollutants during storms is known as 'wash-off.' The principal factor affecting stormwater quality in dry areas is its content of suspended sediments carried by flash floods. The dispersion of suspended sediments and contaminants in stormwater runoff could have been produced by dust storms that are common in dry climates or by soil erosion caused by rainfall events. The degree of soil erosion is influenced by regional factors, including the kind of land use, animal and vehicle numbers, and rainfall patterns. Some of the sources of pollution include the wear of roads, pavements, and vehicles, atmospheric deposition, human activities, construction materials, and surrounding dry soil (IRTCUD, 2001).

Because of dry conditions and long intervals between events, as well as sparse vegetation in dry urban areas that provide little protection against soil erosion, stormwater events in dry regions often have higher pollutant concentrations and loads than elsewhere. However, because annual runoff volumes are lower and storm events are less frequent, total annual pollutant loads from urban catchments in these regions are generally lower than in temperate and humid regions (IRTCUD, 2001).

Maintenance and Management

Maintaining drainage systems is essential for ensuring their functionality, particularly in addressing issues like erosion, sedimentation, and debris accumulation. In dry built environments, the unique climate conditions require more frequent maintenance compared to non-dry regions. Whereas drainage systems in non-dry areas may need annual maintenance or checks following significant rainstorms, those in dry catchments require maintenance after every rainfall event to remain effective.

In dry climates, sediment and gross pollutant control become the foremost maintenance concern. This involves more frequent inlet clean-outs and pipe scouring due to sediment accumulation. Routine maintenance in these regions entails post-rainstorm checks on manholes, repairing damages, inspecting, and restoring concrete and metal components, cleaning sediment and trash racks, and clearing accumulated street debris.

Traditional stormwater management approaches prioritized public safety by efficiently conveying stormwater to receiving waters and controlling its flow. Maintenance targeted the capacity retention of drainage system components. Conversely, the emphasis on multi-objective stormwater management, encompassing quality improvement and ecosystem protection, has led to ecologically based systems. These systems differ significantly from conventional ones, necessitating distinct maintenance and management practices.

2.2.2 Conventional vs Adaptive Methods

In dry cities, especially in the Global South, conventional combined storm drainage systems are common and are designed for relatively minor storm events, typically with a return period of 1 or 2 years. These designs assume that more severe flooding will occur even less frequently, around every 5 to 10 years. However, in these regions, high-intensity storms are typical, and the existing combined drainage infrastructure often struggles to handle the volume of water generated during such events. As a result, the drainage system becomes overwhelmed, resulting in flooding and infrastructure damage (Butler et al., 2018).

The adoption of separate sewer systems in dry regions varies significantly due to factors like infrastructure development, water scarcity, and regional economic and technological capacities. Australia is quite advanced in adopting separate sewer systems, particularly in response to recurring droughts and water scarcity challenges. Cities like Adelaide and Perth have implemented separate systems to manage wastewater and stormwater more efficiently. They are incorporating various WSUD practices such as rainwater harvesting, permeable pavements, and green roofs to promote sustainable water management, as will be discussed further in Chapter 03.

In the MENA region, where economic capacity is lower, the implementation of separate sewer systems has been considered infeasible. This is because rainfall is limited and variable, which makes the argument sensible, especially for cities with average annual precipitation less than 100 mm. However, the challenge of flash flooding stands as an increasing risk, which requires additional focus on other decentralized strategies.

> "It is increasingly being recognized that stormwater and wastewater are not nuisances or threats that should be immediately dealt with but are, in fact, resources that should be managed."
>
> *(Butler et al., 2018) Urban Drainage*

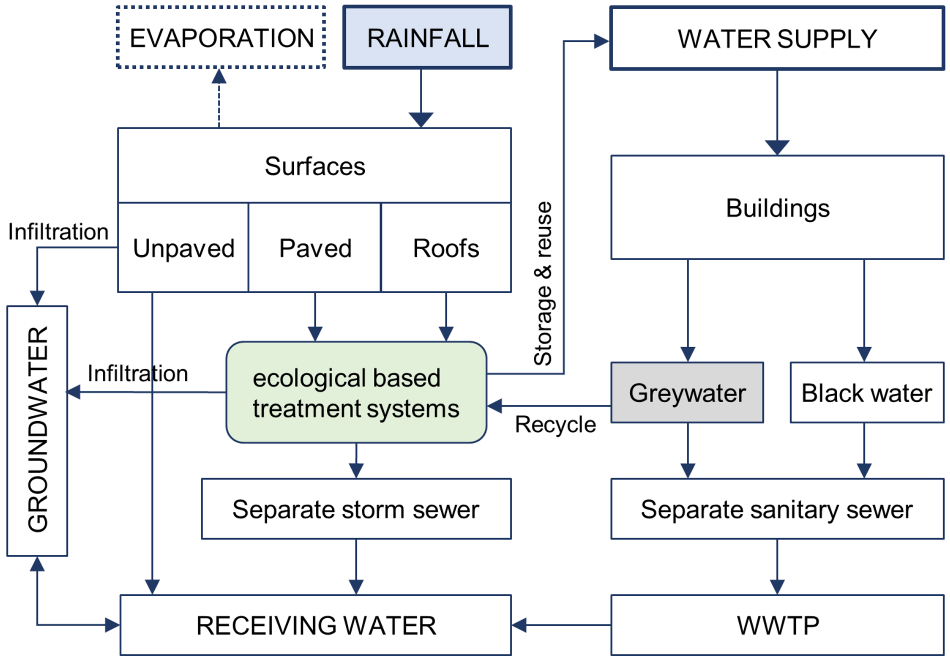


Fig. 2-8: Sustainable urban water cycle, by author based on (Butler et al., 2018)

The sustainable decentralized approach provides a solution, which can slow down and manage stormwater locally, reducing the risk of flooding during intense rain events. These systems focus on using natural processes for water treatment. This approach can lead to higher water quality without the need for extensive piping infrastructure. In addition, sustainable drainage does not just manage stormwater; it contributes to creating more livable and sustainable cities. Green spaces, trees, and water features can enhance the aesthetic appeal of urban areas and improve the overall well-being of residents.

In this section, it has been explained that rainfall in drylands exhibits greater variability in both space and time, often with less frequent but intense events. Evaporation plays a significant role due to factors like radiation and soil temperature. Although soil infiltration rates can be relatively high, prolonged dry spells can lead to compacted or crusted surfaces that hinder water infiltration. Sedimentation is a concern, primarily from suspended particles stemming from soil erosion and dust storms. This sediment transport can block sewers, requiring careful drainage system maintenance.

The stormwater quality in drylands tends to have elevated pollutant concentrations and loads. The dry conditions and infrequent rainfall events, coupled with limited vegetation, offer minimal protection against soil erosion. The primary focus is on addressing sediment and gross pollutant control issues.

In hot and dry built environments where extreme rainfall events are infrequent but impactful, sustainable drainage systems offer several advantages over conventional systems. They address flooding challenges, ensure water quality with minimal piping, blend harmoniously with the urban context, enrich urban design with amenities and biodiversity, and enhance the overall quality of life for city residents. This comprehensive approach aligns with the goals of creating resilient, ecologically balanced, and visually appealing urban environments.

Unlike conventional sewer systems running underground, adaptive methods require above-ground interventions like green roofs, rain gardens, and swales. Designing urban spaces with these technologies requires a thorough understanding of the distinctive nature of the local context, including physical characteristics like topography, soil type, and urban structure. Therefore, the next section moves on to investigating the urban context of dry and hot regions and explores the potential relationship between urban characteristics and flooding.

Overall, understanding the unique challenges of urban drainage in dry climates is essential for implementing effective, context-specific solutions. The focus on sustainable drainage systems, considering both environmental and social aspects, provides a holistic approach to urban water management in these regions.

> “Mixing of wastewater and stormwater in combined sewer systems is fundamentally irrational. It is the consequence of historical accident and remains a cause of significant damage to the water environment.”
>
> *(Butler et al., 2018) Urban Drainage*

2.3 Urban Form and Structure

Urban form or urban morphology can be broadly defined as the physical features and characteristics that shape built-up areas, including the spatial arrangement of streets, building blocks, and open spaces constituting distinct urban tissues. The levels of urban form analysis vary at multiple scales, starting from urban blocks, neighborhoods, cities, to a broader regional scale. What constitutes these forms are groups of physical elements. Each city has its own distinct combination of these elements; however, some common patterns and characteristics may be observed in a region or climatic zone (Dempsey et al., 2008; Oliveira, 2016).

The study of urban forms has long been regarded as an area of research to understand the effect of the physical features of a city on mobility, connectivity, and social cohesion. Nonetheless, this section takes a different approach, seeking instead to understand and describe the peculiar urban characteristics of cities in dry environments that may have a direct or indirect influence on natural urban surface runoff and the provision of green spaces within these cities. Before going into detail in this analysis, it is important to introduce the context of cities in the dry MENA region that are caught in the paradox between heritage and modernization.

2.3.1 Traditional vs Contemporary

The idea of "palimpsest" is one of the main themes of urbanism, which helps to understand the continuous evolution of cities as a sophisticated cultural phenomenon (Khirfan et al., 2021). It signifies how cities over time accumulate layers of history, culture, and development, with each layer representing a different period of urban landscape.

What might be important to point out in this section, in the context of urban palimpsest, is what Stefano Bianca describes as the "structural conflict between traditional concepts and modern planning methods" (Bianca, 2000). He argues that the Modern Movement fundamentally disregards the historically developed urban structures, including their social, cultural, and physical context. In my view, this conflict extends to a serious environmental aspect, which is increasingly becoming more evident due to the impact of climate change.

> "The reason we are interested in 'traditional' forms of building, dwellings and settlement is that we believe that such achievements met human needs in a more **sensitive** way than contemporary and/or alien methods do."
>
> *Janet Abu-Lughod, Disappearing Dichotomies: First World-Third World; Traditional-Modern (ABU-LUGHOD, 1992)*

Environmental constraints of elevated temperatures and scarcity of water resources have been major influences on forming the urban structure of cities in dry climates. Over centuries, dryland settlements have developed common traditional urbanization practices that could adapt to their extreme environments. Despite cultural and social differences, several cities in these climates have common urban characteristics and shared challenges. This is evident, in particular, in terms of neighborhood structure, streetscape, open and green spaces, and even in construction techniques. However, it has been argued that the globalized modern urbanization paradigm has prevailed in recent times, replacing region-specific vernacular practices. Car-centric design and technology are thought to have bypassed almost all local climatic challenges, consequently allowing those cities to grow rapidly. However, certain practices and problems were not possible to evade (Tavassulī, 2016), mainly the lack of infrastructure that is locally tailored to meet the distinctive needs of the local environment. Sprawled cities are the result of a globalized urban planning model that promotes standardized design and segregated land uses with low densities.

In the late 20th century, a new concept of New Urbanism emerged as anti-sprawl and auto-centric development. The concept responds to the loss of traditional neighborhood and community structure by creating a more walkable, mixed-use, and human-scale urban environment. While the New Urbanism concept draws inspiration from traditional practices, it is not a return to the exact urban forms of the past. Instead, it aims to adapt and integrate certain elements of traditional urbanism into contemporary contexts, considering modern challenges and opportunities (Hebbert, 2003).

Cities in the region can be categorized into three types: coastal, riverbank, and inland cities. River cities are limited to those along the Nile in Egypt, such as Cairo, as well as cities located on the Tigris and Euphrates in Iraq, such as Baghdad. Coastal cities include, for example, Tunis, Jeddah, and Alexandria. Inland cities include Sana'a, Amman, and Riyadh.

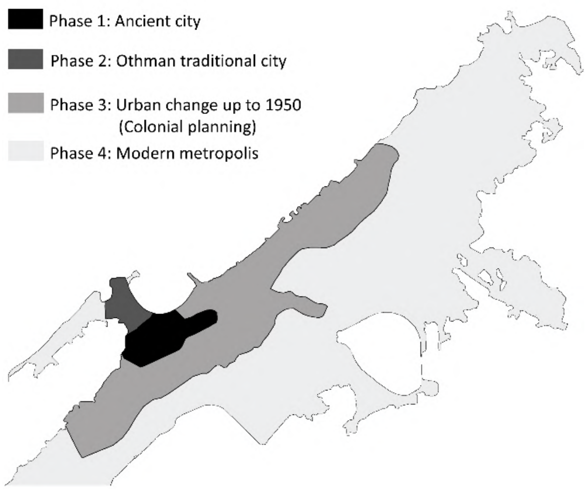
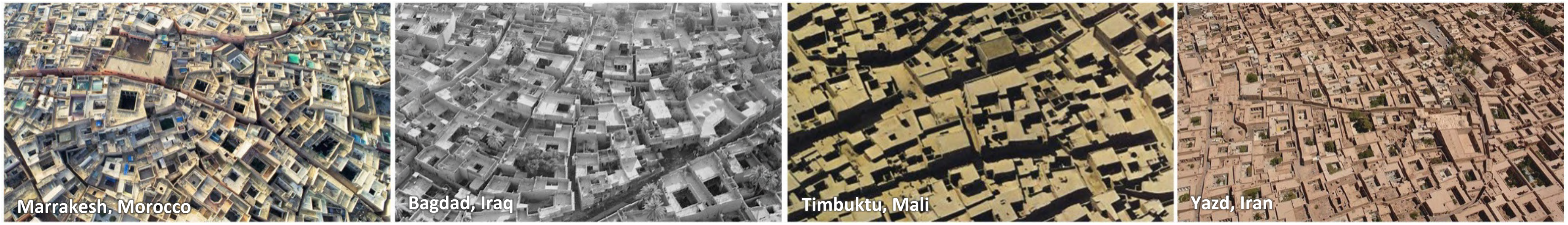


Fig. 2-9: The urban palimpsest of Alexandia City, by author based on (Alii & Abouelfadl, 2022)



2.3.2 Elements of Urban Form

The basic components that collectively shape the physical structure of urban areas in the region will be identified and analyzed, focusing on urban tissue, density, distribution of open and green space, and streets layout. In addition to the transition and differences between the modern and vernacular layers.

Urban Tissue

Traditional cities in the MENA region present a unique urban tissue or form that has evolved over centuries, reflecting the region's climatic considerations. While there is considerable diversity among those cities due to variations in geography, historical periods, and local traditions, some common characteristics can be observed in their urban fabric.

The traditional urban structure of most cities in the region conforms to principles that are completely contradicted by those of the current widely adapted modern planning. One of the basic differences is that the traditional fabric of the city is based on an incremental or organic aggregation process, originating in the definition of socially relevant micro-spaces which are then connected into larger units. Buildings were not conceived as detached objects but as living architectural shells, shaped according to the needs of the local community, prevailing wind patterns, and the desire for shade and privacy (Bianca, 2000). Traditional cities, according to Morris (1994), also feature **courtyards**, where buildings are organized around a central courtyard for the purpose privacy and creates a cooling effect. This was a dominant practice in residential buildings, as well as in the central mosque of the city. **Marketplaces** (Souks and Bazaars) are linear through routes and often shaded. They functioned as social and economic hubs in a way that could be considered as a kind of special open and public space. **Defensive city walls**, while some have been preserved, have

either been integrated into the urban fabric or have given way to modern development.

Historically, water management played a crucial role in the design of Arab cities. Systems like qanats, cisterns, and falaj were integrated into the urban fabric to capture and distribute water efficiently.

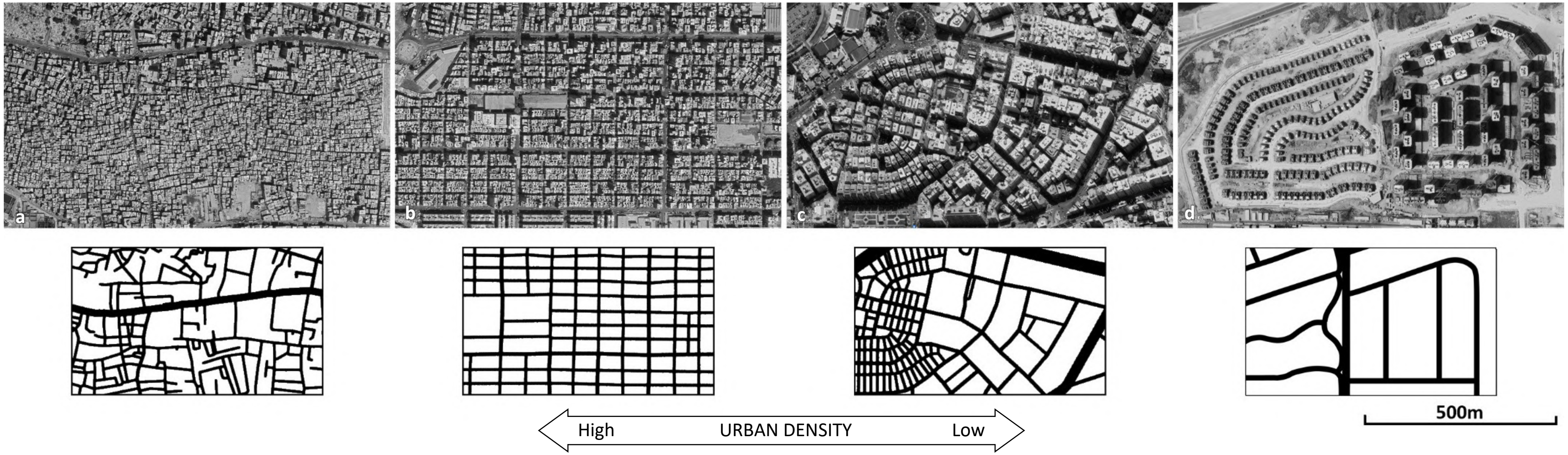


Fig. 2-11: (top)Partial maps from Alexandria showing the modern varying fabrics and densities, from slums (a) with the highest density, to suburb gated communities (d) with the lowest

Images: (Google earth, 2023)
Illustration by author

Fig. 2-10: (left) Traditional urban fabric in historical cores of different cities in the MENA region

Illustration from (Haider, 2022)

In a a preceding era of Graeco-Roman time, some cities had adapted the Hippodamian model, which is a grid-based planning with straight streets intersecting at right angles. However, this gridiron plan was transformed over time into the local traditional, then later Islamic, urban organic form (Morris, 1994). Damascus and Alexandria provide examples of this transformation where organic form and dead-end streets (cul-de-sacs) gradually replaced the earlier grid fabric. Additionally, ancient temples and central public courtyards (Agora) were converted into grand mosques or churches, and grand Roman roads became bazaars.

On the other hand, the **Modern Movement** of urban planning influenced all aspects of cities, where planning has become a comprehensive master plan that lays out a city's development in a systematic way, predicting its future growth and changes (Bianca, 2000). It often involves zoning regulations that divide large areas into smaller blocks with designated land uses. This globalized model has led to standardized city layouts that might not be deeply connected to the local culture or context, let alone the climate.

Moreover, the political and socio-economic situations have even forced two extreme forms: gated communities and slums. Gated communities are characterized by enclosed residential areas surrounded by walls, fences, or other barriers. They can range from small clusters of homes to large developments with amenities. Informal settlements, or slums, have evolved in many cities in the region, especially fast-growing cities with high populations. These settlements seem not merely an informal adaptation of modern urbanism but rather a return to the traditional unplanned growth of the city. Despite not meeting many of its former qualities, they still follow a similar pattern of urban form expansion.

So, in a typical city of the region, different urban tissues can be found, related to the time they were developed: traditional, modern, and informal. These structures are not clearly delaminated from each other but rather intersect in many ways and blend together as cities grow. While traditional urban tissue is highly valued, modernization and urbanization have led to the integration of contemporary architecture and infrastructure within these cities, including their historic cores.

Densities and Compactness

Densities and compactness are crucial factors in cities that significantly differ between the modern and traditional paradigms. Cities in emerging nations have substantially higher densities than those in industrialized nations, particularly in the central metropolis (Richardson et al., 2002).

Traditional urban form often has a compact layout with narrow streets, closely spaced buildings, and mixed land uses. Such compactness fosters walkability as it provides shorter travel distances and reduces the need for extensive transportation infrastructure where walkability is limited in daytime. The compact and dense nature of traditional cities improves the urban microclimate and promotes a strong sense of place and attachment to the urban environment (Schiller & Evans, 2002).

The modern paradigm implies a range of densities and often varies in their level of compactness. While some areas might be densely developed, other parts, especially suburban developments, can be characterized by lower compactness and greater distances between buildings and amenities. The introduction of zoning regulations, prioritization of car-centric design, and the spread of suburban developments have contributed to urban sprawl. This results in low-density, decentralized developments with longer commuting distances. This is especially evident in new desert cities in Egypt, dominated by gated communities, and the urban sprawl in cities of the Gulf region. In general, densities and compactness in cities in the region are much higher than their Western counterparts, in both traditional and informal forms.

Streetscape and Hierarchy

To avoid direct sunlight and hot winds from the desert, traditional streets were built narrow and winding, often with dead ends, forming a network of what is called ‘Urban Street Canyons.’ The road system in traditional cities in the MENA region was not a result of a planning process but rather propagated by the arrangement of buildings and the inadvertent growth of residential quarters, thus showing great irregularity with an organic fabric. This form of street layout and geometry has provided optimal outdoor thermal comfort for human activities, as residents seek shading and protection from the hot wind.

The basic types of streets in this system were cul-de-sacs, alleyways, and thoroughfares. The cul-de-sac is a dead-end street where individual houses are grouped around. They represented a fundamental component of the self-regulatory nature of the city (Morris, 1994). Typical cul-de-sacs were altered in some cities where the dead end forms a larger courtyard, used as common space for residents' social activities (Mortada, 2019).

In modern times, road systems in cities in the region have adopted the modern urban planning approach where wider roads, motorways, large parking lots, and squares dominate the urban structure. Through roads extend, dividing blocks and intersecting each other to create large

Fig. 2-12: Comparison between traditional Street network and hierarchy (left) and modern street layout (right).

Illustration adapted from (Bianca, 2000)
Photos from left: (M. Abd El Ghany, 2019, 2021; Rod Waddington, 2014; tai_mab, 2012)

squares – a perfect channeling system, not only for flowing vehicle traffic but also to convey runoff flows (Fig. 2-12). However, dead-end streets persist in modern times as a common feature attributed to the layouts of historical cores and informal settlements. Furthermore, features such as street verges and pedestrian-friendly streets are notably absent, with perhaps only irregular tree pits on the side of main roads.

Open and green spaces

Referring to the palimpsest urban form of cities in the MENA region, a main characteristic that has remained through time is the lack of public open and green spaces. In the traditional city form, this development is thought to be an adaptation to local climate constraints of scarce water and extreme heat, coupled with sparse green cover or trees for shading. Thus, the presence of a square within this system of street canyons would be considered an exceptional space associated exclusively with either an open market or a courtyard facing a mosque (Oliveira, 2016). In his analysis of traditional urban forms in the region, Stefano Bianca also describes public open space as "limited and reduced to an inward-looking corridor system" (Bianca, 2000). His analysis of the region's cities clarifies the differentiation between limited public space and an abundance of private open spaces represented in introverted courtyards within each house.

> "In contrast to European counterparts, Middle Eastern cities of the Middle Ages had no place of public assembly corresponding to the church square or the space in front of the town hall."
>
> *(A.E.J. Morris, History of Urban Form)*

Green spaces in traditional dry cities were a privilege linked to the wealthy, being present only in rich houses and palaces. The lack of water resources to support greenery made it an uncommon practice, neither for the aesthetic aspect in public space nor as a function of providing shade by trees. Instead, compact urban forms with canyon streets and inner house courtyards were the typical urban adaptation to the hot and dry environment. In such a compact system, squares and open spaces were widely associated with and limited to mosques and markets.

However, while the environmental context has not changed, the later modern urban movement adopted the model of wide streets and inter-district parks and open green spaces. This globalized planning approach, without considering local conditions, has imposed more challenges rather than offering progressive solutions. The lack of shading, high maintenance requirements, and scarcity of water have affected the quality and extent of open and green spaces, limiting their role within the cities in the region. According to Elsheshtawy (2019), it is now uncommon to find inclusive open and public areas in many Arabian cities. Nevertheless, locals tend to utilize other spaces for gathering, such as vacant lots and unofficial community markets. The provision of shading was lost between canyon streets and trees, manifesting a fundamental conflict between traditional concepts and modern Western planning models.

Fig. 2-13: Satellite image of a park in Alexandria indicating a decline of green cover in recent years to more impermeable concrete surfaces (Google earth,2023)

Moreover, there has been a newly introduced concept of public parks in recent years that involves blending open plazas with traditional park spaces (Fig. 2-14). Notably, these examples have drawn attention due to their substantial coverage of concrete in proportion to greenery and trees. This circumstance has sparked public discourse concerning the preferred characterization and function of these newly developed parks—whether parks in such dry cities should compromise vegetation and trees in favor of more paved surfaces and hardscape elements (Mada Masr, 2023). It is evident that the driving factors behind this design approaches include concerns related to the high maintenance requirements and water demand.

Fig. 2-14: Bent El-Shatee Park in Damietta, Egypt as an example of concrete dominant parks (Photo: Elbalad news, 2022)

Boundary walls and barriers

Walls in urban areas are physical structures erected to define property boundaries, provide security, and sometimes serve decorative purposes. They are essential elements of urban planning and property ownership, serving to create a clear delineation between public and private spaces. Various materials are used in wall construction, including timber, soil, stone, metal, and wire. In some cases, living plants like hedges are also used to create fences.

There is no specific research or statistics comparing walls and fences in hot, dry urban areas to other contexts in the world. However, it is widely known that the prevalence of boundary walls and fences in urban areas in the Global South in general, and the Middle East in particular, is much higher than in many other regions such as Europe, North America, or Australia, where the use of low or no fences at all is encouraged and the focus is on promoting a sense of community and urban integration. In Western practices, rather than using physical barriers, urban design often incorporates landscaping and green space to demarcate properties and create a more visually appealing environment. In the Middle East, walls and fences are commonly used to delineate properties, provide security, and maintain privacy. This is due to several factors, including cultural norms, security concerns, and the political situation in the region. The Middle East region has a long history of spatial control through walling, and the construction of walls and fences has increased even more in recent years in response to growing political instability (Pallister-Wilkins, 2015). The strong presence of walls can be easily observed almost all over the city, bounding individuals' properties, gated communities, education and healthcare facilities, sports and leisure areas, public authorities, even fencing parks and open public spaces, anti-migrant walls, separation barriers, counterinsurgency barriers, and several other types. Access to available materials and the innate lack of greenery in these built environments has led to the dominance of impermeable masonry walls with rare presence of green planted fences.

I presume that the transition from traditional inward-oriented, compact urban forms to more outward-looking buildings in the region has led to this prevalence of boundary walls in urban practices. This modern shift towards more open and extroverted designs often conflicts with the societal norms that prioritize the segregation of private and public spheres. As a result, walls and fences have become dominant features in contemporary urban landscapes, reflecting an effort to reconcile modern architectural styles with the region's deeply rooted cultural formality.

Fig. 2-15: Types of typical boundary walls in MENA cities bordering public facilities, private properties and major infrastructures

2.4 The Role of Urban Form in Flooding: Discussion and Key Argument

Upon reviewing the general characteristics of urban drainage in hot, dry cities, a self-perpetuating cycle unfolds due to interrelated factors such as water scarcity, sparse vegetation, and climate extremes. The unique spatio-temporal variability of rainfall patterns causes brief but intense irregular rainfall events, surpassing the city's drainage system capacity and resulting in regular flooding and sewer overflow. Prolonged drought periods limit vegetation growth and the provision of canopy cover, which results in reducing transpiration and increasing direct evaporation. Seasonal density variation in green cover directly contributes to increased demand for water resources.

The harsh environment's inability to sustain durable green cover that has a natural drainage function leads to the use of impermeable materials, which expand the total area of impervious surfaces, hindering infiltration and increasing runoff. In addition, the ongoing impact of climate change is already influencing rainfall patterns and frequencies in dry regions, leading to prolonged droughts and heavy rainfall. The existing provision of drainage infrastructure is indeed less well adapted to additional loads during extreme conditions, and proposed improvements come up against limits of cost and space.

This vicious cycle, influenced by water, vegetation, climate extremes, and inadequate infrastructure in MENA's dry cities, is a major cause of surface water flooding or 'flash flooding' during heavy rainfalls on hard surfaces, overwhelming the combined sewer system. In such a chronic situation where sewer systems beneath the surface are unable to manage stormwater runoff, the city's physical layout and surface features significantly influence flooding risk and impact by determining surface runoff behavior. Urban forms can either exacerbate or mitigate flooding. Therefore, there is a need to investigate and test this hypothetical relationship, particularly in dry built environments.

There is a growing body of literature that recognizes the effect of urban structures on disaster impact and recovery. Recent studies have begun to explore this hypothetical relationship between urban form variables and disaster resilience in general. This includes flood hazards, but rather exclusively limited to river flooding (fluvial flooding) affecting urban areas on floodplains downstream.

Computational model methods have been used in studies to generally optimize the geometries of the urban layout that are least affected by flooding. (Bruwier et al., 2020; Bruwier et al., 2018) uses a 2D hydrodynamic model to analyze the impact of urban patterns on flood flow in lowland river floodplains. The results show that the urban pattern has a significant influence on the depth and velocity of the flood. The study also found that urban patterns can affect flood discharge in different ways depending on the characteristics of the floodplain.

Other studies are based upon several statistical and empirical methods that investigate the topic within the setting of a city or region. For instance, (Kang et al., 2021) explored the relationship between urban forms and natural hazards, particularly floods, and how urban form can increase or decrease flood damage. The study analyzes the dual aspect of urban aggregation and dispersion spatially and quantitatively from a macroscopic point of view. Also, (Brody et al., 2013) examines the effects of different development patterns on observed flood losses across counties fringing the Gulf of Mexico. The study found that the development patterns have a significant impact on flood losses. It argues that higher connectivity is associated with lower risk of flooding, due to the smaller total impervious surface area cover.

A further study conducted by Irajifar et al. (2016) examined the impact of land use mix, population density, building type, and diversity on the recovery progress within a period after the 2010 flood in Brisbane and Ipswich, Australia. The study found that the relationship between post-disaster reconstruction and density is not linear. The advancement of reconstruction in relation to population density increases from low, medium, to high density, whereas the behavior alters in very low and very high-density areas, indicating that medium-high density improves resilience.

The mentioned studies have identified several correlations between flooding and urban parameters related to density, neighborhood blocks, clustering, land use, connectivity, and green space configuration. However, this line of evidence can only be considered a first step towards a more profound understanding of the influence of urban features on flooding. Urban characteristics are not uniform globally; they vary significantly due to specific climates, cultures, terrains, and geographical locations. This variation raises additional questions about unique urban practices and norms that need to be considered. Adding the need to address the threat of pluvial flooding, which results from excessive rainfall and differs from riverine flooding caused by river overflows.

Turning now to the urban form of cities in the MENA region, including Alexandria as a case study in this dissertation, and drawing on the characteristics and features discussed earlier in this chapter, it becomes much clearer to me that there are common urban patterns among cities in the region. These, concluded as the extensive urban barriers and boundaries, may have a major influence on the surface runoff and the severity of flooding. Based on this observation, it is inferred that surface features in urban areas, notably barriers like railroads, tramlines, roads, motorways, and walls, significantly impact flooding occurrence and severity by obstructing stormwater runoff. These barriers are perceived as delineation structures that confine or direct surface runoff in specific zones, which delimit hydrologically independent but interconnected urban regions.

Key Argument

In MENA cities, including Alexandria, extensive barriers that extend across urban areas significantly influence runoff and flood severity. These barriers can be seen as structures that confine or direct stormwater runoff within the micro-basins they delineate.

This spatial decomposition of urban areas to barriers and micro-basins is termed **'Urban Hydrological Regions'** in this dissertation. This concept provides an innovative planning approach for interpreting and addressing surface flooding issues in the region and exploring adaptation measures from an urban morphological perspective. While various urban studies have examined the impact of physical barriers on societal development and community structures, the Urban Hydrological Regions approach distinctively identifies these elements as influential factors in shaping the urban drainage dynamics.

It is essential to acknowledge potential confounding variables and alternative explanations, as highlighted in prior research. Factors like surface permeability, land levels, and street grid orientation may also contribute. Nonetheless, this argument maintains that these morphological parameters influence surface flooding, though their impact varies among micro-basins. Essentially, each micro-basin interacts nearly independently with the surface runoff it generates.

Physical barriers could be categorized as anthropogenic and natural. Structural barriers could be present as motorways, railroads, and boundary walls, or nonstructural such as parks and waterways (Fig. 2-16). Natural barriers are formed by the native terrain and could include hills, mountains, and natural water bodies.

Lynch (1960) explains that each of these elements might change its type depending on the circumstances and the position of the viewer; a motorway could be a path for the driver while perceived as an edge by pedestrians. In the context of the urban hydrological regions approach argued here, a motorway or a boundary wall is considered a cut through urban areas that seals surface runoff flow to

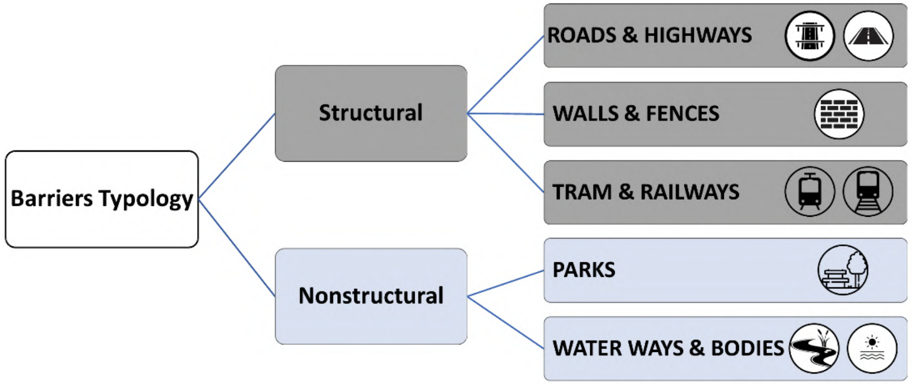


Fig. 2-16: breakdown of barriers typologies (By author)

accumulate on its sides. Or in another case, the road surface could resemble river or canal flow to convey stormwater to lower elevation areas.

Urban green spaces, like outer fringes or green corridors, and water bodies could also work as flow obstructions. They are permeable by nature, but most parks in MENA cities are fenced or walled, blocking runoff flow. In some cases, it is possible for non-fenced parks and green spaces to function as a receiving permeable barrier (as long as soil conditions allow). Yet, a flooded park should be much more accepted and encouraged rather than a street or property.

Moreover, cul-de-sacs may function as urban traps which makes them more susceptible to flooding. Whether attributed to poor planning or a genuine practice in the traditional urban fabric of cities in the MENA region, these street designs are likely to restrict water flow, leading to water buildup and an increased risk of flooding, especially in low-lying areas. On the positive side, the contained nature of cul-de-sacs allows for more localized stormwater management.

Supporting Evidence

Typically, further evidence and analysis are needed to support this argument. Therefore, several theoretical and empirical foundations are presented here on which I can base the outlined claim. Despite an extensive search, no direct evidence or research has been found that specifically examines the relationship between barriers and surface water runoff in urban areas. Rather, other studies have discussed the various impacts of barriers on human activities and well-being but have not considered other aspects like their impacts on water dynamics in cities.

First theoretical evidence includes some research and an overview of developed concepts within the discipline of urban geography that examine patterns of urban development and infrastructure, including the role and influence of urban barriers on cityscapes. Four prominent concepts can be summarized as follows:

URBAN FRINGE BELT - by Herbert Louis, MRG Conzen and J. W. R. whitehand

The urban fringe-belt or *Stadtrandzone* concept, which was developed in Germany more than 50 years ago, was inspired by Conzen's understanding of the long-term importance of physical limitations on urban growth, particularly city walls. The concept has developed and now is based on the realization that the expansion of urban areas occurs through a series of settlement sprawls over long period of time and in irregular manner. In this process of evolving cities, fringe belts are considered an urban element and tend to form at the edge of existing built-up areas, when at later urban expansion it becomes embedded within this built-up area. It contains mostly somewhat open, frequently vegetated places like parks, sports fields, and open land allocated to local institutions. Conzen's research revealed that some cities could have three separate belts: an outer fringe belt at the current perimeter of the town, an inner and center fringe belt embedded within the built-up area (Conzen, 1960; Oliveira, 2016; Whitehand, 1988).

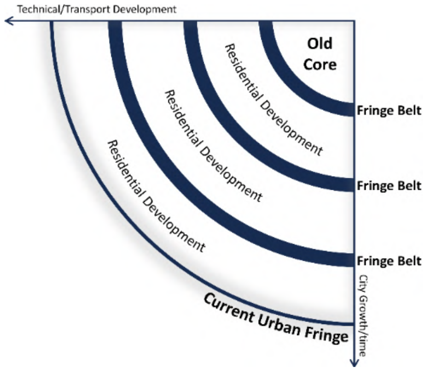


Fig. 2-17: Fringe belts as fixation lines in Conzen's model (Whitehand, 1988).

IMAGE OF THE CITY - by Kevin Lynch

Lynch's work centers on how humans perceive the built environment, both visually and physically. He identified basic elements within the urban fabric that can help shape the depth of our understanding of space as well as the broader mental image of our cities. One of these elements is edge, which pertains directly to the argument presented in this section. He described them as linear elements, usually dividing or cutting through spaces. They mark the discontinuity in the urban fabric and delineate between different areas. Edges could be shorelines, railway tracks, the limits of development, and boundary walls. They could only be perceived visually or have greater physical presence by 'intersecting movement', said Lynch. Another element is path, which is often perceived as an edge as well. He argues that each element might change its type depending on the circumstances and position of the viewer; a motorway could be a path for the driver while perceived as the edge by pedestrians (Lynch, 1960).

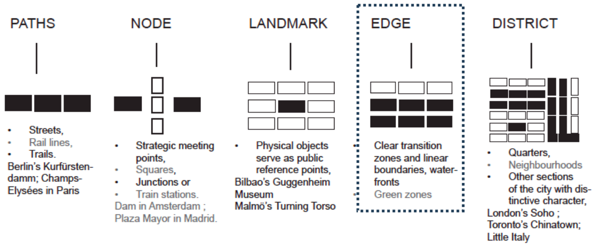


Fig. 2-18: Physical Elements of a city in Kevin Lynch's theory (Jojic, 2018).

THE OTHER SIDE OF THE TRACK

The phrase "the other side of the track" originates from the literal division created by railroad tracks in many towns and cities around the world. Traditionally, these tracks have served as physical boundaries separating more wealthy or privileged neighborhoods from poorer or less desirable ones. This division not only defines geographic boundaries but also creates sharp socio-economic contrasts between adjacent neighborhoods. The tracks act as tangible markers that delineate drastic changes in ethnicity, social class, or crime levels upon crossing from one side to the other (Mitchell & Lee, 2014).

Douglas (2005) discusses how urban barriers, such as railroad tracks, function as physical elements that consolidate groups of people with similar social or ethnic characteristics within close proximity while creating a division that each group perceives negatively when near the other. These barriers act as insulators or buffer zones between dissimilar groups, affecting neighborhood dynamics and land use patterns in ways that go beyond symbolic or formal boundary markings.

Moreover, the notion of division is not restricted to railroad tracks. Residents in urban areas can experience similar segregations through various physical forms of boundaries, including rivers, parks, highways, and other significant barriers (Knight, 1987). These divisions can abruptly alter spatial patterns and intensify socio-economic disparities within a very short distance, highlighting the profound impact of physical barriers on urban settings.

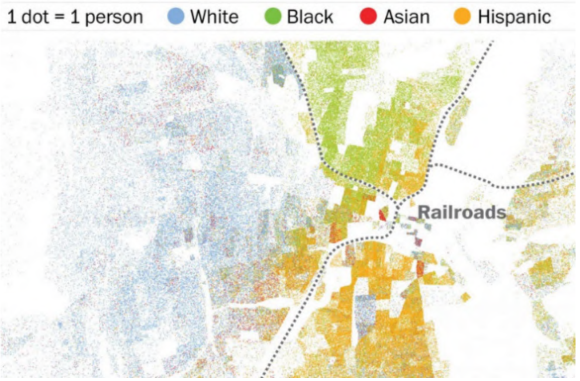


Fig. 2-19: Railroad lines segregating racial neighborhoods in Connecticut, USA (Badger & Cameron, 2015).

CITY OF WALLS - by Teresa Caldeira

In her book, Caldeira provides a thorough analysis of the ways in which crime and violence in São Paulo city have stoked fear and led to several responses, the most demonstrative of which is the construction of walls. Whole urban areas including residential, recreational, and workplaces are isolated from the rest of the city creating fortified enclaves. These protective tactics imply necessarily 'restriction on movement'. This practice ties with a broader pattern that she observes in cities across the world. The physical and sociological elements that permit this kind of separation in the city are the subject of an interdisciplinary investigation by Caldeira. She contends, the construction of walls has been a reaction to the democracy process that followed Brazil's military dictatorship (Caldeira, 2001).

Fig. 2-21: A wall segregating a favela from a wealthy neighborhood in São Paulo (Photo: Tuca Vieira, 2004)

As the previous review has shown, barriers and borders are obviously a topic that is present in the field of urban studies. The different interpretations presented strongly emphasize the role of barriers and boundaries in urban areas and offer valuable insights into their broader adverse effects on human activities and social divisions. While these perspectives do not directly address the hydrological implications of such phenomena, they may implicitly point to other possible influence of barriers on stormwater surface runoff. This suggests that these barriers may delineate distinct urban zones that may each exhibit different responses to flooding during extreme events.

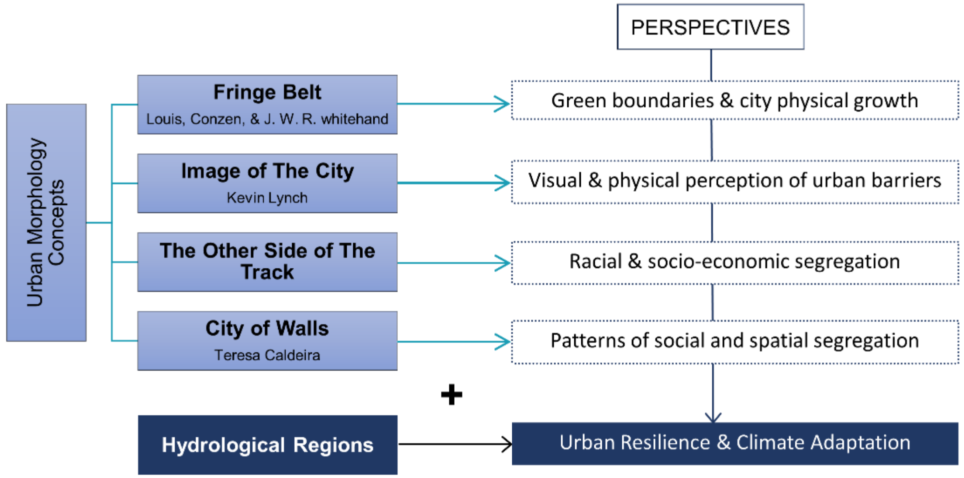


Fig. 2-20: Diverse morphological concepts on the impact of urban barriers on city development support an alternative approach to the phenomena from an urban resilience perspective (By Author)

Second supporting evidence includes direct observation and analysis of heavy rainfall maps in various cities in Germany. A flood map of a typical city in the region would have been a valuable tool to analyze and validate the argument. However, it is unfortunate that a reliable flood map specific to Alexandria is currently unavailable. Nonetheless, an alternative approach I propose involves examining heavy rain hazard maps developed in various German cities. These maps model the case scenario of flooding resulting from extreme rainfall events. Studying these maps allows us to observe the potential runoff behavior in relation to common urban barriers that are also found in cities of dry cities. Despite the climate differences, however, considering the given infrastructure provision, these maps of extremes in European cities provide a relevant analogy as they resemble the effects of regular average rainfall events that likely occur in other drier regions with less developed drainage infrastructure.

The cities of Hamburg, Düsseldorf, Leipzig, and Frankfurt, among others in Germany, have utilized computer-based models to assess flood risks during heavy rainfall. These models consider factors such as slope, elevation, and ground surface characteristics. The maps show a topographic flow path-sink analysis where stormwater on the surface may flow towards the nearest low points, which can include terrain

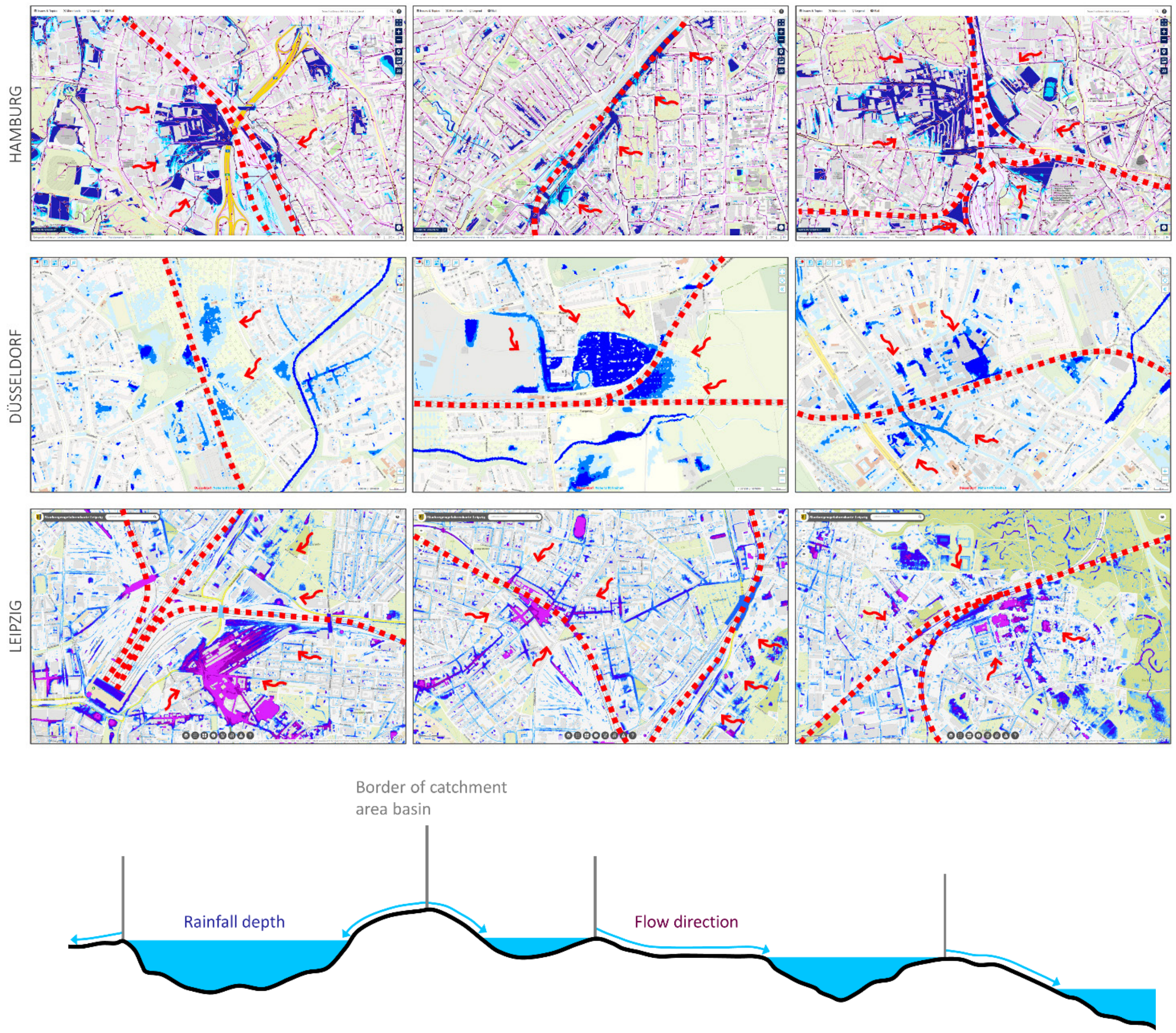


Fig. 2-22: Examples of heavy rain hazard maps from different cities, showing flood inundation areas influenced by railroad barriers (top) (Maps: Heavy Rain Warning Map, 2020; 2021b,c). A concept diagram of flow paths and water depths in relation to barriers (bottom), by author based on (BUKEA, 2022)

depressions or areas obstructed by buildings and walls.

To determine potential flood risk, water levels were calculated for different rain scenarios corresponding to rainfall intensities ranging from 30- to 100-year occurrences. The resulting water levels were classified into several categories, typically ranging from low to extreme. For instance, the categories could include low (up to 10 cm), moderate, high, very high, and extreme (greater than 50 cm or 75 cm). Maps illustrating these categories are available for public access on the respective cities' online geoportals.

By analyzing these maps, the relationship between surface runoff and various urban barriers can be identified. Figure 2-22 exemplifies repetitive cases observed in each city of a significantly higher severity of flooding near extended railroads compared to areas without such barriers. Furthermore, other examples in Figure 2-23 demonstrate instances where major roads are flooded, resembling canals flow that convey water along their length. Conversely, roads in other locations can also function as barriers, leading to the accumulation of water at one or both sides.

Further observations indicate that crossings along extended barriers often serve as breakpoints and are the most susceptible points to flooding, exhibiting the highest water depths in several observed cases.

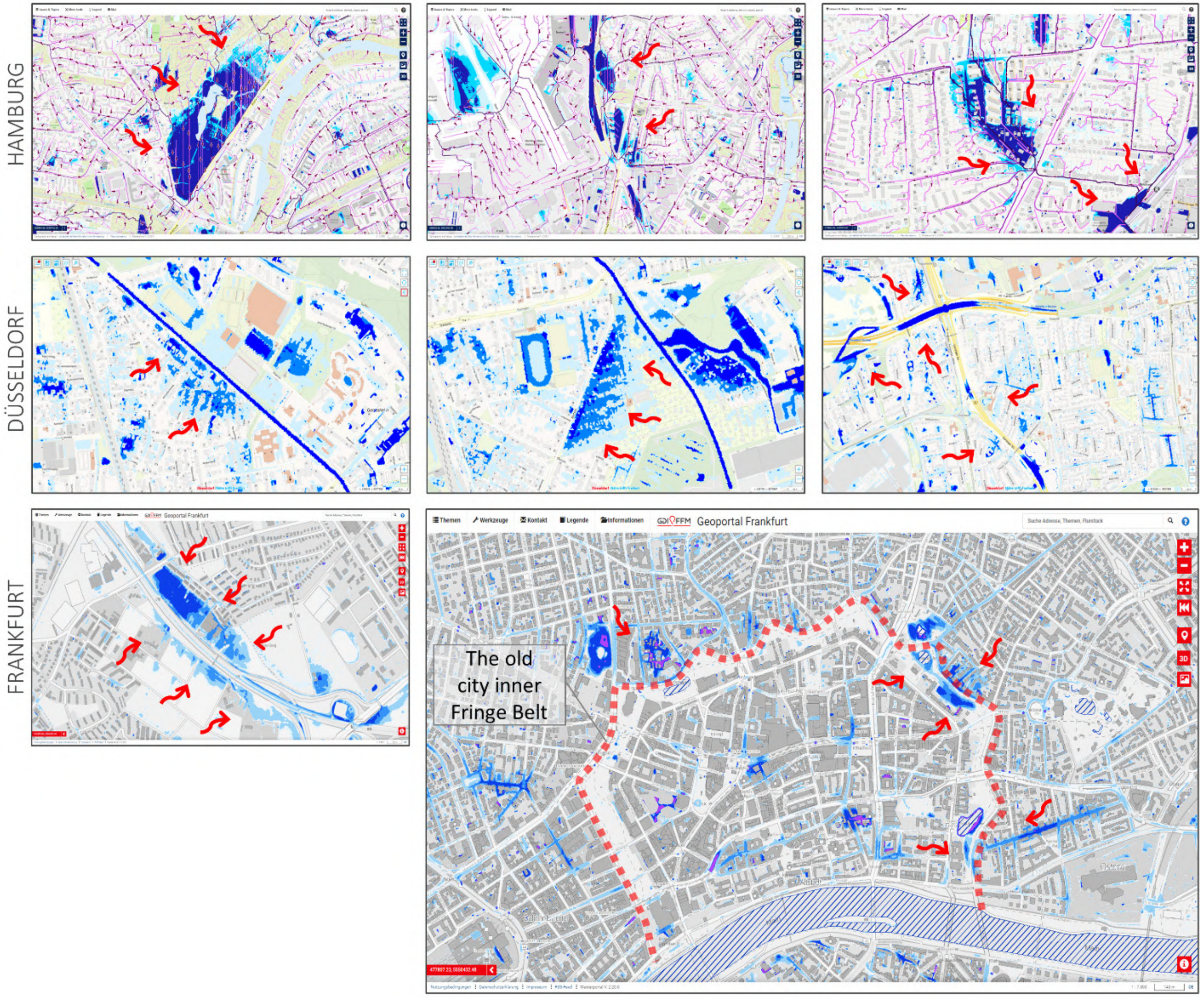


Fig. 2-23: Examples of heavy rain warning maps from different cities showing flood inundation areas influenced by main roads and green belts (Maps: Heavy Rain Warning Map, 2021a,b,c)

An interesting instance depicted in Figure 2-23, from the heavy rainfall map of Frankfurt, illustrates the accumulation of water along the inner and outer boundaries of the historical old city wall, now transformed into a green park encircling the city center. This specific case exemplifies a significant association with the concept of the fringe belt, as previously discussed in this section, serving as an urban barrier and influencing flood occurrence. Nevertheless, it is important to note that not all areas near fringe belts would necessarily be threatened, as other factors of slope, and elevation of the area contribute to determining their potential impact.

The third supporting evidence involves direct observation of extreme flooding events in Alexandria and in various cities in the region. As depicted in Figure 2-24, the imagery captures instances where runoff accumulation during heavy rainfall is obstructed by various barriers. Reports of flooding associated with existing walls are consistently reported across different city locations in the region.

These observations serve to reinforce the hypothesis that urban form and physical barriers play a significant role in contributing to flooding in the urban context of the MENA region. Furthermore, they potentially address a key research question in this dissertation, which seeks to identify the most suitable planning approach that can address the given urban challenges in this region. The concept of urban hydrological regions emerges as a systematic planning approach to mitigate flooding and potentially facilitate the adoption of WSUD concept.

On the other hand, opposing perspectives may argue that the limitations inherent to these observations prevent them from providing a comprehensive context and a full extent of the relevance of this phenomenon across various urban areas. They can potentially be susceptible to observer bias due to selective case selection. Furthermore, visual depictions might fail to capture all factors contributing to flooding in these specific locations, thus introducing subjectivity to interpretations. Demonstrated instances of flooding related to extended barriers may be confined to specific geographic locations and could lack generalizability on a citywide scale or broader phenomenon within urban areas.

Despite that each individual piece of evidence alone might not suffice to establish definitive conclusions. Yet, collectively examining them could offer validation and even suggest the possibility of this occurrence in other urban and climatic settings. Notably, the prevalence of boundary walls and various physical barriers in the region could magnify the likelihood of such causal relationships. This composition of theoretical and empirical evidence has the potential to provide validation to the observed phenomena, offering a foundation for subsequent in-depth investigations.

Overall, it is crucial to recognize that runoff is a multifaceted phenomenon, influenced by diverse factors encompassing terrain elevation, street alignment and surface cover. The degree of impact imposed by barriers on flooding may significantly vary based on the specific context and concurrent variables. Therefore, it is essential to comprehensively address the complexities associated with urban barriers and their hydrological implications on a broader scale across different urban settings. A combination of quantitative and qualitative methodologies is required to investigate the impact of wall and fence density within urban domains, as well as the ramifications of cul-de-sac street configurations and street orientation in relation to urban flooding. Within the confines of this dissertation, these aforementioned areas will be examined within the context of Alexandria City, serving as a showcase study.

Fig. 2-24: Images from various cities, in addition to Alexandria, picturing flood inundation in areas along boundary walls

Photos: Tripoli (Alwasat Gate, 2022), Nabeul (Fethi Belaid, 2018), Amman (M. Hamed, 2019), Abu Dhabi (Khaleej Times, 2020), Alexandria (Youm7, 2020)


Tripoli, Libya (2022)


Nabeul, Tunisia (2018)


Amman, Jordan (2019)


Abu Dhabi, UAE (2020)


Alexandria

3 WSUD IN DRY CLIMATE

3.1 Background

Stormwater management in traditional urban catchments has been largely approached by rapidly draining runoff out from urban areas using a combination of subsurface pipelines and engineered surface streams. Preventing the negative consequences of water inundation on the active use of public space and the potential threat to public safety was the main driving goal. As such, stormwater runoff has been perceived as a nuisance that requires immediate removal, without any value to the amenity or a role in the management of urban water resources.

These conventional methods of stormwater management, however, have been increasingly failing in several urban contexts. Exacerbated by climate change, increased runoff volumes and rates contributed to a surge in pollutants like litter, sediment, heavy metals, and nutrients entering natural water bodies. This escalation in pollution has severely impacted the ecological health of these environments, leading to degradation of waterways, indicative of the unsustainable impact of traditional urban development on ecosystems.

By acknowledging the impact of conventional urbanization on ecosystem degradation, an evolution of stormwater management has been marked by a changing focus towards integrating stormwater quality into overall stormwater management practices (Fig. 3-1). This transformation has been driven by the understanding among professionals that managing both the volume and the quality of stormwater runoff is essential for preserving the ecological health of natural environments. Many cities in Australia, North America, Europe, and East Asia have adopted stormwater quality regulations into their management practices.

Toward the end of the 20th century, there was even an increased awareness of the need for a fundamental shift in urban planning and design that harmonizes with the total urban water cycle. This holistic approach deals with stormwater as a valuable resource and aims at integrating stormwater management into all stages of urban development through an interdisciplinary and multi-objective approach. Instead of focusing solely on flood prevention, stormwater management can also prioritize conserving stormwater as a resource, protecting the health of receiving water, and improving the amenity and aesthetics within the built environment (Fig. 3-2). Yet, the approach has been progressively extending its purpose to tackle climate risks of heat stress and urban drought by putting further emphasis on wastewater treatment and reuse, and urban cooling (Wong, 2006).

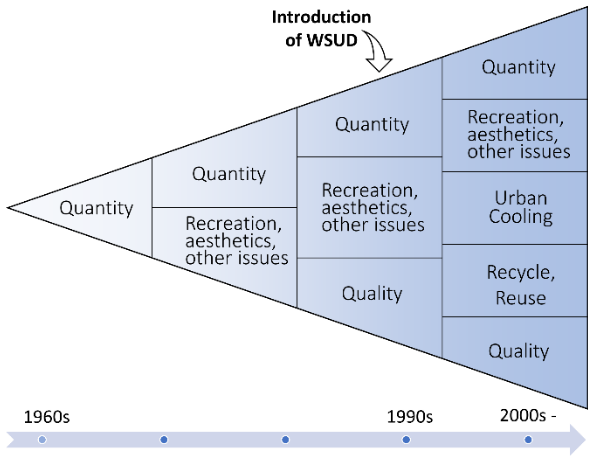


Fig. 3-1: The evolution of stormwater management over the past decades, showing changes in focus from only flood prevention (as quantity) to addressing further diversified aspects and the introduction of the WSUD concept, by author based on (Roy et al., 2008; Whelans, 1994)

One of the earliest global initiatives advocating for this paradigm shift emerged in Australia during the 1990s and is known as Water Sensitive Urban Design (WSUD). WSUD is an approach to urban planning and design that integrates water management within the urban landscape to mimic the natural water cycle. It seeks to mitigate the hydrological impacts of urban development on the built and natural environment (Wong, 2006). WSUD employs all components of the urban water cycle, including fresh water, stormwater, wastewater, and groundwater, in conjunction with other urban infrastructure. The approach recognizes the necessity of interdisciplinary collaboration among urban planners, architects, landscape architects, engineers, ecologists, and hydrologists. It encompasses not only the technical aspects of water management but also considers the social, economic, and ecological dimensions of sustainability (Lloyd et al., 2002).

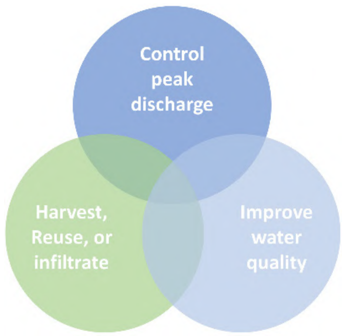


Fig. 3-2: Potential overlapping volume management design objectives, by author based on (AR&R 2019)

3.2 The Concept of WSUD

The concept of Water Sensitive Urban Design (WSUD) has grown beyond its initial focus on stormwater management to encompass a comprehensive framework for sustainable urban water management. The term WSUD was likely first used in Australia in 1994, when Whelans (1994) developed guidelines for residential planning that emphasized the protection of aquatic environments. WSUD integrates the urban water cycle with the constructed form of the city in a cohesive and standardized manner. It is increasingly adopted in new developments in urban greenfield areas and revitalization projects. The core of WSUD is to develop urban systems that are resilient to climate change, efficient in water use, and that regard water as a valuable resource that contributes to the livability of cities, the health of ecosystems, and community well-being (Wong, 2006).

The effective implementation of WSUD involves innovative mechanisms to utilize the integration of Best Management Practices (BMPs) of urban water systems with urban planning and design (Fig. 3-3). Best Planning Practices (BPPs) guide the overarching urban development, ensuring that sustainable water management technologies are embedded within the spatial planning and policy formulation. This method emphasizes the proactive approach to urban design, where water management is considered at the early stages of planning to facilitate the incorporation of WSUD principles into the urban fabric. On the other hand, BMPs focus on the selection of specific techniques and technologies for water conservation, quality enhancement, and sustainable urban drainage. These include techniques such as rainwater harvesting, biofiltration systems, and methods for detention and infiltration.

The incorporation of BPPs and BMPs establishes a comprehensive framework that aligns strategic urban planning with water management practices. This approach underscores the cross-disciplinary and decentralized base of the WSUD concept, paving the way for the development of resilient urban ecosystems that can respond to the pressures of climate change and urbanization, while also enhancing the quality of life for urban inhabitants.

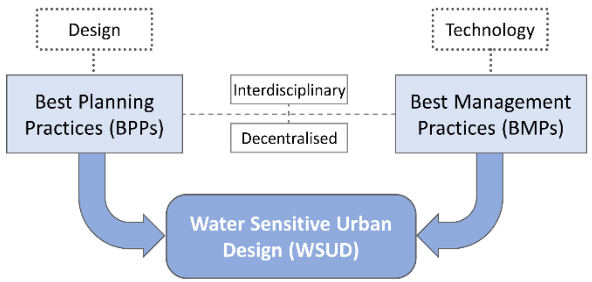


Fig. 3-3: Incorporation of Best Management Practices and Best Planning Practices in WSUD (Lloyd et al., 2002; Whelans, 1994)

Water Conservation and Reuse	Wastewater Management	Stormwater Quality and Utilization
Enhance water efficiency by reducing reliance on potable water, promoting the use of alternative water sources.	Treat wastewater to standards suitable for reuse and safe discharge.	Treat urban stormwater to meet water quality objectives, facilitating its reuse or safe discharge
Climate Resilience	**Ecological Enhancement and Biodiversity**	**Integrated Water Sensitive Design**
Implement adaptive measures to mitigate flooding risks and reducing the urban heat island effect through the strategic use of stormwater.	Establish green infrastructure to improve habitat and biodiversity and protect natural water systems within urban environments.	Incorporate stormwater management into the urban landscape to enhance visual and recreational amenities.

Fig. 3-4: Key objectives of Water Sensitive Urban Design (WSUD), adapted from (Lloyd et al., 2002; Wong, 2006)

The key objectives of WSUD include conserving and reusing water to decrease dependence on potable sources, managing wastewater to meet reuse and safe discharge standards, and treating stormwater to enhance its quality for reuse or safe discharge. WSUD also aims to increase climate resilience by implementing adaptive measures for flooding and urban heat, enhancing ecological diversity and habitat through green infrastructure, and integrating stormwater management into urban designs to improve aesthetics, recreational value, and ecological health while minimizing runoff and impervious surfaces (Fig. 3-4).

The significance of an interdisciplinary approach in WSUD stems from the realization that it is necessary to bring together different expertise from fields such as urban planning, engineering, landscape architecture, ecology, and social science in order to achieve effective results. The convergence of different fields of knowledge enables the development of holistic and innovative solutions. By bringing together perspectives from different disciplines, WSUD initiatives can more effectively address complex issues such as climate change adaptation, urban biodiversity, and community well-being. In addition, the involvement of stakeholders from different sectors encourages the sharing of insights and promotes a sense of ownership in the implementation and success of WSUD projects. Therefore, the interdisciplinary approach is fundamental to realizing the full potential of WSUD.

I n terms of decentralization, WSUD advocates for managing water at a local site and development scale rather than relying solely on centralized infrastructure. By managing water closer to where it is generated, decentralized systems can mimic the natural water cycle to strengthen the resilience of water services against droughts and climate change. Decentralized systems can reduce stress and supplement the capacity of centralized infrastructure. These decentralized systems, including rain gardens, permeable pavements, and green roofs, offer customized solutions that can be tailored to specific local conditions and needs (Sharma et al., 2010).

Decentralized urban water systems refer to the management and treatment of water through a distributed network of small-scale installations and practices within an urban setting, rather than through centralized, large-scale infrastructure. These systems handle the collection, treatment, and reuse of stormwater and wastewater close to their source.

3.3 Global Perspective

The transition to a more holistic and integrated approach for urban water management has been widely adopted around the world, though it is recognized by different names across various countries. In North America, concepts like Low Impact Development (LID) and Green Infrastructure (GI) have been formulated, while the United Kingdom has introduced Sustainable Urban Drainage Systems (SUDS). Australia is known for Water Sensitive Urban Design (WSUD), and China for its Sponge City initiative (Radcliffe, 2019). These terminologies, among others, have gained widespread acceptance and are used internationally, extending beyond their regions of origin (Fletcher et al., 2015; van Leeuwen et al., 2019).

Fletcher et al. (2015) observe that despite the considerable overlap among these terms, there are subtle differences in their application depending on the development characteristics of each region and local institutional context. They point out that all concepts generally align with two core principles: mitigation of the hydrological impacts of urban development and enhancing water quality. Nonetheless, they could possibly be classified according to their specificity and primary focus. Some terms initially describe technical water management techniques or practices, such as BMPs and SUDS. Others, such as WSUD and LID, adopt a more holistic approach, expanding their focus to include the whole urban water cycle (Fig. 3-5).

Moreover, Green Infrastructure (GI) and Water Sensitive Urban Design (WSUD) terminologies are increasingly being adopted globally for their inclusive approaches, which utilize natural processes to establish mechanisms for development. The term Nature-Based Solutions (NBS) has newly emerged as an umbrella term that provides specific technical solutions within broader principles applicable to both built and natural environments (Moosavi et al., 2021). However, Fletcher et al. (2015) emphasize the dynamic nature of these terminologies, noting that their definitions and classifications are subject to evolution over time. This ongoing

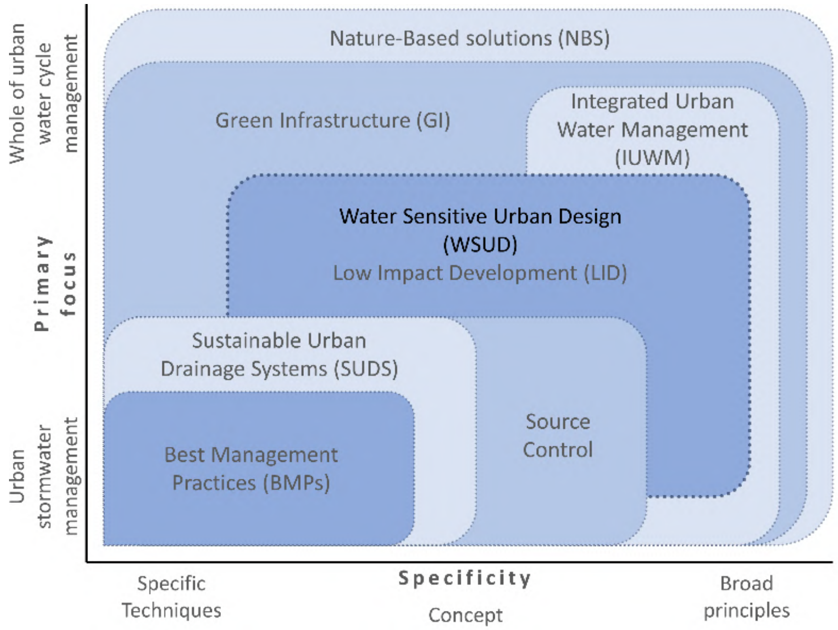


Fig. 3-5: Relationship of WSUD alike approaches according to their specificity and their primary focus, adapted from (Fletcher et al., 2015)

evolution reflects the adaptability and broadening scope of strategies designed to integrate ecological processes into urban planning, highlighting the continual development and refinement of concepts in the field of urban water management.

As illustrated in Figure 3-6, WSUD is predominantly implemented in developed, humid climates. In contrast, dry climates primarily see WSUD practices in Australia and the southwestern United States. Most dry regions across Asia, Africa, and South America continue to face significant challenges in urban water management and are increasingly impacted by rapid climate change. Transferring WSUD knowledge and practices from Australia and the southwestern United States to other dry regions, particularly in the Global South, offers a crucial opportunity to enhance water security, urban resilience, and ecological sustainability. This transfer aims to foster a shift towards more sustainable urban water management and enhance resilience in dry cities, thereby ultimately promoting an exchange of sustainable practices between these regions.

Australia, characterized by its predominantly dry landscape and the highest variability in rainfall and streamflow globally, is particularly relevant to this dissertation's focus. Thus, it is the primary best practice reference study within the scope of this work.

Australia's climate is notably diverse: the central and western plateaus experience a hot desert climate, while the east and southeast coasts have an oceanic climate. The northern coast is subject to a monsoon climate, the southwest coast enjoys a warm-Mediterranean climate, and the intervening areas feature a hot semi-arid climate. This diversity in climatic conditions necessitates different WSUD approaches. In humid regions, the primary aim of WSUD is to mitigate flooding risks associated with the high all-year rainfall. In dry regions, in contrast, the emphasis is on water security to address the challenges of scarce rainfall and drought conditions.

This diversity in WSUD approaches is reflected in the varying policy focuses of the five state planning policies in Australia. As summarized by Choi and McIlrath (2017), Table 3 highlights that, alongside water quality protection, flood management is a primary policy focus in

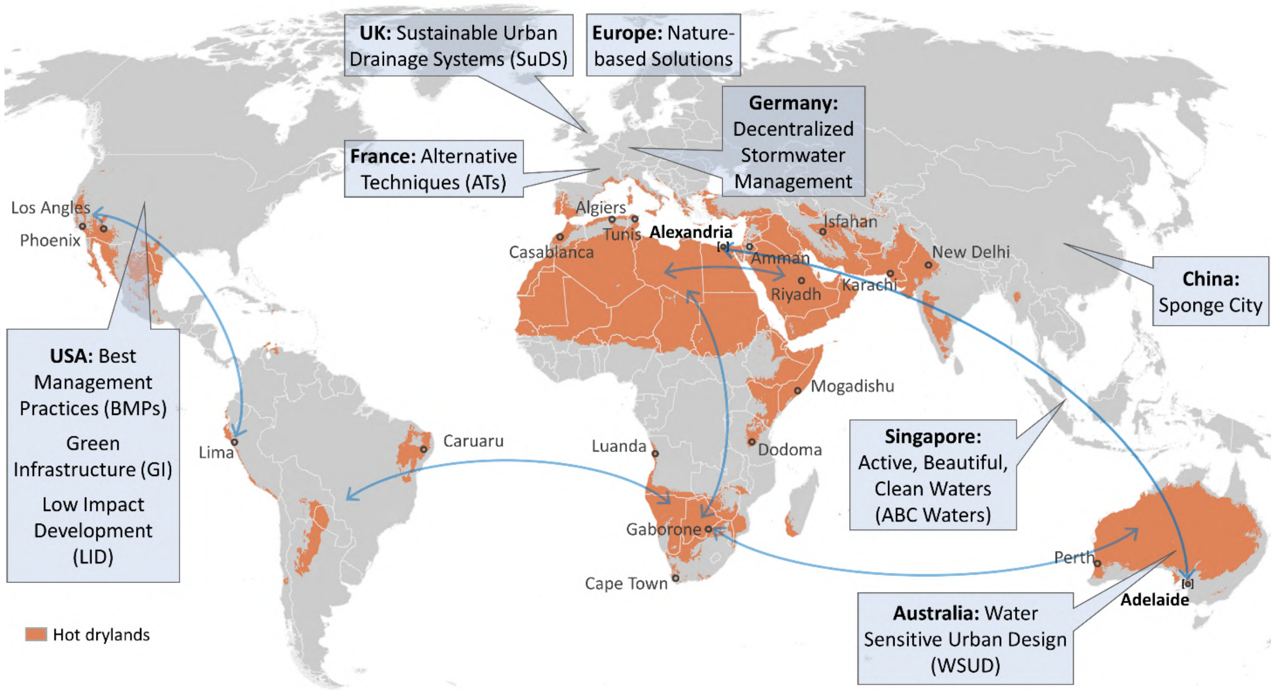


Fig. 3-6: WSUD alike approaches globally, highlighting a required dry environment exchange, by author based on (Fletcher et al., 2015; van Leeuwen et al., 2019)

Queensland and Victoria, whereas water conservation and rainwater harvesting are prioritized in South Australia and New South Wales. Of all the Australian capital cities, Adelaide, in South Australia, has the longest consecutive dry periods. This implies that the WSUD requirements for Adelaide are likely to differ from those in other parts of Australia. This variation has an impact on the supply needs for rainwater tanks to the irrigation requirements of vegetated systems. While this does not rule out the use of vegetated systems in the city, it does highlight the need for additional solutions to adapt to the prolonged dry periods (SA Govt, 2010).

Table 3: Comparison of overarching State Planning Policy on WSUD in Australia (Choi & McIlrath, 2017).

State	Policy focus
Queensland	Flood management and protection of water quality
New South Wales	Water conservation and protection of water quality
Victoria	Flood management and protection of water quality
South Australia	Water conservation, stormwater harvesting and surface water protection
Western Australia	Aquifers and surface water quality

3.4 Impediments and Potentials

While Water Sensitive Urban Design (WSUD) offers a promising framework for sustainable urban water management, its implementation is often challenged by a variety of factors, including financing limitations, community engagement issues, complexity of stakeholders, and the need for supporting policies. Beyond these general impediments described extensively in the literature, the adoption of WSUD technologies faces unique challenges when applied to the specific urban and climate context of dry regions. The distinct characteristics of the built environment in dry climates, which differ markedly from those in temperate and tropical climates, necessitate an elaborated understanding and careful consideration of these challenges to ensure the effective deployment of WSUD strategies in such harsh environments.

3.4.1 Context Specificity

Cities within dry regions exhibit significant variability in their urban context, including differences in compactness, urban fabric, and infrastructure provision. This diversity requires tailored WSUD practices that are not only sensitive to the overarching challenges posed by dry climates but are also adaptable to the specific urban form and infrastructure capabilities of each city. Addressing the unique demands of these environments calls for a focused examination of the obstacles and opportunities inherent in adapting WSUD technologies to local climates, urban forms, and infrastructure systems. By acknowledging and navigating these complexities, cities can develop more resilient and water sensitive urban areas that are better equipped to thrive in dry conditions.

Local climate: The dry climates, marked by extended droughts and infrequent rainfall, pose challenges for the adoption and functionality of WSUD technologies. These conditions particularly affect vegetated WSUD systems, which must withstand the cycles of wetting and drying while maintaining their treatment efficacy and aesthetic appeal. Water scarcity in these regions necessitates WSUD solutions that can effectively harvest and retain rainwater. However, high temperatures complicate water quality management, promoting algae growth and mosquito breeding in water retention basins, which can degrade water and pose health risks. Additionally, the dry built environment is prone to high sediment and pollutant loads, making water treatment more challenging. This requires robust pollutant control measures and the use of treatment technologies that can perform effectively under such conditions, addressing both standard and exceptional pollutant levels.

Varying urban form: Adapting WSUD to various urban forms presents a significant challenge, particularly in the dry MENA regions. The prevalent view is that WSUD practices are best suited to less compact, lower-density developments typically found in North American and Australian suburban communities. This perception contradicts the sustainable urban development goals advocating for denser urban areas. Interestingly enough, a city like Adelaide has successfully integrated WSUD while focusing on growth within their existing urban footprint, notably increasing the proportion of infill development relative to new developments on the urban fringe (Bradley et al., 2021).

In contrast, the densely populated cities of the MENA region and other parts of the Global South face distinct challenges with WSUD adoption due to space constraints. In Alexandria, for example, local officials and professionals have expressed concern for the extensive space demands of WSUD technologies, given the limited availability of land in the city's high-density areas. This situation calls for innovative approaches to integrate WSUD strategies without compromising the dense urban fabric.

Local infrastructure provision: The provision of infrastructure, particularly in terms of water management, varies widely between countries in the Global North and the Global South, imposing distinct challenges for the implementation of WSUD. In many areas of the Global South, drainage infrastructure development has not kept pace with urban growth, leading to significant deficiencies. The inadequate provision of drainage systems increases vulnerability to flooding and also complicates the integration of WSUD technologies that rely on existing infrastructure to function effectively.

Additionally, the lack of green and open spaces in densely populated urban areas further exacerbates the challenges of implementing WSUD. Green spaces are crucial for the success of WSUD strategies as they provide natural areas for rainwater infiltration and biofiltration. The absence of these spaces limits the opportunities to incorporate ecological solutions for water management, such as rain gardens and permeable pavements, which are vital components of the WSUD approach.

Socio-cultural: Socio-cultural differences significantly influence the acceptance and effectiveness of WSUD. Cultural practices, beliefs, and community structures can dictate water usage and management, which may pose challenges when introducing WSUD technologies that alter these traditions. For instance, in communities where water has symbolic significance, proposals to reuse or recycle wastewater can be met with skepticism or resistance, stemming from negative perceptions about purity and safety. These cultural barriers can hinder the adoption of WSUD practices designed to conserve and manage urban water (Sharma et al., 2012).

The considerable variability of local conditions from different climates and regions not only highlights the need for tailored WSUD solutions but also underscores the broader challenges of urban environmental management in different global contexts.

3.4.2 Technological and Knowledge Gaps

In many regions, especially in less developed countries, there is a lack of access to the technologies required for effective WSUD implementation. This includes tools necessary for the capture, storage, and treatment of water, as well as tools for monitoring and managing urban water systems. The absence of these technologies and a deep understanding of WSUD principles among local professionals limits the adoption of WSUD solutions. Additionally, there is often a significant gap in the necessary expertise for proper design, implementation, and maintenance of these systems.

Contractors and maintenance teams frequently lack familiarity with WSUD technologies and principles, leading to issues in construction and ongoing operation. This lack of familiarity can result in WSUD systems that are improperly maintained and therefore less effective (AKBC, 2012). For instance, landscape architect Stephanie Rogers highlights a common scenario where there is a disconnect between the local government implementation and maintenance teams in Adelaide city. Maintenance teams might not be fully aware of how to care for specialized plant species in rain gardens, eventually replacing them with general, less effective species (Interview, 2022).

Institutional capacity also poses significant challenges. Local governments lack the experience needed to integrate WSUD into urban environments effectively. They often do not have the necessary resources, including funding, personnel, and guidelines, to support WSUD initiatives. Most engineers, architects, and landscapers are not trained to incorporate WSUD within engineering specifications and design guidelines, which hinder the adoption and integration of these practices into standard urban development processes (Roy et al., 2008).

Moreover, the typical deficit of critical data required for the planning and implementation of WSUD strategies further complicates WSUD implementation (Myers et al., 2014). This includes the following:

- Insufficient data on designing and implementing strategies that consider the unique climate of dry cities.
- Inadequate information on plant species suited for the dry local climates and soils for WSUD applications.
- Absence of comprehensive city-wide geomorphological analysis and surveys to assess soil infiltration capabilities.
- Limited data concerning the variations and intensities of rainfall, as well as heat maps.

Overall, to effectively tackle the challenges of implementing WSUD across varied urban and climatic conditions, a comprehensive strategy is essential. This includes understanding the specific needs of each region through detailed urban assessments and the involvement of local experts, which helps tailor WSUD practices to accommodate different urban contexts and infrastructure capabilities.

Promoting the exchange of knowledge and best practices from regions that have successfully integrated WSUD in Australia and the Southwest USA, can provide valuable insights for similar dry environments in the Global South. This facilitates global collaboration and adaptation of proven strategies to local contexts.

Also, investing in the advancement of WSUD technologies and enhancing professional education are crucial. Collaborations between academia, industry, and government can spur innovation, while integrating WSUD into educational curricula builds capacity in the design and construction sectors. Additionally, comprehensive training programs aimed at all levels of government and industry could potentially support the widespread adoption of WSUD, helping professionals understand its applications and limitations. Furthermore, establishing partnerships with academic institutions, international development agencies, and the private sector is also vital. These partnerships can help bridge technological and financial gaps, facilitating technology transfer and providing the necessary resources for adopting advanced WSUD tools.

Lastly, creating supportive resources like a national information database can coordinate research and educational efforts, making it easier for professionals to access the latest findings and apply WSUD principles effectively. Through these integrated efforts, regions can develop resilient, sustainable urban water systems that are well-adapted to both local and global environmental challenges.

3.5 WSUD Components and Strategies

WSUD solutions, though well-established and widely implemented in humid regions, are less commonly adopted in dry areas. This section focuses on the adaptability and effectiveness of these solutions in dry climates, specifically examining how they can be tailored to the unique conditions of the MENA region's hot and dry climate. This examination aims to address a central question of this dissertation: How can

WSUD technologies be customized to function effectively in dry conditions?

The discussion is divided into two main parts. The first part explores the various water management techniques used in WSUD, covering the range of functional processes by which water is managed in urban settings (e.g., detention, retention, treatment, infiltration, and urban cooling). The second part reviews the specific structural technologies or systems that are installed to achieve the desired water management techniques (e.g., bioretention, swale, wetland, etc.). It is also worth noting that each system often serves multiple functions, leading to overlaps that can complicate their categorization under different techniques. For instance, bioretention may not only treat water but also support infiltration, detention, or even aid in urban cooling.

A key principle of WSUD design is to first identify the techniques that best meet the specific goals for managing water at a development site. Once these techniques are strategically set, the next step is to select from various WSUD systems that can effectively provide the required function. Usually, there is not just one perfect solution; instead, several options might work well based on the site's specific conditions and context. The best approach usually involves combining several systems together, creating a sequence that works as a unified water management strategy. This combination is often referred to as a "WSUD management train".

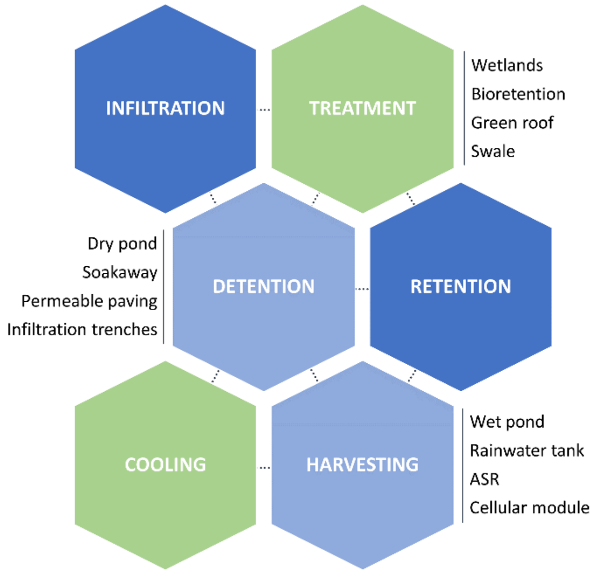


Fig. 3-7: WSUD techniques and technologies (by Author)

3.5.1 Treatment

Water treatment involves enhancing the quality of water before it re-enters the urban water cycle or is used for non-potable purposes. This step is crucial because untreated stormwater contains pollutants that can contaminate receiving water bodies and degrade urban water quality. Since no single method can remove all pollutants and nutrients from runoff, a combination of methods known as a treatment train is used. The design of a treatment train, which involves selecting and sequencing treatments effectively, is vital. Initial treatments typically remove larger pollutants to enhance the efficiency of subsequent processes targeting finer contaminants. Factors including the proximity of treatments to pollution sources and their distribution across a catchment area are also important (Goonetilleke & Lampard, 2019). A comprehensive treatment train incorporates various methods:

- Screening: Includes pretreatment litter traps and gross pollutant traps.
- Sedimentation: Uses basins, ponds, and shafts to settle particulates.
- Filtration and Biological Uptake: Employs biofiltration systems and constructed wetlands.

Screening and sedimentation are engineered treatment technologies designed to optimize the removal of larger pollutants through controlled physical processes. In contrast, filtration and biological uptake are nature-based technologies that integrate into the landscape, using plants and soil to physically filter particulates and biologically degrade pollutants (Fowdar et al., 2018).

Nature-based treatment technologies not only manage water but also enhance aesthetics and provide wildlife habitats. These systems generally require less energy and maintenance. However, they face challenges in dry climates due to extreme heat, high evapotranspiration rates, and sporadic, minimal rainfall, which complicate sustaining healthy plant growth in biofiltration systems or constructed wetlands. Solutions include using drought-resistant plants, implementing shade, utilizing alternative water sources, and integrating smart irrigation systems to maintain the systems' viability and effectiveness.

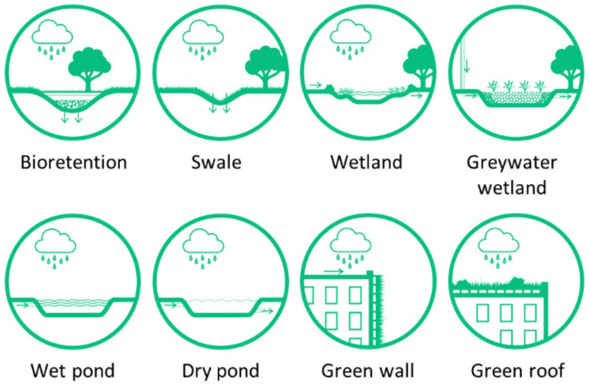


Fig. 3-8: WSUD technologies that provide treatment processes

Another constraint is the need for significant surface space, as seen with constructed wetlands, which urban areas often lack. More scalable options like bioretention cells and green walls, which require minimal space, can adapt better to urban environments. Additionally, high levels of sediments and pollutants typical in dry climates increase the risk of media clogging, hindering water entering subsurface layers (Goonetilleke & Lampard, 2019).

In dry climates, the urban drainage systems are significantly affected by the long dry seasons or the extended intervals between rainfall events, leading to substantial pollutant accumulation. As a result, the first rainfall of the season often carries stormwater with higher concentrations of pollutants compared to subsequent rainfall events. This phenomenon is known as the 'First Flush' (H. Lee et al., 2004). Effective stormwater management practices address this issue through engineered measures designed to reduce various pollutants (Goonetilleke & Lampard, 2019). These are:

Gross Pollutant Traps (GPT): These devices remove solids larger than 5 mm, such as litter and debris, from runoff. Available in various styles like Gully baskets, trash racks, and floating litter traps, GPTs help reduce sediment and litter in downstream treatments, optimizing maintenance.

Sediment Traps: Positioned in areas with high sediment loads, these ponds or chambers prevent sediments from clogging downstream devices like wetlands and bioretention cells. They provide essential retention time for sedimentation and help manage peak flow conditions by temporarily storing stormwater.

Sediment Grooves and Litter Guard Inlets: These techniques collect sediments before they enter bioretention systems, ensuring long-term functionality without frequent sediment removal or filter media replacement (Fig. 3-9).

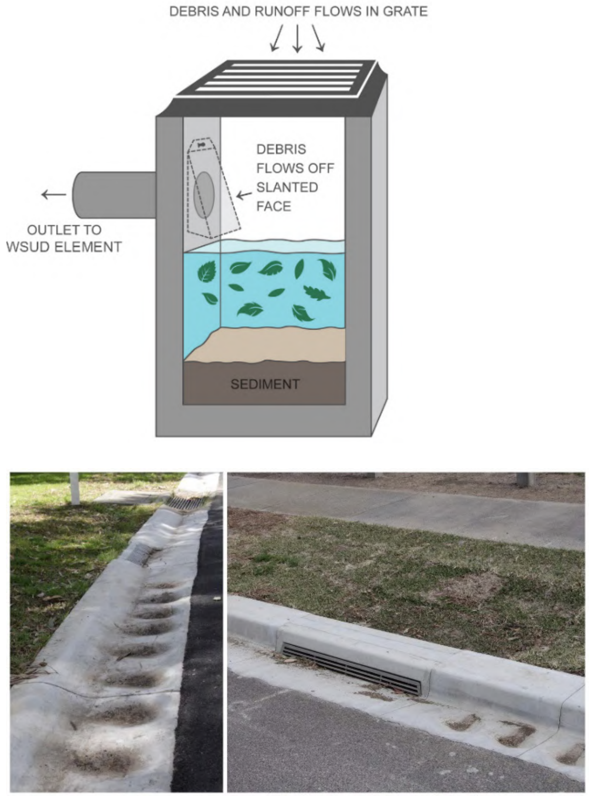


Fig. 3-9: A schematic of a sediments and litter settling chamber (top) Adapted from (KwikTrap, 2016) . Inlet grates and sediment groves in Melbourne, Australia (bottom) (CRC, 2017)

> Recognizing both the seasonal first flush and the initial flush within a storm event is crucial for the effective management and treatment of stormwater. However, Bruce Naumann added, “It is actually the end of the storm that carries the most pollution. This phenomenon, referred to as 'the sting in the tail,' occurs because chemical fertilizers, pesticides, and herbicides, which have saturated the soil, are pushed laterally into creeks and watercourses by the prolonged rainfall. Thus, the tail end of a storm, rather than the first flush, presents the most significant challenges.”
>
> (Interview, 2021)

3.5.2 Infiltration and Detention

Detention and infiltration are both critical stormwater management processes used to temporarily hold runoff, though they function differently in how they manage water discharge. Detention systems collect and store water temporarily, releasing it slowly at a controlled rate into downstream drainage systems. In contrast, infiltration systems allow stormwater to percolate into the soil, naturally filtering it and recharging groundwater supplies. Both processes play essential roles in urban areas to mitigate flooding and reduce peak flow impacts on urban infrastructure.

Detention and infiltration technologies can be broadly categorized based on whether they handle water at the subsurface or surface level.

- Subsurface systems may include infiltration trenches, soakaways, raingardens, geocellular modules and permeable pavement.
- Surface system may include infiltration basin, detention basin or dry pond, and open swales.

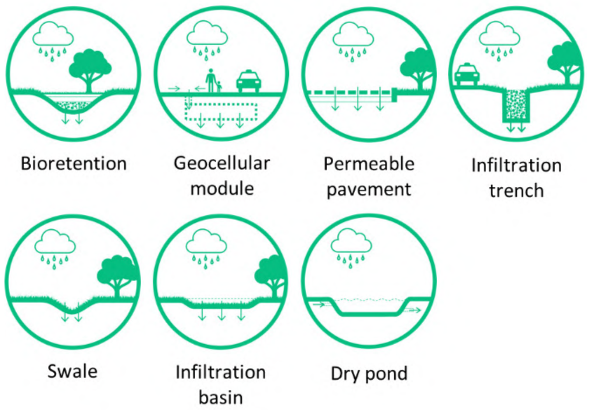


Fig. 3-10: Surface and subsurface WSUD technologies promote infiltration and detention

Subsurface detention and infiltration systems offer several advantages for urban areas. Firstly, they provide initial or comprehensive treatment of stormwater runoff, filtering pollutants before the water either infiltrates into the ground or is discharged into waterways. Additionally, because these systems are located underground, they are unaffected by the harsh surface conditions of dry climates, preventing evaporation and the proliferation of mosquitoes and algae. Subsurface systems are also space-efficient; they do not occupy valuable land on the surface, making them ideal for densely built environments where open space is limited. However, their capacity to manage large runoff volumes is limited compared to that of surface systems, making them less effective alone for significant storm events in areas with extensive impervious surfaces.

On the other hand, surface systems are well-suited to handling large volumes of runoff, making them effective during significant storm events. These systems can be innovatively designed and integrated into urban spaces to serve dual purposes; they can also provide valuable recreational and green spaces for community use. This multifunctional use of open space enhances urban livability while effectively managing stormwater. However, these surface basins often require some form of pretreatment, particularly when the runoff comes from mixed-use urban surfaces. In cases where runoff is collected from cleaner surfaces, like rooftops, the need for pretreatment can be reduced.

In dense urban areas, the key advantage of detention and infiltration systems lies in their ability to address space constraints through strategic design. Surface systems offer **multifunctionality**, serving as both water management solutions and recreational spaces, while subsurface systems minimize land take and efficiently utilize underground spaces without affecting surface area.

Fig. 3-11: A multifunctional basin for stormwater detention and recreational use in Adelaide, Australia (Water Sensitive SA, 2023).

3.5.3 Retention and Harvesting

Retention systems are engineered waterbodies including ponds, wetlands, and reservoirs designed to permanently hold surface runoff, unlike detention systems which do not maintain a consistent level of water. These systems aim to decrease the amount of runoff flowing into stormwater networks and to mitigate flooding. In dry climates, retention ponds and wetlands contribute to urban cooling by increasing evapotranspiration and thermal mass, which help moderate local temperatures and reduce the urban heat island effect. However, they may encounter specific challenges of water loss due to heightened evaporation rates, and potential water quality deterioration. Key issues that require careful management include the risk of mosquito breeding and algae blooms, both of which can adversely affect public health (Walker & Lucke, 2019).

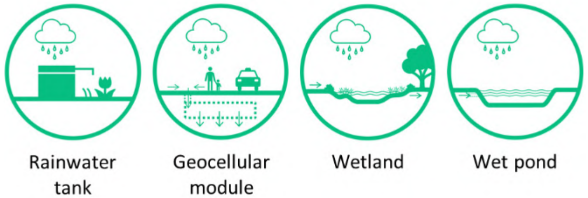


Fig. 3-12: WSUD technologies promote retention and rainwater harvesting

Mosquitoes present a significant challenge in wetland design, particularly in areas with shallow, stagnant water which serves as an ideal breeding habitat. In dry climates, warm temperatures can accelerate mosquito lifecycle processes, leading to rapid increases in populations. To mitigate this risk, Adelaide's technical manual (SA Govt, 2010) suggests several preventive measures, though not all may be applicable in every situation:

- Predator Introduction – Facilitate access for natural mosquito predators, such as fish and predatory insects, to all parts of the water body.
- Permanent Water Sumps – Create deep, permanent pools that provide refuges for predators during dry spells or when water levels are lowered.
- Water Aeration – Install aeration systems, such as floating fountains or submerged devices, to keep water circulating and prevent stagnation.
- Pollutant Control – Implement robust gross pollutant controls at inlets to prevent the accumulation of litter, which can offer additional mosquito breeding sites.
- Channel Maintenance – Ensure that overflow channels are free from depressions that retain water after storms, eliminating residual breeding grounds.
- Weed Management – Promptly remove aquatic weeds, which can harbor mosquito larvae attached to their submerged parts.

Furthermore, algae blooms in retention ponds can be exacerbated by high temperatures and nutrient-rich runoff, particularly nitrogen and phosphorus, which significantly promote their growth. These nutrients, along with organic pollutants from urban runoff, degrade water quality by decreasing oxygen levels through decomposition. The warm, shallow waters typical of retention areas, combined with the abundant sunlight in dry climates, further accelerate algae's photosynthesis and growth.

To effectively manage and prevent algae blooms, it is crucial to address both nutrient inputs and the ecological balance of the water. Strategies should include improving land use management to minimize nutrient runoff, installing vegetation buffers to filter incoming water, and implementing aeration systems to maintain adequate oxygen levels in the water. Continuous monitoring and adaptive management are vital to quickly mitigate factors that could trigger blooms (Walker & Lucke, 2019). Additionally, as highlighted by John Awad and Robin Allison in Adelaide ((Interview, 2021), pretreatment measures to reduce the nutrient load before it enters the retention system (e.g. Biofilters and floating wetlands) are essential for controlling algae growth and maintaining water quality.

Despite their urban cooling contribution, retention ponding systems in dry climates face significant challenges including high land demand and considerable evaporation losses. Additionally, these systems require proactive monitoring and management to mitigate risks associated with mosquito breeding and algae blooms.

Stormwater harvesting is a retention technique aimed at collecting and storing runoff from surfaces like roofs, driveways, and streets for later reuse. Typically stored in tanks, barrels, or underground reservoirs, this water can be used for various non-potable purposes such as irrigation, flushing toilets, and car washing, thereby reducing reliance on municipal water supplies and mitigating urban flooding. Harvesting schemes are highly dependent on the location, capacity, and type of storage used, which are crucial for their effectiveness. In urban areas, providing adequate storage space is a significant challenge due to high land costs and limited availability (Hamlyn-Harris et al., 2019). Storage solutions for stormwater harvesting include:

Tanks and Cisterns: These vary widely in size and material, from small polyethylene tanks to large concrete ones, suitable for above or below-ground use depending on space availability.

Geocellular Systems: Modular units, used under landscapes like playing fields. These systems offer flexible configurations and efficient space use.

Aquifer Storage and Recovery (ASR): This method involves recharging groundwater with harvested stormwater to be retrieved later for use, especially in maintaining green spaces and supporting irrigation during dry periods. ASR is feasible only where geological conditions permit, offering substantial storage capacity with a minimal surface footprint (Dillon et al., 2009). Urban stormwater harvesting, particularly through methods like ASR, has seen significant application in cities like Perth and Adelaide in Australia (Hamlyn-Harris et al., 2019).

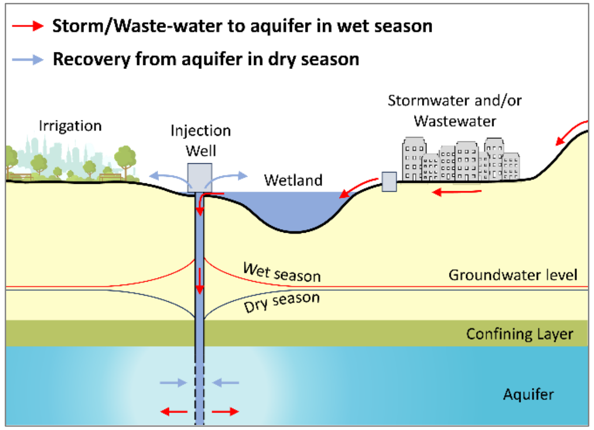


Fig. 3-13: Diagram of the Aquifer Storage and Recovery System at Parafield, by author based on (Dillon et al., 2009)

Condensate and dew harvesting is an additional potential source ideal for non-potable uses like irrigation and flushing toilets. In dry climates, significant amounts of condensate can be produced. Utilizing this condensate is particularly valuable in dry areas where water is scarce. Although installing condensate recovery systems adds about 3% to 5% to the cost of a building's mechanical systems, the potential water savings make it a worthwhile investment, especially in hot climates where AC units run almost continuously (A. Lee et al., 2012; Shahid & SARIM, 2020). Large-scale example project of Dubai's Burj Khalifa have successfully implemented these systems, highlighting their effectiveness in conserving water and supporting sustainable building practices (Fordred, 2010).

3.5.4 Urban Cooling

Urban Heat Island (UHI) is one of the most acknowledged impacts of climate change. The already dry built environment in the region will suffer from increasing climate extremes of higher temperatures and frequent heatwaves. The capacity of various WSUD applications to support urban cooling within urban environments is meant therefore to be harnessed (Rashetnia et al., 2022). WSUD techniques maintain water within urban landscapes, significantly lowering temperatures through enhanced evapotranspiration and surface cooling. These systems not only reduce ambient temperatures but also improve human thermal comfort, especially when combined with vegetation and trees (Jamei & Tapper, 2019).

According to Coutts et al. (2013), WSUD enhances urban cooling through three primary mechanisms:

- Enhanced Evapotranspiration – By creating moist surfaces, WSUD facilitates the natural process of evapotranspiration, which cools the air as water vaporizes.
- Vegetation Support – Provide essential water for vegetation, promoting cooling through both shade and the transpiration of plants.
- Surface Temperature Reduction – WSUD structures help lower the radiative temperatures of surfaces, making urban areas cooler.

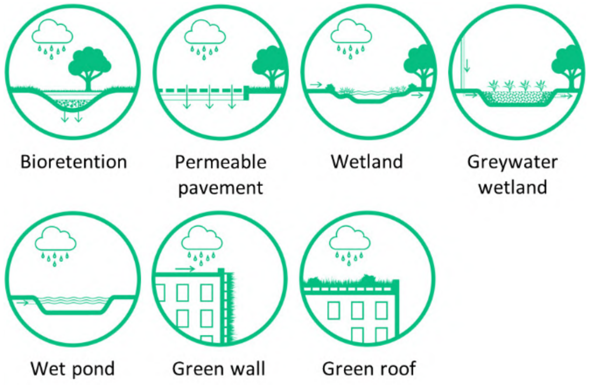


Fig. 3-14: WSUD technologies promote urban cooling

WSUD technologies like stormwater harvesting capture and store rainfall runoff, which can be used for irrigation. This not only conserves potable water but also increases soil moisture, further reducing ground surface temperatures and the overall urban heat load. The cooling effects are exemplified by urban wetlands and water bodies, which maintain lower surface temperatures due to their high heat capacity and the evaporative cooling from their surfaces.

Incorporating trees within WSUD designs or using harvested water to irrigate green spaces significantly lowers local temperatures. Research shows that trees can reduce the Urban Thermal Climate Index by up to 10°C, moving heat stress levels from 'very strong' to 'strong'. Strategic placement of trees in urban areas, considering their shade provision in relation to buildings, is crucial for maximizing this cooling effect (Gunawardena et al., 2017).

WSUD involves a variety of vegetated systems such as raingardens and wetlands, which should be strategically integrated into urban landscapes to mitigate heat. Distributing these elements throughout urban areas promotes infiltration and evapotranspiration, supporting the vitality of urban trees and vegetation. By employing adaptable architectural and landscape design, WSUD can be optimized to significantly enhance urban cooling and improve overall environmental quality.

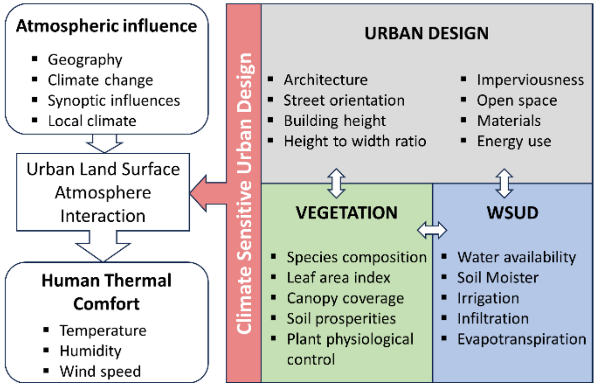


Fig. 3-15: Conceptual diagram illustrating the link between Water Sensitive Urban Design and the environmental factors that affect human thermal comfort, via Climate Sensitive Urban Design and the interactions between urban land surfaces and the atmosphere, based on (Coutts et al., 2013)

WSUD is pivotal in mitigating urban heat in dry climates through its sustainable water management practices that promote evapotranspiration and cooling by supporting vegetation and retaining water in urban landscapes. Strategic implementation and placement of WSUD systems, along with the maintenance of green spaces, particularly trees, are crucial for maximizing the cooling benefits across urban landscapes.

In summary, Effective stormwater treatment not only mitigates environmental risks but also expands the potential for the beneficial reuse of wastewater and stormwater in urban areas, which is a crucial advantage in regions facing water scarcity. By integrating advanced stormwater treatment strategies into urban planning, cities in dry climates can improve water efficiency, enhance public health, and increase resilience to climate variability.

Infiltration and detention systems require the least adaptation consideration to dry climates. They function effectively in various climates and could be incorporated in most urban areas. Further, it is worth mentioning that subsurface infiltration technologies such as trenches and geocelular systems are the most endorsed by interviewees from Alexandria, the case study.

Both mosquito management and algae control require proactive monitoring and maintenance to ensure that retention systems function effectively without posing health risks or environmental problems. Integrating these strategies into the design and ongoing management of retention water bodies in dry climates can help mitigate these risks and maintain the ecological and functional integrity of these systems.

In dry climates, the use of WSUD retention technologies like wet ponds and wetlands presents an ambivalence: while they offer evaporative cooling benefits that reduce urban heat, they also may suffer from significant water losses due to high rates of evaporation. This contradiction should not deter their implementation, but rather guide the strategic placement of these technologies. Decisions should be based on a comprehensive assessment of local microclimatic conditions, the characteristics of the urban landscape, and the specific challenges they aim to mitigate, ensuring that each installation maximizes its potential benefits while minimizing water loss.

What can be also inferred from this section is that although certain technologies are intrinsically more suited for dry conditions, others are required for essential functions. Detention and infiltration technologies, for instance, are easily adaptable with minimal modifications needed for optimal performance, yet they offer limited treatment capabilities. Conversely, vegetated systems provide treatment function but are more susceptible to heat and drought stresses. Surface retention systems, while effective, require substantial space and considerable ongoing maintenance. Therefore, it is suggested that the most effective approach generally involves utilizing these technologies in a complementary manner, tailored to local conditions to maximize their performance in achieving the planned goal.

3.5.5 Review of WSUD Technologies Adaptation

This section explores the adaptability of WSUD systems to dry climates, drawing upon literature, and practical experiences from case studies in Adelaide, Australia, with a specific focus on their technical manuals. Beyond the general descriptions and configurations extensively covered in existing resources, and in line with the primary scope of this dissertation, the discussion focuses specifically on the adjustments and considerations necessary for each system. This includes any aspects related to system design, structure, operation and maintenance, scalability, applications within the regional context, and possible limitations and potentials.

Permeable Pavement

Permeable pavement is a tiled surface of spaced blocks or grid that allow water to pass through into underlying layers. This technology has become a prevalent practice in urban areas globally, not merely functional for stormwater management but also contributing aesthetically and functionally to urban landscapes, serving both pedestrians and vehicular traffic. The typical system comprises permeable material laid on sand bedding and then a base course layer of crushed stone or gravel. This configuration is broadly suitable across various climates, requiring minimal location-specific adaptations.

Permeable surfaces are recognized as a source control measure for rainwater, significantly reducing runoff peak times by decreasing surface flow velocity. The system functions by temporarily holding and filtering stormwater through its bedding and base course layers, then allowing water to gradually infiltrate into the subsoil and recharge the groundwater. In dry regions, where rainfall is sporadic, design modifications may include a focus on capturing and utilizing the limited rainwater, possibly integrating with rainwater harvesting systems.

This adaptation involves enhancing the retention capacity of the base course layer using a membrane liner and incorporating a perforated collection pipe system connected to an underground tank.

However, a primary concern with permeable pavements is the potential reduction in infiltration capacity over time, often due to clogging from accumulated sediments and pollutants, particularly in sandy environments with sparse vegetation and a seasonal rainfall regime (Amirjani, 2013). Regular maintenance, including vacuum sweeping and pressure washing, is essential to maintain the surface's porosity. However, this maintenance requirement could

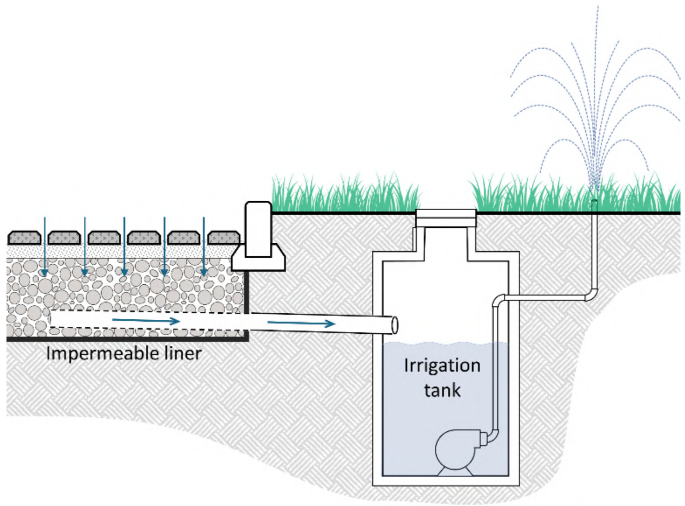


Fig. 3-16: Schematic of pervious pavement for stormwater harvesting (By Author)

result in significant costs over time, including potential system replacement.

Measures to be considered in reduce clogging according to (Drake et al., 2013; SA Govt, 2010) may include:

- Implementing permeable pavements preferentially in fully developed areas, which are typically less prone to high sediment loading compared to undeveloped areas.
- avoid locations susceptible to high sediment loads, either from runoff or windblown sand.
- Applying pre-treatment measures such as sediment traps and vegetated buffer strips, where feasible, to capture sediments before they reach the permeable surface.
- Over-compaction of subgrade soil may reduce the infiltration performance of the system and contribute to clogging.

Permeable pavements in hot climates play a significant role in mitigating the Urban Heat Island (UHI) effect, primarily through increased albedo and enhanced evaporation, which collectively contribute to lower surface temperatures. This mitigation is often achieved by using light-colored materials in pavement construction, which reflect a greater amount of solar radiation and thereby reduce heat absorption (Drake et al., 2013). Several studies, as reviewed by Qin (2015), have explored the development of water-retaining pavements, particularly that retain water near the surface to promote moisture absorption and increase evaporative cooling. These water-retaining paver systems, designed to hold rainwater in the base course layer, are particularly promising for areas

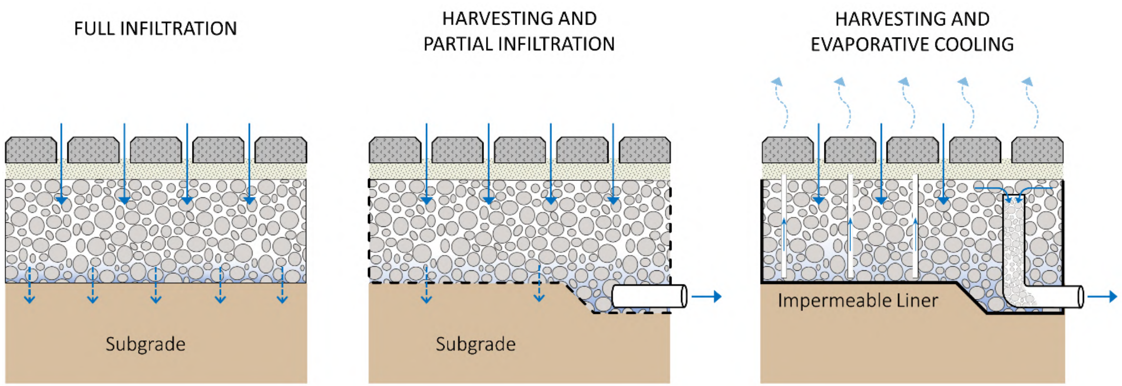


Fig. 3-17: Three types of permeable paving systems can be considered according to the design goals

Adapted from (MidlandBrick, 2024), based on (Bao et al., 2019; Drake et al., 2013)

Permeable paving on Hillview Road in Adelaide features an uncompacted subgrade and substrate stabilizing mesh. The project includes a subsurface detention storage capable of holding 20,000 liters within the gravel voids, with any overflow directed to a 225mm pipe located in the road verge.

source: (Water Sensitive SA, 2023)

where conventional infiltration methods are less applicable due to soil or groundwater limitation.

Furthermore, Bao et al. (2019) and Liu et al. (2018) explored advanced techniques to transfer moisture from the lower drainage layers to the surface. This includes the installation of capillary columns of narrow tubes or porous materials, effectively drawing water to the surface. An alternative approach involves elevating the drainage pipe to enable excess water collection from the higher retention levels, as illustrated in Figure 3-17. These technical modifications could potentially enhance evaporation rates and improve thermal comfort and therefore, require further research and pilot trials in dry urban environments.

Infiltration Basin

surface infiltration basin, or dry pond, is a shallow vegetated depression or basin designed to receive stormwater runoff and facilitate its infiltration into the ground. It typically utilizes the natural landscape and existing soil to promote water infiltration. The size and design of the basin depend on the anticipated volume of runoff and the soil's infiltration capacity. It should accommodate yearly events and larger volumes for 5- to 10-year recurrence storm events (Alan Hoban, 2019). The detention capacity of the system could be improved by an additional drainage layer of base coarse aggregate.

The main function of infiltration systems is to manage runoff discharge on-site by holding large volumes of stormwater and allowing it to infiltrate into the soil. They require no special adaptation to dry climates. However, the multifunctionality feature of the basin could compensate for the challenge of space availability in dense urban areas. Infiltration basins could be best integrated for recreational purposes into existing open spaces of medium to large catchments, including public parks and pocket parks in residential developments. Additionally, they could be most suited along major motorways and as infill in road traffic nodes where soil conditions allow for infiltration. Soil conditions must allow full infiltration of the water volume within 48 to 72 hours after the rainfall event (SA Govt, 2010).

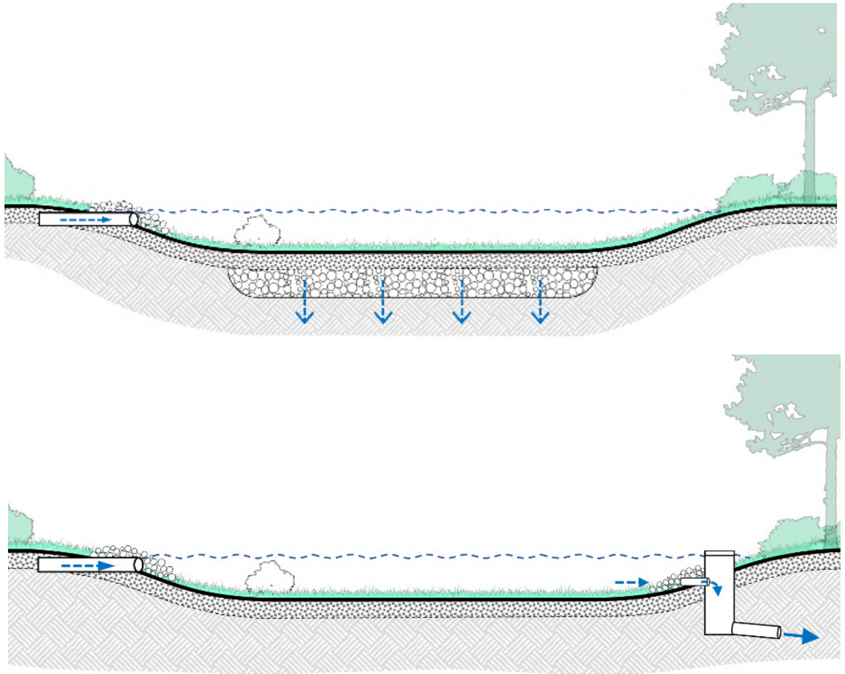


Fig. 3-18: Typical schematic of dry pond systems. infiltration basin (top) and detention basin (bottom) (By Author)

Detention Basin

A detention basin, or dry pond, is a stormwater management system engineered to temporarily hold and regulate stormwater runoff from impermeable surfaces like roads and rooftops. It typically features a ponding area that serves as the primary storage volume, along with an inlet for water inflow and an outlet equipped with mechanisms to control the discharge rate.

Primarily utilized in areas where ground infiltration is minimal or explicitly restricted, detention basins play a crucial role in flood mitigation. They achieve this by capturing large volumes of runoff during intense rainfall, thus preventing immediate discharge into drainage systems. Additionally, these basins facilitate a preliminary treatment process, where coarse sediments can settle before the stormwater is gradually released at a controlled rate to local waterways or drainage systems.

Detention basins are often used in conjunction with other stormwater management practices, such as wetlands. They function in this case as a sedimentation settling pond to provide the initial phase in a treatment train (SA Govt, 2010).

Despite their utility, the implementation of detention basins in densely populated urban areas can be challenging due to their medium to large size, which demands considerable space. However, they are generally dry outside of rainy periods. This characteristic allows them to be seamlessly integrated into urban landscapes as multifunctional open spaces that can be utilized for recreational activities, as elaborated before in this section.

Infiltration Systems

Infiltration trench is a linear subsurface structure designed to receive and detain stormwater runoff and allow it to infiltrate into the underlying soil. It consists of a trench filled with a permeable material, such as crushed stone or gravel, which provides storage capacity for stormwater while sustaining human activity on the surface. The trench is typically wrapped in geotextile fabric to prevent the surrounding soil from penetrating the gravel fill and clogging the system. However, the system can be repurposed to retain stormwater for collection and reuse by applying an impermeable membrane that fully or partially prevents infiltration. Soakaways have a similar structure and function, but they receive runoff via a perforated pipe inlet. The soakaway, thus, is completely embedded into the subsurface of a given landscape. Leaky wells are similar as well but take a cylindrical form rather than being linear and can be supported with large-diameter perforated pipes.

These technologies are effective in reducing runoff volume and enhancing groundwater recharge. They primarily provide mechanical filtration and may require additional pre-treatment to prevent clogging in sediment-rich contexts. Often, infiltration systems are integrated with buffer strips or overlaid with pervious pavements to form an effective water treatment chain (Yang et al., 2019). They provide an opportunity for infiltrating runoff from roofs, walkways, parking lots, and low to medium traffic roads without consuming a substantial amount of land area. They are particularly suited for linear infrastructures like railroads, or in dense urban areas where space is limited, and installation of surface systems is not applicable. Considering the proximity to existing structures and the soil condition, infiltration trenches are ideally utilized in areas with high permeability soils. Nevertheless, soakaways and leaky wells can be adapted for less permeable soils to provide passive irrigation to nearby vegetation (SA Govt, 2010).

Furthermore, geocellular modules function similarly to soakaways but are comprised of prefabricated cells made from high-density polyethylene or equivalent materials, instead of natural gravel. These systems serve as retaining structures to support trafficked or non-trafficked paved areas while providing a higher water storage capacity due to their substantial void ratio. The modular nature of the system offers flexibility and scalability in sizing; they can be adapted to different site conditions and can be installed under areas subjected to human or vehicle traffic, like pavements, green spaces, parking lots, and other urban zones. Design considerations for these infiltration systems include maintaining adequate distance from nearby structural foundations or applying an impermeable liner to the side near the structure.

The complete lining of the system can transform it into an underground stormwater reservoir. However, the system lacks any treatment mechanism. Therefore, in the case of storage, a pre-treatment method is required. Like all subsurface infiltration systems, geocellular systems are prone to clogging, which can significantly impair their effectiveness. Regular maintenance, including the inspection and cleaning of pre-treatment devices and system components, is crucial for optimal performance. Moreover, the availability of materials and manufacturers may also limit the option of choosing a geocellular system (O'Brien et al., 2016).

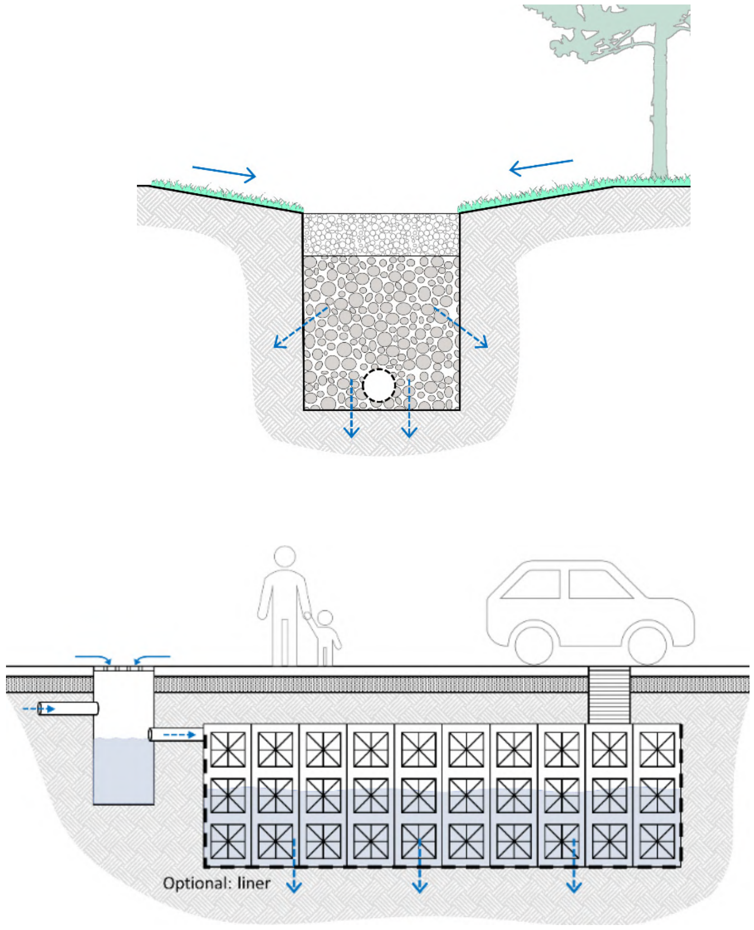


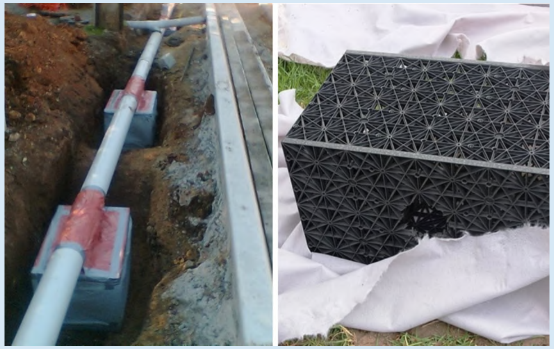
Fig. 3-19: Schematic cross section of infiltration trench (top) and subsurface geocellular module systems (bottom) (By Author)

Henley Annex, Park Lane – A small residential subdivision in the City of Charles Sturt, utilizes onsite stormwater retention to manage runoff. The system directs runoff to a dry basin at the development's downstream end. Runoff is temporarily stored in a gravel-filled sub-structure allowing water to seep into the porous sub-structure to a depth of 0.30 m. The basin is designed to handle a 10-year recurrence event, and the basin empties in less than an hour. Any overflow from more significant events is directed to the local stormwater sewer network.

Source: (Water Sensitive SA, 2023)

Dorset Avenue, Colonel Light Gardens – Stormwater runoff flows along the curb and gutter into a stormwater entry pit. The base of the pit is filled with 20mm aggregate to facilitate infiltration into the subsoil. The pit is connected to an 8.6-meter length of 150mm diameter perforated pipe, situated within a 950mm deep soakage trench below the natural ground level. This infiltration system in the road verge passively irrigates the area and manages water flow.

Source: (Water Sensitive SA, 2023)



City of Burnside, Union Street – he city council has initiated the installation of small-scale, sub-surface stormwater retention systems as part of ongoing curb and gutter improvement. these systems are intended to capture stormwater, facilitating the irrigation of soil and young trees through infiltration, while also reducing the velocity and peak volumes of stormwater runoff entering urban creeks. The design involves collecting household roof runoff in 105-liter underground storage crates, known as B-Pods, located within the street verge. This water infiltrates into the surrounding soil, with any excess being discharged onto the street. The only visible components of the system are the inspection pits.

Source: (Water Sensitive SA, 2023)

Bioretention

Bioretention, also known as biofilter systems or rain gardens, are excavated basins or trenches filled with porous filter media and planted with vegetation to remove pollutants from stormwater runoff. The vegetated system receives runoff from adjacent surfaces and temporarily retains it in subsurface layers to allow biological and physical filtration of the runoff as it percolates downwards through the layers. The water can then infiltrate into the soil or could otherwise be detained for collection and storage.

A typical bioretention system design consists entirely of engineered soil. First, an underdrain layer of gravel that provides detention and retention capacity. This layer is protected by pea gravel or geotextile to prevent clogging. Then the filter media layer, which usually consists of construction sand, topsoil as a growing medium, and drought-tolerant native plants. Since runoff inflow is likely to exceed the percolation rate into the filter media, a water ponding depression is required at the top of the bioretention system to temporarily collect runoff.

Maintaining vegetation in bioretention systems within dry climates or areas with prolonged dry periods can be difficult. To address this, the filter media can be enhanced to boost its water retention capability, thereby providing plants with sustained water access. The selection of the type and amount of filter media additives should be done with guidance from a qualified professional. Potential compost may include garden waste, pine bark, wood chip fines, sugar cane bagasse, or composted sawdust.

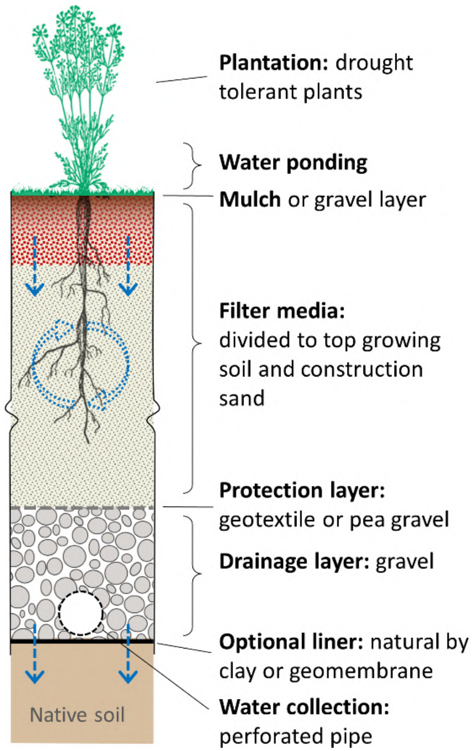


Fig. 3-20: Typical bioretention system configuration (by author)

For dry climates, it is advisable to use deeper filter media and to incorporate a submerged zone to ensure adequate moisture availability for plants. At the base of the system, retained treated water may infiltrate into the underlying native soil below. However, it is recommended that the system be fully lined with an impermeable material and incorporate a raised outlet which allows for a longer-lasting submerged zone (Payne et al., 2015; SA Govt, 2010). The water reservoir provides a source of water to sustain vegetation for several weeks (passive irrigation). A waterproof lining material for the bioretention system would prevent infiltration and instead allow water to accumulate in the gravel storage layer. In this case, a collection pipe would be installed to collect excess water from the bottom of the basin and discharge it through an elevated outlet at the upper level of the drainage layer. The collected treated water could be reused for active irrigation during long dry periods. The system could also work in clay soils with low hydraulic conductivity. Nonporous soil acts like an in-situ liner, preventing infiltration and promoting water retention. This is an advantage of bioretention, which can adapt its function to different soil conditions (SA Govt, 2010).

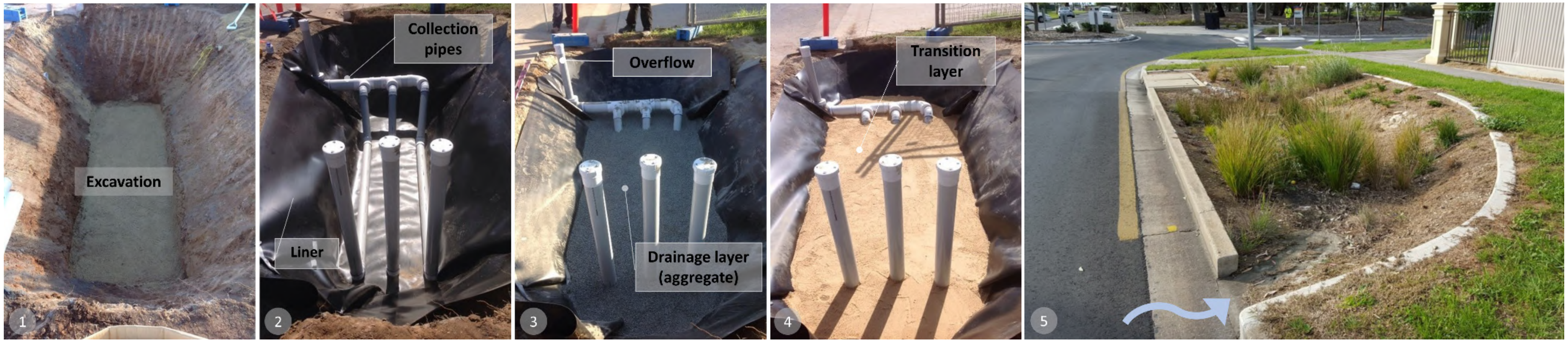


Fig. 3-21: Typical bioretention example installation from Murchison St. in Adelaide (Water Sensitive SA, 2023)

Incorporating a **raised outlet** to establish a submerged zone is crucial for maintaining adequate moisture for plants. This feature helps lessen the system's reliance on external watering, enabling it to endure extended dry periods. The depletion rate of water from this submerged zone is influenced by its depth, the evaporation rate, plant water use rates, and the duration of the dry period. During longer dry spells, it may be necessary to provide additional irrigation.

In lined systems, high runoff flows in severe events must be either discharged into an overflow structure or diverted (bypassed) from the system. Furthermore, the traditional gravel drainage layer could be replaced with a geoceluular modular that can increase the water retention capacity of the system.

According to Robin Allison ((Interview, 2021), it is unlikely for a bioretention system to develop algae bloom since the natural variation of rainfall patterns allows the cycle of wetting during the rainfall and completely drying out between storm events, so the system is not continuously loaded or wet. For the same reason, bioretention may not support mosquito breeding habitats. Even possible water ponding on the system surface typically will last for only approximately 6 hours after a storm event (Payne et al., 2015).

Plant selection is critical for bioretention in such harsh climates. A drought-tolerant vegetation mixture of sedges, tufted grasses, and perennials with extensive fibrous root systems is seen as the appropriate choice to maximize water quality and enhance infiltration performance. Turf grass is not recommended at all, as its shallow roots do not contribute to the filtration performance of the system and its high-water demand (SA Govt, 2010). Tree plantings in bioretention can provide an additional shading canopy layer which may protect the understory plants and bioretention surface from severe drought during extreme heat events (Water by Design, 2015).

Furthermore, lined bioretention systems for water storage require a sufficient size and depth allowing tree root growth. Tree pits should either be unlined or have enough capacity to accommodate a healthy tree of mature size (Payne et al., 2015). Stephanie Rogers (Interview, 2021) echoed this point, noting that trees in bioretention basins should avoid the deeper ponding areas and be planted on the elevated mounds of the system. She emphasized the importance of maintenance to the performance of such systems.

Impermeable Liner is a layer that may fully or partially encase the base and sides of bioretention systems. It prevents water infiltration into the surrounding soil, which is beneficial for collecting treated water for reuse in stormwater harvesting schemes. In some cases, lining only one side of the system is required to protect nearby structures. Liners can be constructed from local or imported compacted clay or made from various synthetic products.

Mulch is a common soil covering used in urban landscapes because it absorbs pollutants and reduces direct evaporation from the soil surface. It requires frequent maintenance and replacement, and in dry climates, it fades over time in the sun. Therefore, a top layer of light-colored cobblestones or gravel may be more beneficial in hot climates. Light-colored rocks increase albedo, reducing water requirements for plants. Gravel and rocks also do not require maintenance after large flood events (Houdeshel et al., 2012). McMillen (2013) stated that a 5 cm layer of mulch greatly reduces evaporation at the surface, and a 10 cm layer provides additional protection from evaporation.

In contrast, the Australian Guidelines for Stormwater Biofiltration Systems (Payne et al., 2015) advise that mulch should not be used in stormwater biofilters. There is the potential for organic material to be drifted by water flow and clog drains. Gravel mulch can be helpful in reducing ponding depth for safety reasons, but it also significantly impedes plant spread and can retain heat, increasing stress on plants. They generally advise using a high planting density and being careful when setting seedlings to encourage faster vegetation growth. Another way to reduce drying is to shade the area with trees, if possible.

Besides its capability of managing stormwater and supporting greening, bioretention's flexibility in size, shape, and appearance allows it to be seamlessly integrated into various urban settings, including individual development sites, streetscapes, civic spaces, parklands, and near waterways and natural areas. These systems can either blend into the local landscape or stand out as a distinct landscape feature (Alan Hoban, 2019). There are four primary types of bioretention systems:

Bioretention Basins: These are typically large, end-of-pipe systems with a filter media surface area ranging from 100 to 800 square meters. They are often situated adjacent to parklands or natural areas and serve as centralized facilities for stormwater treatment.

Bioretention Swales: Functioning both to treat and convey stormwater, these are integrated within the base of a swale. Commonly found in road landscapes and parking areas, bioretention swales incorporate all the essential components of a bioretention system.

Bioretention Planters: These at-source systems capture stormwater runoff from impervious surfaces like pavements and are typically integrated into streetscapes. They are designed to be passively irrigated by stormwater inflows and generally support a variety of plants including shrubs, grasses, sedges, and occasionally trees.

Bioretention Tree Pits: Combining the functions of a traditional street tree and a bioretention system, these small installations treat and infiltrate stormwater right at the source. While trees are the main type of vegetation used, shrubs, grasses, and sedges are also incorporated to enhance aesthetics and maintain the permeability of the filter media.

Fig. 3-22: Example types of bioretention systems showing their adaptability to various scales and urban settings (Photos: Water Sensitive SA, 2023)

Swale

Swales are linear, vegetated, open drains used to convey stormwater runoff collected from adjacent impermeable surfaces. They promote infiltration and enhance sedimentation while vegetation slows the velocity of water. Therefore, swales can ideally work in a cascade system because they provide initial pretreatment of runoff before conveying it to another element such as a wetland, bioretention, or infiltration system. Swales are typically vegetated with turf grass for this purpose. Alternatively, they may have a dense plant cover to perform the treatment method as a bioretention basin. In this case, they could simply be an extended linear bioswale.

There are no special structural measures to adapt swales to the dry climate, other than what has already been discussed under bioretention systems. However, there are some risks associated with the prolonged hot dry period. The difficulty of maintaining a grass-lined swale without irrigation could cause vegetation to die and bare land to be exposed, increasing soil erosion during subsequent rainfall events (SA Govt, 2010). In addition, the heavy accumulation of lettering and debris during the dry season has the potential to impede the flow within the swale, leading to adverse consequences of waterlogging, reduced infiltration, and compromised water quality. Therefore, it is advisable to consider integrating the swale system within an already irrigated landscape, such as parkland, where regular maintenance and system monitoring can be readily provided. Alternatively, for scenarios where continuous maintenance may be challenging, the implementation of extensively planted bioswales is is strongly recommended.

These bioswales exhibit a greater level of self-sufficiency and require moderate maintenance (Alan Hoban, 2019). Their application can be particularly suitable in car park areas or incorporated into linear streetscapes, serving as street median strips and verges along major roads. Perhaps in this case, the system could be partially lined with impermeable membrane and a runoff collection drainpipe could connect the system to a number of stormwater underground tanks installed in interval along the swale for storing and reusing water for irrigating. I would also suggest that swales could also potentially be well integrated into a permeable fencing wall system that can replace the current extensive masonry walls bounding properties and along railroads.

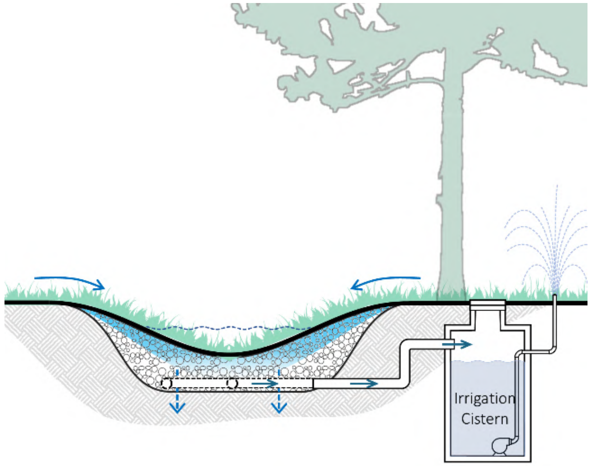


Fig. 3-23: A schematic cross section of swale system supplemented with stormwater harvesting and reuse tank (By Author)

Urban Wetlands

Urban wetlands for stormwater treatment are engineered or constructed shallow systems that mimic the natural functions of natural wetlands by incorporating aquatic vegetation, soil, and water. A typical configuration of a wetland would comprise, first, an inlet sedimentation basin to allow settling of coarse sediments. Then, a macrophyte zone , which is a range of shallow vegetated water basins to uptake soluble contaminants and filter out fine particles; a high-flow bypass to channel excess flow during extreme storm events; and an outlet pond that manages the wetland's maximum and lowest water levels , as well as how quickly water is released after storms (SA Govt, 2010).

Constructed wetlands are designed to manage and treat stormwater runoff in urban areas and are seen in structure and functioning as an advanced form of detention basins (Myers et al., 2014). They can hold runoff from larger storm events and prevent flooding. Their extensive vegetated environment promotes sedimentation and fine biological treatment processes to remove pollutants. The discharge of water from the system is essential for maintaining the wetland's ecological functions. The end use of treated water outflow from wetlands needs to be taken into consideration during the design phase in accordance with the scale and location of the wetland within urban areas. Water can be delivered to nearby water bodies such as a stream, river, or lake. In addition, wetlands can be utilized for rainwater harvesting and reuse for irrigation of open green spaces. For this purpose, the system works in conjunction with Aquifer Storage and Recovery (ASR) schemes , where the treated stormwater from large catchments can be directly recharged into groundwater aquifers through injection wells for later extraction and reuse (David & Pyne, 2017).

Integrating wetlands into urban areas requires a significant amount of land, as these ecosystems typically need large spaces to function effectively. The design of urban wetlands is generally aimed at large developments or catchment-scale projects and is particularly suitable for areas with soil that has low to very low infiltration capacity. Urban wetlands are highly valued as community assets because they provide public amenities and enhance the local environment. In dry regions, the water levels in these wetlands can vary, fluctuating with the intensity and patterns of rainfall. Although these variations in water levels can pose aesthetic challenges, they can be creatively incorporated into landscape designs, allowing the wetlands to serve as multifunctional spaces that adapt to changing conditions throughout the seasons (SA Govt, 2010).

he primary risks associated with wetlands in dry climates include the potential development of algal blooms and mosquito breeding, both of which necessitate preventive measures. As discussed earlier in this chapter, to ensure the effective performance of these systems, several key factors must be managed. Specifically, the detention time should ideally be set at 72 hours, with a minimum of 48 hours. This system requires a sedimentation basin and a gross pollutant trap at the inlet zone to remove coarse sediments, litter, and debris (Headley & Tanner, 2006). Additionally, diverting and conveying stormwater from large urban catchments can present significant challenges, especially in dense urban areas. The extension of surface open drains is often limited in these settings. The absence of separate stormwater sewer pipes can also pose an obstacle, though a piping system could be installed if feasible.

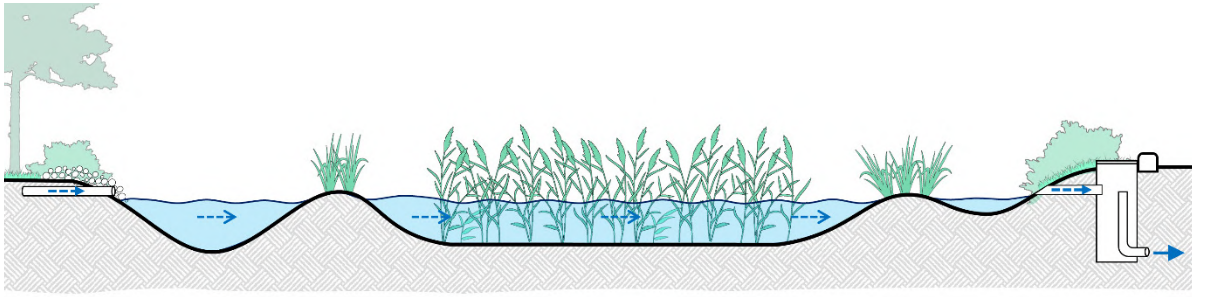


Fig. 3-24: A schematic cross section of typical stormwater urban wetland (By Author)

Waterford Circuit wetland – The wetland plays a crucial role in stormwater quality treatment and passive reuse. It forms part of a comprehensive treatment train that includes swales, raingardens, and detention basins. Rain gardens initially treat stormwater from nearby streets. This is facilitated by a series of cascading weirs that guide runoff from the rain gardens to a small detention basin, eventually leading to the wetland. This wetland is uniquely designed with a series of baffles to maximize retention time and enhance water quality. Furthermore, the wetland is part of a larger system of combined wetlands and ornamental lakes that manage flood risks for significant storm events, specifically designed to handle a 100-year recurrence. The site’s landscape design integrates a second-tier retaining wall, nature strips, and adaptable public spaces to provide flood protection while maintaining high amenity values.

Source: (Water Sensitive SA, 2023)

Retention Basin

A retention basin, also known as a wet pond, is a stormwater management facility designed to collect and store stormwater runoff. Typically constructed as an excavated basin, it maintains a permanent pool of water, with water levels that fluctuate primarily between dry and rainy seasons. Retention basins receive large flows of stormwater runoff from urban catchments channeled to the basin through a network of streets, swales, and open storm drains or underground pipes. Similar to wetlands, retention basins face significant challenges in managing algal blooms and mosquito breeding. To maintain and enhance the performance of these systems, it is crucial to implement preventive measures. One effective strategy is the use of pretreatment measures to reduce the nutrient load in the water entering the system. This can involve an initial treatment phase of runoff through a biofilter or bioswale, depending on the site conditions (Walker & Lucke, 2019).

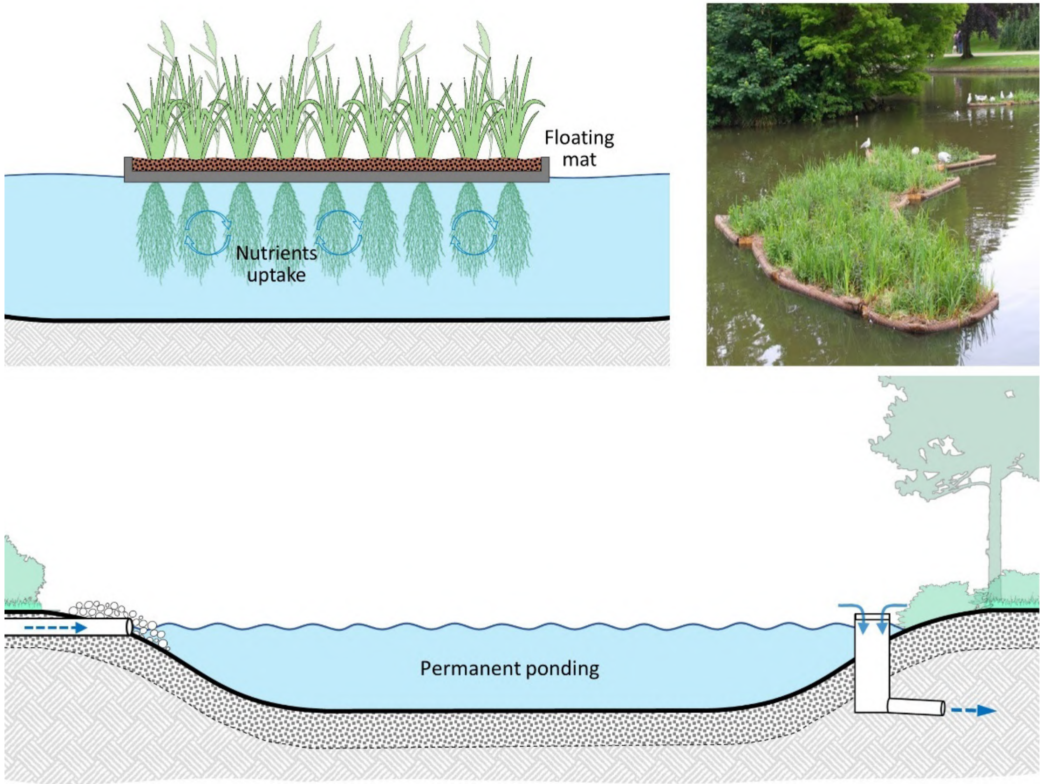


Fig. 3-25: A schematic cross section of typical retention pond (bottom). Schematic and an example of a floating wetland system (top).

Illustration by author based on (Ayres et al., 2022)
Image: (Biomatrix, 2024)

Additionally, the treatment performance of retention basins can be significantly improved by integrating constructed floating wetlands (CFW). These are floating platforms or beds that support the growth of various aquatic plants on the water's surface without soil. The mobility of these floating beds allows for the development of an extensive root system that extends into the water. This hydroponic growth enables the direct uptake of nutrients and contaminants by the plants, enhancing the overall pollutant removal capacity of the system (Ayres et al., 2022).

The Wharf Street Basin project in Perth, Australia, transformed an inaccessible stormwater basin in Cannington into a multifunctional community smart park. This innovative initiative integrates effective stormwater management with recreational amenities, addressing flood risks and improving water quality through natural filtration processes. The redesigned space now features walking trails, seating areas, and educational installations, serving as a vibrant community hub. Native vegetation enhances biodiversity and aesthetics, while smart technologies provide real-time water monitoring. This project exemplifies the successful integration of WSUD with community development, promoting sustainability and urban livability.

source: Josh Byrne & Associates (JBA), 2023

Green Roofs

Green roofs are layered systems that support vegetated spaces on top of buildings or structures. A typical green roof system comprises a plant cover, lightweight growing medium (substrate), and a drainage layer, in addition to filter, waterproofing, and root barrier sheets. The depth of the substrate and plant diversity may vary, indicating different types. Shallow systems less than 150 mm are referred to as extensive green roofs, deep systems exceeding 300 mm are intensive green roofs, and systems between 150-300 mm are semi-intensive green roofs. The greater the depth, the better the function the system can provide.

Green roofs offer numerous benefits, including effective stormwater management. By reducing the proportion of impervious surfaces on rooftops, these systems help capture and retain rainfall. This water is then used by the plants and lost through evapotranspiration, which delays its entry into urban drainage systems and helps prevent flooding during intense rainfalls. Additionally, as water moves through the green roof, it undergoes mechanical and biological filtration, which helps remove pollutants, thereby enhancing water quality. However, the design and efficiency of these stormwater management roofs in dry climates depend on several factors, including the local climate, the structural attributes of the building, the configuration of the system, and the types of plants used. These elements collectively influence how well the green roof performs its functions.

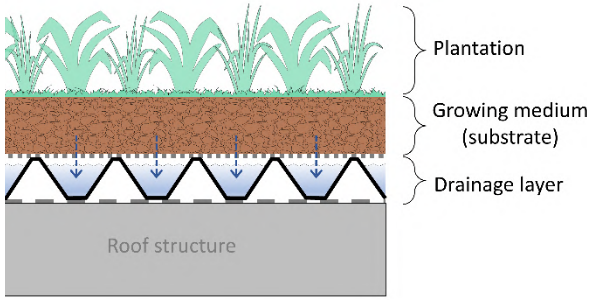


Fig. 3-26: Main configuration of green roof setup (By Author)

A variety of plants from coastal or dry regions are often suitable for green roofs, as they are well-adapted to challenging environmental conditions such as extreme temperatures, high UV exposure, drought, salty winds, and nutrient-poor soils, sometimes even pure sand. The higher the elevation of the green roof, the more extreme the environmental conditions, making the selection of plant species increasingly critical and limiting the variety of plants (SA Govt, 2010). When selecting plants for green roofs in dry climates, several key factors need to be considered:

Plant Layout: It is essential to apply sustainable landscaping principles to optimize the ecological and practical benefits of the green roof.

Orientation and Slope: The direction the roof significantly affects sunlight exposure. South-facing roofs receive more sunlight, while north-facing roofs may be shaded.

Surrounding Context: The proximity of other buildings can affect the amount of shade a roof receives, influencing plant growth and selection.

Research by the University of New Mexico (Dvorak, 2021) highlights that reflected heat and radiation from a south-facing, brown-colored facade can stunt the growth of plants near the base, underscoring the importance of considering all environmental impacts when designing green roofs.

The growing medium in a green roof system is fundamental for supporting vegetation. It should be lightweight, well-draining, able to retain moisture effectively, and resistant to biological degradation over time. The composition of the growing medium is particularly crucial in dry climates as it can enhance the roof's environment. The thermal properties of the media (conductivity and heat capacity) play a significant role in protecting plant roots. By incorporating "organic and other non-coarse, lightweight materials," the media can provide thermal insulation, shielding the roots from extreme temperatures (Beecham et al., 2019; Simmons, 2015). A study by Razzaghmanesh et al. (2014) identified an optimal media mix composed of 50% organic compost and 50% lightweight aggregate, including scoria, composted pine bark, and hydro-cell flakes. This combination not only facilitates water and gas exchange due to its porosity but also enhances nutrient supply and retention through its organic content, fostering a healthy root-zone ecology vital for plant growth.

The drainage layer is a vital component of green roofs, designed to regulate water flow on the roof surface. This layer typically consists of porous materials like lightweight aggregates, gravel, or specially engineered plastic sheets. These materials not only ensure controlled drainage of excess water but also retain sufficient moisture to support plant growth (Beecham et al., 2019).

Advancements in green roof technology include the integration of water-holding materials within the system's profile. For example, a green roof in Adelaide utilized this technology and demonstrated a 100% retention rate during summer and nearly the same for other seasons (SA Govt, 2010). Such results highlight its potential as a design tool to achieve desired water retention levels.

Various materials can be employed to enhance stormwater retention, particularly in hot climates. These include:

- Granular light weight aggregates like scoria, expanded clay, perlite, slate, and crushed bricks or roofing tiles, are known for their high-water absorption capacity.
- Modular drainage boards, typically made from high-density polyethylene, provide excellent load-bearing capacity and effective water retention and drainage.
- Hydro-cell foam and flakes, made from synthetic foamed resin, offer an innovative alternative to traditional materials by combining water retention with accessibility for plant roots.

It is important to note that some of these synthetic drainage systems may not be widely available and could be limited to specific markets. Despite this, the use of the modular boards and other water retention media continues to grow among commercial green roof manufacturers, aiming to improve stormwater management in challenging climates.

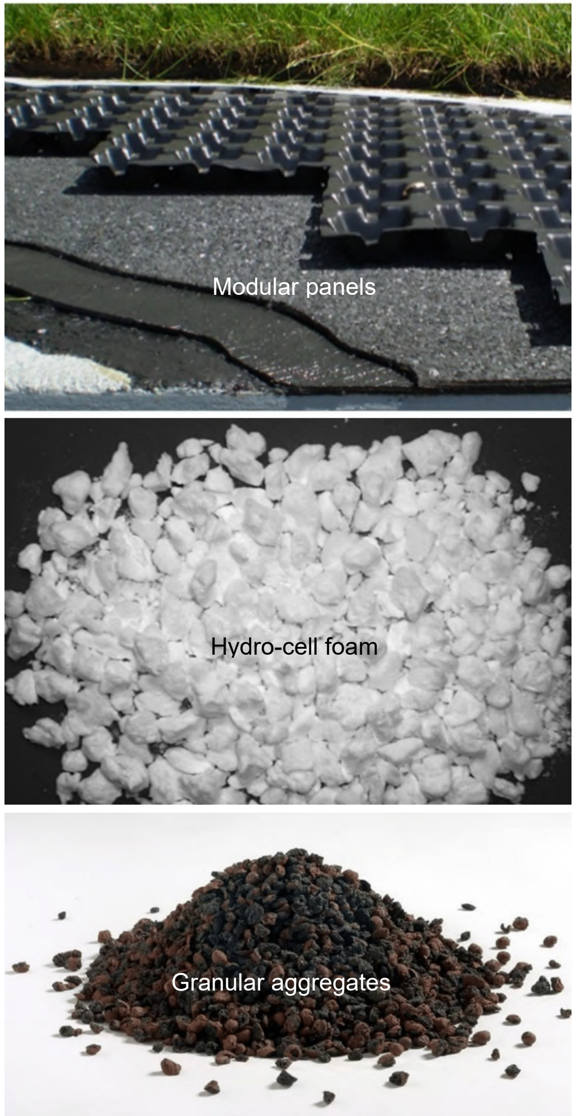


Fig. 3-27: Example of a synthetic and natural green roof drainage materials (Cascone, 2019)

Green WALLS

Green walls are structural systems that are integrated into urban settings to support the growth of vegetation on vertical surfaces. These systems have similar functions to green roofs and are known by different names reflecting their different configurations. A green façade usually involves plants such as climbers or creepers that are rooted directly in the ground or in above-ground planters. When these plants grow, they either cling directly to the façade of the building (attached green façade) or use physical supports attached to the façade (detached green façade). Living wall systems, on the other hand, utilize prefabricated modular panels that hold soil along with integrated irrigation systems to support a variety of plants. These panels can be attached to freestanding structures or directly to a building wall.

While green wall systems function effectively as vertical gardens when properly watered and maintained, they pose a challenge in dry climates as vegetation must thrive in a harsh environment. In addition to this is the high maintenance and cost of installation, especially with living walls. The considerations for selecting plants and growing media are similar to those that apply to green roofs. However, green walls can avoid heat stress and direct sunlight by being installed on facades facing away from the sun. They are ideal for high-density urban areas due to their small footprint and numerous benefits. A detailed review of the performance of green walls in dry climates is presented by Karima and Oldham (2018).

Green walls have long been utilized, but their use for specific benefits such as thermal comfort, stormwater management, and as graywater treatment systems is a more recent development. These walls can treat greywater and reuse it for different purposes including flushing toilets or irrigating public spaces, providing a sustainable source of non-potable water. Modern green wall systems are designed to handle both graywater and stormwater. The configuration of water input can be parallel, using graywater in the dry season and both types in the wet season, or sequential, using only stormwater during the wet season (Fowdar et al., 2018). Graywater is considered a viable water source for green wall irrigation because it is rich in nutrients and is continuous throughout the year (Prodanovic et al., 2017).

Above-ground planters or underground trenches used for green facades can also serve as biofilter systems (bioretention). When graywater or stormwater is discharged into these systems, it can temporarily collect in a pond, especially in the case of rainwater, before percolating vertically through the filter media. As the water percolates, it interacts with plant roots, media, and microbial communities that promote biological and physical processes to treat the water and remove pollutants. The resulting clean effluent can then be safely discharged or collected for reuse (Fowdar et al., 2018).

Mounted modular living wall systems represent another configuration for treating stormwater and graywater. These systems use modular panels, usually in the form of pots and blocks, to facilitate the growth of vegetation on vertical surfaces. The water is distributed evenly across the panels via a distribution system. As the water flows vertically down through the wall system, it is treated by the same processes provided by the filter media. The treated water is then collected at the base of the wall where it can be drained or diverted for reuse inlandscape irrigation or other non-potable applications (Prodanovic et al., 2020). Perini and Rosasco (2013) found that green facades are more suitable for graywater treatment than living walls due to their simpler installation and less expensive plumbing installation. Nevertheless, living walls offer a greater variety of planting techniques and plant selection, in contrast to green façades, which are limited to climbing plants.

Rainwater Tank

Rainwater tank systems are a method of capturing and storing roof runoff. Excess water from these tanks can be directed to landscaping, stormwater treatment systems such as swales or bioretention facilities, or to the municipal storm sewer system. Rainwater tanks not only reduce stormwater runoff but also reduce dependence on the main water supply by providing alternative water sources for non-potable uses such as laundry, toilet flushing, and irrigation. They can also be designed to protect against flooding by incorporating a reserved air space within the tank (Alan Hoban, 2019).

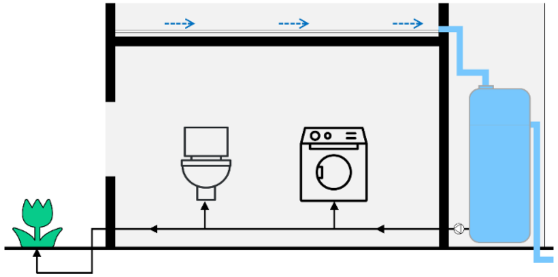
However, in dry climates, rainwater tanks can present challenges in providing breeding grounds for mosquitos, particularly when tanks have inadequate insect protection. Certain roofing materials, including those using lead flashing and bitumen coatings, are also unsuitable for collecting water intended for human use (Zhu et al., 2004). Therefore, when designing a rainwater harvesting system in dry climates, it is essential to maintain water quality and prevent mosquito infestation.

In urban settings, the pathway from ‘roof-to-gutter-to-tank-to-use’ acts as a treatment train. Rainfall runoff from roofs may contain contaminants like soil and debris washed off during storms. The quality of runoff is also influenced by roofing materials and maintenance practices. According to Adelaide’s Technical Manual (SA Govt, 2010), key design considerations include:

- Installation of mesh screens on all inlets and outlets to block leaves, debris, vermin, and mosquitoes.
- Use of a first flush device to discard the first, most contaminated portion of rainfall after dry period.
- Regular cleaning of gutters and roofs to remove leaves, debris, and branches.
- Prevention of water ponding in gutters to eliminate mosquito breeding sites and prevent eggs from entering the tanks.

Rainwater tanks are available in various materials, but it is crucial that they are designed to obstruct sunlight to inhibit algae growth. Additionally, these tanks should be equipped with a first flush device, which redirects the initial runoff from the roof during rainfall events, especially after a long dry period. It includes a primary mesh screen to trap leaves and debris, along with a containment area for the diverted water, which gradually empties through a small outlet between rain events. A first flush diverter can be attached to individual downpipes, or a larger diverter can be used to manage multiple downpipes simultaneously (Sharma, 2015).

Rainwater tanks demonstrate significant versatility in scale and application. Typically installed at the lot level in residential units, these tanks can also be expanded to street-level implementations within larger development projects. They are designed either as above-ground or below-ground storage solutions, with the latter often placed in trafficked areas due to their load-bearing capabilities. For larger communities, cluster-scale or communal rainwater systems are employed. These systems aggregate roof runoff into a centralized tank via a collective collection network, and then redistribute the water to individual households through a network system (Alan Hoban, 2019). Additionally, 'Waterwalls' are an innovative solution for settings where space is limited, offering a compact yet effective means of rainwater storage and providing aesthetic as well as functional benefits to urban environments.



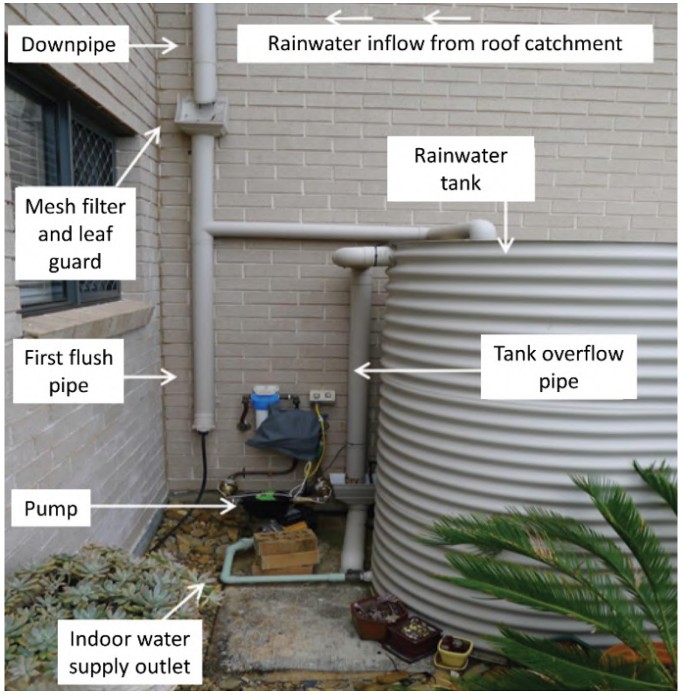


Fig. 3-28: Typical end-user connections for using rainwater in households and an example of a typical residential rainwater system setup with an external pump in Queensland, Australia (Sharma, 2015)

Greywater Constructed Wetland

Constructed wetlands (CWs) are engineered systems designed to mimic natural wetland functions, utilizing vegetation, soils, and microbial communities to enhance water quality. These systems typically consist of a shallow, graded basin lined with low-permeability soil or impermeable materials to prevent water infiltration. The wetland bed is filled with a gravel or sand substrate, which supports aquatic plants and serves as a medium for microbial growth. CWs are primarily used to treat water with lower nutrient levels, including domestic greywater and rainwater (Stefanakis, 2022).

In dry climates, factors need to be carefully considered during implementation to ensure the wetlands function as intended. First, the performance of constructed wetlands may be impacted by high rates of evapotranspiration (ET), sometimes exceeding 40%, which can significantly alter the water balance within these systems and lead to increased water salinity values (Rybka & Shchegol'kova, 2021; Stefanakis, 2020). This could reduce the quality of water intended for non-potable reuse;

therefore, minimizing water loss through ET becomes a critical task for CWs in dry climates.

When designing constructed wetlands (CWs) for dry climates, it is crucial to opt for a subsurface flow system that maintains the water level and flows entirely beneath the substrate surface to shield it from direct sun radiation and high temperatures (Rybka & Shchegol’kova, 2021). The design should minimize the area footprint while still achieving the required effluent quality. Selecting wetland plant species with high Water Use Efficiency (WUE), those with lower transpiration demands but high biomass productivity, is essential. This involves conducting thorough research on local wetland plant species to assess their water demand and calculate the WUE index, which measures water used via transpiration per unit of dry matter produced (Stefanakis, 2020). Additionally, providing shade for the CW cell, either through tree planting or nearby structures, can help reduce evaporation losses.

Addressing the common issue of sand and dust accumulation in dry climates, which can clog the system and damage both the flow mechanism and vegetation, might involve the installation of synthetic fencing or strategic tree planting around the CWs. These measures not only offer shade but also decrease wind speed and protect against sandstorms (Rybka & Shchegol’kova, 2021).

Another concern is to avoid the possibility of mosquito breeding and algal bloom. Designs that expose water surfaces, such as free water surface (FWS) CWs, should be avoided. Instead, vertical or horizontal subsurface flow systems are recommended to avoid the aforementioned issues. After all, effective design, construction, and management of CWs are essential to control potential nuisances and ensure the system's health and functionality (Stefanakis, 2020).

In terms of application, the most economically feasible and beneficial uses of CWs concerning public health in urban areas include using treated water for garden watering and irrigation, as well as for toilet flushing and laundry in domestic settings. These applications not only conserve water but also provide a sustainable solution for water management in dry regions.

At the Kendeda Building in Atlanta, USA, greywater is collected from showers, sinks, and water fountains into a primary treatment tank where organic materials and pollutants are filtered out. From there, it is pumped to a constructed wetland cell. The treated water is then discharged into soakaway trenches at the north end of the site for infiltration into the groundwater. The wetland, prominently located at the front entrance, serves both educational and aesthetic purposes.

Source: (Pishdad & Shah, 2019)

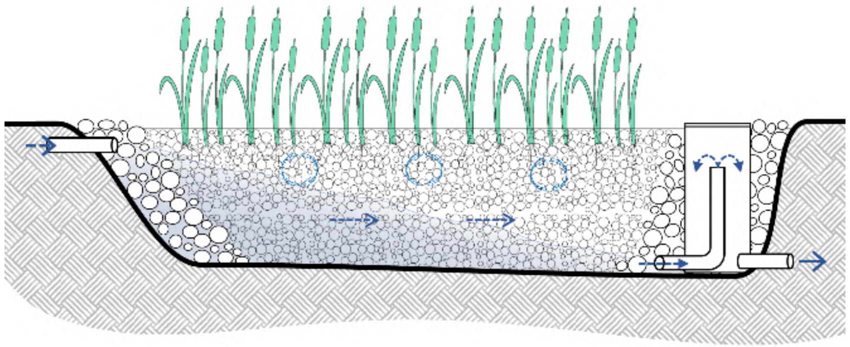


Fig. 3-29: A schematic cross section of typical Subsurface flow constructed wetland (By Author)

3.6 International Reference Example: Adelaide, South Australia

Adelaide is the capital and major city of South Australia, situated on a narrow plain between the Gulf St Vincent and the Mount Lofty Ranges. The Greater Adelaide metropolitan area includes 18 local district councils, usually referred to as a city council. Its area covers 3,259.8 km² and is home to a population of nearly 1.4 million (ABS, 2021).

The center of the metropolitan area is the CBD, which is laid out in a grid pattern enclosed by parks on all sides. The CBD is the focal point for commercial activities, governmental functions, and cultural institutions. The suburban areas extend mainly to the north and south along the flat plains. Residential zones are predominantly low-density, characterized by single-family houses, which is typical of Australian suburban development. Recent development trends show an increase in higher-density residential townhouses and apartment complexes, particularly near the city center and along major transit routes (Gurran, 2011).

The transportation network in Greater Adelaide includes an extensive road system, public bus services, a tram line running from the CBD to the coastal suburb of Glenelg, and commuter rail lines connecting outer suburbs to the city center. Industrial zones are primarily located in the northwest and the south near major transportation hubs and along the main arterial roads leading out of the city (SA Govt, 2017a).

Characterized by a Mediterranean dry climate, Adelaide experiences hot, dry summers and cool, wet winters with maximum daily high temperatures averaging 29°C in January. The seasonal precipitation patterns are highly variable, indicating a distinct annual rainfall gradient: from 500 mm to 700 mm in the east in the Mount Lofty Ranges and foothills, and from 300 mm to 500 mm in the west in the plains (Maier et al., 2013).

The city experiences the longest continuing of dry period among Australian capital cities, with periods of seven to ten days with temperatures exceeding 40°C not being unusual (SA Govt, 2010). Therefore, the WSUD strategies needed for the Greater Adelaide Region differ from those in other parts of Australia. The highly seasonal rainfall influences everything from the supply dynamics for rainwater tanks to the irrigation demands of vegetated WSUD systems. For example, bioretention basins that depend solely on stormwater inflows might be effective in Melbourne, but are likely to fail during Adelaide's hot, dry summers. This does not imply that vegetated systems are unsuitable for this dryer region; rather, it indicates the installations often need to incorporate additional storage solutions, to provide necessary irrigation during prolonged dry spells (SA Govt, 2010).

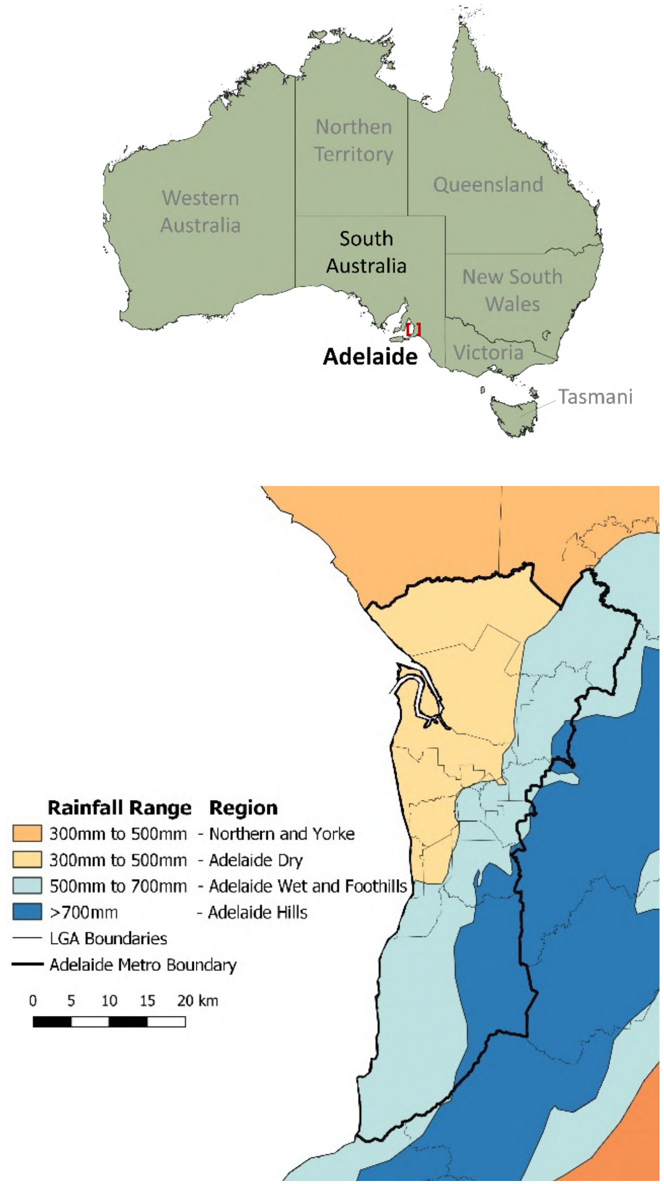


Fig. 3-30: Rainfall regions for the Adelaide metropolitan area (Water Sensitive SA, 2023)

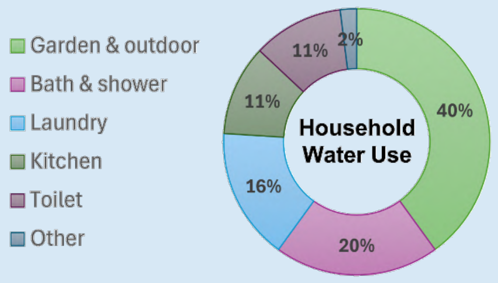
Greater Adelaide Metropolitan, Photos: (Adelaide City Council 2022)

3.6.1 Adelaide Urban Water Story

The Millennium Drought

Adelaide's fresh water supply primarily relies on capturing surface water flowing from different catchments on the Mount Lofty Ranges, which is stored in 10 local reservoirs with a combined capacity of nearly 200 gigalitres. This system aimed to cover the city's annual demand, in addition to serving as a mitigation measure for minor events and replenishing groundwater aquifers through infiltration from the natural streambeds. However, the region's limited and variable rainfall patterns often result in variable reservoir levels, only sometimes reaching full capacity (Maier et al., 2013).

To ensure a consistent water supply, Adelaide has, over the years, supplemented these natural inflows with water drawn from the Murray River. The water is pumped through two pipelines to the city, approximately 56 km across the Mount Lofty Ranges. On average, the river supplies the metropolitan area with around 40% of its annual freshwater consumption. In years of drought, this share usually increases significantly to reach 90% of the demand. The excessive exploitation of the river's water has resulted in increased levels of salinity to the limits where it is no longer suitable for use (Radcliffe et al., 2017).



The average household in Adelaide consumes 475 liters of water per day. According to data from South Australia Water, surprisingly around of 40% of this usage is only for outdoor irrigation of private gardens and lawns. This data indicates that providing alternative non-potable water resources for irrigation and other uses could notably decrease overall water consumption (SA Govt., 2017b).

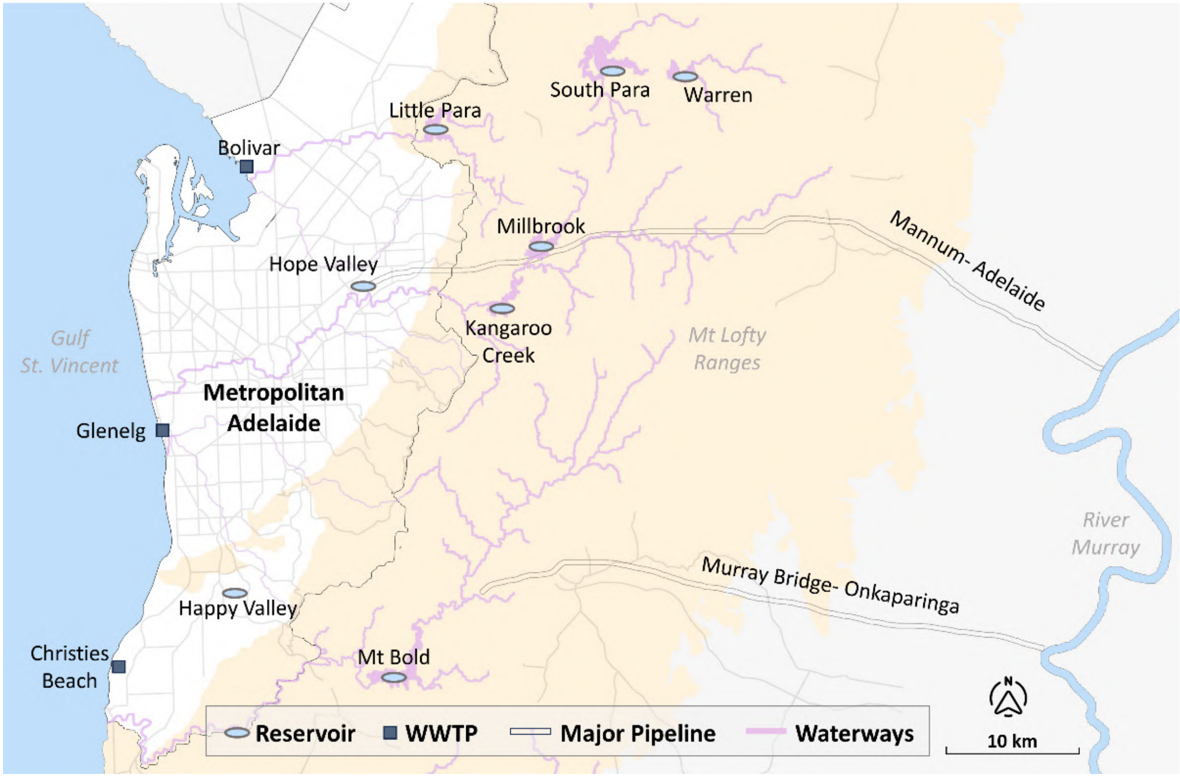


Fig. 3-31: Urban water system in Adelaide, Adapted from (Maier et al., 2013)

The region's limited rainfall and periodic extended drought had an aggravating effect of reducing inflows from both systems in the Murray-Darling Basin and Adelaide’s local Mount Lofty Watershed during the recent millennium drought, which led the city to recognize the risk of relying only on its already depleting traditional water sources and highlighted water security as an urgent issue needing new approaches for integrated urban water management that address the unique challenges posed by aridity. In response to this, the South Australian government first introduced water restriction and demand management policies, followed by further major water reforms that resulted in a new comprehensive water security plan: "Water for Good" (SA Govt., 2009). The plan outlines a long-term strategy to ensure the sustainable management of water resources in South Australia, with a focus on achieving water security and resilience in the face of increasing challenges from climate change and population growth. The city thereby developed plans to conserve existing water resources for drinking purposes, diversify water resources by introducing desalination as a non-rain-dependent source, and recognize alternative resources such as stormwater and wastewater as valuable resources for recycling and non-potable reuse.

The strategic objectives of the water security plan are elaborately aligned with the goal of transitioning South Australia into a water-sensitive state. This objective is also a fundamental aspect of the Planning Strategy, which directs the urban and regional development of South Australia. Within this framework, "Water for Good" acknowledges the critical role of WSUD in fostering more habitable urban setting (Maier et al., 2013). Consequently, it advocates for significantly enhancing the prominence of WSUD, particularly in Adelaide, as a key component in realizing these developmental and environmental goals.

Urban Drainage and Flooding in Adelaide

The city’s location on a gently sloping plain characterizes its hydrological landscape by a series of watercourses. The primary river system in Adelaide is the Torrens River, which flows across Adelaide from its source in the hills into the sea. In addition, a network of several creeks and tributaries feeds these rivers. The water flow in Adelaide’s waterway system is highly fluctuating, related to the rainfall pattern. Smaller creeks are dry most of the year and run only during the rainy season. However, excessive water discharge during severe storm events can exceed the capacity of watercourses and overflow, making low-lying areas along the creek lines prone to flooding.

The waterways are also connected to the storm sewer network, as the separation of stormwater and sanitary sewage systems is common practice in urban infrastructure planning in Adelaide. This approach is employed to mitigate the adverse effects of combined sewer overflow (CSO) during heavy rainfall events. The storm sewer system in Adelaide is designed to manage rainwater runoff from the city’s streets, parking lots, rooftops, and other impermeable surfaces, channeling it into the existing natural waterways and then to the sea. This system impacts the waterways as it contributes to the flow load, increasing the risk of flooding. Additionally, this system has posed serious concerns about the quality of water discharged through the stormwater network, leading to a greater need for strategies to ensure stormwater quality management for healthier receiving waters.

On the other hand, the sanitary sewer system in Adelaide is responsible for collecting and transporting domestic and industrial wastewater from homes, businesses, and industries to wastewater treatment plants. The network covers the whole metropolitan area with more than 8,700 kilometers of pipes. Wastewater is transported for treatment to four major wastewater treatment plants. The treated water effluent is either discharged to the sea or recycled and reused for public green space irrigation.

In view of Adelaide's water context, defined by the constraints of aridity and the necessity for water quality preservation, the city has adopted a shift towards an integrated approach of WSUD that embeds total water cycle management into urban planning and development. Such a decentralized approach harmonizes land use with water management and ensures that urban hydrology supports a resilient, and livable city.

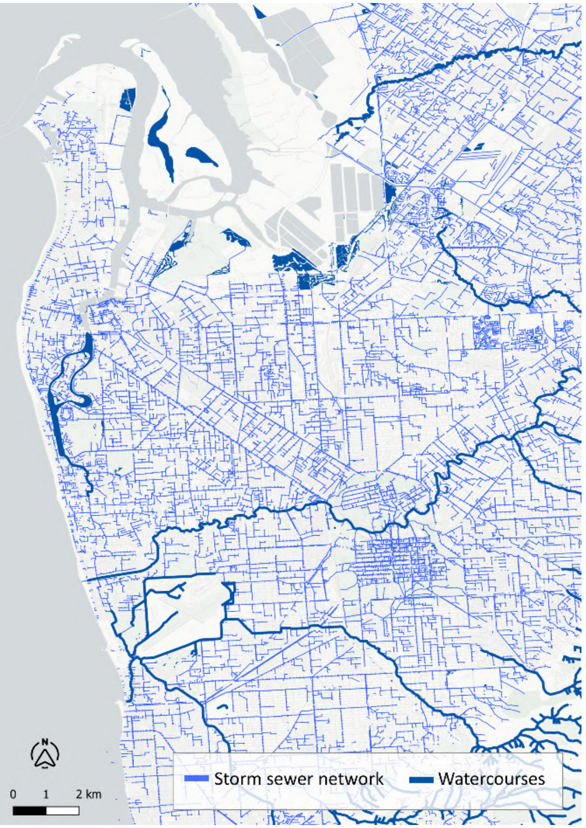


Fig. 3-32: Storm sewer network and water courses in Adelaide, by author based on (DATA SA, 2020)

3.6.2 Adelaide Approach to WSUD

According to Radcliffe (2018), the origin of Water Sensitive Urban Design (WSUD) in South Australia dates back to the 1990s, marked by the construction of pioneering stormwater quality treatment systems in Adelaide. The late 1990s saw the launch of the 'Watercare' program under the Catchment Water Management Act, aimed at enhancing waterways and promoting the early general concept of what is now known as WSUD. South Australia has since made significant progress in the planning, design, implementation, operation, and monitoring of stormwater recycling projects. Notably, early initiatives by local districts introduced stormwater treatment wetlands combined with aquifer storage and recovery (ASR) systems to efficiently store treated water during periods of low demand (Radcliffe et al., 2017). While there were no mandatory requirements and state targets for WSUD at this time, the primary focus on WSUD was driven by community concerns about the impact of urban development on local watercourses, as highlighted by the Adelaide Coastal Waters Study initiated in 2002 (Fox, 2007).

A thorough examination conducted by Myers et al. (2014), assessing 236 WSUD projects in Greater Adelaide, identified various motivations for WSUD adoption, including freshwater usage reduction, stormwater water quality enhancement, flow management, and preserving streetscape vegetation. The study found that while multiple factors often influenced WSUD implementation, the primary drivers were flow reduction, water conservation, and water quality improvement. Local councils showed great interest in integrating WSUD systems into existing road and drainage upgrades, with a broader strategy of using roadside open spaces to manage and reuse stormwater runoff. Interestingly, this proactive approach was not driven solely by a response to the level of flooding risk in specific areas, but rather by the role of 'champions' who seized every available opportunity to adopt the WSUD approach in line with their commitment to the principles of sustainable stormwater management.

According to the study, besides the drivers to improve water quality and manage flow, local urban councils have seen a great opportunity in improving urban amenity that can be gained along with these objectives. They were keen to investigate creative methods to utilize WSUD vegetated systems for passive irrigation to support the growth of street trees and other associated landscapes. WSUD measures aimed at managing stormwater flow, which have been implemented mostly on a large scale wetlands, were utilized for water harvesting schemes where treated runoff is reused for direct irrigation of open green spaces. Further, WSUD measures have been seen as more cost-effective in terms of reducing the financial load of freshwater supply and avoiding the high cost of conventional sewer drainage installation, especially in medium-sized urban development.

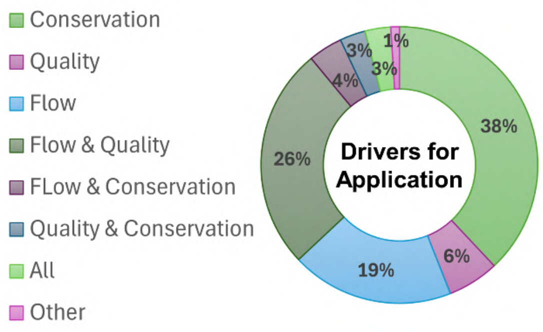


Fig. 3-33: Main drivers behind the adoption of WSUD technologies in 236 sites in Adelaide, Adapted from (Myers et al., 2014)

The planning and implementation of WSUD in Adelaide significantly differs from practices in humid regions, which primary focus on mitigating runoff inundation in urban areas. Adelaide's approach is more expansive, covering the entire urban area where it is possible to conserve water and enhance amenities, not just addressing flood-prone areas.

3.6.3 Policies Development

In the absence of a state-level strategy framework, the progressive adoption of WSUD concepts in Adelaide was, for many years, guided only by mandatory water restrictions policies following the millennium drought, including requirements for alternative water supplies to all new homes. Additionally, local initiatives for water quality improvement included policies for stormwater detention at the local government level, mandating the integration of detention mechanisms to limit flows from development (Radcliffe, 2018).

However, in 2008, the government made its first attempt to formalize a unified strategy and implementation of WSUD by initiating the project ''Institutionalizing Water Sensitive Urban Design in the Greater Adelaide Region,'' led by the Department of Planning and Local Government. The project aimed to formalize WSUD principles into government planning and urban development programs. Key outcomes of the project were the WSUD Framework (SA Govt., 2008) and WSUD Technical Manual (SA Govt, 2010). The first released Framework in 2008 offered a systematic approach to applying WSUD principles within the Greater Adelaide Region, aiming to meet defined targets and promoting uniformity in integrating WSUD practices into both new and existing projects. In 2010, the technical manual was released with 16 chapters outlining in detail 12 WSUD technologies. The document is intended as an implementation guideline for urban planners, engineers, landscape architects, and related professionals in the design, implementation, and maintenance of WSUD systems in urban development projects.

Ongoing efforts to enhance capacity-building and secure political backing for WSUD implementation in Adelaide have been pivotal. A significant achievement of this initiative was the establishment of "Water Sensitive SA" in 2017. This association represents a collaboration between South Australian state and local governments and the Cooperative Research Centre for Water Sensitive Cities (CRC) (Water Sensitive SA, 2023).

Current WSUD policies and principles:

In addition to state planning policies, South Australia has been engaged in its most comprehensive planning reform in 25 years. This reform process began in 2013 with the establishment of an expert panel on planning reform and has involved extensive consultations and research to create a new statewide planning system. Supported by the Planning, Development and Infrastructure Act 2016, this new system has been active since March 2021. It features several tools designed to modernize the planning process. Among these is the

Planning and Design Code, which includes specific provisions for WSUD and urban greening in new developments (Bradley et al., 2021).

The Code has become the sole set of guidelines for assessing development applications across the state, replacing all previous development plans. In its Phase 3 (urban areas), the Code includes various provisions that support WSUD and urban greening. It emphasizes the importance of integrating natural systems into urban settings and establishes performance objectives for green and canopy coverage in urban areas. These objectives specify minimum requirements for landscaped areas, deep soil zones, and tree planting for both residential and commercial projects. Additionally, the Stormwater Management Overlay in the Code emphasizes rainwater retention and detention to conserve water and improve the quality and management of stormwater runoff. The Code aligns WSUD principles with soft landscaping policies and aims for developments to

Table 4: Comparison of overarching State Planning Policy on WSUD in jurisdictions (SA Govt., 2013).

PERFORMANCE PRINCIPLES	PRINCIPLE INTENT	STATE-WIDE PERFORMANCE TARGET	PRIMARY FOCUS
Water Conservation	Ensure water systems are efficient and prioritize sustainable local sources when safe and suitable.	Comply with South Australian residential water efficiency standards.	Residential development
		Promote water efficient techniques in non-residential urban settings.	Commercial, industrial, and institutional development
		Best practice irrigation management in outdoor irrigated open spaces.	Irrigated open space areas
Runoff Quality	Improve urban runoff quality to protect and enhance water environments, supporting ecological and water management goals.	Achieve pollutant load reductions: - Total suspended solids by 80% - Total phosphorus by 60% - Total nitrogen by 45% - Litter/gross pollutants by 90%	Residential, commercial, industrial, and institutional development, and roads, streets, and thoroughfares
Runoff Quantity	Limit hydrological impact of urban environments on watercourses and ecosystems, maintaining pre-development conditions as closely as possible.	For waterway protection, ensure runoff rate does not exceed pre-development 1-year ARI peak flow.	
	Manage flood risk, by limiting the rate of runoff to downstream to appropriate levels.	For flood management, ensure no increase in 5-year ARI peak flow and no added flood risk for 100-year ARI peak flow.	
Integrated Design	Align WSUD planning, design, and management with broader objectives to achieve multiple beneficial outcomes.	Support green infrastructure to enhance public amenity, habitat protection, and population well-being through collaborative stakeholder involvement	

incorporate WSUD techniques for stormwater reuse. This represents a move towards specific, measurable performance-based policies that address stormwater quality, peak flow, and overall runoff volume, marking a significant shift from more general environmental protection policies (Bradley et al., 2021).

Currently employed policies and instruments relevant to WSUD in South Australia are generally addressed in three overarching state government documents:

Water Sensitive Cities in SA (SA Govt., 2013) – is a policy document outlining the SA Government's perspective on WSUD. it outlines the government's role in supporting WSUD usage statewide, offers WSUD performance principles, and establishes stormwater pollutant reduction targets as detailed in Table 4.

The 30-Year Plan for Greater Adelaide released in 2010 and updated in 2017 (SA Govt, 2017a) – The regional plan establishes interconnected strategic goals that impact Adelaide's transformation into a water-sensitive city.

The Planning and Design Code (Plan SA, 2022) – Is an official instrument under the Planning, Development and Infrastructure Act 2016 for assessing development applications in South Australia.

3.6.4 Implementation of WSUD in Adelaide

Adelaide has effectively incorporated WSUD practices throughout its metropolitan area, applying these strategies across a variety of urban scales to maximize environmental and community benefits. These applications range from large-scale initiatives, such as the management of entire urban catchments and district-level projects focusing on comprehensive stormwater management, to smaller-scale implementations in individual buildings and streetscapes. In open spaces, WSUD systems like wetlands and retention basins enhance natural water cycles and biodiversity, while in urban streetscapes, rain gardens and permeable pavements reduce runoff and increase aesthetic value. Additionally, many buildings incorporate green roofs or onsite water harvesting systems.

Water Sensitive SA has created an interactive map that offers a comprehensive view of completed WSUD projects across Adelaide's metropolitan regions. This map is based on a study of the WSUD asset inventory compiled by the Goyder Institute for Water Research. The study of the Implementation of WSUD Infrastructure in Greater Adelaide (Myers et al., 2014), aimed at identifying the extent and nature of WSUD being implemented as of 2014. The study developed a directory of 236 implemented WSUD projects across the city, which comprised 461 WSUD systems. The analysis of projects concluded that most WSUD installations are in Adelaide's inner-urban areas, with a prevalence of smaller-scale systems due to space constraints. Larger water management projects, like Aquifer Storage and Recovery (ASR), are typically situated further from the central business district (CBD). Therefore, the decision to implement a particular WSUD feature is heavily influenced by the space available; councils with extensive open spaces opt for larger systems, which are easier to manage and more feasible, while those in densely built inner-urban areas rely on smaller, street-scale bioretention systems due to limited space. At the time of the study, most WSUD projects in Adelaide were retrofitting rather than infill or greenfield development. WSUD concepts were integrated into renovating existing developments. These initiatives aim to enhance stormwater management within public lands, streetscapes, and open spaces, reflecting a significant motivation by local municipalities to adopt WSUD practices in urban plans.

The study also indicates a growing trend in the adoption of WSUD, with an increasing number of projects realized over time (Fig. 3-34). Initially focusing on early WSUD technologies, like wetlands, permeable paving, and water recycling, significant activities were recorded in 1999, including major wastewater recycling projects and trials in innovative paving and wetlands development. Particularly after 2010, there has been a significant surge in WSUD implementations. According to the researchers, this is attributed to various factors, including enhanced funding, water scarcity concerns, improved local government capabilities, and the introduction of locally tailored guidelines in 2010, the WSUD Technical Manual.

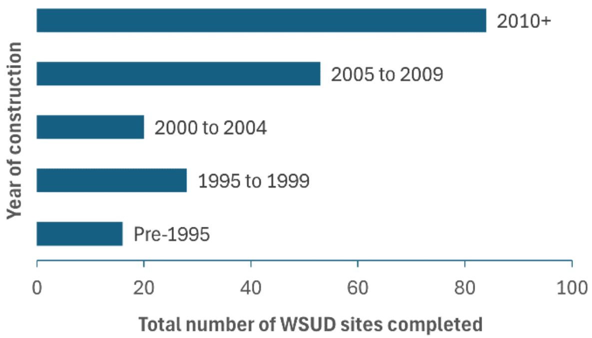


Fig. 3-34: WSUD sites completed with respect to time, Adapted from (Myers et al., 2014)

The investigated 236 sites are each equipped with WSUD technologies, where some sites involved multiple systems. Figure 3-35 presents the share ratio of the total 461 WSUD systems identified in all investigated sites. What stands out in this chart is the high share of bioretention systems with 42% of total recorded systems, followed by wetlands, ASR, and infiltration systems with 19%, 12%, and 7%, respectively. The data indicates water reuse share is less than 10%, combining both stormwater reuse and wastewater recycling. Green roofs and ponds were notably less adopted in most projects.

Bioretention systems are prevalent, identified at 50 sites with 192 individual systems, demonstrating their versatility and effectiveness in various urban densities and settings. They can achieve multiple benefits, including treatment, flow management, as well as supporting vegetation for open green space and urban cooling. Their adaptability in size makes them particularly suitable for inner-city areas. Wetlands share many benefits with bioretention but are typically more viable in new, low-density developments due to their larger spatial requirements.

Aquifer Storage and Recovery (ASR) ranks as the third most common WSUD system implemented in Adelaide. ASRs are often integrated with wetlands in major stormwater harvesting schemes. Further, infiltration systems are present as they do not require much space and are widely used throughout the city for passive irrigation through trenches and soakaways. Besides, they are very effective in situations where they can serve as multifunctional spaces for recreational activities.

However, the results also show green roofs and ponds are the least implemented. According to the technical manual, extensive green roofs have not been successful in Adelaide due to the challenges posed by the region's very dry and hot summer conditions, which affect the root systems of plants growing in shallow substrates. Ponding systems are unfavorable for practitioners in Adelaide. This may be due to their limited treatment capabilities, substantial

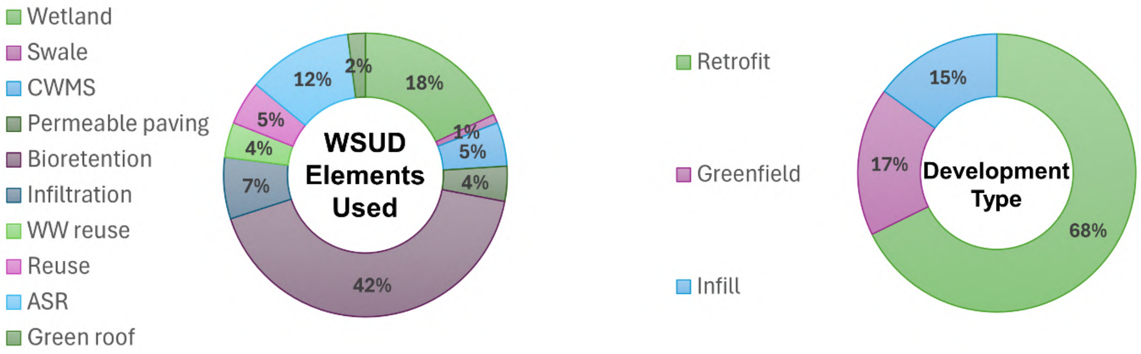


Fig. 3-35: Type of developments that incorporate WSUD features (right). Identification of WSUD technologies applied in 236 sites in Adelaide (left), Adapted from (Myers et al., 2014)

space and maintenance demands, and issues like algal blooms and mosquitoes. Where space allows, wetlands are generally preferred for their broader environmental benefits.

Thus far, this section has concentrated on the WSUD technologies implemented in Adelaide in recent years, evaluating their viability and preference. The rest of this section introduces example projects that explore the application of these technologies and their specific impacts at various scales.

Holland Street upgrade, Thebarton

The project presents an exemplary street-scale application of WSUD principles in an urban context. Thebarton is a district bounded by the River Torrens to the north and Adelaide's CBD area to the east. The district was primarily an industrial area, with many factories and warehouses. However, in recent years, there has been significant redevelopment and gentrification in the area, resulting in a mix of residential, commercial, and industrial properties.

An elaborate study has identified major urban challenges facing the district of Thebarton (JPE, 2013) including difficult cycle and pedestrian connections, limiting the access to the river, and poor streetscape amenity and safety measures. Also, the streetscape is dominated by vehicular traffic and parking areas. In addition, the industrial and business land use of the area, characterized by increased paved surfaces, heightened the risk of flooding and increased pollution carried by runoff to the River Torrens.

To address these issues, the local council has initiated a development program with a vision for upgrading streetscapes across the council area. The initiative aims to enhance stormwater management through WSUD, boost urban biodiversity, and prioritize pedestrian-friendly environments and livability with reduced traffic. The council's strong endorsement of WSUD practices has become a feature of recent developments in the area. Given its proximity to the River Torrens, there is a pronounced focus on adhering to stormwater quality improvement measures as specified in the State's WSUD Policy. The project's description and outcomes are stated by Water Sensitive SA (2023) as follows.

Project description:

A 200 m section of the northern part of Holland Street, extending from Anderson Street to the plaza where the street meets River Torrens, has been transformed into a dynamic, multifunctional public space. This transformation was completed in 2018 as a showcase of a comprehensive design strategy that integrates stormwater management, biodiversity, green space, and creative placemaking, with a strong emphasis on WSUD principles and infrastructure that prioritizes cycling and walking. A key feature of the project is its self-sustaining irrigation system, which utilizes an embedded stormwater harvesting and reuse system.

Key WSUD implementation includes the installation of interconnected biofiltration beds along the street that capture and treat stormwater runoff from paved areas, which then feeds into an underground tank in the plaza for site irrigation. The distribution of vegetated planters throughout the streetscape also enhances biodiversity, mitigates urban heat, and offers social and economic benefits to the area. Additionally, the design preserves existing street trees on the western side and introduces new trees on both sides and in the plaza. The new trees were installed in 'StrataVault' modules. Instead of using a standard compacted subgrade, this method offers structural components to support standard surface bedding and pavements. The system allows for a relatively uncompacted growing medium around the trees, promoting healthy growth.

The plaza features a sunken garden planter that enhances the area and creates a street verge between the heavily used shared walkway bridge and the comfortable, multipurpose space. The sunken garden not only adds aesthetic value but also functions as a WSUD rain garden, collecting stormwater runoff from the plaza and surrounding catchment, including building rooftops and the adjacent large brewery paved site. The treated water is stored in a 50,000-liter concrete tank constructed under the plaza pavement. Any excess water over the capacity of the tank is directed through a planted swale before being discharged into the river. The harvested water sufficiently covers most of the irrigation requirements to sustain the landscape within the street and plaza during the non-rainy season.

Project outcomes:

- Managing surface runoff reduces the risk of flooding and improves water quality before it discharges into the river.
- Promoting water conservation by the integration of stormwater storage and reuse systems for irrigation.
- Mitigating urban heat island by increasing vegetated areas and tree canopy cover.
- Enhancing biodiversity by incorporating green spaces and native vegetation.
- Improving community well-being by enhancing the aesthetic value of urban areas and creating more livable, attractive, and resilient urban spaces.

Fig. 3-36: Holland Street and Plaza upgrade.

Photos: (JPE, 2013; Water Sensitive SA, 2023)

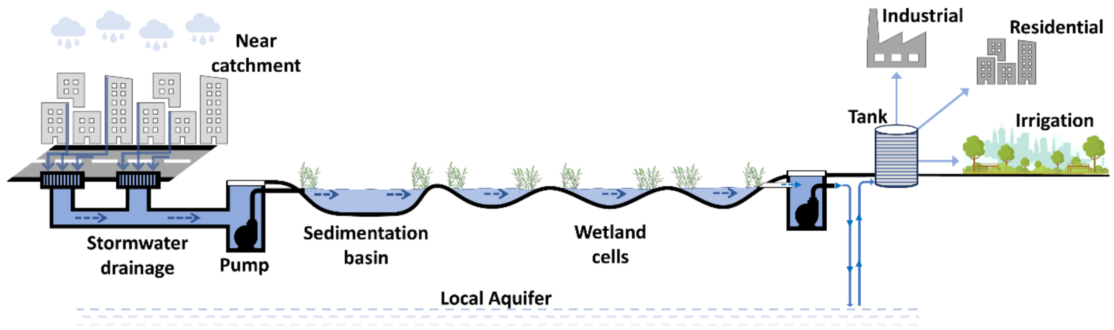
Catchment scale: Waterproofing the West

Waterproofing the West initiative, as detailed in a case study by CRC (2018), was launched by the city council of Charles Sturt in Adelaide. It is a comprehensive stormwater management strategy designed to mitigate flood risk, address water scarcity, and improve stormwater quality in a developed urban setting. This innovative project integrates WSUD principles to create a large-scale system that captures, treats, and repurposes stormwater for use across western Adelaide, treating up to 2,400 ML annually for non-potable applications such as irrigation, toilet flushing, and other domestic uses.

Project description:

Central to this initiative are a series of constructed wetlands, covering a total of 11 hectares at locations including Old Port Road, West Lakes Golf Course, Cooke Reserve, and St Clair. Wetlands receive stormwater from the surrounding local urban catchment as well as diverted excess flows from the River Torrens. The captured stormwater is treated to a water quality suitable for recycled use and injected for storage into local aquifers to be extracted back for non-potable uses.

The Old Port Road Wetlands and Stormwater Drainage system is a crucial element of the Waterproofing the West initiative, situated on the main arterial road connecting Adelaide with Port



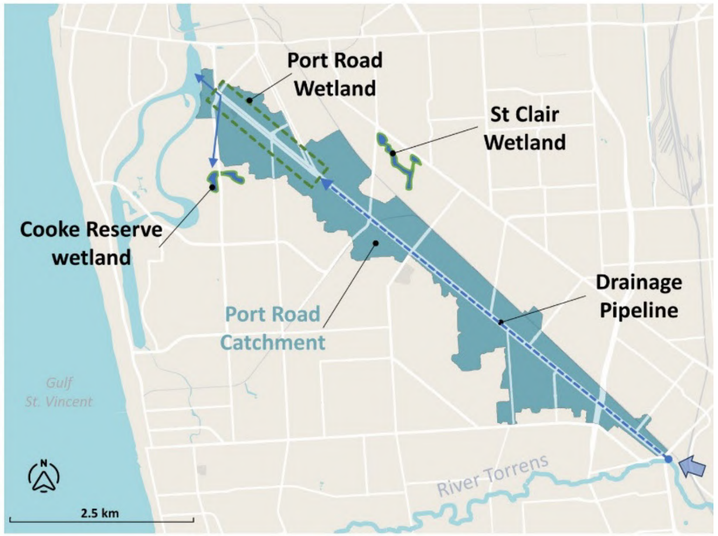


Fig. 3-37: Old Port Road waterway restoration project.

Illustration by author based on (CRC, 2018), (Photos: Design Flow, 2023)

Adelaide. This area, originally designated for a railway and canal, now hosts a wide median strip repurposed for stormwater management due to the railway's relocation and the canal's cancellation. A drainage system runs under the median which is used to carry stormwater drained from the catchment areas on both sides of the road to discharge into the sea. However, its aging infrastructure has caused frequent flooding, impacting local properties and essential services. The project involves revitalizing a 2.6 km section of this road with a redesigned channel to support a naturalized waterway and wetlands. Additionally, part of the treated water from the road is diverted to Cooke Reserve and the West Lakes Golf Course wetlands for further purification and aquifer storage and recovery (ASR). Cooke Reserve, adjacent to Frederick Road and near the golf course, features six ASR wells for injecting treated water approximately 210-260 m deep into an aquifer.

Fig. 3-38: Cooke and St Clair wetlands (Water Sensitive SA, 2023)

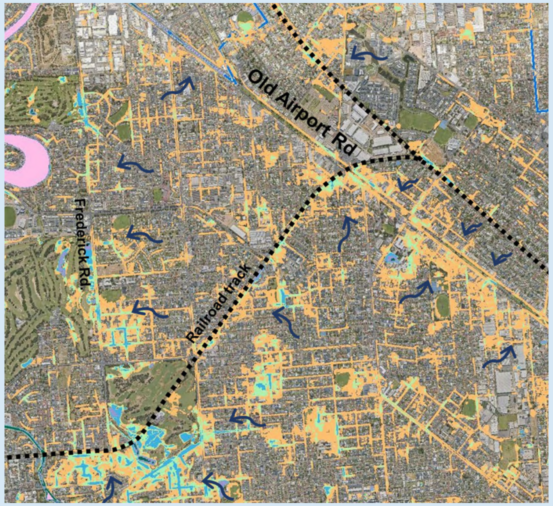
The St Clair wetland has been integrated into a large new residential housing subdivision, which is extensively landscaped to become the central feature of the new development. The wetland complex includes a detention system and sedimentation basins leading to biofiltration ponds with approximately five to seven days of detention time. Stormwater runoff from the immediate surrounding urban catchment feeds into the wetland and is treated before injecting harvested water into the same aquifer. The system supports nearly 1,200 homes by providing non-potable water for various household and landscaping needs, such as flushing toilets, watering gardens, washing cars and paving, and filling ornamental ponds and water features.

The case study highlights two significant insights: firstly, properties equipped with recycled water connections are more appealing and attractive to potential buyers due to the reduced cost of water and exemption from state water restrictions. Secondly, the homeowners did not have to install rainwater tanks on their plots, which saves space and is more feasible.

Project outcomes:

The project outcomes highlight several key achievements in integrating WSUD solutions to the challenges of urban resilience and aesthetics.

- Urban alternative water supply innovation: By utilizing runoff and River Torrens flows, the development has significantly cut potable water use by 555 ML/year.
- Flood Control: The initiatives also play a crucial role in local flood management, addressing the historical issue of localized flooding in the area.
- Fostering Water-Sensitive Communities: The use of recycled water in homes has heightened awareness and altered perceptions regarding water sustainability in a water-scarce community. Additionally, the introduction of wetlands and enhanced irrigation practices have added aesthetic value, created an ecological habitat, and improved the quality and resilience of green spaces, contributing to better local amenities.



Worth noting the observation of flood spread mapping and flood depths in extreme rainfall event, highlighting the impact of major roads and railroad tracks as barriers that influence water accumulation.

Map: Adapted from (IntraMaps, 2023)
Photo: City of Charles Sturt, 2023

3.6.5 Greening and Cooling of dry Adelaide

Adelaide's urban environment, marked by elevated temperatures and temporal precipitation, is expected to experience more extreme weather conditions due to climate change. Projections indicate a significant rise in the frequency of hot days, with the average number of days with temperatures above 35°C expected to escalate from 20 days during the 1981–2010 period to 26 by 2030, reaching 32 by the end of the century Similarly, extreme heat days over 40°C are projected to grow from 3.7 to 5.9 by 2030, and to 9 by 2090, marking Adelaide as one of the Australian capitals most affected by increasing heat extremes (Gunn et al., 2017).

A strategy to transform Adelaide into a cooler city involves increasing soil moisture and healthy vegetation to mitigate urban heat through key processes of evapotranspiration and shade. Urban green spaces, therefore, are important for Adelaide to increase vegetation cover to better manage higher urban temperatures, as outlined in the Urban Greening Strategy for Metropolitan Adelaide, conceived by the Green Adelaide initiative (SA Govt., 2022). The strategy envisions a cooler, greener, and more climate-resilient city. However, achieving this requires an efficient and sustainable source of water within urban landscapes. In this sense, rain and wastewater are seen as resources that can be utilized for that purpose. This dual approach aims as well to curb stormwater management expenses, mitigate flood risks, and improve microclimates for the city's inhabitants.

The WSUD concept and principles are central to this goal by adopting innovative non-conventional water sources for sustaining green spaces. WSUD strategies offer a sustainable approach to mitigate urban heat and improve thermal comfort. Urban areas can benefit from WSUD practices that retain water in the landscape, thus supporting cooling through evapotranspiration and shading by an enhanced tree canopy. Coutts et al. (2013) suggest that integrating WSUD technologies with urban vegetation can significantly lower temperatures and enhance human comfort. In Adelaide, harvested rainwater and recycled wastewater are key to watering urban greenery, with irrigation methods varying by scale and water source, including both passive and active techniques. The phenomenon of moisture formation on roof and façade surfaces, commonly referred to as dew, alongside the condensate from air-conditioning systems, presents another potential water source for sustaining urban green spaces.

Passive irrigation method

Passive irrigation utilizes natural mechanisms and designs to distribute and store water to vegetation without external mechanical aid. It channels stormwater to plants using gravity, either across the surface for vertical infiltration into the soil or through subsurface methods that replenish deeper soil moisture accessible to plant roots. This approach helps sustain plants and trees during dry weather by enhancing the soil's ability to hold moisture beneath the surface. Various passive irrigation techniques are used in Adelaide, including several vegetated WSUD elements like bioretention systems, swales, and wetlands, which capture and treat stormwater. Other ways to enhance vegetated lawns are by directing stormwater to open detention basins or wicking lawns. Passive irrigation elements can be applied on small to medium scales and are subdivided into two categories: self-watering landscapes and wicking lawns.

Self-Watering Landscapes: Self-watering street trees and planters: street landscapes comprising street trees and garden beds in urban areas often face growth challenges due to compacted soil and limited access to natural water sources. These settings where greenery is planted are characterized by highly impervious surfaces like roads and pavements, which restrict rainfall infiltration and soil moisture replenishment. Besides the typical challenges of lacking regular maintenance and provision of water connections, this often results in trees with limited growth and diminished canopy coverage. Passive irrigation systems address these issues by channeling stormwater runoff directly to the soil, providing the necessary moisture for trees to achieve their growth potential.

Wicking lawns: These include turf areas, sports fields, and garden beds, and feature a subsurface water storage layer that helps support plant and tree vitality through capillary action, drawing water upward to the roots. By maintaining soil moisture for longer periods, this method minimizes water loss from evaporation and ensures roots have direct access to water. The subsurface storage maintains soil moisture over extended periods by reducing water losses due to direct evaporation and efficiently provides roots direct access to water. The system is engineered to manage excess water by allowing overflow to prevent soil saturation, ensuring optimal moisture levels for vegetation growth.

The Australian government, in cooperation with Water Sensitive Cities (CRC), issued the national guideline for passively irrigated landscapes, Designing for a Cool City (CRC, 2020a). This guideline aims to promote the adoption of passive irrigation techniques using stormwater in Australian urban environments. It introduces self-watering landscapes and their benefits, including cooling urban areas. The guideline offers strategic advice on designing these systems to fit various urban landscapes, emphasizing important design, construction, and maintenance considerations.

Active irrigation method

Active irrigation involves the use of mechanical systems to deliver water directly to vegetated landscapes. This can include sprinkler irrigation and drip irrigation methods. In Adelaide, active irrigation supplied by recycled wastewater or harvested rainwater is applied on various scales. Domestic household and community rainwater tanks represent small-scale implementation. Rainwater is harvested from rooftops and is used for irrigating private gardens, either manually or through an irrigation network. The wide implementation of rainwater tanks in Greater Adelaide was also driven by the requirement of the State government for alternative water supplies to all new homes and some renovations to existing allotments (Myers et al., 2014). Harvesting at large-scale applications of reusing rainwater and recycled wastewater for irrigation of green spaces involves the technologies of ASR integrated with constructed wetlands, and wastewater recycling. The following example projects represent large-scale harvesting and recycling schemes for green space irrigation in Adelaide.

Glenelg to Adelaide Parklands (GAP)

The Glenelg to Adelaide pipeline project, as detailed in a study by CRC (2020b), was initiated to provide a sustainable supply of alternative water resources for maintaining the Adelaide Parklands. The project focuses on the treatment and distribution of recycled water from the Glenelg Wastewater Treatment Plant to irrigate the Adelaide Parklands, which is a significant park system encircling the city center. This extensive urban green space, spanning approximately 900 hectares, traditionally depended on freshwater for irrigation. However, water restrictions during the millennium drought significantly impacted the park's quality, as well as the overall green space in Adelaide. An alternative water supply was required. In addition, the project aligns with the city's objectives to protect receiving waters and reduce the amount of treated wastewater returned to the marine environment.

Launched in 2010, the GAP project aimed to mitigate the park's vulnerability to the local dry climate by supplying 400-800 megaliters of recycled wastewater annually for irrigation and other non-potable uses. The project included a new tertiary treatment plant that treats secondary effluent discharged from the existing Glenelg WWTP. The technology involves a combination of micro-screening, ultrafiltration membranes, ultraviolet, and chlorination disinfection processes. The treated water is distributed via a 40-kilometer underground pipeline (marked as a purple line) across Adelaide's city center.

Over more than a decade now, the project has achieved many benefits beyond its set goals. The recycled water is enriched with minerals and nutrients that enhance plant growth and vitality. A reliable and low-cost alternative water supply has contributed to a cool and green city by preserving the park greenery throughout the dry season, supporting its function as an amenity

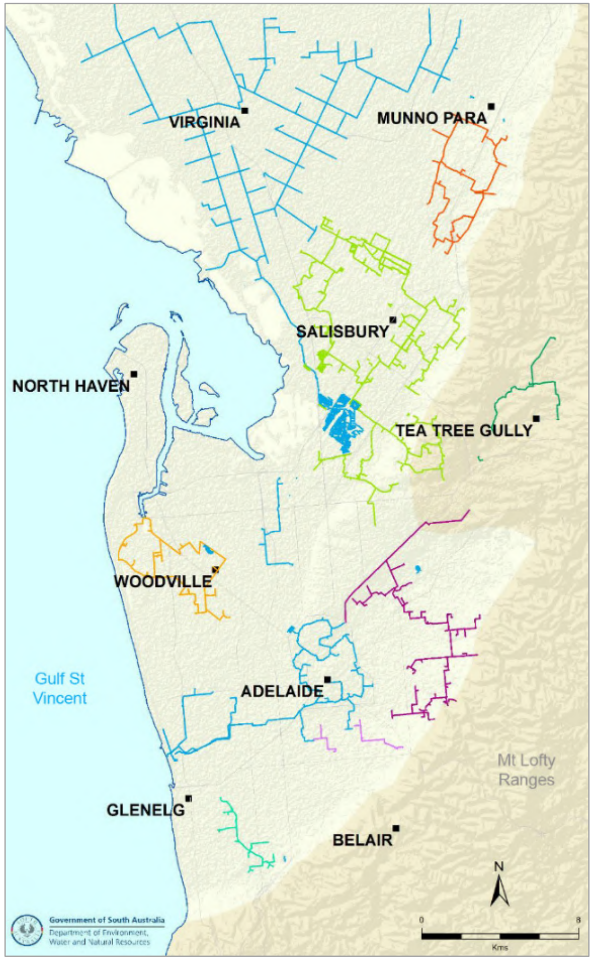


Fig. 3-39: Alternative water distribution networks by city councils in the Adelaide Metropolitan Area (DEWNR, 2017)

and community asset. In addition, irrigating large areas of land improves the microclimate and alleviates the urban heat island effect.

Purple Pipelines – Are pipes typically colored purple to distinguish non-potable water distribution systems from traditional potable (drinking) water pipelines. The use of purple pipelines helps to prevent accidental cross-connection with potable water supplies, reducing the risk of contamination.

The recycled water is also repurposed for other non-potable domestic uses. Approximately 450 million liters per year of recycled water are pumped in separate purple pipe networks across Adelaide for uses such as toilet flushing, laundry washing, and garden irrigation. Besides, another irrigation scheme supplies 12 billion liters of recycled water per year from the Bolivar Wastewater Treatment Plant to provide additional recycled water to horticulture growers in the Northern Adelaide Plains (Laurenson et al., 2010).

Adelaide Airport irrigation trial

SA Water and Adelaide Airport have conducted a trial on a 4ha site within the airport to provide evidence on the effectiveness of large-scale irrigation in promoting urban cooling. Over a two-year period, this initiative focused on evaluating how irrigation in the open spaces of Adelaide International Airport could lead to temperature decreases. By employing aquifer storage and recovery (ASR) techniques, stormwater was harvested and utilized to water the site. Temperature differences between irrigated and

Fig. 3-40: Location of airport irrigation trial project and Glenelg recycled water network to the park land and Victoria Square green track

Map by author based on data from (DATA SA, 2020)
Photo: (Adelaide Parklands Assoc., 2023)

control sites have been rigorously monitored, revealing that irrigated areas are consistently 2.4 to 3.8°C cooler, with surface temperatures showing even greater discrepancies. The findings suggest a vast potential for utilizing airport lands for crops that contribute to cooling, extending cooler air to adjacent areas (Ingleton et al., 2020).

Victoria Square green tram track

Adelaide features a green track in the heart of the city at Victoria Square. On the square's western side, three segments of varying lengths border the central public space. The green track is vegetated with Kikuyu grass over at least 150mm of topsoil. A subsurface drip line system provides the irrigation needs of the vegetation, supplied by recycled water sourced from the Glenelg Pipeline to meet its water requirements (Pfautsch & Howe, 2018).

Fig. 3-41: Adelaide green tram track at Victoria Square (Photo: Philip Mallis, 2015)

3.6.6 Design Flow Methods

Designing WSUD elements is an elaborate process that involves determining and assessing various aspects, including site suitability, soil characteristics, design targets, and system configurations. Key to this process is the quantification of design flows, which involves estimating the rates and volumes of water runoff that a system is expected to manage. The accuracy of these calculations is vital for ensuring the system's reliability. In this context, two predominant design methodologies are employed globally: single event (design storms) and observed record modeling (continuous simulation). Selecting the most appropriate method hinges on the design goals and regional climate attributes, underlining the importance of a tailored approach to WSUD systems design and modeling.

The first design storm approach is the most common and is also known as the traditional method for designing street storm drainage. Design storms are synthetic rainfall events that are used to represent the critical storm conditions for a given location. They are typically derived from historical rainfall data and are selected to represent the peak flow of a critical storm for a specific return period (e.g., 10-year or 100-year storm), where WSUD systems are designed to handle the runoff generated by this discrete event. The predefined storm input in design storms makes the model relatively simple to apply and requires less data than continuous simulation models. The method is better suited for projects where a simplified estimate of the peak runoff rate and volume is sufficient, such as for preliminary design or screening of alternatives (Packman & Kidd, 1980).

However, such a capricious approach, according to Argue and Allen (2004) and IEAust (2006), has raised significant concerns among both Australian and international researchers and practitioners. The method assumes that runoff during critical weather events is not influenced by storm successions or water stored from earlier storms. Assumptions based on the consideration of a full emptying of the system before the beginning of the successive design storm event may not accurately represent real rainfall patterns and can lead to over- or undersized storage volume of the system.

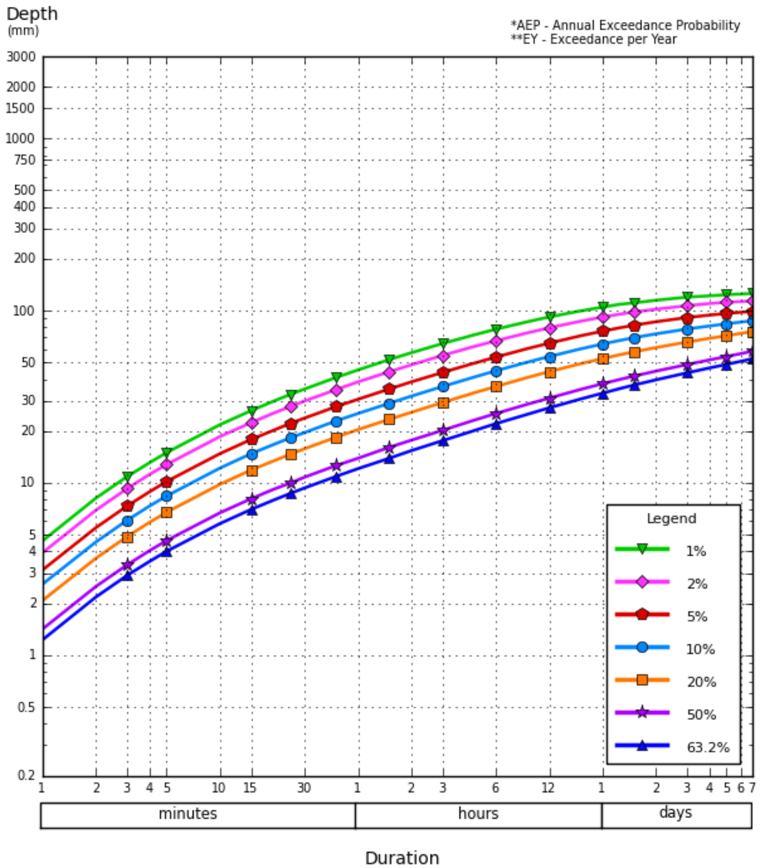


Fig. 3-42: Example of Intensity-duration-frequency (IDF) curve for Adelaide, Australia (BOM, 2022)

A key critique of the design storm approach in Australia was discussed by Boughton (2003) and Kuczera et al. (2006). The article points out significant evidence that using initial average estimation for design flow calculations can be problematic and biased. Kuczera and other experts recommended a shift towards a more systematic and precise approach to address the issue of inter-event emptying. They, along with the Australian runoff quality guide to WSUD (IEAust, 2006), advocated the continuous simulation approach as a better alternative for more realistic modeling conditions.

Continuous simulation involves the utilization of historical time series rainfall data (typically 20 years or more) together with a catchment runoff model to generate a continuous runoff generation flow record for the catchment. This approach considers the temporal characteristics of rainfall patterns in periods without rainfall, as well as the cumulative effects of multiple storm events in the rainy season. Continuous simulation models can provide a more comprehensive evaluation of long-term hydrologic behavior. However, they are more complex and require a significant amount of data, which can limit their applicability in some cases (Boughton, 2003).

The simulation model generates hydrological curves for a catchment area, district, or city, reflecting its historical rainfall patterns. The curves are based on the concept that the system effectiveness decreases as antecedent soil moisture increases, by linking rainfall excess to prior soil moisture. The model takes account of the following key assumptions:

- The Equivalent Impervious Catchment Area (A_{EIA}) connected to the system, calculated using a suitable runoff coefficient.
- Diversion of all major runoff exceeding the flow limit (Q_{lim}) to a bypass before entering the system.
- System overflow upon reaching full capacity.
- Consistent infiltration rate (or supply to collection system) is maintained during storage.

System performance is evaluated through hydrological effectiveness (R), also called retention efficiency, as the ratio of the system's usable capacity to the total runoff event volume, shown as a percentage (Fig. 3-44).

These hydrological effectiveness curves graph the relationship between two independent variables of storage and discharge unit flow. Storage needs are quantified as a percentage of the *Mean Annual Runoff Volume* (% MARV), while discharge concerns the flow rate exiting the system (q), through infiltration, slow release to a collection cistern, or both. Identifying unit discharge rate (q) considers parameters of the host soil hydraulic conductivity and the effective impervious area (Fig. 3-45).

The curves can be utilized in both ways: they can either help determine the necessary storage capacity or identify the discharge rate required to meet a specific efficiency target based on the climate and location. Locating the discharge unit rate (q) on the graph, with respect to the required *Retention Effectiveness* (R), indicates a corresponding storage ratio of the (% MARV). The method allows for trial adjustment of the system's volume size or replacing soil with a higher hydraulic conductivity rate to reach the optimum hydrological effectiveness of the system that meets the design requirements and suits the site conditions.

As suggested by the Australian runoff quality guide to WSUD and The WSUD technical manual for greater Adelaide (IEAust, 2006; SA Govt, 2010), when the primary goal is to sensitively manage stormwater pollution, the hydrological effectiveness curve method proves useful. While the design storm method is recommended for scenarios where managing peak flows and flood mitigation are the primary concerns. However, the (IEAust, 2006) suggest

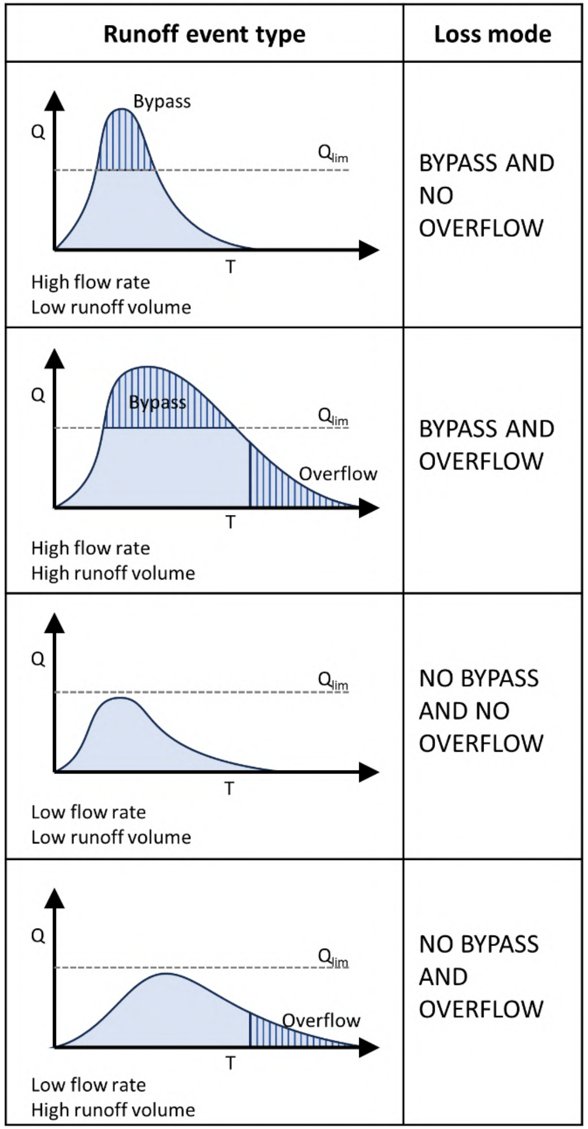


Fig. 3-43: Hydrological Event Processes. Adapted from (Boughton, 2003; SA Govt, 2010)

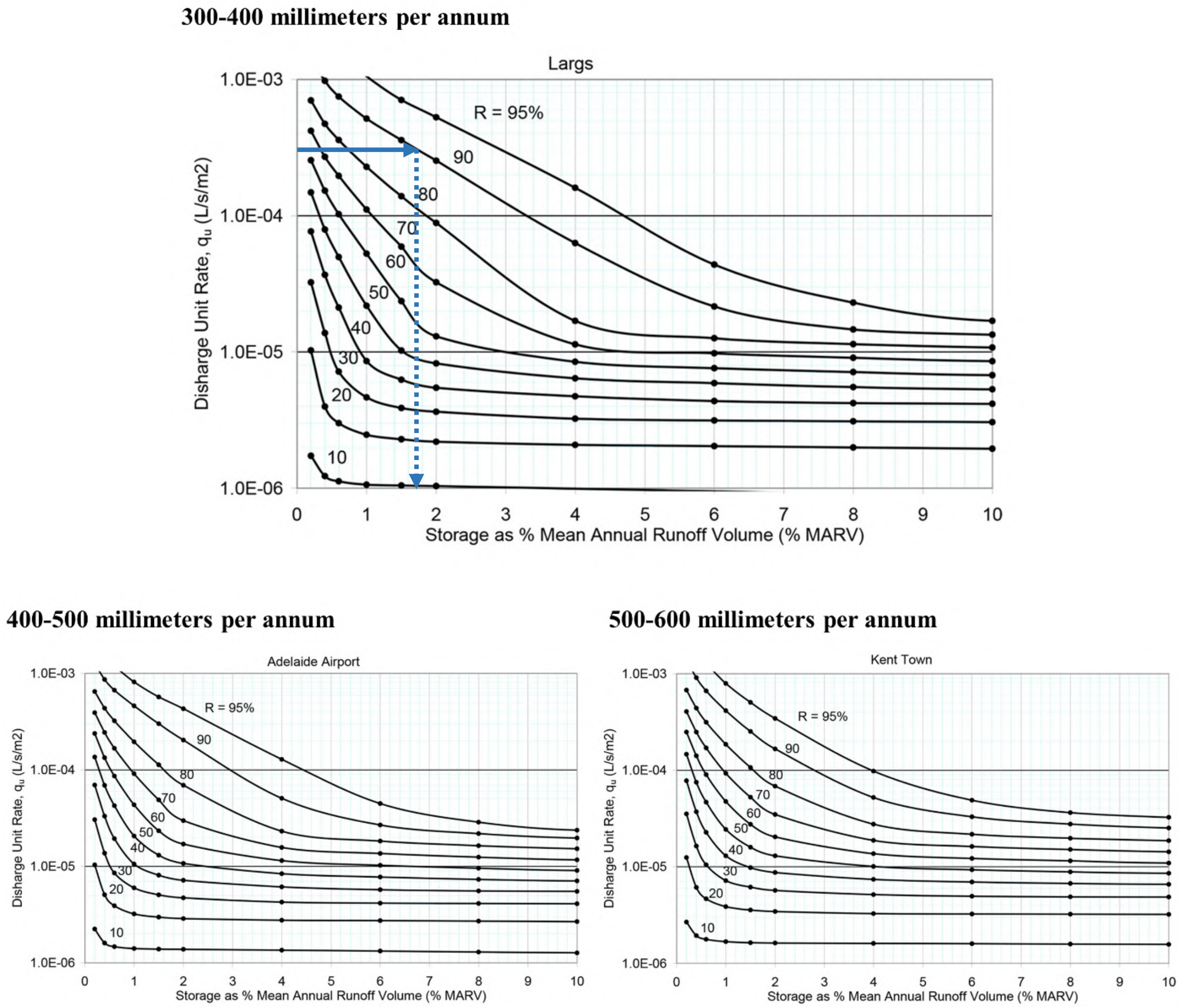


Fig. 3-44: Example Hydrological Effectiveness Graphs of various city councils in Adelaide metropolitan areas (SA Govt, 2010)

implementing both design approaches when both peak flow management and pollution control are critical, and applying the larger.

The planning and implementation of WSUD in dry Australia has a more expansive approach covering the entire urban area where it is possible to conserve and treat stormwater while enhancing amenities, not just addressing flood-prone areas. This broader scope may offer another possible explanation for the preference for the continuous simulation design flow method over the design storm method commonly used in humid regions.

> ”The distinctive features of arid and semiarid regions, and the effects of the hydrological processes which occur in them, underline the need for modelling approaches which may be different from those developed for humid regions.” *(PILGRIM et al., 1988)*

In conclusion, the success of hydrological modeling largely hinges on data quality rather than the model's sophistication. Arguably, the biggest challenge in simulating dry climates is the lack of available data (Pilgrim et al., 1988). Therefore, the selection of the appropriate method for WSUD design requires a thorough understanding of the project's needs and limitations, taking into account the particular characteristics of the region.

3.7 Lessons from Adelaide

Adelaide's experience with WSUD offers profound insights into urban water management in a region with a dry climate. The city's approach integrates comprehensive urban water management strategies to address its unique challenges of variable rainfall, periodic droughts, and flooding, and reliance on conventional water sources.

Adelaide has moved towards an integrated management approach that not only addresses water scarcity but also includes stormwater and wastewater as critical elements of the urban water cycle. This paradigm shift was catalyzed by the Millennium Drought, which underscored the limitations of relying solely on traditional water sources. Adelaide's approach underscores the importance of diversifying water sources beyond traditional reservoirs and river water. The introduction of stormwater harvesting schemes and the reuse of wastewater have been crucial in enhancing water security and reducing dependency on vulnerable natural sources. The development and integration of the WSUD concept into Adelaide's contemporary urbanization has been pivotal in achieving this goal. WSUD in Adelaide is not merely a set of technical solutions but a strategic approach that has been effectively mainstreamed into the city's urban planning and design practices.

The city, notably, has set its primary focus on stormwater harvesting and reuse. It intensively incorporates stormwater storage techniques within most WSUD implementations, mostly in conjunction with nature-based treatment technologies like bioretention, swales, and wetlands. Adelaide has significantly broadened the applications of water retention and storage to a range of implementations in different settings and at various scales, from small-scale installations like rain gardens or domestic rainwater tanks, community and street level, to large-scale projects like wetlands and ASR at the catchment level. The experience in Adelaide shows that WSUD solutions must be scalable and adaptable to different urban settings and tailored to fit local conditions and urban planning requirements, necessitating the need for unique, context-driven design guidelines and considerations. The implementation of WSUD technologies in Adelaide has proved that both bioretention and wetland systems are the most adopted practices to fulfill the multiple goals of local councils in Adelaide. The design and implementation of WSUD technologies in the city show a tendency towards subsurface or enclosed systems rather than open water ponding. The sealing of bioretention systems with impermeable liner material is predominantly practiced in the city to promote retention and for collection for further storage.

Urban planning in Adelaide has also integrated WSUD strategies to mitigate flood risks in certain areas. The city's adaptive approach demonstrates the multiple benefits achievable by WSUD solutions. By retaining and reusing stormwater within the urban environment, the total runoff volume is reduced, alleviating pressure on sewer systems. Additionally, WSUD practices in Adelaide have enhanced the aesthetic and ecological value of urban spaces. Green infrastructure contributes to urban cooling, improves air quality, and supports biodiversity.

Projects in Adelaide demonstrate the effective use of open public space and streetscape in retaining and treating urban stormwater runoff. The use of public open space for managing urban stormwater can be achieved using a number of WSUD decentralized techniques that not only perform their primary role in treating and holding stormwater but also create attractive green spaces and habitats that can increase recreational amenity and adjacent real estate values. On the other hand, the city's experience with supplying sufficient irrigation for larger green areas shows that wastewater recycling and stormwater harvesting schemes are essential solutions in supplementing water demands.

One interesting insight from Adelaide is that despite the absence of mandatory WSUD requirements until 2022, Adelaide has seen extensive WSUD integration across various development types. These included residential homes, street layouts, parking facilities, subdivisions, multi-unit developments, commercial and industrial zones, and public spaces. The effective adoption of WSUD in Adelaide has benefited from robust community involvement and the creation of encouraging policy frameworks. Initiatives by local councils played a pivotal role in enhancing community understanding and acceptance of WSUD methodologies. Additionally, ongoing monitoring and evaluation of WSUD projects in Adelaide help refine and optimize water management strategies. The approach to documenting and analyzing WSUD projects provides essential data and valuable feedback that guides future developments and policy adjustments.

The design flow method adopted in Adelaide is another interesting finding. The city's experience underscores the benefits of using continuous simulation methods over the design storm technique in WSUD modeling, particularly given the local planning approach that addresses the whole urban area. This approach allows for the optimization of WSUD systems to manage both typical and extreme weather conditions effectively, ensuring they meet the main targets of stormwater retention and quality requirements.

In conclusion, the integration of technology, policy, and community involvement in Adelaide has contributed to an urban water management system that enhances the city's capacity to face future climatic challenges while improving the quality of urban life. Adelaide’s proactive WSUD projects, initiatives, and wide implementations serve as a model that Alexandria and other cities with similar climatic conditions could emulate. These implementations from Adelaide contribute to the primary objective of this dissertation: to develop a spatial framework for WSUD in dry climates, particularly tailored for Alexandria and the broader MENA region. The insights obtained from Adelaide’s experience have been instrumental in identifying the key adaptation goals and principles applicable to dry environments, which could be explicitly incorporated into the conceptual framework introduced in this dissertation.

Moreover, the distinct urban densities in Adelaide and Alexandria (each within their unique regional contexts) have highlighted the importance of scalability and sizing flexibility in the selection of WSUD technologies. This adaptability aspect is essential for effective WSUD strategies that cater to varying urban densities. Furthermore, a thorough review of the performance and limitations of WSUD technologies in dry climates is crucial for developing a selection tool aimed at optimizing WSUD implementation in these regions. This review underpins the methodological approach of the dissertation, ensuring that the proposed framework is both robust and applicable to specific local needs.

4 WSUD SPATIAL FRAMEWORK

The framework is a structured conceptual model for understanding and analyzing spatial information that guides the utilization of physical spaces and infrastructure for integrating WSUD practices into the urban development process. For promoting a Middle Eastern and North African approach to WSUD, it is imperative to consider local dependent factors in the development and implementation of the framework to ensure its effectiveness and acceptance within the broader urban context of the region. The framework aims to mainstream WSUD concept and technologies in the current spatial planning and development schemes.

The conceptual model outlines a set of principles, methodologies, and instruments that address the water related challenges in the region and are based on the findings drawn from previous chapters. Key components that have been developed include, first, setting performance-based principles and targets that emphasize achieving desired urban water management and conservation outcomes. Second, an interdisciplinary water sensitive urban analysis and planning approach that considers hydrological, environmental, and urban factors to form the delineation of spatial boundaries and the identification of key linear infrastructure assets to be addressed accordingly. Third, a systematic evaluation and assessment of the adaptability of WSUD technologies to the local urban and climatic conditions while offering selection prioritization based on the predefined performance criteria. Finally, a planning and data management instrument that integrates all previous aspects in a spatial decision support system that guides the selection of appropriate WSUD strategies and applications for various urban areas. The framework components work together and feed each other in an integrative approach. This approach focuses not only on the implementation of sustainable urban drainage systems but also on developing comprehensive tools and methods for the effective integration and adoption of WSUD.

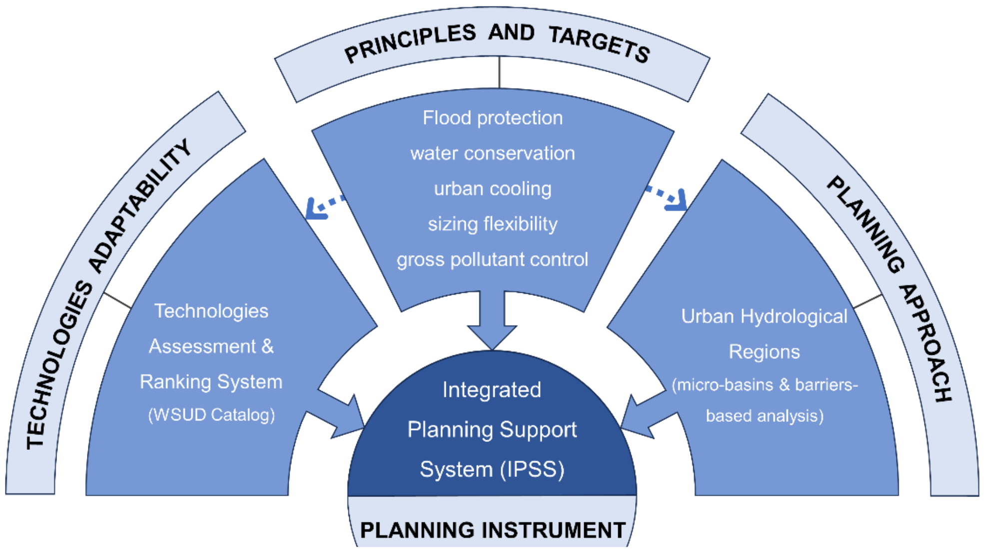


Fig. 4-1: Spatial Framework for WSUD adaptation in hot dry climates (By author)

Characteristic of the WSUD Framework:

- Establishes clear WSUD principles and targets customized to the local context.
- Provides a unifying approach for WSUD with the city's urban water management goals and strategies.
- Facilitates the integration of WSUD into local municipalities and the city infrastructure and open space projects.
- Utilizes the local planning and development system to promote WSUD.
- Recommends and outlines practical implementation mechanisms for WSUD.

4.1 Principles and Targets

WSUD seeks diverse outcomes with overarching principles, commonly centered on improving water security, climate resilience, livability, and preserving water bodies and ecosystems. However, the context in which goals are set necessitates careful consideration of local circumstances. Goals may align with general principles, address some from different perspectives, or combine others based on local drivers and challenges. For instance, regions prioritize WSUD goals based on their climate and urban setting. In dry Australia, the focus is on water conservation practices driven by the stressing conditions of water scarcity, while in humid Europe and most of North America, the emphasis is much directed towards flood protection addressing water abundance.

In examining the MENA region's arid urban environment, as discussed earlier in this dissertation, a dual challenge of managing both flooding and drought emerges. This unique context places the region in a position to draw on experiences from both humid and dry climates, necessitating the acquisition of knowledge and adaptation processes from both (Fig. 4-2). In Alexandria, key goals include promoting both **water conservation** and **flood control** strategies. Additionally, the sparsely vegetated local environment, constrained by limited water resources and high temperatures, highlights the potential to integrate stormwater and wastewater management into urban and landscape design. Incorporating water-sensitive practices, such as raingardens and other vegetated systems, into green spaces can enhance urban resilience and aesthetics while maximizing overall urban amenity. This approach not only mitigates climate risks but also contributes to a paradigm shift that views **urban greening** as a solution rather than a burden, thus improving the livability of built environments in arid regions. Effective water management and green spaces can also help mitigate heat island effects, making **urban cooling** a vital goal.

Urban development and human activities generate pollutants that stormwater runoff can carry into water systems. Therefore, another typical goal is ensuring the **treatment of stormwater runoff** to protect natural receiving waters and their associated ecosystems from the risk of contamination.

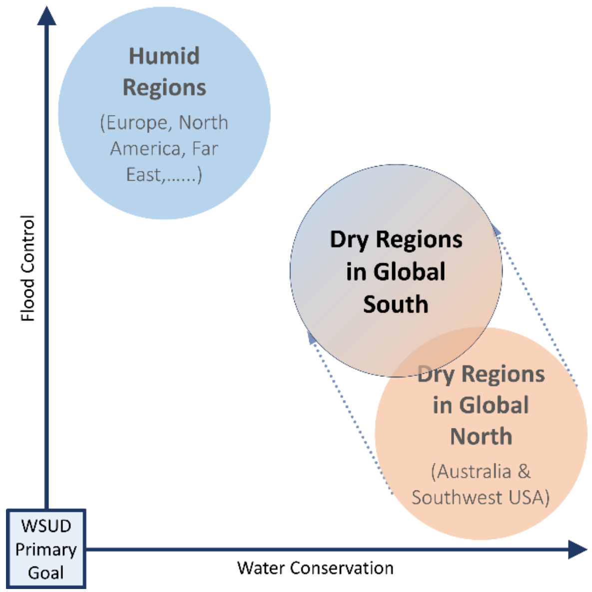


Fig. 4-2: A diagram illustrating the difference in WSUD primary goals between dry and humid regions, showing the occurring shift of dry regions in the Global South towards considering both goals (By author)

These varied goals in fact synergize with each other and are achievable through the adoption of the **decentralized approach** of WSUD and related techniques that seek to closely mimic the natural drainage regimes and typically manage runoff close to source. This reduces the strain on centralized water infrastructure and minimizes the impact of urban development on the natural water cycle.

The following set of guiding principles support these goals to transform traditional urban water management and the implementation of WSUD in the MENA region. They are addressed further and promoted through relevant targets and the planning process.

WSUD Guiding Principles:

- Promote water conservation and resource protection.
- Mitigate risks related to climate extremes including drought, floods, and public health.
- Preserve and enhance natural waterways and ecosystems.
- Align post-development runoff with predevelopment natural conditions.
- Incorporate water cycle management into urban and green space design for enhanced amenity.

The practical implementation of WSUD principles is facilitated through four key measurable performance-targets: managing runoff, conserving water, cooling urban areas, and ensuring sizing flexibility. These targets serve as major criteria governing the deployment of WSUD measures and technologies. Meeting each of them is required as needed according to the site scale, type, and spatial features at hand. Primarily, targets to mitigate flooding and water stress are essential and must be fulfilled. Other Secondary targets are addressing heat stress and urban density. This classification is reflected in the WSUD selection catalog and the spatial decision support system.

1- Managing Runoff

This target addresses the need to effectively manage the excessive stormwater runoff flow and inundation within urban environments, ensuring decentralization and providing treatment capacity.

- *Managing the Rates of Runoff:* Regulate the velocity of runoff flow by reducing connected sealed surfaces to prevent destructive peak flow during heavy rainfall.
- *Managing the Volume of Runoff:* Integrate measures to promote retention, detention, and infiltration, intercepting stormwater at its source to reduce the overall volume of runoff.
- *Improving Quality of Runoff:* Implement on-site stormwater treatment measures to minimize pollutants and contaminants that could impact receiving water bodies and ecosystems.

2- Conserving Water

This target focuses on optimizing water usage in urban areas, emphasizing the reuse of rainwater and greywater to reduce reliance on municipal freshwater supplies.

- *Provide Alternative Water Sources for Irrigation:* Advocate using alternative water sources for irrigating green spaces, reducing the demand for potable water.
- *Capture and Store Rainwater:* Encourage the implementation of systems for collecting and storing rainwater at the domestic level for non-potable uses.
- *Use of Greywater:* Promote the use of treated greywater for non-potable purposes, supporting domestic water recycling.
- *Large-Scale Water Recycling Schemes:* Explore large-scale schemes utilizing nature-based treatment processes to transform stormwater or treated wastewater into valuable resources for storage and reuse.

3- Urban Cooling

This target recognizes the pivotal role of green and blue spaces in improving microclimate.

Decreasing Urban Heat Island Effect (UHI): Increase irrigation capacity to support the expansion of green spaces and water bodies, enhancing shading through improved tree canopies. Green roofs and walls on buildings also play a crucial role in urban cooling.

4- Sizing Flexibility

The assessment of each WSUD technology should not only be restrained to their drainage performance but also with consideration to meet the local built forms. Stressing the question of how these systems can be applied in varying and more specifically high-density urban areas (Sagala et al., 2022). The availability of space was a major comment repeatedly stressed by experts in most interviews conducted within the work of this dissertation as a spatial constraint to the implementation of large-scale systems. In high-density urban areas, where space is often limited and development pressures are high, it is important for the implementation of decentralized solutions to consider systems that are flexible and can be adapted to varying site conditions.

- *Scalable Technologies:* scalable systems like bioretention and pervious pavements, in addition to other system require subsurface volumes and less space on the surface such as soakaway and geomodular systems, are likely be suitable than other.
- *Multifunctional Systems:* considering multifunctionality as an effective use of available space that combine purposes of stormwater management and amenity (Rieke Hansen et al., 2019). This approach ensures that WSUD measures can efficiently address various urban water management challenges while minimizing spatial constraints.

Gross Pollutants Control: Given the nature of urban drainage in dry climates, controlling gross pollutants emerges as a perpetual concern. Stormwater in dry environments often carries high pollutant loads, especially during the initial runoff (first flush) of urban catchments during rainfall events. This has been consistently noted in the case of Adelaide, Alexandria and other cities, and echoed as well by experts' insights in interviews. Thus, addressing gross pollutants and sediment management is considered in this framework as an additional aspect that must be constantly considered in any planning and design process, regardless of what other targets may take precedence.

- Pollutant Load Management: Addressing the high pollutant loads in stormwater, especially during initial runoff, is crucial. Effective sediment management and gross pollutant control are essential in planning and design processes to ensure sustainable urban drainage.

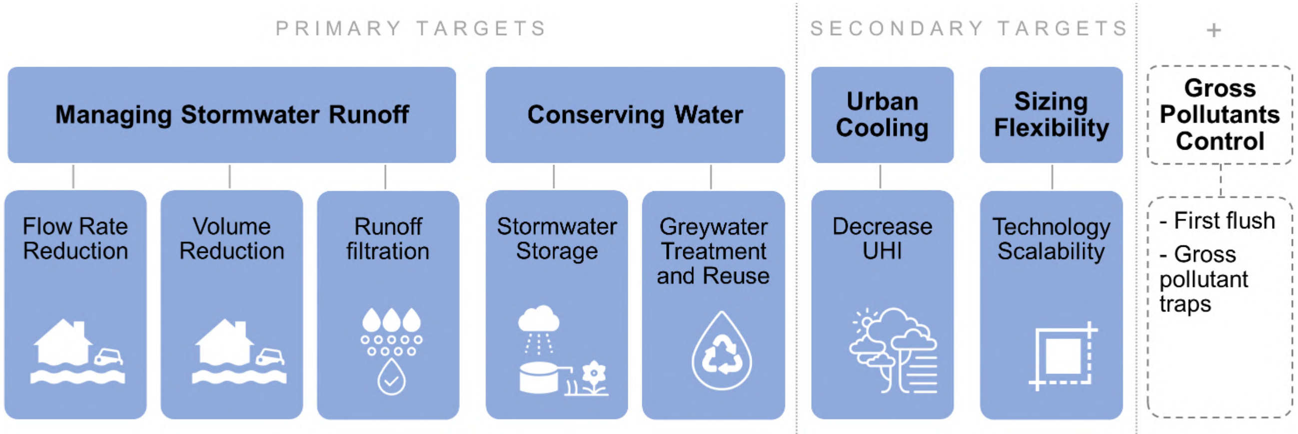


Fig. 4-3: City-wide primary and additional WSUD performance targets (By author)

4.2 Planning Approach

As discussed in Chapter 2, excessive physical barriers in urban areas combined with inadequate drainage infrastructure can exacerbate the threat of flooding by obstructing stormwater runoff and directing it to certain areas. This particular setting of a dry built environment in the MENA region suggests the spatial approach most suitable for water-sensitive urban planning and design. A climate-responsive interdisciplinary planning approach considers hydrological, environmental, and urban structure factors. Termed in this dissertation as Urban Hydrological Regions, this planning system spatially decomposes urban areas into discrete micro-basins confined by extended physical barriers and delineates them as areas with distinct surface flooding characteristics.

The mapping and analysis of hydrological regions of an urban area primarily involve identifying the location and extent of those major barriers that potentially or provenly obstruct runoff flow, as well as the resulting basins. These basins do not follow any existing administrative subdivisions, such as districts, councils, or municipalities, but are constituted solely by the areas the barriers demarcate.

The diagram in Figure 4-4 presents an overview of a multi-stage, integrative approach for water-sensitive planning and design. The outlined process is based on the segmentation of hydrological regions concept, which commences with a mapping phase where the existing conditions are surveyed by identifying the location and extent of the barriers and boundaries. These delineate the urban area into manageable and smaller catchment zones (micro-basins) that contribute differently to the risk of flooding.

The second phase is a thorough evaluation of micro-basins and barriers, typically aimed at understanding their dynamics and assessing their capacity and limitations for water-sensitive implementations. The analysis encompasses

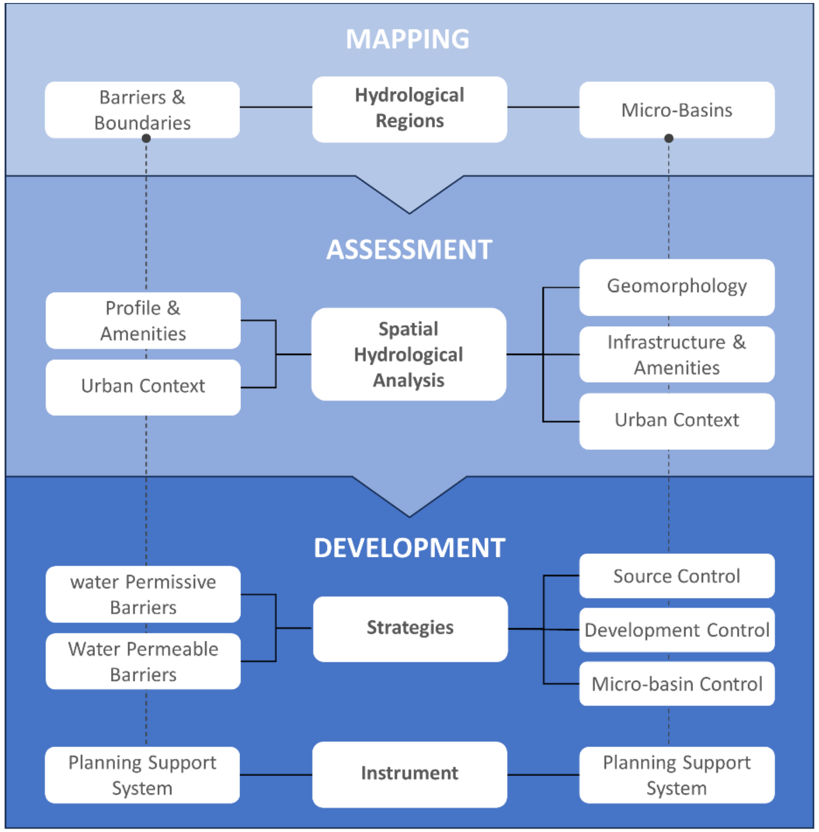


Fig. 4-4: Planning approach process and Structure (By author)

spatial, hydrological, geotechnical, and environmental aspects. It examines both surface and subsurface conditions to acquire a multi-dimensional perspective on urban water dynamics.

The final phase involves the deliberate placement of water-sensitive development plans for both basins and barriers accordingly. The development can formulate appropriate mitigation strategies that address the nature of each and the type of risk it generates. While developing these tangible techniques, various integral instruments and methods are employed to support and facilitate the decision-making and implementation processes.

This planning approach pertained to Urban Hydrological Regions is detailed as follows:

Urban Barriers and Boundaries

Urban barriers and boundaries refer to the physical features and structures that separate different areas within a city or urban environment. These barriers and boundaries can include structures like motorways, walls, fences, rivers, railroads, and other infrastructure that create divisions within urban areas. They serve various purposes, such as controlling traffic flow, providing security, and separating land uses.

Mapping Criteria: These constitute a set of parameters crucial for a comprehensive depiction of urban barriers, selected based on their role in impeding water flow. Factors considered include the barrier's location, extent across the urban layout, elevation from the ground surface, and its impacting width. The criteria include:

- Main Roads and Motorways that have two ways with a total width equal to or exceeding 40 meters, featuring a substantial spacer, like a high median strip or concrete blocks (Jersey barrier).
- Rail Transit Lines include both walled tram and railroad tracks that cut across urban areas.
- Water Courses within developed areas and protected with guarded sides like seafronts, lakes, and canal sides.
- Local Walls and Fences include substantial fencing walls which could be mapped for further analysis and development within a micro-basin.

The Assessment: Involves a systematic spatial analysis of physical characteristics and the adjacent settings of barriers' profiles, in addition to the assessment of underlying soil hydraulic properties. Since homogeneity along the barriers is unlikely, the analysis serves as the foundation for selecting WSUD strategies and technologies to be applied accordingly.

The development of barriers: Aims to dramatically reduce their obstructing nature, transforming them into 'permissive barriers' that actively engage with surface runoff and allow water flow through in various directions, into the ground, along or across the barrier. This involves integrating decentralized measures that enhance the barrier's ability to promote infiltration, evapotranspiration, water conveyance, and ensuring permeation to both sides. Complete blocking should be considered only purposefully for barriers protecting highly vulnerable areas, with measures in place to prevent negative impacts on other areas. This approach involves delivering WSUD applications along these different linear infrastructures. Their substantial extent presents a significant asset and opportunity to establish an integrated water-sensitive and green corridors designed to treat, store, and convey stormwater, reducing the risk and severity of flooding. This approach also facilitates the connection of stormwater management sites across micro-basins.

Methods and Instruments: involve breaking down each barrier into typical profile typologies that can be addressed with appropriate WSUD design implementation. Each profile can be integrated into the WSUD decision-making model developed in this chapter.

Urban Micro-basins

Micro-basins are micro urban catchments, representing discrete hydrological zones characterized by their independent surface drainage. They typically cover limited spatial extents and could be considered to have a crucial role in urban water management, particularly in cities like in the MENA. The concept of micro-basins is integral to understanding localized hydrological processes, soil erosion dynamics, and the efficient utilization of water resources at a finer scale. As the basins result from the intersection and crossing barriers, criteria for identifying micro-basins consider all zones delimited or entirely confined by one or more types of those barriers, within the overall extent of urban areas.

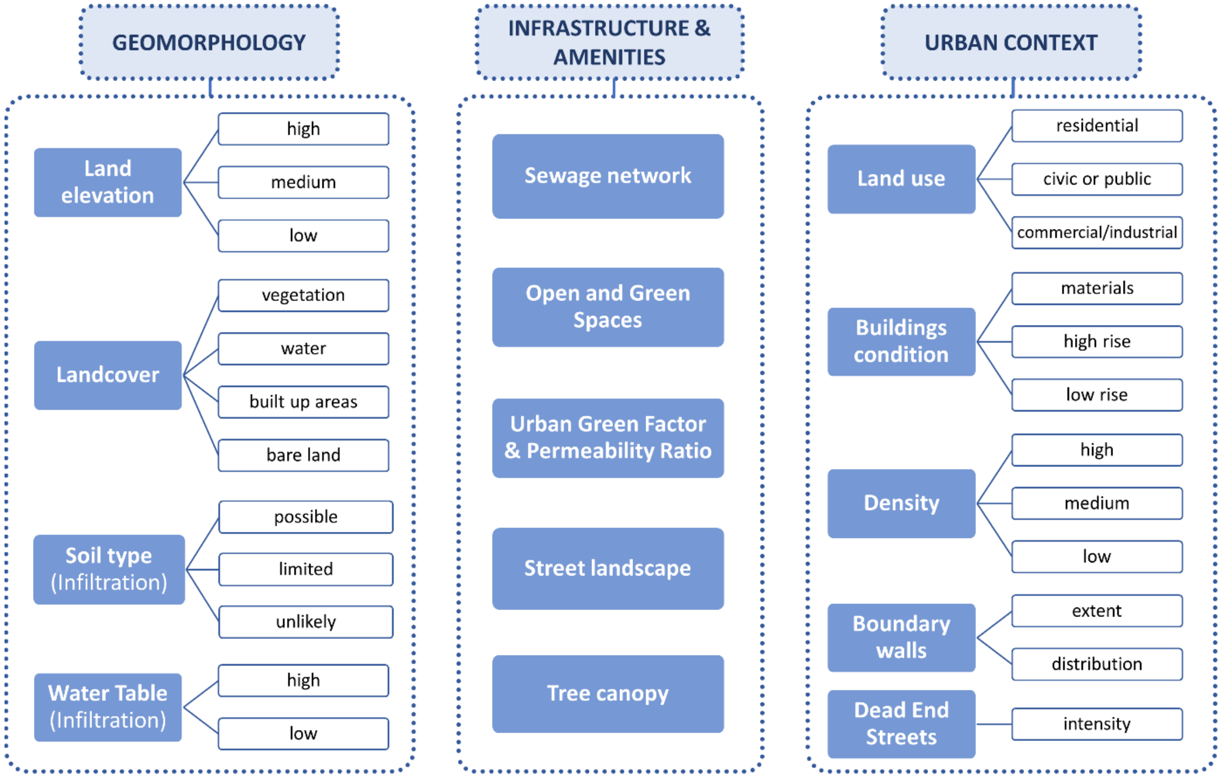


Fig. 4-5: Micro-basins spatial analysis framework (By author)

The assessment: Involves investigating various urban geospatial aspects and environmental characteristics on the micro-catchment scale including the following:

- Geomorphology – Encompasses a range of geospatial data analyses aimed at providing a comprehensive image of the city's landscape. This includes surface features of land elevation and land cover, as well as various geotechnical data to gain insight into subsurface characteristics, including soil classification and water table levels across the entire city.
- Urban Context – Component addresses the built-up features and organization of the urban areas, including land use and zoning, building conditions, different urban densities, boundary walls, and the extent and distribution of street dead ends in relation to flooding hotspots.
- Infrastructure and Amenities – Covers the physical structures necessary for the functioning of a city, including the drainage system and streetscape. Amenities encompass ecosystem services that are pivotal to inhabitants' well-being, such as urban green areas and tree canopy.

The outcomes of this analysis are classified into leveled parameters and serve as input for the decision support system.

The development strategy: Aims at managing stormwater at different levels by applying decentralized measures that start with localized control at individual properties and build up to the management of entire micro-basin catchments. This hierarchical, multi-scale approach ensures effective stormwater management tailored to the dynamics of urban areas. The diagram in Figure 4-6 illustrates the approach as follows:

- Source Control – This foundational level aims at the immediate management of rainwater where it falls. By employing localized solutions like rain gardens, permeable pavements, green roofs, and rainwater harvesting systems, these systems intercept and utilize stormwater at the property or plot level. The overarching goal at this stage is to prevent uncontrolled runoff and promote the natural hydrological cycle.

- Site Control – Recognizing that not all stormwater can be managed at the source, the second tier addresses the site-specific measures within a development. Through the implementation of detention basins or retention ponds, excess water is managed by temporary on-site storage. At this level, implementations can also support gradual infiltration and ensure a controlled release into a stormwater collection system or directly to watercourses.

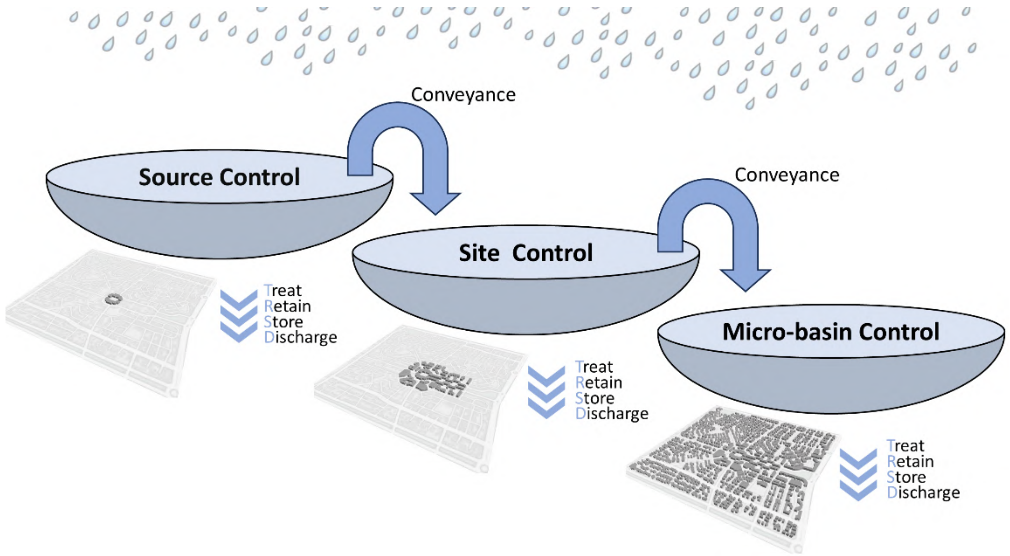


Fig. 4-6: Schematic represents an adapted hierarchical approach to manage stormwater in hot, dry regions, based on SuDs management train (CIRIA, 2016)

- Micro-basin Control – The third level addresses water management on an even larger scale, incorporating measures for multiple sites or entire micro-basins. At this level, the approach entails the use of larger detention facilities and constructed urban wetlands, which are designed to handle larger runoff volumes accumulated from the whole micro-catchment.

The strategy prioritizes a sequence of processes to manage stormwater at each stage before discharge, including treating stormwater for pollutants removal, retaining water within the system to sustain green spaces or promote cooling, and storing treated water for further reuse. The final discharge of water may be through infiltration or into waterways. Further, ensuring that excess water in each stage is passed from one level to the next through a conveyance system. Connecting this approach with the applications of WSUD technologies suggests that large-scale measures can be utilized on the scale of micro-basin to

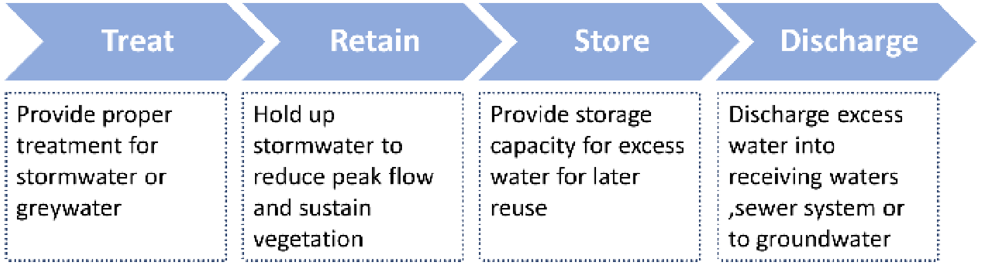


Fig. 4-7: Discharge process at each management level (By author)

development control. Medium-scale measures are best utilized for source to development control scale. Nonetheless, other aspects and constraints of the availability of space may impact any decision.

Instruments: employed to support the planning and design process utilize a decision-making model that integrates inputs from the catchment-based spatial analysis to optimize the design and placement of WSUD technologies in the predefined micro-basins, as well as assist in mapping spatial suitability for WSUD implementation across urban areas.

The identification and analysis of micro-basins can provide insights into the local factors that contribute to flooding and help develop targeted interventions to mitigate their impact. For example, if a micro-basin is identified as a significant contributor to flooding in a particular area, measures such as constructing retention ponds or improving drainage infrastructure can be implemented to reduce the risk of flooding.

Overall, considering micro-basins and barriers as an approach for mapping and analyzing urban areas is an important step in developing effective strategies to mitigate the impact of urban flooding. The importance of this approach is especially evident in urban contexts where existing drainage infrastructure is failing and under-designed, and extreme rainfall events can exceed the capacity of the combined sewer system. In extreme events, the overflowing of the system is imminent, allowing the local nature of the surface to control the runoff flow formed by surface characteristics. This approach aims to address urban flooding locally and facilitate the adoption of WSUD practices on various scales.

4.3 WSUD Catalog

The Water Sensitive Urban Design (WSUD) Technologies catalog is a comprehensive repository tailored for urban areas in dry climates. It encompasses detailed information on a wide range of systems, covering retention, detention, infiltration, harvesting, and reuse techniques. This catalog serves as a vital resource for practitioners and planners, providing access to knowledge and evidence-based practices to enable informed decision-making for incorporating WSUD into urban development projects. Its utility lies in standardizing the adaptation and selection process of WSUD technologies to effectively address the unique challenges of different urban settings.

The catalog is divided into two main complementing sections:

- Technical Considerations and Adaptation Measures, which provides detailed information on the specific technical considerations and adaptation measures required for each technology to perform optimally in dry climates. This section is presented thoroughly in Chapter 3.
- Relevance Ranking. This section offers a systematic assessment and prioritization of the suitability of various WSUD options in the local context.

Ranking System

The ranking system is a selection tool for choosing appropriate WSUD strategies and components. It uses the Multi-Criteria Decision Analysis (MCDA) method to evaluate and compare different alternatives by assigning relative preferences to various solutions based on performance targets (Belton & Stewart, 2001). The key aspects of the ranking system are outlined as follows:

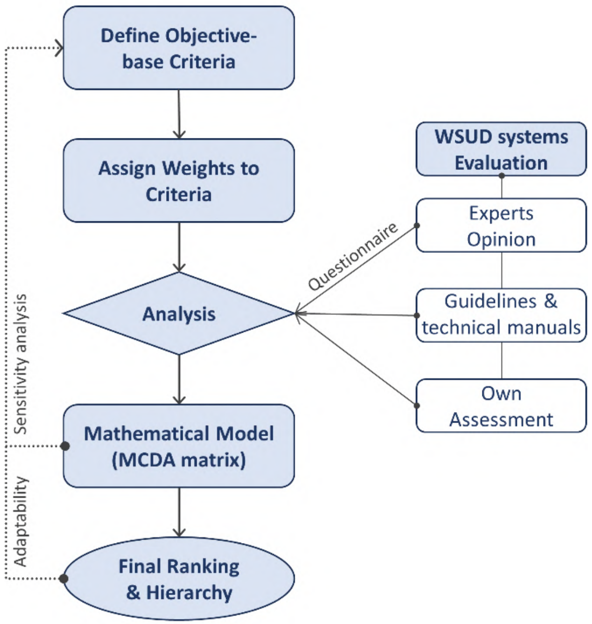


Fig. 4-8: Structure and process of the ranking system (By author)

1- Targets-Based Criteria:

The first step in establishing the ranking system is to determine measuring criteria that reflect the general goals of the WSUD approach in dry climates. These criteria are derived from the specific targets identified in the framework. They include performance measures for flood control, stormwater treatment and storage, greywater treatment, urban cooling, and sizing flexibility.

2-Weighting of Criteria:

Assigning appropriate weights to each criterion reflects their relative importance. Hierarchical weighting, a common approach in complex decision-making scenarios (Stillwell et al., 1987), helps prioritize criteria related to primary targets like flood control and water conservation, which are given more weight than secondary targets of urban cooling and sizing flexibility. This prioritization is validated through stakeholders' and experts' opinions. The weighting of criteria and resulting hierarchy can be dynamic, requiring sensitivity analysis and regular reassessment to ensure the system remains effective and responsive to changing conditions and evolving technologies.

Fig. 4-9: General weight of each criterion

3- Assessment and Scoring:

After establishing criteria and their weights, WSUD solutions are evaluated based on these criteria. Comprehensive data on each WSUD system's performance were acquired from several sources including scientific studies, technical manuals, and guidelines. To obtain additional input from experts, a questionnaire with instructions was shared with a panel of experts who have relevant knowledge and experience in WSUD technologies to seek their assessment of each WSUD system's performance against the criteria based on their personal experience (Annex B). They were asked to assign value scores attributed to the performance range from low, medium, to high. The evaluation form comprises the WSUD cards for detailed definition and description of each system, as well as a description of the measuring criteria, such as:

- *Runoff Flow Rate Reduction:* The effectiveness of the system in slowing down the speed of surface runoff during rain events.
- *Runoff Volume Reduction:* The total volume of stormwater that the system can absorb or detain.
- *Runoff Filtration/Treatment:* The capability of the system to filter and remove contaminants from stormwater to improve water quality.
- *Stormwater Storage:* The capacity of the system to contain and store stormwater for reuse.
- *Greywater Treatment:* The specific capacity of the system to treat and repurpose greywater.
- *Urban Cooling:* The degree to which the system can improve the microclimate and mitigating the heat island effect.
- *Sizing Flexibility:* The adaptability of the system in size and shape to fit different urban spaces and density constraints.

After compiling all the collected data, final scores are assigned to each system based on compiled data and expert assessments and processed in the MCDA matrix. These scores are aggregated with reference to the assigned weights to calculate an overall score for each system. High-scoring solutions are ranked based on their overall scores, indicating their suitability for implementation (Fig. 4-10).

The chart in Figure 4-11 displays the final hierarchy of the different WSUD systems in descending order of appropriateness. Wetlands and Bioretention systems top the chart, indicating they are the highly appropriate based on the general weighted criteria. This results match the findings on Adelaide's practices dominated by these both systems as well. The following in ranking are retention and infiltration systems like Rainwater Tanks, Geocellular and basins Systems, primarily for their capabilities in flood protection and water conservation. Unexpectedly, Green Walls are ranked higher than Green Roofs due to their ability to meet multiple criteria effectively. Despite the fact that the top-ranking systems suggest they are among

CRITERIA	Pervious Pavement	Infiltration Trench	Geocellular System	Infiltration Basin	Bioretention System	Swale	Urban Wetland	Constructed Wetland	Detention Basin	Retention Basin	Green Roof	Green Wall	Rainwater Tank
	WSUD EIEMENTS												
Runoff Flow Rate Reduction	💧💧💧	💧💧	💧💧💧	💧💧💧	💧💧	💧💧	💧💧💧	💧💧	💧💧💧	💧💧💧	💧💧	💧	💧💧💧
Runoff Volume Reduction	💧💧	💧💧	💧💧	💧💧💧	💧💧	💧💧	💧💧💧	💧💧	💧💧💧	💧💧💧	💧💧	💧	💧💧💧
Runoff Filtration	💧💧	💧💧	💧	💧💧	💧💧💧	💧💧	💧💧💧	💧💧💧	💧	💧	💧💧💧	💧💧💧	💧
Stormwater Storage	💧	💧	💧💧💧	💧	💧💧	💧	💧💧💧	💧💧	💧	💧💧	💧	💧	💧💧💧
Greywater Treatment	-	-	-	-	💧💧💧	-	💧💧	💧💧💧	-	-	-	💧💧	-
Urban Cooling	💧💧	💧	-	💧	💧💧💧	💧	💧💧💧	💧💧	💧	💧💧	💧💧	💧💧💧	-
Sizing Flexibility	💧💧💧	💧💧💧	💧💧💧	💧	💧💧💧	💧	-	💧💧	💧	💧	💧💧💧	💧💧💧	💧💧

N/A =– Low= 💧 Medium= 💧💧 High= 💧💧💧

Fig. 4-10: The final evaluation scoring of WSUD elements performance against the set criteria the most suitable for implementation, all solutions can be strategically integrated to complement each other and achieve specific goals. For instance, Rainwater Tanks can work effectively with Green Walls by compensating for the latter's limited stormwater storage capacity. Despite Urban Wetlands excelling in most criteria, they require large open spaces, which can be a limitation. In contrast, Bioretention systems offer high flexibility in scaling and fitting into various densities and landscape settings.

Therefore, the selection process involves the strategic integration of these solutions to achieve specific goals, considering the given conditions of each area. The resulting hierarchy is adaptable to shifting priorities and the dynamic nature of urban environments. This adaptability may necessitate recalibrating criteria weights, ensuring the ranking remains relevant at a local scale, whether for a micro-basin or specific urban development. Ultimately, the WSUD Catalog is not just a prioritization tool but could be the foundation for an Integrated Planning Support System (IPSS) that considers all these spatial aspects and other characteristics across micro-basins.

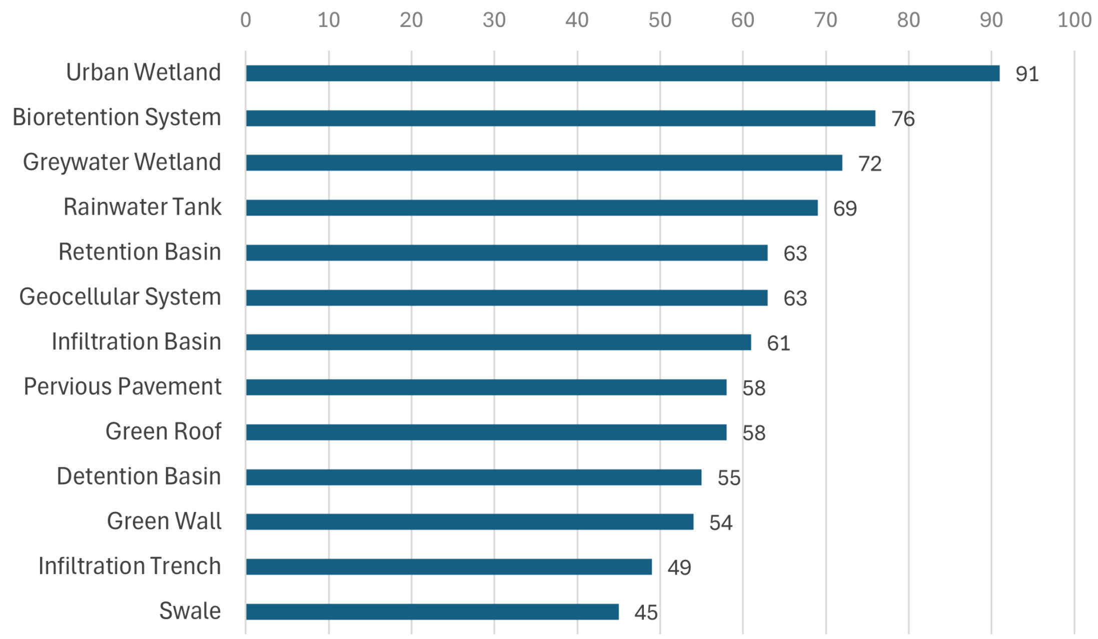


Fig. 4-11: The general ranking of different WSUD technologies

4.4 Planning Instrument

Integrated Planning Support System (IPSS) for WSUD in dry climates is a tool designed to aid decision-makers and urban planners to make informed decisions about the process of planning and design of WSUD applications. The primary objective of the IPSS is to provide analytical tools and information that enhance planning efficiency and effectiveness, and to mainstream the WSUD approach in the current spatial planning and development practices. The concept of Planning Support Systems (PSS), first introduced by Harris (1989), represents an approach in urban and regional planning, emphasizing the integration of Geographic Information Systems (GIS) and other emerging technologies. The concept centers around enhancing decision-making in planning by providing integrative multidisciplinary tools with a strong focus on analytical capabilities and adaptability to different planning contexts.

The IPSS utilizes a computational decision-making model that integrates outputs from the main framework components developed in this chapter as WSUD catalog, targets, and catchment-based spatial analysis. The model deploys the relevance ranking MCDA matrix in input analysis to optimize the design and placement of WSUD technologies in predefined urban catchments down to large scale development. As well as assist in mapping spatial suitability for WSUD implementation across urban areas. Several studies have attempted to develop similar planning tools, most notably the work of Kuller et al. (2017; 2019; 2020), Guerrero et al. (2020) and Sarabi et al. (2022).

WSUD planning suitability as explained by Kuller et al. (2017) refers to its two different sides: 'Opportunities' indicating a place requirements and limitation to WSUD applications; and 'Priorities' indicating the requirements of WSUD applications to function in a place. This perspective underscores the correlative relationship between WSUD applications and urban context where, for example, particular urban settings might have higher opportunity for adopting WSUD technologies than other, such as low-density areas or areas with higher green space ratio. While other space has higher priority for WSUD specific applications that suits its pressing challenges despite its urban context, such as high flooding risk areas (hot spots), which require an informed selection of technologies only can meet the challenge and suite the context. The system introduced here concerns this approach in its model development.

Key components of the IPSS System involve an elaborated data acquisition and management to be fed into the mathematical decision-support model and analytical techniques that utilize collected data. The development of the model (Fig. 4.12) involves, first, the delineation of the urban area to several micro-basins. Each basin contains a set of information covering urban features and characteristics retrieved from the spatial hydrological analysis (e.g., land use, density, heat map, infiltration potential, etc.). The compiled spatial analysis parameters are linked to a pool of WSUD systems through several assessment criteria that allow the model to develop decisions influenced by these connections.

Criteria, as previously described in this section, have relative weights reflecting their importance in the hierarchy. The model allows adjusting those weights in response to the connected indicators' thresholds, reflecting change in priorities in a micro-basin. Nevertheless, the subjectivity of criteria weights is addressed through an iterative participatory process with relevant stakeholders (Ferretti & Montibeller, 2016). Lastly, the model features a pool of 13 WSUD technologies representing those referred to in the WSUD Catalog and covering various infiltration, detention, retention, treatment, and storage strategies.

Central to the model are the spatial parameters and criteria as the main input to drive the decision process. Raw spatial data are reconstructed in the form of corresponding spatial indicators, setting thresholds on a value scale in accordance with WSUD design requirements and the assessment criteria. This procedure aims to interpret the significance of data value normalization concerning the appropriateness of a site for the establishment of WSUD technology as well as its influence on prioritizing criteria. For instance, urban density data can be normalized on a scale from low to high, which influences the weight of the sizing flexibility criterion. In some cases, an indicator of a spatial parameter is directly connected to a specific WSUD system representing either negative or positive attribution to exclude or include the system. For example, a building condition indicator below average, might directly exclude the possibility of considering green roofs for implementation, while high slope in an area would directly boost the option of pervious surfaces.

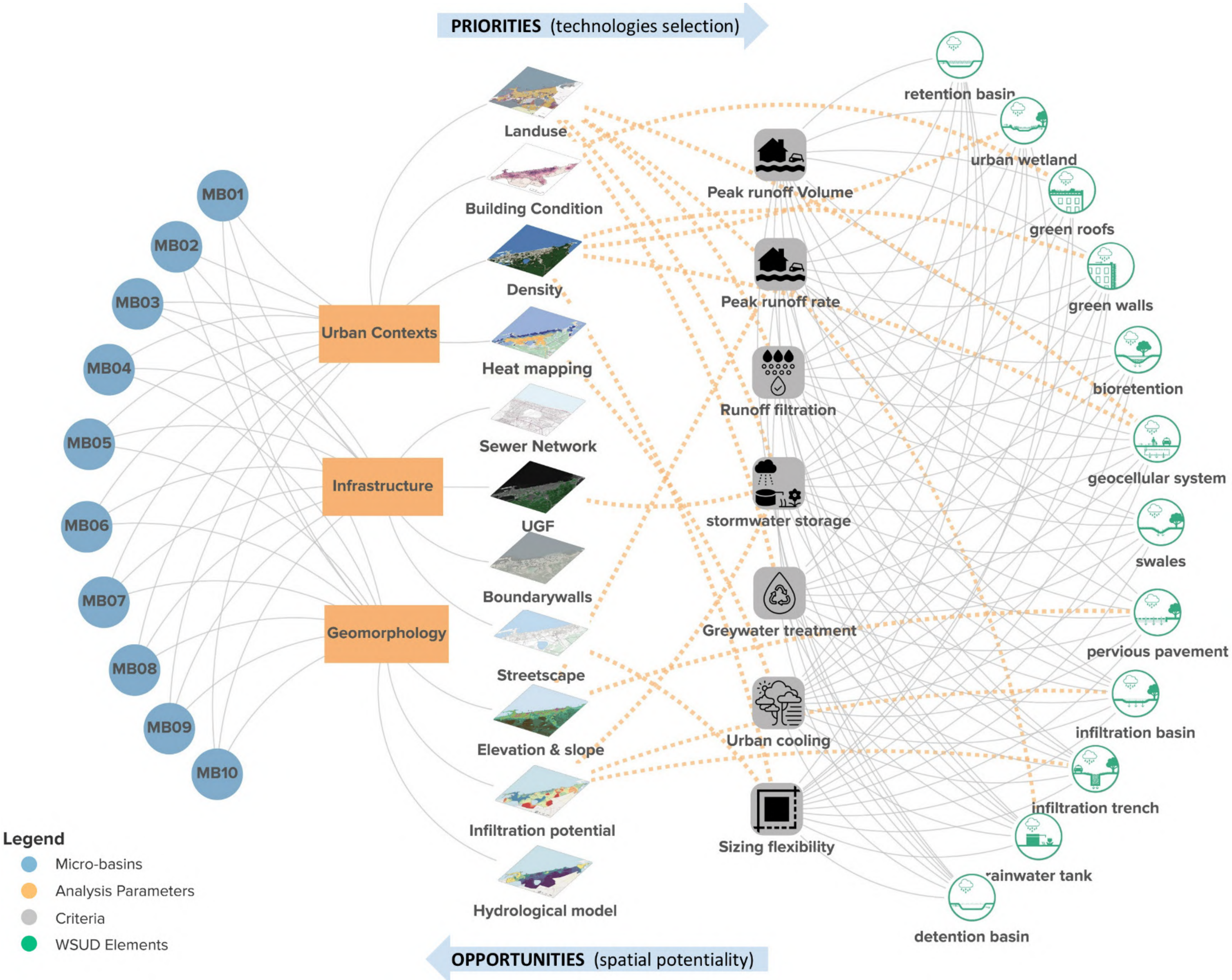


Fig. 4-12: Diagram illustrates the structure, connections, and flow processes of the decision-making model (By author)

This structure allows the model to process either way; towards the selection of combination of the appropriate WSUD technologies that best work in the investigated micro-basin or development, or towards mapping the highly potential areas for accommodating WSUD technologies, which can further develop into an opportunity index map. The full functionality of the system requires coupling the spatial indicators to criteria and technologies. Applying combination rules algorithm (Malczewski & Rinner, 2015) is a systematic approach to determining all the possible arrangements and connections that can be formed between these components. This process is closely related to the criteria weighting as both are iterative and involve the participation of experts and other stakeholders. Ultimately, the system has the flexibility and potential for further enhancement by integrating socio-economic and cost factors. Along with the utilization of Geographic Information System (GIS) technology to facilitate participation and the execution of analytical processes in an algorithmic and automated manner.

To sum up, the WSUD spatial framework can serves as a tool for city planners and policymakers, facilitating strategic resource allocation, infrastructure development, and the creation of cohesive urban landscapes that effectively address the challenges of flooding and droughts in Alexandria City. Importantly, it lays the foundation for a water-sensitive transition that could be replicated in other cities across the MENA Region. Nevertheless, potential limitations may occur. Several challenges associated with the framework include scale limitation resulting from the inherent spatial heterogeneity of urban areas. The diverse characteristics within and between micro-basins can complicate the uniform application of the framework model. Additionally, the framework's dependency on accurate spatial data poses challenges, particularly in data-scarce regions where data acquiring is both challenging and resource-intensive.

It is also likely that micro-basins area limits do not coincide with the typical administrative subdivision of municipal districts, which is challenging and may require additional coordination and communication efforts between administrations to avoid any conflicts in decisions and planning. Moreover, the absence of supportive regulatory frameworks and tailored policies for WSUD may hinder widespread adoption, emphasizing the need for clear guidelines and standards. To address cost implications and funding challenges, innovative funding mechanisms and policy structures that incentivize implementation are essential. Furthermore, the framework has limited consideration of human behavior and social factors. However, community engagement and participation are essential to be adequately involved in the planning and implementation process as a major stakeholder in an integrated approach. Overcoming these challenges necessitates continuous refinement and collaborative efforts among researchers, urban planners, and policymakers to enhance the framework's adaptability and effectiveness in diverse urban settings.

5 ALEXANDRIA CITY

This chapter focuses on the City of Alexandria as the chosen case study to demonstrate the adoption approach of Water Sensitive Urban Design (WSUD) strategies in hot and dry climates. The insights and knowledge developed throughout this dissertation were applied to the city, following the 'Spatial Framework' developed in chapter 3. The examination involves detailed mapping, analysis, and development of interventions based on the micro-basins and barriers planning approach. Additionally, an example featuring a specific micro-basin illustrates the implementation of a site-scale WSUD, including calculations of the spatial requirements needed to manage different extreme weather events.

5.1 Background and Context

Alexandria, Egypt’s second largest city and a Mediterranean port, presents a complex urban context shaped by its history, location, and dynamic socio-economic factors. Its urban form, structure, and characteristics reflect a blend of ancient heritage, colonial influences, and modern developmental pressures. The city extends along the coast on a narrow and moderately elevated strip, situated between the sea to the north and Lake Mariout and agricultural land (partially reclaimed wetlands) to the south. The city's topography is relatively flat, with an average elevation of just 5 meters above sea level, which makes it vulnerable to climate extremes and the threat of sea level rise (Farouk, 2023).

As a coastal city, Alexandria’s development is heavily influenced by its geographical boundary of the Mediterranean Sea to the north and Lake Mariout to the south, confining urban sprawl and encouraging density within the available land. This geographical setting has led the city’s expansion to be in a linear form along the shoreline, primarily to the east. This is considered the main limitation to the growth of the city, resulting in extreme densification of urban areas.

The city currently covers 230,000 hectares with a total population of nearly 5.5 million, 98% of whom are living in urban areas with an average density of 2300 inhabitants per square kilometer (CAPMAS, 2022). The high population density has prompted extensive vertical development, with many new high-rise buildings complementing older, multi-story structures. However, current plans for new developments are aiming to expand the urban area further across the agricultural low plains in the southern hinterland of the city.

The city's waterfront, marked by the Corniche, plays a crucial role in urban life and form, hosting both recreational spaces and significant economic activities. Limited green spaces and public parks are a significant urban issue, although developments in newer suburban areas are attempting to address this deficit.

Overall, Alexandria's location and topography have a significant influence on its climate and environmental conditions. The city's proximity to the Mediterranean Sea and the Nile River delta helps to moderate its climate, while its low elevation makes it vulnerable to flooding.

The scope of the case study area focuses on the main urban area of the city from Aboukir in the east to the El Max drain to the west. From the south, considering the city’s urban expansion limits (SUP Alexandria, 2013).

Fig. 5-1: Alexandria metropolitan area

Map: (Bing maps, 2023), Photos by author and others

5.2 Spatial Hydrological Analysis

This analysis examines the spatial context and hydrological processes in Alexandria City, with the aim of assessing the interactions between water, landscape, infrastructure, and urban environments. The primary focus is on understanding how water flows within the city, identifying natural and artificial drainage patterns, and evaluating the efficiency of existing water management systems. Additionally, it examines the consequences of urbanization and climatic changes on Alexandria's hydrological systems to identify flood impact and water-related risks.

5.2.1 Climate and Precipitation

Alexandria is known for its semi-dry Mediterranean climate. According to the Köppen-Geiger classification, the city's climate borders on hot desert (Bwh) and approaches hot semi-dry (Bsh), with hot dry summers from May to October and mild rainy winters from November to April. The average annual temperature in Alexandria is 22°C. The hottest months are June to September with an average high temperature of 31°C. The cool weather extends from December to March with an average high temperature of 18°C and an average low temperature of 10°C. Temperature variations throughout the year are relatively mild, with an average temperature range of 10-12°C between the coldest and hottest months.

Relative humidity in Alexandria varies throughout the year. During the summer months from June to September, humidity is generally high, averaging between 60% and 80%. During the winter months, humidity is generally lower, ranging from 50% to 70%. The daily norms of highest relative humidity in Alexandria typically occur in the early morning hours, when dew can form on cold, flat surfaces. Despite the high humidity in Alexandria, the sea breeze keeps the humidity at a comfortable level. The prevailing north wind blowing from the Mediterranean softens the severity of the desert temperature. The hot and dry sirocco winds, known as Khamasin, typically occur in the spring. The winds originate in the Sahara and blow over North Africa for several days, carrying dust and sand and causing temperatures to rise.

According to most sources, the average annual precipitation in Alexandria is nearly 200 mm. Due to the temporal variability of precipitation, which is a major characteristic of this climate, the precipitation pattern in the winter months is less frequent and tends to be concentrated in a series of intense storm surges. Locals refer to these events as Nawat, for which they have developed a forecast of their annual recurrence over decades, including approximate dates, probability, and intensity of rain, and duration of the storm (table 5). Thirteen of these storms are accompanied by rainfall, nearly 5 of them with high to very high rainfall intensity. However, the Egyptian Meteorological Authority (EMA) does not rely on these observed forecasts from Nawat, rather on meteorological data obtained from weather observation stations in Alexandria.

Table 5: Approximate duration and intensities of typical seasonal Storms in Alexandria (APA, 2019)

Date	Storm name	Days	Intensity
02. Jan.	Ras Elsana	4	average
12. Jan.	Elfayda Elkobra	6	very high
19. Jan.	Elghetas	3	average
28. Jan.	Elkaram	7	high
18. Feb.	Elshams Elsoghra	3	high
02. Mar.	Elsaloum	2	average
09. Mar.	Elhosoom	7	low
18. Mar.	Elshams Elkobra	2	very low
24. Mar.	Awaa	6	very low
Almost no rainfall from April to September			
20. Oct.	Elsaliba	3	very low
16. Nov.	Elmaknasa	4	very high
22. Nov.	Baki Elmaknasa	4	average
04. Dec.	Kasem	5	very high
19. Dec.	Elfayda Elsoghra	5	average
28. Dec.	Eid Al Milad	2	very high

Great rainfall variability and predominately extreme events in the city require closer observation and deliberate data gathering to understand the frequency and the dimensioning of rainfall events. While 16 weather stations are distributed and covering most of Adelaide's city, rainfall measurement in Alexandria is recorded by 4 stations: Ras El Teen, Aboukir, Nozha, and Borg El-Arab airport, all of which are located outside or at least on the outskirts of the city. They are not connected, and it is not clear whether one or two of them are still in operation.

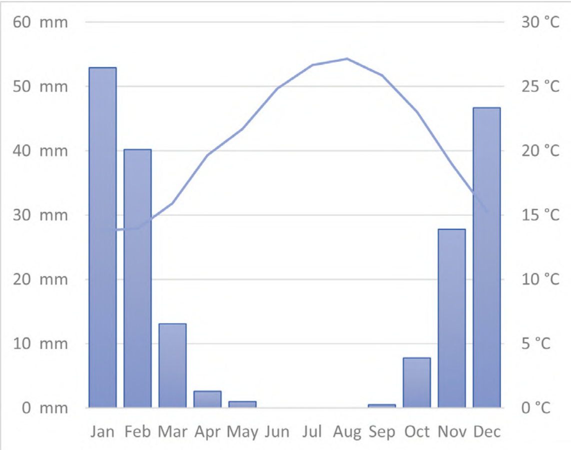


Fig. 5-2: Average monthly rainfall and temperature in Alexandria, based on (Gado, 2020)

Dr. Gado (Interview, 2022) pointed out the difficulties of obtaining serious data for short durations from the local meteorological authority. Therefore, researchers tend to base their analysis on satellite data or data available on international meteorological platforms, but only limited to daily rainfall time series. Various researchers have attempted to study the statistical characterization of extreme rainfall in Alexandria. Between 30- and 70-year data series have been analyzed to assess rainfall intensity for different return periods. When sub-daily gauge rainfall was not available, the researchers utilized a combination of observed daily ground data and available satellite data. Their analysis sought to develop a reliable probability model for rainfall intensity in Alexandria and other cities in Egypt. A summary of the results can be found in Annex C.

In her study, Young (2018) discusses the lack of data presenting the intensity and frequency of rainfall in data-scarce regions such as Alexandria. She analyzed the results from previous studies and, using statistical methods of the maximum likelihood estimation (MLE), she concluded the most probable estimates of daily rainfall intensity in Alexandria (Table 6). Comparing data from both Alexandria and Adelaide shows higher intensities in Adelaide for the same recurrence years (Figure 5-3).

Table 6: Estimated depth of daily rainfall intensity for different return periods in Alexandria

P_{2} mm	P_{5} mm	P_{10} mm	P_{20} mm	P_{50} mm	P_{100} mm
31.5	43.0	53.0	64.0	80.0	93.6

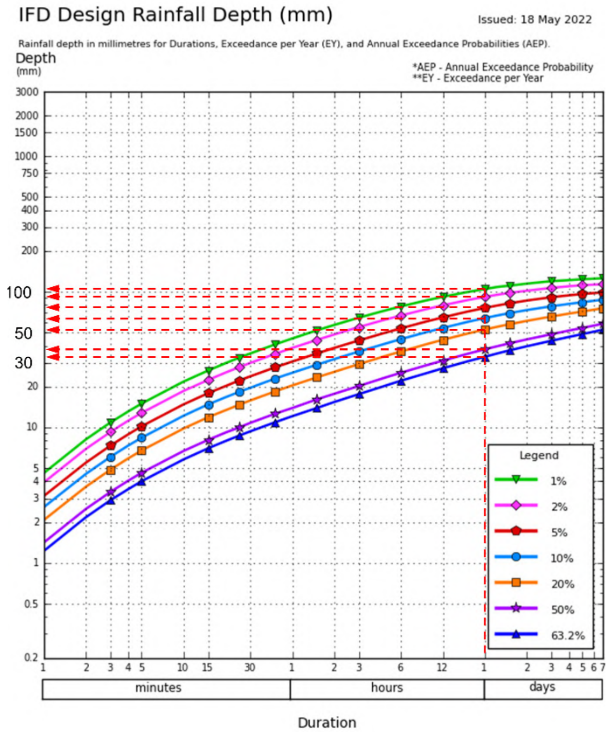


Fig. 5-3: A day rainfall depth in mm for different annual exceedance for Adelaide, Australia (BOM, 2022)

The debate and discussion surrounding the threat of sea-level rise and its impact on coastal cities are supported by various local and international organizations. While the media in Egypt occasionally covers this topic, the government has developed plans to address the risk. However, in my perspective, the threat of extreme rainfall events, coupled with inadequate infrastructure and high levels of sealed land surfaces, poses a more immediate and substantial risk to the city compared to sea-level rise. While both are important factors to consider, the focus of this dissertation highlights the urgency to respond to the tangible risks associated with heavy rainfall and urban infrastructure vulnerabilities.

5.2.2 Drainage System

The urban drainage system in Alexandria is primarily designed to manage both combined sewage and stormwater, except for the Corniche Road which is provided with a separate stormwater line along the road. As the primary summer destination in Egypt, Alexandria attracts more than one million visitors during the summer months. The Alexandria Sanitation and Drainage Company (ASDCO) reports that the network was initially designed to handle the increased load during these 'dry' summer months, when the city's population typically rises. The combined sewer network covers approximately 94% of the urban areas, with a total design capacity of 1.8 million cubic meters (mcm) per day and a maximum capacity of 2.2 mcm per day. During the rainy season, up to 30% of this capacity (0.7 mcm per day) is allocated for stormwater management (Interview, 2022). The system's design for stormwater capacity is based on a 2-

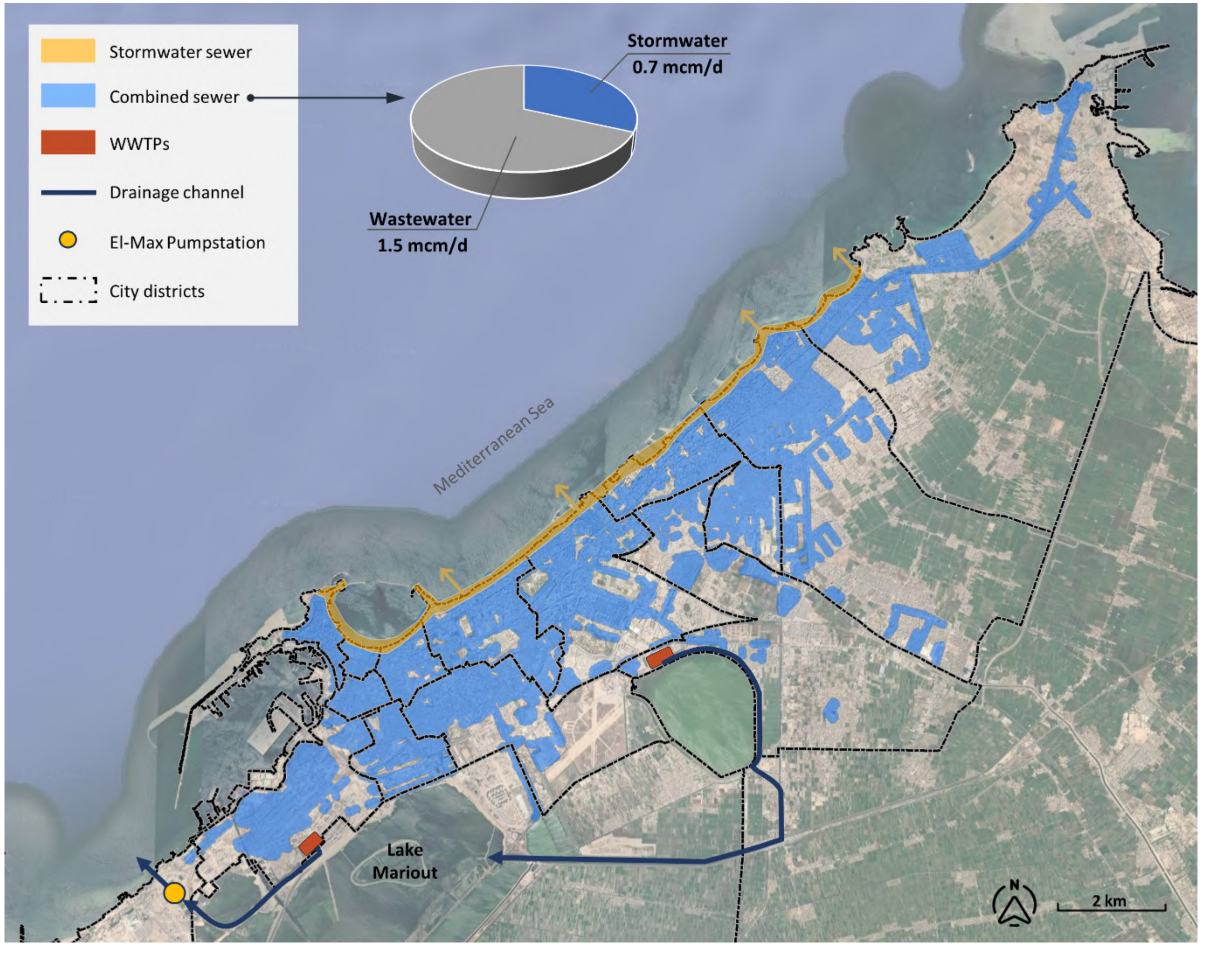


Fig. 5-4: urban drainage components and Combined sewer system maximum capacity share as million cubic meters per day, based on (ADSCO ,2022)

year return period with a rainfall intensity of 26 mm over 2 hours (Young, 2018).

The urban area is served by two main wastewater treatment plants (WWTP): the East WWTP and the West WWTP. All domestic, commercial, and industrial wastewater, along with stormwater, is channeled to these plants via a combined sewer system. The treated effluent from both the East and West WWTPs is ultimately discharged into Lake Maryut and subsequently pumped to the sea through the El-Max pumping station (Figure 5-4). Both plants have undergone upgrades from primary to secondary treatment levels, and the system's capacity has been expanded in an attempt to accommodate the rapidly increasing population. However, these enhancements are still insufficient to manage the increased frequency and intensity of rainfall events (AASTMT & Egis, 2011).

Rapid urbanization has outpaced the capacity of Alexandria's aging drainage and sanitation infrastructure to manage the runoff from impervious surfaces effectively. In recent years, the city has frequently experienced intense rainfall events that have overwhelmed the sewer systems, leading to widespread street flooding and water accumulation in various areas. Officials have acknowledged that the intensity and frequency of rainfall and extreme weather events now exceed the system's capacity to cope (Zevenbergen et al., 2017).

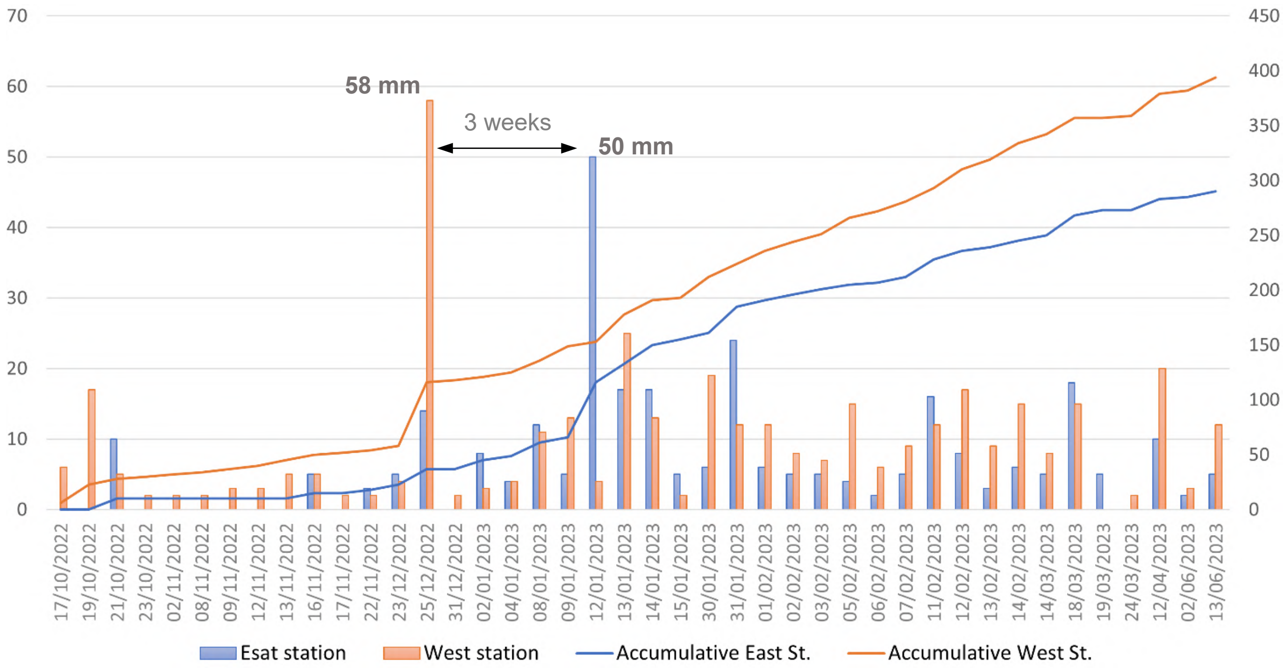
5.2.3 Surface Runoff and Flooding

As previously indicated, it appears that rainfall has traditionally held a lower priority for the city of Alexandria in its urban planning endeavors. Consequently, with the increasing demand on infrastructure and the frequent occurrence of climate extremes, the vulnerability of the city to flooding has become more evident than ever before. Unfortunately, the absence of reliable historical records documenting significant rainfall events poses a challenge in analyzing potential anomalies that could signify such a critical threshold. Nevertheless, it has been suggested by city officials and experts that the extensive illegal expansion of urban areas and especially the massive vertical expansion of residential buildings have exerted immense pressure on the drainage network, contributing significantly to the impact of flooding. Extreme rainfall events occurred in 2011 and 2015, causing severe damage to lives and properties. The flood impact would last for several days after the event, including, for example, residential and commercial property damage and building structure damage. Disruptions of local services such as electricity and water supply, and street blockages caused by high water depth, would also disturb food supply and emergency vehicles. In the last two years, it has become even more severe, with the government announcing the cancellation of school and university attendance for several days.

The damaging rainfall event intensity in 2015 was estimated at around 30 to 40 mm. Until these dates, the city had not undergone substantial flooding, and there was no historical flood event data to compare with the event in 2015 (Zevenbergen et al., 2017). In recent years, starting in 2019, these extreme rainfall events have become more expected and are considered periods of emergency that may recur regularly every year. Yet no intensity records of these events have been publicly available. Interestingly, a group of non-specialist weather enthusiasts observing climate data and weather forecasting have started to publish records online (*Alexandria Rain*, 2023). The group has been collecting rainfall measurements over the past 11 years. They started with one rain gauge on a building's rooftop located west of the city and since 2019, they have added another rain gauge atop a building in the eastern side of the city. I have been able to follow their records for the winter season 2022-23, from October to June, as shown in Figure 5-5. The chart illustrates readings of two rain gauges that cover the eastern and western parts of the city, distanced around 13 km. In addition, the accumulative and total annual rainfall is presented for each.

What can be clearly seen is that rainfall quantities vary to some extent over the eastern and western parts of the city. Most rainfall events during the season were below the 20 mm per day limit, which the network can handle according to the described capacity and limitation. The two major events had depths of 50 and 58 mm per day, respectively. Both events reportedly had significant flooding impacts causing severe damage to properties and blockades of public services. According to the return period analysis in Table 6, these rainfall intensities fall under the 10-year recurrence. Each event occurred on one side of the city while the other side did not receive the same intensity of rainfall – fortunately much less.

Seeing this data as a typical rainfall pattern in Alexandria confirms previous flooding reports in the last few years. An alarming concern that could be raised here is the time span between major events and the spatial variability of high-intensity occurrence, which can greatly affect the severity of the flooding event. The chart shows the two major events with almost 3 weeks apart and occurring in two different parts of the city. Two extreme rainfall events were reported in 2015 with only one week in-between (Zevenbergen et al., 2017).



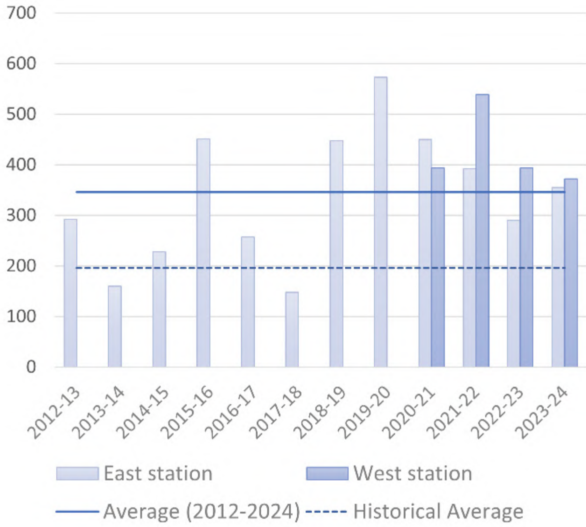
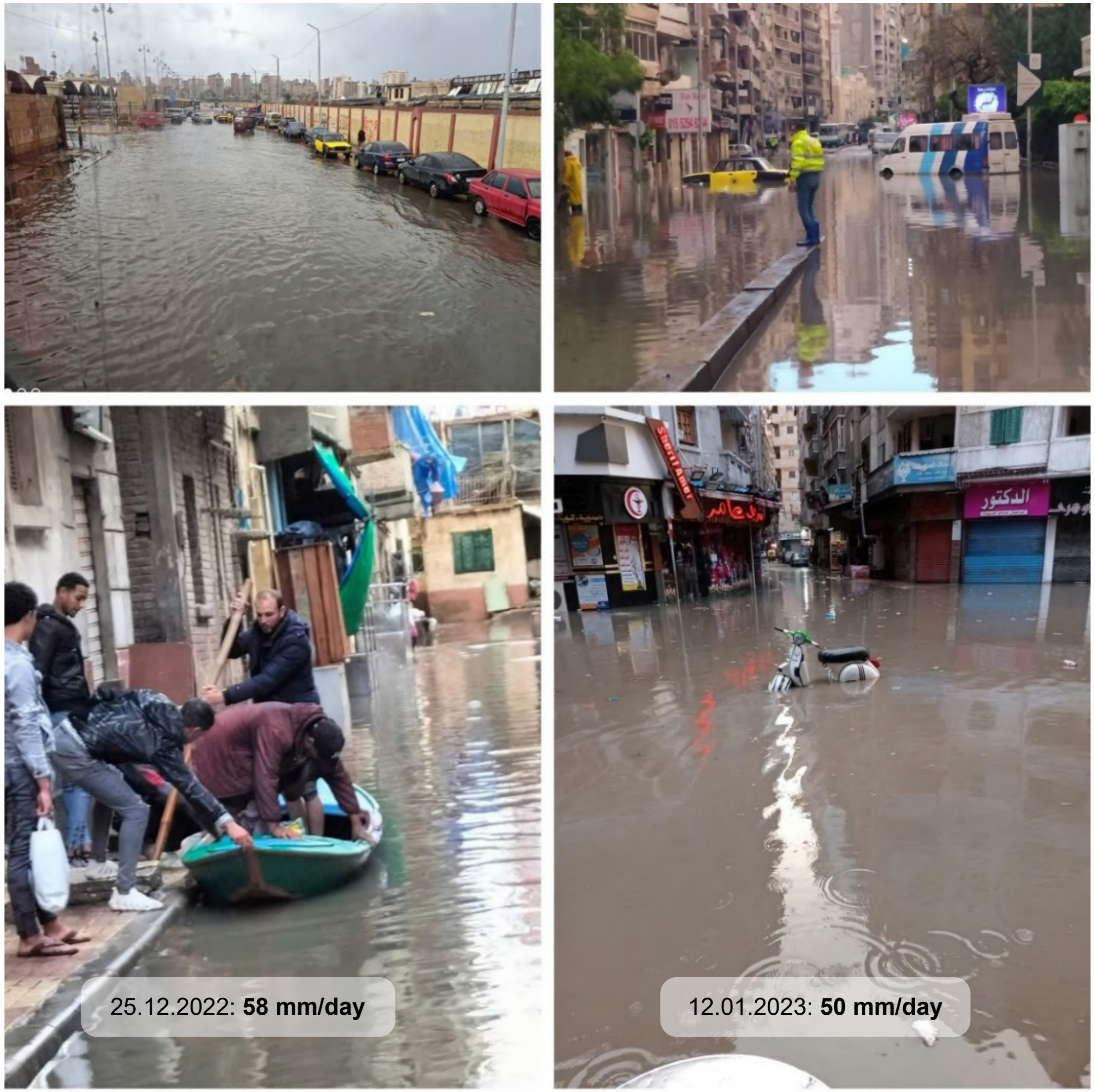


Fig. 5-5: Record of rainfall events and accumulation from each east and west rain gauge station for the winter season 2022-23 (top). Comparison between the last decade and historical rainfall annual averages showing a recent increase of almost 150 mm (bottom) (AASTMT & Egis, 2011; Alexandria Rain, 2023)

Inundated streets during two extreme rainfall events, 3 weeks apart (right) Photos: (Alexandria Rain, 2023)



Anticipating these spatial variabilities by weather observation could enhance the response of the city to flooding events. Identifying high-risk areas could concentrate the readiness and recovery efforts in a much more efficient way.

Furthermore, plotting Alexandria Rain data of the total annual rainfall in Figure 5-5 shows differences in the total annual rainfall with almost a 100 mm gap between the eastern and western sides of the city. Most importantly, the average annual rainfall over the last 11 years indicates a rainfall of 350 mm, nearly doubling the long-recorded average of 196 mm for the period 1957 to 2015, according to Young (2018).

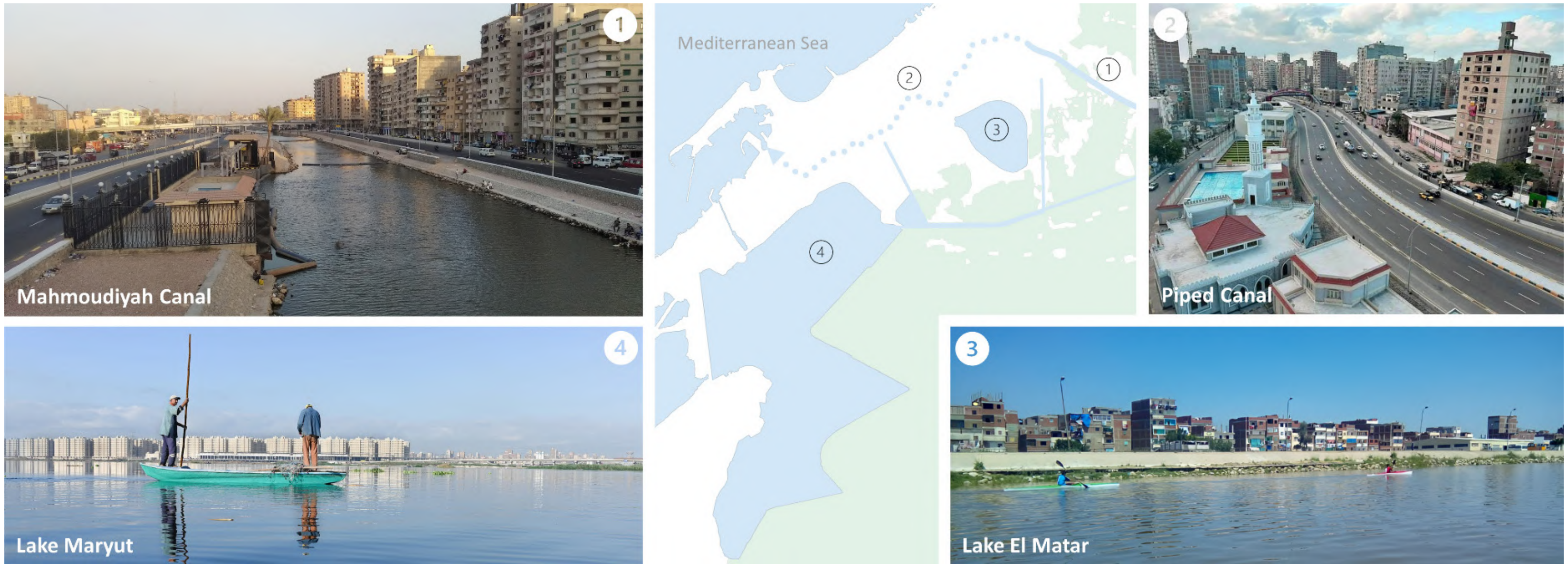
A valid critic could question the accuracy of these measurements and the reliability of one season’s data to be seen as tangible trends. However, this data is believed to be much more indicative of the real current rainfall patterns since the magnitude of extreme flooding events reported widely in the city is evident from the data measured. The measurements would rather, if inaccurate, indicate less runoff depth but not overestimate. Inaccuracy in measurement would rather indicate. Secondly, the data confirms the high rainfall temporal and spatial variability typical of dry climates.

5.2.4 Water Bodies

Lake Maryut is a shallow water body consisting of two divisions: the main basin southwest of the city and a narrow arm that extends for about 60 km along the northwestern coast. The lake is a shallow brackish water body with an average water depth of 1.5 m and is not directly connected to the Mediterranean Sea. The lake has been an integral part of the local economy and a vital source of livelihood for the city community as it hosts various aquaculture activities, including large tracts for fisheries.

The main supply source of water to the lake is a network of irrigation and drainage channels that transport drainage from cultivated land west of the Delta. In addition, the lake receives treated domestic and industrial wastewater from the two main wastewater treatment plants and the industrial facilities in the area around the lake. Therefore, the lake is facing challenges of pollution and habitat degradation due to significant nutrient loading, making it severely contaminated and eutrophic. Efforts have been made to restore and protect the lake's ecosystem, including measures to improve water quality and conserve the surrounding wetlands. The water level of the lake is kept at 2.0 m below sea level by pumping excess water to the Mediterranean Sea through the El Max pumping station. Other minor flows are lost through evaporation. (Beevers, 2020; Emad Khalil)

The Mahmoudiyah Canal, until 2020, served as a significant hydrological feature in the city, providing a crucial source of freshwater derived from the Rosetta branch of the Nile River. Recently, as part of a traffic expansion initiative, the canal has been transformed into underground pipes, integrated into an arterial road axis. In the past, the canal used to utilize subsidiary channels to distribute fresh water throughout the city, but these channels have gradually vanished, replaced by modern subterranean pipelines (Girard et al., 2014).



Another sequestered water reservoir, called **El-Matar Lake**, is an artificial lake with an average depth of 2.5 m - 3.0 m. The lake is supplied with water from the Nile River through an inlet connected to the Mahmoudiyah Canal. Any excess water is discharged through an overflow outlet into Lake Maryut via a network of surrounding drainage channels. However, the water level in the lake has significantly decreased in recent years due to the overall decline in water supply from the Nile, as well as the ongoing transformation project of the canal (Helal et al., 2020).

Potentials associated with utilizing existing water bodies emphasize the role of a decentralized approach at the streetscape level by introducing nature-based treatment systems that hold up and treat the excessive runoff before discharge directly to the nearest water body or into the Mahmoudiyah through stormwater pipelines. Since a large volume of runoff collected in sewers all over the city ends up eventually in the lake anyway as effluent discharge from the two main wastewater treatment plants, it becomes possible to utilize this resource to establish a water equilibrium and overcome the current dilemma of supply and flooding while simultaneously providing a water source for irrigation and other non-potable purposes.

Fig. 5-6: (left) water bodies in Alexandria

Map illustrated by author
Photos from Google maps by:
1: Yahya Ahmed, 2020
2: Alexandria, 2021
3: Medhat Farouk, 2017
4: Ibrahim Omar, 2022

5.2.5 Challenges and Potentials

Alexandria is vulnerable to the impacts of climate change, as the city is experiencing changes in rainfall patterns, with more intense and less predictable storms that overwhelm existing drainage systems. Higher temperatures lead to increased evaporation rates, affecting soil moisture and runoff patterns, as well as exacerbating extreme weather conditions of heatwaves and droughts. Additionally, land use transformation due to urbanization has altered runoff dynamics and disrupted drainage waterways in Alexandria. The resulting increase in impervious surfaces and impeded natural water flows has reduced the effectiveness of natural drainage systems and significantly heightened flood risks.

Moreover, the city's infrastructure lacks the adaptability required to manage the rapidly changing climatic conditions. Originally, the existing infrastructure was not designed to accommodate current runoff volumes. In addition, the city’s sewage system is aging and has not been sufficiently maintained or upgraded to meet these increasing challenges. For years, the problem was addressed as a maintenance issue of the often-clogged network, which is indeed part of the problem, but not as significant as perceived. Maintenance efforts, including annual campaigns to clear clogs from the sewer system, have proven inadequate in preventing flooding and associated damage.

The interaction of these factors has led to a compounded effect on flood risk in Alexandria. Climate change introduces more intense hydrological events. Urbanization alters the landscape in ways that prohibit the natural water cycle, while the limitations and deterioration of infrastructure prevent adequate response to these new challenges. Together, these factors necessitate comprehensive planning and significant investment in resilient infrastructure to effectively mitigate future flood risks. Developing adaptive strategies, such as the WSUD approach, maintaining the existing sewer systems, and revising urban planning regulations, are essential steps toward reducing Alexandria's vulnerability to flooding and drought.

In recent years, as flooding has become more frequent (occurring one to two times per rainfall season), it has become evident that the risk extends beyond mere sewer clogging and aging. The severity of the situation has prompted a shift in approach by city officials. The Alexandria Sanitation and Drainage Company (ASDCO) first began deploying vacuum tanker trucks across the city to manage flooding hotspots by clearing stormwater from streets and discharging it into water bodies.

Following the significant flooding in 2015, an anticipatory flood management project was launched in collaboration with the IHE Delft Institute for Water Education. This project aimed to enhance early warning systems and utilize existing water bodies as stormwater detention areas, pumping out water to the sea prior to heavy rainfall events to create additional storage capacity. The project recommended expanding and improving the capacity of existing drainage systems and developing flood forecasting, evacuation, and recovery plans (Bhattacharya et al., 2018; Zevenbergen et al., 2017). The discussions did not extend to decentralized solutions such as those found in WSUD, and there has been no further information on the implementation of these recommendations.

More recently, the "New Delta" project was announced by the government to extend transmission pipelines that will transfer domestic and agricultural drainage from Alexandria to irrigate over 2.2 million feddans in the western desert. The government argues that stormwater could add significantly to the volume being

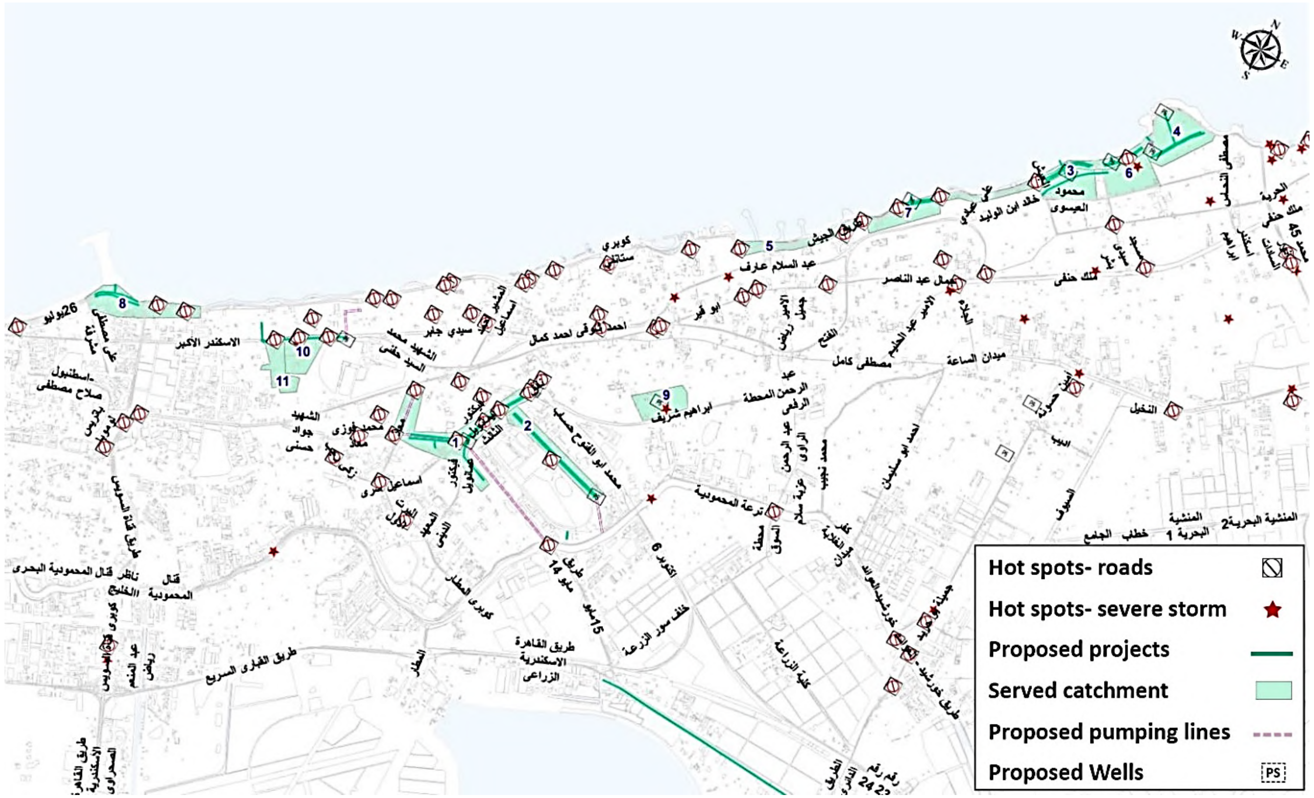


Fig. 5-7: Right- Location of flooding hotspots and proposed zones for stormwater separation (ADSCO, 2022).

Top- Vacuum tanker clearing inundated stormwater hotspot in Alexandria (Photo: Alexandria Rain, 2023) transported to the project site and will alleviate flooding risk in the city (Gazette, 2021).

Despite these measures, the need for feasible and effective solutions is still urgent. An initiative to separate stormwater from the sewage network was implemented recently. According to official reports from ASDCO, the project targets 11 flooding hotspots in Alexandria. The project included the construction of a separate network to drain rainwater to the nearest waterbody. The first phase, completed in 2023, focused on critical flooding neighborhoods, primarily collecting stormwater from coastal areas along the Corniche Road to discharge directly into the Mediterranean Sea, as well as establishing separate stormwater drainage in inner areas of the city, connected to the stormwater line under the Mahmoudiyah axis.

However, there may be significant environmental concerns stemming from the recent stormwater separation projects in Alexandria. While these initiatives could help alleviate urban flooding, they potentially overlook critical impacts on the quality of receiving water and the broader threats to aquatic ecosystems. The discharge of untreated stormwater might introduce pollutants from urban runoff into aquatic environments, severely degrading water quality. Such practices do not align with contemporary environmental management standards that prioritize the ecological health of urban waterways. The accumulation of pollutants could have long-term deleterious effects on marine habitats, potentially leading to significant ecological and economic consequences for the city, which relies on these water bodies for recreation, fishing, and tourism.

The integration of WSUD strategies could offer a viable solution, serving as a crucial intermediary process between the collection of stormwater and its discharge into the sea. Biofiltration systems, constructed wetlands, and swales technologies can effectively treat stormwater, removing pollutants before they reach aquatic environments.

Furthermore, there is a significant opportunity to utilize the collected stormwater to sustain vegetated WSUD treatment technologies to enhance urban green spaces. Besides, harvesting this treated water for storage and subsequent non-potable uses in irrigation and industrial processes, could represent an alternative water source to mitigate drought. Thus, including WSUD in Alexandria’s stormwater management strategy is thought to be necessary to ensure that water management practices contribute positively to both urban and ecological well-being.

Regarding rainwater harvesting and reuse, the Library of Alexandria has a very exclusive experience in the city. During a visit to the library, Emad Said (Interview, 2022) presented the system's function and process, as well as its limitations. The library's main building, featuring a massive roof that tilts toward the sea, utilizes this design to collect rainwater efficiently. This water is stored in an underground 40 m³ cistern, where it is pumped back, after filtration, to supplement the water supply for roof cleaning when needed.

Key components of the system include four pumps that manage overflow by directing excess water to the sea to ensure the system can cope with surplus volume without structural risk. Additionally, the tank is equipped with a float valve connected to a freshwater source to maintain adequate water levels during prolonged dry periods. An innovative aspect of the system is its integration with the building's air conditioning, where water condensate from the cooling tower is collected and added to the tank. Most interestingly, Emad explained that condensate dew forming on the roof surface overnight significantly contributes to the tank’s volume during the non-rain season.

He highlighted the system's benefits in reducing the library's potable water demand and minimizing stormwater discharge into the city's sewer system. He also emphasized the importance of regular maintenance. Possible system failures due to pump clogging or operational breakdowns can lead to water accumulation, potentially damaging the roof structure or causing overflow that might flood the underground service floors. Overall, this rainwater harvesting system at the Library of Alexandria stands as a robust model of how urban structures in dry climates can effectively implement harvesting strategies, and clearly demonstrates the potential to expand on integrating such practices into the city and others in similar climates.

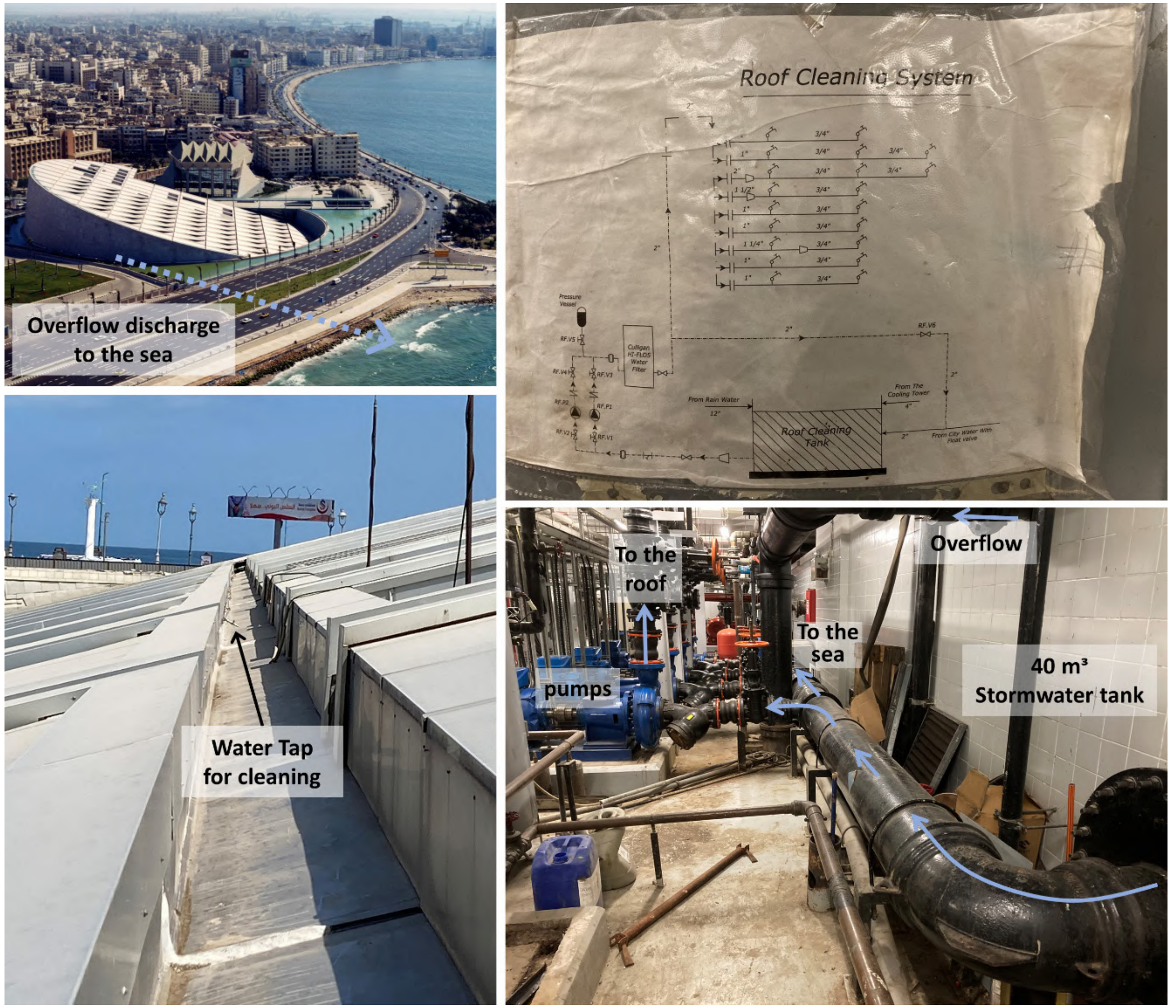


Fig. 5-8: Components of the rainwater harvesting and reuse system in the Library of Alexandria (right). Condensate water from air conditioners generating surface runoff (bottom) (Photos by Author)

5.3 Urban Hydrological Regions: Micro-basins and Barriers

Based on the planning approach framework developed and introduced in this dissertation in chapter 4, mapping of urban barriers and resulting basins in Alexandria City aims to provide information on the nature and extent of these barriers as delimitation lines, which subdivide the city into several connected hydrological regions. A systematic analysis framework of both surface and subsurface characteristics of the micro-basins and various barriers provides an intricate view of the local factors that contribute to flooding, as well as insights into the potential and limitations of incorporating water-sensitive practices.

5.3.1 Mapping Basins and Barriers

Alexandria's railway network consists of two regional rail lines and one local domestic line. The Aboukir local line runs parallel to the coast for a length of 21.7 kilometers from Aboukir station to Alexandria's central station (APTA, 2023). The line cuts through almost the entire city and separates the urban area to the north and south. The other two lines are regional connections to Cairo (Alex-Cairo line) and to other cities along the northwest coast to Matrouh City (Alex-Matrouh line). An additional short line connects the harbor to the regional lines. The Egyptian railway network is not electrified but runs on diesel fuel (SUP Alexandria, 2013).

The Alexandria Tramway consists of two lines, the Raml Tram and the Al Madina Tram, which connect different neighborhoods throughout the city (APTA, 2023). Both lines differ in their track system. The Al Madina line has a paved-in tramway structure, as the rails are embedded in the paved surface of a street. In this system, both street and tramway traffic share the same road surface, which is not considered a barrier according to the criteria developed in this study. The other Raml line has an open tram track system, also known as a ballasted track, where the rails are fastened with a layer of ballast rock, similar to conventional railroad tracks. Unlike paved-in rails, open tram tracks are typically not completely enclosed by concrete or other materials. The Raml track is a segregated tramway that runs within its own right of way and structurally separates two streets on both sides. Therefore, the Raml tramway is considered here as a main demarcating barrier.

Three main regional motorways connect Alexandria to the region: the Cairo-Alexandria Desert Road, the Agricultural Road, which connects the city to Cairo through the main cities of the Nile Delta, and the International Coastal Road, which runs along the northern coast of Egypt, connecting the city to other major Mediterranean ports. The motorways typically have multiple lanes in each direction, which are separated by substantial median islands and side concrete guardrails.

Due to the rectilinear shape of the city, the main local roads run parallel to the coastline, while some other main roads perpendicular to it connect the city in the other direction. The first main artery is Corniche Road, which stretches along the waterfront for almost 20 km and has an average width of 35 meters (Elhamy, 2012). Most of its length incorporates a median street strip with high curbs. The second main artery is the Mahmoudiyah Axis – a 21 km long former Mahmoudiyah Canal transformed into a new arterial road 80 to 120 m wide with 6 to 8 lanes in each direction (Girard et al., 2014). Other perpendicular main roads include Suez Canal Road and Forty-Five Road. Both roads are about 30 meters wide and incorporate street medians. Because these main roads are perpendicular to arterial roads and railroads, their profile changes at various parts depending on which other road they must cross, either through tunnels or over bridges. They cut through the city against its longitudinal expansion, dividing it into three sections according to their historical development.

Furthermore, protected watercourses are considered barriers and are mapped as well. These include the remaining length of the

Mahmoudiyah Canal within the city limits, as well as the El-Max Canal at the western harbor.

As the main roads, railroads, and watercourses were overlaid on the city's map, a clear form of the urban hydrological regions appears as micro-basins confined by those barriers.

In the city, micro-basins can be systematically categorized into three primary groups, determined by their proximity to key transportation arteries and railroads, such as train and tram lines, with further subdivisions determined by additional barriers.

- Costal basins (01, 02 and 09) have direct access to the Mediterranean Sea. Basin (01) represents the historic inner city, while Basin (02) extends eastward along the coastline, terminating at Abukir Harbor. Notably, Basins 01 and 09 partially face the western harbor; however, their access to the sea is impeded by a masonry wall encircling the harbor. Basin (09) has indirect access through the El-Max canal.

Inter-Railroad basins include Basin (03), which is located between the tram and city train lines. In addition, Basins (04, 05, and 06) are situated between the two train railroad lines, forming a central zone centered around the Mahmoudiyah axis.

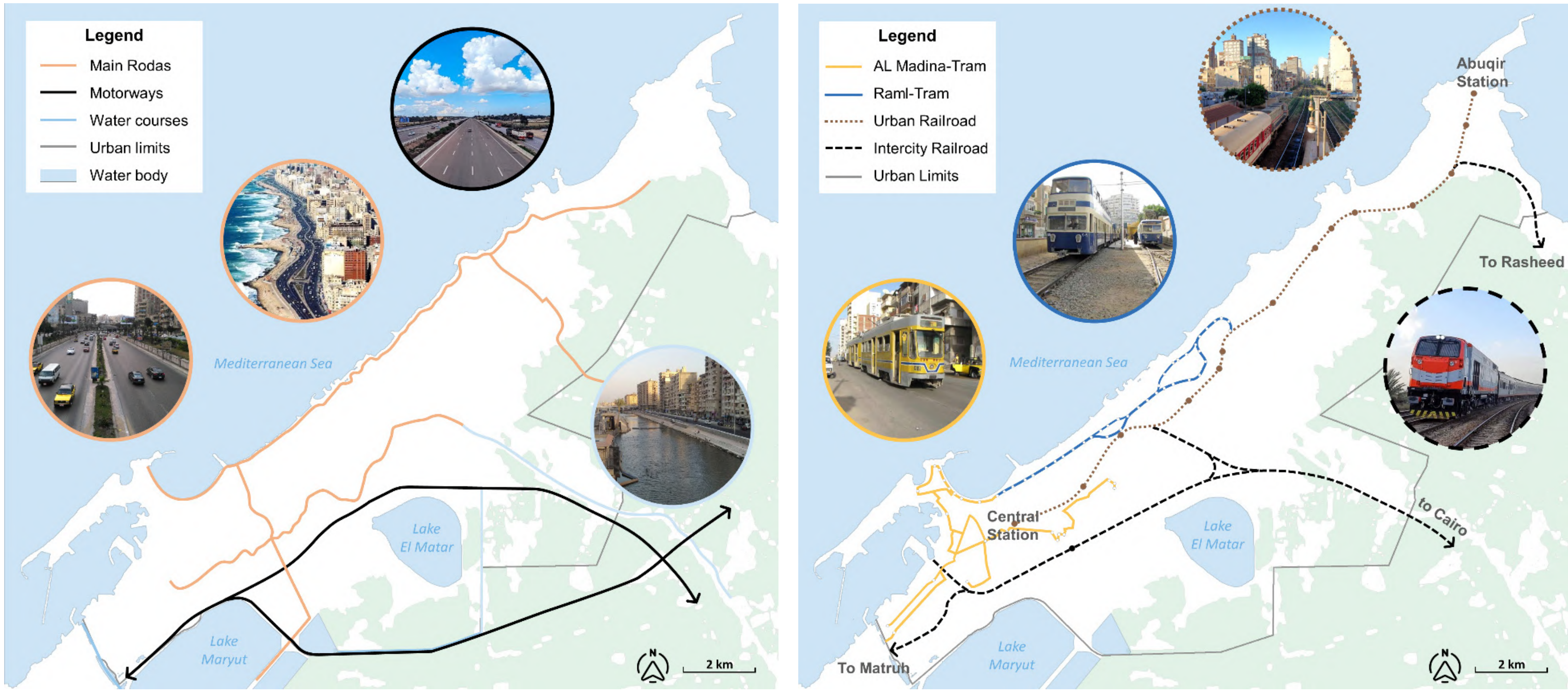


Fig. 5-9: Mapped barriers in the city. Tram and railway lines (right), main roads and water courses (left)

- Hinterland basin (07) and the fringes of Basin (05) are located on the current agricultural plain at the city's outskirts, residing south of the railroad and motorway.

Some of these micro-basins have access to diverse water bodies and watercourses, including the main Basin (08), which fronts Lake Mariut, and the sub-basin (07b), surrounding Al Matar Lake. Basins (05b and c) are flanking the sides of the Mahmoudiyah Canal.

It can be noted that micro-basins are not entirely isolated from each other. Each basin connects with its adjacent counterparts through street crossings and, or underpasses. Moreover, in some areas, two barriers may merge into one forming an even stronger block. The dynamic nature of micro-basins becomes evident when considering their adaptability to the ever-evolving urban development of the city. Under specific circumstances, new basins may emerge, while existing ones may amalgamate or undergo division with the introduction of new barriers.

This comprehensive subdivision presented here stems from an analysis based on maps and in-depth on-site investigations conducted in Alexandria, reflecting my own understanding of the urban setting.

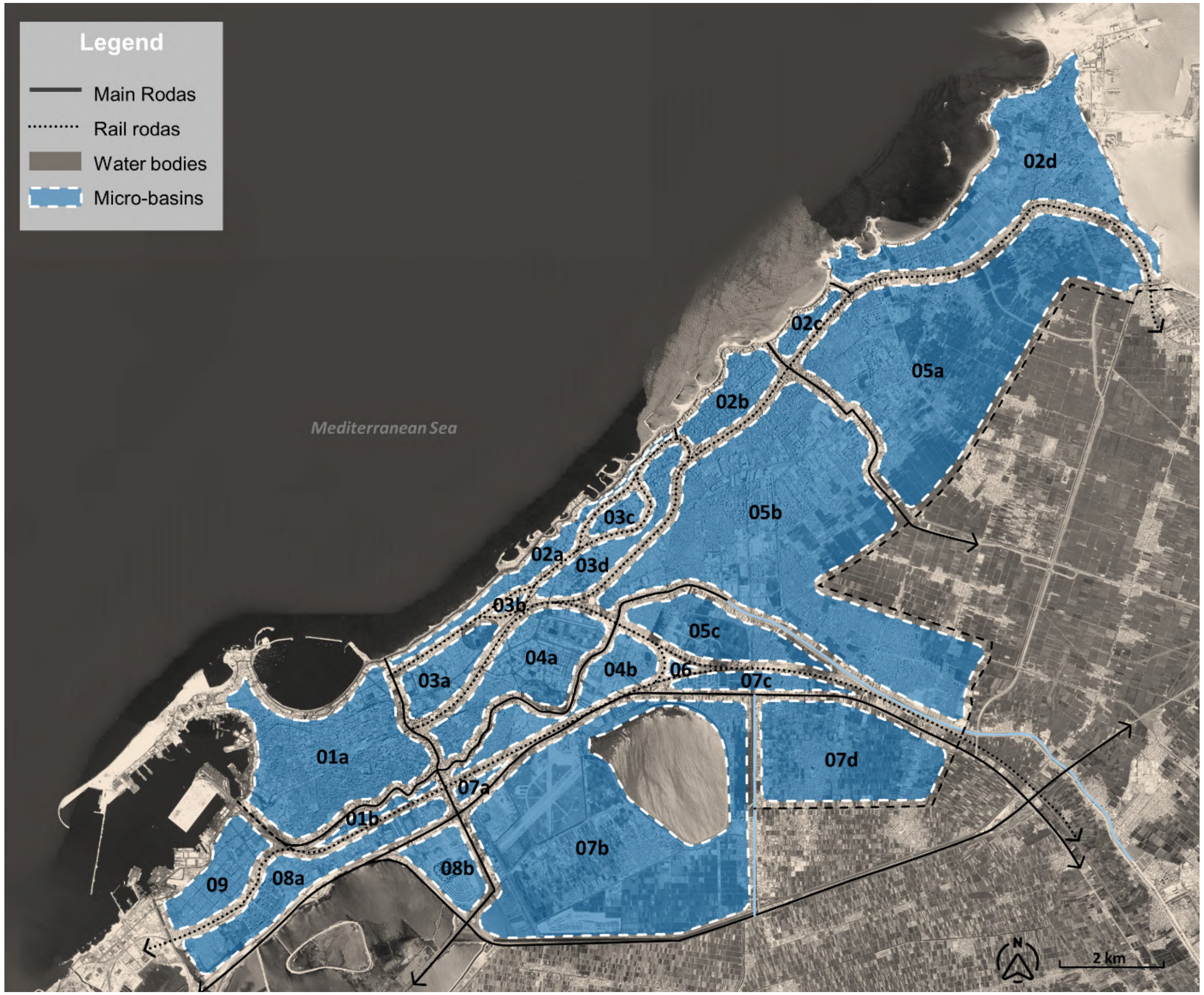


Fig. 5-10: Mapped 9 micro-basins and their subdivides within the urban area of the city

5.3.2 Water-Sensitive Micro-basins: analysis and development

A systematic spatial analysis of Alexandria is undertaken in this section, guided by the framework developed and presented in chapter 4. Within this approach, an investigation of both surface and subsurface characteristics of the city is conducted and interpreted at the local level of each micro-basin. The framework outlines a diverse array of urban aspects under three main categories: geomorphology, infrastructure and amenities, and urban context. It is necessary to clarify, however, that this dissertation does not engage all aspects with uniform depth. Given the vast and multifaceted nature of the city's urban environments, the research strategically allocates depth of analysis. Priority is given to those aspects most pertinent to the dissertation's core objectives and arguments. This approach ensures a focused examination, allowing for a thorough investigation of key factors that may influence the WSUD planning process, while acknowledging the broader urban context within which these elements operate (Fig. 5-11).

The outcomes of this analysis are classified into leveled parameters and serve as input for the decision support system, which guides the decision-making process regarding the proper selection of WSUD strategies and elements that suit the various urban settings of the city of Alexandria.

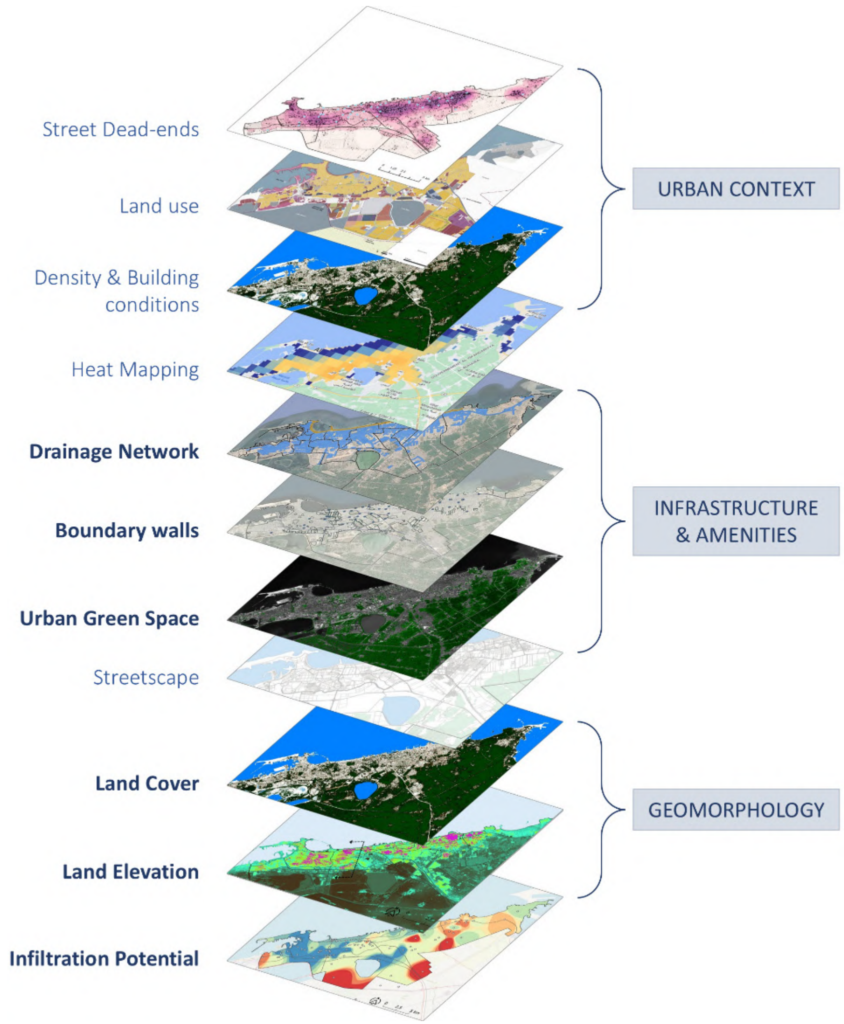


Fig. 5-11: Overview on different analysis aspects highlighting the aspects investigated in depth

Geomorphology

Land Cover

Urban land cover classification involves identifying and categorizing different types of land cover in urban areas, such as buildings, roads, sidewalks, parks, and other infrastructure. This classification is usually done using remote sensing techniques, via satellite imagery or aerial photography, to create a detailed map of land cover within a city or metropolitan area. Land cover mapping is important to facilitate the integration of blue and green infrastructure in urban landscapes. By identifying and mapping different land cover types within an urban area, planners can better understand existing conditions and potential opportunities for incorporating water-sensitive designs and techniques.

This dissertation applies land cover mapping and classification at the micro-basin level to develop various surface parameters for each basin, including built-up density, permeability ratio, and urban green factor. This helps evaluate the extent of each basin's contribution to stormwater runoff and its association with flooding risk. Land cover classification can also help identify priority areas for green infrastructure intervention, as well as suitable areas with more vegetation, bare land, and water bodies that could potentially be incorporated into a water-sensitive urban development plan. Ultimately, these and other parameters are the key inputs to the decision support tool.

Data were acquired and processed on the web-based earth observer application Sinergise Sentinel Hub EO Browser (EO-Browser, 2022). The web-based tool provides analysis and instant visualization of various satellite imagery using analytic algorithms (many of which are available on GitHub) including Urban Classified, Normalized Difference Vegetation Index (NDVI), and Normalized Difference Water Index (NDWI).

The Urban Classified Script is a fully automated land-cover map, where the algorithm identifies clusters of pixels in the image based on their spectral or textural properties (Lillesand et al., 2015). According to the author of the script, Monja Šebela, it uses NDWI, NDVI, barren soil, and B11 to distinguish between water, built-up areas, barren areas, and vegetated areas. In the script, water is colored blue, vegetation is green, built-up areas are white, barren soil is brown, and all other pixels are dark green. Monja explains that the script is particularly useful in dry regions because it can distinguish very well between bare ground and buildings, which most other visualizations fail to provide.

Fig. 5-12: Workflow of calculating area share of 5 landcover types in each micro-basin (Illustration by Joseph Benjamin)

The Urban Classified Sentinel 02 raster with 30 m resolution (Annex C) was retrieved and initial calculations were conducted by the author. Data was checked and further synthesized by Joseph Benjamin during his 10-week internship in 2023. A supervised object-based classification was carried out using the ArcGIS Image Classification Wizard. Using training samples for four land cover types (urban, barren, water, and vegetation), a classification schema was created to segment the image. The output of this was converted from a raster to a polygon layer. A script was developed to calculate the land area for each micro-basin covered by the four classification types. Then, agricultural land use was manually separated from urban green cover in the appropriate micro-basins (Fig. 5-12).

Accuracy and limitation of the results discussed in this section are indeed crucial considerations in this context. Generally, advancement in remote sensing techniques and GIS technology have led to improved land cover classification. However, challenges of mixed pixels, temporal variability, and data quality constraints remain significant factors in obtaining reliable classification results (Lillesand et al., 2015). Therefore, while these findings are suitable for demonstrating the basic surface characteristics of each basin at a conceptual level, further validation methods and on-site investigations are necessary to substantiate these results before proceeding with detailed planning.

Interpretation of land Cover Classification results as shown in Figure 5-13 is as follow:

- Built-up areas: what can be clearly seen in this chart is the high percentage of impervious surfaces as built-up area by more than 60 % in most micro-basins, reaching its highest in the densely historic center and costal basins with up to 80 % of sealed surfaces.
- Bare land: as an indication of aridity, bare land is present in every basin in the range of 20 % to 30 % of its total area. Such land cover could be undeveloped (infill) land plots, or an indication of degrading green spaces due to the insufficient maintenance and water irrigation. Therefore, bare land and green space categories may vary proportionally between rainy and dry season as the effect of

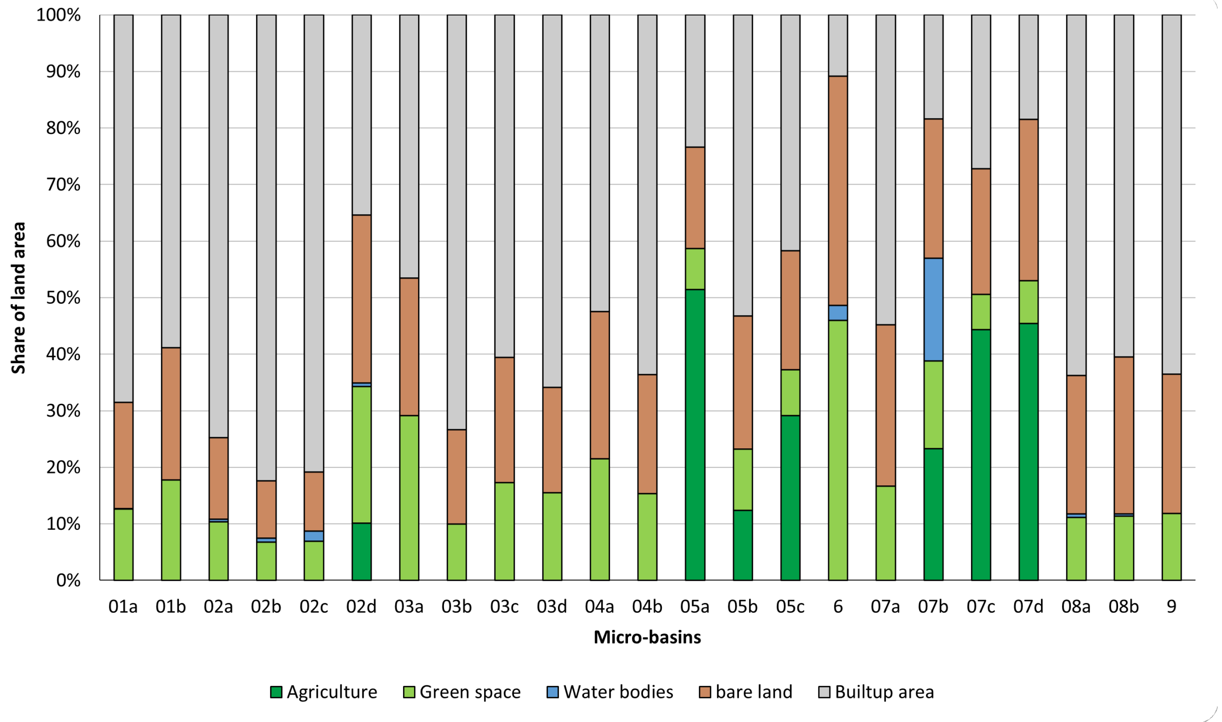


Fig. 5-13: Breakdown of landcover share area in each micro-basin (Illustration by Joseph Benjamin)

availability of water or moister is a key aspect of determining their area.

- The green spaces, or vegetation cover: percentage in each micro-basin ranges between less than10% to maximum 20% of the total basins’ area, which is clearly very low.
- Agriculture: is an arable land concentrated in the city’s hinterlands micro-basins located in the extend of deltaic plain. They are planned to be integrated in new urban areas as the city expands. Projecting landcover trends of existing urban area on the hinterland basins subject to urban expansion will result in continues increase of impervious land cover.
- Water bodies: have a minor presence in micro-basins, except the basin (07b) encompassing Lake EL Matar, in addition to other minor recreational water bodies.

Overall, the implications for land cover for water-sensitive urban planning and flood mitigation are immense. The land surface classification shows an imbalanced proportion of land cover with an obvious dominance of sealed surfaces in most micro-basins due to the high built-up density. There are also large bare land areas, in some basins even larger in proportion than green cover. In addition, hinterland micro-basins have less built-up area in favor of agricultural lands. Therefore, balancing surface cover in each basin is required with the aim of reducing total impervious surfaces and increasing green cover, to control flood peaks and volumes while enhancing livability and quality of urban areas.

Potentials include utilizing the available bare land plots, or in what so called infill lands, in a water sensitive strategy that could incorporate WSUD elements to improve stormwater detention and gradual infiltration while providing additional amenities landscape within the dense fabric of the city. However, the matter of ownership may raise a challenge to the management of any intervention. Further, an opportunity to integrate open water bodies in all basins proportionally, especially as development criteria in the urbanization of hinterlands in form of urban wetlands. This would contribute significantly to the management of flood risk, as well as promoting urban cooling and adding quality to the related communities.

Land Elevation

Precise land survey data regarding the specific elevations of various locations within Alexandria is unfortunately not available for conducting this study. Nevertheless, the main topographical elevation of Alexandria, according to references, indicates that the city expands on a relatively flat ridge with some slight variations in elevation. Most of these variations decline towards the Mediterranean Sea on one side, and on the other side, the southern slope of the city declines toward the low-lying hinterland areas below the mean sea level. The land elevation of the city is approximately 5 meters above sea level, with a range between -10 m to 20 m. This relatively low elevation is due to the city's coastal location along the Mediterranean Sea, making the city vulnerable to sea-level rise and coastal erosion. Shuttle Radar Topography Mission (SRTM GL1) elevation data with a spatial resolution of 30 meters was used to generate the Digital Elevation Model (DEM) of Alexandria City in Figure 5-14 (OpenTopography, 2022).

The interpretation of land elevation and its impact on flooding in the city reveals that natural runoff from the ridge on which the city is situated flows towards both the sea and the low-lying hinterland (former lagoons). This natural drainage pattern is disrupted by urbanization and its physical features, including major barriers of railroads and arterial roads.

To address this issue, it is essential to first analyze the city’s topography and its effect on surface runoff at a micro-basin scale. This localized perspective allows for understanding how runoff within each micro-basin affects adjacent basins and the broader city. Figure 5-14 illustrates the areas of high elevation within each micro-basin. These elevated spots determine the dominant direction of runoff guiding it from higher to lower levels, either away from or towards bordering barriers. This analysis helps identify how present barriers, such as roads and railways, may potentially obstruct natural flow and the further consequences for basins interconnection points at road crossings and underpasses. Understanding the topographical characteristics of a micro-basin in relation to its confining barriers is crucial for identifying flood-prone areas.

Additionally, areas situated between two elevated lands are particularly more vulnerable to flooding where stormwater runoff is likely to accumulate. Besides, future urban expansion on low-lying hinterland including existing development projects may face an increased risk of flooding, especially in the lowest areas of the micro-basins south of the railroad line.

Therefore, central to the water sensitive approach is the implementation of 'source control' measures, strategically placed in higher elevation areas within each micro-basin. This approach proactively manages stormwater runoff at its origin, effectively preventing the buildup of water depth in lower elevation areas.

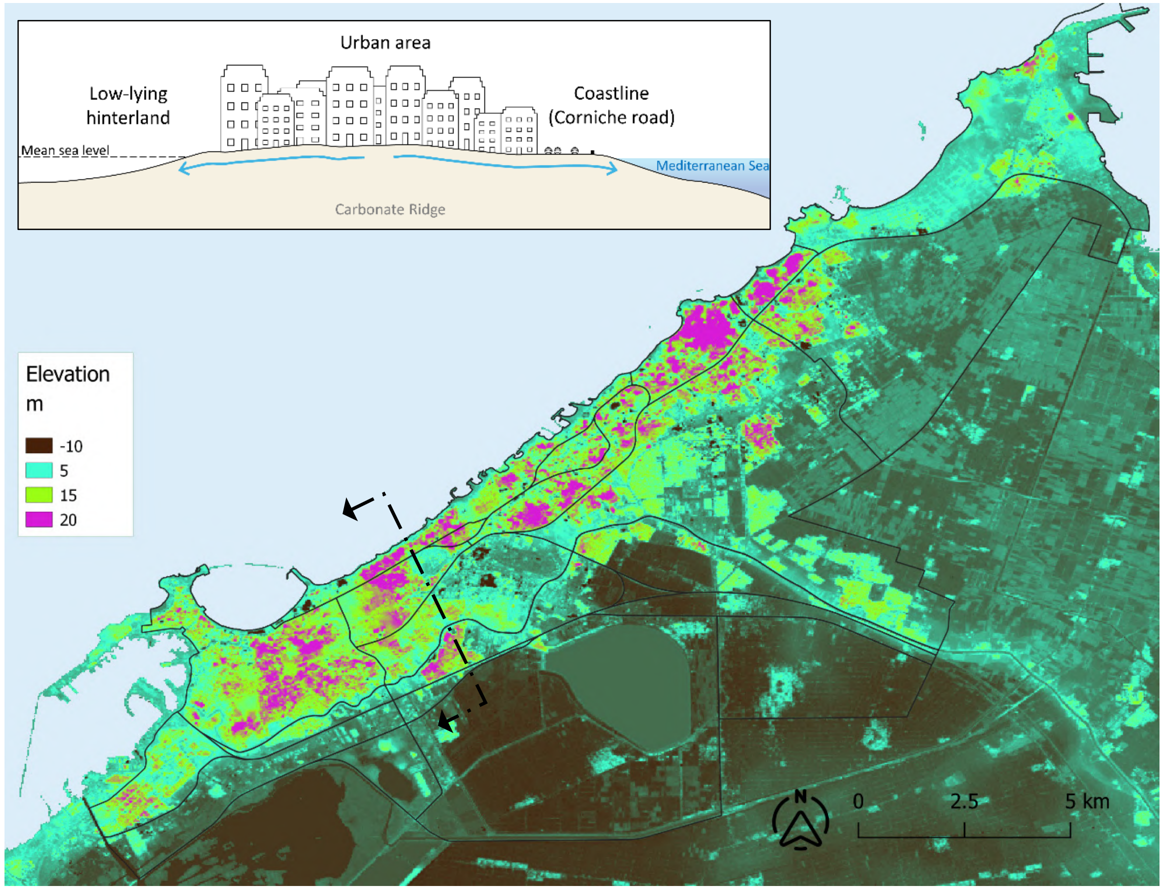


Fig. 5-14: Digital elevation model map (DEM) of the study area; And schematic cross-shore profile showing the general topography of the city

Map: processed in QGIS by author
Section profile: By author based on (Frihy et al., 2004)

Infiltration Potential Mapping

An infiltration suitability map, also known as an infiltration potential map (IPM), is a geospatial tool that assesses and categorizes the suitability of an area for water infiltration based on a range of physical and environmental factors. This map serves as a valuable resource for understanding the likelihood and ability of the soil to allow infiltration, a crucial aspect of water management and environmental planning. The primary data used in the creation of an infiltration potential map include geotechnical factors that collectively provide insights into the suitability of areas for the infiltration of runoff. These geotechnical factors encompass several key natural characteristics of the subsurface environment (RISA, 2018):

- The unsaturated subsurface soil layer structure with the determination of different types, the associated depth, and the infiltration capacity of each.
- The level of the groundwater table and its depth from the top surface.
- The terrain or slope characteristic derived from a Digital Terrain Model or other sources.

To create the infiltration potential map, data on these geotechnical factors are collected through documented borehole logs, which provide information about soil types and groundwater table depths at specific locations within the study area. This data is then processed using geographic information systems (GIS) and hydrological models to generate a comprehensive map that categorizes areas based on their suitability for water infiltration.

It is important to note that while the infiltration potential map is a valuable tool for preliminary assessments and decision-making, it does have limitations in terms of accuracy, especially when it comes to the implementation level. Therefore, it should not substitute for on-site investigations before detailed design work. Instead, the map serves as an initial indicative screening tool, offering valuable insights for research, planning, and aiding in the identification of potential site constraints and suitable WSUD technologies.

Borehole data used:

During a research stay in Alexandria in September 2022, a total of 102 borehole logs were collected from various sources to cover wide areas (Annex C). The location of the boreholes is fairly well distributed across the city but with a low data density that presents gaps in between. This is due to either the unavailability of data on specific locations such as green spaces and cemeteries or the limited availability of borehole logs. These data are usually not accessible to the public and are only provided by certain consulting firms, contractors, and clients, including local governments, with their permission. The sources for the collected borehole logs data are as follows:

- 38 boreholes from Alexandria Sanitary and Drainage Co. (ASDCO)
- 47 boreholes from General Authority for Educational Buildings (GAEB), retrieved from (Khalil, 2009)
- 09 boreholes from Fathi Abd Rabbo Consulting Bureau (FACB)
- 08 boreholes from Horema Geotechnical and Soil Engineering Services

Subsoil infiltration capacity and depth:

An essential prerequisite for the infiltration of rainwater into the soil is to determine the permeability of the soil and then the extent of the depth of infiltration, which is determined either by the depth of the soil layer itself or by the water table level, whichever is closest to the surface. Soil permeability can be described as the ability of the soil to allow water to pass through and infiltrate into the ground. Factors of texture, grain size, and distribution determine the permeability of a soil and are expressed by the coefficient of hydraulic conductivity. According to the US Hydrology National Engineering Handbook (NRCS, 2009), soils are classified into four hydrologic soil groups based on their infiltration capacity (Table 7). The range of infiltration potential is from high in Group A, where the soil

Table 7: hydrologic Soil Group Classification and Definition, based on (NRCS, 2009)

Soil type	K_{sat}	Group	Meaning	K_{sat}
Sand	4.74	A	High infiltration potential	> 1.42
Loamy Sand	1.18	B	Moderately High infiltration potential.	0.57 – 1:42
Sandy Loam	0.43	C	Moderately low infiltration potential. Water seepage through the soil is relatively limited.	0.06 – 0.57
Loam	0.13			
Silt Loam	0.26			
Sandy Clay Loam	0.06			
Clay Loam	0.04	D	Very low infiltration potential. Water seepage through the soil is restricted.	< 0.06
Silty Clay Loam	0.04			
Sandy Clay	0.02			
Silty Clay	0.02			
Clay	0.01			

K = saturated hydraulic conductivity, in/hr

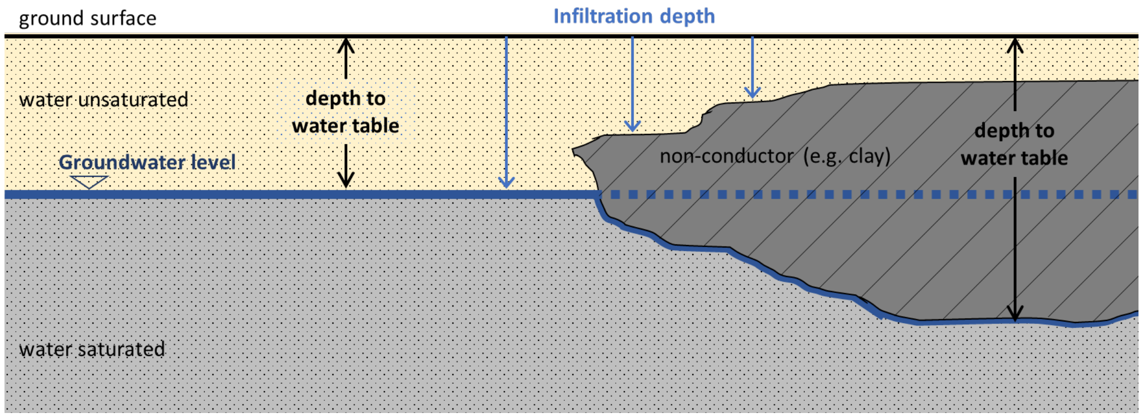


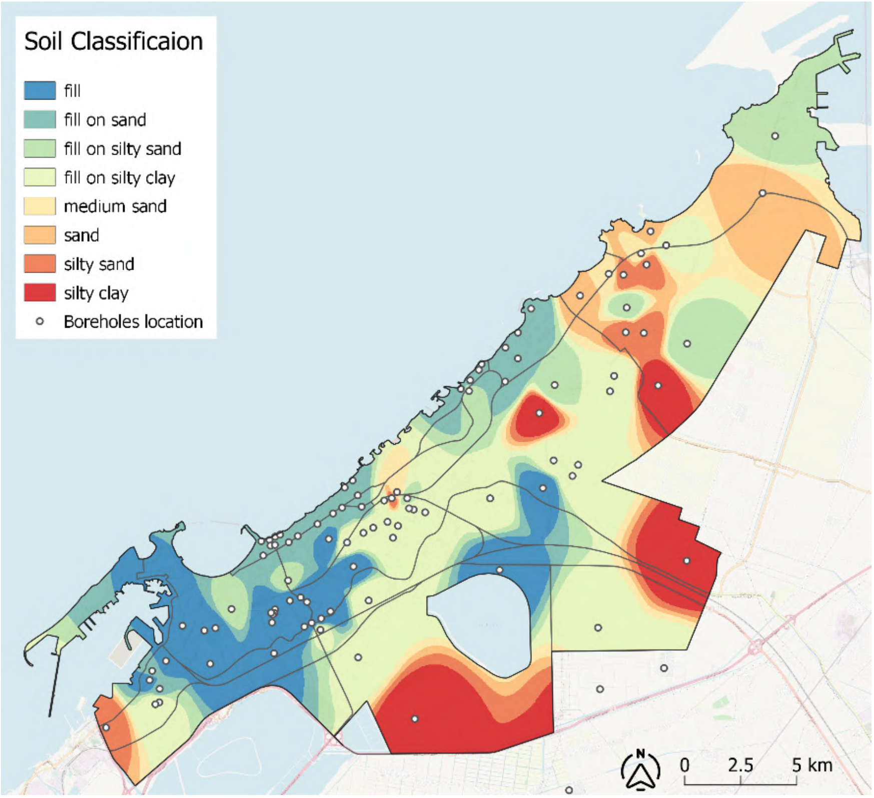
Fig. 5-15: Schematic sketch explaining groundwater level, depth to water table and the infiltration depth, by author based on (RISA, 2018)

is predominantly sands and fillers, to very limited capacity in Group D, where the soil has a high silt and clay content that restricts water seepage through the soil. Groups B and C are considered transitional categories with moderate infiltration capacity, tending towards Groups A and D depending on the ratio of sand, silt, and clay content of the soil.

Infiltration depth is another important factor in determining the infiltration capacity of a soil. For impermeable soils, the allowable depth to infiltrate rainwater depends on the thickness of the layer and the level of the near-surface water table (Fig. 5-15). Two conditions can occur when compiling borehole data that provide information about subsurface properties: the water table is below the lower depth of the permeable soil layer or, in other cases, above it. In the first case, the depth of infiltration is limited to the thickness of the permeable soil layer; in the other case, the groundwater level limits the depth at which stormwater can be infiltrated.

Groundwater level:

As indicated in Figure 5-16, the groundwater level refers to the elevation of the water table in a subsurface aquifer measured relative to a reference point of the sea level or the earth's surface. Groundwater levels can fluctuate depending on natural factors such as precipitation and geology, as well as human activities such as pumping and irrigation.



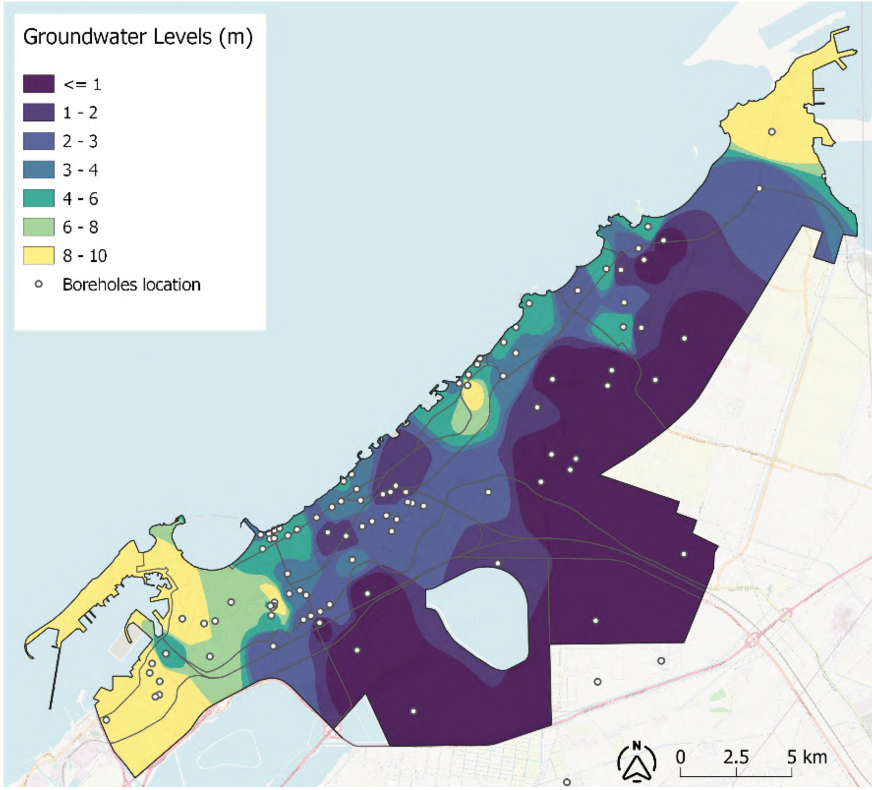


Fig. 5-16: IDW interpolation of the soil types (left) and groundwater levels (right) based on collected point boreholes data (processed and illustrated by author in QGIS)

Groundwater levels for all identified sites in Alexandria are recorded in each associated borehole log. All depths were measured from the top surface of the investigated site. The collected point data are extracted and interpolated using the Inverse Distance Weighted Method (IDW) in QGIS and arranged in zoned classes.

Both the soil and water table maps are instrumental in giving insight into the geological and topographical attributes of the city. The soil classification map (Fig. 5-16) reveals the presence of a fill layer with variable depth over wide areas of the city. This fill layer is a cohesive soil mass accumulated by urban activities over long periods and consists of an amalgamation of sediments and debris including sand, dirt, silt, rubble, and crushed stones undergoing compaction and cementation processes. This soil generally provides good drainage properties. However, its drainage capacity could be limited to the layer's total thickness and the properties of the underlying native soil, which vary in this case between mostly sandy soil as a geological characteristic of the ridge along the cost, and silty clay in the low-laying deltaic plain.

> **Interpolation** is a method used to estimate values for locations where there are no measured data points based on the values of surrounding data points. It involves interjecting an unknown value intermediately between two other known values. The use of interpolation is intended to create a smooth representation of the geodata across the surface of the study area. (Li & Heap, 2014)

Additionally, the infiltration properties may be affected by the levels of groundwater depth. In low-lying hinterlands, the water table resides close to the surface, often within a depth of 3 meters or less. As terrain elevation ascends above sea level, the water table recedes deeper underground. The most profound groundwater levels, surpassing 6 meters in depth, are encountered in the historic city center, Abukir, and some areas along the coast.

Terrain or slope:

Slope is another factor that determines the suitability of an area for infiltration. Rainwater runs off more quickly on sloping surfaces, so the water cannot settle sufficiently to infiltrate into the ground. In addition, the risk of landslides increases due to the high-water content in sloped soils. Therefore, integrating an infiltration system on a steeply sloped site may require special consideration in sizing and design and could result in higher costs. However, the influence of slope on stormwater management design must be considered on a case-by-case basis.

Based on the working map for decentralized rainwater management in Dortmund, retrieved from RISA (2018), Table 8 classifies the percentage of slope with associated impacts and risks. According to this classification, a slope of 12% is critical for implementing any infiltration system, and below this value, the risk gradually decreases. Alexandria has relatively flat terrain with low slopes in very limited areas. Generally, the slope in the city does not exceed 6% except in very limited site-specific cases. Therefore, in Alexandria, slope was excluded as one of the determining factors for the suitability of infiltration systems because it is not applicable within the scope of the city.

Table 8: Land slope classification (RISA, 2018)

Slope	Influence on infiltration measures
< 5%	No restriction
5 – 7.5%	Medium creation effort, possible danger of spring water
7.5 – 12%	High construction cost; reduced usability of potential cultivation areas; increased danger of blackwater and slope water
> 12%	Inefficient, no standard solution

Infiltration Potential Classification:

The information from the interpolation model is incorporated into classes and compiled into a classification map (Fig. 5-17). The infiltration potential classification specifies varying degrees of suitability for infiltration across the city, categorized as unlikely, limited, probable, or possible, each with specific implications:

Unlikely: Infiltration potential is limited to only 1 meter below the surface of the topsoil due to the low permeability of the subsoil. Instead of infiltration, an attenuation feature with controlled discharge to nearby water bodies or to the sewer system, preferably to a separate system, is recommended for areas in this category.

Limited: Infiltration potential is moderately low (within 2 meters of the subsurface). In this case, the permeability of the subsurface would allow infiltration. Nevertheless, there may be limitations, such as the height of the water table or the thickness of the subsurface being limited to this range.

Probable: Infiltration potential is moderately high (from 2 meters to 5 meters of subsurface). Both the permeability of the soil and the water table allow for proper infiltration. However, the limitations of the total depth should be considered when choosing the proper infiltration system. In these locations, it is recommended to avoid large-scale systems like basins that attenuate large volumes of runoff, and instead use medium and small-scale systems, such as swales or bioretention.

Possible: There is a very high potential for infiltration (greater than 5 meters). In these areas, the water table is at a sufficient depth and the subsurface proves to be very permeable. It is considered suitable to integrate any of the infiltration systems at these sites, including infiltration basins, infiltration trenches, swales, permeable paving, and geocellular modules.

The results the map demonstrates can be interpreted to describe the varying infiltration potential in relation to the different micro-basins, as well as the case along the barriers. It can be seen from the map that the infiltration potential is *Unlikely* in micro-basins in the hinterlands, which are part of the reclaimed wetland in the lower deltaic plain. Conversely, micro-basins located on the elevated main urban area along the coast show higher infiltration potential, ranging from *Probable* in most of the mid and eastern parts to predominantly *Possible* in the western part, particularly in the old historic city.

Additionally, the map highlights the infiltration potential along the different identified barriers. Tramway and railway lines, as well as main roads running along the area near the coast, predominantly sit on permeable soil with relatively deeper subsurface water tables, indicating moderately high to very high infiltration

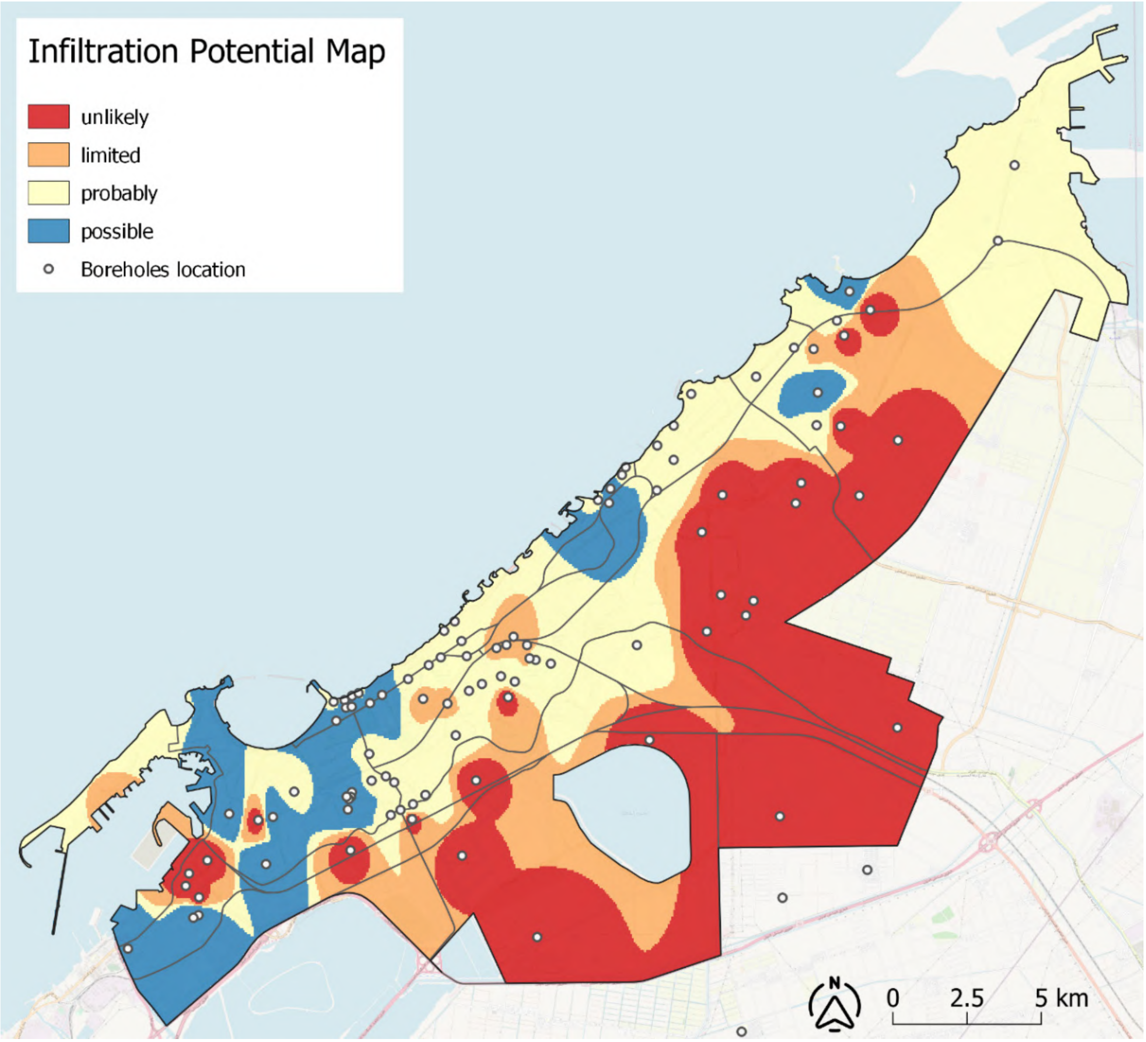


Fig. 5-17: Map showing range of infiltration potential over the urban area, based on interpolated discrete point boreholes data (processed and illustrated by author in QGIS)

potential. While different sections along Mahmoudiyah Road exhibit varying infiltration potential, motorways and parts of railway lines extending into the lower hinterlands, particularly south of Mahmoudiyah Road, display low to very low infiltration potential.

Overall, the geotechnical map offers insights into infiltration possibilities within micro-basins and along barriers. Micro-basins' subsurface features range from homogeneous to heterogeneous, necessitating addressing each with adequate WSUD strategies. For instance, areas with moderate to very high infiltration potential within micro-basins should integrate elements supporting infiltration, while different sections of barriers should be addressed accordingly. This notably emphasizes the importance of taking subsurface characteristics into statutory land use planning, in order to improve the capacity to adopt WSUD design practices in urban areas.

However, the qualitative aspect of stormwater runoff and restrictions on infiltrating into the soil should be regulated, particularly in areas with land uses prone to contamination like industrial zones and landfills, to prevent any possible contamination of groundwater. It is important to note that the infiltration classification of ‘limited’ in most areas results from interpolation rather than borehole data. Reliable accuracy of such a map requires more extensive borehole coverage. Thus, the map presented here, based on the collected data, is intended as indicative only and is used as a preliminary screening tool for the purpose of this dissertation, while site-specific assessments remain imperative for detailed design considerations.

Infrastructure and Amenities

According to the analysis framework, sewage network and capacity lays under this section, but the topic has already been presented and discussed earlier in the first section of this chapter. Other aspects are included in the following.

Open and Green Spaces

Urban green spaces (UGS) are defined as land surfaces within urban areas that are partially or wholly covered by vegetation like grass, trees, shrubs, or other plant types. These include parks, gardens, urban forests, and cemeteries, as categorized by the World Health Organization (WHO, 2017). UGS can be publicly accessible or restricted, as seen in private properties. Beyond their environmental and societal contributions, serving as the "lungs of cities," UGS are crucial in the WSUD approach. They constitute major components in treatment and detention functions provided by WSUD technologies. Accordingly, this section aims to analyze the existing green infrastructure and urban green spaces in Alexandria, investigating the challenges and underscoring their potential for integration into city-wide water-sensitive planning.

The importance of UGS in the context of dry climates stems from their crucial role within the WSUD approach in mitigating the impacts of urban extreme conditions like heat waves and flooding, while offering solutions to the dilemma of sustaining vegetation growth in this harsh environment.

An overview of the existing open and green spaces in cities shows various typologies. Several inventory systems have been developed to categorize the different types of UGS. For instance, Hofmann and Gerstenberg (2014) clustered UGS based on privacy versus public access, as well as functionality versus enjoyment. Another inventory was created by Swanwick et al. (2003) where they divided UGS into four primary categories: amenity green space, functional green space, semi-natural habitats, and linear green space. Bell et al. (2007) n their proposal of several inventories, distinguished between parks and gardens, natural and semi-natural spaces, green corridors, urban farms, outdoor sport facilities, churchyards, and cemeteries. Some other systems tend to include open space and streetscape greeneries, such as squares, street green verges, tree alleys, and railroad banks, as a distinctive typology (Rall L. et al., 2015).

Due to the wide differences in UGS characteristics between contexts, regions, and climates, it has been assumed that it is not applicable for one system to cover all types (Ignatieva & Mofrad, 2023). The UGS inventory system applied to the analysis in this section considers combining some of these systems, primarily based on the setting of the green space and the range of services it provides as a distinct space. In addition to the accessibility of the space by the public, semi-public, or as a private space, where the extent of potential and limitations could be determined. Typologies help in establishing a systematic framework that integrates landscape into water-sensitive urban management. The UGS inventory in Alexandria can be categorized and concluded into the following types:

Urban parks – are public open green spaces within the city that offer recreational spaces for residents. They can vary in size and design, ranging from small pocket parks to large public parks, some are built in recent time and historical parks as old as from the past centuries. Botanic garden and zoo also are considered under urban parks. They are typically fenced with boundary walls and have controlled access.

Residential green space – refers to designated vegetated lots within residential communities that are intentionally designed or preserved to provide recreational space. These green areas can take various forms and serve different users depending on their accessibility. For instance, private gardens or rooftop gardens are only accessible to the owners of the associated property. Community and allotment gardens are semi-public spaces that serve a community or cluster block.

Landscape around buildings – refers to the intentional design and integration of vegetation and landscaping features in the areas surrounding buildings. These landscapes can be classified into two categories based on the building's use: either public institutional or commercial. For public institutional buildings, such as healthcare facilities, universities, schools, sports clubs, mosques, and churches, these landscapes serve as integral components of the campus. On the other hand, commercial buildings, including hotels and beach clubs, also incorporate green spaces, which are basic requirements to enhance the overall appeal and create a welcoming environment for visitors. In this typology, the landscapes and open areas can cover a significant portion of the plot, reaching up to 60% of the total area. However, it is worth mentioning that these green spaces are typically accessible exclusively to the users or occupants of the respective facility, ensuring a controlled and private environment.

Cemetery green spaces – are vegetated areas within cemeteries, composed of a combination of natural landscapes and designed elements.

Vacant land green spaces – or what so-called Spontaneous Green Spaces by Kowarik (2018), are undeveloped urban lots where spontaneous vegetation grows naturally without any management or intervention. These areas of land are usually scattered into military open lands or just infill plots within residential or industrial blocks and mostly uninhabited and not accessible.

Streetscape green spaces – refer to the incorporation of green elements, such as trees, plants, and landscaping, within the urban streetscape. They can be found along sidewalks, medians, road verges, public squares, railroad banks, and other public spaces within the urban fabric.

The urban green spaces in Alexandria reflect the city's dense built-up areas and the challenges associated with growing vegetation in dry environment. The green spaces are limited and unevenly distributed across the city, impacting urban livability and ecological aspects.

Fig. 5-18: Typology of urban green space in Alexandria (By author based on google earth 2023)

Distribution: The distribution of green spaces in Alexandria is not uniform. Areas in the central districts of the city are better served in terms of the availability of public gardens and parks compared to more densely populated and industrial areas east and west of the city. The major existing UGS, primarily established since the eighteenth century, are located on the periphery and outside the old city's historical core. These include two public parks, cemeteries, and sports clubs, along with green spaces linked to university campuses and public buildings predominantly concentrated in these areas. Other significant parks are found on the outskirts, to the south and east of the main urban area. Smaller green spaces, which are sparsely scattered without a clear pattern, include private properties and green allotments within some residential developments. Spontaneous green spaces also appear along tram and railway tracks, as well as on infill vacant lots throughout the city. UGS within streetscapes are limited to arterial and main roads, major squares, and areas beneath bridge nodes.

Current Status: The increasing demand on land for urban growth in such high urban density has led to a significant decrease in existing green areas. This reduction has not been compensated by equivalent new green spaces, nor has it kept pace with rapid urban development. For instance, historical parks of Antoniadis and Shalalat have seen reductions of 20% and 56%, respectively, in their total areas over time (Heysham, 2017), see also Figure 2-14 in Chapter 2. Moreover, green spaces integrated into streetscapes are continually being reduced due to traffic expansion projects aimed at increasing vehicle capacity at the expense of pedestrians and green areas.

According to Ministry of Environment in Egypt (MEE, 2016) retrieved from Farouk (2023), Alexandria has approximately 684 acres of green space. Considering the population of 5.5 million according to the latest census, the availability of green space is a mere 0.5 m² per person. This is just half the share that was available in 2004 and is further decreasing (Fig. 5-20). According to the World Health Organization's recommendation, the provision of 9 square meters of green space per capita is essential, but Alexandria falls short of this benchmark (WHO, 2012).

In terms of quality, the already insufficient public UGS are deteriorating gradually. Lack of maintenance, including inadequate irrigation, affects plant growth and the quality of green cover. Vegetation in most public areas does not withstand the water shortage and heat stress during summer months. The two primary limitations for supporting and developing green

Fig. 5-19: Distribution of major UGS in Alexandria (google earth 2023)

spaces in Alexandria, according to experts, include:

- The unavailability of a sustainable water resource to supply the constant high demand and cost of water for UGS irrigation.
- The extensive financial and human resources required to provide constant maintenance of UGS in the city.

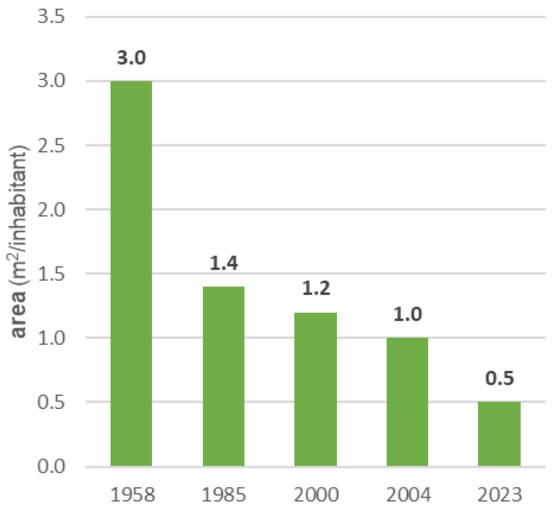


Fig. 5-20: Decreasing share of green space per person in Alexandria, based on (Farouk, 2023)

Any kind of landscaping involving vegetation in the city requires a reliable source of water and a method for constant irrigation on a regular basis. According to experts in Alexandria, certain sports clubs and private resorts along the western coast have begun to supplement their water supply for irrigation with extraction from groundwater wells, a practice that has become necessary given the decreasing availability of traditional water resources.

Affording a sustainable water supply for irrigation is very challenging, especially in recent times as the available water resource is decreasing. It is becoming more urgent in the city to provide an alternative water resource for green space irrigation. This necessity has led sports clubs in the city to supplement their water supply for irrigation from groundwater wells they bore within their grounds, according to experts (Interview, 2022). They add that it has been a well-established practice in private resorts along the western coast for many years.

Besides plant care, irrigation networks or manual irrigation methods require funds for construction and regular maintenance. The high demands for management and maintenance of green spaces, coupled with local councils' inability to provide sufficient financial and human resources, mean that the quality and quantity of public UGS continue to degrade, both as amenities and ecological assets. This trend has led to the emergence of "concrete parks," which are criticized for prioritizing low maintenance over ecological and recreational benefits, as discussed earlier in Chapter 2.

Ultimately, A small portion of UGS in Alexandria endure in the public realm of streets and squares, and much of it belongs to the establishment were built within its premises and can only benefit from. Green space in the city has become a choice of individuals where they have available space to provide and resources to sustain rather than a coordinated city policy aimed at improving quality of life and building urban resilience.

Prospects: It is obvious how challenging it is in Alexandria to sustain green spaces in its climate and urban settings. Therefore, a paradigm shift and a new approach are needed to mitigate the UGS vulnerability to the local dry climate. The WSUD concept and green practices may be seen as an opportunity to interdependently support existing and the expansion of new UGS while mitigating the risk of flooding.

Large parks and sports fields could benefit from incorporating multifunctional WSUD systems for detention and retention, which would enhance soil moisture and provide passive irrigation while still maintaining their recreational functionality. Runoff from impermeable surfaces and rooftops could be redirected into rain gardens, swales, ponds, and subsurface infiltration systems. A centralized approach, similar to the Glenelg project in Adelaide described in Chapter 3, could be adopted to provide supplementary irrigation during dry spells using recycled wastewater after tertiary treatment at local wastewater treatment plants.

Given the increasing reliance on groundwater extraction for irrigation in Alexandria, it may be beneficial to use extraction wells to inject harvested rainwater into the ground for later use during dry periods. Moreover, private properties and commercial and institutional buildings should adopt rainwater harvesting techniques, collecting runoff in cisterns with overflows directed to surrounding landscapes. In the dry season, stored water could be used for irrigation. Additionally, if space allows, integrating greywater treatment and storage for irrigation could be viable. Treatment would involve integrating constructed wetland or biofilter systems within the green space, which could treat greywater discharged from the building to supplement irrigation requirements.

Vacant infill lands represent a significant opportunity to expand the UGS footprint, particularly in densely urbanized areas where space for new amenities is scarce. These lands, often characterized by expansive permeable surfaces, are ideally suited for various WSUD applications, such as stormwater basins or rain gardens that support vegetation and promote soil moisture and infiltration.

Fig. 5-21: An Example vacant infill plot after storm event in Abu Dhabi, UAE (ARUP, 2018)

In line with the centralized approach to using recycled wastewater for irrigation, vacant land tracts along Mahmoudiah Road and near the East WWTP could be utilized for wetland treatment parks. These parks would receive effluent discharges and provide tertiary treatment before distributing the treated water to nearby parks. This proposal, along with other WSUD strategies at the road scale, will be further elaborated in the section on urban barriers' development later in this chapter. However, the safety of nearby structures and necessary protection measures must be considered, especially given the high-density urban context.

The feasibility of these initiatives may be impacted by varying ownership rights and existing land use plans.

Additionally, cemeteries, as large green spaces within urban environments, can significantly contribute to stormwater resilience. Recent research underscores the potential of multifunctional cemeteries not only as burial grounds but also as crucial elements of urban green infrastructure to manage stormwater and mitigate flood risks (LEUTA, 2019; Shale, 2014). Such initiatives have been already adapted in cemetery development projects. For example, the Green-Wood Cemetery, New York in 2022, and Mount Olivet Cemetery, Washington, D.C. in 2018. Indeed, the urban context and structure of cemeteries in Alexandria and the region, in general, differ greatly from those examples, but it may be feasible to conduct further investigations to examine the possible potentials and limitations of cemetery green space in Alexandria to function beyond burial sites, contributing to ecological and stormwater management objectives.

The following section will introduce a valuable metric tool that can facilitate the management and control of green space cover and surface permeability at the micro-basin level.

Urban Green Factor (UGF)

Urban Greening Factor (UGF) is a metric used to measure the amount of greenery in urban areas. It is a numerical indicator that considers various aspects of green infrastructure, such as parks, gardens, street trees, and green roofs. The UGF was developed to help policymakers, planners, and developers make informed decisions about the design and development of urban environments.

The UGF typically ranges from 0 to 1, with higher values representing a greater amount of green infrastructure. A UGF score of 1 would indicate that an area has as much natural surface area as possible, while a score of 0 indicates insufficient greening and completely sealed areas. UGF takes into account several factors, including the size of green space and pervious surfaces. The metric also considers the potential for surface cover to infiltrate stormwater. It also considers environmental benefits of improving air quality, mitigating the urban heat island effect, and promoting biodiversity (Juhola, 2018).

The UGF was originally developed in Berlin as the Biotope Area Factor ‘Biotopflächenfaktor’ in 1994 to set standards to promote ecological design in the city (Berlin, 2021), and has then been adopted in several cities around the world (Dahlan et al., 2022).

$$\text{Green Factor} = \frac{\text{Total effective green area}}{\text{Total site area}}$$

Element weighting factors are assigned to each surface under four categories: paths and traffic, vegetation, water bodies, and buildings. Factor scores might differ from city to city according to their local urban settings and requirements. Generally, roads and streetscape factors could vary between 0.0 for completely sealed surfaces and 0.1 to 0.4 for partially permeable surfaces. Vegetation scores range from 1.0 for natural vegetation to 0.4 for lawns. Further scoring details can be observed from London and Berlin's plans (Berlin, 2021; GLA, 2023)

Cities have also set targets for UGF based on and driven by their local conditions. For example, the London Plan recommends a score of 0.4 for predominantly residential development and a score of 0.3 for predominantly commercial development (GLA, 2023).

Given the circumstances in Alexandria, it is apparent that targets may vary for different locations in the city, where a more sophisticated system of targets is needed to match different existing urban conditions and densities. In a

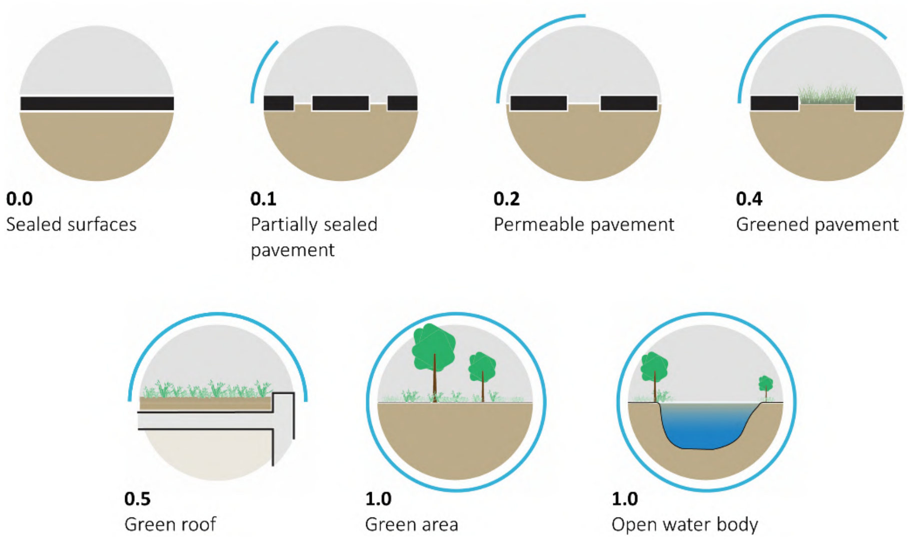


Fig. 5-22: Various surface cover types and suggested factor scores for Alexandria
Illustrated by Mohamed Elfouly, based on (Berlin, 2021; GLA, 2023)

dense urban area, residential uses could have lower score targets than commercial or public buildings. In new and less dense residential developments, on the other hand, a high target score should be sought.

Consistent with the planning approach developed in this dissertation, this UGF method has been adapted more broadly to be applied at the level of micro-basins in the city of Alexandria (Fig. 5-22). The data of land surface cover has been reused and processed for this UGF indicator. However, it is recommended that a detailed UGF system be implemented on a development scale in the city.

Five different surface typologies, according to the earlier land cover analysis, have been identified in Alexandria. Their associated weighting factors are as follows:

Table 9: Weighting factor of each surface typology

Factor	Surface type
1.0	Vegetated area (e.g., parks, gardens and streetscape greeneries)
0.5	Bare Land areas (e.g., all noncovered surfaces)
0.0	Sealed areas (e.g., buildings, street asphalt and paved surfaces)
1.0	Water Bodies (e.g., lakes and ponds)
0.8	Agricultural Lands (e.g., farming and crop lands in the outskirts)

This approach has been applied to the study area to present the current global UGF of each micro-basin. The results show that, with the current green space status of the city, almost half of the basins have a UGF between 0.2 and 0.4. Four basins are below that range, and others are above it, with two basins over 0.7. The basins with the highest factors are on the outskirts, with less built-up area and considerable agricultural lands.

In such a dense urban setting where open space is minimal and available space is extensively built-up, rooftops have the most significant contribution to the total stormwater runoff. In contrast, in the less dense settings of other cities, roads are considered the major generators of runoff in urban areas.

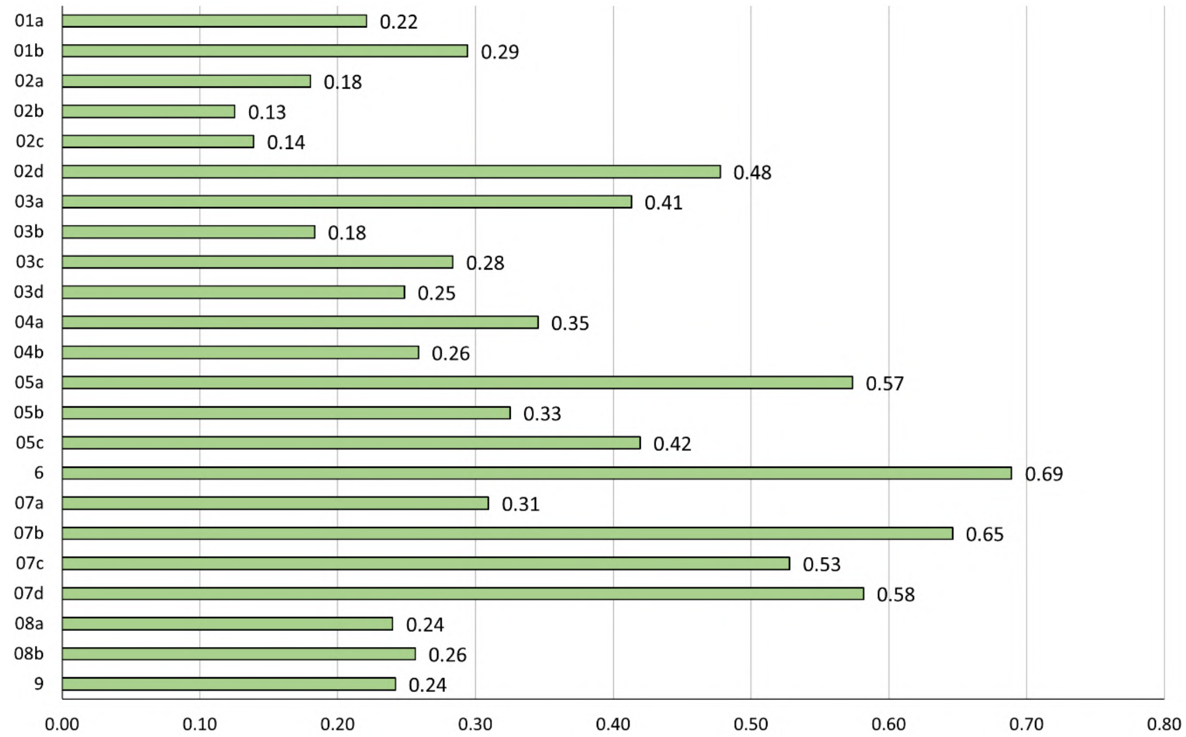


Fig. 5-23: Global UGF scores of each micro-basin (Illustration by Joseph Benjamin)

Streetscape

Understanding the streetscape characteristics and typology of Alexandria is essential for developing effective WSUD at street level, especially in high-density urban contexts. The street layout of Alexandria exhibits a blend of grid patterns and organic street networks. The central areas, particularly around the historic city center and along the Mediterranean coast, often follow a grid pattern. In contrast, the older neighborhoods and newer informal urban extensions feature more organic, irregular street patterns with many dead-end streets. Except for primary arterials and secondary roads, local streets are typically narrow with minimal sidewalks. The street drainage slope presents another challenge. Drainage is typically directed towards the outer sides of the streets rather than towards an inner median.

Street vegetated verges along sidewalks are generally absent as well. Trees are sparsely present, resulting in a weak tree canopy except in minor parts of older main roads. Recent traffic projects often neglect the inclusion of trees, exacerbating the lack of green infrastructure. In this dense urban context, tree pits could be an ideal solution to enhance green coverage, drawing inspiration from successful implementations in other cities like Adelaide. However, the selection of tree species for Alexandria's streetscape must consider form, climate, and existing services and infrastructure. Currently, Ficus nitida trees dominate the city streets, along with some palm trees and Poinciana trees. However, this choice has faced significant criticism. Dr. Nabil Elhady from Cairo University argues that Ficus nitida, despite its drought resistance, is not suitable for Egypt's urban context. The dense foliage of these trees traps dust, reducing air quality, and provides breeding grounds for flies. He suggests that Ficus trees might be more appropriate for the outskirts of the city as barriers against dust storms and winds. Alternative tree species have been proposed to address these issues. Dr. Ahmed recommends planting edible trees such as the Carob Tree, Doum Palm, Sycamore, and Jacaranda trees (Interview, 2022). However, each of these species has limitations, including the vigorous roots of the Carob tree, which may not be suitable for all street typologies.

Overall, from the current investigation, it is apparent that further research is required to provide a comprehensive street tree selection and configuration guideline for different streetscape typologies in Alexandria.

> A critical question remains: What are the ideal street tree species that could be suitable for the different street typologies in Alexandria?

Urban Context

The historical layering of Alexandria City—from Hellenistic foundations, through Roman and Arab influences, to modern impacts—profoundly influences its contemporary urban context. Analyzing this context is a foundational process in the development and implementation of WSUD strategies. It involves a detailed examination of various aspects of the city's wider area. This analysis aims to understand how these urban characteristics influence and contribute to the planning and design of WSUD initiatives. By providing a comprehensive overview of the urban environment, the analysis ensures that WSUD strategies are effectively integrated into the public and private space design of the city. This section explores the urban context of Alexandria City, focusing on the key elements that shape its physical landscapes.

Land-use

The role of land use in urban stormwater management is pivotal, as the type and extent of land use significantly influence both the quantity and quality of urban runoff (Pinto et al., 2023). Land use patterns determine the nature of surfaces (permeable vs. impermeable) and the presence and type of pollutants due to the various activities. Different land uses contribute distinct types and amounts of pollutants to stormwater. For example, industrial areas may introduce heavy metals, oils, and chemicals, while residential areas might contribute nutrients, sediments, and bacterial contamination (Goonetilleke et al., 2005). Proper understanding of the land use impact on runoff can help in the planning and design of suitable WSUD techniques.

Alexandria exhibits a diverse mix of land use patterns that underscore its diverse urban fabric and reflect its population density and urban sprawl. The city's landscape is categorized into residential, commercial, industrial, recreational, and historical zones. Mixed residential and commercial uses predominate in the main urban area. Industrial zones, however, are segregated and placed in the peripheries and near port facilities. These peripheral zones serve as centers for a variety of industries, including petrochemical, textile, and food processing sectors. The city also integrates administrative, educational, and recreational spaces within the residential fabric, promoting a dynamic urban landscape where various land uses coexist (AASTMT & Egis, 2011; Abourisha, 2016).

The micro-basins display mixed land-use patterns, with none defined by a single use.Iindustrial zones, particularly along the southern railroad (basins 07a and 08a), are prominent over other land uses. These industrial and brownfield areas have higher impermeable surface cover that typically generate highly polluted stormwater runoff. Constraints on soil infiltration may take place in such setting unless additional treatment is introduced in order to prevent soil and groundwater contamination (Jayasooriya et al., 2020). Micro-basin 03a has a high portion of public land use dedicated to institutional and service buildings. This suggests that public areas in this micro-basin could be most suitable to demonstrate the feasibility and benefits of WSUD implementation.

Buildings Condition

Buildings are important in the WSUD approach as they represent the initial basic urban element to encounter in controlling stormwater runoff in a city. The possibility to apply WSUD building-scale technologies of green roofs, living walls, and rainwater tanks, greatly relies on the physical status of the building at the time of intervention. Factors of materials, static structure design, and height are determinative in integrating WSUD elements into the design of any existing or new building.

According to a survey by the General Organization for Physical Planning in Egypt (GOPP), introduced in (AASTMT & Egis, 2011), the building stock in Alexandria is relatively old and of deteriorating quality. The old historic city core has the oldest buildings and the most vulnerable to heavy rainfall events. Most of the buildings are multi-story apartment buildings. The main building material is reinforced concrete in most buildings. There has been continuous irregular replacement of old mid-rise residential buildings over the last decade with new high-rise apartment buildings with more than nine stories. The city-wide infill development has resulted in a highly mixed building pattern, with old residential buildings side by side with high-rise new ones and public buildings. The buildings' heights vary a lot throughout the city and are quite observable in the city's skyline.

Rooftops are accessible and widely occupied in residential apartment buildings and are used for living and various domestic activities in many cases. These rooftop domestic activities may hinder the implementation of green roof systems for stormwater management or at least require some innovative solutions to make it possible. On the contrary, public buildings' rooftops usually have limited access and are utilized exclusively for some of the building's utilities, so they have potential for green roof retrofits.

Fig. 5-24: A skyline of the city showing the highly varying buildings heights and conditions
Photo: (Ahmed Mostafa, 2023)

Urban Density

Alexandria exhibits a gradient of density and typology, ranging from densely populated areas in the city's core to more sparse suburban settlements. The city’s urban fabric is generally very compact yet marked by a lack of green spaces. High and medium-density areas are often characterized by multi-story apartment buildings, reflecting the city's historical growth patterns and the need to accommodate the fast-growing population within limited urban space. Suburban zones comprise either very dense informal settlements or, conversely, lower-density housing developments and gated communities, including villas and detached houses, mirroring socio-economic stratification and current urban expansion trends (Soliman & Soliman, 2022). A demonstration of the different urban densities in Alexandria was presented earlier in Chapter 2, Figure 2-11.

The integration of WSUD within urban environments characterized by high density, such as Alexandria, involves specific challenges as well as opportunities. The typically higher proportions of impervious surfaces increase stormwater runoff volume and pollutant load, while space constraints significantly challenge the integration of traditional WSUD elements to manage this runoff. Despite these challenges, densely populated environments also foster innovative WSUD solutions like green roofs, vertical gardens, and permeable pavements, which utilize limited space efficiently. Dense settings also promote the integration of WSUD technologies into multi-functional public spaces, enhancing both utility and aesthetics. Such environments benefit from an integrated planning approach that can synergistically address land use, transportation, and water management, leveraging the compact nature of the area to implement holistic and sustainable water-sensitive strategies.

Urban built-up density was presented as the percentage of each micro-basin occupied by the “urban” classification in Figure 5-13. The highest densities are in older areas in the city center, in micro-basins along the coast, and in informal settlements. The least dense micro-basins are those on the outskirts of the city.

Boundary walls

In line with the initial argument presented in this dissertation regarding the correlation between flood inundation and the prevalence of physical urban barriers in the region, it is noteworthy to further investigate the phenomenon in Alexandria. An observable widespread practice in the city is fencing walls, where nearly all public and private properties are enclosed by fences, with residential blocks being the only exception. The types of these boundarywalls varies across commercial, industrial, civil, and military purposes, with masonry being the primary construction material for walls in the city, complemented by iron fences in some instances, typically supported by a base of 30-100 cm.

As runoff is generated within and outside the bounded properties, the potential impact of fencing walls on flooding is influenced by two primary factors: the surface grading towards or away from the wall and the permeability of the surface within and outside the bounded plot. If the walled area is situated at a higher elevation than the surrounding area, the contribution of runoff from outside the wall is minimal. Conversely, if the walled area is at a lower elevation, the contribution of runoff from outside may be higher than from within the property. In Alexandria, surfaces outside any wall are predominantly sealed with street pavers and asphalt, whereas the composition inside the wall varies greatly. If the interior surface is predominantly sealed, it can significantly contribute to total runoff and exert pressure on the break points of the wall, typically the gates (Fig. 5-25). However, this impact is mitigated in cases where the interior surface has high permeability (e.g., parks, cemeteries, etc.).

It is deemed essential to map the distribution of boundary walls in the city to analyze their nature and understand their potential impact on surface runoff in each micro-basin (Fig. 5-26). Mapping efforts were based on personal knowledge and observation of the city, augmented by visual mapping using aerial imagery from Google Maps. Criteria for mapping included walls extending over 200 m, whether as linear standing walls or enclosing properties. Walls of very small properties of villas and schools were excluded. Additional data from a colleague involved in mapping exercises of industrial areas at Alexandria University supplemented the mapping efforts. While the map largely reflects the city's actual situation, measurements of walls are approximate, and some walls may have been overlooked, necessitating detailed and accurate field mapping for further study.

In an attempt to comprehensively understand and analyze the extent of this relationship on a micro-basin scale, the chart in Figure 5-26 presents a quantitative assessment of boundary walls as a proportion of the total area in each micro-basin that is enclosed by walls. The chart further indicates the total share area of permeable and non-permeable surface cover within and outside each walled section. This quantification is expressed as a percentage of the total micro-basin area, providing a clear visual representation of the extent to which different surface types are present. Permeable surfaces are grouped as vegetated green space and unvegetated bare lands, while non-permeable surfaces are those considered buildings and paved surfaces. The same categorizing was applied to the calculated total areas falling within the boundary wall. Standing walls not confining any space were excluded. The chart reveals a significant variation in the percentage of walled areas among the micro-basins. Predominantly residential basins typically exhibit less than 10% walled spaces, while basins dominated by public land uses of institutions and services indicate wall coverage ranging from 30% to 50%. Basins with military pocket zones and those characterized by industrial activity may have wall coverage reaching up to 60% of the total micro-basin area. However, these shares are subject to constant change due to urbanization trends, which unfortunately tend toward an increase in walls and sealed surfaces at the expense of vegetated permeable areas.

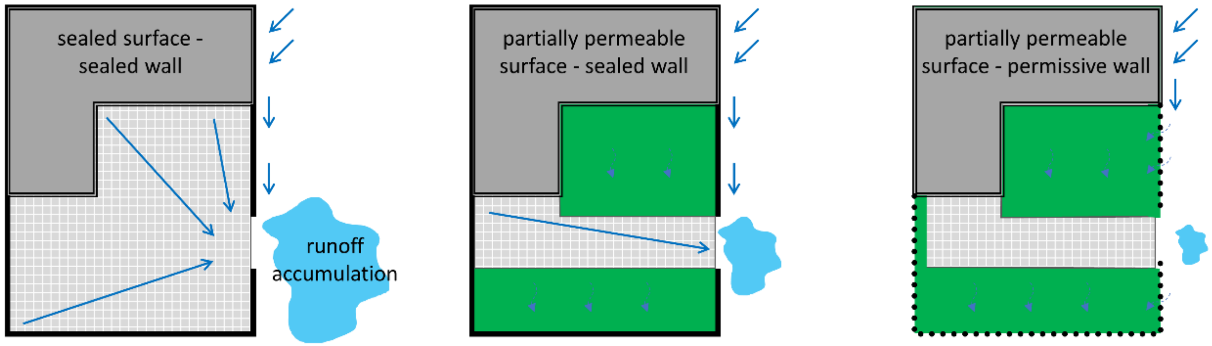
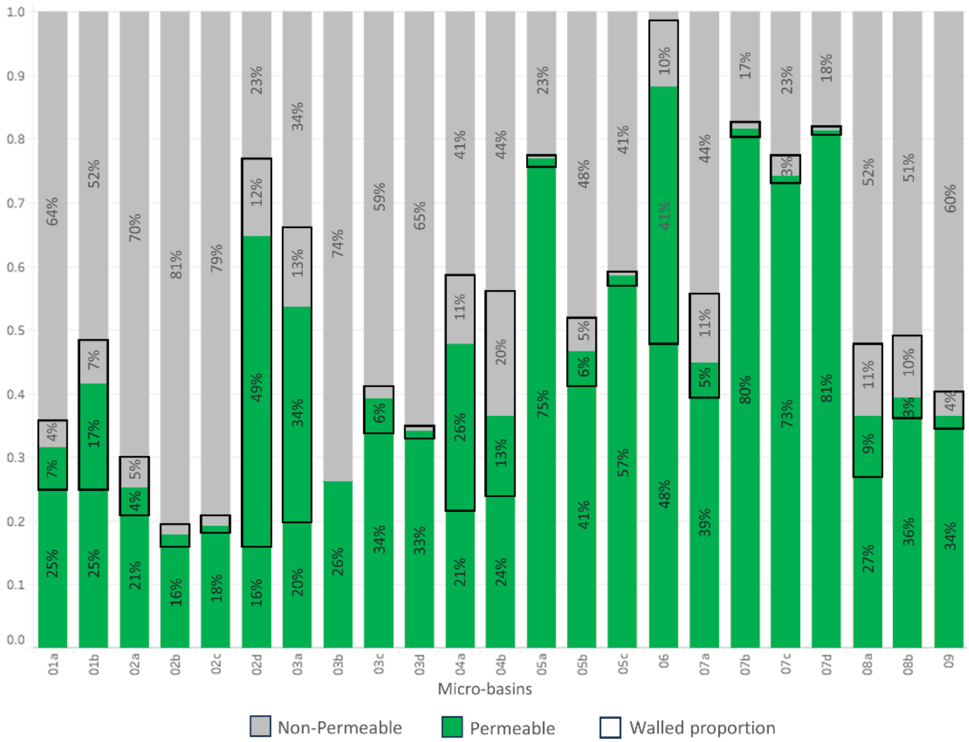
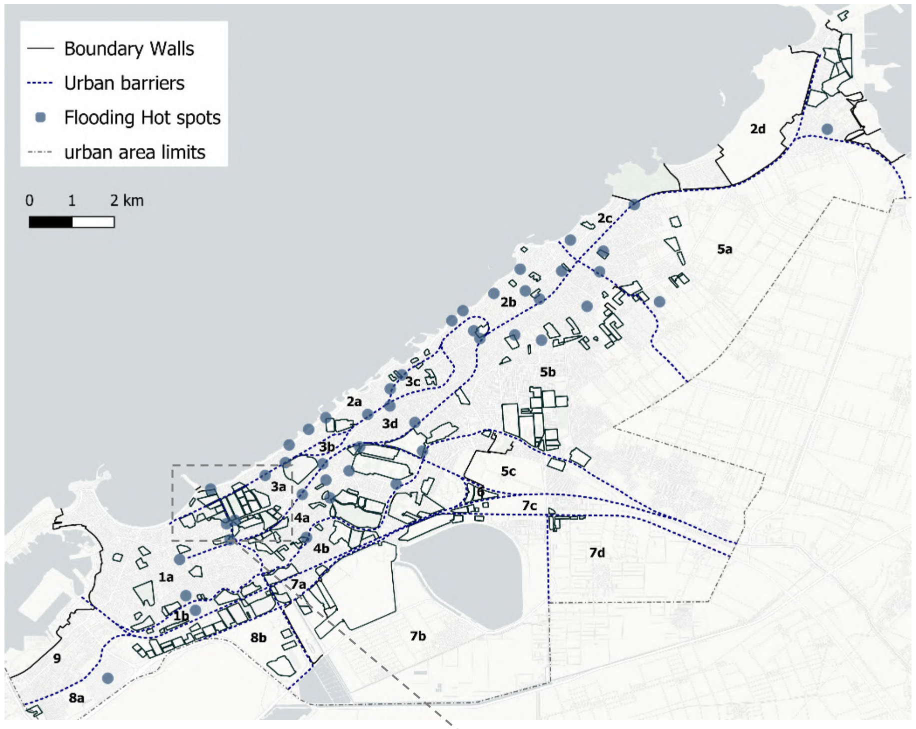


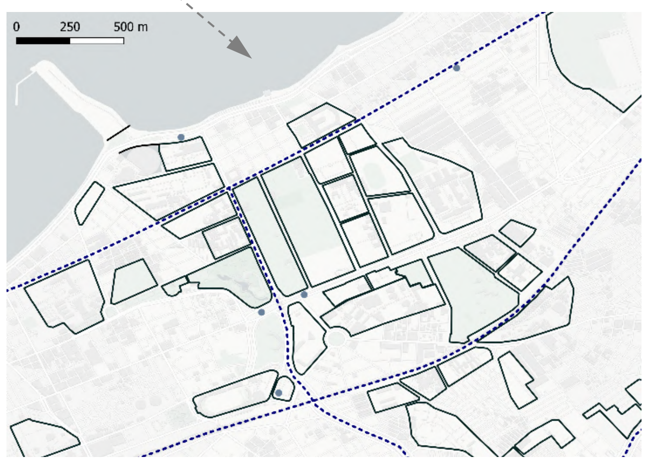
Fig. 5-25: A schematic Illustrating the possible relation between boundary wall's structure and the in and outside permeability of surfaces on the accumulation of runoff (By Author)

Furthermore, overlaying data maps provided by ADSCO in Alexandria, indicating frequently reported flooding hotspots, onto boundary wall mapping allowed for exploration of potential correlations. The data reveals that many flooding hotspots are relatively close to boundary walls or urban barriers including main roads, railroads, and tram tracks, which are also wall-fenced. These observations appear to support the suggestion to develop a 'Wall-Surface Cover' balance index for each basin that incorporates wall characteristics with the urban green factor (UGF). Correlating UGF targets of a development with the permeability along boundary walls could be beneficial. This index can aid in the assessment of flooding risk and as a tool for reducing its risk in such a heavily fenced urban context.

Controlling the ratio of walls does not necessarily consider eliminating the walls themselves, as the phenomenon is deeply rooted in cultural backgrounds that cannot be easily forsaken.







Therefore, a reasonable approach could be to develop a porous fencing wall or, in a broader sense, a 'Water Sensitive Wall' model; a boundary wall that would provide protection and privacy while allowing surface runoff to flow or be absorbed into the soil by integrating typical linear WSUD elements such as swales or infiltration trenches. Further research is required in this area to investigate the various systems, plantations, and structures that would possibly be applicable for developing the wall model.

Fig. 5-26: Mapping of boundary walls and flooding hotspots in Alexandria showing the extent and potential impact of the phenomena. The chart presents the proportions of permeable to impermeable surfaces in each micro-basin as inside and outside walled areas

Data and map by author
Chart by Joseph Benjamin

Cul- de- sac (street dead ends)

The spatial analysis in this aspect aims to investigate how the location and intensity of dead-end streets may influence flooding in particular areas. Using geographic information system (GIS), dead street ends were mapped in the city and overlaid with available data representing reported flooding hotspots into one map (Fig. 5-26). First, the street layout was obtained from OpenStreetMap (OSM, 2023).

Non-automotive road types (including footways and paths) were deleted, and the layer was clipped to the study area. The micro-basins boundary was appended to the clipped roads layer. The data were processed and transformed, converting the roads layer into a new points layer of dead-end roads and counting the number of dead-end points within each micro-basin.

The results show the intensity of dead-end streets concentrated mostly in the old historic core and along the train line to the east of the city. This analysis could not visually detect any concrete evidence for the relationship between dead-end streets and flooding areas. However, further investigation and probably more data are required to draw a comprehensive conclusion.

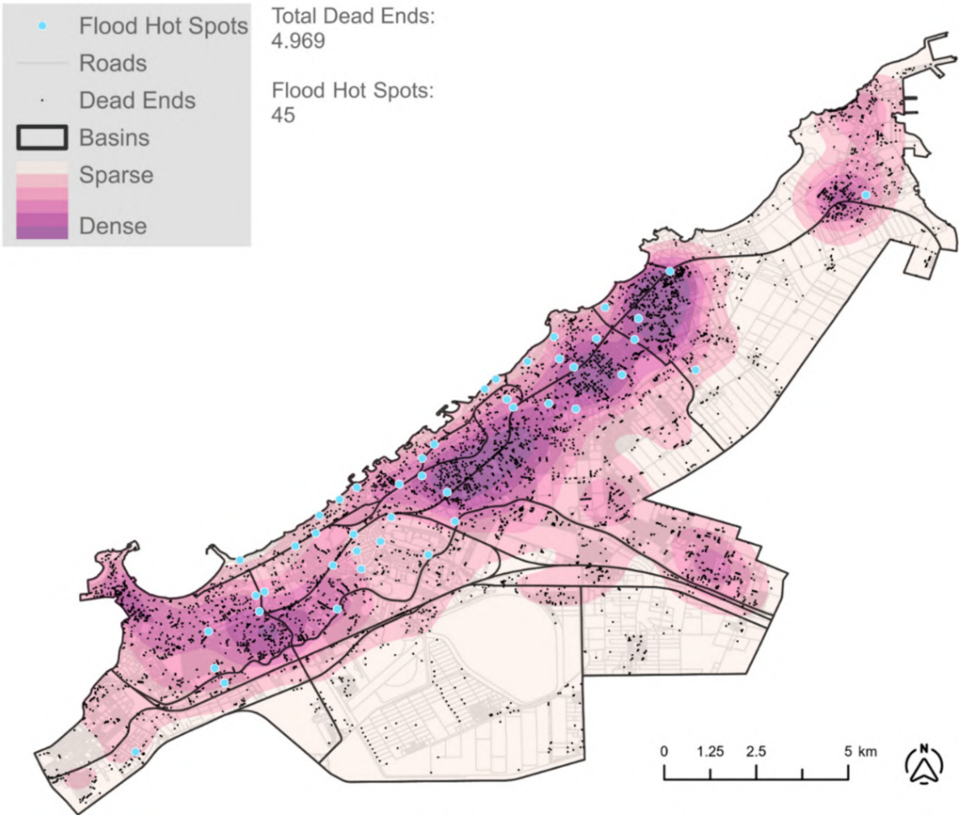


Fig. 5-27: Mapping of dead-end streets in Alexandria locations of flooding hotspots

Data synthesized and illustrated by Joseph Benjamin
Image: (*youm7*, 2020)

5.3.3 Water-Sensitive Barriers: analysis and development

In accordance with the developed framework, this section presents in detail two types of major barriers cutting through the city of Alexandria: railroad tracks and main roads. Under the "tracks" barrier, the city's local train and tramway lines were analyzed. In addition, potentials and recommendations for the transformation of each line into linear green infrastructure were explored. Other examples of major roads were covered through the investigation of the 'Corniche' and 'Mahmoudiyah' arterial roads.

Tramway Track

The Alexandria Raml tramway is a notable historical feature of the city. It was first established in 1860 as a horse-drawn tramway and was later electrified in 1902, making it one of the oldest electric tramways in Africa and the Middle East. The tram line was introduced to support the city's expansion toward the east and extends parallel to the coastline for 14.11 km from the city center, including 25 stations (APTA, 2023).

The significance of the tramway within the urban fabric of the city is that a large strip of urban area along the Corniche, with 400m at the widest point and 200m at the narrowest, is bordered by the tram track, which is in micro-basin (mb02). The track also separates mb02 from the adjacent micro-basin (mb03). Additionally, the line branches off and re-joins in two areas, thereby bounding an additional two sub-basins. The track runs between two sides of the road, having two lanes on each side. In some particular areas, the track lies between the side road and the back of buildings on the other side.

Because the line was not initially powered when it was established, one of its most important design features is that it runs almost entirely on a flat level and does not follow the changing elevations of the surrounding area. Therefore, the profile of the line takes different forms depending on the topography of the area it crosses.

The surface profile extends for a total of approximately 7.4 kilometers and exists where the road is at the same level as the track, which is separated from the roads either by a sidewalk, fencing wall, or other materials. In another case, the road rises in an upward direction following the natural terrain, so the track is at a lower excavated level, supported by retaining walls of varying forms and heights, which extend for a total of 2 kilometers. A third profile occurs where the road is lower and the tram track is elevated above a compacted embankment, which extends for a total of 3.5 kilometers. The tram stops are reinforced concrete structures on a platform that is at the same level as the track. Formal crossings are generally present at each stop for pedestrians and vehicles on the surface tracks and for pedestrians only, with steps on the upper and lower tracks. However, some informal crossings exist exclusively on surface tracks.

The substructure of a tramway system refers to the components that support the track and ensure its stability and safety. The substructure typically includes a combination of ballast, sleepers, and subgrade. Ballast is a layer of crushed rock or gravel that is placed underneath and around the track. It helps to distribute the weight of the track and tram evenly across the ground, while also allowing for proper drainage and preventing the growth of vegetation. The subgrade is the natural or engineered ground surface upon which the ballast and sleepers are placed, serving as the foundation for the track. In addition to these core components, the substructure of a tramway system may also include various other elements, such as drainage systems, retaining walls, and culverts, depending on the specific needs of the location and environment (Esveld, 1997).

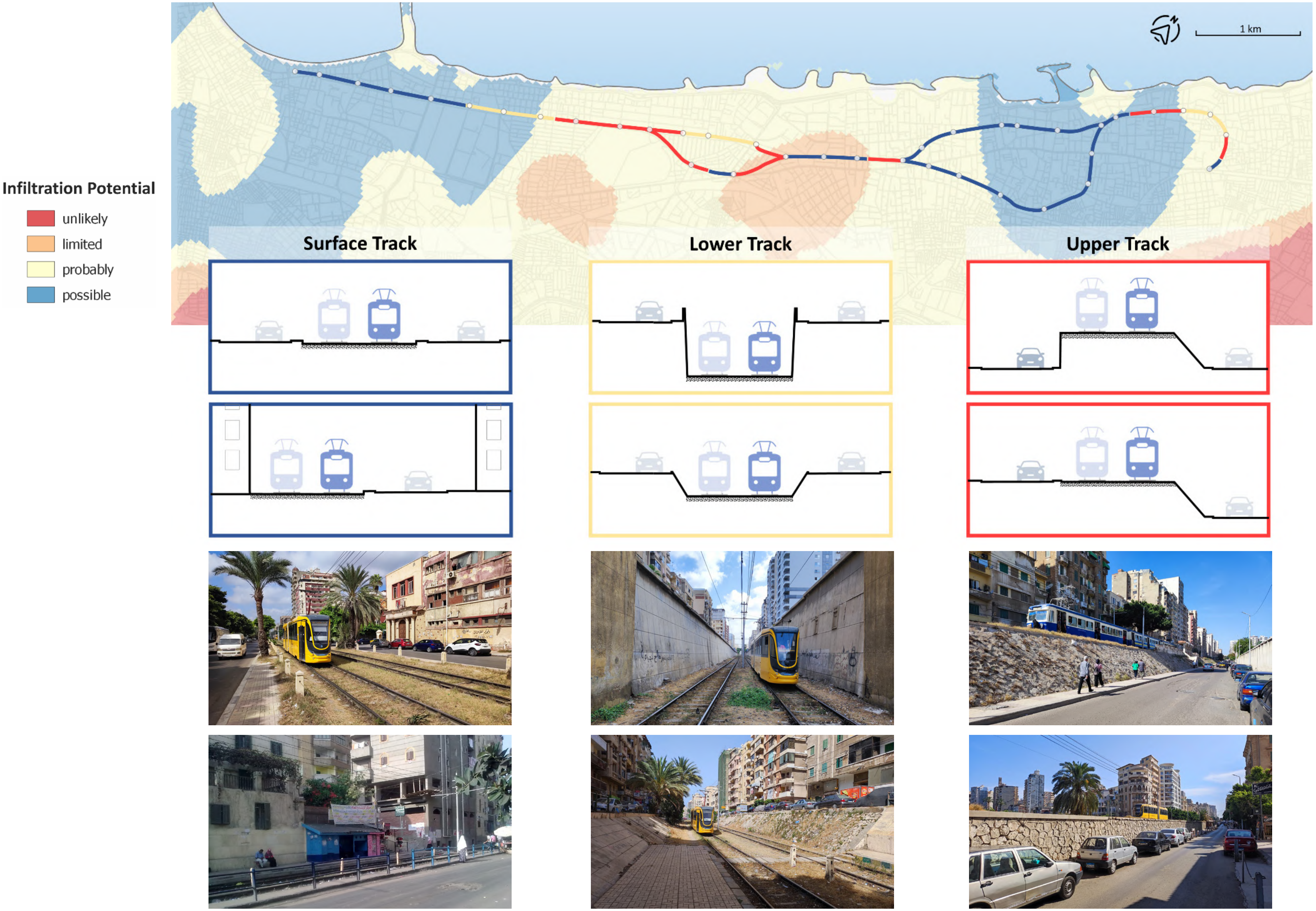


Fig. 5-28: The three main types of transversal profiles of the tramway line in Alexandria (Illustration and photos by Author)

The observed absence of collector drains along the track may indicate that drainage was not considered in the design, likely due to the presumed local dry climate conditions of relatively low annual precipitation. Additionally, the high permeability of the underlying sand or fill soil prevents the saturation of the line substructure. According to stormwater engineers from ASDCO (Interview, 2022), during heavy rains, accumulated rainwater from heavily flooded roads is sometimes pumped to the nearby tram track ballast surface, where the water quickly percolates into the ground through the ballast structure. The high permeability of the subsoil can be validated by the infiltration potential classification.

Lower tracks are more vulnerable to flooding in areas near stations and crossings, where inundated water from streets can flow into the track line. Upper tracks, on the contrary, contribute significantly to the runoff generated from the track surface and retaining walls, flowing into the adjacent streets.

The line is electrified through overhead electric traction supply wires. The poles suspending the system along the track are located in the median between tracks. Both side strips of the line are constituted by the changing type of profile, either as retaining wall, fencing wall, pavement, or just a curb boulder. Any solution should be adjustable to these changing profiles.

As described previously, the track appears as an open area with ballast rock and no apparent vegetation. Although some locations along the track sides feature Ficus and palm trees, their presence is sporadic and limited. However, in recent years, the track has exhibited spontaneous growth of greenery in different areas, which has caught the attention of residents and garnered positive aesthetic feedback. While the exact cause of this natural change is uncertain, a probable explanation is that it may be related to the increase of total annual rainfall in the last decade, which could sustain the growth of native plants without direct human intervention. Additionally, the accumulation of sediments on the ballast rock over time may provide a favorable growing medium for plants.

A recent study by Heneidy et al. (2021) investigated the spontaneous floral diversity along railway and tram tracks in Alexandria. The native plant types were identified and described in the study as highly adaptive, despite the high level of disturbance in such a unique urban-industrial ecosystem. The study highlights the importance of managing and conserving these ruderal habitats as they can serve as valuable refuge areas for rare and endangered species. However, it is important to note that further investigation and analysis may be needed to fully understand the factors contributing to this habitat revival and to determine any potential implications for the track's overall ecological and aesthetic value.

The segregated tram track has an average width of approximately 10 meters. The side streets are mostly around 8 meters wide, and the outer sidewalks vary between 1m to 2m from the building line. While the outer sidewalks serve as major pedestrian routes for commuting and property access, their narrow width and extensive underground services may pose some constraints to the integration of water-sensitive

Fig. 5-29: Typical tram track setting in Alexandria

elements. In contrast, the inner sidewalks are generally unused and only serve as spaces between vehicles and tram traffic; therefore, they may have greater potential for reutilization. However, the different profiles along the line may present challenges in developing tailored solutions suitable for each one. The electric traction power supply poles and their underground conduits usually present a constraint, but fortunately for Alexandria tramway, the power supply system is located in the median between the tracks rather than on the sides.

Building water-sensitive tram tracks

The proposed transformation concept is based on the conceptual planning approach to develop existing barriers into water-sensitive linear infrastructure. This entails introducing solutions that promote and sustain greening along the track while managing stormwater through vegetated systems, creating a more permissive nature of the barrier that does not obstruct flow. The proposed interventions aim at utilizing runoff in different directions to serve required goals and according to the site conditions:

- Into the soil by promoting the infiltration and retention of runoff within and on the sides of the track, while improving evapotranspiration over the whole system.
- To allow for penetration of the track on both sides, which could potentially spread runoff and reduce water inundation on one side of the track.
- The incorporation of measures that can convey stormwater along parts of the line to another management system or to allocated storage locations where treated stormwater can be stored for later reuse.

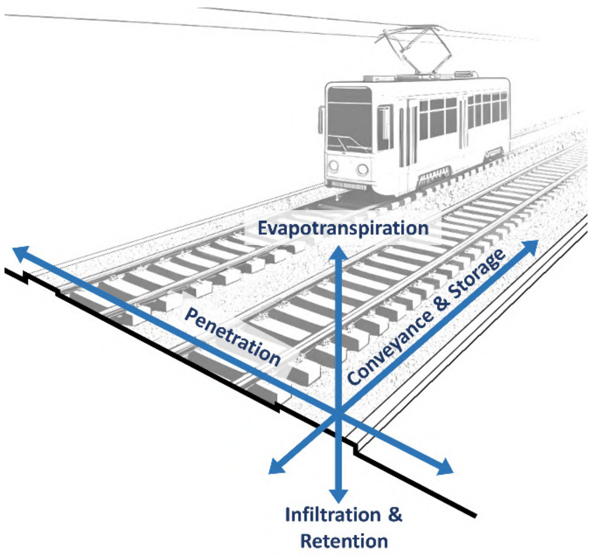


Fig. 5-30: The multi-directional development strategy of tram track barrier (By author)

Achieving this development strategy involves two key components: greening the track with a vegetation system and integrating WSUD technologies along the track. What follows is an elaboration on each.

The greening of the track entails adopting suitable vegetation systems that are compatible with the track's structure and local environmental conditions. The book "Track Greening" by the German Green Track Network (Schreiter & Kappis, 2016) provides practical guidelines for designing and maintaining green track systems, particularly for light rail and tram projects. This handbook highlights several benefits of green tracks, including their ability to retain up to 70% of the annual average stormwater per square meter, provide urban cooling, mitigate the urban heat island effect through evapotranspiration, and shield groundwater from pollutants. Additionally, green tracks enhance the aesthetic quality of urban areas by adding significant new green spaces in densely populated settings. For example, (Henze & Siemsen, 2003) noted that 4 kilometers of single track could yield over one hectare of greenery, suggesting that in a city like Alexandria, implementing double green tracks could create up to 2 hectares (20,000 m²) of green space.

Tram track structure types are either slab track or comprising sleepers and ballast. Vegetation systems can be installed and adjusted to the technical requirements of both systems to accommodate the vegetation system and the respective thickness for the vegetation base layer (growing media layer). Slab track systems allow soil depth of more than 70 cm. A deeper vegetation base layer provides better stormwater retention capacity and healthier plant growth (Henze & Siemsen, 2003). In Alexandria, the existing ballast track structure would typically allow vegetation base depth of 14.5 cm to a maximum of 20.5 cm, limited by the level of sleepers. However, the subbase soil along Alexandria's track is highly permeable and can potentially also contribute to the water retention characteristics of the vegetation base layer.

> "Maintaining a balance proportion between facilitating a fast stormwater runoff during heavy rainfall and providing sufficient water retention for lengthy dry periods is particular challenge when designing green track and the solution for this basic problem is always going to be a compromise between both requirements." *(Schreiter & Kappis, 2016) Track Greening*

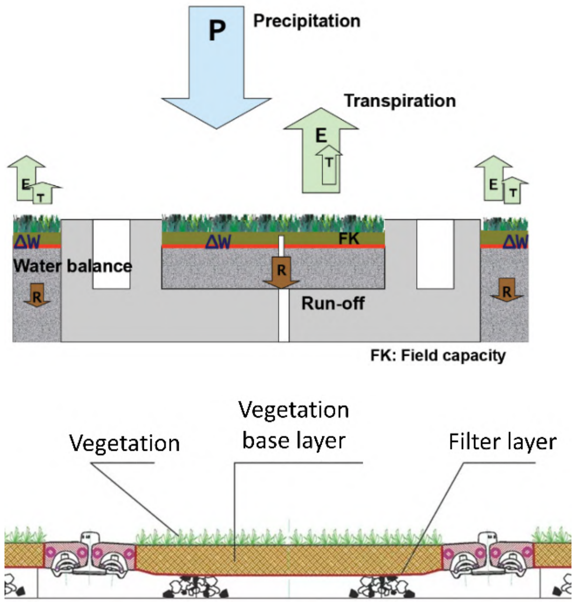


Fig. 5-31: Water balance in a tram track naturation and schematic structure of grass track system 'Kassel' (Schreiter & Kappis, 2016), Graph: Kraiburg Strail GmbH

Vegetation used in track greening falls into two main categories: Grass Track and Sedum Track. Under appropriate conditions, both types are viable for ballasted tracks. However, a minimum vegetation base layer of 15 cm is necessary for grass to thrive; otherwise, it may experience drought stress or complete loss during prolonged dry spells unless supplemental irrigation is provided. Conversely, sedum plants like succulents, known for their drought and heat tolerance, are ideal for shallow, extensive vegetation systems and require minimal maintenance and irrigation (Henze & Siemsen, 2003). Green Tracks with sedum plant systems can, on average, retain 50% of total annual precipitation, while Green Tracks with grass vegetation systems retain 70% (Henze & Siemsen, 2003; Siegl et al., 2010).

Fig. 5-32: Grass and Sedum vegetation types for green tracks (Schreiter & Kappis, 2016)

Regarding irrigation, grass tracks typically need constant irrigation, especially during extended dry periods. Options include mobile irrigation using water tankers, sprinklers, or subsurface drip tape systems. However, mobile irrigation is labor-intensive, and pop-up sprinklers are not recommended due to high evaporative losses and potential operational interference. Subsurface drip tape systems are highly efficient.

These systems deliver water directly to the root zone, reducing evaporation and are particularly effective in hot, dry climates. They operate as closed-loop, low-pressure networks ideal for confined areas like light rail tracks. Irrigation could be sustained using recycled wastewater either from a distribution line or from integrated underground tanks in onsite stormwater treatment systems like bioretention planters (Henze & Siemsen, 2003). In Alexandria, the irrigation needs could potentially be supplied using recycled wastewater either from a distribution line or from integrated underground tanks in onsite stormwater treatment systems like bioretention planters.

Fig. 5-33: Ballasted tracks before and after greening in Berlin (Image: Dreger, BVG and Schreiter, IASP)

Turning now to the second component of incorporating WSUD technologies along the line where each typology profile is addressed as follows:

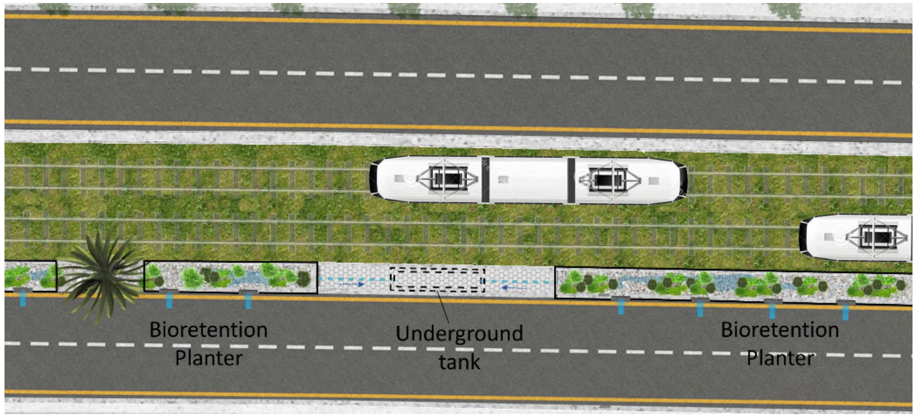
Surface track – The strip between the track and street, including the verge and pavement in surface profiles, could be utilized to accommodate WSUD elements to treat and store runoff collected from adjacent streets. The stored water can be reused for irrigating the track's green cover during the dry season. Bioretention systems are found to be the most suitable element, considering their sizing flexibility and treatment capability, along with an underground concrete tank to store the treated water. Both elements can be connected and placed where allowable.

The design concept considers sealing the planter system with an impermeable liner and providing a raised perforated underdrain. The intent is to harvest stormwater and additionally provide protection to the track substructure from any possible negative impact of water seepage under the track. Runoff from the street is drained to the planter, where water can be gradually filtered and temporarily stored in the drainage layer. Treated water may then be delivered through the collection pipes to the concrete water tank. Underground tanks can be placed between each pair of planters and connected to both. Water may then be pumped into the irrigation network to irrigate the grass or sedum track.

An alternative drainage option in areas where the installation of tanks is not possible could consider connecting the underdrain to the conventional sewer system or promoting infiltration instead. However, the installation of system lining should remain, at least partially applied to the side of the tracks in case of infiltration. In addition, any connection to the existing sewer system must avoid any reverse flow, which could negatively damage the planter system or the tank.

Planting the bioretention requires dense vegetation and various drought-tolerant plant types with extensive rooting systems that are well adapted and can sustain through the wetting and drying cycle over the year. Ground cover, reeds, flowers, shrubs, and hedges are types that could be selected for planting. However, as elaborated in Chapter 3, trees are not recommended in underdrained systems with drainage pipes and require sufficient depth. Additionally, the growing height and density of selected plants could be managed to functionally replace existing masonry fencing structures.

Other WSUD systems, such as infiltration trenches and soakaways, could also be employed. However, stormwater harvesting might be limited in this case due to the lower treatment capacity of infiltration systems. Also,



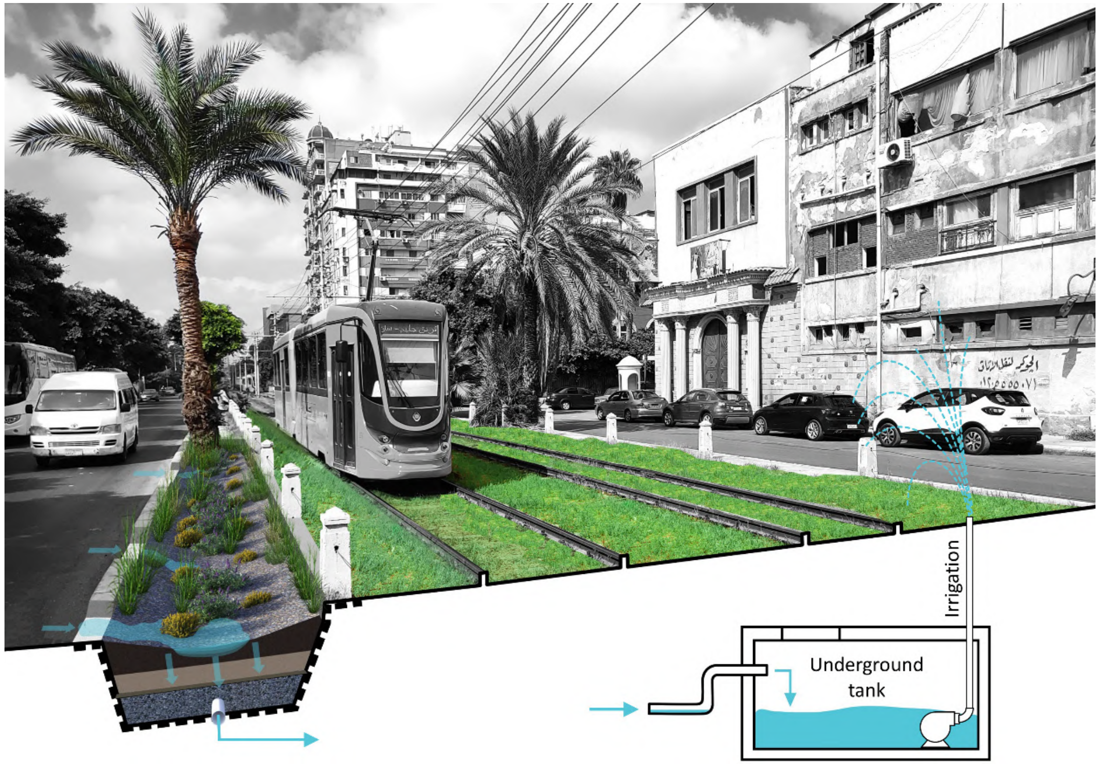


Fig. 5-34: Proposed integrated concept of bioretention street planter, storage tanks and green track systems for surface tram profile (Illustration by Mohamed Elfouly, photo by author)

the sediment load of the street catchment should be considered for further pretreatment measures if required.

Lower and upper tracks – The difference between track and street levels is supported by retaining structures. Moderate to high heights are supported by almost vertical reinforced concrete walls, while low heights are supported by inclined gravity stones and boulders. The intervention concept focuses on using the vertical surface of existing retaining wall structures, created from level variations, for stormwater retention and encouraging evapotranspiration through vegetated systems.

In the case of vertical high walls, runoff from upper streets is diverted to successive WSUD elements in a vertical cascade by gravity to the track lower level. The system aims to manage runoff volume and quality in a treatment train while enhancing self-sustained surface and vertical green spaces. Several WSUD elements can be employed, including bioretention planters, green walls, and potentially green roofs and storage water tanks as well.

Starting from the upper street level, sealed bioretention side planters treat runoff flowing from the street surface and store it in the drainage layer. Excess water is discharged through a raised perforated underdrain to a vertical greening module installed on the side of the retaining wall. The suggested green wall system is a wall-based vertical planter module, with each group of modules assembled in a framing system and mounted on the existing wall. Each bioretention planter could be connected to one or more green wall systems through drainage pipes that deliver stormwater for further treatment and retention.

The cascading system could be extended to incorporate water tanks that store excess treated water from green walls to be reused during the dry season for irrigation of either track greening or the green wall itself. Other potential applications appear particularly where stations' rooftops meet the retaining wall, which can be utilized for green roofs.

The track line runs in an east-west direction; therefore, installing the green wall system could be more efficient on the north-facing wall to avoid direct sun radiation. The system can be recurrently distributed along the line wall. The lining of bioretention planters is crucial in this setting to protect the retaining wall structure from any damage that might be caused by water seepage. Further, ground-based green wall systems might be limited because of the high risk associated with subsurface water retention near the track subgrade and retaining wall foundations.

In the case of sloped retaining walls, a modular planter system is proposed to replace the plain masonry blocks. The planter boxes, also known as vegetated or plantable retaining walls, combine traditional geotechnical engineering with ecological and stormwater management principles. The system offers slope stability to the walls of the track while functioning as

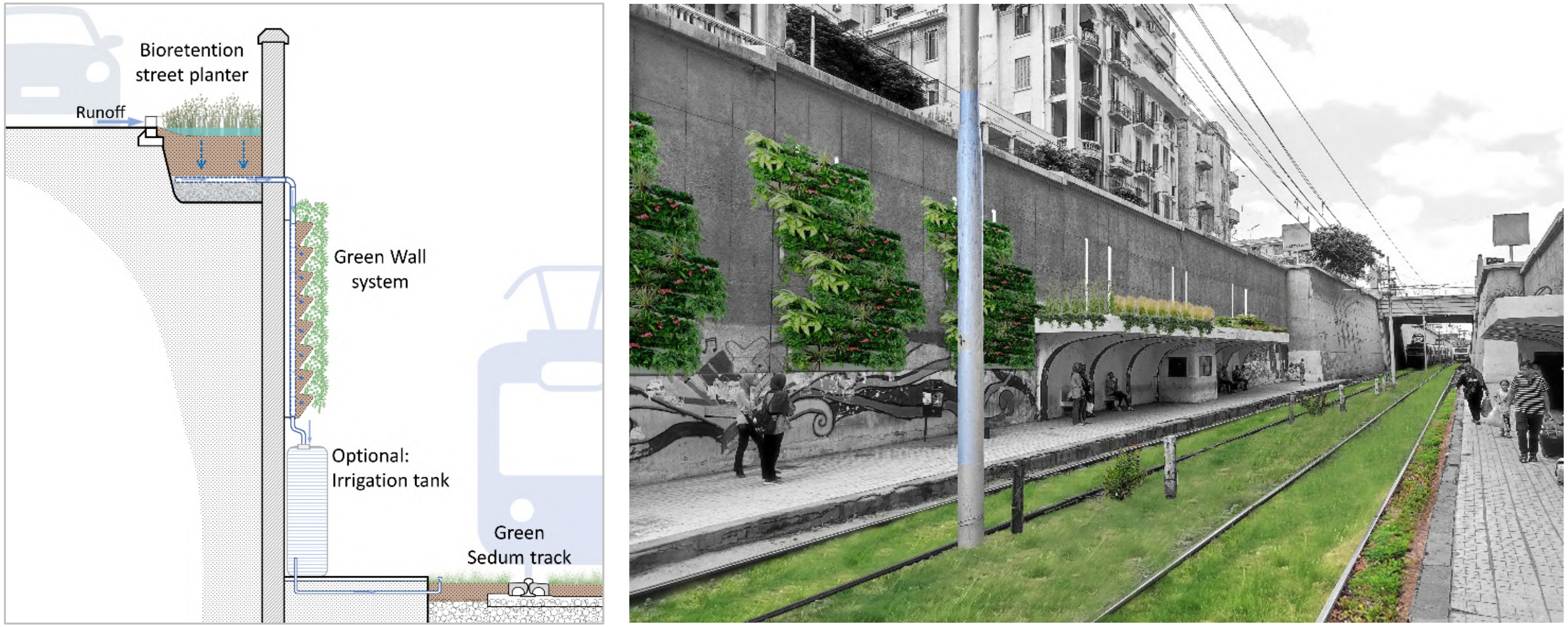


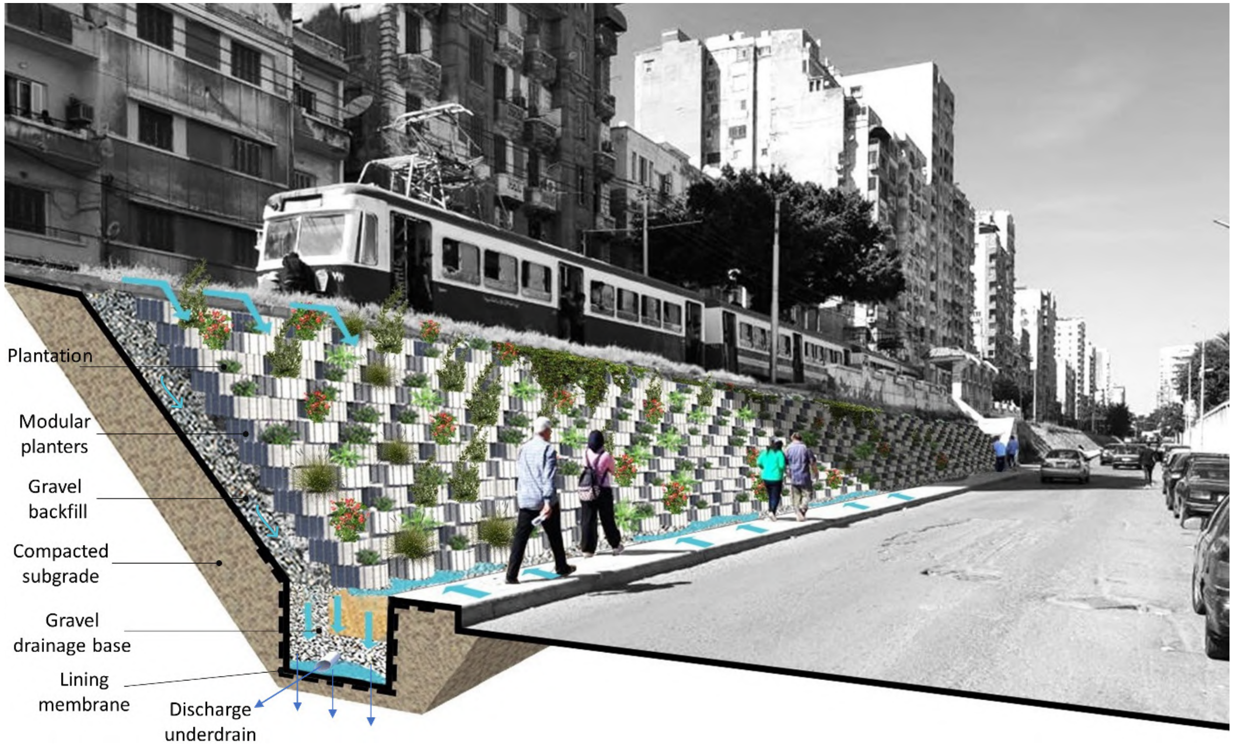
Fig. 5-35: Proposed integrated concept of bioretention street planter, green wall and green track systems for lower tram profile
Illustration by Mohamed Elfouly on photo by Author – Cross section by Author

bioretention, contributing to runoff flow control and improving green space amenities and evapotranspiration. These plantable retaining wall techniques apply to both upper track and lower track cases.

The wall structure typically consists of modular hollow planter blocks made from a variety of materials in various forms, which can be filled with soil and planted with vegetation. The planters are lined up in an overlapping tiered level to the required height. An integral part of such a retaining wall system is a gravel layer behind the wall that improves stability and essentially works as a drainage layer to facilitate the removal of excess water. A linear bioswale is suggested to be integrated at the stone base of the wall to enhance system drainage and provide additional retention capacity.

During rainfall events, runoff flows down from upper levels to the tiered surface. The vegetation and porous structure of the wall allow for water treatment and seepage through the blocks to the drainage layer. Treated water is accumulated in the drainage base and can either infiltrate into the subsoil or be collected through a perforated underdrain pipe to a storage system. Key considerations for the system's efficiency and durability are:

- Vegetation provides biological treatment and promotes evapotranspiration. Drought-resistant native plants with deep rooting systems can thrive and enhance the stability of the retaining structure.
- Proper removal of excess water through the gravel backfill drainage layer is essential to prevent water buildup behind the retaining wall, reducing hydrostatic pressure and improving wall stability.



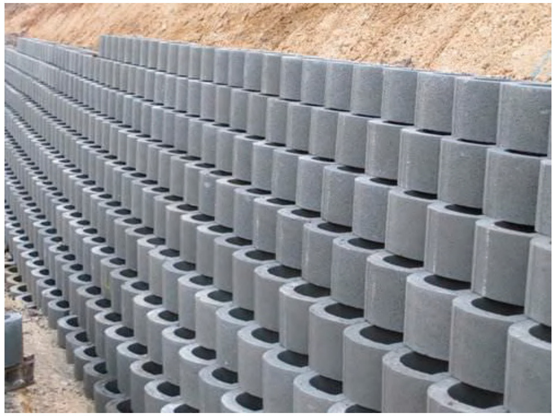


Fig. 5-36: Proposed integrated concept of bioretention street planter and modular retaining wall blocks system for upper tram profile.

Left: Illustration by Mohamed Elfouly on photo by author
Right: Example Blocks system (archiexpo.de 2023)

The modular wall is adjustable to different slope angles and moderate vertical heights with the consideration of adding reinforcement straps that provide structural stability to the wall by anchoring it to the backfill. Green retaining wall planters can manage runoff and promote infiltration while supporting greenery and providing aesthetic value to the wall. The system reduces the runoff generated from its surface and receives flows from both higher and lower surface levels.

To conclude, the proposed WSUD solutions for the transformation of tram track barriers offer multiple benefits, not only in reducing flooding and conserving water but also in enhancing urban amenity, improving the microclimate, and stabilizing embankments. However, the effectiveness and feasibility of these strategies depend on several factors, foremost maintaining the safety of the track system structure, including soil conditions and various engineering considerations. Particular risks associated with the exposure of the rail track to stormwater runoff could jeopardize the operation and maintenance of the infrastructure. This may occur where uncontrolled large amounts of water accumulation on and near the track could damage the track structures and wash out or destabilize the ballast. In the case of the tram track in Alexandria, the study suggests that these risks might be mitigated due to the high permeability of the soil and the use of impermeable liners in bioretention systems – a condition that may not be present in other locations.

Fig. 5-37: Further variations of modular blocks system for sloped retaining wall in lower track, and strait wall in upper track (Illustration by Mohamed Elfouly on photos by author)

Current research primarily focuses on different vegetation cover systems for tracks and irrigation methods. There are no documented projects or studies evaluating or monitoring the success of incorporating WSUD technologies along rail tracks. One particularly relevant project is the Metro Green Line between Minneapolis and St. Paul, United States. This project integrates various WSUD technologies to manage stormwater runoff along the 11-mile light rail corridor, including bioretention planters, infiltration trenches, permeable pavers, and tree trenches. According to information from the project and an interview with Forrest Kelley from Capitol Region Watershed District organization (Interview, 2023), the systems were installed along the outer edge of the corridor and on side streets rather than directly on or near the rail track. The design and construction process faced challenges due to numerous above- and below-ground utilities and contaminated soils.

Overall, despite safety concerns, these proposed interventions provide valuable insights into the potential for incorporating WSUD technologies along linear railway corridors. Nonetheless, substantial work remains to technically validate these solutions, and further research and analysis are necessary to assess their suitability for Alexandria and other cities in the region.

Corniche Road

The Corniche Road is a major seaside artery road in Alexandria, running almost 17 km along the city's waterfront. In 2006, a development project was undertaken to widen 14.5 km of the road, increasing its width from 12 meters to an average of 35 meters (Elhamy, 2012; Frihy et al., 2004). The aim of the project was to increase traffic capacity and create a wide promenade with parking areas. As a result of the project, many of the sand beaches along the waterfront were lost in favor of extra lanes for the road and the promenade. However, 3.5 km of the old promenade on the fishing harbor was preserved and not included in the development project.

The current road has 3 to 5 traffic lanes in each direction, with a varying high curbed median strip. The width of the median is 3 m on average; it becomes widest at turnarounds and shrinks to just a border curb thick in the narrowest last 5 km of the road. The typical profile of the new promenade is mostly an inner and outer pavement divided by concrete fencing modules, which is interspersed at distances with service clusters of parking lots, amenities, and shaded seating units. The ground surface cover along the promenade is significantly sealed with pavement and asphalt.

The sidewalk on the building side varies in width with a maximum of 3 m. The median strip is noticeably high – 25 cm, and in some areas, it goes up to 60 cm at the old promenade. This raised curb is speculatively meant to protect vegetation and prevent spontaneous pedestrian crossing. In some parts of the promenade, the fencing separates the pavement on the street side from the lower level of the sand beach with a retaining wall of various heights. This design separates the promenade from the beach. Overall, the development project is described in a recent study as pedestrian unfriendly due to the extreme lack of greenery and shading. Sealed asphalt and paved surfaces are dominant, with minimal greenery except in the median strip in some parts along the road (SUP Alexandria, 2013).

Observing the original topography of the shoreline elevation along the road shows variation between 2.41 m and 12.27 m (Frihy et al., 2004). This variability affects runoff under heavy rainfall to flood lower areas between two higher ones (Fig. 5-38). The considerable runoff volume received from perpendicular connection roads, sloping towards the corniche, also contributes to the total flooding effect. Therefore, an effective strategy would focus on reducing the source of runoff coming from higher elevation while increasing resilience and discharge at threatened areas on lower elevation.

The infiltration potential of the area along the waterfront, according to the IPM map, has been identified as moderate to very high. Besides, the late road expansion project had involved earthwork of engineered subgrade structure to support the road extension. According to Frihy et al. (2004), the backfill is sand soil and is protected from the seaward by 300–800 kg quarry stone boulders and the arrangement of 10-ton concrete blocks on top (Fig. 39). To adopt WSUD solution and prior to any implementation, a detailed investigation of the existing subsurface condition of the Corniche, including the extent and depth of the sand and quarry stones, is required.

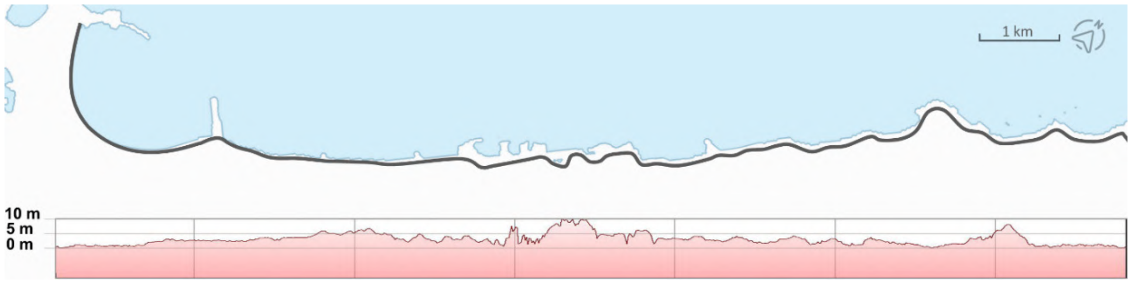
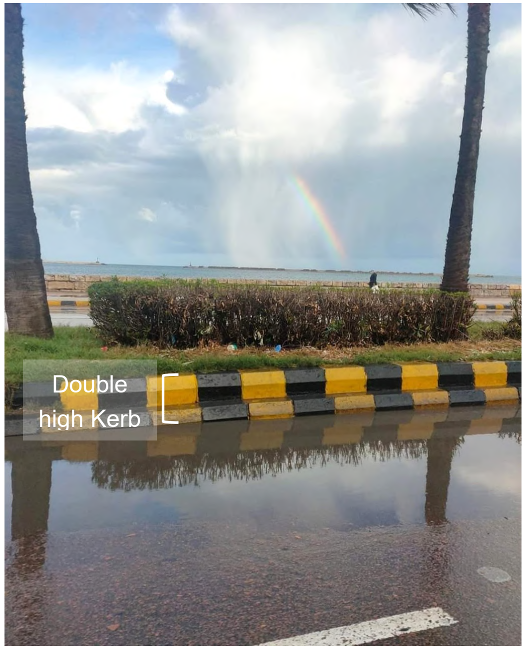
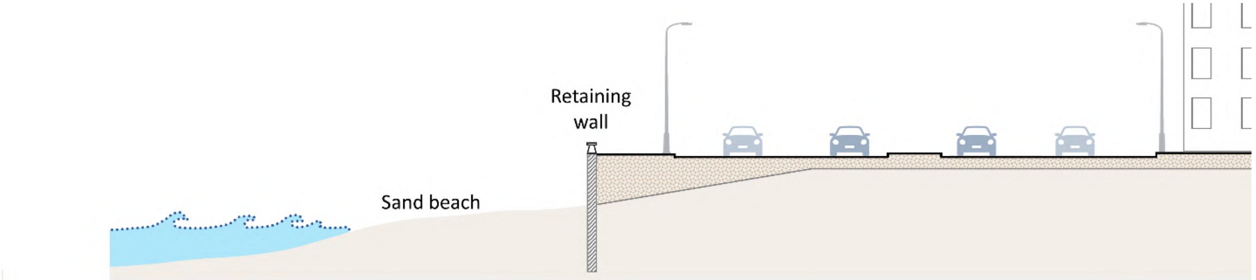


Fig. 5-38: Road elevation profile along the Corniche promenade (by author based on google earth)





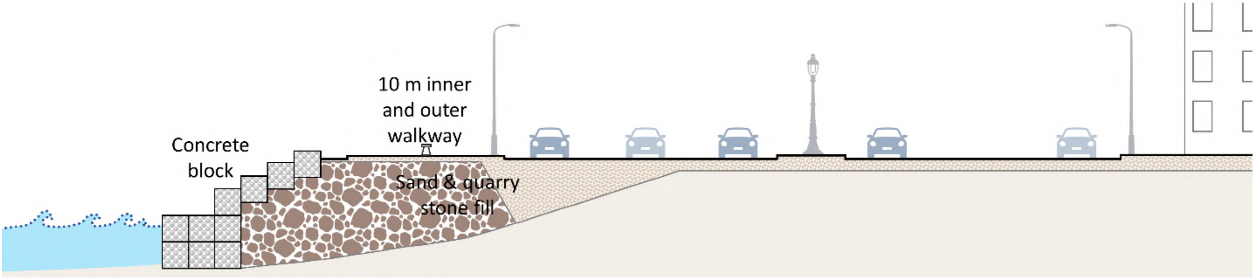


Fig. 5-39: Schematic cross-shore sections of two main Corniche Road profiles

Illustration by author based on (Frihy et al., 2004)
Photos: (Alexandriarain, 2022)

Building water-sensitive Corniche Road

In consistency with the development strategy of transforming road barriers into water-sensitive and green assets, the basic design concept of Corniche Road involves the three-direction permeability introduced previously in this section. However, the runoff penetration should work in one direction toward the sea rather than in two directions as in other cases. Increase the permeability of surfaces by introducing infiltration and retention capacities to the vast existing sealed surfaces along the promenade.

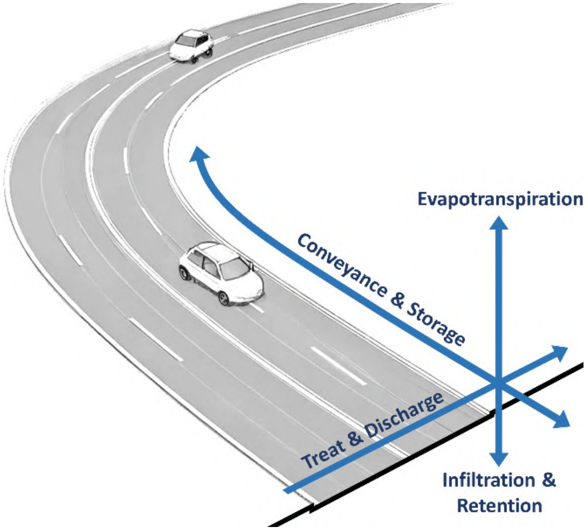


Fig. 5-40: The multi-directional development strategy of Corniche Road barrier (By author)

Different WSUD solutions may adjust to the setting and conditions of each profile typology of the promenade. This is to consider the provision of bioretention planters and underground water tanks to treat and store stormwater before discharging excess water into the sea. The planters themselves are recommended to be sealed and incorporate retention capacity to sustain greenery and promote evapotranspiration. The stored rainwater can be reused during the dry season and for other non-potable uses as well. In addition, there is an opportunity to utilize the median strip for bioswales where possible. The road median could also facilitate these processes by adding a conveyance capacity to transport and treat runoff. In particular lengths where the median ends at a road turnaround, bioswales could be sealed for capturing and delivering stormwater to an underground storage tank. The stored water can be used to irrigate the wide vegetated turnaround median. Permeable pavement might not be effective in this setting where the system is highly prone to clogging due to sand sediment load and significant human activity during summer.

The following conceptual interventions for the seaside promenade are proposed for service clusters and surface promenade profiles to demonstrate possible water-sensitive transformation. The significant available pavement area observed in service clusters offers the opportunity to integrate WSUD elements for managing stormwater flow and improving urban space by introducing vegetated landscapes. For example, the wide strip spreading between the parking areas and the main road could accommodate bioretention planter cells to capture stormwater runoff during rainfall events (Fig. 5-40). The stormwater can be gradually filtered through the sealed vegetated planters, retained in the gravel sublayer, and drained to an underground storage tank for later reuse in irrigation. The excess water from the tank can then be discharged directly to the sea. The design could diversify between sealed cells with under-drain for collection and unsealed cells for infiltration according to the space and storm design constraints

The high traffic on the main road and the attributed expected higher sediment load may require a gross pollutant control measure. Different solutions might be considered according to the expected load and maintenance requirements, including grated inlets for barrier curbs backed with boulders and gravel or an additional sedimentation chamber connected to each cell. A holistic redesign of clusters could be elaborated to incorporate different variations, additional bioretention cell types, or further WSUD elements where available and according to the conditions of each cluster.

In a similar way, a WSUD approach can be employed along the two-sided promenade. The design concept utilizes patches of modular concrete fencing for transforming into landscaped stations with stormwater management features. The stations can be at regular distances and incorporate a designed bioretention system combined with bench seats and a tree for shading. The benches and proper plantations can replace the separation fence.

The bioretention system could combine both lined and unlined planter cells. The hybrid system captures runoff from surrounding promenade impervious surfaces. The lined cells retain water in a submerged layer and incorporate a raised outlet, which drains water into the middle unlined cell for infiltration. This configuration allows for tree planting in the middle cell while still providing retention capacity within the system to sustain vegetation and especially fencing hedges in the rest of the system. The side planter cells could still support an additional outlet discharging treated water into the sea under extreme rainfall events.

A third typical profile of the promenade is the retaining wall. This section has limited space available for any intervention at the pavement level. However, the proposed design concept is to deliver street runoff from the upper level to biofilter planters at the lower level of the wall base before discharging water into the sea (Fig. 5-37). A sedimentation chamber could be the first treatment measure to receive stormwater runoff from the road. Then water is piped under the pavement to the outer side of the wall and down to above-ground planters aligned along the base of the retaining wall. Water is treated gradually and discharged from the bottom of the planter into the sea.

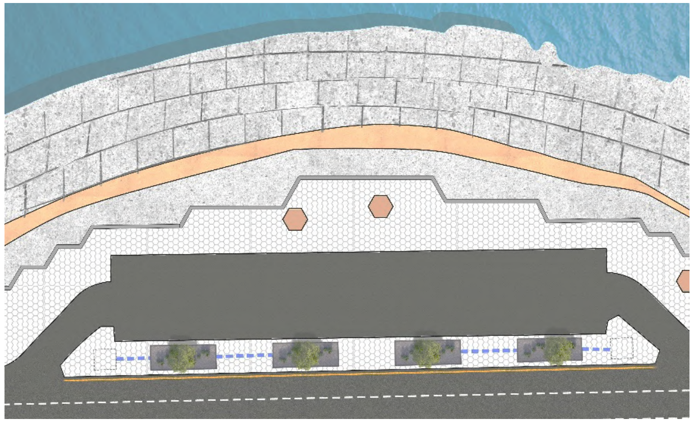
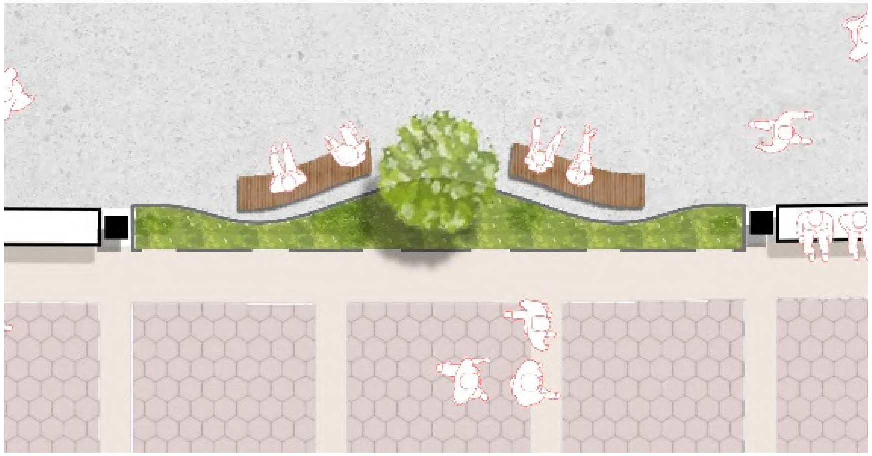


Fig. 5-41: Proposed integrated concept of bioretention planters and storage tanks systems in surface cluster example area (Illustration by Mohamed Elfouly on photo by author)

However, a key aspect to be considered in these proposals is the challenges of coastal planting and the required high maintenance. In addition to the typical requirements for vegetation and plant selection in such a dry climate, salt-tolerant plants are essential to tackle the strong wind, salt spray, and saline soil present conditions at coastal areas. After all, further investigation is required to determine the effect of salt accumulation in relation to retention in lined systems and unlined systems where water retention may increase soil salinity or not.

> Conventional landscaping at coastal areas of Alexandria with non-native plants require high and costly maintenance, especially for regular wash off salt to keep soil salinity under threshold levels.
>
> Hosny Salem (Interview, 2022)



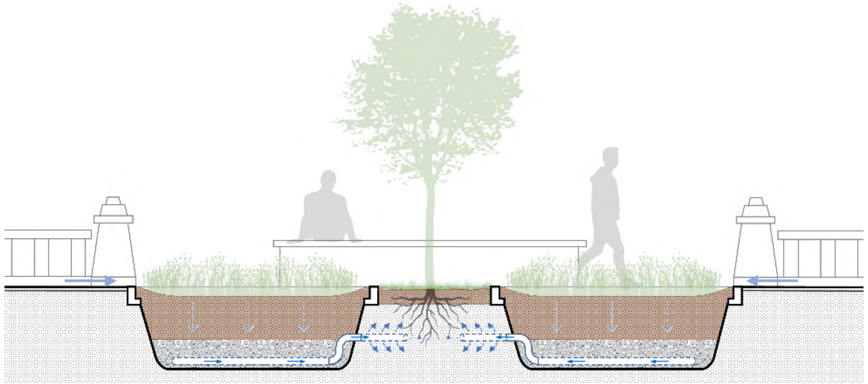


Fig. 5-42: Proposed concept of bioretention planters in surface cluster example area

Illustration by Mohamed Elfouly on photo by author
Cross section by author

These proposed WSUD conceptual interventions along Corniche Road could reduce pressure on the conventional sewer system during heavy rainfall and improve the amenity of the promenade while protecting the marine ecosystem by preventing the uncontrolled discharge of heavily polluted water into the Mediterranean Sea. Such decentralized measures could be potentially integrated as well with the recent separation of stormwater drainage projects to ensure best management practices and harmonize centralized engineered solutions with non-conventional nature-based processes.

Mahmoudiyah arterial road

The Mahmoudiyah Canal is a historic waterway that connects the Nile to Alexandria and is an important source of fresh water supply and navigation. Recently, the canal was announced as part of the Mahmoudiyah Axis urban development project, which involved backfilling 21 km of the canal and converting it into a main arterial road. The road axis spans 80 m to 120 m wide and includes a uniform main asphalt roadway of 50 m with 6 to 8 lanes in each direction, separated by a concrete barrier (Jersey barrier) rather than a median kerb. In addition, two service roads of 10 m width are on both sides, which follow the borderline of the existing building blocks (Girard et al., 2014).

There is a considerable remaining space of the total axis span that forms large vacant tracts of land with more than 200 m long and an average of 30 m width each. They are clearly observed on-site as barren lands stretching along the axis, between the main and service roads, and only a few of these lots are developed for public services. A mapping from available satellite images identifies their distribution (Fig. 5-43, 44). This available space apparently has the potential to be utilized for WSUD interventions.

Fig. 5-43: Example of the resulting bare land tracts extending along the road (Illustration by author, photos: Mohammed Hamdy, 2022)

Water from the canal continues to flow through three large pipelines embedded under the road surface. According to landscape irrigation expert Osama Elbaz (Interview, 2022), all public parks and sports clubs still largely rely on withdrawn water from this pipeline for supplying part of their irrigation requirements. However, the supply has been reduced dramatically since the transformation of the canal into a pipeline.

Recent plans to manage heavy storms in the winter season include taking a similar approach to the Corniche Road to install separate stormwater drainage in high-risk areas adjacent to the road, connected to the pipeline beneath. However, as described earlier in this chapter, the same concern remains regarding the negative impact of discharging polluted and low-quality runoff without any pre-treatment.

Building water-sensitive Mahmoudiyah Road

The main concept of building a water-sensitive Mahmoudiyah Road is taking advantage of the available large lots resulting from the development project to manage excess stormwater runoff and prevent flooding. Additionally, utilizing the installed pipes running under the road to provide alternative recycled water to increase water supply capacity for irrigation demand.

Various WSUD strategies could be employed in the vacant lots as nature-based treatment systems, including wetlands and bioretention to hold and treat large water volumes before discharge or infiltration. The available space in these large tracts could potentially be utilized as multifunctional space to incorporate runoff infiltration or detention systems, which should be connected to and receive treated runoff from those proposed wetlands or bioretention. The selection of a particular element depends mainly on the condition of subsoil at the addressed location, besides the source of water to be managed, either stormwater, domestic greywater, or treated blackwater. According to the infiltration potential map (IPM), infiltration capability varies along the road. Most of its length is classified as *Limited* to *Probable* infiltration.

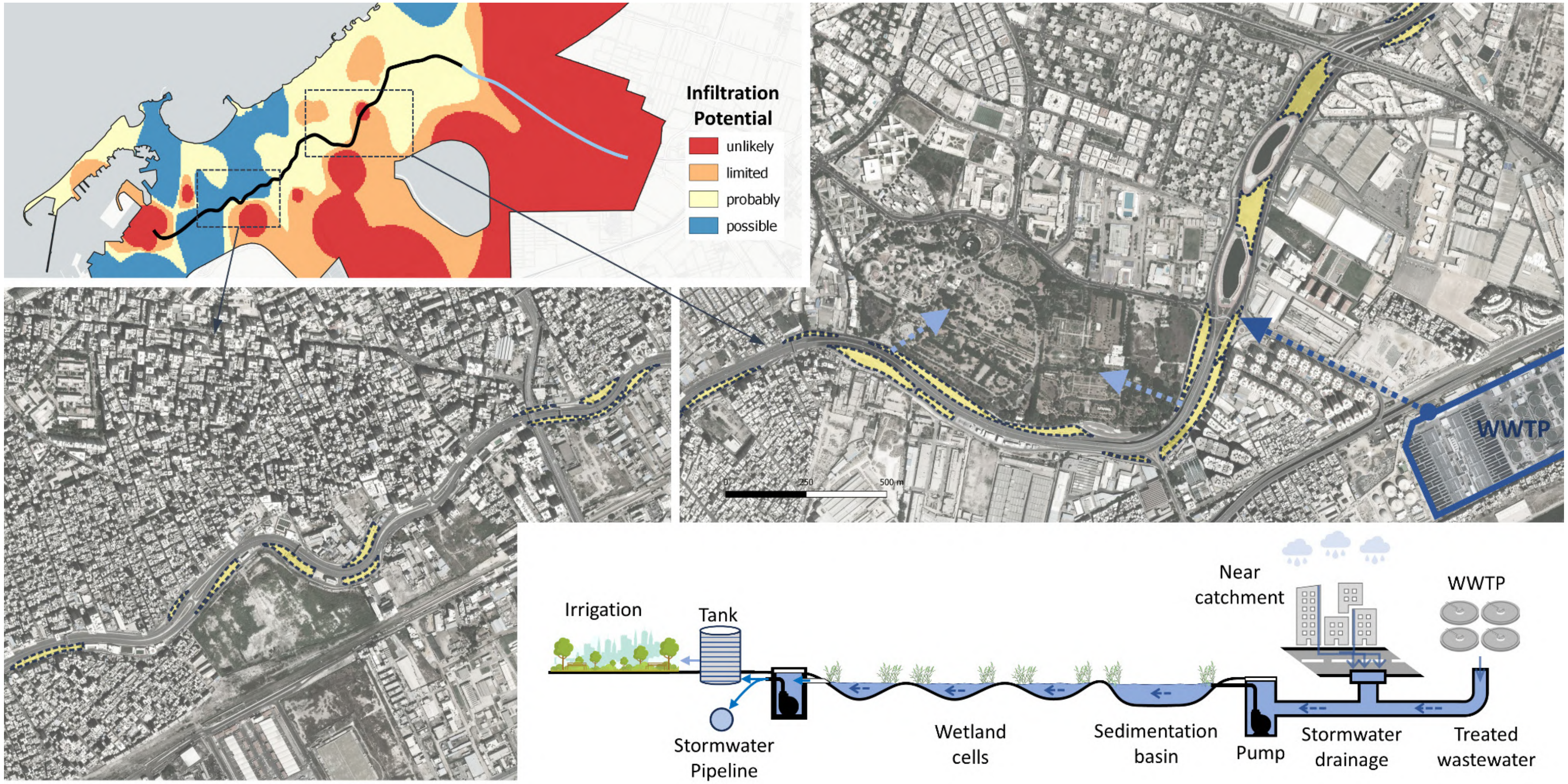


Fig. 5-44: Conceptual section of the decentralized WSUD strategy for Mahmoudiyah Road (By author)

Inspired by the Old Port Road Stormwater Drainage project in Adelaide, the space and form of vacant lots along the road allow for the integration of urban wetlands at stretches located in low soil permeability zones. Direct runoff from the road and the surrounding urban catchment area can be diverted to the wetland or delivered through the planned separate stormwater drainage. Water can be detained and treated in the wetland system over several days before discharging through an outlet to the stormwater under pipes. During the dry period, the wetlands could receive secondary treated effluent from the nearby East wastewater treatment plant to provide further tertiary treatment and detention time before supplying irrigation purposes of large park spaces and sports fields. In addition, the vacant land tracts can accommodate bioretention cells to be applied on a smaller scale in conjunction with underground water tanks to harvest treated stormwater for later non-potable reuses. In other zones where infiltration potential is higher, raised outlets from bioretention lined cells could be connected to a soakaway trench for infiltration after retaining volume of water in the submerged retention layer of the cell system. The soakaways were meant in this setting to offer additional volume capacity for water to infiltrate over longer distances and play a role in providing passive irrigation for potential landscapes in such large spaces. Moreover, greywater constructed wetlands could be connected to the public buildings at the location (e.g., schools, sports facilities, etc.) to receive both greywater and stormwater for treatment before directing water for either storage, infiltration, or discharge to the drainage pipeline.

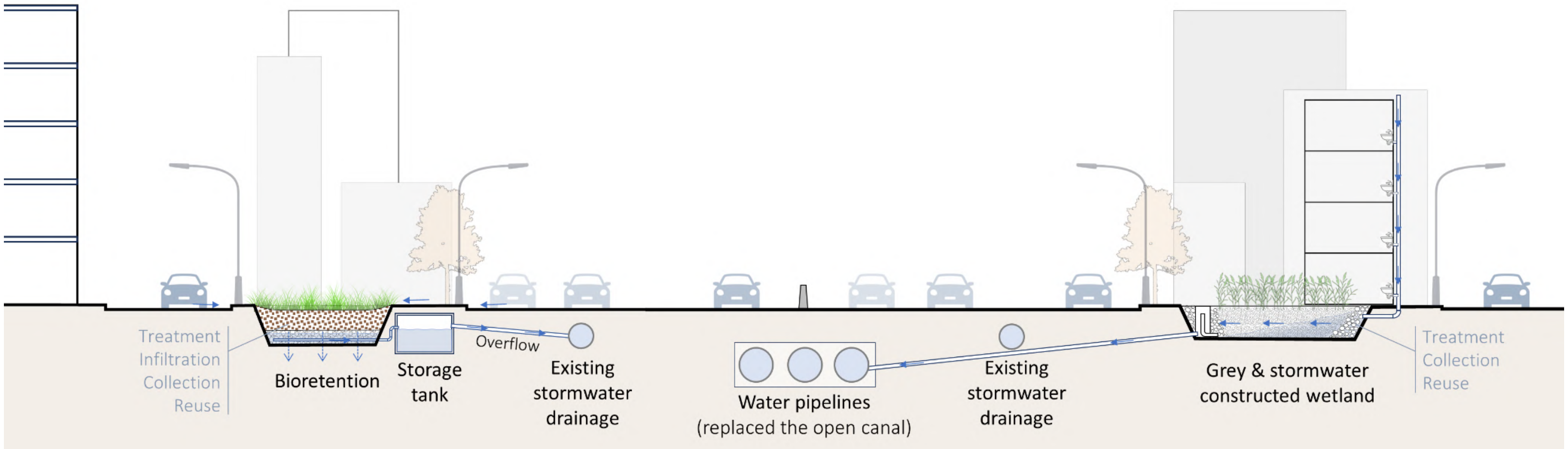


Fig. 5-45: A map showing the distribution and infiltration potential of bare land tracts, and conceptual schematic of treatment wetlands along the road (By author)

5.4 Site-scale Application

5.4.1 Introduction and Aims

The established WSUD hierarchical multi-scale approach in this dissertation employs decentralized measures across different urban scales, starting with localized control at individual properties and building up to the management of an entire micro-basin catchment. In this section, a real example ongoing project within one of the micro-basins in Alexandria is used to apply and assess the viability and effectiveness of WSUD strategies at a typical site-scale. The specific aims of this application are:

- To demonstrate the application and impact of WSUD technologies on a site scale, offering a model for replication in similar initiatives.
- To estimate the area requirements for WSUD vegetated systems compared to the planned open space under different rainfall intensities of 5 and 10-year return periods.
- To assess the design's sensitivity in relation to WSUD components and space available, while identifying efficiency thresholds for design elements under these varying rainfall intensities.

The selection of an urban site project to apply and test the contribution of WSUD to managing peak flows and runoff volumes in Alexandria was undertaken considering the importance of representing typical urban catchments and development typologies, ensuring that the findings are broadly applicable, and the model can be replicated both within the city and regionally.

5.4.2 Site Selection and Characteristics

The City of Alexandria can be spatially divided into two main urban domains: the existing central urban area and the newly developing suburbs expanding on the outskirts of the city. The central area includes the city center and densely populated surroundings. It is marked by a diverse urban setting, which imposes a challenge in finding a representative site example in such inconsistent patterns. In contrast, the suburban expansion zones are subject to new plans for city expansion, including several residential and mixed-use developments currently in progress. These areas are planned with a consistent layout, characterized by lower densities, larger plot sizes, and extensive green spaces including parks, recreational areas, and greenbelts (Fig. 5-46). The new developments appear to offer wide potential for a WSUD approach and the best setting to present its benefits. Therefore, the application focuses on a site within these new developments.

New Alexandria Development

The New Alexandria project is one of the current ongoing large developments under the New Urban Communities Authority (NUCA, 2021). The mixed-use development occupies an entire small micro-basin (8b) and incorporates major residential blocks with diverse commercial and service facilities. The development, according to NUCA, spans nearly 175 hectares and is situated at the intersection of the International Coastal Road and Cairo Alexandria Road. The development layout design is considered low density, accommodating land blocks of various land uses where buildings are clustered within open landscape areas and parking areas. Green spaces account for 20.5% of the total development area, and roads infrastructure 11.5%. Situated on reclaimed land from Lake Maryut, the project site features a relatively flat grade level, raised 2-3 meters above the lake water level. The subsoil formation is primarily soft clay and silty clay with high moisture content. However, the reclamation had involved overlaying a compacted fill layer of graded granular soil up to the development design level (Ali, 2022). The infiltration potential is classified as limited to probable due to the soil's average permeability and the expected elevated groundwater table.

Applying the hierarchical planning approach, and based on the mentioned characteristics of the project, it is sought to integrate WSUD elements in a management train starting from buildings to the entire micro-basin. Given its proximity to the lake, the project site has significant potential for on-site urban water management to enhance treatment, retention, and storage at each level before final discharge into the lake. However, within the scope of this section, calculations are confined to the site scale, with notes on possible broader implementation at the micro-basin scale.

One of the planned development blocks covering 24.36 hectares was selected for application and calculations. As depicted in Figure 45, this mixed-use area primarily features low-rise apartment buildings and service facilities. The buildings are arranged in clusters surrounded by open green spaces and paved pathways, with a significant portion of the vegetated landscape concentrated within the clusters' internal spaces. There are also substantial car parking areas distributed among the buildings and extending along the local street sides, separated by paved curbs. The layout includes a two-way street divided by an approximately 2 m wide vegetated median strip. The project layout plan and all area estimations were roughly drafted by the researcher based on design drawings available from the city's official websites. Surface materials were identified based on the construction norms of similar projects in the city.

5.4.3 Concept Design

The design strategy adopts onsite chain management to treat, retain, and store stormwater before final discharge or infiltration. The selection of specific technologies to incorporate within the prototypical new project site is based on the ranking provided in the WSUD catalog, in addition to considering the aim of the application and suitability to the project setting. Green roof systems are selected for building applications, and bioretention, rainwater tanks, and permeable paving systems for the surrounding sitescape application.

Fig. 5-46: Typical urban expansion new developments and the selected site for calculations (NUCA, 2021)

Bioretention in the concept design is the primary vegetated system to be assessed and compared against the actual planned green space and the overall site available surface areas. Other systems, such as green roofs and permeable paving systems, will be incorporated and assessed in consecutive scenarios.

To improve drought resilience and support vegetation, the type of bioretention cell selected is a sealed system with a submerged zone and collection underdrains. The system can receive runoff flows from roads, pavements, or rooftops and retain water in a drainage gravel layer that allows the vegetation to access water during dry periods. Excess water is drained via slotted underdrainage raised pipes at the top of the gravel storage to prevent overflow of the system. Treated drained water can be utilized for further storage if applicable for reuse or directed to another WSUD element such as a pond or wetland within a holistic micro-basin management train. Rainwater storage and reuse involve the installation of underground tanks distributed and connected to bioretention cells. The tanks are equipped with pumps for landscape irrigation during extended dry periods. The system design guides the overall configuration of the bioretention cells as follows:

Inlets: The system cells may receive overland flow from adjacent impermeable surfaces or through underground inlet pipes.

Ponding depth: The depth that allows stormwater to temporarily pond before it filters downward through the filter media. The temporary ponding depth for bioretention systems ranges from a minimum of 100 mm up to 300 mm according to the Adelaide technical manual (SA Govt, 2010). Since the system is designed here to receive runoff from larger storm events, an average of 200 mm ponding depth was applied.

Filter media: The filter media's primary function is to sustain plants and remove pollutants. Saturated hydraulic conductivity represents the rate at which water can move through the bioretention system's filter media when it is fully saturated. This rate, according to the technical manual, should ideally be in the range of 150-350 mm/hr. The design of the system here considers 150 mm/hr to balance soil water retention that supports healthy plant growth and provides adequate treatment of the expected high runoff flow. The Bioretention Guideline (Payne et al., 2015) recommends a filter media layer depth of at least 400 mm. To accommodate deeply rooting plants and accept runoff from roofs and pavements, 600 mm is recommended, or deeper for trees. For the purpose of the conceptual sizing in the application here, a typical depth of 600 mm was applied.

Choker layer: A transition layer of 100 mm finer aggregate (pea gravel) that separates the filter media and protects the gravel layer below.

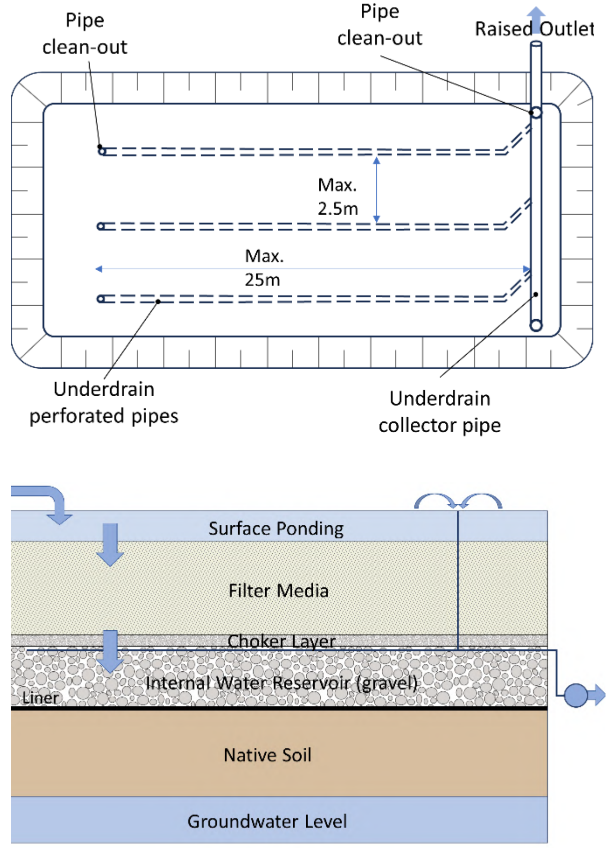


Fig. 5-47: conceptual diagram of bioretention system, by author based on (Water by Design, 2015)

Internal water reservoir: A submerged gravel zone with reasonable voids to retain water, which provides extended stormwater retention between inflow events, and works as a drainage layer connected to a raised outlet pipe for water harvesting and conveyance. For the best possible water treatment and drought resistance, a submerged zone depth of 400–500 mm is recommended(Payne et al., 2015).

Underdrain: Underdrainage pipes collect treated stormwater and convey flows across the base of the bioretention system. The underdrain system consists of a main raised outlet connected to a collector pipe and more branching perforated pipes. The number and diameter of pipes is determined based on their sufficient outflow capacity, which must be greater than the filter media infiltration flow. The perforated pipes should be distributed at intervals of 2.5 m maximum spacing and 25 m length. In addition, inspection and cleanout points are required.

Liner: For harvesting and conveying treated stormwater, a liner must create an impermeable seal from the bottom to the top of the system and all relevant hydraulic connections.

Table 10: Concept design parameters

System component	Adopted value
Surface ponding	200 mm
Filter media	600 mm / 150 mm/hr
Choker layer	100 mm
Perforated pipe	100 mm diameter
Water storage reservoir	400 mm

5.4.4 Modeling and Scenarios

The intention of the calculation is to determine the total required surface area of the bioretention cells to be placed across the planned landscape to efficiently manage runoff volume generated from two rainfall events of 5-year and 10-year return periods. The results will then be compared with the current planned open landscape available space. An initial step was setting the baseline estimation as the actual surface space demand of bioretention for ordinary urban design practices in the city. The calculated area will be assessed as a ratio of the currently planned green space total area. The baseline establishes a reference point against which the impact of applying any further technologies can be measured.

Besides the system configurations, sizing a bioretention system involves determining the surface area of the cells required to capture the runoff volume generated from the contributing catchment by the design storm events. Calculating this surface area depends mainly on both the depth of ponding and the saturated hydraulic conductivity of the filter media in relation to the runoff volume to be received during a storm event. Therefore, the underdrainage pipes need to be designed to manage outflow from the system based on detailed calculation. The design principle is that the conveyance capacity for the overall perforated and collector underdrain pipe system must be greater than the filter media infiltration flow.

The following formula outlines a method for calculating the surface area of a bioretention system (A_p):

$$\boldsymbol{A_p = i \times D \times A_{imp} \,/\, [d_p + (K_f \times D)]}$$

Where:

i = Design storm intensity (m/h)

D = Design storm duration (h)

A_{imp} = Catchment impervious area (m^2)

d_p = Design surface ponding depth (m)

K_f = Saturated hydraulic conductivity of the filter media (m/h)

This formula integrates various parameters to ensure that the designed system can handle the anticipated runoff effectively. It accounts for the surface area needed to facilitate the infiltration of stormwater volume through the filter media at a rate determined by the ponding depth and saturated hydraulic conductivity.

The design storm intensities (i) are typically measured in millimeters per hour (mm/h). Based on local daily rainfall statistics presented earlier in this chapter, the daily intensities are 43 mm and 53 mm for recurrence intervals of 5 years and 10 years, respectively. The time of concentration (h) is the duration over which the design storm intensity is applied. It is estimated for this calculation at 2 hours, reflecting the short storm events known to Alexandria. The design flows are as follows:

- 5yr design storm = 21.5 mm/h
- 10yr design storm = 26.5 mm/h

The impervious areas within the site catchment (A_{imp}) that directly contribute to runoff include rooftops, pedestrian pavements, parking lots, and roads. Surface materials typically used in such residential developments in Alexandria are highly impermeable. Rooftops are usually cement tiles, pavements are seamless impermeable tiles or concrete slabs, and road and parking lot surfaces are typically asphalt.

The identified runoff coefficient (C) for all these surface material types is 0.9 (DWA, 2005).

The total volume of runoff generated from the impervious areas is calculated by applying the Rational Method, considering the surfaces' runoff coefficients and the rainfall intensity for the design storm duration equal to the time of concentration. The surface area needed is proportional to the combined depth of both surface ponding (d_p) and water drained by percolation through the filter media during the design storm ($K_f \times D$) in relation to the calculated total runoff volume.

Beyond baseline calculations, additional WSUD technologies were integrated in stages to assess their impact on green surface space demand. The technologies considered include:

Permeable Pavements: Permeable Interlocking Concrete Pavement (PICP) systems were applied to pedestrian pavers and parking lots. These systems consist of interlocking blocks with open joints over a base course of uncompacted open-graded aggregate. They reduce surface runoff by allowing stormwater to drain through and either infiltrate into the soil or be detained temporarily. The runoff coefficient for permeable pavement is 0.5.

Green Roofs: extensive green roofs were proposed for building rooftops. These roofs can reduce runoff rates and peak volumes, subsequently decreasing the required bioretention surface area. Typically, 70% of the total roof area is applicable for green roofs due to building services occupying 30% of the roof area. The average runoff coefficient for extensive green roofs is 0.5.

Calculations of scenarios were conducted in sequence, considering first applying the permeable pavement (Scenario 01) and then adding extensive green roofs in addition to permeable pavements (Scenario 02). Each scenario was compared to the baseline area of planned green space to determine the reduction in bioretention surface area required due to the additional WSUD technologies.

5.4.5 Results and Discussion

Closer inspection of the area's breakdown of existing surfaces reveals a predominance of impermeable surfaces covering 84% of the site's total plot area. The permeable surface area, which includes the planned green space, constitutes 16%, appearing less than expected in such low-density development. Roads and parking lots contribute significantly to stormwater runoff, alone constituting 39% of the total site area. Pedestrian pavements and rooftops are also notable contributors, representing 21% and 24%, respectively.

Most of the planned landscape is active green space concentrated in large open areas between buildings. These spaces are designated for recreational use, which can limit the integration of bioretention systems without compromising their primary function. Other mapped passive green spaces are much more suitable for bioretention systems, offering an opportunity to maximize the utility of these typically underused areas for effective stormwater management. The site layout shows additional passive impervious pavement surface areas adjacent to roads and parking lots that could potentially be available for placing bioretention cells, consequently increasing the total green area in the project site.

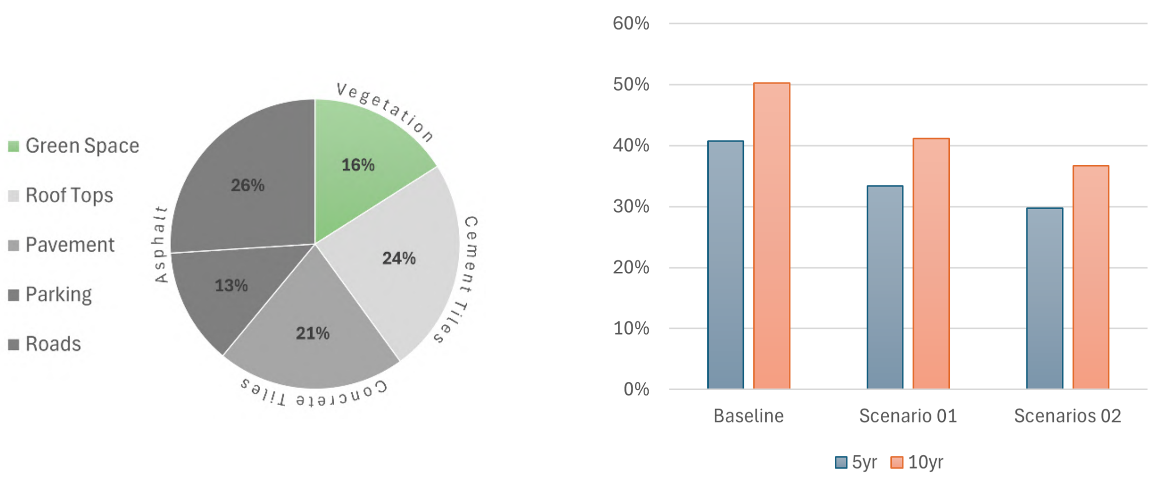


Fig. 5-48: Breakdown of the existing surface cover by share areas and materials (left). Required bioretention footprint ratio of the planned green space in different scenarios (right)

Green space labeled as **'Active',** such as public garden, play space, open lawn, etc., is an accessible green space associated with physical activity or active recreation by people. On the contrary, **'Passive'** green space is inaccessible and usually associated with streetscape elements such as in roundabouts, road verge planters, etc.

The baseline scenario, with 84% impervious area, shows that 41% to 50% of the green space would need to be allocated to bioretention cells to effectively manage runoff for 5 and 10-year storm events. As illustrated in Chart 5-47, the implementation of additional WSUD measures significantly enhances surface permeability and water retention capacity, thereby reducing the proportion of surface area required for bioretention. In Scenario 01, the introduction of permeable pavements reduces the impervious area to 62%. Accordingly, the green space needed for bioretention systems is reduced to 33% for a 5-year storm event and 41% for a 10-year storm event, reflecting an 8% reduction in the required bioretention area compared to the baseline. Further improvements are observed in Scenario 02, where the implementation of green roof systems decreases the impervious area to 55%. This scenario results in bioretention requirements of 30% for a 5-year storm event and 37% for a 10-year storm event, further decreasing the proportion of green space required for bioretention systems.

Table 11: Applications and corresponding Impermeable area for different scenarios.

Scenarios	Impervious area (m^2)	Ratio	Applications
Baseline	179102.628	76%	-Bioretention
Scenario 01	146,691.51	62%	-Bioretention -PICP
Scenario 02	130659.92	55%	-Bioretention -PICP -Green Roof

According to bioretention design guidelines (Alan Hoban, 2019; STEP, 2024), the typical bioretention footprint (R) ratio ranges from 5% to 20% of the catchment's impervious area.

$$\boldsymbol{R = A_{imp} \,/\, A_p}$$

The system configurations developed for this application result in a bioretention ratio (R) of 9% to 11% for the respective storm designs.

or Alexandria, it is reasonable to assume that, on average, 1 m² of vegetated bioretention area is required for every 10 m² of impervious area to manage storms with 5 to 10-year recurrence intervals.

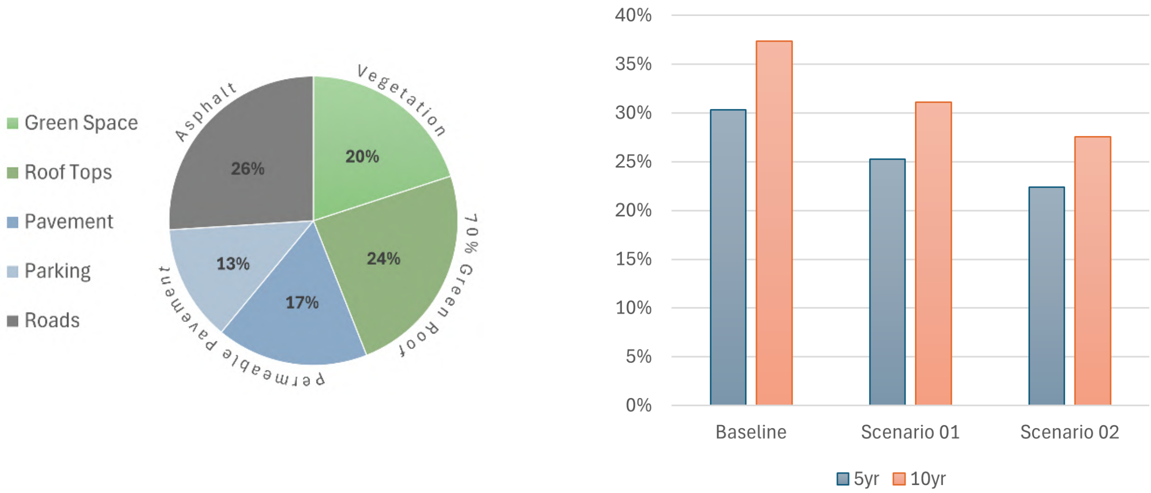


Fig. 5-49: Optimized green space ratio and its impact in the various scenarios

Despite these ratios appearing reasonable, they can still be considered overly large in the case of a 10-year storm, particularly in the baseline scenario where 50% of green space could be required for bioretention. Given the limitation on implementing bioretention in predominantly active green spaces, an average of 30% could be presumed relatively feasible, achievable only in Scenario 02 under the 5-year design storm.

These results and site analysis, nevertheless, suggest that the total share of green space needs to be increased in such types of developments by including additional passive green spaces within streetscapes and parking areas. Incorporating WSUD systems like bioretention and bioswales can increase the total share of green space to approximately 20% of the total site footprint. This increase would improve the project's capacity to manage runoff from rainfall events up to 10 years while maintaining the optimum utilization of space for technical and recreational purposes. Meanwhile, larger interbuilding active green spaces could remain primarily for recreational use or be utilized as multifunctional stormwater management areas, like shallow infiltration or detention basins, supporting both runoff management and recreational activities. As shown in Figure 5-48, the optimized green space area has reduced the allocation share of bioretention surface to between a minimum of 23% and a maximum of 32% in both scenarios.

5.5 Validation and Proofing

This dissertation posits a framework for WSUD tailored to the hot and dry conditions of the MENA region. It introduces a novel approach that manages urban areas as discrete hydrological regions and employs WSUD decentralized strategies across different urban scales. A comprehensive research design has been implemented to scrutinize the theoretical constructs of the framework by validating the findings and analyzing the empirical evidence. Drawing from an extensive literature review and lessons learned from global best practices, the theoretical framework was meticulously developed to encapsulate the core concepts of WSUD and adaptation strategies in dry urban environments. This framework strategically guides the adoption of WSUD, aligning with established knowledge and observations.

The methodological approach comprised a mixed-methods strategy, integrating quantitative data with qualitative expert interviews and consultations. This methodological triangulation helped to corroborate findings across different data sources, thereby reducing the potential for confounding results. The empirical research focused on a case city within the MENA region, selected for its archetypal characteristics to ensure that it reflects the diversity of urban settings in the broader region and enhances the generalizability of the findings. Building on this foundation, the WSUD conceptual framework developed here was applied to the Alexandria case. Spatial mapping of micro-basins and barriers in the city demonstrates a significant presence of various barrier types across the urban area, delineating it into distinct zones. Additionally, the comparison of frequently reported flooding locations with mapped urban barriers and extensive boundary walls provides strong indications of their impact on flooding. These findings corroborate earlier observations about the role of urban barriers in flooding. Initial assessments of a possible similar impact of street dead-ends suggest that further investigation is needed, as current data are insufficient to determine relationships. More extensive data on the characteristics of flooding hotspots and a deeper investigation into causative circumstances are required for additional validation.

The empirical insights from expert interviews in Alexandria, in addition to the results revealed from the spatial analysis of the city's urban area, further support the developed set of principles and targets for adopting WSUD in dry regions. The current geomorphic investigation, including land cover and surface permeability analysis, has demonstrated that despite the relatively permeable native soil in wide areas of the city, the surface is highly sealed due to urbanization, contributing to generally reduced soil absorption and high surface stormwater runoff. The results' inconsistency of analysis parameters among micro-basins reflects their discreteness and the way each may react to extreme events and the generation of runoff.

Analysis of current climate trends shows an increase in average annual precipitation over the last decade, with extreme rainfall events becoming more frequent and overwhelming the drainage system. The investigation highlights the current drainage system's inability to manage the increased intensity and frequency of rainfall, exacerbating the adverse impacts of flooding. Additionally, the investigation reveals that despite the average high infiltration potential in a wide area of the city, the surface is intensively sealed with impermeable materials. The insufficient green cover provisions in the city and mounting challenges in sustaining vegetation are primarily due to the high management demand and the incapacity of resources caused by water scarcity and persistent drought conditions.

Regarding the quantitative assessment of WSUD applications, the systems design and calculations were carried out at the level of a residential area within one of the identified micro-basins. The WSUD objectives were defined in accordance with the presented framework, and the selection of technologies was guided by the ranking system. The results support the proposed hierarchical management approach, where site applications were found to be able to effectively manage runoff from regular rainfall events and large events up to a 10-year recurrence interval. For extremely large storm events (20-year, 50-year, and beyond), additional management measures may be required at the micro-basin level. However, the recommended increase in the proportion of green space from 16% to 20% of the total site area raises further questions regarding the optimal proportion of surface cover in other commercial or industrial developments, which also appear to be consistent with the earlier discussion on the need to establish an Urban Green Factor (UGF) targets system for different land uses.

The relatively low permeability of soil in the project area requires the provision of additional space for retention systems to manage larger runoff volumes on the micro-basin level. Wetlands or retention basins, for example, could be considered for the micro-basin management level. This recommendation is likely applicable also to all new development plans in the Alexandria hinterland, which ultimately have the potential to restore wetlands and lagoons that were once a natural feature of the landscape in this area. On the contrary, in the densely populated main urban area of the city, there is not as much space available for such large-scale WSUD systems, but infiltration potential is generally high enough to enable the use of subsurface systems like geocellular modules, infiltration trenches, and soakaways as viable solutions.

Another critical insight that emerges from this finding indicates the importance of recognizing both active and passive uses of green space in urban environments. It becomes clear that merely analyzing the availability of green spaces in terms of surface area is insufficient, but understanding their use within the general setting is crucial for selecting appropriate WSUD technologies for specific projects. This observation also highlights the significance of the multifunctionality concept in WSUD planning for both dense and sparse urban settings where green spaces are limited or predominantly allocated for active use. Accordingly, these considerations necessitate the integration of both the qualitative and quantitative aspects of green space utilization into the spatial framework's analysis parameters and selection model.

Viewing these results within the broader city context proves the importance of multi-layered spatial analysis in understanding the complex relationship between urban surface and subsurface features, which can vary from area to area. This allows us to better implement WSUD solutions that are tailored to the needs and conditions of each location. Therefore, further testing of applications and pilot projects in different environments with different densities and land uses is needed.

Overall, the insights from Alexandria, along with confirmed observations about the role of urban barriers and boundaries on surface runoff and flooding, further support the argument and established understanding of dry environments as a basis for the WSUD adoption framework developed in this dissertation. Nevertheless, it is important to note that the proof of the conceptual model and its applications is an ongoing process. Continuous assessments are essential to provide feedback on various aspects of the conceptual framework, ensuring its continuous refinement and improvement.

6 CONCLUSION AND OUTLOOK

This dissertation began by acknowledging the pressing challenges of extreme drought and flooding that urban areas in dry MENA regions face, especially given the increasing pressures of climate change and population growth. It underscores the urgent need for a paradigm shift in urban planning and design to align with the total urban water cycle. Adopting a WSUD approach has become critical in effectively balancing these adverse conditions of water excess and scarcity. The primary aim of this research was to address the uncertainties and challenges of adopting the WSUD concept in such climates by developing a framework model tailored to the specific conditions of the region. This framework is designed to create practical and scalable WSUD innovative practices and planning approaches to guide planners and practitioners toward sustainable urban water management.

The dissertation sought to empirically examine this model through a case study of Alexandria City, providing a practical context for applying WSUD principles and strategies and demonstrating how urban form and structure can be optimized to build resilience in the region's dry urban environments. The developed framework provides a comprehensive method to integrate water-sensitive practices into the urban development process in cities of the region. Key elements of the framework include setting performance-based targets for water management, introducing a novel planning approach that delineates spatial boundaries for effective integrated analysis and planning, and conducting a systematic evaluation of the adaptability of WSUD technologies to local contexts. Supported by a planning and data management tool, this framework can facilitate the selection and application of WSUD strategies across urban areas. The construct of the model was informed by the understanding of the distinctive urban morphological and hydrological features of the dry built environment in the region, as well as the insights gained from examining Adelaide City's long and elaborated experiences in adapting WSUD practices to its dry context.

Key Findings

This dissertation addressed multiple research questions which fall under three main areas. The key findings that answer these questions will be discussed in respect of each of the question areas.

Q1- Understanding water in dry built environment

The investigation has shown the extensive coverage of drylands across the Earth's surface, with a substantial area concentrated in the MENA region. As a considerable part of the global south, the region includes several densely populated cities. The examination of this dry built environment highlights the critical role of decentralized adaptable urban drainage solutions. These solutions must not only mitigate the risks of flash flooding but also maximize water conservation and reuse, incorporating integrated management of wastewater, stormwater, and other unexploited resources like dew and condensate water.

The findings uncover a significant potential link between urban form and surface runoff management, highlighting how the region's unique urban structures, marked by widespread impervious surfaces and scarce greenspaces, exacerbate stormwater runoff and increase flood risks. Cultural and environmental factors further intensify these issues by contributing to variations in urban density and the prevalence of barriers, fencing walls, and street dead-ends. The nuanced understanding of the interaction between urban physical features and drainage dynamics has given rise to the central concept of 'Urban Hydrological Regions' in this dissertation, which includes micro-basins and barriers. This concept underpins a novel planning approach integrated into the developed framework.

Q2- Prior experiences and strategies for the adoption of WSUD in dry climates:

The empirical investigation in Adelaide has shown that WSUD is adaptable to the unique environmental challenges of dry urban environments. The city has effectively tailored WSUD strategies to accommodate infrequent but intense rainfall events and prolonged drought periods, focusing on citywide water conservation rather than solely on flood risk management. This adaptation strategy includes the diversification of water sources through the incorporation of stormwater and wastewater reuse alongside traditional water supplies. Strategic utilization of various WSUD technologies, such as bioretention systems, wetlands, and aquifer storage and recovery (ASR) in treatment and harvesting schemes, demonstrates the city's proactive management of both water scarcity and urban flood risks effectively. These initiatives not only improve water security but also enhance urban resilience and livability by providing green infrastructure that promotes urban cooling and biodiversity. The case of Adelaide also underscores the crucial role of community involvement and supportive policy frameworks in the successful adoption of WSUD practices, despite the absence of a mandatory regulatory framework until recently. Establishing strategic targets that integrate WSUD from the early stages of urban planning and design, alongside public participation and capacity building, has proven essential for securing public support and ensuring the effective implementation of WSUD.

Further insights from the city's implementation, supported by literature, indicate that all WSUD technologies can be adapted with specific design adjustments, typically including:

- Support subsurface water retention for collection, passive irrigation or urban cooling.
- Incorporate harvesting techniques and develop storage solutions at various scales.
- Utilize drought-resistant plant species.
- Provide effective water treatment and manage nuisances in surface-based retention systems.
- Manage gross pollutants and runoff first flush effectively.

The investigation revealed that WSUD technologies differ in their adaptation needs. While some are inherently better suited for dry conditions, others are essential for their unique functional benefits. Thus, the most effective strategy typically involves using these technologies collaboratively, customized to local conditions to optimize their performance and achieve the desired objectives.

Q3- Transition framework and the applications of WSUD in the dry MENA region (Alexandria)

The key findings from Alexandria affirm the effectiveness of delineating urban spaces into micro-basins and barriers as an innovative WSUD planning approach most suitable for the typical urban context of the city. This structured method enables precise identification and analysis of unique urban and hydrological characteristics within each zone, fostering the development of locally tailored WSUD policies and solutions. By breaking down the urban landscape into manageable linear elements and zones, the implementation of WSUD becomes both contextually relevant and impactful. The case study also highlights the advantages of integrated urban spatial analysis that utilizes a multi-layered range of interdisciplinary factors and attributes. The synthesized urban metrics derived from this analysis are crucial for identifying key WSUD implementation areas, providing detailed and quantifiable insights into spatial aspects within each micro-basin. These metrics facilitate informed decision-making, effective planning, and robust evaluation and monitoring of WSUD strategies. Nonetheless, continued improvements are needed in the quality and accessibility of these urban metrics to make them more reliable for decision-makers and researchers.

Observations in the city regarding the relatively high urban density and limited space stress the importance of utilizing multifunctional spaces and infill development for WSUD integration in dense environments. These findings collectively indicate that micro-basin-based land use planning is essential in the WSUD adoption process, by strategically determining the distribution and management of land resources to meet WSUD objectives and ensuring adequate spatial allocation of WSUD strategies.

Moreover, the results emphasize that green spaces and nature-based solutions are essential in the WSUD approach for providing multiple functions and benefits. Yet, the current presence of greenery in the city and others in the region tend to be 'introverted', with green spaces predominantly confined to private domains (behind walls) rather than public areas. This inherent cultural pattern points to the need for enhanced public awareness and engagement in WSUD practices, and involving the community actively in planning and decision-making processes while building technical capacity are essential steps towards effectively embedding WSUD into Alexandria's urban fabric and the broader region. Additionally, the investigation has raised important questions about the potential linkages between boundary walls, private greenery, and surface permeability and their effects on flood risk. This suggests that further investigation is needed to fully understand these dynamics and to ultimately develop an informative boundary wall indicator on a micro-basin level that can guide the planning and implementation of WSUD.

Finally, the proposed WSUD interventions along Alexandria's rail tracks and major roads demonstrate the potential of linear infrastructure to manage and reuse stormwater, greywater, and secondary wastewater. Furthermore, proposals for the new residential project site show the layout's capacity and limitations for onsite stormwater management in response to varying rainfall events. The application results suggest a minimum required green space ratio, underscoring the critical multifunctional role of green spaces in effective WSUD implementation. These interventions demonstrate the capability of such technologies to balance the current extremes and support vegetation within the project.

Outlook

Reflecting on Adelaide's experience with WSUD and its implications for the MENA region has revealed several key adaptation principles. Adelaide has focused on water conservation and quality improvement, necessitating comprehensive urban planning and a preference for specific design flow modeling methods. In contrast, cities like Alexandria, which face both drought and flooding extremes, require a balanced approach to both flood protection and water conservation. This dual focus is integrated into the developed planning support system, which combines local threat-driven approaches with broader planning strategies based on opportunity and suitability. The findings suggest that both storm and continuous modeling design flow methods are of vital use in addressing specific flooding hotspots or facilitating city-wide implementation. Moreover, Adelaide's well-developed infrastructure, particularly the urban drainage system, and relatively low population density have facilitated WSUD adoption. However, the variability in urban fabric and density found in the Global South's dry regions presents greater challenges. Consequently, flexibility in the sizing and scalability of WSUD technologies is crucial to meet the diverse local urban settings effectively.

In essence, as urban densification increases and climate change intensifies weather extremes worldwide, these analogical inferences have significant global implications for understanding how the differences between dry and humid climates may gradually diminish under these pressures. This suggests that dry regions, particularly those in the Global South, could serve as global models for both developed humid and dry regions in anticipating and preparing for a climate-resilient future.

This dissertation highlights the transformative potential of the WSUD in rebalancing urban green space in the MENA region, challenging the conventional view that regards green spaces as burdensome. Traditionally, greenery, heat, drought, and flooding are perceived as separate or even conflicting issues, especially in water-scarce environments. However, this dissertation reveals that within the WSUD holistic approach, these aspects are not merely challenges; they form integral components of a dialectical relationship. Within this relationship, green spaces are not only capable of coexisting with the extremes of dry climates but can actively alleviate them. The cases of Alexandria and practices from Adelaide demonstrate that strategically designed green spaces can effectively reduce flooding and urban heat, conserve water resources, and enhance recreational urban amenities and overall quality of life. Several questions, nevertheless, remain to be answered as to which native plants and trees are suitable for the city's various street layouts and other green spaces, and to what extent alternative water resources in the region's urban areas can be used to supplement the water requirements of the green spaces, e.g. grey water and wastewater.

Generalization

The findings of this dissertation, although derived from specific case studies, hold significant relevance for the broader MENA region due to shared climatic conditions, water security challenges, and urban characteristics. As discussed in Chapter 2, most cities in the MENA region experience similar extreme weather conditions characterized by chronic aridity and sporadic heavy rainfall, leading to severe surface flooding. The region's limited freshwater resources and water security issues are persistent themes in both research and governance. Many urban development characteristics, including population densities, city structure, availability of open and green spaces, urban expansion patterns, and other related aspects, are largely consistent across the MENA region. These broader commonalities highlight the potential for the widespread adoption of WSUD principles, enabling cities to replicate the strategies and insights gained from the case study.

The WSUD spatial framework developed in this dissertation is flexible and adaptable. It allows for modifications to suit various local conditions and resource availability in each city within the region. This adaptability ensures that the framework can address the unique challenges and opportunities presented by different urban environments in the MENA region.

Limitations and Areas for Future Research

The development of the WSUD planning approach in this dissertation is based on observations and arguments that need to be contextualized within certain limitations. Notably, the lack of prior research examining the relationship between urban physical features and surface flooding, which might introduce a personal observation bias. To address this, further research is required to investigate the complex dynamics between urban physical barriers and stormwater runoff flow. Additionally, exploring other urban elements such as street network orientation, dead-end streets, and boundary walls could further elucidate their correlation to flooding impacts. Research could also extend into adapting WSUD strategies within densely built historical cores and expanding peri-urban informal areas.

The integration of WSUD practices into urban planning heavily relies on comprehensive multidisciplinary data. In Alexandria's case, the scarcity of official rainfall data and limited geospatial information can affect the reliability of urban analysis and WSUD implementation studies. Although data triangulation and contextual positioning were employed in many cases to mitigate these issues, the case study's proofing application was largely constrained by the absence of hydrological effectiveness curves and limited expertise in hydrological modeling and sizing WSUD technologies. Therefore, there is a pressing need to enhance the availability and accessibility of reliable rainfall data by expanding the network of weather stations. Developing comprehensive maps of heavy rainfall hazards, urban heat, and land cover among others would also support more accurate analysis and decision-making. These improvements would also significantly enhance flow design modeling in the region, enabling the effective use of rainfall exceedance probability models and hydrological effectiveness graphs.

The urgency of diversifying water resources in the MENA region, particularly focusing on underutilized sources like water condensate and greywater, is evident. Further research could significantly advance the integration of these resources into vegetated WSUD systems and support sustainable urban greening practices in general. This would involve not only technical evaluations but also assessments of social acceptance. Additionally, compiling a vegetation repository with information on local native species of drought-resistant plants and trees with recommendations of each for suitable urban settings (streetscape, gardens, parks, green roofs, and walls) would be of significant need towards these efforts.

This dissertation also identifies a gap in research regarding the integration of WSUD strategies along linear traffic infrastructures of tram and railway tracks. Detailed studies are necessary to assess any limitations or considerations and to technically validate the WSUD solutions proposed in this dissertation. Furthermore, there is a need to develop water-sensitive fencing wall models that accommodate cultural norms while preventing runoff blockage and enhancing permeability.

To support WSUD objectives, ongoing efforts to align policies across different scales and sectors are required. This includes integrating water management with land use planning and urban development policies. Building technical capacity through training programs for planners, engineers, and other relevant professionals is essential. Also, WSUD pilot projects can provide practical guidance and test different methods, supported by longitudinal studies to track WSUD performance over time, assessing durability, maintenance needs, and effectiveness.

More broadly, for future research, it is imperative to conduct interdisciplinary and comparative studies across urban centers in the MENA region to uncover relationships and patterns that can enhance our comprehension of urban development and planning in these areas, particularly how these patterns interact and impact urban water management practices. Extending this research to global dry regions would provide insights into how different urban contexts tackle similar climate challenges. Such studies can uncover best practices and innovative adaptation solutions of WSUD strategies. Moreover, fostering knowledge exchange between dry regions is crucial. Establishing networks for sharing insights and collaborating on WSUD initiatives can bridge technological and knowledge gaps, promoting innovation and developing adaptable WSUD frameworks for dry climates.

Overall, this dissertation has gone some way towards enhancing our understanding of the role of urban structure on surface runoff in dry climates, highlighting its profound implications on water issues and flood management. By addressing the specific research questions, this dissertation has provided a roadmap for urban water management initiatives in Alexandria and has laid the groundwork for future investigations and practical interventions aimed at enhancing the resilience of urban areas across the broader region. It has demonstrated how a context-tailored WSUD planning approach can transform urban development and water management practices in dry urban environments. Ultimately, this work not only progresses the theoretical framework of WSUD but also presents a pragmatic blueprint for its application, underscoring the urgent need for its broader adoption to protect urban environments against the escalating challenges of global climate change.

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8 APPENDICES

Appendix A: Expert interviews guideline

Appendix B: Evaluation and Ranking of WSUD technologies

Appendix C: Alexandria urban Analysis and data

Appendix D: Adelaide documents

Appendix A: Interviews Guideline

Expert interviews have been instrumental in gathering nuanced perspectives for this dissertation, particularly drawing on best practices from Adelaide, Australia, and a case study in Alexandria, Egypt. Additionally, general interviews with researchers and practitioners provided essential information on specific topics and projects supporting the research. The insights gained from these experts were pivotal in constructing and validating the conceptual framework and ensuring the practical applicability of the proposed solutions. The interdisciplinary nature of the WSUD topic necessitated interviews experts from diverse fields in diverse urban planning, water management, and environmental sustainability.

The interdisciplinary nature of WSUD necessitated engaging experts from diverse fields and disciplines. To ensure comprehensive coverage, interviews were conducted across a wide range of sectors, encompassing city authorities, academic institutions, consultants, and professionals. Therefore, the interviews were generally open-ended, with questions tailored to each interview according to the specific field and the expertise of the interviewee.

Interviews conducted in Adelaide:

Interviews in Adelaide were conducted with experts from both public and private organizations actively engaged in various facets of WSUD planning and implementation. Many of these experts were identified during the 5th Water Sensitive Cities Conference (South Australia), held online from March 15–18, 2021, organized by the Cooperative Research Centre for Water Sensitive Cities (CRCWSC). Additional experts were recommended by initial contacts or identified through online searches. The interview design aimed to leverage their extensive experience in adopting WSUD, focusing on the challenges and opportunities associated with implementing this approach in a hot and dry climate. The interviews were conducted online and recorded with the interviewees' permission for the purpose of this dissertation.

Interview Partners:

Robin Allison	Founding Director of DesignFlow, a specialist water sensitive urban design consultancy based in in SA - robin@designflow.net.au Online interview: May 11, 2021
Bruce Naumann	Manager Salisbury Water at the City of Salisbury, Adelaide - bnaumann@salisbury.sa.gov.au Online interview: June 11, 2021
John Awad	Research Fellow at The University of South Australia in the areas of water treatment and WSUD- John.Awad@unisa.edu.au Online interview July 6, 2021
Stephanie Rogers	Landscape architect at Outerspace Landscape Architects, and former Design + Strategy at Adelaide City Council - stephanie.r@outerspacestudios.com.au Online interview: March 22, 2023

Interviews conducted in Alexandria:

The WSUD concept is relatively new and less familiar among experts in Alexandria. Therefore, a different approach was required for the interview design. The semi-structured interview questions were aiming to collect information on the discipline or sector of the interviewee's expertise. These questions can be divided to four main themes:

- Understanding the Current Situation: Gathering insights on the existing conditions and solutions implemented in the context of the interviewee's expertise.
- Introducing WSUD Concepts and solicit feedback: Providing an overview of WSUD technologies using WSUD Cards as a communication tool to demonstrate various technologies and their functions. This part aimed to elicit technical considerations and assess the suitability of these technologies for the city's context.
- Future Expectations and Potentials: Exploring the interviewees' perspectives on prospects and potential developments of their discipline or sector related to WSUD in Alexandria.
- Additionally, the interviews were a good chance to acquire available data needed for the research, and to further identify potential interviewees.

The interviews were conducted in person during a field research stay in Alexandria in September 2022. Other interviews were conducted online and per phone earlier in January of the same year. These interviews were not recorded due to various reasons, including the comfort and preferences of the interviewees and setting considerations. Instead, detailed notes were taken during each interview to ensure that all relevant information and insights were accurately captured. This approach facilitated open and unreserved discussions, allowing interviewees to freely share their views and expertise.

The network of selected organizations for interviews were meant to cover various public and private sectors involved in the urban development and water management aspects, including Local administrations, water and sanitation company, academics in universities, in addition to consultants and experts in the fields of geotechnical, landscaping and public green space management.

Interview Partners:

Wafaa Bassily and Amira Elkholy	Head of planning Sector at Alexandria Drainage and Sanitation Company (ADSCO) - wafaa_bassily@yahoo.com Master Plan Manager, Planning Sector at Alexandria Drainage and Sanitation Company (ADSCO) - amira.elkholy@gmail,com Personal interview: September 15, 2022
Tariq Al-Qai'i	former Chairman of the Alexandria Municipal Council and Landscaping professor at Alexandria University. Personal interview: September 13, 2022
Fathi Abd Rabbo and Zaki Mahmoud	partners at Fathi Abd Rabbo Consulting Bureau (FACB) - www.facbegypt.com, and professors in Structural Engineering Department, Alexandria University. Personal interview: September 15,20, 2022

Ahmed Elkhawalka	Horema Geotechnical and Soil Engineering Services - www.horema.net Personal interview: September 5, 2022
Mohamed Elaraby	Director of landscaping at HEADS consultancy Personal interview: September 22, 2022
Osama Elbaz	Independent expert of landscape irrigation networks Personal interview: September 8, 2022
Hosny Salem	landscaping expert and general manager of Green Oasis Nursery - hosny.salem@yahoo.com Personal interview: September 6, 2022
Emad Said	Head of Construction maintenance Department at The Library of Alexandria - emad.aly@bibalex.org Personal interview: September 20, 2022
Tamer Gado	Professor at Tanta University with focus on estimation of extreme hydrologic events and rainfall frequency analysis using satellite precipitation products - tamer.gado@f-eng.tanta.edu.eg Online interview: January 8, 2022
Walid Elabarki	Professor of sanitation at department, faculty of engineering, Alexandria University Phone interview: January 9, 2022

General interviews:

Shelley Shepherd	Program Manager New WAter Ways and Director Urbaqua, Perth, Australia - shelley@urbaqua.org.au Phone interview: July 27, 2020
Forrest Kelley	PE Regulatory Division Manager at Capitol Region- Watershed District (CRWD) - fkelley@capitolregionwd.org Online interview: March 7, 2023, for the Metro Green Line project, Minnesota, USA
Ahmed Mustafa	Senior Research Fellow in Urban Flood Modeling at Urban Systems Lab, New York, USA - amustafa@newschool.edu Online interview: November 8, 2021

WSUD Communication Cards:

RAIN GARDEN

(also known as biofiltration systems and rain gardens) are excavated basins or trenches that are filled with porous filter media and planted with vegetation.

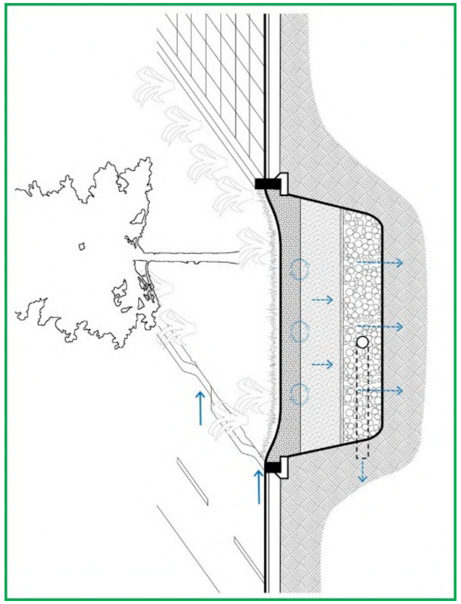
Function:

- Reduce runoff volume & peak flow rate
- Treatment runoff & remove nutrients
- Retain rainwater to support greenery

Can be used in:

- Basin
- Swale
- Tree pit
- Street side planter
- Street median

Rain garden draining street runoff at Garden and Magnolia Sts. ©Ron Kleinknecht, www.whatcomwatch.org



SWALE

Shallow vegetated channels used to store and/or convey runoff and remove pollutants. They convey the runoff to the next stage of the treatment train and can promote infiltration as well.

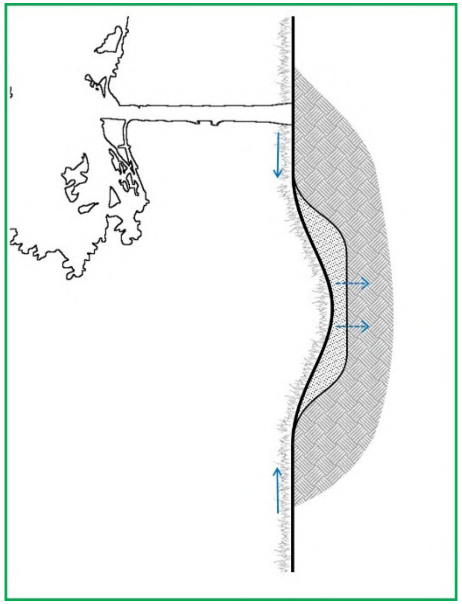
Function:

- Reduce runoff volume & peak flow rate
- Treatment runoff & remove nutrients
- Store or convey runoff

Can be used in:

- Parking lots
- Road sides
- Parks
- Residential

Swale in Mangawhai, New Zealand ©www.kaipara.govt.nz



PERVIOUS PAVING

Surfaces of spaced blocks that allow to infiltrate stormwater through the surface into underlaying layer where water can be stored before infiltration into soil, reused, or discharged to drainage system.

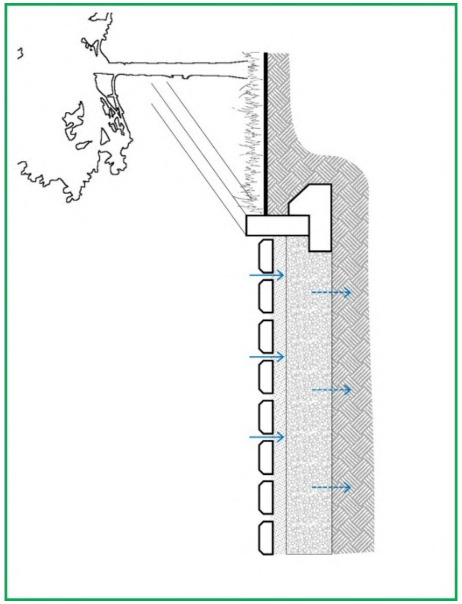
Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater

Can be used in:

- Parking lots
- Sidewalks
- Driveways
- Plazas

© www.containtherainjoco.com



INFILTRATION TRENCH

Shallow stone filled trench with or without inlet that receives stormwater runoff from adjacent impermeable surface prior to infiltration into the soil.

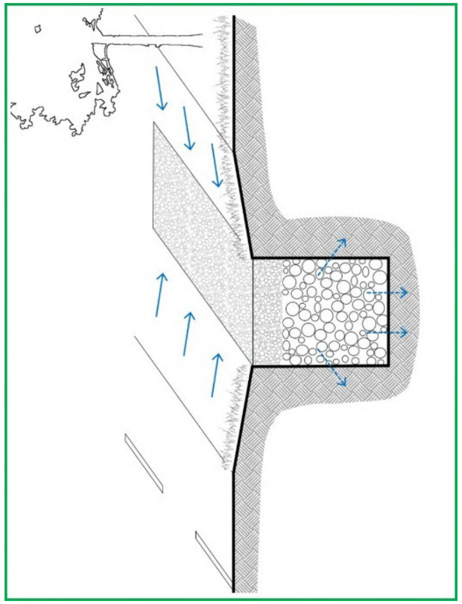
Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater

Can be used in:

- Parking lots
- Sidewalks
- Driveways
- Plazas

© www.sustainablestormwater.org



GEOCELLULAR SYSTEM

Underground modular system holds rainwater surface water runoff prior to infiltration into the soil, or as storage tank for non potable uses .

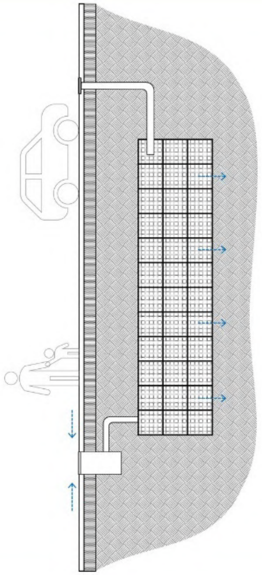
Can be used:

- Parking lots
- Plazas
- Sport fields
- Open spaces

Function:

- Reduce runoff volume & peak flow rate
- Store rainwater for non-potable uses

© www.allesgruen.com



INFILTRATION BASIN

Shallow basin with no outlet that receives stormwater runoff from adjacent impermeable surface prior to infiltration into the soil.

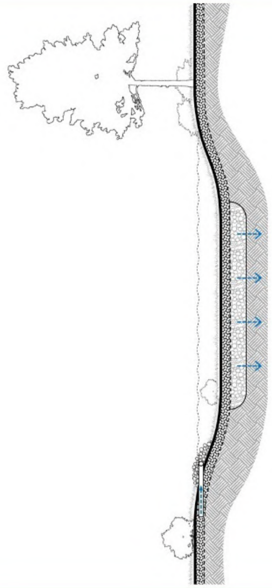
Can be used in:

- Parks
- Road sides
- Communal spaces
- Open spaces

Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater

Infiltration Basin at Anawan Street, Massachusetts, USA ©MassDOT, www.flicker.com



WETLAND

Shalow basin incorporate both ponded water and aquatic vegetation that use enhanced sedimentation, fine filtration and biological uptake processes to remove pollutants from runoff.

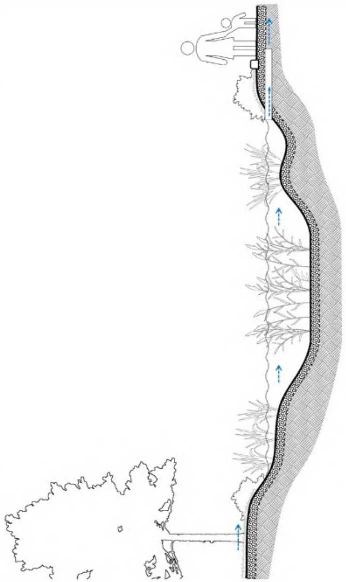
Can be used:

- Parks
- Waste water treatment facilities
- Communal spaces

Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater
- Retain rainwater to support greenery

Cooke-Reserve wetland, South Australia ©DesignFlow



GREYWATER WETLAND

Subsurface flow treatment system composed of a shallow basin filled with water, a substrate material (mostly gravel or sand) and planted with vascular plants.

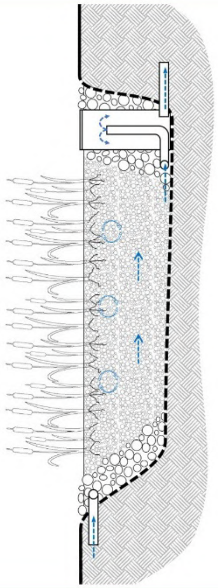
Can be used:

- Waste water treatment facilities
- Communal spaces

Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater
- Retain rainwater to support greenery

Wetland at Kendeda Building, Atlanta, Georgia ©www.ise.gatech.edu



GREEN ROOF

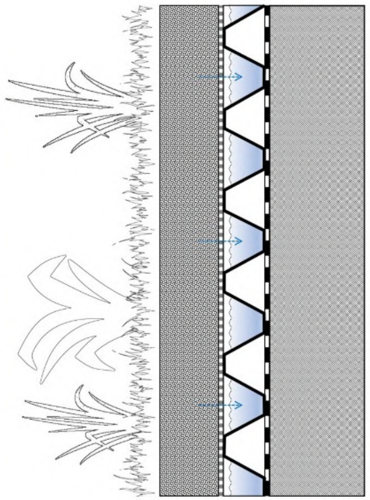
Green roofs are a series of layers consisting of living vegetation growing in substrate over a drainage layer on top of built structures

Can be used in:

- Roof tops
- Underground car parking
- Bus and tram stations

Function:

- Reduce runoff volume & peak flow rate
- Remove pollutants & treat stormwater
- Retain rainwater to support greenery



RAINWATER TANK

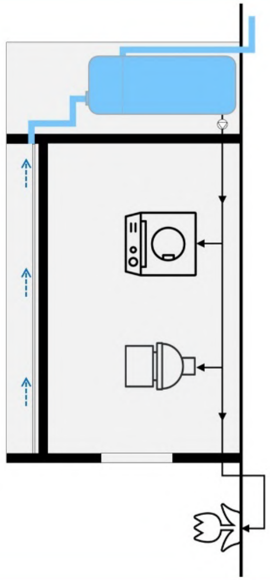
Rainwater tanks can capture and store stormwater collected from rooftops that can be used for commercial, industrial and domestic non potable uses.

Can be used in:

- Under ground
- Above ground
- Communal spaces

Function:

- Reduce runoff volume & peak flow rate
- Store rainwater for non-potable uses



Appendix B: Evaluation and Ranking of WSUD technologies.

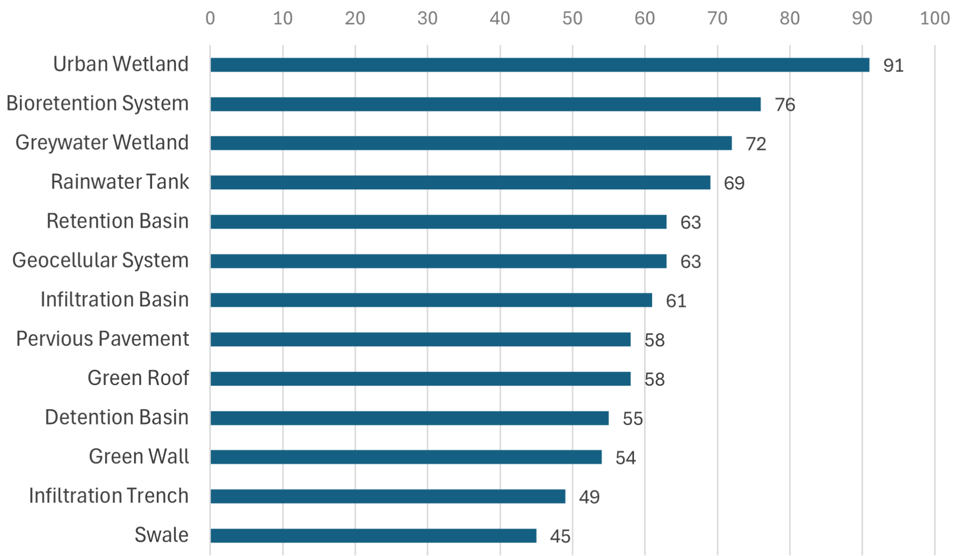
1- Experts' evaluation of WSUD technologies

	Runoff Flow Rate Reduction					Runoff Volume Reduction					Runoff Filtration/Quality					Stormwater Storage					Greywater Treatment					Greywater Treatment					Sizing Flexibility				
	D	R	Q	H	G	D	R	Q	H	G	D	R	Q	H	G	D	R	Q	H	G	D	R	Q	H	G	D	R	Q	H	G	D	R	Q	H	G
Pervious Pavement	30	30	30	0	100	30	30	60	30	100	30	30	30	0	100	0	0	0	0	100	0	0	0	0	-	0	30	30	30	30	30	100	100	60	100
Infiltration Trench	60	100	60	60	30	60	100	30	100	60	60	30	100	100	100	30	60	30	60	60	30	30	0	30	-	30	30	30	60	30	100	60	60	100	100
Geocellular System	60	100	30	60	60	60	100	100	60	60	30	0	0	30	0	60	100	100	60	100	0	30	0	0	-	0	0	0	0	-	100	100	100	100	100
Infiltration Basin	100	100	60	60	60	100	100	60	100	30	60	60	30	30	60	60	100	100	30	30	30	60	0	0	-	30	60	60	0	-	100	60	100	100	30
Bioretention	60	60	60	60	100	60	60	60	100	100	60	100	60	100	100	60	60	30	100	100	60	60	0	60	-	60	60	60	100	60	100	100	30	60	60
Swale	30	60	100	60	60	30	60	60	100	60	60	100	60	60	100	30	60	30	60	60	30	60	0	0	-	30	60	60	60	60	100	60	30	60	100
Urban Wetland	100	100	0	60	100	100	100	0	100	60	100	100	0	100	100	60	100	100	100	100	100	60	0	60	-	100	100	100	100	60	60	60	60	60	30
Greywater Wetland	60	60	30	0	100	60	30	30	60	60	100	100	100	100	100	60	30	30	30	30	100	100	100	60	-	60	60	100	100	60	100	60	60	30	30
Detention Basin	100	60	100	100	100	100	30	100	30	60	30	30	30	30	100	30	30	100	30	30	30	0	0	0	-	30	30	0	30	30	30	60	60	0	30
Retention Basin	60	100	100	100	100	60	100	100	60	100	60	100	60	30	100	60	100	100	30	100	60	60	0	30	-	60	60	60	30	30	30	60	60	60	30
Green Roof	60	60	100	60	60	60	60	100	60	100	60	30	30	60	100	30	60	30	60	30	60	30	0	0	-	100	30	60	60	60	60	100	30	100	100
Green Wall	30	30	0	0	-	30	30	0	30	-	30	30	0	30	-	30	30	0	30	-	30	60	0	0	-	60	100	100	100	-	60	100	30	100	-
Rainwater tank	60	100	100	100	60	60	100	100	60	100	30	30	0	60	30	100	100	100	60	60	0	0	0	0	-	0	0	0	60	30	60	100	100	100	100

D:	Prof. Dr.-Ing. Wolfgang Dickhaut	Umweltgerechte Stadt- und Infrastrukturplanung, HafenCity Universität Hamburg	wolfgang.dickhaut@hcu-hamburg.de
H:	Dipl.-Ing. Sven Hübner,	bgmr Landschaftsarchitekten GmbH	huebner@bgmr.de
R:	Dr. Michael Richter	Geoökologe at HafenCity Universität Hamburg (HCU)	michael.richter@hcu-hamburg.de
Q:	Dipl.-Ing.Justus Quanz	M.Sc. Justus Alexander Quanz, Ministry for Environment Climate Energy and Agriculture Hamburg, Department of Landscape Planning and Urban Greenery	j.quanz@posteo.de
G:	Average scores were estimated based on evaluations retrieved from several technical manuals, guidelines and literature.	WSUD - Greater Adelaide Region Technical Manual	(SA Govt, 2010)
		Water Sensitive Urban Design Approaches and Their Description	(Alan Hoban, 2019)
		CIRIA SuDS Manual	(CIRIA, 2016)
		Low Impact Development Manual for Southern California	(LID Center, 2010)
		Performance of low-impact development best management practices: a critical review	(Hager et al., 2019)
		Combining Green-Blue-Grey Infrastructure for Flood Mitigation and Enhancement of Co-Benefits	(Alves Beloqui, 2020)
		Permavoid Technical Manual	(Polypipe, 2016)
		Low-Impact Development: An Innovative Alternative Approach to Stormwater Management	(Coffman et al., 2000)
		Quality issues in harvested rainwater in arid and semi-arid Loess Plateau of northern China	(Zhu et al., 2004)
		Low Impact Development: Design Guide for Saskatoon	(Saskatoon, 2016)

2- Final scoring and hierarchy

	Criteria & Weighting	Runoff Volume Reduction	Runoff Volume Reduction	Runoff Filtration	Stormwater Storage	Stormwater Storage	Greywater Treatment	Sizing Flexibility	Total
		20%	20%	20%	20%	10%	5%	5%	100%
WSUD Technologies	Pervious Pavement	100	60	60	30	0	60	100	**58**
	Infiltration Trench	60	60	60	30	0	30	100	**48.5**
	Geocellular System	100	60	30	100	0	0	100	**63**
	Infiltration Basin	100	100	60	30	0	30	30	**61**
	Bioretention	60	60	100	60	100	100	100	**76**
	Swale	60	60	60	30	0	30	30	**45**
	Urban Wetland	100	100	100	100	60	100	0	**91**
	Greywater Wetland	60	60	100	60	100	60	60	**72**
	Detention Basin	100	100	30	30	0	30	30	**55**
	Retention Basin	100	100	30	60	0	60	30	**62.5**
	Green Roof	60	60	100	30	0	60	100	**58**
	Green Wall	30	30	100	30	60	100	100	**54**
	Rainwater Tank	100	100	30	100	0	0	60	**69**



Appendix C: Alexandria analysis

1- Record of Annual rainfall from 2012 to 2024 (*Alexandria Rain*, 2023)

Year	**Rain gauge** (mm)	
	East station	West station
2012-13	292	-
2013-14	160	-
2014-15	228	-
2015-16	451	-
2016-17	257	-
2017-18	148	-
2018-19	448	-
2019-20	573	-
2020-21	450	394
2021-22	392	539
2022-23	290	395
2023-24	355	372
Average	**346 mm**	

2- Record of rainfall events and accumulative in (mm) from each east and west rain gauge stations during rainy season 2022-23 (*Alexandria Rain*, 2023)

Date	17/10/2022	19/10/2022	21/10/2022	23/10/2022	02/11/2022	08/11/2022	09/11/2022	12/11/2022	13/11/2022	16/11/2022	17/11/2022	22/11/2022	23/12/2022	25/12/2022	31/12/2022	02/01/2023	04/01/2023	08/01/2023	09/01/2023	12/01/2023	13/01/2023
Esat station	0	0	10	0	0	0	0	0	0	5	0	3	5	14	0	8	4	12	5	50	17
West station	5	17	5	2	2	2	3	3	5	5	2	2	4	58	2	3	4	11	13	4	25
Accumulative East St.	0	0	10	10	10	10	10	10	10	15	15	18	23	37	37	45	49	61	66	116	133
Accumulative West St.	6	23	28	30	32	34	37	40	45	50	52	54	58	116	118	121	125	136	149	153	178

Date	14/01/2023	15/01/2023	30/01/2023	31/01/2023	01/02/2023	02/02/2023	03/02/2023	05/02/2023	06/02/2023	07/02/2023	11/02/2023	12/02/2023	13/02/2023	14/02/2023	14/03/2023	18/03/2023	19/03/2023	24/03/2023	12/04/2023	02/06/2023	13/06/2023
Esat station	17	5	6	24	6	5	5	4	2	5	16	8	3	6	5	18	5	0	10	2	5
West station	13	2	19	12	12	8	7	15	6	9	12	17	9	15	8	15	0	2	20	3	13
Accumulative East St.	150	155	161	185	191	196	201	205	207	212	228	236	239	245	250	268	273	273	283	283	**290**
Accumulative West St.	191	193	212	224	236	244	251	266	272	281	293	310	319	334	342	357	357	359	379	382	**395**

3- Summary of return levels for previous studies in Alexandria data. Retrieved from Young (2018)

Annual Maximum

Study		P2 mm	P5 mm	P10 mm	P20 mm	P50 mm	P100 mm
AASTMT and Egis (2011)	LN	26	39	49	59	73	84
AASTMT and Egis (2011)	Expo	24	41	54	67	84	96
Gado (2017)	GEV		38	51		88	109
Awadallah et al. (2017)	LN	26	43	55	69		
Haktanir et al. (2013)	GEV	26	35	45		70	85

Peaks over threshold Methods (POT)

MLE		**31.5**	**43**	**53**	**64**	**80**	**93.6**
Lmoments		32	43	51.7	61	74	84.5

4- Bore holes data:

38 boreholes from Alexandria Sanitary and Drainage Co. (ASDCO)

47 boreholes from General Authority for Educational Buildings (GAEB), retrieved from thesis (Khalil, 2009)

9 boreholes from Fathi Abd Rabbo Consulting Bureau (FACB)

8 boreholes from Horema Geotechnical and Soil Engineering Services

No.	District	Location	Coordinates	Ground water level	Soil	
				m	Type	Depth in m
1	El-Montaza	Ard linen company	31.24898712924916, 29.995417602499042	0.50	FILL/ SILTY SAND	2,0/2,0
2		ElBakatushi School	31.20473610103737З, 30.034335546514992	0.30	SILTY CLAY	11.0
3		Elras Elsoudaa school	31.251266256979275, 30.012943978258125	0.20	FILL/ SILTY CLAY	2,0/18,0
4		El Manshya El Bahria Prep School	31.248858360929916, 30.025881258337446	0.50	SILTY CLAY	8.0
5		Ard Laurent	31.22998871726083, 29.99510657270404	0.65	FILL/ SILTY CLAY	2,0/11,0
6		Khalf elras elsouda	31.24740112293644, 30.011725408900276	0.60	FILL/ SILTY CLAY	2,0/18,0
7		El-Hussainiya School	31.172375238572478, 30.008781964292286	0.90	SILTY CLAY	10.0
8		ElHaramain School	31.279284319998176, 30.02249656672598	0.70	SILTY FINE SAND	5.0
9		Toson School	31.311657586525676, 30.060388180750795	10.00	FILL/SILTY FINE SAND	2,0/8,0
10		Ard cathrine	31.26224109597852, 30.016360191415373	6.00	SILTY MED SAND	10.0
11		Omar Makram School	31.241925199135693, 29.990850960046313	1.10	SILTY CLAY	12.0
12		ElAmrawi School	31.262051327998705, 30.02170875596554	1.00	SILTY SAND/SILTY CLAY	2,0/13,0
13		Al Nabawi Al Mohandes School	31.276721460624774, 30.015695829404756	1.40	SILTY SAND	8.0
14		Islah School	31.259383763420047, 30.0344643802855	0.80	FILL/ SILTY SAND	2,0/5,0
15		Ezbet Mohsen School	31.226086573782357, 30.00064980117656	0.80	FILL/ SILTY CLAY	2,0/6,0
16		Metwally Abu Mustafa School	31.228857246547115, 30.002340034949555	1.00	FILL/SILTY CLAY	2,0/3,0
17		maamora gate	31.284151019336168, 30.02829484893396	0.90	FILL/SILTY CLAY	2,8/10,0
18		train- mandara	31.276968647604058, 30.011346695839126	5.00	MEDIUM SAND	15.0
19		Montaza station	31.282118841135574, 30.020882725933802	2.50	MEDIUM SAND	7.0
20		Toson	31.297301386448375, 30.056704221413653	2.10	SAND	10.0

No.	District	Location	Coordinates	Ground water level	Soil	
					Type	Depth in m
21		Elmontaza	31.287668819244587, 30.023685495409442	6.00	SAND	10.0
22		Aswaq Elsherif	31.27147399996094, 30.00290772388023	2.30	SAND	10.5
23		Elnamoos bridge	31.220435023475687, 29.976394738309633	2.10	FILL/ SILTY CLAY	3,0/7,50
24		Mohamed Nagib ST.	31.255654774829093, 29.98457343868465	3.80	FILL/ SAND	1,5/13,5
25			31.26818962980804, 29.988467933904786	4.50	FILL/ SAND	1,8/13,2
26			31.25839033932199, 29.98090989484975	4.50	FILL/ SAND	1,8/13,2
27			31.262172990044743, 29.984580877817177	4.00	FILL/ SAND	1,75/13,25
28			31.249849967458125, 29.980829602683855	3.70	FILL/ SAND	1,9/13,1
29		Shaarawy St.	31.248009270306124, 29.96774220873505	3.60	FILL/ SAND	1,3/13,7
30			31.254269264998868, 29.973898927476725	3.70	FILL/ SAND	1,6/13,4
31			31.250174386307364, 29.970509484146824	5.20	FILL/ SAND	1,7/13,3
32			31.252800952921376, 29.9730765631324	5.00	FILL/ SAND	1,7/13,3
33	East	Abis1	31.17768386454395, 30.0276414738822	0.50	FILL/SILTY CLAY	2,0/10,0
34		Leisure forest	31.202386647588884, 29.979189852783243	1.20	FILL	5.0
35		Ard Elawayed	31.2230241302968, 29.991950392951765	0.40	FILL	4.0
36		Mahmoud Zaki Salem	31.247465538280807, 29.970193612845296	9.50	FILL/ SILTY SAND	1,0/10,0
37		Tariq bin Ziyad School	31.268451893198176, 30.016626231966164	2.50	FILL/ SILTY SAND	2,0/13,0
38		Abis 10	31.187870850800333, 30.00819404905591	0.50	FILL/ SILTY CLAY	1,0/10,0
39		New Maria co.	31.220482985165702, 29.94737980133855	1.20	SANDY LOAM/SILTY SAND/CLAY	1,0/4,0/5,0
40		American school	31.220438587710976, 29.95195506948147	1.25	FILL/ SILTY SAND	3,5/11,5
41		Mina contracting	31.222032946337357, 29.948950929123992	1.20	COARSE SAND/SILTY SAND	5,4/0,6
42		Fawzy moaaz	31.209316250616844, 29.93424677628507	1.20	FILL/ SILTY CLAY	4,0/6,0
43		Bus station garage	31.219885466809934, 29.9451663705427	1.75	FILL/ SILTY CLAY	5,0/5,0
44		Elnamoos bridge	31.220435023475687, 29.976394738309633	2.10	FILL/ SILTY CLAY	3,0/7,50
45			31.217914950079184, 29.952515209766705	2.70	FILL/ SILTY CLAY	2,0/9,1
46			31.216912873408585, 29.957251147264262	2.70	FILL/ SILTY CLAY	4,0/7,0
47			31.213502233435925, 29.949240678705813	2.70	FILL/ SILTY CLAY	3,0/11,0
48			31.214512550663297, 29.946158346224387	2.70	FILL/ SILTY CLAY	4,0/3,0
49			31.21741716041683, 29.939048623564997	2.70	FILL/ SILTY CLAY	3,0/9,0

No.	District	Location	Coordinates	Ground water level	Soil	
					Type	Depth in m
50			31.213040525910166, 29.941928497130263	2.70	FILL/ SILTY CLAY	5,0/5,0
51			31.210522395192097, 29.947763087701997	2.70	FILL/ SILTY CLAY/ SAND	1,0/4,0/5,0
52	Middle	Abis 1/8	31.127947350316035, 29.961059884012748	1.00	SILTY CLAY	7.0
53		Books storage, prepatory	31.191951098147854, 29.92936165383609	2.75	FILL	9.0
54		Commerce Senior	31.194660354321186, 29.917386666189245	3.80	FILL	11.0
55		Abis 4	31.14689586209681, 29.999685072852067	0.70	SILTY CLAY	14.0
56		Elabassia Elthanawia	31.192464111285627, 29.9130066002333	10.00	FILL	12.0
57		Abis 8	31.12275403704169, 29.94166436832827	1.00	SILTY CLAY	7.0
58		Amr Ibn Al-Aas Primary	31.191553152356157, 29.912798354732683	10.00	FILL	13.0
59		Eliskandrany	31.191158710938396, 29.91231694860366	10.00	FILL	10.0
60		Ard Elwekala	31.203275997369946, 29.936101301592643	3.10	FILL	6.0
61		Nadi Elsaid	31.180377304079023, 29.937503487920974	0.20	FILL/ SILTY CLAY	1,0/7,0
62		El Sawaleh Primary	31.191619966027414, 29.911832974143206	5.20	FILL	7.0
63		Salah El Din Primary	31.189168860842344, 29.9121078716089	5.10	FILL	13.0
64		El Rawda Primary	31.164897424646178, 29.954216722675735	0.90	SILTY CLAY	12.0
65		Moharam Pik Train Station	31.18732994442464, 29.926387260601008	0.70	FILL/ SILTY CLAY	4,60/10,0
66		Al Hadrah qebly	31.19469841560747, 29.940616428339588	0.60	FILL/ SILTY CLAY	2,0/10,0
67		Ibrahimia	31.210218285848857, 29.928840267789194	1.80	FILL	8.0
68		Olympic sport club	31.199752954627826, 29.916857286567016	3.80	FILL/ SILTY SAND	3,0/ 3,0
69		Central station	31.19255969211184, 29.90017280131604	6.80	FILL/ SILTY SAND	1,0/7,0
70		University Building	31.209665611625905, 29.908937821419954	3.60	FILL/ SAND	3,0/7,0
71			31.20997382625052, 29.911373241463544	3.50	FILL/ SAND	4,0/6,0
72			31.210777991234295, 29.91301406635503	7.00	FILL/ SAND	4,0/11,1
73			31.211302093391343, 29.91449045143799	4.00	FILL/ SAND	4,0/11,0
74			31.20853834210149, 29.911683217436842	5.20	FILL/ SAND	6,0/9,0
75			31.206047340632978, 29.90951662643031	5.50	FILL/ SAND	7,0/8,0
76			31.208721369223426, 29.912964522057123	5.10	FILL/ SAND	3,0/12,0
77			31.2093885124754, 29.91702943789421	6.00	FILL/ SAND	11,0/4,0
78			31.210956142037606, 29.919709721133902	5.50	FILL/ SAND	9,8/5,2
79		Cleopatra	31.224951234829383, 29.93586453552952	3.80	FILL/ SAND	1,3/13,7

No.	District	Location	Coordinates	Ground water level	Soil	
					Type	Depth in m
80			31.223150573918335, 29.93351746981366	4.30	FILL/ SAND	1,0/14,0
81		Sporting	31.221200950506482, 29.937383521495697	3.10	FILL/ SAND	2,0/13,0
82			31.218110352117158, 29.932777314906765	3.40	FILL/ SAND	2,2/12,8
83			31.216630503632015, 29.930083356655036	3.50	FILL/ SAND	2,0/13,0
84			31.213980631079195, 29.925503362086154	2.90	FILL/ SAND	3,1/11,9
85			31.21833595068582, 29.938544827286503	3.15	FILL/ SAND	0,7/14,3
86		Canal El souez	31.190180935954782, 29.92659095503882	3.00	FILL	10.0
87			31.189089003843478, 29.923814020941794	2.90	FILL	11.0
88			31.19549153451962, 29.920550992697397	3.00	FILL	10.0
89			31.19434298134264, 29.92242077664086	3.00	FILL	10.0
90			31.188120605183087, 29.921649951213357	2.90	FILL	10.0
91	West	Ikhlas Krantina Complex	31.169067990332397, 29.878890564402667	10	FILL/ SILTY CLAY	3,0/3,0
92		Karantina School Complex	31.168581905478984, 29.877743314359655	10	FILL/ SILTY CLAY	3,0/3,0
93		Abdul Rahman Al Kawakibi School	31.18715451916908, 29.892172987256703	8.70	FILL	10.0
94		Elorouba School	31.162690869258377, 29.86319246426459	10.00	SILTY MED SAND	10.0
95		Elshaheed Ahmed Abdelazis school	31.181412829087545, 29.91269307554746	2.00	FILL	6.0
96		ElMafrozah School	31.17464277200676, 29.876049380732677	10.00	FILL	6.0
97		Kabs Elcoton	31.172475835732207, 29.87900745103659	10.00	FILL/ SAND STONE	4,0/5,0
98		Gate 27 . School	31.176997697710807, 29.87678375446334	10.00	FILL/ SAND STONE	4,0/5,0
99		ElQabbary School	31.179497111615074, 29.880856408423607	4.70	FILL	7.0
100		Kom El Shoqafa School	31.178770621535207, 29.89389842341496	7.40	FILL	12.0
101		Ras El Tin School	31.187760376782443, 29.895451588794696	7.40	FILL	7.0
102		AElMunir B School	31.18835374815083, 29.88571419206028	10.00	FILL	10.0

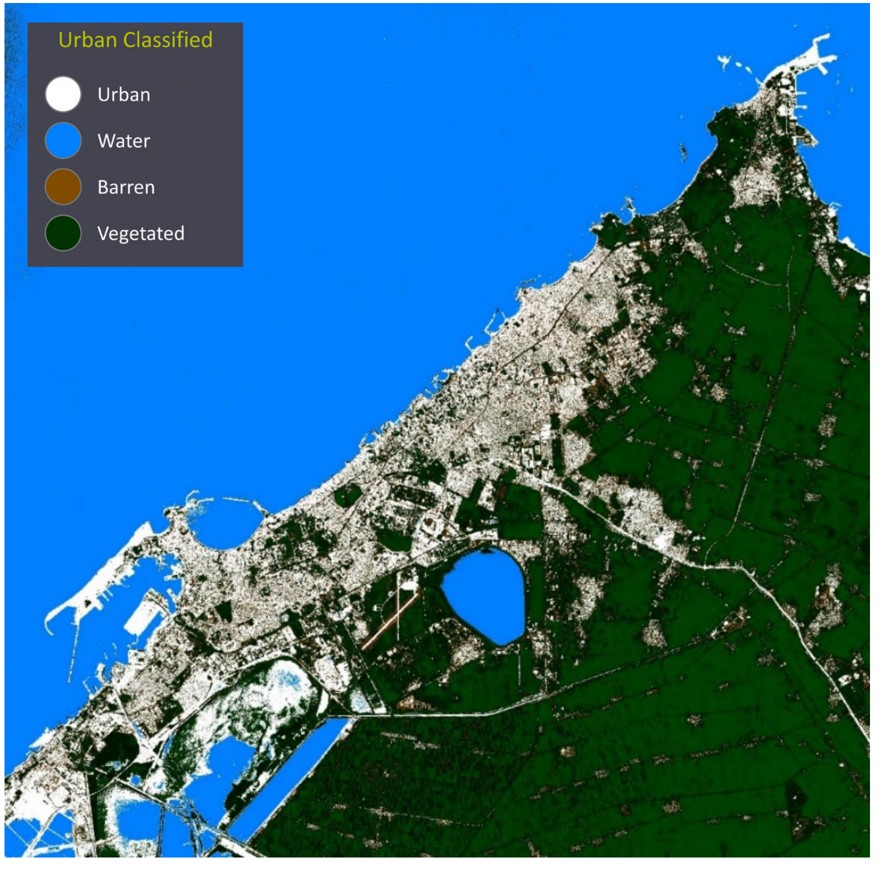
5- Land cover calculations and satellite imageries

Micro-basin	Total area	Land Surface Cover					Urban Green Factor*	Land permeability	Urban Density
		Green cover		Water bodies	Bare land	Built up area			
		Agriculture	Urban Green space						
	km²	km²	km²	km²	km²	km²	0 - 1	%	%
01a	10.16	0.0	1.28	0.01	1.91	6.96	**0.22**	**31%**	**69%**
01b	1.24	0.0	0.22	0.00	0.29	0.73	**0.29**	**41%**	**59%**
02a	4.16	0.0	0.43	0.02	0.60	3.11	**0.18**	**25%**	**75%**
02b	2.95	0.0	0.20	0.02	0.30	2.43	**0.13**	**18%**	**82%**
02c	1.15	0.0	0.08	0.02	0.12	0.93	**0.14**	**19%**	**81%**
02d	13.28	1.34	3.21	0.09	3.94	4.70	**0.48**	**65%**	**39%**
03a	2.88	0.0	0.84	0.00	0.70	1.34	**0.41**	**53%**	**47%**
03b	0.30	0.0	0.03	0.00	0.05	0.22	**0.18**	**27%**	**73%**
03c	1.04	0.0	0.18	0.00	0.23	0.63	**0.28**	**39%**	**61%**
03d	3.22	0.0	0.50	0.00	0.60	2.12	**0.25**	**34%**	**66%**
04a	5.95	0.0	1.28	0.00	1.55	3.12	**0.35**	**48%**	**52%**
04b	4.04	0.0	0.62	0.00	0.85	2.57	**0.26**	**36%**	**64%**
05a	20.98	10.8	1.52	0.00	3.77	4.90	**0.57**	**77%**	**48%**
05b	24.69	3.06	2.68	0.00	5.80	13.15	**0.33**	**47%**	**61%**
05c	5.18	1.51	0.42	0.00	1.09	2.16	**0.42**	**58%**	**59%**
6	0.37	0.0	0.17	0.01	0.15	0.04	**0.69**	**89%**	**11%**
07a	0.84	0.0	0.14	0.00	0.24	0.46	**0.31**	**45%**	**55%**
07b	27.65	6.45	4.29	5.02	6.80	5.09	**0.65**	**82%**	**24%**
07c	2.57	1.14	0.16	0.00	0.57	0.70	**0.53**	**73%**	**49%**
07d	8.61	3.91	0.65	0.00	2.46	1.59	**0.58**	**82%**	**34%**
08a	5.02	0.0	0.56	0.03	1.23	3.20	**0.24**	**36%**	**64%**
08b	2.38	0.0	0.27	0.01	0.66	1.44	**0.26**	**39%**	**61%**
9	3.37	0.0	0.4	0.00	0.83	2.14	**0.24**	**36%**	**64%**

*Surface type	Factor
vegetation (trees, woodland, grassland)	**1**
Wetland or open water	**1**
Agriculture land	**0.8**
Bare land	**0.5**
Sealed surfaces (concrete, asphalt)	**0**

Images are retrieved from the web based earth observer application Sinergise Sentinel Hub EO Browser (EO-Browser, 2022).

- The Urban Classified Sentinel 02 raster with 30 m resolution
- The Green city Sentinel 02 raster with 30 m resolution. The script Uses NDVI to color Sentinel-2 images and create awareness of green areas in cities around the World.



6- Boundarywalls Calculations

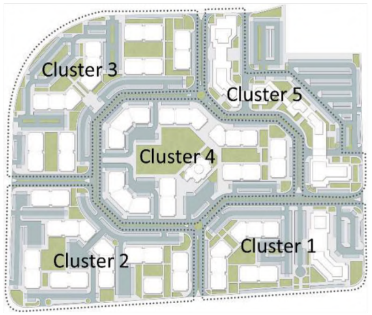
Micro-basin	Total Area	Permeable Area	Walled Total	Walled Permeable
	Km2	Km2	Km2	Km2
01a	10.17	3.21	1.14	0.70
01b	1.25	0.52	0.29	0.21
02a	4.14	1.04	0.39	0.17
02b	2.95	0.52	0.10	0.05
02c	1.15	0.22	0.03	0.01
02d	13.28	8.58	8.10	6.47
03a	2.88	1.54	1.33	0.97
03b	0.30	0.081	0	0
03c	1.03	0.40	0.08	0.06
03d	3.21	1.10	0.07	0.04
04a	5.95	2.83	2.22	1.56
04b	4.03	1.47	1.30	0.51
05a	20.98	16.08	0.40	0.25
05b	24.69	11.54	2.75	1.45
05c	5.18	3.02	0.11	0.07
6	0.36	0.32	0.20	0.14
07a	0.83	0.37	0.14	0.04
07b	27.65	22.6	0.67	0.40
07c	2.57	1.9	0.11	0.03
07d	8.61	7.00	0.11	0.06
08a	5.01	1.82	1.04	0.47
08b	2.37	0.93	0.31	0.07
9	3.36	1.23	0.20	0.07

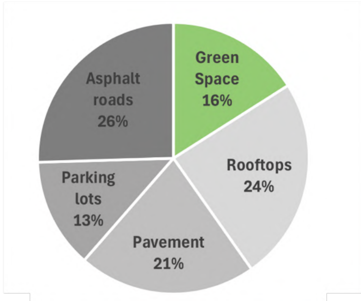
7- Calculation of Scenarios for Site-scale Applications:

Detailed spreadsheet based on the current planned green space

Surface material	Clusters (m^2) 1	2	3	4	5	Roads (m^2)	Total m^2	%
Green Space	5018.22	5973.45	9452.01	8814.49	4043.10	4487.16	37788.43	16%
Rooftops	9070.20	12114.32	11357.10	13972.46	10741.81	-	57255.89	24%
Pavement	8149.49	9657.10	10180.28	12457.21	6098.26	3559.72	50102.05	21%
Parking lots	6002.64	6387.38	7032.78	4551.02	1993.07	4958.80	30925.68	13%
Asphalt roads	4665.64	8508.33	7178.96	4904.49	-	34931.16	60188.57	25%
Total	32906.17	42640.57	45201.13	44699.67	22876.24	47936.85	**236,260.63**	100%

Baseline (Bioretention) material	C	A_{imp}	Scenario 01 (+Permeable pavement) material	C	A_{imp}	Scenario 02 (+Permeable pavement+70% Green Roof) material	C	A_{imp}
Tiles	0.9	51530.30	Tiles	0.9	51530.30	Green Roof	0.5/0.9	35498.65
Tiles	0.9	45091.84	PICP	0.5	25051.02	PICP	0.5	25051.02
Asphalt	0.9	27833.12	PICP	0.5	15462.84	PICP	0.5	15462.84
Asphalt	0.9	54169.72	Asphalt	0.9	54169.72	Asphalt	0.9	54169.72
		178,624.97			**146213.88**			**130182.23**
		76%			62%			55%





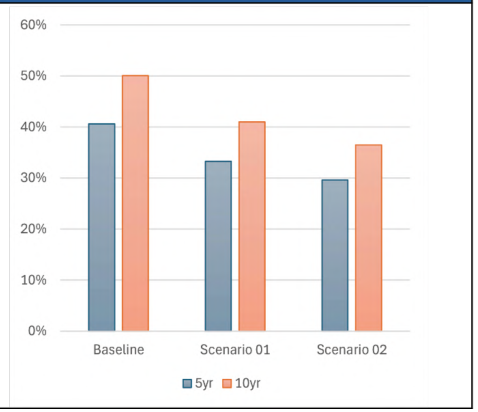
	i	D	d_p	K_f
5yr	26.5 mm/h	2 h	0.2 m	150 mm/hr
10yr	21.5 mm/h			

$$A_p = i \times D \times A_{imp} / [d_p + (K_f \times D)]$$

i = Design storm intensity (m/h)
D = Design storm duration (h)
A_{imp} = Catchment impervious area (m^2)
d_p = Design surface ponding depth (m)
K_f = minimum acceptable saturated hydraulic conductivity of the filter media (m/h)

Required bioretention surface area and ratio from total planned landscape

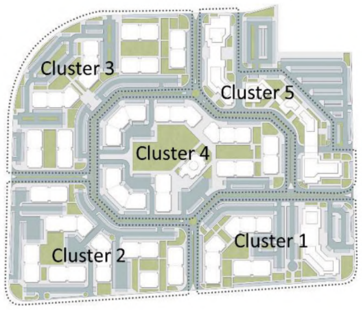
	A_p (5yr) m^2	A_p (5yr) %	A_p (10yr) m^2	A_p (10yr) %
Baseline **178,624.97 m^2**	15361.75	**41%**	18934.25	**50%**
Scenario 01 **146213.88 m^2**	12574.39	**33%**	15498.67	**41%**
Scenario 02 **130182.23 m^2**	11195.67	**30%**	13799.32	**37%**

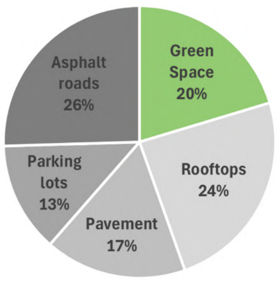


Detailed spreadsheet based on the proposed minimum green space

Surface material	Total	
	m²	%
Green Space	48080.43	20%
Rooftops	57255.89	24%
Pavement	39810.05	17%
Parking lots	30925.68	13%
Asphalt roads	60188.57	25%
	236,260.63	100%

Baseline (Bioretention)			Scenario 01 (+Permeable pavement)			Scenario 02 (+Permeable pavement+70% Green Roof)		
material	C	A_{imp}	material	C	A_{imp}	material	C	A_{imp}
Tiles	0.9	51530.30	Tiles	0.9	51530.30	Green Roof	0.5/0.9	35498.65
Tiles	0.9	35829.04	PICP	0.5	19905.02	PICP	0.5	19905.02
Asphalt	0.9	27833.12	PICP	0.5	15462.84	PICP	0.5	15462.84
Asphalt	0.9	54169.72	Asphalt	0.9	54169.72	Asphalt	0.9	54169.72
		169,362.17			**141067.88**			**125036.23**
		72%			60%			53%





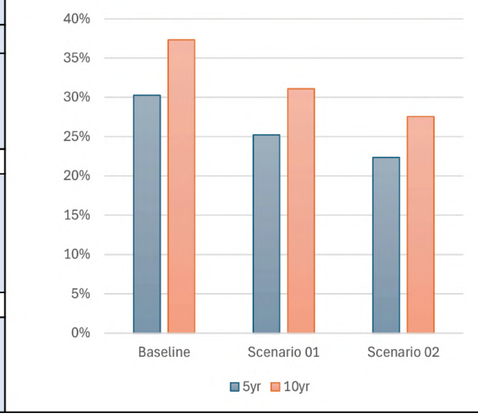
	i	D	d_p	K_f
5yr	26.5 mm/h	2 h	0.2 m	150 mm/hr
10yr	21.5 mm/h			

$$A_p = i \times D \times A_{imp} / [d_p + (K_f \times D)]$$

i = Design storm intensity (m/h)
D = Design storm duration (h)
A_{imp} = Catchment impervious area (m²)
d_p = Design surface ponding depth (m)
K_f = minimum acceptable saturated hydraulic conductivity of the filter media (m/h)

Required bioretention surface area and ratio from total planned landscape

	A_p (5yr)		A_p (10yr)	
	m²	%	m²	%
Baseline **169,362.17** m²	14565.15	**30%**	17952.39	**37%**
Scenario 01 **141067.88** m²	12131.84	**25%**	14953.2	**31%**
Scenario 02 **125036.23** m²	10753.12	**22%**	13253.84	**28%**



Appendix D: Adelaide documents

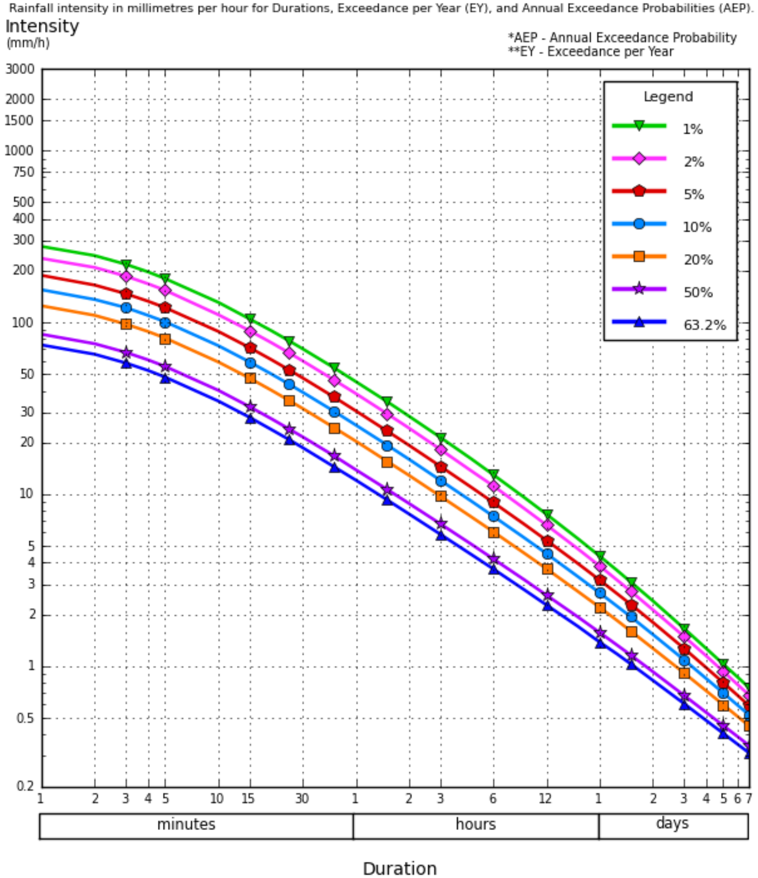
Figure 1.1

Nearest grid cell Latitude: 34.8375 (S) Longitude: 138.5875 (E)

IFD Design Rainfall Intensity (mm/h)

Issued: 18 May 2022

Rainfall intensity in millimetres per hour for Durations, Exceedance per Year (EY), and Annual Exceedance Probabilities (AEP).

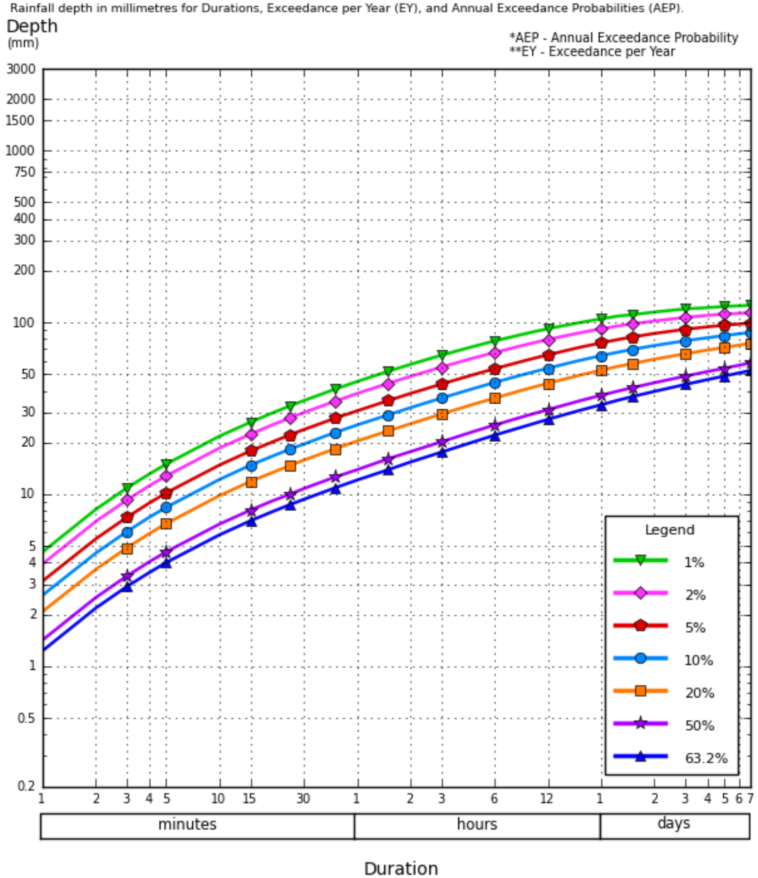


Nearest grid cell Latitude: 34.8375 (S) Longitude: 138.5875 (E)

IFD Design Rainfall Depth (mm)

Issued: 18 May 2022

Rainfall depth in millimetres for Durations, Exceedance per Year (EY), and Annual Exceedance Probabilities (AEP).



9 GLOSSARY

Algal blooms – A rapid increase in the population of algae in an aquatic system, typically visible as a green, yellow, brown, or red film on the surface. These blooms can be harmful due to the production of toxins or by depleting oxygen in the water.

Average recurrence interval – The average time interval between events of a certain magnitude, such as floods. It represents the average time between occurrences of a specified event.

Aquifer – A geological formation capable of storing and transmitting significant quantities of water. Aquifers are critical sources of groundwater.

Brownfield – A property previously used for industrial or commercial purposes and potentially contaminated by hazardous substances, complicating its redevelopment or reuse.

Combined Sewer Overflows – Events where untreated municipal wastewater and stormwater are discharged into a body of water from a combined sewer system due to excess volume exceeding the treatment capacity, typically during heavy rainfall.

Urban catchment – An area within an urban environment where water from rain converges to a single point at a lower elevation, typically flowing into a storm drain, sewer system, or natural body of water. Unlike natural catchments, urban catchments are significantly influenced by human activities and urban infrastructure.

Effluent – The water or wastewater outflow that is discharged into a natural body of water. Effluent can originate from a variety of sources, including industrial, commercial, and residential sewage treatment.

Evapotranspiration – The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

Greywater – Relatively clean wastewater from domestic activities such as laundry, hand basin, and bathing, which can be recycled on-site for uses like landscape irrigation and constructed wetlands.

Infill development – The practice of developing vacant or under-used land plots within existing urban areas that are already largely developed.

Passive irrigation – A sustainable landscaping technique that utilizes natural precipitation and landscape design to water plants without the need for mechanical irrigation systems.

Relevance ranking – In the context of information retrieval systems, this refers to the process of sorting or ordering search results or data sets according to their perceived relevance to a user's query.

Runoff – The portion of precipitation that flows over the land surface and is not absorbed into the soil.

Sediment – Particles of organic or inorganic matter that accumulate in a loose, unconsolidated form. Sediments are typically deposited by air, wind, and water flow.

Secondary Treatment – A wastewater treatment process that removes dissolved and suspended biological matter using biological processes, typically involving aeration and microbial action, following primary treatment.

Tertiary Treatment – An advanced water treatment process following primary and secondary treatment, aimed at removing remaining contaminants. This stage improves water quality to meet specific standards for discharge or reuse.

Tree Canopy Cover – The proportion of an area's ground surface covered by the vertical projection of tree canopies, expressed as a percentage. It is an indicator of urban forestry density and environmental quality.

Urban Form – The spatial layout and structure of an urban area, including the arrangement of buildings, roads, public spaces and key services such as transport.

Urban Drainage – The process and infrastructure involved in the collection, transportation, and disposal or treatment of rainwater and surface runoff in urban environments. Urban drainage systems are designed to manage water flow, prevent flooding, and reduce the impact of contaminants in residential, commercial, and industrial areas.

Urban Heat Island Effect – A phenomenon where urban areas experience higher temperatures than their rural surroundings due to human activities, resulting in a microclimate that is significantly warmer. This effect is primarily caused by the modification of land surfaces and waste heat generated by energy usage.