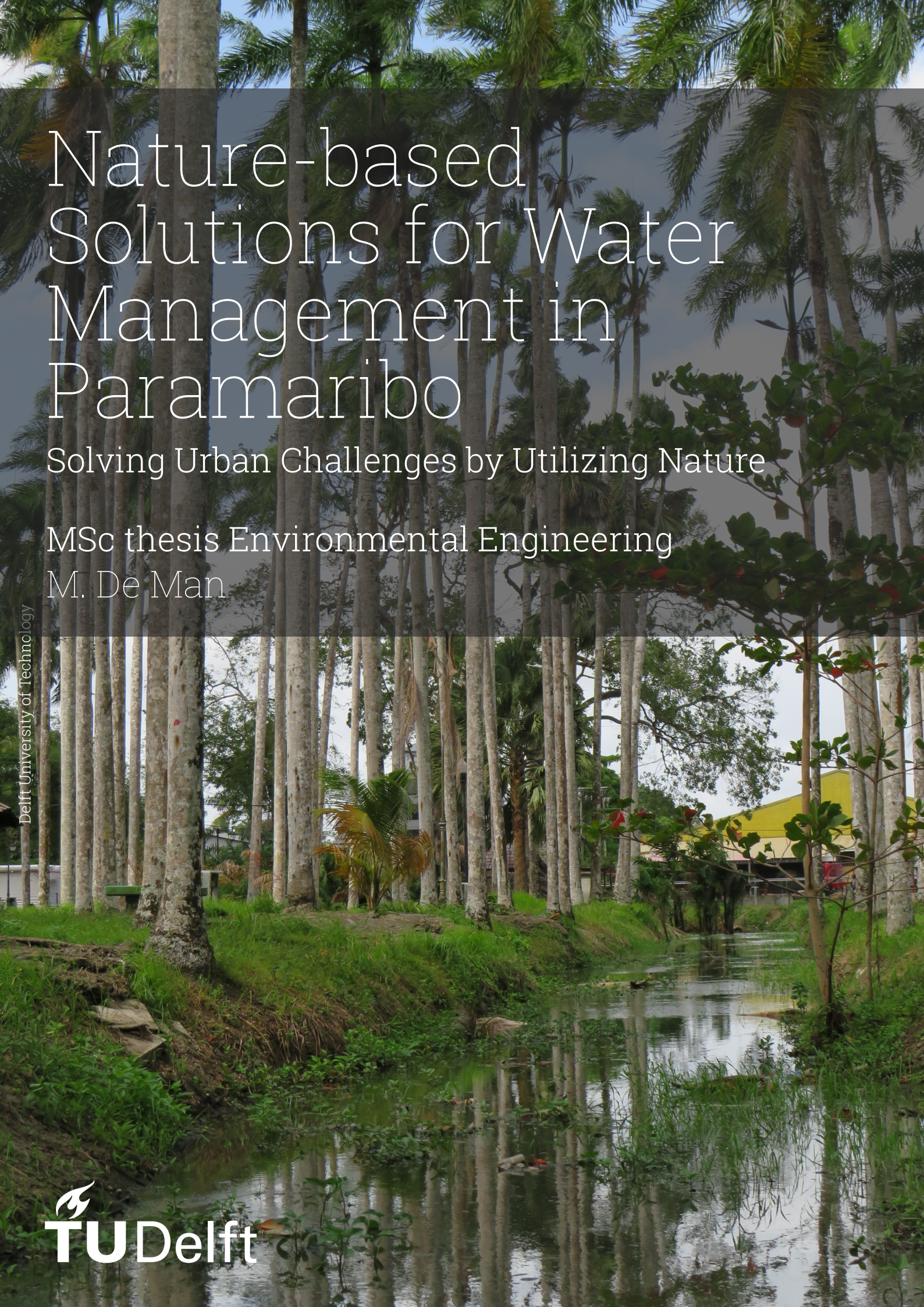

Nature-based Solutions for Water Management in Paramaribo

Solving Urban Challenges by Utilizing Nature

MSc thesis Environmental Engineering

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Solving Urban Challenges by Utilizing Nature

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Preface

This thesis marks the culmination of my journey as a Master's student in Environmental Engineering at Delft University of Technology. The research presented here reflects my passion for developing sustainable and resilient solutions for urban water management. By focusing on Nature-based Solutions (NbS) in Paramaribo, Suriname, this work blends my academic interests with a strong commitment to addressing real-world environmental challenges.

I am grateful to my supervisors, Dr. Ir. J.A. Van der Werf and Dr. E. Mostert, for their guidance, support, and insightful feedback throughout this process. Job's collaborative and encouraging approach made this project feel like a team effort, which added a special dimension to the whole experience. I am also deeply thankful to Ir. N. Sardjoe and Dr. Ir. F.C. Boogaard from Deltares, whose dedication to positive change in water management has truly been an inspiration for me as a student.

A special thanks goes to the dedicated individuals from the Ministry of Public Works in Suriname and AdeKUS, Daan, Roel, Lorenso, Ginny, Jan-Willem, Martijn, as well as to all the other people I had the pleasure of meeting over the past year in Paramaribo. Their generosity in sharing their time, knowledge, and perspectives has greatly enriched not only this study but also my personal and professional growth, making this journey an unforgettable experience.

Max de Man
Delft, August 2024

Summary

This thesis investigates the potential of Nature-based Solutions (NbS) to address urban water management challenges in Paramaribo, Suriname. The city, characterized by intense rainfall and inadequate drainage infrastructure, frequently faces significant flooding, highlighting the urgent need for sustainable and resilient solutions. The research focuses on the applicability of NbS as an alternative to traditional grey infrastructure, particularly in the context of rapidly urbanizing tropical environments, where such solutions are still relatively unexplored.

Paramaribo faces a range of urban water management challenges, including high surface runoff and socio-economic impacts from frequent flooding. These issues are exacerbated by rapid urbanization, leading to extensive soil sealing that reduces the natural capacity for water infiltration. Against this backdrop, the thesis explores the potential of NbS as a promising but underutilized solution, particularly in tropical settings where existing literature on this topic is sparse. The study emphasizes that small-scale investigations, such as this one, can be critical in addressing the gap between theoretical research and practical implementation.

The literature review discusses various types of NbS, such as green roofs, bioswales, and permeable pavements, highlighting their potential benefits, including runoff reduction, water quality improvement, and biodiversity enhancement. However, in the context of Paramaribo, these co-benefits work differently.

The research focuses on a study area around Wakapasi in Paramaribo, using it as a small-scale case study to explore broader urban challenges. The selection of a smaller study area allows for detailed investigation, offering valuable insights into the effective implementation of NbS in similar contexts. The study acknowledges that while NbS holds promise, the challenges of ensuring their effectiveness in tropical environments must be critically examined.

Methodologically, the study employs a Multi-Criteria Analysis (MCA) to evaluate different NbS options based on effectiveness, cost, and social acceptability. Semi-structured interviews with local stakeholders and think-tank discussions emphasize the importance of local knowledge and institutional support, advocating for a bottom-up, participative approach to climate adaptation. The full-scale bioswale tests at AdeKUS provide empirical data, but the results are presented with critical nuance. While the bioswale tests did not show an emptying time of less than 24 hours, which is typically desirable to avoid standing water, the tests did not attract mosquitoes or pests. Additionally, the potential for preferential flow due to vegetation growth is noted, which could significantly increase infiltration rates over time, potentially by tenfold, once native vegetation fully establishes.

The results offer a mixed assessment of the potential for NbS in Paramaribo. On one hand, the bioswale tests demonstrate tangible measures that can be integrated into urban landscapes, providing proof of efficacy within a clearly defined context. The study also provides a clear description of the conditions under which NbS designs should be implemented based on the context of the region, offering practical guidance for future projects. However, the research also highlights the limitations and challenges, particularly in achieving rapid infiltration rates in combination with heavy rainfall and the uncertainties associated with long-term performance.

The study concludes by reflecting on the broader implications for urban water management in Paramaribo and similar tropical environments. The findings suggest that NbS could play a significant role in enhancing urban resilience, but their success depends on careful design, robust stakeholder engagement, and adaptive management strategies and the potential effects need to be researched further. The thesis emphasizes the potential for a bottom-up implementation strategy, where local involvement and incremental, evidence-based approaches guide the deployment of NbS. However, it also underscores the importance of remaining critical about the efficacy of these solutions, as the success of NbS is not guaranteed and must be rigorously tested and adapted to local conditions.

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Nomenclature

Terminology

Term	Definition
Asset management	The systematic process of operating, maintaining, and upgrading infrastructure assets cost-effectively.
Black water	Wastewater from toilets containing human waste.
Co-benefits	Additional positive outcomes from a policy or project, beyond the primary goal, such as improved air quality from a green infrastructure project.
Co-creation	A process involving multiple stakeholders, including the public, in the design and implementation of solutions or projects.
Developing country	A nation with a lower level of industrialization, lower standard of living, and lower Human Development Index (HDI) as defined by the World Bank and HDI metrics.
Full-scale test	A comprehensive test of a system under real-world conditions and in full-size to assess its performance and feasibility.
Grey infrastructure	Man-made structures like dams and concrete channels used for water management in flood control.
Grey water	Wastewater from sinks, showers, and laundry that doesn't contain human waste.
Green infrastructure	Natural or nature-based solutions for managing water, such as wetlands and green roofs, aimed at reducing flooding, improving water quality, and enhancing biodiversity.
Measure	A specific action or strategy implemented to achieve a desired outcome, such as reducing flood risk.
Permeability	The ability of a material or soil to allow water to pass through it.
Return period	The average time interval between occurrences of a specific event, such as a flood or rainfall event.
Septic tank	Underground settling tank for treating household sewage, separating solids from liquids before disposal.
Soil sealing	The covering of the ground with impermeable materials like concrete and asphalt, preventing water infiltration.
Think-tank	An organization or group dedicated to research and advocacy in areas such as policy, economics, and social issues.
Wadi	Dutch term for bioswale, derived from the Arabic word for riverbed.
Durotank	Cylindrical (water) tank made of plastic, used for rain or drinking water storage.

Abbreviations

Abbreviation	Definition
CC	Climate Change
CRC-Tool	Climate Resilient Cities Toolbox
DEM	Digital Elevation Map
GCMs	Global Circulation Models
GrnI	Green Infrastructures
NbS	Nature-based Solutions
PI	Power-Interest
RCP	Representative Concentration Pathways
RH	Relative Humidity
SLR	Sea Level Rise
SuDS	Sustainable Drainage Systems
WSUD	Water Sensitive Urban Design
	Alternative terms for NbS
BMPs	Best Management Practices
LIDs	Low Impact Developments
SuDS	Sustainable Drainage Systems
WSUD	Water Sensitive Urban Design
	Types of NbS
BP	Bioretention Ponds
BS	Bioswales
CW	Constructed Wetlands
GR	Green Roofs
GW	Green Walls
PP	Permeable Pavements
RG	Rain Gardens
TP	Tree Pits

Organizations

Abbreviation	Definition in Dutch	Definition in English
AdeKUS	Anton de Kom Universiteit van Suriname	Anton de Kom University of Suriname
BuZa	Ministerie van Buitenlandse Zaken	Ministry of Foreign Affairs of the Netherlands
GoS	Surinaamse Overheid	Government of Suriname
NCCR	Nationaal Coördinatie Centrum Rampenbeheersing	National Coordination Center for Disaster Management
OW	Ministerie van Openbare Werken	Ministry of Public Works of Suriname
PTC	Polytechnisch College	Polytechnic College
ROM	Ministerie van Ruimtelijke Ordening en Milieu	Spatial Planning and Environment
SWM	Surinaamsche Waterleiding Maatschappij	Suriname Water Supply Company
TU Delft	Technische Universiteit Delft	Delft University of Technology

1 Introduction

Reading Guide *This chapter begins with an overview of the significant challenges that urban environments face concerning water management, emphasizing the dual issues of flooding and droughts in Section 1.1. Following this, the focus shifts to Nature-based Solutions (NbS) in Section 1.2, exploring their potential as sustainable alternatives to conventional grey infrastructure to manage urban water. The chapter then narrows down to the specific context of Paramaribo in Section 1.3, discussing the city's unique water-related challenges exacerbated by its geographical and socio-economic conditions. Subsequently, the chapter examines the institutional and technical aspects of implementing NbS in Paramaribo, considering the current infrastructure and governance frameworks. Based on these issues, the research question is formulated in Section 1.4. Finally, Section 1.5 breaks down the overall structure of the report, guiding the reader through the subsequent chapters and their contents.*

1.1. Urban Water-Related Challenges

Historically, human communities have thrived near water sources, making use of the benefits that water provides, such as facilitating transport routes, supplying drinking water, and moderating the heat stress. However, hydrological dynamics can cause fluctuations in the availability of water, particularly resulting in droughts and flooding. Addressing these difficulties while profiting from the advantages of water systems in a sustainable way is essential for urban resilience.

Urban water management is a multifaceted discipline that addresses the planning, development, distribution, and management of water resources in urban environments [1]. Its complexity arises from the need to balance the supply of water for consumption, sanitation, and industrial use with the mitigation of water-related hazards such as flooding and contamination. Urban areas globally face a variety of water-related challenges exacerbated by factors such as climate change, rapid urbanization, and industrialization. Poor drainage infrastructure and increased surface runoff due to rapid urbanization contribute to the heightened risk of floods during heavy rainfall events. Furthermore, both industrial activities and the large amount of households contribute to water contamination, leading to degraded water quality and harm to ecosystems and public health. Especially when combined sewers overflow during floods. During dryer conditions other challenges arise, persistent water scarcity in various regions further compounds these challenges, leading to conflicts and economic distress [2]. Additionally, urban areas often experience droughts, impacting water supplies and ecosystems [3]. These examples underscore the critical need for creative and sustainable water management strategies suited to urban environments to address these diverse challenges [4].

Soil Sealing and its Impact on Urban Hydrology

Soil sealing refers to the covering of natural land surfaces with impermeable materials such as asphalt and concrete, a common practice in urban development. This process significantly alters the natural hydrological cycle and has profound implications for water and soil management in cities. According to Fini et al. [5], soil sealing disrupts the natural infiltration of rainwater into the ground, leading to increased surface runoff and reduced groundwater recharge. The absence of infiltration reduces the soil's ability to filter pollutants, resulting in higher concentrations of contaminants in surface water bodies.

Moreover, the reduction in green spaces exacerbates the urban heat island effect, where cities become significantly warmer than their rural surroundings. The study Fini et al. [5] demonstrates that the use

of permeable and porous pavements can mitigate some of these adverse effects by allowing water to percolate through the surface, thus reducing runoff and promoting groundwater recharge.

Limitations of Grey Infrastructure

Grey infrastructure (GI) encompasses traditional engineering solutions such as dikes, dams, retention tanks, and sewer systems. While these structures are essential for managing water supply and mitigating flood risks, they often fall short in addressing the complex and dynamic challenges posed by urban water management. This form of water management arose from the idea that flood risk is the biggest threat. Dong et al. [6] highlights several limitations of GI:

1. **Monofunctional Nature**
   Grey infrastructure typically focuses on single-purpose solutions, such as flood control or wastewater removal, without considering broader environmental and social benefits. This narrow focus can lead to unintended consequences, such as habitat destruction and reduced biodiversity.
2. **High Maintenance and Costs**
   GI requires significant financial investments for construction and ongoing maintenance. The lifespan of such infrastructure is finite, necessitating periodic replacement and upgrades, which can be economically burdensome for municipalities.
3. **Environmental Impact**
   Grey infrastructure can negatively affect urban water drainage systems. For example, traditional drainage systems often fail to mimic natural water cycles, leading to issues like reduced groundwater recharge and increased surface runoff. This can contribute to urban flooding and water quality problems.
4. **Lack of Resilience**
   GI is often less adaptable to changing conditions compared to more flexible, nature-based approaches. As urban areas continue to grow and climate patterns shift, the rigidity of grey infrastructure can become a liability, unable to accommodate new or unforeseen challenges.

Given this vision of the future, a deliberate, comprehensive, and long-term solution is essential. GI is often mono-disciplinary, addressing only the issues directly related to water excess. However, interdisciplinary approaches to solving contemporary challenges frequently provide solutions that also benefit other aspects, such as enhancing livability, environmental quality, and social interaction. Additionally, grey infrastructure demands extensive upkeep, can be expensive to construct, and typically requires replacement after a lifespan of 50 to 100 years.

Given these limitations, there is a growing recognition of the need for integrated and sustainable urban water management strategies that can address multiple objectives simultaneously. This includes a shift towards Nature-Based Solutions (NbS), which leverage natural processes to enhance urban resilience and provide multiple co-benefits.

1.2. Nature-based Solutions

Unlike GI, NbS utilize natural elements like vegetation and soil to manage storm water and restore local ecosystems, offering a more holistic approach to urban challenges, serving several co-benefits alongside urban drainage. NbS implementation contributes to the concept of sponge cities, transforming urban landscapes into more resilient ecosystems [7]. Incorporating nature-based features enhances the water infiltration and storage capacity of urban areas, thereby improving their resilience to water-related challenges. This sponge city effect helps reduce the volume and velocity of storm water runoff, mitigating flood risks and preventing overwhelmed drainage systems.

These strategies are described in the literature using terms such as Sustainable Drainage Systems (SuDS), Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Green Infrastructures (GrnI), and Nature-based Solutions (NbS) [8]. These terms vary regionally, reflecting contextual differences in sustainable urban development approaches. In this thesis, I use the term NbS to encompass the entire array of climate-adaptive measures that utilize natural elements to combat soil sealing. Other terms fall under the umbrella of NbS, which is most often used to describe solutions based on natural processes, in healthy or restored ecosystems, and their services to address sustainability, including climate-related challenges [9]. I use this term because it's widely understood by the general public, even without a hydrological background, making it an effective way to communicate complex ideas.

Integration of these strategies into urban planning is imperative, given the varied environmental contexts and challenges encountered across different locations. The selection of suitable measures hinges on factors such as climate, land use patterns, and hydrological characteristics. Therefore, a tailored approach to urban planning is essential to effectively tackle soil sealing and its associated impacts in diverse urban settings. Nature-based approaches have been increasingly incorporated into legislation, emphasizing the importance of sustainable development [10]. Green infrastructures, either independently or in combination with grey infrastructures, positively influence the infiltration and storage capacity of urban water systems.

1.3. Water Related Challenges in Paramaribo

Since nature-based features are found to improve resilience to water-related challenges, I want to contribute to the existing research stream by exploring these sustainable water management strategies further. A place which faces difficult challenges during the wet season is Paramaribo. Therefore, this thesis focuses on researching sustainable and resilient urban water management strategies for Paramaribo.

Paramaribo faces a significant challenge during the wet season: pluvial floods become the most pressing issue, severely affecting daily life and the city's infrastructure. The city's drainage systems struggle to manage the large volumes of water from intense tropical rain showers [11]. Widespread damage to homes, roads, and utilities results from this inundation, disrupting essential services and endangering the safety of residents.

Water Nuisance in Paramaribo in 2023

Recent extreme rainfall in Paramaribo has led to severe flooding, causing major disruptions and damage throughout the city. The government has quickly set up a water crisis team to tackle the immediate problems, as many areas are inundated, and some ministries and offices have had to close. Homes and streets are flooded, making it difficult for people to get around. The National Coordination Center for Disaster Management (NCCR) is working to identify the most affected areas and provide assistance. Health and social services are also mobilized to help those in need.



Figure 1.1: Water nuisance on the streets of Paramaribo (source: Deltares)

Source: Waterkant, 2024

Rapid urbanization and inadequate drainage infrastructure worsen pluvial floods, highlighting the urgent need for proactive steps to improve the city's resilience to extreme weather events. As outlined in Section 1.1, urbanization results in soil sealing, leaving less space for water to infiltrate and causing pluvial floods, sometimes for several hours after a heavy rainfall event.

In Paramaribo, urban land cover grew from 105.29 to 259.65 km^2 between 1987 and 2005, a 146.60% increase, significantly impacting the area's drainage capacity [12]. This rapid expansion exacerbates flooding risks, as seen in cities like Mumbai, where urbanization and poor drainage systems have led to severe flood incidents during monsoon seasons [13].

Moreover, the rainy season exacerbates existing challenges, such as poor water quality. Because sewage pipes are not separated, the rainwater brings polluted and untreated effluent from residences and industries to the streets. In this way, people are exposed to pathogens from human waste, medicine, and other chemical toxins, resulting in health risks.

During the dry season, different challenges emerge, including droughts and long dry periods resulting in reduced water availability. Water is a crucial resource in a city, used for transportation, drinking, in households, maintaining ecosystems, agriculture, and reducing heat stress. However, high evaporation rates and limited space for water storage due to green infrastructure add to the complexities of

managing water resources in Paramaribo.

Persistent drought is a driver for other challenges. Combined with rising sea levels, saltwater is intruding on the land and salinizing freshwater sources. This negatively affects groundwater quality and hence crops and other flora. The higher water head of the sea, coupled with the lower head of fresh groundwater, increases the pressure differential, causing more saline water to flow into these freshwater reserves. This intrusion degrades the quality of the reserves, making the water less valuable and suitable for consumption by plants and humans. As saline water infiltrates freshwater aquifers, it reduces the availability of potable water and agricultural irrigation, exacerbating water scarcity and threatening food security. Additionally, the increased salinity can harm native vegetation and aquatic ecosystems, leading to further environmental degradation. These challenges outlined are addressed within the framework of the *Joint Cooperation Programme: Water, Subsurface, and Climate*, with which this thesis is closely aligned.

Context of Joint Cooperation Programme: Water, Subsurface, and Climate

The challenges outlined are acknowledged among stakeholders participating in the *Joint Cooperation Programme: Water, Subsurface, and Climate*. This initiative is dedicated to fostering sustained collaborative endeavors centered on three key themes: urban resilience, coastal management, and asset management. It facilitates the convergence of Dutch and Surinamese entities, encompassing governmental bodies, academic institutions, and private sector specialists. Key participants include the Ministry of Public Works of Suriname (OW), the Anton de Kom University of Suriname (AdeKUS), and Deltares. Employing co-creation processes, providing technical support for urban planning, establishing a knowledge hub to encourage collaboration, and offering training opportunities, they strive to enhance water management in Suriname. This thesis serves as an integral component of this overarching programmatic effort.

When NbS are used to address these water-related issues, it is important that they fit well within the context of Paramaribo. This context can be divided into three aspects: technical, socio-economic, and institutional. These aspects encompass various barriers and benefits that need to be analyzed to ensure successful implementation of NbS [14]. The technical aspect involves the feasibility and adaptability of NbS in local conditions. The socio-economic aspect considers the acceptance, costs, and benefits to the community. Lastly, the institutional aspect addresses the governance, policies, and regulatory frameworks required to support NbS. Understanding these dimensions is crucial for designing effective and sustainable urban water management strategies tailored to the specific needs of Paramaribo.

Institutional Challenges

Addressing water-related challenges in Paramaribo involves navigating several institutional hurdles [11]. The division of responsibilities and the need for enhanced cooperation among government ministries and the private sector are crucial areas for improvement. The current distribution of duties across various government bodies presents an opportunity to foster more effective collaboration and integrated planning for the city.

Efforts are underway to develop sustainable planning strategies, though the absence of clear standards and a comprehensive strategy for green measures represents a foundational step for future development. The constraints on budgets for new projects and the maintenance of existing infrastructure, as noted in the Master Plans of 2001 and 2024, reflect broader challenges faced in many regions. These circumstances underscore the importance of innovative financial strategies and efficient resource allocation.

Addressing overdue maintenance and exploring new techniques present significant opportunities for progress. Strengthening capacity within ministries and expanding training opportunities can support the implementation of innovative solutions. By focusing on these areas, there is considerable potential to enhance the effectiveness of water management and contribute to the city's long-term sustainability. These challenges are not unique to Paramaribo and are encountered globally, highlighting the universal need for adaptive and forward-thinking approaches in water management.

1.4. Research Question

This thesis aims to explore how NbS can be effectively utilized to address the environmental and socio-economic challenges faced by Paramaribo. The primary research question guiding this study is:

How can Nature-based Solutions be effectively utilized to address the environmental and socio-economic challenges of Paramaribo?

The main research question is subdivided into four subquestions, with three representing the aspects of technical, institutional, and socio-economic considerations. The final subquestion focuses on developing a concrete spacial design for Wakapasi.

1. Which Nature-based Solutions are suitable considering the socio-economical and hydrological conditions of Paramaribo, and how can they be adapted to fit these conditions?
2. What potential impacts can Nature-based Solutions have on water management in Paramaribo?
3. How can Nature-based Solutions be institutionally implemented in Paramaribo?
4. How can Nature-based Solutions be integrated into the spatial planning of Wakapasi, Paramaribo?

More detailed explanations and justifications for these aspects, drawn from the literature review, will be provided in Chapter 2.

1.5. Structure of this Report

After the introduction of this thesis, I review the relevant literature in Chapter 2, and find how this thesis can contribute to the knowledge about NbS especially in the context of Paramaribo. Based on this, the scope and purpose is presented. Lastly this research present some frameworks from literature that shaped the methodology of this research. From here, Chapter 3 provides relevant context on both Paramaribo and Wakapasi, the study area where most of the research is based on. Additionally relevant other contributions and current investments that could be of use in this thesis are broken down, to further shape the possibilities for potential collaboration during a month of fieldwork, where most of the research activities took place. In Chapter 4, the choice for these research activities are justified and the links between the research activities are explained. All activities tell something about one or more of the main aspects of NbS formulated for this topic: socio-economical, technical and institutional. Additionally, the specific method per research activity is elaborated on, making it understandable and reproducible. These results are presented in Chapter 5 and discussed along the three main aspects in Chapter 6. The insights for Wakapasi are than projected over other parts of Greater Paramaribo with perhaps other conditions and typologies, providing indicative designs and guidelines. The chapter is finished with discussion of the general implications of this thesis and a comparison with existing literature on NbS topics or different parts of the world with similar conditions. Conclusions that can be drawn from this thesis are highlighted in Chapter 7, and recommendations for an implementation strategy are given likewise for follow-up research both related to Paramaribo and NbS.

2

Literature Review and Scoping

Reading Guide *This chapter provides a comprehensive literature review on NbS in Section 2.1. It begins by discussing an array of NbS and their co-benefits described in the literature. The next section reviews the lessons learned from the application of infiltration facilities like BSs. In Section 2.1.5, this research is justified based on identified gaps in the literature. This section addresses the importance of conducting full-scale tests and multifaceted studies in Paramaribo to validate NbS effectiveness in tropical conditions, highlighting the necessity of involving socio-economic and institutional contexts alongside technical aspects. Finally, Section 2.3 presents the scientific frameworks used in this thesis.*

2.1. Literature Review NbS

The literature selected for this thesis is aligned with the themes of water management and the specific context of Paramaribo. Each source provides critical insights relevant to these themes, contributing to the research. The thematic diagram in Figure 2.1 illustrates the application of this literature within the thesis. Furthermore, a systematic review matrix presented in Appendix A details the specific themes each source addresses, showcasing how the literature underpins the research findings. The topics correspond to the flowchart depicted in the figure.

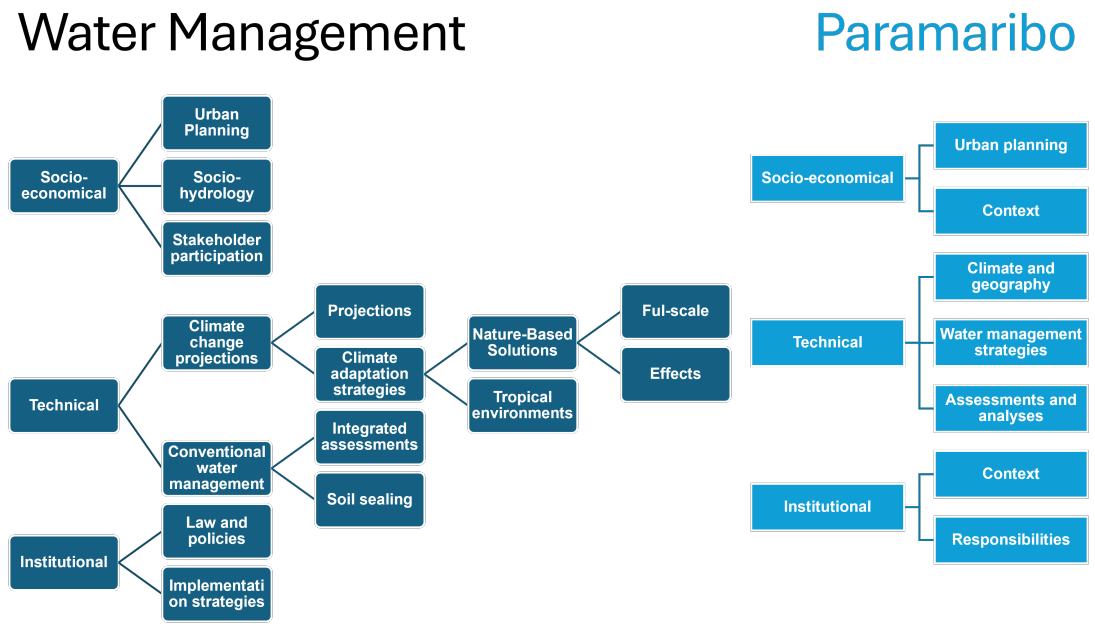


Figure 2.1: Thematic overview of literature used in this thesis, illustrating the specific topics and their relevance to the research themes in water management and the context of Paramaribo.

2.1.1. Types of NbS

An array of nature-based measures offers diverse co-benefits and varying suitability for different contexts and locations. This thesis draws on recent literature to explore a selection of NbS, highlighting their components, functions, and applications [15]. Tsatsou's selection of NbS types was based on a systematic review of the literature, ensuring a comprehensive and evidence-based approach. The measures in this selection are illustrated in Figure 2.2. Common NbS include bioswales (BS), rain gardens (RG), bioretention ponds (BP), tree pits (TP), constructed wetlands (CW), green roofs (GR), green walls (GW), and permeable pavements (PP) [15, 16]. These solutions can range from very simple designs to more complex systems. While each type of NbS has unique characteristics, they share several similarities. All NbS aim to manage stormwater, reduce urban heat, improve water quality, and enhance biodiversity. For example, both BS and RG are designed below ground level to capture and infiltrate stormwater runoff, thereby reducing the volume and improving the quality of water entering urban drainage systems.

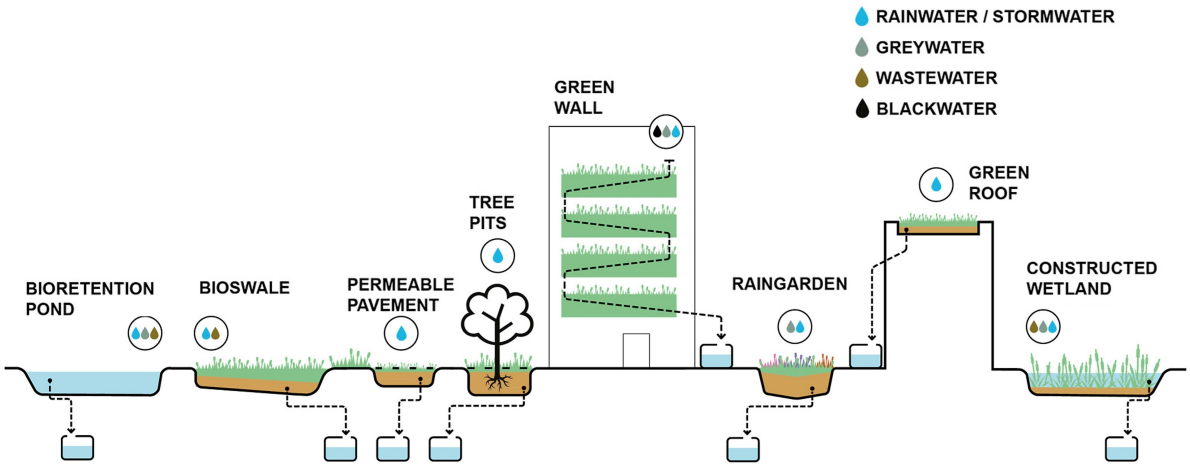


Figure 2.2: A scheme of a selection of NbS type 3 (highest level of ecosystem services) from recent literature [15] with their typical water input.

Infiltration facilities, such as BS, RG, BP, and CW, vary in complexity and specific applications. BS, which are linear, vegetated channels, are particularly suited for managing runoff from roads and larger green areas. RG and BP, typically smaller and more versatile, can be integrated into residential landscapes and urban parks, with BP being larger and engineered with specific soil media and vegetation to provide significant flood mitigation and water quality benefits. CW, on the other hand, are more focused on water treatment, leveraging natural processes to filter with high removal of pollutants before it re-enters the environment [17].

There are distinct differences in their applications and effectiveness. BS, RG, and BP focus on stormwater management through infiltration and runoff reduction. TP, however, focus on intercepting rainfall and providing shade, primarily addressing urban heat and enhancing streetscape aesthetics [18].

GR and GW, while contributing significantly to aesthetic and environmental benefits, also add more load to building structures. GR, installed on various building types, retain and detain precipitation, reduce energy consumption, and provide habitats for urban wildlife. PP, used in areas like parking lots and pedestrian paths, can easily be integrated into the urban landscape but have limited infiltration capacity compared to other greener NbS [19]. Each NbS, while diverse in form and function, collectively contributes to a more resilient, sustainable urban environment by addressing specific challenges through natural processes and materials.

All types of NbS are constrained by the space in which they can be applied and, therefore, by the landowner. Applying NbS on private land can be more challenging than on public land, and this varies by type. For example, GW and GR are primarily associated with private property, whereas BW, TP, and RG can also be implemented on public land. Additionally, PP and CW are often linked to public spaces.

2.1.2. Potential effects of NbS

The primary hydrological benefit of NbS is their ability to retain water, thereby mitigating high runoff peaks and reducing urban flooding. Additionally, NbS offer a range of other advantages. Studies by Wong and Brown [7], Cohen-Shacham et al. [20], and Anderson et al. [21] suggest that green infrastructure provides additional values such as ecological benefits, aesthetics, and recreational opportunities. Specifically, Alves et al. [22] quantify these benefits, showing that NbS can significantly improve urban biodiversity and air and water quality. However, the study also highlights potential challenges, such as the variability in effectiveness depending on local conditions and the need for ongoing maintenance to sustain these benefits. Co-benefits, which are the positive outcomes beyond the primary objectives, include enhancements in biodiversity, climate regulation, and social well-being. These benefits contribute to the overall sustainability and resilience of urban environments, although achieving them may require careful planning and management to address potential issues effectively.

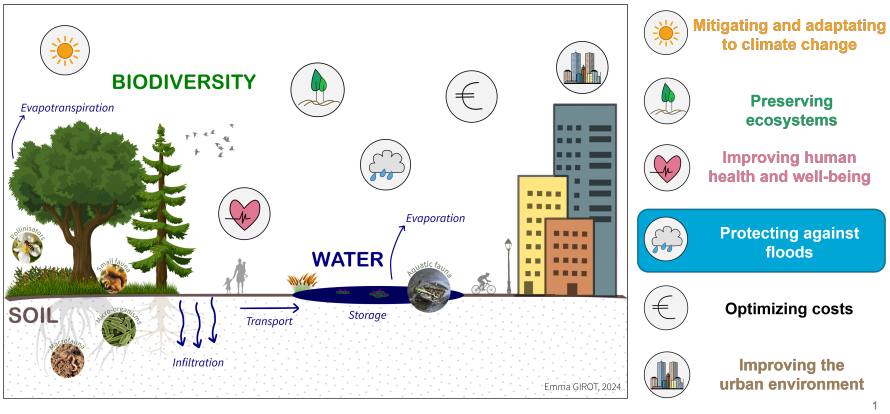


Figure 2.3: The potential ecosystem services of sustainable urban drainage systems.

The integration of NbS has been shown to effectively mitigate heat stress in urban areas. Green spaces provide shading, latent cooling, and transpiration, thereby reducing ambient temperatures and enhancing thermal comfort [23, 24]. These studies underscore the importance of NbS in alleviating the urban heat island effect, yet they also highlight that the effectiveness can vary depending on the specific context, which suggests that the cooling potential may differ in tropical environments due to high relative humidity and its impact on cooling efficiency. Careful planning and maintenance are essential to ensure long-term effectiveness in these varying conditions.

NbS serve as sanctuaries for biodiversity within urban environments, providing habitats for a diverse array of plant and animal species [22]. Green spaces created by NbS offer vital refuges for native flora and fauna, supporting ecosystem health and fostering ecological connectivity. This preservation and enhancement of biodiversity contribute to the conservation of genetic diversity and ecosystem services, which are essential for human well-being and the functionality of urban ecosystems. To maximize these benefits, it is crucial to increase the sizes of green spaces and connect smaller ones using green corridors [25]. Additionally, several studies emphasize that NbS can provide substantial ecosystem services, including clean water, air, and recreational spaces [26, 27, 28]. However, in the case of Suriname, the attraction of biodiversity is not always positive, as it may lead to the unwanted attraction of mosquitoes, pests, and snakes. These challenges highlight the need for careful design and management to balance the benefits of biodiversity with potential risks.

NbS not only offer ecological benefits but can also contribute significantly to the social and psychological well-being of urban communities. Research by Panno et al. [29] and Colléony and Shwartz [30] indicate that access to green spaces promotes physical activity, recreation, and relaxation, fostering positive social interactions and community engagement. By creating inviting and inclusive environments, NbS enhance the sense of place and identity within neighborhoods, thereby strengthening social ties and promoting mental health and well-being among residents.

In terms of environmental quality, Pereira et al. [31] note that NbS act as natural filters, improving the quality of water, soil, and air in urban settings. The vegetation and soil in NbS absorb and remove various pollutants from stormwater runoff, including heavy metals, nutrients, pathogens, and organic compounds. Vorenhout and Boogaard [32] further elaborates on the mechanisms involved, such as filtration, adsorption, absorption, plant uptake, and microbial degradation. These processes are critical

for water purification and air quality enhancement, demonstrating the comprehensive environmental benefits of NbS.

Literature can be divided on the cost of NbS compared to conventional drainage systems. While some indicate that NbS involve higher costs, mostly because of the high value of land cities and the frequent maintenance, others assume that maintenance and construction can be significantly lower. When social costs and benefits are taken into account in a integrated assessment, NbS seem to offer a promising alternative.

A comparison between NbS and traditional grey infrastructure reveals significant differences in resilience and adaptability to changing environmental conditions. NbS can demonstrate greater resilience and flexibility in the face of climate change, as they can naturally adjust to fluctuations in temperature, precipitation patterns, and extreme weather events [33]. This adaptability positions NbS as a sustainable approach to urban water management, better equipped to handle future climate uncertainties compared to grey infrastructure.

2.1.3. Lessons Learnt from Application of NbS

The implementation of NbS in various regions has provided valuable insights that are critical for their effective application in Paramaribo. These lessons emphasize the importance of strategic planning, stakeholder engagement, and adaptation to local contexts.

In the European Union, successful NbS implementation has been driven by early stakeholder engagement, building robust local evidence on NbS effectiveness, and addressing the path dependency of conventional grey infrastructure through policy reforms and training programs. Innovative financing mechanisms, such as green bonds and public-private partnerships, are essential to support NbS adoption. Supportive policies and legal frameworks further facilitate the integration of NbS, while local knowledge hubs can enhance capacity building and knowledge sharing [34].

In Colombia, the experience with NbS highlights the necessity of active collaboration among local communities, governments, and the private sector. Effective policy frameworks and institutional support are crucial for the success of NbS projects. Long-term monitoring and evaluation ensure sustainability and effectiveness, while adapting NbS to local environmental and social contexts is vital. Securing adequate funding for maintenance and scaling up successful initiatives remains a key challenge [22].

BSs represent a specific type of NbS that has proven effective in managing urban stormwater. The implementation of SuDS, including bioswales, in Bogotá, Colombia, showcases their environmental, social, and economic benefits beyond runoff control. A multiscale methodology was applied to optimize the placement and types of SuDS, focusing on citywide, local, and microscale levels. While this approach has been successful in Bogotá, adaptations are necessary for Paramaribo, considering differences in local climate zones and environmental conditions [16].

In the Netherlands, bioswales, also known as wadis, have been widely implemented across municipalities over the past two decades. These systems have generally performed well in managing stormwater, particularly in infiltrating runoff within 24 hours, even under extreme weather conditions [35]. However, their effectiveness is highly dependent on location-specific conditions, design, construction, and maintenance practices. The extended residence time of stormwater to 48 hours, in response to drought challenges in the Netherlands, highlights the importance of adapting these systems to local conditions. For Paramaribo, this could involve modifications to account for its unique rainfall patterns and soil types.

Effective pollutant capture by bioswales requires long-term environmental performance data. The accumulation of contaminants in the topsoil necessitates regular monitoring and maintenance to prevent degradation. The choice of vegetation is crucial, as plant species that tolerate both drought and prolonged inundation can enhance performance and reduce maintenance costs. Unsustainable materials, such as geotextiles, can lead to clogs and reduced infiltration capacity. Therefore, sustainable, self-maintaining natural systems are more suitable, especially in contexts like Paramaribo where asset management is challenging.

The use of BSs in urban areas has shown promise in contributing to climate adaptation, enhancing both stormwater management and green space. However, the successful integration of these systems requires careful consideration of environmental technology, systems design, urban planning, and ongoing maintenance. These aspects are vital for tailoring BS designs to local conditions, ensuring their effectiveness and sustainability in managing stormwater and enhancing urban resilience in Paramaribo [15].

2.1.4. NbS in a Tropical Environment

Figure 2.4 shows that practical research on NbS has largely been centered in North America, Europe, East-Asia, and Australia, and rarely in tropical conditions. There are only eight practical examples worldwide. Therefore, data is scarce, making it hard to reliably conclude on the effect of NbS [36]. Although calculations and feasibility studies have been conducted and promise high potential [5, 6, 33, 37, 38, 15], full-scale tests have not yet been implemented widely.

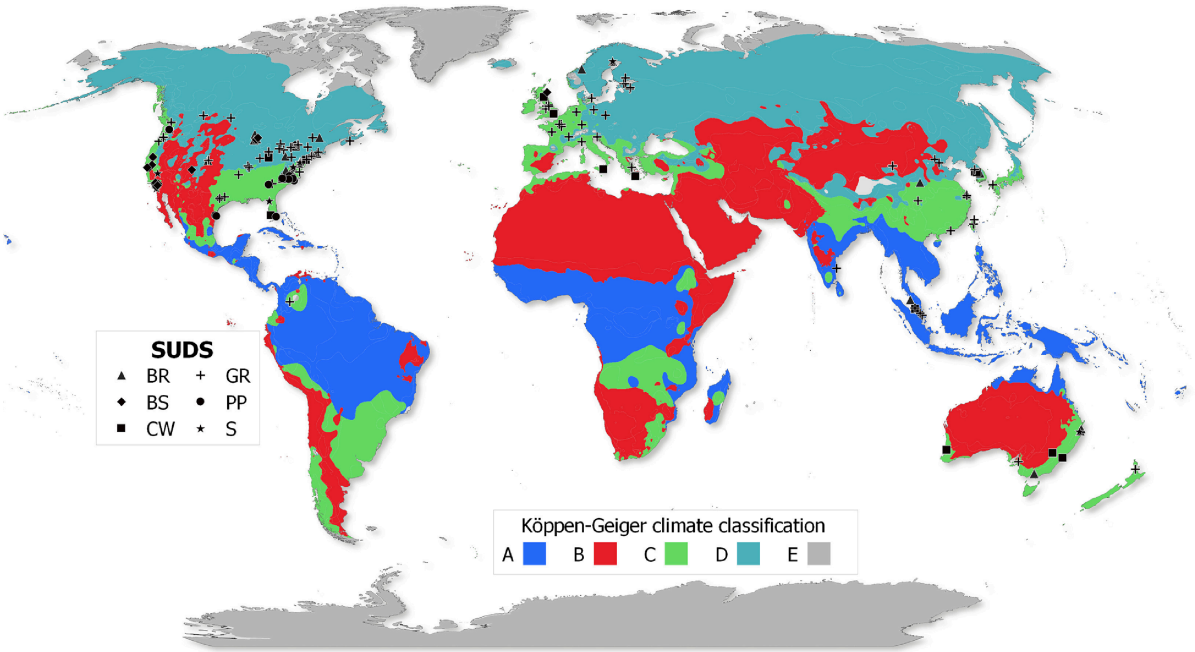


Figure 2.4: Location of selected SUDS [36]. Abbreviations: BR – bioretention cell; BS – buffer and filter strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale. Köppen-Geiger climate classification: A (tropical), B (arid), C (temperate), D (continental) and E (polar).

Ahmed et al. [39] claims to be the first detailed study on NbS in a developing tropical country. This is relevant because I intend to conduct similar research and want to review the useful information from this paper in my study. The research conducted in Thailand utilized a multi-criteria decision analysis approach to identify the best site for NbS implementation and employed the Personnel Computer Storm Water Management Model to develop a numerical model. The study demonstrated that a bioretention system could reduce runoff volume by at least 14% and pollutants by at least 14-20%.

In comparison, the study by Antuña-Rozado et al. [40] focused on the implementation of NbS in Brazil, highlighting experiences from both Europe and Brazil. This study emphasized the co-creation and systemic, inclusive approaches to NbS, involving various stakeholders to enhance urban resilience and sustainability. For example, in São Paulo, local initiatives such as the Owls' Food Garden and Spring's Square have transformed urban areas through community engagement and the application of agroforestry techniques. These projects not only improved local biodiversity and ecosystem services but also demonstrated social benefits by enhancing community cohesion and providing educational opportunities. This approach contrasts with the more technical and model-based methods used in the Thailand study, underscoring the importance of contextual and cultural factors in NbS implementation.

Voyde et al. [41] contributes valuable insights into the effectiveness of GR in reducing runoff peaks in the tropical environment of New Zealand. The findings demonstrate that GRs can significantly moderate runoff hydrology with similar climatic conditions. Additionally, the study by Lim and Lu [42] on Singapore's Active Beautiful Clean Waters Program presents another perspective on NbS in tropical urban environments. This program implemented over 60 LID projects within 10 years, including rain gardens, bioretention systems, and GRs, to manage stormwater. The findings revealed that while these systems performed well in particulate removal, their nutrient removal efficiency was less satisfactory. The program's success is attributed to the comprehensive integration of technical, regulatory, and community engagement strategies, highlighting the multifaceted nature of successful NbS implementation.

However, it is important to note that the contexts of Singapore and New Zealand may not be entirely representative of other developing tropical locations due to its unique socio-economic status, strong governance, and substantial financial resources dedicated to urban infrastructure projects.

Despite these differences, the promise of NbS for other tropical cities is significant. A deeper growing media, higher air temperatures, and greater plant biomass in tropical areas should increase evapotranspiration losses, enhancing rainfall retention by GR systems compared to temperate climates [42]. Additionally, local community involvement plays a crucial role in the success of NbS projects, as community engagement can enhance maintenance, increase project acceptance, and ensure that solutions are tailored to local needs and conditions. Therefore, while Singapore's experience offers valuable insights, it is crucial to adapt and validate these findings in diverse tropical

Several studies worldwide, as discussed in this section, have faced challenges in actual implementation. This phenomenon, commonly referred to as the implementation gap, refers to the discrepancy between research findings and practical application. Despite the generation of valuable insights and recommendations, these studies often remain theoretical, with authorities struggling to transition from planning to execution. This gap can stem from various factors, including limited resources, bureaucratic hurdles, and a lack of institutional capacity. contexts to fully harness the potential of NbS.

2.1.5. Relevance of Researching NbS in Paramaribo

In response to the challenges identified, conducting small-scale studies can provide a practical approach to bridging the implementation gap [34]. These studies allow for more manageable scopes, enabling focused and actionable solutions that can be realistically executed. A later chapter of this thesis will explore all studies conducted in Paramaribo, offering a detailed analysis of their outcomes and the specific barriers encountered during implementation. This examination aims to identify practical strategies that can facilitate the effective application of research findings in similar urban environments.

Given Paramaribo's unique environmental conditions—characterized by varied soil types, frequent heavy rainfall, and the challenges posed by drought and heat—it is crucial to conduct full-scale tests to validate these findings locally. Full-scale tests provide concrete data and practical demonstrations of the benefits of NbS, which are essential for informed decision-making and can stimulate further implementation.

Moreover, it is essential to conduct a multifaceted study that not only addresses the technical aspects of NbS but also considers the socio-economic and institutional contexts specific to a developing city like Paramaribo [43]. Understanding the interplay between these factors, including climate extremes such as drought and heat, is essential for developing solutions that are both effective and sustainable. The notion that successful actions can lead to further actions is particularly relevant here, as successful demonstrations of NbS can create a positive feedback loop, enhancing urban resilience in tropical regions. This aligns with the overarching goals of this thesis, aiming to improve the adaptive capacity and sustainability of urban environments in response to climate challenges.

2.2. Purpose and Objectives of this Thesis

The purpose of this research is to address the identified literature gap concerning the implementation of NbS in the specific context of Paramaribo. I will conduct multiple research activities in Paramaribo, focusing on action-oriented and participatory methods. The research will be grounded on three crucial aspects: technical, institutional, and socio-economic. Large studies are often difficult to implement, so a smaller scope was chosen. The scope area for this thesis will be Wakapasi, Section 3.3 provides elaborate justification and context for this area. In this way, I can introduce concrete measures instead of merely discussing principles and systems, which can be vague. It is also crucial that the techniques and this thesis remain uncomplicated to ensure the participation and ownership of the local community. By engaging the community and simplifying the approach, the project can achieve greater participation, acceptance, and effectiveness.

2.3. Scientific Frameworks Used in this Thesis

2.3.1. Action Research

Action research is a methodological approach designed to address complex real-world problems through a cyclical process of planning, action, and reflection. It emphasizes practical problem-solving and iterative development, making it particularly suitable for research that seeks to integrate theory with practice.

In this study, the methodology is grounded in the framework provided by Aken and Andriessen [44], as illustrated in Figure 2.5. This influential handbook offers a structured approach to design-oriented research, where methodologies are not rigidly predetermined but evolve in response to ongoing findings

and practical experiences. The book provides valuable frameworks and tools that guide researchers in bridging the gap between theoretical concepts and practical applications.

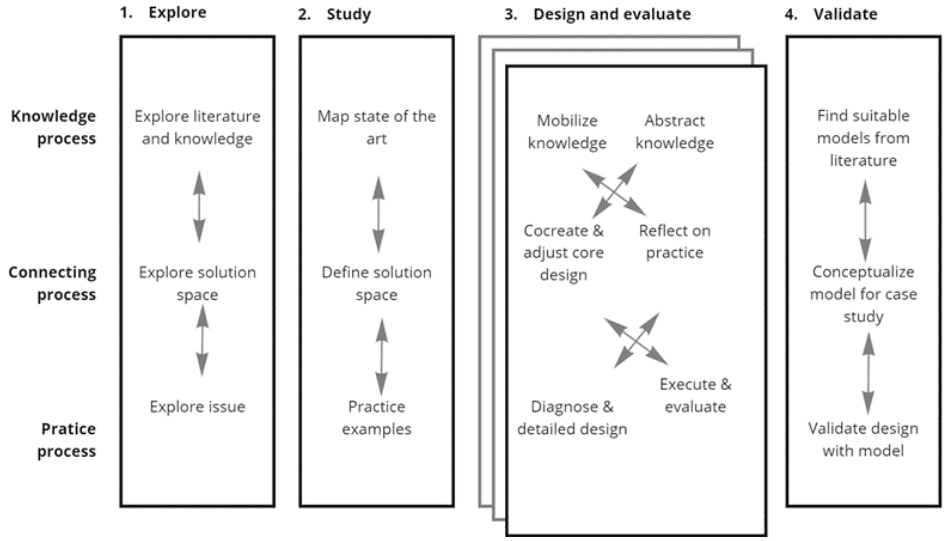


Figure 2.5: Research questions and subquestions with corresponding disciplines within integral water management (Figure based on illustrations from Aken and Andriessen [44].

2.3.2. Participation in Water Management

Ridder et al. [45] emphasise that public participation in water management takes various forms, each with its own implications for power and influence, ordered from low to high:

- **Information**: Information dissemination methods such as information meetings, markets, websites, and advertisements provide stakeholders with relevant information about water management issues.
- **Reaction**: Stakeholder reactions can be gathered through consultations, surveys, and public hearings, allowing for feedback on proposed water management plans or policies.
- **Discussion**: Discussion-based participation involves engaging stakeholders in focus groups and working groups, facilitating dialogue and exchange of ideas.
- **Contribution**: Stakeholders can contribute to or challenge evidence through participatory modeling exercises, involvement in steering groups, or participation in citizen juries.
- **Co-Decide**: In some cases, stakeholders may have opportunities to co-decide on water management issues, such as through binding citizen advice or involvement in water users' associations.

Historical Case Study: The Afobaka Dam and the Consequences of Insufficient Public Participation in Suriname

The Afobaka Stuwdam in Suriname serves as a stark reminder of why stakeholder participation is essential in water management projects. Built to power an aluminum smelter, the dam flooded a vast area of land, affecting local communities. Saamaka and Aukan/Ndyuka Maroon communities were particularly impacted, facing forced displacement. Although ALCOA engaged with community leaders and obtained agreements, the full impact of the project was not adequately communicated or understood. The construction of the dam and its reservoir had devastating consequences, as highlighted by Lobach [46]. While this story might be more extreme compared to the application in this research, it underscores the importance of inclusive decision-making processes to protect the rights and well-being of all stakeholders involved.

For effective stakeholder participation in water management, a combination of information dissemination, opportunities for stakeholder reaction, discussion-based engagement, and contributions/challenges to evidence is crucial [47]. These methods ensure transparency, inclusivity, and collaboration in decision-making processes. Ideally, stakeholders should have opportunities to (co-)decide on water management issues through involvement in binding citizen advice or participation in water users' associations, promoting ownership and accountability. Co-creation processes, which involve collaborative

efforts among stakeholders to develop solutions collectively, encompass elements of discussion, evidence contribution/challenge, and (co-)decision-making, aligning with the ideals of proper stakeholder participation.

Benefits of Co-Creation

Co-creation in the design phase of NbS offers numerous benefits, particularly in urban settings like Wakapasi. Previous projects have highlighted the risks of failure due to inadequate stakeholder engagement, lack of participation, and absence of ownership. Engaging stakeholders in a co-creative process ensures that the solutions are tailored to local needs and contexts, thereby increasing the likelihood of successful implementation. Keeys and Huemann [48] highlight the advantages of a co-creative approach include:

- **Diverse Expertise**: Engaging participants from different backgrounds enhances the range of knowledge and skills available. This diversity leads to more robust and well-rounded solutions.
- **Holistic Perspective**: Considering multiple viewpoints leads to more comprehensive and integrated solutions that address various aspects of the problem.
- **Innovation**: Collaborative processes often spark new ideas and innovative approaches, as the interaction of diverse perspectives can lead to creative problem-solving.
- **Sustainability**: Solutions developed through co-creation are more likely to be sustainable due to broader support and acceptance from stakeholders.
- **Efficiency**: Shared understanding and collaboration streamline the implementation process, reducing the time and resources needed to achieve results.
- **Social Cohesion**: The process strengthens community bonds and encourages collective responsibility, fostering a sense of ownership among participants. Enabling participators to maintain work in the research field, even after completion of this thesis
- **Local Knowledge**: Leveraging participants' intimate knowledge of the city enhances the relevance and effectiveness of solutions, ensuring they are grounded in local realities.
- **Feasibility**: Diverse input helps ensure that proposed solutions are practical and achievable, increasing their likelihood of being adopted and maintained.

Incorporating action research and co-creation into this thesis aims to align the research with the specific needs of the Paramaribo community and avoid any biases that might arise from external perspectives. This approach ensures that the research findings and proposed solutions are both practical and relevant to the local context.

3

Context

Reading Guide: *This chapter provides the essential background on the geographical, climatic, socio-economic, and urban planning contexts of Paramaribo, relevant to the discussion of Nature-based Solutions (NbS). Section 3.1 introduces the city's geographic and climatic characteristics, with a focus on hydrology and future climate projections as covered in Section 3.1.1. The socio-economic situation, including urban structure and planning strategies, is presented in Section 3.1.2. Section 3.2 summarizes current investments and ongoing projects in urban drainage and environmental management. Finally, Section 3.3 presents the Wakapasi area as a key study site for the thesis, chosen for its strategic importance and potential for evaluating NbS.*

3.1. Context of Paramaribo

3.1.1. Geography, Climate and Hydrology

Paramaribo is situated along the tidal Suriname river, basically extending the 350 km coastline with 50-150 km inland and therefore increasing the vulnerability for coastal flooding. The geography of Paramaribo is largely formed by the tidal Suriname River, characterized by a relative low and flat elevation Figure 3.1, typical for coastal delta cities. Additionally, the city's geography is accentuated by sand ridges, primarily formed through sediment deposition from the Suriname River over time, contributing significantly to Paramaribo's landscape. Smaller sediments types, silt and clay, are dominant and lead to an overall low permeability of the ground, posing challenges systems, particularly in urban areas with extensive building cover and pavement [5]. Detailed mapping of the soil structure and vegetation can help in finding permeable locations for nature-bases infiltration facilities [49].

Paramaribo experiences relatively consistent temperatures, with an average mean around 27°C throughout the year (Figure 3.2). Historically, four distinct seasons are recognized in terms of precipitation patterns. A short rainy season in December and January, followed by a short dry season from February to April, a long rainy season from March to August and finally a long dry season from September to November [50]. Each season having its own water-related challenges such as droughts, and flood risk. Some argue that the seasonal transition effectively condenses these patterns into two main seasons, causing even more challenges concerning flood risk and droughts. This can also be supported by the precipitation data in Figure 3.2 and recent historical climate analysis and projections by Koole [51].

During the rainy season in Suriname, heavy rainfall events are characterized by precipitation amounts ranging from 10 to 20 mm within a span of 30 to 60 minutes. Typically, the rainy season features frequent, intense downpours, with a 1-year return period resulting in 44 mm of rain over two hours and 75 mm in a single day. In contrast, a rarer event occurring once every ten years (T10) leads to significantly higher rainfall, with 59 mm in two hours and up to 159 mm in one day. The tropical climate and high humidity levels in Paramaribo significantly exacerbate heat stress within the city. The average heat stress index typically hovers around 85%, while nighttime conditions often drive it up to 100%, intensifying the discomfort experienced by residents [52].

Rainwater, cascading onto streets and rooftops, is channeled through combined sewer systems, predominantly open. These combined systems capture both rainwater and the effluent from septic tanks. A network of drainage canals facilitates the conveyance of storm water to lower-lying areas within the city and eventually to the Suriname River. Gravity flow suffices during low tides, with intermittent acti-

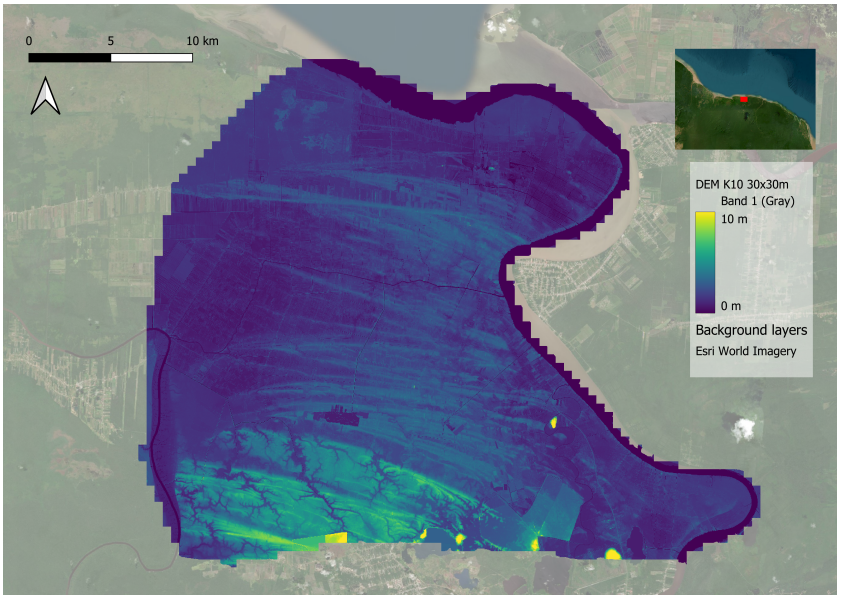


Figure 3.1: DEM of Greater Paramaribo with sand ridges indicated in yellow on higher elevation compared to clay layers with lower permeability (Source: Deltares, RHDHV, Ilaco, Kavel10, 2022).

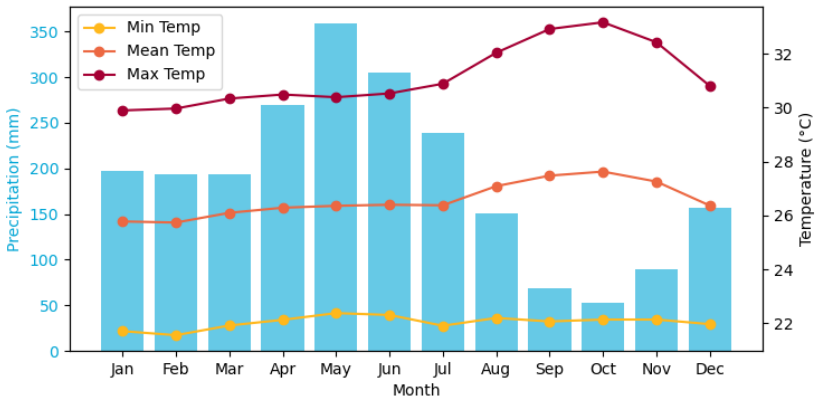


Figure 3.2: Monthly climatology with precipitation in mm (left axis) and maximum, minimum & average temperatures in °C (right axis) in Paramaribo from 1991-2020.[53].

vation of pumping stations required to manage high tides or heavy rain showers effectively. However, maintaining these systems is challenging for the city administration. Poor maintenance, blockages in drainage channels, and non-functioning pumping stations often lead to pluvial flooding during heavy rainfall.

Water on the streets can cause damage to buildings, infrastructure and affect the livability of the city, but if the quality of this water is poor, it can also result in health risks. Because the rain water and waste water drainage are combined in one sewer system, pluvial flooding can take water into the streets. Wastewater treatment remains an infrequent practice in Paramaribo. Select private entities treat their wastewater before its discharge into drainage canals. Conversely, the majority of households, hospitals, and industrial facilities rely on septic tanks to contain both black and grey water, which is then channeled into the drainage system. Septic tanks provide primary treatment by allowing solids to settle and scum to float, but they do not effectively remove nutrients, pathogens, or other pollutants from wastewater. There is no legislation mandating wastewater treatment in Suriname. Entities that do treat their wastewater, or are considering doing so, are driven by restrictions from third parties, tourism companies seeking sustainability certification, embassies following overseas government regulations, or industries that require treatment for their production processes.

Future Projections

Infrastructure investments are long-term commitments, often with lifespans extending beyond 50 years. Consequently, their design must not only address present needs but also guarantee sustainable functionality throughout their operational lifetime. Achieving this necessitates a forward-thinking approach that incorporates future projections into the design process. Given that water is frequently identified as a primary vulnerability in infrastructure systems [54, 55], it becomes imperative to integrate resilience measures that anticipate and adapt to potential challenges such as changing climate patterns, population growth, and urban development.

Looking at these future projections, urban expansion is a dominant phenomenon in Suriname, particularly concentrated in its capital, where economic and educational opportunities draw Surinamese citizens, driving extensive urban sprawl [12]. This rapid urbanization in Paramaribo has led to significant soil sealing and drainage issues. The increase in impervious surfaces, like roads and buildings, has exacerbated runoff and flooding risks [12]. Notably, districts like Commewijne and Wanica have seen population growths of 27.5% and 37.5%, respectively, from 2004 to 2012 [12]. Implementing sustainable urban drainage systems (SuDS) is recommended to manage stormwater and mitigate the negative impacts of soil sealing [12].

Rising sea levels present a substantial threat to coastal protection in Paramaribo, straining the drainage capacity of storm and wastewater systems. Projections suggest that pumping stations may soon operate daily during high tide, and eventually, continuously to mitigate flooding during heavy rainfall like showcased in Figure 3.3. Present-day sea level rise (SLR) is anticipated to exceed the global rate, with projections indicating a rise of 4 mm/yr, resulting in an estimated increase of 78 cm in the Suriname River by 2100 for RCP5-8.5 [51].

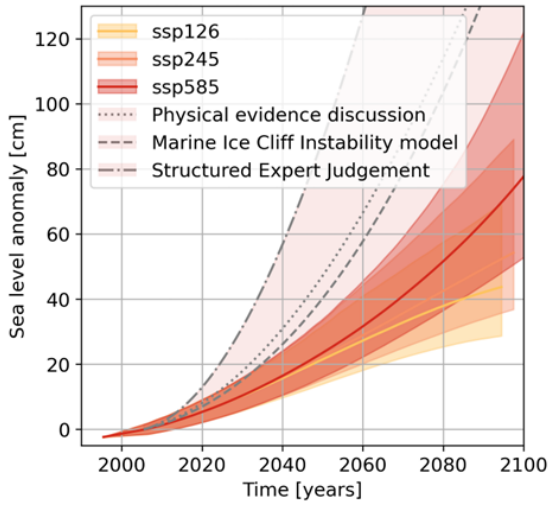


Figure 3.3: Projected Sea Level Rise (SLR) in centimeters up to 2100 under various scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) and more extreme scenarios [51].

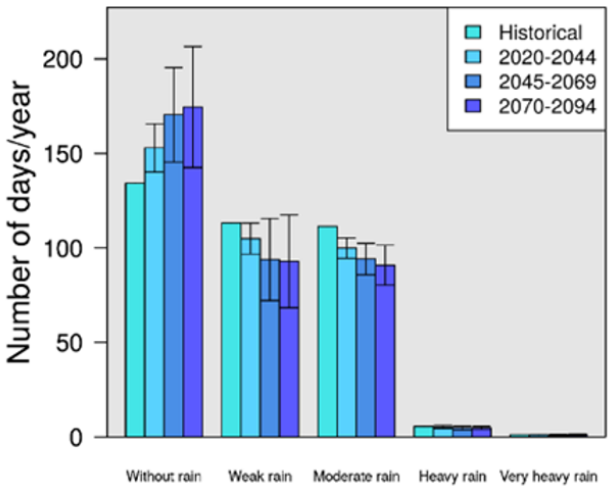


Figure 3.4: Projected increasing number of days without rain in Paramaribo for SSP2-4.5 up to 2094 with corresponding uncertainty [56].

Global Circulation Models (GCMs) project a mean temperature rise of 2 to 3°C by 2050 for RCP5-8.5 [57, 51]. Additionally, more extreme temperatures are anticipated [51]. While variations with other, more optimistic RCPs are relatively minor, a significant temperature increase in Paramaribo is highly probable. Precipitation projections exhibit seasonal disparities and large uncertainties. Generally, rainstorms during the wet season are expected to intensify, with projected increases of up to +40% for RCP5-8.5 [57, 51]. Conversely, the number of rainless days, especially during the dry season, is forecasted to rise as Figure 3.4 shows, accentuating the intensity of seasons and underscoring the imperative for a resilient urban environment. Ultimately, the delineation of distinct seasons may blur, leaving only one prolonged wet and one dry period instead of the four seasons of the past. All seasonal climate projections for temperature and precipitation in Paramaribo are summarized in Table 3.1.

3.1.2. Socio-Economic Situation

Paramaribo, the capital city of Suriname situated along the Atlantic coast, has a population of around 623,000 [53], housing half of the country's inhabitants and serving as its economic hub. Suriname has a promising foundation for sustainable socio-economic development, supported by its abundant

Table 3.1: Seasonal Climate Projections for Temperature (T) and Precipitation (P) absolute observations from 1991-2020 and projections relative to historical observations. For different scenarios: Low (L) and High (H) Emission, Dry (d), and Wet (w) Scenarios for 2050 and 2100 [51].

		Obs	Ld2050	Lw2050	Hd2050	Lw2050	Ld2100	Lw2100	Hd2100	Hw2100
Season	*Variable*									
DJFM	**T**	25.9 °C	0.9 °C	0.8 °C	1.5 °C	1.4 °C	0.8 °C	0.7 °C	3.8 °C	3.7 °C
	P	623.9 mm	-13.7%	-8.1%	-21.1%	-13.0%	-12.3%	-7.3%	-45.6%	-28.6%
AMJJ	**T**	26.4 °C	0.8 °C	0.8 °C	1.4 °C	1.4 °C	0.7 °C	0.8 °C	3.9 °C	3.7 °C
	P	1062.5 mm	-5.0%	0.6%	-8.3%	1.1%	-4.4%	0.5%	-21.4%	6.1%
ASON	**T**	27.4 °C	1.0 °C	0.9 °C	1.7 °C	1.5 °C	0.9 °C	0.8 °C	4.2 °C	4.1 °C
	P	465.4 mm	-12.3%	-5.3%	-18.8%	-7.9%	-11.1%	-4.8%	-41.9%	-15.2%

natural resources, fertile land, and freshwater. The economy heavily relies on gold and bauxite mining as well as tourism, with approximately 75% of exports tied to the gold industry [12]. Notably, a significant portion of this gold is produced within the informal sector, with 90% in 2018 [58]. This heavy dependence on international markets and tourism leaves Suriname vulnerable to external economic fluctuations. Recent setbacks, compounded by the COVID-19 pandemic, have led to fiscal crises, rising unemployment, and increased poverty [53]. The government's limited resources exacerbate these challenges, increasing reliance on international assistance and financial organizations.

Suriname is on the verge of transformative socio-economic changes due to recent oil discoveries in Block 58 [59]. While Guyana has already seen significant economic benefits from its oil sector, Suriname is still progressing through its development phase. If successful, these developments could substantially boost Suriname's economy, create job opportunities, and enhance infrastructure, potentially reshaping the country's economic landscape significantly.

City Structure and Urban Planning

Paramaribo's architectural heritage, particularly its UNESCO World Heritage-designated wooden buildings, showcases a blend of Dutch, European, North American, and Creole influences, reflecting Suriname's multicultural identity. The city is largely green, though grey infrastructure solutions are often employed in spatial planning due to the frequent maintenance required for rapidly growing vegetation and weeds [60]. According to the classification system developed by Stewart and Oke [61], the city is predominantly characterized as Open Lowrise (LCZ 6). This classification, which typically includes low-rise buildings with abundant vegetation, enables systematic comparison of urban temperatures with other locations.

Wetlands are crucial to Paramaribo's environmental health. Since 94% of Suriname's land is covered by tropical rainforests and wetlands, these areas are essential for flood management, water quality, and ecosystem support [12]. Protecting and restoring wetlands is vital for improving the city's resilience to climate change and managing urban growth.

Downtown Paramaribo demonstrates compact urbanization, a model that could be expanded city-wide. Promoting mixed-use developments and integrating public spaces can support vibrant and sustainable urban environments. Currently, Paramaribo has about 11% public space compared to 25% in cities with similar climates, like Cali, Colombia [12]. Additionally, approximately 18% of land remains unused [60], much of which is held in family ownership following inheritance, as shown in Figure 3.5.

Effective urban planning in Paramaribo depends on collaborative decision-making, involving government agencies, local communities, and the private sector. This inclusive approach is crucial for developing strategies that meet diverse needs. The Inter-American Development Bank (IDB) and the Government of Suriname (GoS) stress the importance of incorporating environmental, urban, and fiscal sustainability into planning processes [12].

To address urban sprawl and improve land use, Paramaribo's development strategy focuses on compact building and clear distinctions between developable and non-developable areas [60]. The plan also proposes creating semi-self-sufficient satellite towns within a 20 km radius, well-connected to the city by efficient public transport [60]. Moreover, developing public spaces and green areas, and utilizing natural waterways for transportation and recreation, aims to reduce traffic congestion and enhance the city's livability [62].

Current challenges in spatial planning include overlapping land concessions, inadequate zoning, and land degradation, even in protected areas. These issues highlight the need for updated legislation and

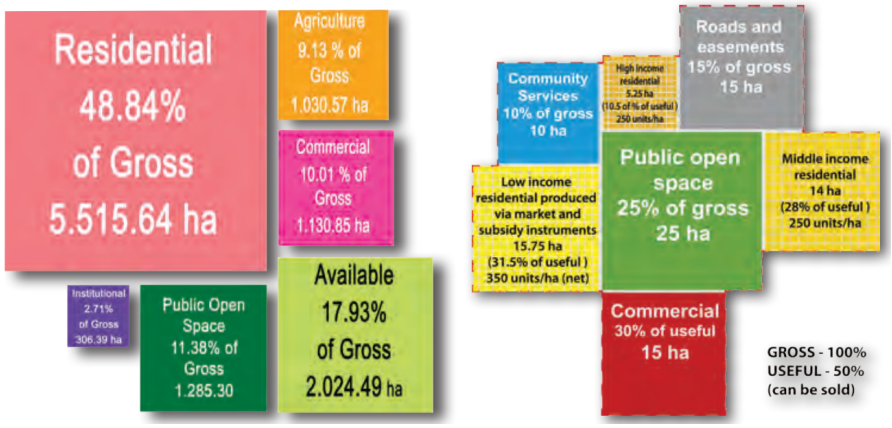


Figure 3.5: Division of land use in Paramaribo (left) compared to Cali (right), with similar climatic conditions [12].

improved land information systems [54]. The National Adaptation Plan emphasizes integrating climate change considerations into urban planning, particularly for infrastructure and housing [54].

The Environmental Planning Act of Suriname [63], established in 1972, does not fully address the needs of modern urban planning, such as climate change adaptation. To better meet these needs, a new law, the *Wet Ruimtelijke Ordening* (Spatial Planning Act), is being developed and is expected to be enacted soon. This new legislation aims to incorporate strategies for climate resilience, comprehensive land use, and updated zoning regulations, providing a stronger framework for sustainable development and effective urban management.

3.2. Current Investments & Other Works

Several large studies, such as the the Saramacca Canal System Rehabilitation Project (SCSRP), the Urban Growth Study and Water Resources Asssment by USAID have thoroughly assessed the urban drainage challenges related to this context. Therefore there is a reasonable amount of assessments, and problem definitions. Additionally, there is an overview suggested grey intervention methods that could improve drainage in the city, empathizing the need for careful asset management [54]. Through these studies, high resolution DEMs and hydrodynamic models were made available.

Tropenbos Suriname is among the initiatives contributing to NbS in Paramaribo. They engage in agroforestry projects aimed at promoting climate change adaptation and improving land management, particularly in areas like Brownsweg, Brokopondo district. Additionally, Tropenbos Suriname contributes to local governance by integrating traditional knowledge with formal governance structures and by creating detailed 3D maps for land planning. Their efforts also extend to public awareness and education, including urban tree tours that foster appreciation of natural environments, and they conduct research to support sustainable practices.

The Paramaribo Urban Rehabilitation Program (PURP) is currently focused on the Waterkant area. The project includes the removal of parking spaces along the street to make way for urban green spaces. However, there is limited incorporation of blue infrastructure, which refers to water management elements like ponds and wetlands, in the urban planning. This approach aims to enhance the environmental and aesthetic appeal of the historic center while addressing sustainability concerns.

Keesmaat [64] evaluates a participative tool for its effectiveness in assessing NbS for mitigating urban floods in a study area near the Jodenbreestraat. It includes sensitivity analysis and model comparison with hydrodynamic simulations, particularly in areas with high rainfall and runoff. The thesis also recommends using smaller study areas to better manage spatial effects and improve model performance.

3.3. Introduction to the Wakapasi Study Site

Following broader efforts across Paramaribo, attention now turns to a more focused area—the Wakapasi site along the Sommelsdijckse Kreek, as shown in Figure 3.6. This smaller, strategically chosen study site addresses the implementation gap identified earlier in Chapter 2, providing a concentrated setting to evaluate the effectiveness of NbS and fostering more effective collaboration with local stakeholders and concrete designs. The selection is based on several key factors:

- **Water-related challenges**: Some parts of the study site still exhibit significant soil sealing, providing a diverse context within the region for evaluating the effectiveness of NbS. While Wakapasi experiences little water nuisance due to its proximity to a creek connected to a pumping station, northern areas of the study site, such as Julianalaan, suffer from serious inundation.
- **Stakeholder Opportunities**: The presence of numerous stakeholders, including influential businesses and government entities, offers substantial opportunities for collaboration and implementation of NbS. Various organizations advocate for entrepreneurs' interests, and the Districtcommissaris of Paramaribo Noord, along with neighborhood managers, oversee the region.
- **Strategic Importance**: Wakapasi plays a crucial role in the city as a highly visited area, hosting major city events and landmarks such as the Palmentuin, Onafhankelijkheidsplein, and Fort Zeelandia.

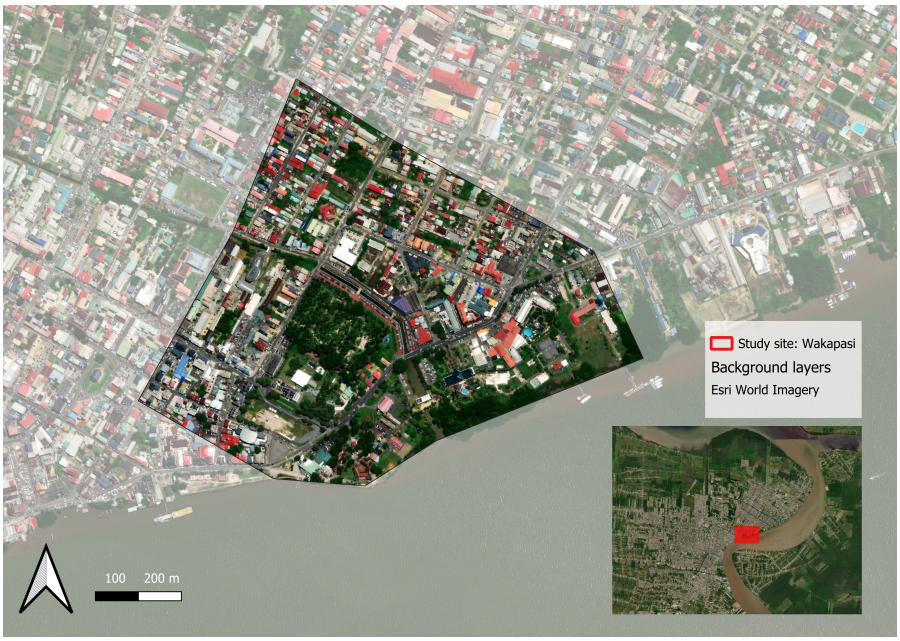


Figure 3.6: The Wakapasi study site, highlighted around the Palmentuin and Onafhankelijkheidsplein, two major landmarks of the city.

The Sommelsdijckse Kreek has a long history dating back to the 17th century when it was expanded for drainage and transport. Initially serving as a vital waterway for the early settlement, it became increasingly important as the city grew. Over time, the creek's role evolved with urbanization, leading to challenges in maintenance and water management. In 2011, the creek was paved to facilitate maintenance [65]. Despite this modernization, it continues to play a crucial role in the study area by channeling water to the Suriname River via the pumping station. This function is vital for managing water distribution and preventing flooding, though drainage and maintenance issues remain ongoing concerns.

Wakapasi and its surrounding area feature a mix of land use types, predominantly public spaces and businesses, with some housing. It is generally greener than other parts of the city. The local climate zones that can be defined within the study site are given in Table 3.2. Most tourism in the city is centered around the Palmentuin and the nearby Kleine Dwarsstraat and Van Sommelsdijckstraat, which host numerous bars, restaurants, and hotels. The Torarica hotel chain owns most of the riverbank north of the pumping station, while the south primarily hosts governmental buildings. Major city events are celebrated at Onafhankelijkheidsplein, Wakapasi, and the Palmentuin, attracting thousands of visitors.

Table 3.2: Local Climate zones from \textcite{stewart2012local} for different sections in the study site.

Location	Local Climate Zone
Palmentuin	Dense trees (LCZ A)
Paved inner city	Lightweight lowrise (LCZ 7)
Other	Sparsely built (LCZ 9)

Significant development in the region comes from private initiatives, with Wakapasi itself being privately owned. The area also hosts various small businesses such as craft shops, coffee shops, flower shops, and bars, represented by an association.

Various stakeholders in the study area have the potential to contribute to the implementation of NbS, either due to their organizational responsibilities or their proximity to the project site. Figure 3.7 categorizes these stakeholders within a Power-Interest diagram, highlighting those with the most relevance and influence for this specific initiative in the top-right section of the figure. It is important to note that this diagram is tailored specifically to the topic of NbS in this context and does not reflect the general roles or influence of these stakeholders outside of this scope.

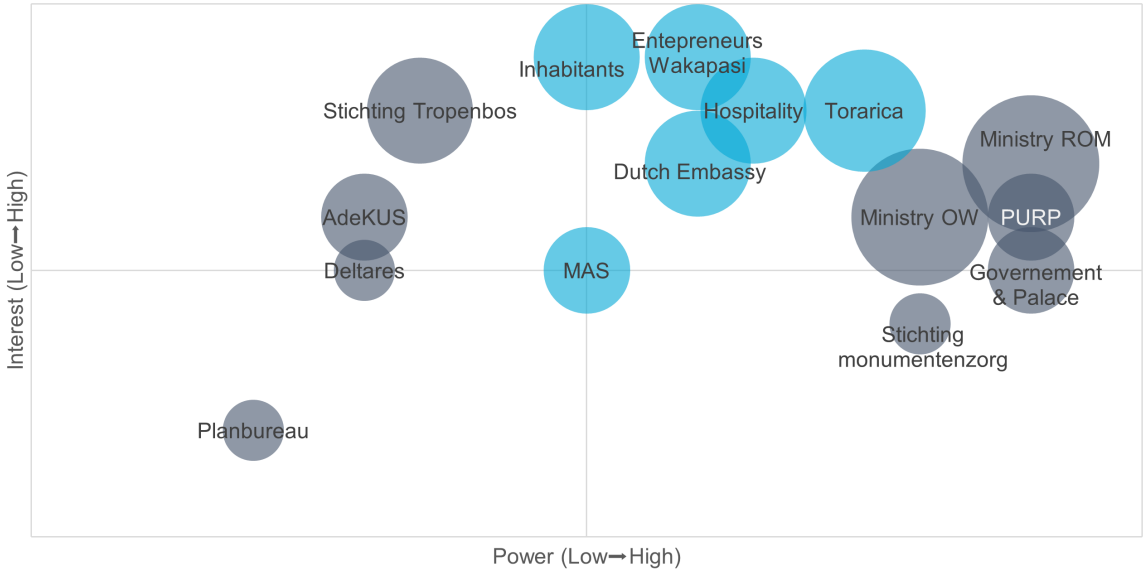


Figure 3.7: Power-Interest diagram illustrating stakeholder involvement in the implementation of NbS. Circle sizes represent the significance of each stakeholder's potential role. Blue circles denote stakeholders based in the study area, while grey circles represent organizations that may participate in the process.

4

Methodology

Reading Guide *This chapter outlines the methodology employed in this research. It begins with the rationale and justification for the selected approaches in Section 4.1 and continues with detailed descriptions of each research activity, including the use of Multi-Criteria Analysis (MCA) in Section 4.2.1, semi-structured interviews in Section 4.2.2, think-tank sessions in Section 4.2.3, a full-scale test at AdeKUS in Section 4.2.4, and simulations in Section 4.2.5. Each section explains the methods, procedures, and considerations taken into account to ensure comprehensive and accurate data collection and analysis. The chapter also addresses the limitations encountered during the research process.*

4.1. Overview of the Methodology

During this research, I selected a set of NbS for co-creation activities to make discussions about implementation more concrete and engaging. I justified this selection using a multi-criteria analysis (MCA). To explore the three main aspects of NbS, I set up various research activities, each designed to shed light on one or more of these aspects.

To incorporate the socio-economic context of Paramaribo, I interviewed a wide range of stakeholders about their perceptions of the city's challenges and their thoughts on potential interventions and implementation methods. These interviews helped establish the initial boundary conditions for our strategy and design.

To assess the technical feasibility of NbS, I conducted a full-scale test. This test was used to gather data and engage stakeholders in discussions about system performance. Although the test was limited to two locations, I used the results to simulate the potential impact across the entire Wakapasi study site. These simulations considered different implementation scenarios derived from the system analysis.

At the end of the fieldwork, I organized a think-tank session where various stakeholders provided input on all aspects of the research. This session fostered dialogue among them and allowed for a productive exchange of ideas. Throughout all activities, I ensured participation of all major stakeholders from local communities, officials, academia, and businesses.

After the fieldwork, I conducted follow-up interviews with some participants to discuss new results and gather further input. Moreover, results from certain activities, such as the system analysis and full-scale test, were used to update the simulations to validate the expected effect of the employment of NbS. While most activities focused on Wakapasi, I kept an eye on potential implementation in the greater Paramaribo area.

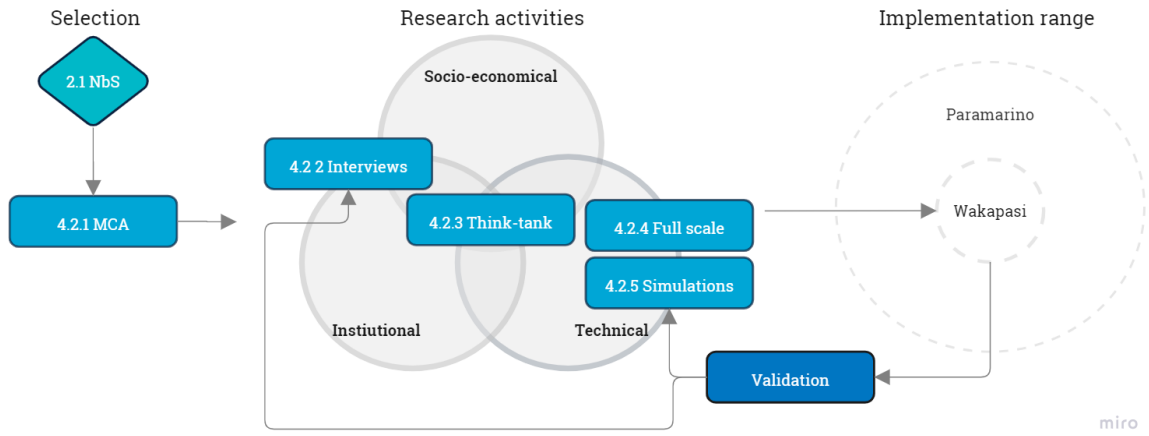


Figure 4.1: Flow chart of the research activities in this thesis with corresponding chapters. Processes without corresponding chapters are indicated in dark blue, theoretical chapters in turquoise, and research activities from the methodology in light blue. The research focuses on the Wakapasi region and is later applied to the rest of Paramaribo. Designs and findings are continuously validated by participants to enhance the accuracy of the simulations.

4.2. Methodology per Activity

4.2.1. Multi-Criteria Analysis

Multi-Criteria Analyses (MCAs) can be used to analyse and compare potential intervention methods. I therefore used it to asses several NbS for the context of Wakapasi, to give insight in the potential of different types of NbS for different locations and conditions in the neighborhood and make a pre-selection for which NbS are most suitable for further investigation.

In this thesis, I assess a range of NbS identified from the literature in Section 2.1.1. These measures include bioswales, bioretention ponds, tree pits, constructed wetlands, green facades, green roofs and permeable pavement. I evaluate these NbS compared to the status quo and analyze each solution based on the criteria outlined in Table 4.1. With this comprehensive evaluation I aim to identify the most effective and sustainable strategies for managing urban water challenges in Wakapasi specifically. I selected these criteria and weights based on earlier practices, specific requirements for Paramaribo and interviews before and during fieldwork. For instance, asset management turn out to be important based on lessons-learned in Section 2.1.3 and also appears to be a challenge for existing infrastructure in Paramaribo, making it an important criterion to incorporate.

The weighted MCA methodology is based on the manual by Dodgson et al. [66]. The scoring of NbS and the weighting of criteria were conducted by myself, drawing on insights gained during fieldwork in Suriname and the expert opinions of established academics in the water sector. The scoring of NbS and the weighting of criteria are conducted by myself, drawing on insights gained during fieldwork in Suriname and the expert opinions of established academics in the water sector. The weights assigned to each criterion range from 1 to 3, and these weights are normalized to ensure they sum up to 1. The weights are highlighted in Figure 5.2. The weighted scores are calculated using the equations in 4.1 and 4.2.

The MCA was used to evaluate various NbS types, leading to a selection of those most appropriate for further investigation. The remainder of the methodology is based on this decision, and further elaboration on the results of the MCA is given in Section 5.1, and calculations are displayed in Appendix D.

Table 4.1: Criteria used to analyse the suitability of different NbS types for Paramaribo.

Criterion	Description	Indicator
Cost	Includes both the initial investment required for the implementation of solutions and the maintenance and operation costs over time, ensuring a clear understanding of the financial implications.	Initial investment; Maintenance and operation costs
Environmental impact	Assesses the environmental impact, focusing on how solutions affect local ecosystems, biodiversity, and carbon footprint, as well as resource efficiency, which promotes the conservation and optimal use of resources like water and energy.	Environmental impact; Resource efficiency
Efficacy	Evaluates the ability of solutions to mitigate flood risks, improve water quality, and retain water, which is crucial for managing urban water bodies and reducing the risk of flooding.	Flood mitigation; Retention; Water quality improvement
Asset Management	Looks at the durability and longevity of the infrastructure, ensuring that solutions are robust and have a long lifespan, and their adaptability to changing environmental conditions and urban needs.	Durability and adaptability; Maintenance intensity
Urban Integration	Examines how well the solutions integrate with existing infrastructure and services, as well as their scalability, or the potential to expand these solutions across different urban areas.	Integration with existing infrastructure & local expertise; Scalability
Private Domains	Considers stakeholder acceptance, gauging the support and acceptance from private property owners and the broader community to implement measures on their terrain, the possibility for creating a legal framework for guiding property owners towards implementation of the measure, and the opportunities for public-private partnerships that can facilitate collaboration and funding to move to widespread implementation throughout Paramaribo.	Stakeholder acceptance; Legal and policy framework
Co-benefits	Addresses the benefits to the community, including improvements in quality of life through recreational and aesthetic enhancements, and contributions to public health and safety by mitigating heat islands and providing green spaces.	Community benefits; Public health and safety

$$TS = \sum_{i=1}^{n} \frac{S_i}{n} \tag{4.1}$$

$$TWS = \sum_{i=1}^{n} \frac{W_i \cdot S_i}{n} \tag{4.2}$$

Where:

TS : Total Score, which is the average of all the scores
S_i : Score for the i-th criterion
n : Number of criteria
TWS : Total Weighted Score, which takes into account weights assigned to each criterion
W_i : Weight for the i-th criterion

4.2.2. Semi-structured Interviews Approach and Frameworks

This methodology, grounded in qualitative research frameworks, enables the collection of rich, detailed data through semi-structured interviews. This approach provides the flexibility necessary to explore diverse perspectives, contributing significantly to the depth and breadth of the research insights.

I root the methodology employed in this study in qualitative research principles, specifically leveraging semi-structured interviews conducted during a field trip to the case study site. This approach aligns with established qualitative research literature, which underscores the importance of flexibility and depth in capturing participants' experiences and perspectives [67, 68].

Selection and Ethical Considerations

I utilize purposeful sampling to ensure a diverse and relevant range of perspectives among the interviewees, encompassing local residents, community leaders, and professionals directly or indirectly involved in the case study topic. This method, as advocated by Maxwell [69], aims to maximize the relevance and richness of the collected data. The selection process includes representatives from all sectors of the quadruple helix model - academia, industry, government, and civil society. A complete list of participants is given in Appendix B. Figure 4.2 illustrates the collaborative and interactive nature of these four categories. Within each category, participants were ultimately chosen based on encounters during fieldwork. This encounter-based sampling method means that participants were not selected randomly but were identified as key stakeholders through interactions and observations in the field. This approach allowed for the inclusion of individuals who are directly engaged with or affected by the case study topic, thereby ensuring a depth of insight and relevance.

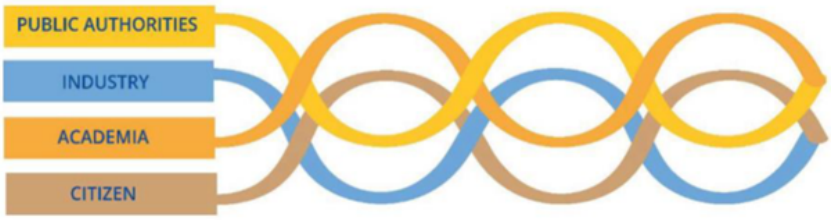


Figure 4.2: The Quadruple Helix Model of Innovation. This conceptual framework extends the traditional triple helix model by incorporating civil society or the public as the fourth helix. In this study, the quadruple helix model guided the selection of participants, aiming to capture diverse perspectives from all four sectors.

The selected group of participants thus includes a variety of voices, each bringing unique insights and experiences to the study. This non-random selection was essential to speak with as many key stakeholders as possible within the limited time frame of the fieldwork, ensuring a comprehensive and nuanced understanding of the issues at hand. Given the subjective nature of interviews, it's essential to interpret the findings within their context. Seeking confirmation from multiple sources helps validate the information gathered and enhances the overall credibility of the research.

All research I did was in accordance with the Human Research Ethics guidelines of Delft University of Technology I anonymize all participants to protect their privacy. I obtain consent after informing participants about the study's purpose, ensuring voluntary and informed participation.

Structure of Semi-Structured Interviews

I employ semi-structured interviews, which combine pre-determined questions with the flexibility to explore emergent themes. This approach, supported by Ruslin et al. [67], facilitates a more in-depth understanding of participants' perspectives by allowing them to share their own stories without the constraint of rigidly steering questions. The interviews lasted between half an hour and three hours, allowing for a comprehensive exploration of the participants' insights and experiences.

1. **Initial Open Discussion**
   I begin interviews with open-ended questions to establish rapport and gather unbiased initial responses. These questions, such as "What is it like to live here?" or "How do you like the way this street is laid out?", encourage participants to share their initial thoughts and feelings freely.
2. **Specific Core Discussion**
   Subsequently, I introduce specific questions related to the thesis topic after the initial phase. These questions are designed to probe deeper into key areas of interest for this thesis. The specific questions depend on the interview's topic and the participant, ensuring relevance and depth in the exploration of each individual's perspective.

Main Topics of Discussion

The main topics discussed during the interviews include:

- Local perceptions and experiences related to Wakapasi.
- Challenges and opportunities identified by participants.
- Suggestions and expectations for future developments.
- Opinions on specific NbS and their application.

Data Collection and Analysis

To ensure participants provide honest responses and avoid simply telling what they think is desired, questions are deliberately framed to allow for a clear ”no” as an answer. For example, asking whether floods occurred recently, even when they have not occurred. This approach encourages genuine and candid responses, providing insight into the honesty of the respondents.

Notes are taken during each interview to capture and present remarkable responses. Thematic analysis is employed along the main discussion points which were highlighted earlier to identify patterns and themes across the data.

Limitations

I refrained from making audio recordings or transcriptions of interviews to promote honesty, spontaneity, and privacy. Conducting interviews in spontaneous settings without recording devices captures authentic perspectives, as individuals express themselves more naturally without scrutiny. This approach respects participants' privacy and fosters candid participation, creating a relaxed atmosphere and reducing refusals. In my opinion, this method is more suitable for the context of Suriname. However, not recording audio can lead to data loss and reliance on memory, which may miss details and hinder referencing specific quotes. The lack of transcriptions limits supportive material for analysis, impacting the reliability and comprehensiveness of findings and providing no permanent record for validation.

4.2.3. Think-Tank Methodology and Frameworks

This section outlines the methodology and frameworks employed during the think-tank session organized to co-create NbS for Wakapasi. A think-tank is a collaborative workshop that brings together a diverse group of stakeholders, experts, and community members to brainstorm, discuss, and develop solutions to complex challenges. Grounded in the principles of co-creation and stakeholder engagement, this participatory methodology emphasizes the inclusion of a wide range of perspectives and expertise. The goal is to foster innovation while ensuring the sustainability and feasibility of the proposed solutions. The think-tank session was a joint effort by Deltares, AdeKUS, and the Ministry of Public Works, conducted at the conclusion of the field trip.

Organization and Participants

The think-tank, held at the Ministry of Public Works, was organized to include a diverse array of stakeholders identified during fieldwork. Participants were drawn from various sectors, including local residents, community leaders, engineers, and academics, ensuring that a broad spectrum of perspectives was represented. The diversity in age, gender, and professional background contributed to a rich and inclusive dialogue. Key organizations involved included PTC, ROM, Ilaco, Tropenbos, AdeKUS, the Ministry of Public Works, the Dutch and American embassies, and entrepreneur organizations. Participants were grouped randomly to encourage the exchange of ideas across different sectors and backgrounds.

Agenda Structure of the Think-Tank

The think-tank followed an agenda designed to maximize participant engagement and productivity. The activities and their corresponding rationale are summarized in Table 4.2.

Table 4.2: Activities during the think tank and their rationale for inclusion in the agenda.

Activity	Content	Rationale
Presentation	The session began with a presentation that introduced the concept of NbS, provided an overview of the thesis, and outlined the specific input required from participants.	This introduction was essential to ensure that all participants had a shared understanding of NbS and the objectives of the session, enabling them to contribute informed and relevant insights.
Brainstorming	Participants engaged in group discussions, where they explored the main topics below, sketched ideas, elaborated on concepts, and documented the outcomes of their discussions.	The brainstorming sessions were designed to stimulate creativity and encourage local experts to generate ideas on how NbS could be applied within the context of Paramaribo.
Break and Walk Around	A break allowed participants to move around, discuss ideas with members of other groups, review the outputs of different groups, and contribute additional input for various neighborhoods using post-its on posters.	This activity aimed to provide a more informal setting where participants could freely contribute ideas, ensuring that all perspectives were captured, even outside the structured group discussions.
Pitches	Each group gave a short presentation summarizing their findings, designs, and responses to the key discussion points.	The pitches ensured that all participants were informed about the ideas and requirements from other regions of the city, facilitating a comprehensive understanding of the proposed solutions.
Open Discussion	Following the pitches, participants engaged in an open discussion to reflect on the session's key points and synthesize the ideas presented.	This discussion was crucial for summarizing the ideas, identifying the most suitable approaches, and distinguishing between general strategies and region-specific solutions.

Main Input During Think-Tank

Each group was provided with sketching materials, fact sheets summarizing the presentation, and a set of specific questions to guide their discussions. These questions focused on key aspects of implementing NbS, including motivation and responsibility, management and maintenance, feasibility, spatial planning, and potential alternatives. The think-tank discussions were structured to explore stakeholder motivations and responsibilities regarding NbS implementation. Next, the groups considered who should manage and maintain these solutions and whether it is feasible for residents and NGOs to assume this role. Feasibility in the context of Paramaribo was a central theme, as participants shared their general opinions on using NbS to address urban challenges. The groups also discussed spatial planning, identifying areas where NbS could be integrated into public spaces. Finally, alternative solutions offering similar benefits were considered, exploring whether these might be more suitable in certain contexts.

Locations and Context

The discussions were tailored to address the varying conditions and challenges across different neighborhoods in the city:

- **Wakapasi**: A green, economic, and tourist center with many potential collaboration opportunities but no significant issues related to water nuisance.
- **City Center**: Characterized by high soil sealing, limited space, and significant damage from pluvial flooding, as well as high daytime temperatures and critical main roads.
- **Wintiwai**: A lower-income residential area with medium soil sealing and significant damage from pluvial floods.
- **Lelydorp**: A suburban area with low soil sealing, expected urbanization, high elevation, and no significant water nuisance issues.

Data Collection and Analysis

Participants were provided with neighborhood maps, post-its, large sheets of paper, pencils, and other supplies to facilitate discussion and documentation of their ideas. They were encouraged to write down as many ideas as possible, focusing on key discussion points highlighted earlier. During the pitches and general discussions, notes were meticulously taken to ensure that all ideas and comments were recorded for further analysis. This comprehensive approach to data collection allowed for a detailed evaluation of the think-tank outcomes after the session.

Limitations

While think-tanks are valuable for quickly generating ideas from diverse perspectives, their effectiveness can be constrained by group dynamics and time limitations. In large groups, participants may hesitate to share ideas due to fear of judgment, dominance by more outspoken members, or pressure to conform, leading to fewer unique contributions. This issue has also been observed during interviews conducted in the field, where certain participants' assertiveness can overshadow the contributions of others. In contrast, face-to-face interviews allow for personalized interaction and focused attention, often leading to deeper and more candid insights. Individuals tend to be more comfortable and open in one-on-one settings. Therefore, while think-tanks are useful for gathering a wide range of ideas, their limitations suggest that combining them with individual interviews might yield more comprehensive results.

4.2.4. Full-scale Test with Bioswales at AdeKUS

The full-scale test was designed to assess the technical implementation process and gather data on NbS performance in real-world conditions. While lab experiments provide valuable insights, only through full-scale implementation can we truly understand how these solutions perform and whether they meet our expectations. Additionally, encountering difficulties during the test enables us to identify challenges that may not have been apparent in theoretical or lab studies. This includes understanding the complexities of obtaining permits, accurately estimating costs, and developing realistic timelines for initiation, design, construction, and maintenance. By undertaking a full-scale test, we gain practical insights that are crucial for the successful implementation of NbS projects and for ensuring their long-term effectiveness and sustainability.

The test involved monitoring the BS's response to precipitation, focusing on processes such as retention, infiltration, and evaporation. This involves evaluating how the BSs manage water through processes such as retention, infiltration, and evaporation. By monitoring these processes, we aim to understand the effectiveness of the BSs in handling stormwater and their impact on the local water balance.

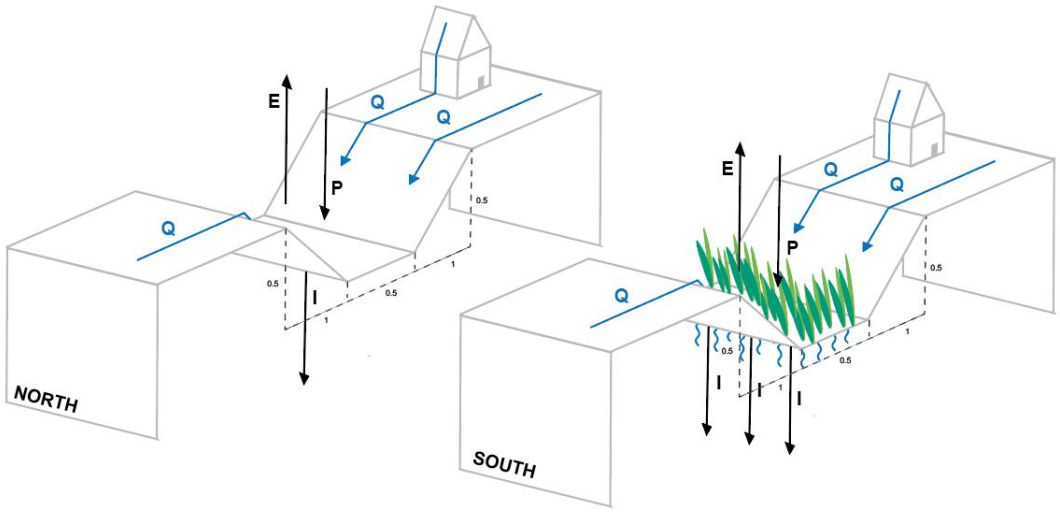


Figure 4.3: Design of BSs at AdeKUS. Both BSs facilitate rainwater inflow (P+Q), allowing it to evaporate (E) and infiltrate (I). The southern BS incorporates vegetation to enhance infiltration capacity. Dimensions are specified in the design.

1. **Initiation**
   A BS was installed near University Building 17, as shown in Figure 4.4, to address recurring water accumulation on the paved parking lots and walkways, which posed safety hazards and prevented parking. Soil samples were taken and analyzed. The project was supported by the university, an engineering firm, a contractor, and a gardener.
2. **Design**
   During the design phase of the BS, collaboration among the contractor, university, and engineering firm was crucial. The primary consideration was to utilize the low elevation ground to facilitate natural water flow from sealed surfaces such as roofs, parking lots, and roads into the BS. Design restrictions were implemented to prevent drowning of vegetation and to ensure that the settling time of the water was not excessively long, thereby optimizing the functionality of the BS. Additionally, a specific criterion was established wherein at least 10 percent of the paved surface area must be allocated for the BS, based on a Dutch rule of thumb [35]. This meticulous planning and design phase laid the foundation for the successful implementation of the BS, integrating both functional and ecological considerations into its construction. Furthermore, comprehensive mapping of underground infrastructure was undertaken to prevent conflicts during construction and to ensure the integrity of existing utilities.
3. **Construction**
   The soil profile was measured and mapped using a leveling instrument. The surrounding soil was then equalized to ensure that overland flow would direct into the BS. Careful excavation of the BS was conducted, as maps of the underground structure were not available. A professional operated a mini-excavator for this task. The excavated soil was used to further equalize the surrounding area. Vegetation was planted afterward, and existing grasses were cleaned beforehand to prevent them from overgrowing the new plants.
4. **Maintenance and Continuity**
   It is important to allow helophytes to grow to enhance the infiltration and filtering capacity of the BS. However, this growth takes time, and as such, the full benefits of these plants in improving the BS's performance cannot be registered immediately. Periodic mowing is necessary to prevent grasses from overgrowing the newly planted vegetation. Additionally, since the water level sensor does not log its data automatically, it must be manually read out.



Figure 4.4: Pre-construction images of the southern BS site.



Figure 4.5: Locations of the two constructed BSs at AdeKUS with paved surfaces and roof, along with their corresponding areas. Also shown are the locations where photos in Figure 4.4 were taken.

Measurement Campaign for the Southern BS at AdeKUS

The measurement campaign involved setting up instruments to monitor water balance fluxes, such as retention, infiltration, and evaporation, in response to precipitation. The test setup, illustrated in Figure 4.6, involves a monitoring well designed with perforations and covered with a socket to prevent clogging. This well is used to monitor groundwater levels in the BS. A TD-Diver sensor is installed within the monitoring well, connected via a cable and fixed to the top of the well casing. This Diver sensor measures pressure variations within the well. Additionally, a barometer is positioned elsewhere on campus to record atmospheric pressure, and a reference well is installed 400 meters from the BS using similar equipment for comparison.



Figure 4.6: Test setup for the southern BS at AdeKUS, including diver water level measurements, precipitation data from a nearby weather station, and rough estimates of evaporation rates to calculate the intake of the swale. Additional footage of the BSs will be continuously updated on ClimateScan

Data Processing

The test setup operates during the early stage of the rainy season to capture changes in water levels and pressures associated with precipitation. This period is chosen to observe the response of the BS to rainfall events, providing insight into the efficiency of the swale's infiltration capacity.

In Appendix C, I processed groundwater monitoring data by managing various tasks such as data initialization, loading, and pre-processing of Diver sensor and barometer readings. I calculated the water level in the well by performing barometric compensation and compensating for the length of the cable that the diver is attached to, as described in Equation 4.3 and illustrated in Figure 4.7. I used the bottom of the BS as the reference water level and indicated the states of the BS with respect to the water level in Table 4.3.

Table 4.3: State of the BS based on the water level with the bottom of the BS as a reference point.

h water level (mm)	State	Meaning
$h < 0$	Groundwater table is below the bottom of the BS	The groundwater level remains beneath the base of the BS.
$h = 0$	The BS is empty	The BS contains no water.
$0 < h < 500$	The BS is filled	Water has accumulated in the BS, covering the bottom but not reaching its maximum capacity.
$h = 500$	The BS is completely filled	The BS has reached its maximum capacity, holding water up to its brim without overflowing.
$h > 500$	The BS overflows	Water volume exceeds the BS's capacity, resulting in overflow onto surrounding areas or drainage systems.

$$h = TOC - CL + \frac{9806.65 \times (p_{\text{diver}} - p_{\text{baro}})}{\rho_{\text{water}} \times g} \tag{4.3}$$

Where:

h : Water level in the BS or well (cm)
TOC : Top of the monitoring well with respect to reference level (cm)
CL : Cable length (cm)
p_{diver} : Pressure measured by Diver sensor (cmH2O)
p_{baro} : Pressure measured by barometer (cmH2O)
ρ_{water} : Density of water (kg/m^3)
g : Acceleration due to gravity (m/s^2)

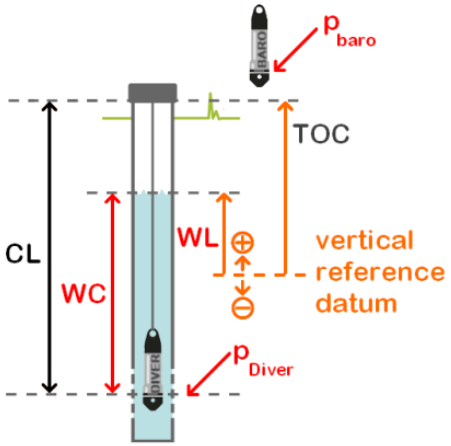


Figure 4.7: Test setup for water level measurements with TD-Diver datalogger and barometer in the BS at AdeKUS (Figure from diver manual)



Figure 4.8: Weather station from HydrometCloud used due to connection issues with the personal weather station. This station is the closest alternative with available data and similar conditions.

The primary weather station intended for this study was the personal weather station that is installed close the BSs. However, due to limited access to the required 2.4 GHz connection on campus, this option was not feasible. As a result, climatological data was sourced from the Ring_Harbour weather station (AWS Suriname), depicted in Figure 4.8. Located approximately 15 kilometers from the BS research site and closer to the coastline, this station served as a relevant alternative despite not being the initial choice.

Precipitation data from this station is used to assess rainfall at the BS site. Additionally, temperature, wind speed, and relative humidity data were utilized to perform an indicative calculation of the open water evaporation in the BS. These parameters are essential for understanding the water balance and evapotranspiration rates in the study area.

The open water evaporation rate is calculated because the BS is predominantly filled with water. Typical climatological data for Paramaribo, such as relative humidity, temperature, and wind speed, are taken from different weather stations with similar conditions. This is necessary as the weather station in the test setup was not operational at the time of the research. These calculations provide an indication of which process is dominant in the release of water in the BS: evaporation or infiltration. Drainage is considered negligible, as the water is being retained in the swale.

4.2.5. Simulations

To assess the potential effect of widely employing full-scale NbS tests in the study area of Wakapasi, I conduct a series of simulations. These simulations are based on the urban water balance model, illustrated in Figure 4.9. The script used to perform these simulations is provided in the appendix.

The study begins by creating a land use map for the Wakapasi neighborhood. This map divides the

area into distinct elements as shown in Table 4.4. Using this map, the model incorporates various land use types to simulate water flow and balance under different conditions.

The Urban Water Balance Model

Even though many hydrological analyses have been performed in Paramaribo, as described in Section 3.2, specific aspects related to NbS have not been extensively researched, necessitating my own observations. I carry out these observations continuously during fieldwork, particularly during heavy rainfall events, to identify bottlenecks in the system such as pluvial flooding or sewage overflow. Interviews with local experts and stakeholders offer in-depth insights and contextualize the observed data, helping pinpoint where water flows, identify system bottlenecks, and determine potential roles for NbS interventions. Additionally, I accomplish this through a combination of observations, interviews, and literature review. I conduct observations through GIS satellite imagery and existing products of Deltares to gather real-time and spatial data. The technical analysis of the water system in Wakapasi and Paramaribo aims to map and understand the components and provides a foundational understanding of the water system.

The Urban Water Balance (UrbanWB) model is a lumped conceptual tool designed to simulate the water balance in urban environments, helping planners and resource managers understand water distribution and flow within cities. The model evaluates water inputs and outputs, including precipitation, evapotranspiration, runoff, and infiltration, while accounting for both natural factors (e.g., rainfall, soil properties) and human activities (e.g., land use, drainage systems). The ”lumped” nature of the model means it categorizes areas by land use type, assigning average hydrological behaviors to groups rather than individual plots. This simplification aids in efficiently simulating various urban development scenarios.

The schematic representation helps assess the applicability of the water system analysis to Paramaribo by estimating key parameters such as the size of the closed sewage system, land use patterns, and interception capacities. Understanding these parameters is crucial for evaluating the current state of the water system and identifying areas where NbS can be implemented effectively. By doing so, the UrbanWB model provides critical insights that inform decision-making and policy development for sustainable urban water management.

However, the UrbanWB model has certain limitations. It does not account for the specific locations of different land uses within the urban area, which means it cannot model the effects of spatial distribution on water flow and storage. Additionally, the model may not capture the intricacies of highly localized hydrological phenomena, focusing instead on broader trends and patterns. Despite these limitations, the UrbanWB model remains a valuable tool for urban water management, providing critical insights that inform decision-making and policy development.

Table 4.4: Elements and Water Flows within Urbanwb model (Source: Deltares).

Elements		**Water flows**	
A	= area	P_atm	= precipitation
atm	= atmosphere	E_atm	= evaporation
PR	= paved roof	T_atm	= transpiration
CP	= closed paved	R_up	= decoupled runoff
OP	= open paved	R_ow	= runoff to open water
UP	= unpaved	I_uz	= infiltration
OW	= open water	P_gw	= percolation
UZ	= unsaturated zone	D_ow	= drainage
GW	= groundwater	S_out	= downward seepage
MSS	= mixed sewer system	R_mss / R_swds	= runoff to sewer systems
SWDS	= stormwater drainage system	SOF	= sewer overflow on street
SO	= sewer overflow	Q_ow	= discharge to open water
WWTP	= waste water treatment plant	Q_out	= discharge to outside / WWTP

Simulating NbS application in Wakapasi

I conducted a simulation to evaluate the hydrological impact of converting 5% of the unpaved area in the study area into infiltration facilities, utilizing historical weather data as a baseline. This simulation forms part of a broader analysis aimed at understanding the potential benefits of NbS.

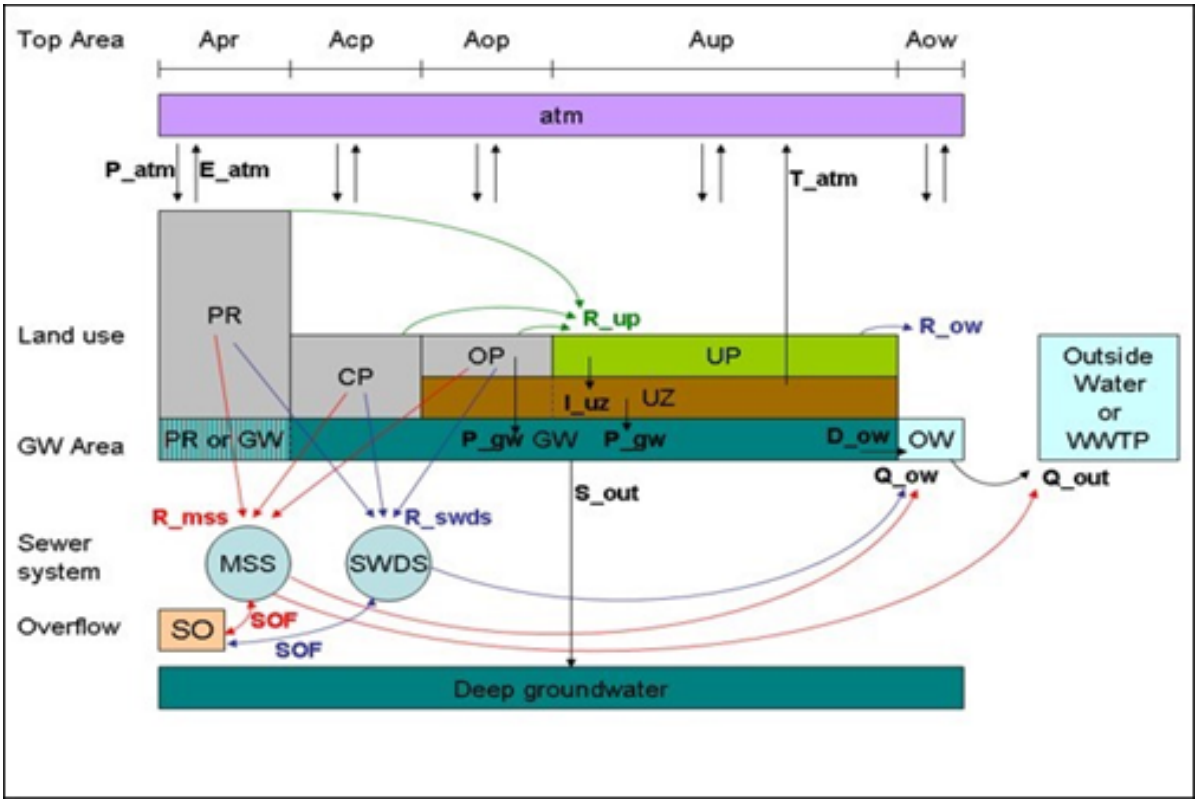


Figure 4.9: Schematic overview of Urbanwb model used for simulation of NbS in Wakapasi. This scheme describes the water flow paths in an urban environment. Description of elements and waterflows are given in Table 4.4 (Source: Deltares).

The simulation, based on a zero-dimensional mass balance model with parameters from previous model studies [64], is designed to assess the effects of this specific NbS implementation on key urban water flows such as sewage overflow, groundwater recharge, and surface runoff. A land coverage map of the neighborhood was used to accurately represent the distribution of paved and unpaved areas in the study.

The simulation process began with establishing a baseline scenario, which represents the current urban water balance without any NbS interventions. This baseline serves as a control for comparison. The chosen NbS scenario, involving the conversion of 5% of the unpaved surface area into infiltration facilities, was then simulated under historical and projected future climate conditions to evaluate its potential impact on the urban water system.

Limitations

There are several limitations to this study. Firstly, the reliance on historical data may limit the accuracy of the simulations in reflecting future conditions. Incorporating more accurate climate projections could significantly enhance the reliability of these simulations, providing a better representation of potential future scenarios. Additionally, the projections are provided per season rather than per intensity, which would be more desirable for this application. Variations in dry and wet days within the same season could potentially offset each other, affecting the overall results. While different implementation scenarios could be used to iterate and refine the simulations, this has not been done in the current study, which may limit the exploration of a broader range of potential outcomes. These limitations suggest that the simulations are subject to a degree of uncertainty, particularly regarding input data and model assumptions.

5

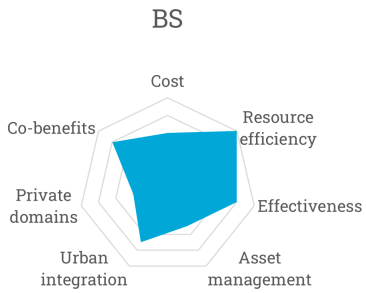
Results

Reading Guide: *This chapter presents the results of the research activities conducted in this thesis. It begins with an MCA to identify a set of NbS suitable for Paramaribo, as detailed in Section 5.1. Next, it highlights the thematic analysis of interview responses in Section 4.2.2, followed by the results from the think-tank in Section 5.3. Finally, data analyses from the full-scale test and simulations over Wakapasi are presented in Section 5.4 and Section 5.5, respectively.*

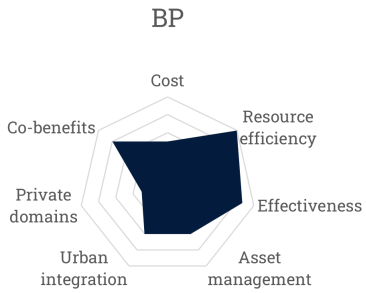
5.1. Analysis NbS on Multiple Criteria

In this multi-criteria analysis, I evaluate various NbS, highlighted from recent literature [15], based on multiple criteria considering the context of Wakapasi, Paramaribo, outlined in Table 4.1. I set up the criteria based on literature and the specific context and needs of Paramaribo, retrieved from stakeholders that participated in interviews and the think-tank. Each NbS type is scored on a scale from 1 to 5 per criterion, with 1 predicting deterioration than the status quo, 3 indicating similar effects and 5 predicting significant improvement after utilization of NbS regarding that criterion. The scores are presented in Figure 5.1. What stands out is that BS, BP, TP, CW, and GW, in particular, receive high unweighted scores.

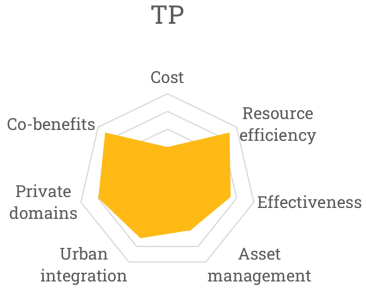
Large areas in the figure represent positive unweighted scores for the specific measure. For instance, BSs have lower construction costs compared to conventional sewer systems while providing similar functionality in terms of flood risk management. However, some expect higher maintenance costs and the high value of land in inner cities to offset these savings. As a result, the cost is scored at 3, indicating comparable expenses. In contrast, PPs can be effective and more sustainable, but replacing conventional roads with PPs can be expensive, leading to a lower score of 1.



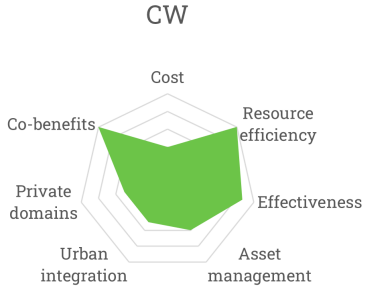
(a) Bioswale



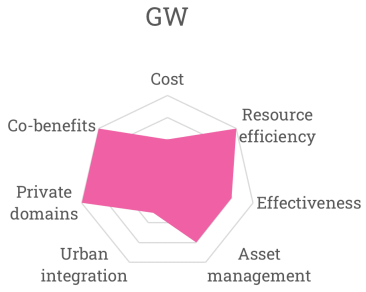
(b) Biopond



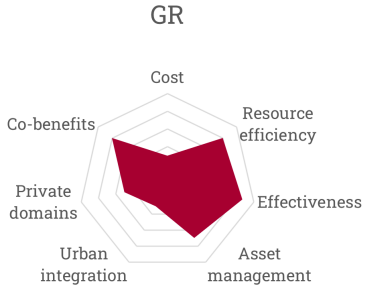
(c) Tree Pits



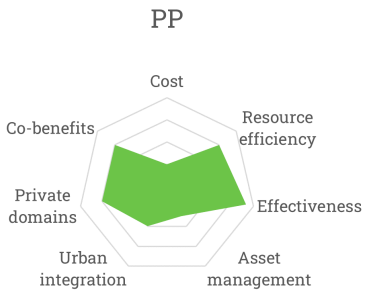
(d) Constructed Wetland



(e) Green Wall



(f) Green Roof



(g) Permeable Pavement

Figure 5.1: Various green infrastructure solutions assessed on multiple criteria without weights.

The weights of the criteria are assigned such that costs and efficacy in reducing flood risk are prioritized, as these are essential requirements for the measures. Asset management and urban integration have also proven to be crucial based on past practices. Following these are co-benefits, private domains, and resource efficiency, which are not the top priorities for Paramaribo at the moment. All weights are visualized in Figure 5.2.

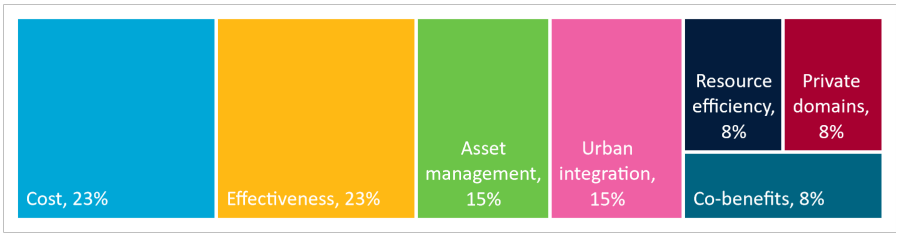


Figure 5.2: Weights for criteria.

Infiltration facilities such as bio ponds, bioswales, and constructed wetlands score highest in Figure 5.3 due to their relatively simple construction and the availability of sufficient space or areas where pavement is unnecessary. These facilities effectively address key water-related challenges, including flood risk, drought, heat stress, and poor water quality. In contrast, permeable pavements are less suitable for Paramaribo due to their high construction and maintenance costs, which are given high priority. Green walls are ineffective in reducing flood risk and add structural load to buildings, which most structures in the city cannot support, highlighting the impact of the assigned weights. Similarly, green roofs are heavy and retain less water compared to infiltration facilities, making them less practical for the city's needs. Structures scoring lower than 3 are not included in further research, as this integrated assessment indicates they do not offer sufficient improvements relative to their costs and effects compared to the status quo. 33

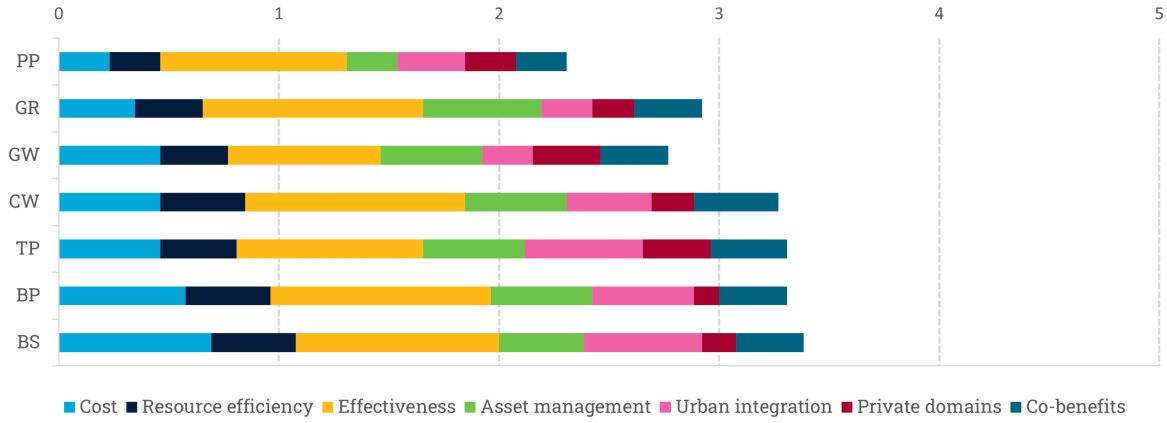


Figure 5.3: Weighted scores for different types of NbS based on criteria from Table 4.1. With abbreviations: PP = Permeable Pavement, GR = Green Roof, GW = Green wall, CW = Constructed Wetland, TP = Tree pit, BP = Bio pond, BS = Bioswale.

5.2. Interviews

The interviews listed in Appendix B provided valuable insights into the implementation of NbS in Paramaribo, with key findings summarized in Table 5.1. An overview of the main considerations from different sectors is illustrated in Figure 5.4.

The interviews reveal a general struggle among stakeholders regarding where to start and which organization has the capacity to lead initiatives in Wakapasi. While there is willingness to participate, stakeholders agree that clear guidelines are necessary to streamline efforts. Public authorities are uncertain about the effectiveness of infiltration in the city's impermeable clay soils. However, some industry participants point out that vegetation in other parts of Suriname has improved drainage through preferential flow paths. There is also skepticism about the potential of NbS to retain water without attracting mosquitoes, pests, and snakes. Additionally, concerns are raised about whether investments should focus on expanding and intensively maintaining the drainage network instead of relying solely on NbS.

The thematic analysis in Figure 5.4 highlights differing opinions on the implementation of NbS. Public authorities, who are more aligned with grey infrastructure, are inclined to support new infrastructure projects. In contrast, other respondents appreciate the concept of green cities but are deterred by the intensive maintenance required. While there is a willingness to participate in NbS implementation, it is often linked to direct benefits such as local solutions to water nuisance or subsidies. Most sectors, including public authorities, believe that the responsibility for implementing NbS should lie with the government but lack clarity on which organization has the capacity to address these challenges effectively. Furthermore, some suggest a closer examination of existing infrastructure, which already incorporates green elements, to evaluate its potential in addressing the city's challenges.

Table 5.1: Highlights of responses during interviews

Topic	Public Authorities	Industry	Academia	Citizen
Local perceptions and experiences related to Wakapasi.	Water quality is a significant concern, especially during the dry season when minimal water is discharged from the pumping station, leading to unpleasant odors from the Sommelsdijck Creek. Fall hazards in the creek at Wakapasi are currently mitigated with fences, which are, however, dangerous for children. There is no water nuisance in the Wakapasi study area, but further towards Julianalaan, water blocks roads and enters homes and businesses. People seek cooling near the waterfront and in shaded areas; the Palmentuin is less frequented due to poor visibility and limited social safety.			
Roles and impacts of different stakeholders in Wakapasi.	The government holds responsibility for the city's green policy but currently lacks sufficient capacity to manage and implement these initiatives effectively.	Businesses affected by water nuisance are eager to take effective measures. If not, such actions should be mandated through legislation and regulations.	-	Schools and businesses can contribute through citizen science. The community can be motivated to implement NbS on their properties with proper initiative and support from an organization.

Topic	Public Authorities	Industry	Academia	Citizen
Challenges and opportunities identified by participants.	There is a need for standards and guidelines, as there is currently uncertainty about where to start. Opportunities exist for improving drainage by clearing drainage channels, as the current system is not robust. NbS can enhance this. Funds are typically allocated for infrastructure rather than asset management.	Preferential flow paths can significantly enhance the infiltration capacity of BSs. For example, reeds in Lelydorp have greatly improved drainage capacity in a small plot. Using locally growing plants is desirable. BSs can also be utilized for the post-treatment of water from septic tanks in Suriname. NbS function as systems with a broad range of effects on various stakeholders. For engineers, solutions are often client-specific and localized, making NbS not always the obvious choice.	Infrastructure must have a certain level of multi functionality. A simple BS alone does not provide enough value to be integrated into urban planning, especially in Paramaribo. Green infrastructure will always need to be combined with gray infrastructure.	-
Suggestions and expectations for future developments.	Significant progress in preventing water nuisance can be made by expanding the drainage network, not entirely convinced of the potential effect of NbS.	There is a divide in opinions regarding the effectiveness of NbS. Some executors are skeptical about infiltration through clay layers, while others, particularly engineers, are more optimistic.	-	Green spaces in the city are highly desired, but on a personal level, the additional maintenance required often leads to preference for paving.
Opinions on specific NbS and their application.	There is no preference for specific structures; interest lies in professional opinions and their implementation. Generally, the less maintenance required, the better.	Combining the functions of BSs with the positive effects of permaculture and helophyte filters is beneficial.	Many green structures in Paramaribo already fulfill their intended functions without the NbS label. Therefore, the application of NbS is particularly interesting in the city center.	There are concerns about pests and mosquitoes with the introduction of standing water in the city.

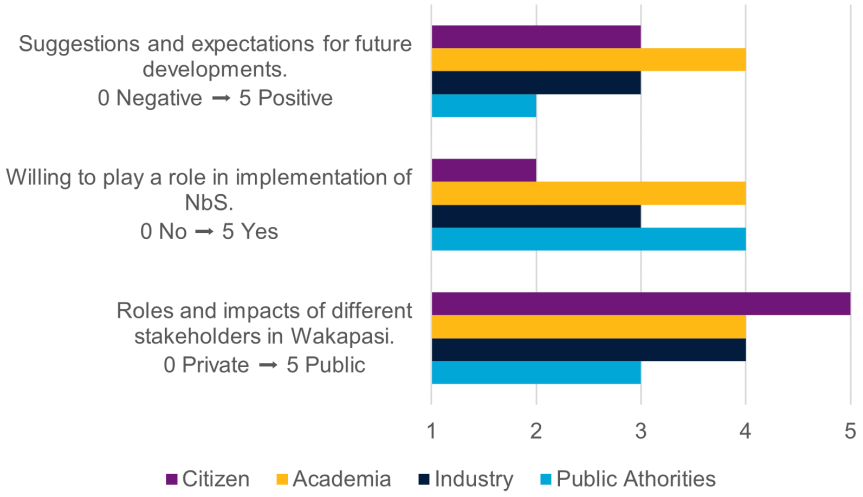


Figure 5.4: A summary of insights from various sectors regarding three key considerations for design and strategy.

5.3. Think-tank main statements by participants

During the think-tank that is conducted as described in Section 4.2.3, input was given by over 20 participants on different topics regarding to this research. Some deliverables of the participants are provided in Appendix E, and presented in this section.

Local Perceptions and Experiences Related to Wakapasi

Flooding and heat stress are identified as the biggest problems in Paramaribo. Participants indicated that they were not aware of the local problems there. Wakapasi, on the other hand, is well known among all participants. The smell from the Sommelsdijckse Creek and obstructions in the drainage channels were specifically mentioned as concerns in Wakapasi. Opportunities in Wakapasi exist due to the business activities and potential collaborations with successful companies, as well as the large amount of public space.

Roles and Impacts of Different Stakeholders in Wakapasi

The feasibility of Wakapasi largely depends on the cooperation between government and private sectors, potentially through Public-Private Partnerships (PPP). Participants highlighted the importance of collaboration between government entities, private companies (such as Werkse for green space maintenance), neighborhood managers, and district commissioners (DC) for effective monitoring. Stakeholders have distinct roles: the government oversees public spaces, while private initiators manage their properties. Coordination among utility companies and governmental bodies is crucial for successful implementation.

Challenges and Opportunities Identified by Participants

Challenges identified include the need for legislation to support sustainable urban expansion, seasonal time management for maintenance, and ensuring green policies such as conserving existing green areas and implementing green roofs where possible. Managing the complexity of spatial planning, including mapping inundation areas and existing infrastructure like cables and pipelines, was also highlighted as a significant challenge. On the other hand, opportunities include utilizing natural gradients for drainage to reduce maintenance, incorporating BSs in residential areas for efficient water management while keeping primary and secondary drains open, and engaging communities in bottom-up initiatives like BSs to foster local ownership and understanding.

Suggestions and Expectations for Future Developments

Suggestions for future development include integrating open drainage systems to handle large volumes of rainwater, simulating and planning for the expansion into private areas, implementing wastewater treatment laws, and promoting a green mindset across the nation, emphasizing the government's role in greening urban areas. Expectations include government and private sector collaboration in maintaining green spaces, legislation to support the sustainable development of urban areas, involving relevant

ministries (e.g., BOG, OW, ROM) to coordinate green policies aiming for more than 10% green space in public and private plots, and the perception that the responsibility for urban greening lies with the government, particularly among OW officials.

Some innovative ideas were proposed, such as creating green canals and open paved pedestrian paths in shopping areas within the city center where car roads are currently located. These canals could incorporate NbS structures for water retention and infiltration.

Opinions on Specific NbS and Their Application

Participants expressed strong motivation for sustainable urban expansion, preparing for climate change, preventing flash floods, and promoting water and soil health. The community values Wakapasi as a solution that aligns with these goals. However, there is a general sense that success hinges on expanding these solutions to private properties and incorporating them into legislation.

Top-down approaches suggest that Suriname should project an image of being a green country, requiring significant legislative changes. Any development that reduces water space, such as parking garages, should include compensatory green provisions within the project. Bottom-up approaches emphasize the importance of communication, coordination, and collaboration among utilities and government agencies. Community involvement in installing BSs is crucial, targeting areas where residents understand their benefits. Additionally, centralized treatment areas for greywater purification, particularly in tourism, schools, businesses, government land, and vacant plots, are recommended.

5.4. Data Analysis of the Full-scale with Bioswale at AdeKUS

The data analysis for the AdeKUS BS provides insights into its performance and environmental impact. Figure 5.5 shows the geological profile of the location where the BS is constructed. This profile reveals that the site is predominantly composed of clayey soil, with its low permeability.



Figure 5.5: Geology of the measuring well. The vertical axis represents the depth in centimeters. The red line indicates the mean lowest groundwater level, and the red dot represents the diver. The well and its casing are illustrated to the right of the geological layers. All measurements are taken from the ground level.

The measurement campaign, depicted in Figure 5.6, showed that water levels in the BS generally tracked precipitation patterns. However, an discrepancy observed on May 1st, where water levels rose despite minimal rainfall, could be attributed to inaccuracies in the data from the weather station, which was located 15 km away from the site. Additionally, it is important to note that these measurements were taken prior to the introduction of vegetation into the BS, which could impact water retention and infiltration in subsequent tests.

The evaporation rate was approximately 3.3 mm/day, consistent with other research in Suriname [70]. Detailed calculations are provided in Appendix F. This suggests that evaporation has a minor role in the reduction of water levels, with the majority of water release attributed to infiltration. Additionally, this relatively low evaporation rate may limit the cooling effect of the BS, possibly due to the high relative humidity in the region.

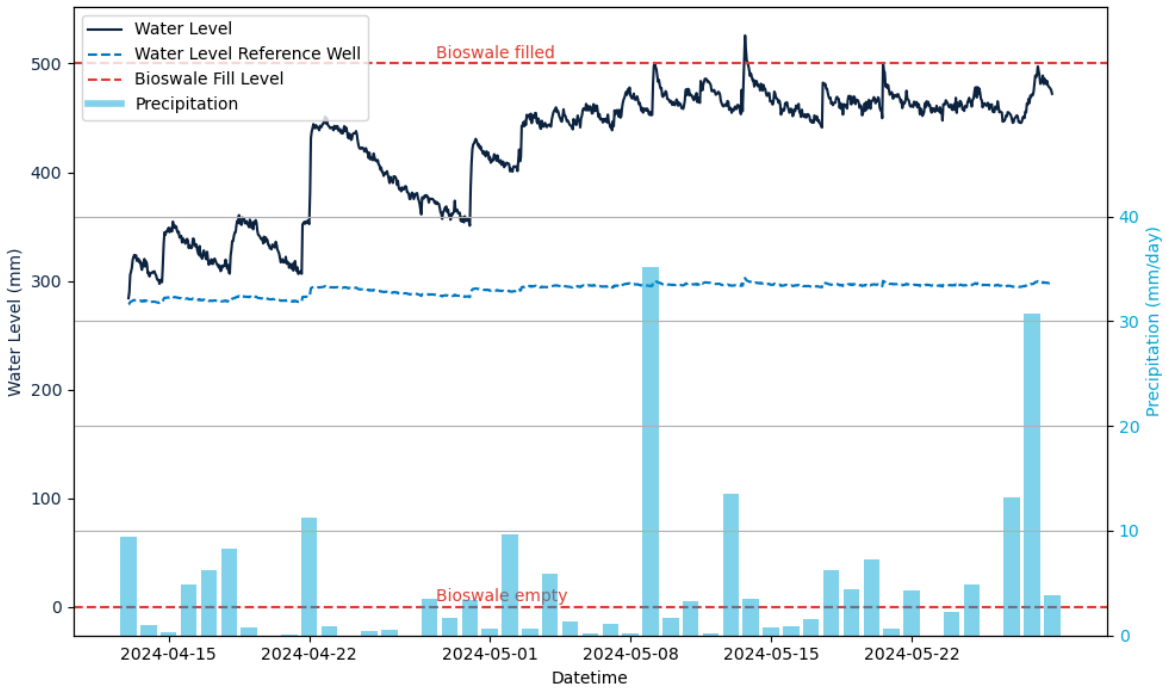


Figure 5.6: Water level response in the BS relative to precipitation during a full-scale test

Criteria for Identifying Infiltration Events: To clearly define infiltration events, the following criteria were applied:

- No significant rainfall events (>10 mm) during the infiltration event.
- The event duration must exceed two days.

These criteria help ensure that the infiltration events are accurately identified and not influenced by external factors like heavy rainfall. Events meeting these criteria are highlighted in Figure 5.7 with a red dashed line.

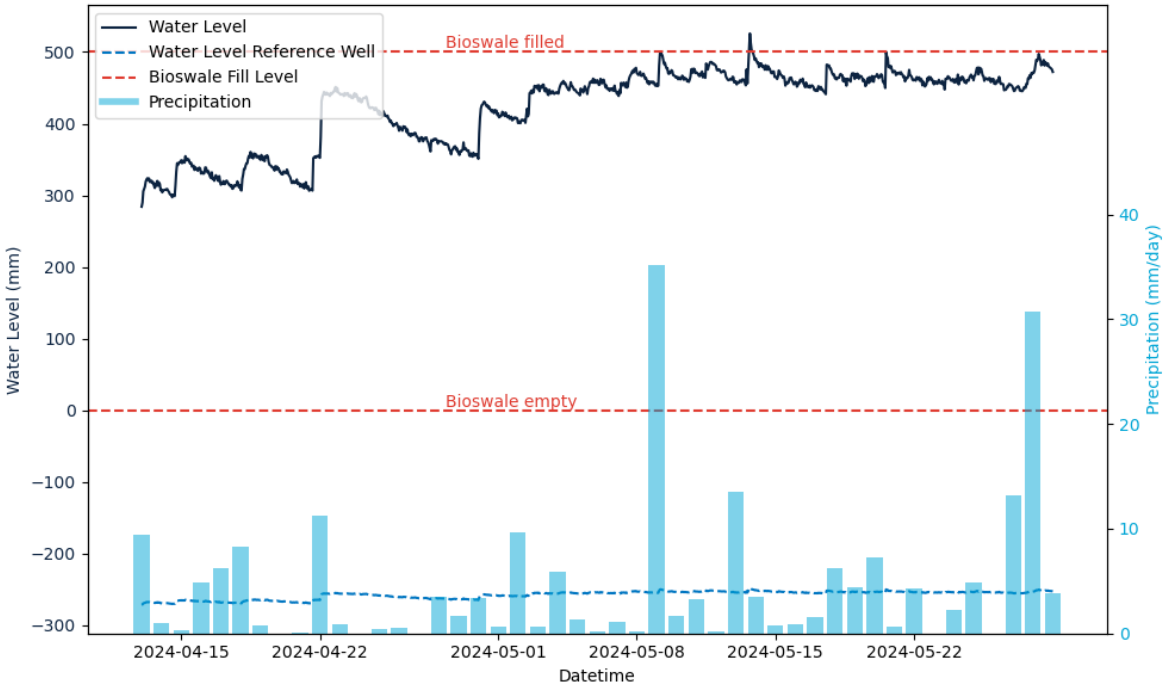


Figure 5.7: Infiltration events in the bioswale.

The heaviest rainfall event occurred from May 13th to May 15th, indicating that the surrounding area contributes to water infiltration into the BS. The permeable soil around the BS contrasts with others, which are often bordered by impermeable surfaces such as asphalt. The highest recorded infiltration rate during this event may not fully represent the BS's maximum capacity. The actual maximum infiltration capacity, approximately 25 mm/day, is shown in Figure 5.8, aligning with results from other double ring infiltration tests on campus.

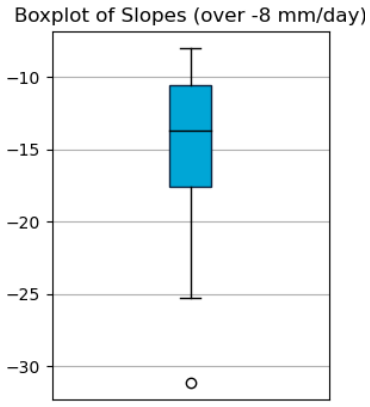


Figure 5.8: Boxplot of the infiltration rates of the bioswale

Additional clarifying scripts, plots, calculations, and descriptions are available in Appendix G.

The measurement campaign, as depicted in Figure 5.6, reveals that the BS generally aligns with precipitation patterns, indicating a responsive design. However, an unusual increase in water levels on May 1st, despite minimal rainfall, suggests potential inaccuracies in data from a distant weather station located 15 km away. This highlights the need for more localized weather data to better correlate water levels with actual precipitation.

Evaporation rates, calculated using the Penman-Monteith equation from weather station data detailed in Appendix F, did not exceed 4 mm/day. This low rate indicates that the decrease in water levels is predominantly due to infiltration rather than evaporation. As shown in Figure 5.8, infiltration rates reached up to 30 mm/day. While this suggests that the BS effectively facilitates water infiltration, it also implies that the BS's capacity may be insufficient to handle pluvial flooding during heavy rainfall events.

The low permeability of the clayey soil and the high groundwater table contribute to this limitation. According to design principles [35], a BS should ideally drain within 24 hours to manage subsequent rainstorms and prevent issues such as waterborne diseases and mosquito breeding [71]. This concern was also noted during co-creation sessions, emphasizing the need for improvements in the BS design to meet these standards.

Despite these limitations, the BS could offer additional benefits that warrant further exploration. Preliminary estimates from the Climate Resilient Cities Toolbox (CRC-Tool), as shown in Table 5.2, suggest a minor reduction in heat following the BS's construction. This finding is consistent with the low evaporation rates calculated, indicating potential benefits such as reduced heat stress, enhanced biodiversity, and improved water quality.

However, the significant overestimation of costs in the CRC-Tool predictions highlights that these estimates are preliminary and should be interpreted with caution. Accurate cost assessments are essential for future planning and the successful implementation of similar projects. In summary, while the BS at AdeKUS demonstrates effective water retention and low pest activity, its performance in terms of infiltration and drainage falls short of optimal standards.

Table 5.2: Estimated effects of the two bioswales at AdeKUS from CRC-tool. A = Area; V = Volume ; R = Groundwater recharge; RTF = Return time factor; E = Transpiration evaporation; HR = Heat Reduction.

Measure	A (m^2)	V (m^3)	R (-)	RTF (mm/y)	E (mm/y)	HR (C)	Cool areas	Costs ()	Costs ($/y$)
BS South	127.52	64	1.04	2	0	0.02	0	10,520	105
BS North	49.96	25	1	0	0	0.01	0	25,274	2,366

5.5. Simulations for Implementation of NbS in Wakapasi

Simulations based on a 5% implementation scenario of unpaved areas in Figure 5.9, using historical data, show minimal impact on the groundwater table, as illustrated in Figure 5.10. According to the simulations, the groundwater table rises with 5% on average, the soil moisture content with 1% and the sewage overflow does not show significant change.

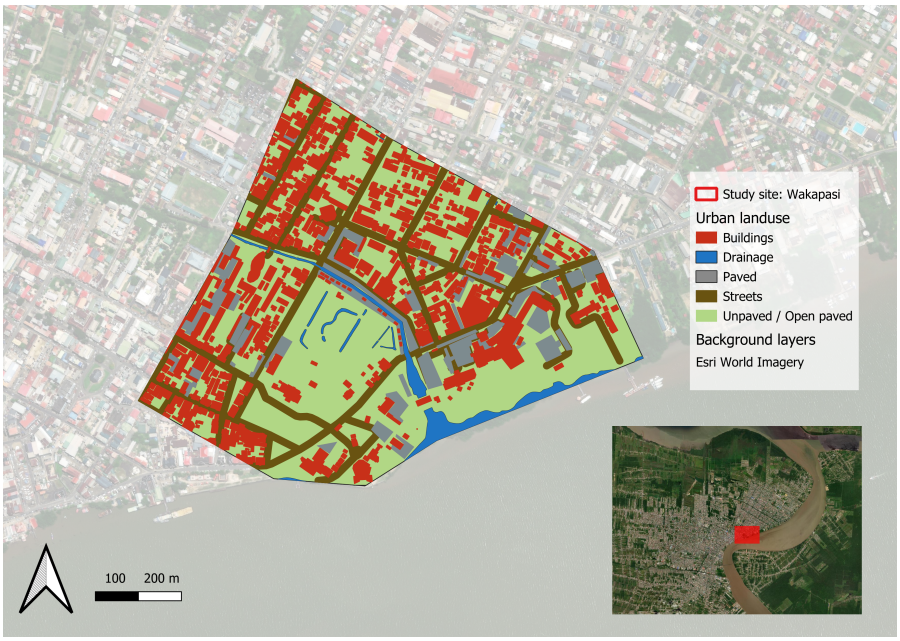


Figure 5.9: The land use map of the study site, which is the foundation for the simulations of the hydrological behaviour of the site. With 36% unpaved, 27% paved, 25% buildings, 9% open paved and 3% open water.

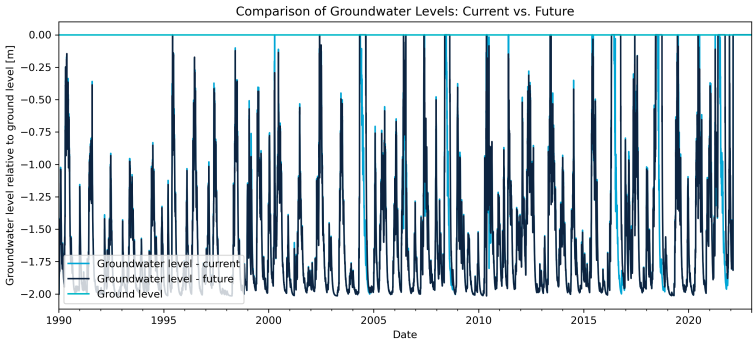


Figure 5.10: Simulations of groundwater table for a when 5% of the unpaved land surface would change into infiltration facilities according to the Urbanwb Model.

6

Discussion

Reading Guide: *This chapter presents the results of this thesis through three main pillars: socio-economic, technical, and institutional. The socio-economic context relevant to the implementation of NbS in Paramaribo is discussed in Section 6.1. Technical considerations, guidelines and indicative designs are covered in Section 6.2 with design principles and visualizations respectively in Chapters 6.1 and 6.2.2, while institutional implementation and strategies are addressed in Section 6.3. The results from Wakapasi are then projected onto Greater Paramaribo in Section 6.4 to illustrate how design principles and typologies can be applied in other regions. Following this, Section 6.5 highlights the key points of discussion and research limitations, and Section 6.6 provides a comparison with existing literature for validation purposes.*

6.1. Socio-Economic Context to be Considered for NbS

Based on the lessons learned from NbS around the globe as discussed in Section 2.1.3, we understand that the use of unsustainable materials in NbS can have long-term drawbacks. For instance, geotextiles, which are installed to prevent clogging and control infrastructures, can themselves become clogged after several years [35]. Furthermore, these infrastructures require frequent maintenance, which poses a significant challenge in Suriname due to the current struggles with asset management and limited resources for financing infrastructure.

Given this context, low-cost and low-maintenance infrastructures are particularly suitable for Paramaribo. While real-time control systems could potentially help by retaining and releasing water at desirable times, they are not feasible in Paramaribo's socio-economic context. These systems require intensive asset management, substantial financial resources, and capacity that is currently lacking in the responsible institutions, as highlighted by Werf et al. [72].

Approximately 50% of the land use in Paramaribo is residential [12], making public participation essential in efforts to combat soil sealing. Focusing solely on public terrain has proven insufficient, even in the Netherlands [19]. Fieldwork in Paramaribo revealed that the local population is notably enterprising compared to other countries with high NbS employment rates. Many residents build or design their own houses, manage household-scale drainage, and possess substantial knowledge about managing heavy rainfall. They maintain their own piping systems rather than relying on professional plumbers, indicating that ownership and participation are critical for successful NbS implementation.

However, the relatively new concept of NbS has not yet reached the wider public in Paramaribo. Therefore, knowledge sharing and accessible activities introducing NbS are crucial for its successful adoption. Engaging the community through educational campaigns and practical demonstrations will be key to fostering the necessary understanding and involvement for NbS to thrive. From experience during fieldwork, private instances and households are positive towards nature-based interventions, but need empowerment and provided with technical guidelines to come to implementation. Community engagement practices inspired on the Netherlands might be very useful here, considering the the entrepreneurial nature of the people in Suriname.

Community Engagement in Dutch Municipalities: Effective Climate Adaptation Strategies

Dutch municipalities engage communities in climate adaptation through participative initiatives. Examples include programs like NK Tegelwippen (National Tile Flipping Championship) and Tegeltaxi (Tile Taxi), alongside awareness campaigns such as Weerwoord 2030.

NK Tegelwippen is a competitive event where municipalities and their residents remove pavement tiles from their gardens and replace them with greenery. This low-cost initiative not only reduces soil sealing but also promotes community involvement and environmental stewardship, achieving NbS coverage on private terrains.

Tegeltaxi offers a convenient service to collect and dispose of the removed tiles, making it easier for residents to participate in greening their surroundings. This program ensures that logistical barriers to participation are minimized, encouraging wider involvement.

Weerwoord 2030 is an awareness campaign that educates the public on climate adaptation measures and encourages proactive steps towards a more resilient environment. By raising awareness and providing practical information, this campaign fosters a community spirit geared towards sustainable practices.

One of the keys to the effectiveness of these initiatives is their politically neutral approach, which garners broad support across diverse community segments. This neutrality is crucial as it ensures that the efforts are seen as collective, community-driven projects rather than politically motivated actions. Intrinsically motivating people, rather than forcing them, proves to be more effective. This approach can be a challenge in Suriname, where government or ministry often claims credit for investments, potentially leading to partisan divides and reduced public engagement.

6.2. Technical Design and Efficiency of NbS

The implementation of NbS in Wakapasi presents several challenges and considerations that must be addressed to ensure their effectiveness. A key aspect is the simplicity of the technique used. While simpler systems might be easier to maintain, they are not necessarily free from issues such as clogging. Fragmentation and compacting can lead to clogging, reducing the effectiveness of the system [73]. Therefore, it is essential to balance simplicity with functionality to maintain long-term efficiency.

The permeability of the soil and the groundwater table are critical factors in determining the infiltration capacity of bioswales (BSs). Effective infiltration depends heavily on these factors, as any limitations can significantly hinder the performance of BSs. Vegetation plays a vital role in this process, not only by improving water quality but also by enhancing infiltration rates. Research has shown that vegetation can increase infiltration rates by up to tenfold, primarily through the creation of preferential flow paths in low-permeability soils [74, 75, 76]. These flow paths, formed by the roots of vegetation, allow water to bypass the more resistant soil matrix, thereby accelerating the infiltration process. While engineered vegetation can be highly effective in establishing these pathways, it is often prohibitively expensive for larger areas. On the other hand, naturally growing vegetation, though slower to establish, can achieve superior long-term results. As plants grow and die, they contribute to the development of healthier soil and more extensive flow paths, further enhancing infiltration capacity over time. It is crucial to raise public awareness about the importance of this vegetation to prevent it from being mistaken for weeds, which are often perceived negatively but play a key role in the functionality of BSs.

The ongoing research indicates that vegetation will be introduced after the current study period, allowing for the effects to be observed and analyzed in the future. However, there are broader environmental factors to consider, such as sea level rise, which can elevate groundwater tables and create less favorable conditions for infiltration facilities. These changing conditions must be accounted for in the design and implementation of NbS.

Moreover, while NbS can contribute to reducing flood risk, they may not be sufficient on their own. A combination of green and grey infrastructure is often necessary to achieve the desired outcomes. This hybrid approach can enhance water retention and improve livability while effectively mitigating flood risks. The integration of these systems requires careful planning and coordination to ensure they complement each other and address the unique challenges posed by the local environment.

6.2.1. Design Principles and Guidelines

These findings are summarized in indicative guidelines for the construction of infiltration facilities such as BSs are formulated in Table 6.1 based on the findings presented in this thesis, as well as from studies

and practices from various parts of the world, including tropical regions. The key design principles for BSs in Paramaribo include allowing native vegetation to grow within the BS. This approach increases the infiltration capacity and humus content, and it facilitates the purification of water. The use of native plants also enhances the ecological resilience of the BS.

Table 6.1: Indicative guidelines for bioswales in Paramaribo.

Design Parameter	Unit	Europe [77]	Colombia [16]	Suriname	Justification
Swale area/drained area	m^2/m^2	5-10		**5**	Lower range due to heavy rainfall
Distance to houses	m	>1	4	**4**	Similar foundation types
Swale water depth till overflow	m	<0.3		**<0.5**	Reduced visibility from vegetation; lower infiltration rates
Longitudinal slope	V:H	1:3 or less	1:3	**1:5**	No need for mowing device access
Thickness of filter soil	m	0.3-0.5		**0.5**	Lower permeability; consider coarse material to limit water exposure
Humus in top layer	%	3-5		**3**	Increase expected with vegetation growth
Infiltration capacity Kd	m/day	>0.086	>0.01	**>0.086**	Identify the most permeable soil
Overflowing frequency	1/year	0.2-2		**>10**	High frequency of tropical rainstorms
Time to empty hour	hour	<24		**<48**	New guidelines informed by lessons learned
Distance to GWL	m		>1	**>1**	High groundwater table and low permeability

The selection of BS sites should be strategic, focusing on areas with lower local elevations to facilitate natural water flow into these sites. However, it is also essential to ensure that overall city elevations are sufficiently high to promote water retention, management, and infiltration across all urban areas, releasing low-lying areas that cope with water nuisance and preventing high groundwater tables. Additionally, selecting locations with highly permeable soil types is crucial to ensure effective water infiltration and management.

To minimize the nuisance caused by mosquitoes, pests, and snakes, the BS should be designed to empty within 48 hours after a rainfall event. This can be achieved by incorporating coarse materials, such as coconut husks, which prevent standing water and promote rapid drainage.

6.2.2. Visual Impression of NbS in the Study Site

Combining these findings result in the following designs for paved sites in Paramaribo. The visual impressions in Figure 6.1 will not all be immediately implementable, but can give an impression of the green-blue possibilities in the study area.



Parking near Onafhankelijkheidsplein before



Parking near Onafhankelijkheidsplein after



Park near Fort Zeelandia before



Park near Fort Zeelandia after



Park near Fort Zeelandia before



Park near Fort Zeelandia after



Sidewalk before



Sidewalk after

Figure 6.1: Comparison of the conditions before and after the intervention (Visual impressions by Anne Moonen)

6.3. Institutional Implementation of NbS

The successful implementation of NbS in Paramaribo may benefit from a comprehensive approach that combines both top-down and bottom-up strategies.

6.3.1. Top-Down Strategy

A top-down strategy involves the Ministry actively implementing NbS in public spaces. This approach could ensure that large-scale projects are coordinated and executed with the necessary oversight and consistency. Key ministries, such as OW and ROM, might collaborate to plan and execute these projects. OW can assist with the implementation, while ROM can provide support in identifying appropriate locations. Their joint efforts might streamline the process, leverage shared expertise, and maximize the impact of the initiatives.

However, the capacity and financial resources of these ministries are limited. Therefore, while a top-down strategy is important, it might not be sufficient on its own. The ministries could prioritize projects based on available resources and focus on areas where they can achieve the most significant impact.

6.3.2. Bottom-Up Strategy

Complementing the top-down approach, a bottom-up strategy could engage resourceful stakeholders willing to collaborate on NbS projects. Entities such as Torarica, various touristic locations, and the Dutch Embassy could play a pivotal role in this grassroots approach. These stakeholders often have the resources, motivation, and influence to drive NbS projects within their domains.

Engaging these stakeholders might involve building partnerships and leveraging their interest in enhancing the local environment and promoting sustainability. By starting with willing collaborators, the implementation of NbS could gain momentum and demonstrate tangible benefits, encouraging broader participation.

6.3.3. Responsibilities and Motivation

To ensure effective communication and support for the NbS program, an independent third party, such as Tropenbos, could be involved. This organization might facilitate communication, provide technical support, and help coordinate efforts among various stakeholders. Tropenbos would need support to carry out these roles effectively. Using an independent facilitator might help prevent any negative associations with the government and stimulate collaboration. This approach is inspired by practices in the Netherlands.

Dividing clear responsibilities among the involved parties might help address the fragmentation of responsibilities and thus tackle the implementation gap. OW can help with implementation, ROM can assist in finding suitable locations, and Tropenbos can handle communication and support, inspired by Dutch practices. This clear division of responsibilities could ensure that each party knows its role and contributes effectively to the overall success of the NbS program.

The motivation to participate in NbS appears to be present among the stakeholders and the community. However, for these efforts to be sustained and effective, people might need to be actively reached, stimulated, and compensated. There needs to be financial support or compensation, but after an integrated assessment of the benefits of NbS, this might pay off in the long term. There could be less heat stress, less damage due to floods, and reduced investments for grey infrastructure because some water will be retained and released later than the big discharge peaks during heavy rainfall events. Compensation can take many forms, from financial incentives to public recognition and support for related projects. People themselves might maintain the implemented solutions, fostering a sense of ownership and responsibility.

6.4. Bigger Perspective: What Does This Say About NbS in Greater Paramaribo?

Starting with a neighborhood like Wakapasi offers the opportunity to create tangible examples of NbS with the support of local stakeholders. These initial implementations can serve as models, demonstrating the effectiveness of NbS, and can be adapted and scaled to other neighborhoods across Greater Paramaribo. This approach allows for the customization of NbS to address the specific needs and characteristics of different areas, contributing to a more resilient and sustainable urban environment citywide.

The application of various NbS strategies should consider the unique urban typologies across the city. For example, green roofs could be installed in wealthier neighborhoods with high building density, providing both aesthetic and environmental benefits. In areas with dense populations or recreational spaces, tree pits could be introduced to reduce heat stress by creating shaded areas. Bio-swales (BSs), with their versatile design, can be integrated into a wide range of urban settings, helping to manage stormwater across different environments.

The analysis presented in this thesis indicates that the suitability of locations for implementing infiltration measures is influenced by multiple factors, many of which can be effectively mapped. These maps provide critical tools for identifying potential sites to expand the bottom-up strategy from Wakapasi to other areas within Greater Paramaribo. Key resources in this mapping process include Digital Elevation Models (DEMs), observation-based flood maps, soil maps, and urban density maps. By overlaying these datasets, promising locations for the implementation of infiltration facilities can be identified, as illustrated in Figure 6.2. Furthermore, socio-economic conditions, although not directly represented in the cartographic data, are crucial to consider due to their significant impact on the feasibility and success of these measures. The indicators used for each map and the rationale for their application are detailed in Table 6.2.

Table 6.2: Indicators per map explaining how the map is used to define potential locations for expansion of the NbS implementation strategy.

Map	Indicators	Motivation
DEM (Digital Elevation Model)	Water flow paths, Groundwater depth	Identifies natural water flow paths and helps locate upstream areas for rainwater infiltration to prevent downstream flooding. Prioritizes higher elevated areas with deeper groundwater tables for more effective infiltration.
Observation-based Flood Map	Water flow paths, Flood-prone areas	Highlights regions with recurring floods or drainage bottlenecks. Used with DEM data to focus on areas where upstream infiltration can prevent downstream flooding or where flood risks are highest.
Soil Map	Soil permeability	Identifies areas with highly permeable soils that are more effective for infiltration-based solutions, ensuring quick water absorption and reducing surface runoff.
Urban Density Map	Soil sealing extent, Financial risk	Focuses on areas with extensive impermeable or paved surfaces where infiltration measures can mitigate runoff. Prioritizes urban areas where floods pose significant economic risks.
Socio-economic Data *(no map)*	Economic resources, Community needs	Considers the socio-economic conditions of neighborhoods to tailor interventions. In wealthier areas, more extensive measures might be feasible, while in lower-income areas, cost-effective solutions that provide substantial community benefits are prioritized.

To ensure clarity, Figure 6.2 does not consolidate all maps into a single figure. Instead, different combinations of maps are available in the repository, as referenced in Appendix C. The optimal use of these combinations is through an interactive format, which enables users to comprehensively evaluate all indicators for identifying successful locations. A significant challenge in this analysis is the absence of soil data for the city center—an area anticipated to have high potential due to its extensive soil sealing, frequent flooding, and elevated flood risks. The focus is generally on highly elevated, urbanized areas with permeable soil that contribute to downstream flooding. These areas are most effective for the implementation of infiltration facilities. However, the lack of crucial soil data hampers the ability to create

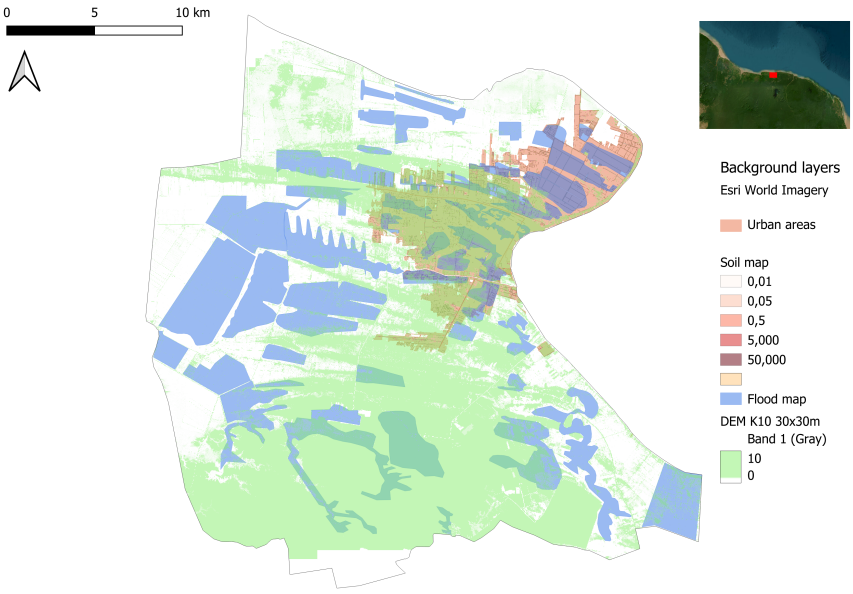


Figure 6.2: A combination of three indicative maps for the identification of potential sites for infiltration facilities in Greater Paramaribo. These maps include: 1) an observation-based flood map, 2) an urban density map highlighting intensively urbanized areas, and 3) a DEM highlighting elevations over 1.5m NSP.

a reliable overview of potential sites. The inclusion of this missing data would allow for a more accurate assessment of soil permeability in the city center, which is essential for producing a dependable analysis of suitable locations.

6.5. Main Discussion on Findings

The findings of this study suggest several important implications for the implementation of NbS in Paramaribo.

Firstly, infiltration tests should be conducted for vegetated swales to indicate the impact of preferential flow through plant roots. Additionally, the response of these systems during different seasons and over the years should be researched to understand their potential effects during dry periods and their functionality over their lifetime.

Secondly, the reliability of the simulations conducted in this study is low, making it difficult to accurately assess the effects on the neighborhood scale. As a result, strategies for NbS implementation derived from this study can only serve as initial ideas for where to start.

Thirdly, scaling up NbS for different typologies in the city means that different NbS options that did not pass the MCA in this research might become relevant. Furthermore, for individual locations, it might be important to concretely combine grey and green infrastructure and delve more deeply into the specifics of each site than was possible in this study.

6.6. Comparison with Literature

The findings of this study align with existing literature on NbS, but also reveal some critical downsides that warrant attention.

This study aligns with the literature's emphasis on the importance of integrating solutions into urban planning and considering the specific context of each location [15, 22, 34]. Justifying the challenges associated with permeable pavements, green walls, and green roofs, such as high construction and maintenance costs, structural load limitations, and limited water retention capacity. However, the literature also underscores the potential of innovative materials and designs to overcome these challenges. While these solutions may not seem immediately practical for Paramaribo, dismissing them without exploring such innovations could be premature.

The socio-economic context analysis in this study echoes the literature's emphasis on the importance of public participation and ownership in the successful implementation of NbS [12, 60, 50]. The identified

need for low-cost, low-maintenance solutions and the challenges posed by asset management and financial constraints are common themes in urban NbS studies, particularly in developing countries. The study's recommendation for knowledge sharing and community engagement aligns with documented best practices. However, the study underestimates the potential difficulties in shifting public perception and behavior towards sustainable practices, which can be a significant barrier. Effective community engagement requires sustained effort and resources, which might be challenging in a context with limited financial and human capital.

The technical findings related to the BS at AdeKUS, including the impact of vegetation on infiltration capacity and water quality, are supported by similar studies [78]. The observed limitations of BSs in low-permeability soils and the influence of high groundwater tables are consistent with existing research on university campuses. Additionally, the combination of green and grey infrastructure to enhance flood risk mitigation is a widely recognized strategy in the literature. However, this study did not demonstrate an effective reduction of flood risk, suggesting that the integration of these infrastructures needs to be more robustly planned and implemented to achieve the desired outcomes.

7

Conclusion

Reading Guide: *This chapter synthesizes the key findings of the thesis and is divided into three main sections. The conclusions regarding the applicability of NbS in Paramaribo are discussed in Section 7.1, where key topics include flood mitigation, water quality improvement, and social co-benefits. The scientific contributions, particularly in the context of NbS in tropical urban environments, are detailed in Section 7.2, highlighting the multidisciplinary framework introduced by the study. Finally, Section 7.3 offers recommendations for future research. This chapter connects the findings to broader scientific discussions and suggests pathways for future research.*

7.1. Conclusions Derived from the Findings of This Thesis

This thesis has systematically explored the applicability of Nature-based Solutions (NbS) in addressing the water management challenges of Paramaribo. The findings suggest that NbS can potentially offer effective solutions for managing urban water issues, particularly with little resources and limited complexity to enhance participation.

The study indicates that NbS, when tailored to the specific environmental conditions of Paramaribo, could contribute to increased urban resilience. The case study of Wakapasi demonstrates that interventions such as bioswales and other infiltration facilities can be integrated into the city's infrastructure to manage stormwater and reduce the impacts of pluvial flooding. However, the effectiveness of these solutions appears to be highly dependent on local factors such as soil permeability, rainfall patterns, and the existing drainage infrastructure and should therefore be further researched.

Furthermore, the socio-economic context of Paramaribo suggests that NbS may provide additional benefits beyond environmental improvement. By enhancing public spaces and contributing to urban livability, NbS could also support social well-being. However, the research identifies several challenges that may limit the implementation of NbS in Paramaribo, including institutional capacity, financial constraints, and the need for greater community and stakeholder engagement. To overcome these challenges and fully harness the potential of NbS, more research is required on their efficacy, the ecosystem services they provide, and the most suitable implementation strategies for the rest of Paramaribo.

The study emphasizes the importance of a collaborative, bottom-up approach to implementing NbS, involving various stakeholders in the design and execution processes. This approach could help to overcome some of the identified challenges, although it requires careful planning and coordination among different sectors.

7.2. Contribution to Scientific Field

This thesis contributes to the scientific understanding of NbS in tropical urban environments, particularly in developing regions where empirical studies are limited. The research provides data and insights from full-scale tests conducted in Paramaribo, offering a case-specific analysis that may inform future studies and policy development. The small scale of the study area and its participative nature make the findings particularly well-suited to the specific regional context, while also allowing for parallels with other regions. This enables scientific comparison and contributes to a broader understanding of NbS in similar settings. The findings suggest that NbS can be a viable component of urban water management

strategies in similar contexts, though their effectiveness may vary based on local environmental, social, and institutional conditions.

The study also introduces a multidisciplinary framework that combines technical, socio-economic, and institutional perspectives, offering a holistic approach to NbS research. While this framework may be applicable to other studies, its effectiveness in different settings would require further validation.

7.3. Recommendations for Follow-Up Research

Given the findings and limitations identified in this study, several recommendations for follow-up research are proposed. First, it is crucial to conduct long-term monitoring of the implemented NbS in Paramaribo, particularly at the AdeKUS campus, to assess their performance over time. This should include detailed studies on the influence of preferential flow paths, which could also be investigated at other existing bioswales in the city.

Second, research should focus on the potential of NbS to reduce heat stress in tropical urban environments. The AdeKUS site offers a unique opportunity to explore this, given its distinct climatic conditions and existing infrastructure.

Third, a targeted measurement campaign at AdeKUS, integrating soil moisture sensors, video observation, and climatic data from the operational weather station, would provide comprehensive data to understand these dynamics and assess the effectiveness and impact of NbS. Systematic observation of mosquito attraction in relation to NbS is essential. This should involve studying the relationship between retention time, water quality, and other environmental factors. Such efforts would contribute to developing and testing full-scale, context-specific designs optimized for the unique environmental and socio-economic conditions of tropical urban areas.

Finally, monetizing the co-benefits of ecosystem services provided by NbS, such as flood mitigation, heat stress reduction, improved air quality, and enhanced social well-being, could provide valuable insights into the long-term economic viability of these solutions. By assigning a monetary value to these benefits, decision-makers can more accurately assess whether the initial investments in sustainable solutions are justified by the potential returns. This approach could also help in comparing NbS with traditional grey infrastructure, offering a clearer picture of the long-term savings and co-benefits that NbS could deliver. In cities like Paramaribo, where financial constraints and limited resources often pose challenges, understanding the full economic value of NbS could drive more informed and sustainable urban planning decisions, ultimately contributing to the city's resilience and livability.

These recommendations aim to build on the findings of this thesis and contribute to a more comprehensive understanding of the potential and challenges of NbS in urban water management, particularly in tropical developing urban regions such as Paramaribo.

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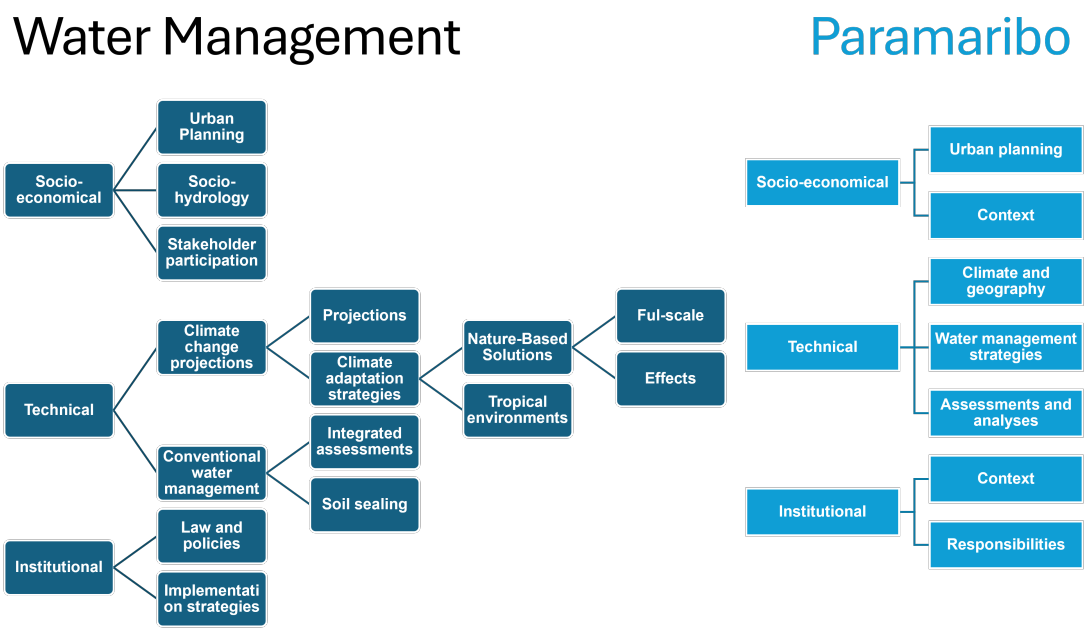
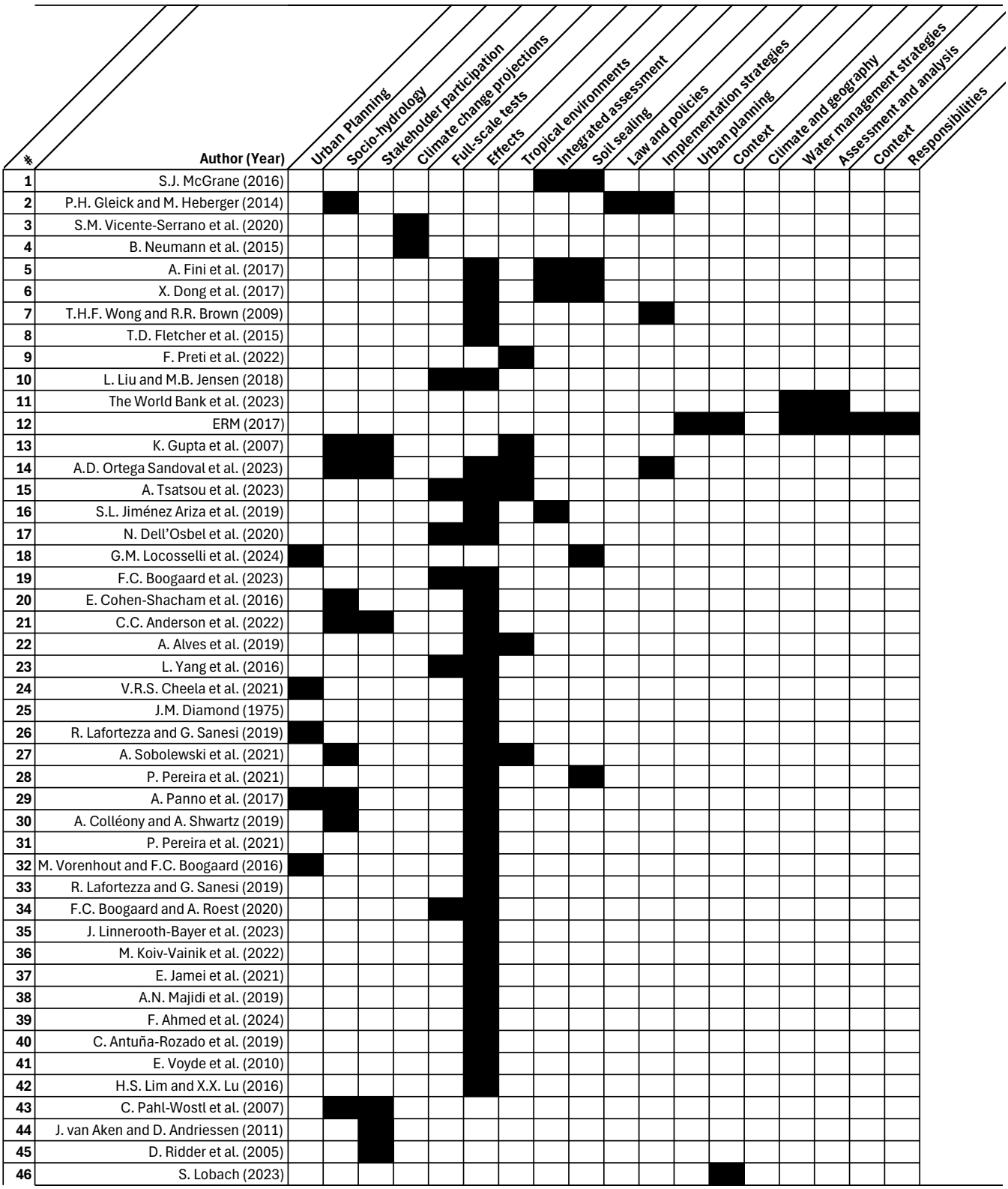
A

Systematic Review Matrix for Literature




#
Author (Year)
Urban Planning
Socio-hydrology
Stakeholder participation
Climate change projections
Full-scale tests
Effects
Tropical environments
Integrated assessment
Soil sealing
Law and policies
Implementation strategies
Urban planning
Context
Climate and geography
Water management strategies
Assessment and analysis
Context
Responsibilities
1 S.J. McGrane (2016)
2 P.H. Gleick and M. Heberger (2014)
3 S.M. Vicente-Serrano et al. (2020)
4 B. Neumann et al. (2015)
5 A. Fini et al. (2017)
6 X. Dong et al. (2017)
7 T.H.F. Wong and R.R. Brown (2009)
8 T.D. Fletcher et al. (2015)
9 F. Preti et al. (2022)
10 L. Liu and M.B. Jensen (2018)
11 The World Bank et al. (2023)
12 ERM (2017)
13 K. Gupta et al. (2007)
14 A.D. Ortega Sandoval et al. (2023)
15 A. Tsatsou et al. (2023)
16 S.L. Jiménez Ariza et al. (2019)
17 N. Dell'Osbel et al. (2020)
18 G.M. Locosselli et al. (2024)
19 F.C. Boogaard et al. (2023)
20 E. Cohen-Shacham et al. (2016)
21 C.C. Anderson et al. (2022)
22 A. Alves et al. (2019)
23 L. Yang et al. (2016)
24 V.R.S. Cheela et al. (2021)
25 J.M. Diamond (1975)
26 R. Lafortezza and G. Sanesi (2019)
27 A. Sobolewski et al. (2021)
28 P. Pereira et al. (2021)
29 A. Panno et al. (2017)
30 A. Colléony and A. Shwartz (2019)
31 P. Pereira et al. (2021)
32 M. Vorenhout and F.C. Boogaard (2016)
33 R. Lafortezza and G. Sanesi (2019)
34 F.C. Boogaard and A. Roest (2020)
35 J. Linnerooth-Bayer et al. (2023)
36 M. Koiv-Vainik et al. (2022)
37 E. Jamei et al. (2021)
38 A.N. Majidi et al. (2019)
39 F. Ahmed et al. (2024)
40 C. Antuña-Rozado et al. (2019)
41 E. Voyde et al. (2010)
42 H.S. Lim and X.X. Lu (2016)
43 C. Pahl-Wostl et al. (2007)
44 J. van Aken and D. Andriessen (2011)
45 D. Ridder et al. (2005)
46 S. Lobach (2023)

#	Author (Year)	Urban Planning	Socio-hydrology	Stakeholder participation	Climate change projections	Full-scale tests	Effects	Tropical environments	Integrated assessment	Soil sealing	Law and policies	Implementation strategies	Urban planning	Context	Climate and geography	Water management strategies	Assessment and analysis	Context	Responsibilities
47	E. Mostert (2003)			■						■	■								
48	L.A. Keeys and M. Huemann (2017)			■															
49	B. Bockhorn et al. (2017)					■	■												
50	M. Soerohardjo et al. (2008)													■					
51	E. Koole (2024)											■	■	■	■	■	■	■	■
52	World Bank (2024)				■			■											
53	A. Sobolewski et al. (2021)																		
54	Government of Suriname (2019)											■		■	■	■	■	■	■
55	GCCA+ (2021)													■	■				
56	Helena Antich-Homar et al. (2022)														■				
57	L. Bouaziz et al. (2020)													■	■				
58	C. Malmström (2018)												■						
59	Staatsolie (2024)												■						
60	R. Aluvihare et al. (2010)											■							
61	ID Stewart and TR Oke (2012)								■	■									
62	D.A. Lachman et al. (2021)											■	■						
63	Stedebouwkundige Wet (1972)											■						■	■
64	P. Keesmaat (2023)						■	■	■						■	■			
65	H.A. Sijlbing (2011)												■	■					
66	J.S. Dodgson et al. (2009)										■	■							
67	R. Ruslin et al. (2022)			■															
68	J. Vaivio (2012)			■															
69	J.A. Maxwell (2012)													■					
70	V. Naipal et al. (2013)						■	■											
71	F.C. Boogaard et al. (2021)										■								
72	J.A. van der Werf et al. (2023)										■								
73	E. Fassman-Beck et al. (2015)						■				■								
74	Keith Beven et al. (2013)						■												
75	John L. Nieber et al. (2010)						■												
76	NJ Jarvis (2020)						■												
77	F.C. Boogaard (2015)						■												
78	M. Leroy et al. (2016)						■												

B

List of Interviews

Table B.1: List of interviews and topics during field work with different stakeholders within the Quadruple Helix

Date	Quadruple Helix	Topic
17-3-24	**Community**	Salt intrusion and flood risk Nickerie
17-3-24	**Community**	Pluvial flooding, sewer pipes and gravel box intervention
	Academia	Monitoring network and possibility of bioswales in the inner city
18-3-24	**Community**	Water nuisance in the home
	Industry	Possibility measurement network, interventions and support
20-3-24	**Government**	Legislation and regulations, fitting NBS into streetscape
	Industry	Possible interventions, implementation, individualism and NBS
21-3-24	**Community**	Citizen science, implementation and stakeholders
22-3-24	**Community**	Livability of the city
23-3-24	**Industry**	Helophytes, infiltration in clay and permaculture
24-3-24	**Industry**	Sustainable industry, rainwater harvesting and NBS
26-3-24	**Industry**	Overall problem definition Wakapasi
26-3-24	**Community**	Overall problem definition Wakapasi
27-3-24	**Community**	Water flooding and incorporation of bioswales in the streetscape
28-3-24	**Industry**	Private responsibility, sustainable water use
29-3-24	**Industry**	Embedding NBS
30-3-24	**Community**	Embedding NBS, stakeholders
2-4-24	**Academia**	NBS on AdeKUs, multifunctionality
2-4-24	**Academia**	Functionality, drainage and rainy season
2-4-24	**Industry**	Functional operation, drainage and rainy season
3-4-24	**Industry**	Potential for inclusion of NBS in spatial planning
3-4-24	**Government**	NBS, dewatering, maintenance, authority, think tank
5-4-24	**Government**	Measurement campaign water, soil and air
7-4-24	**Industry**	Room for water
8-4-24	**Government**	Urban dewatering and decision making processes
15-4-24	**Industry**	Types of native plants possibly for a bioswale
12-5-24	**Industry**	Types of plants in a bioswale

C

Repository information

This appendix provides information, code and figures on the repository created to support two parts of this thesis.

- Author: Max de Man (TU Delft & Deltares)
- Repository: `https://github.com/maxdeman11/mscthesisparamaribo.git`

The repository contains the following components:

Data Analysis of Bioswale Response at AdeKUS Campus, Paramaribo

- A comprehensive analysis of the response of a full-scale test bioswale located at the AdeKUS campus in Paramaribo, Suriname.
- Includes code for converting TD-Diver data into water level measurements.
- Provides detailed data analysis and accompanying figures.

Simulations of NbS for Wakapasi Neighborhood

- Simulations exploring the potential impact of NbS under various climate and implementation scenarios for the Wakapasi neighborhood in Paramaribo.
- Detailed information about the model used for these simulations can be found at `https://publicwiki.deltares.nl/display/AST/Urban+Water+balance+model`.

Maps for potential implementation of NbS in Greater Paramaribo

Maps provided to indicate suitable locations in Greater Paramaribo

- Digital Elevation Models (DEMs)
- Permeability and soil maps
- Urban density
- Observation-based flood maps

For further details, please refer to the full thesis report once it is available on the TU Delft repository.

D

MCA

Scores								
Description	**Criterion**	**BS**	**BP**	**TP**	**CW**	**GW**	**GR**	**PP**
Initial Investment	Cost	4	3	2	2	2	1	1
Maintenance and Operation Costs	Cost	2	2	2	2	2	2	1
Environmental Impact	Resource efficiency	5	5	4	5	4	4	3
Resource Efficiency	Resource efficiency	5	5	5	5	4	4	3
Flood Mitigation	Effectiveness	4	4	3	4	3	4	4
Retention	Effectiveness	4	5	4	4	3	5	4
Water Quality Improvement	Effectiveness	4	4	4	5	3	4	3
Durability and Adaptibility	Asset Management	4	4	4	4	4	4	2
Maintenance Intensity	Asset Management	1	2	2	2	2	3	1
Integration with Existing Infrastructure	Urban Integration	4	4	3	2	1	1	3
Scalability	Urban Integration	3	2	4	3	2	2	1
Stakeholder Acceptance	Private Domains	2	2	5	3	5	4	3
Legal and Policy Framework	Private Domains	2	1	3	2	3	1	3
Community Benefits	Co-benefits	4	4	5	5	4	4	3
Public Health and Safety	Co-benefits	4	4	4	5	4	4	3

$$TS = \sum_{i=1}^{n} \frac{S_i}{n}$$

Total Scores								Weights
Criterion	**BS**	**BP**	**TP**	**CW**	**GW**	**GR**	**PP**	
Cost	3,0	2,5	2,0	2,0	2,0	1,5	1,0	23%
Resource efficiency	5,0	5,0	4,5	5,0	4,0	4,0	3,0	8%
Effectiveness	4,0	4,3	3,7	4,3	3,0	4,3	3,7	23%
Asset management	2,5	3,0	3,0	3,0	3,0	3,5	1,5	15%
Urban integration	3,5	3,0	3,5	2,5	1,5	1,5	2,0	15%
Private domains	2,0	1,5	4,0	2,5	4,0	2,5	3,0	8%
Co-benefits	4,0	4,0	4,5	5,0	4,0	4,0	3,0	8%
Total	**3,5**	**3,4**	**3,6**	**3,5**	**3,1**	**3,1**	**2,6**	100%

$$TWS = \sum_{i=1}^{n} \frac{W_i * S_i}{n}$$

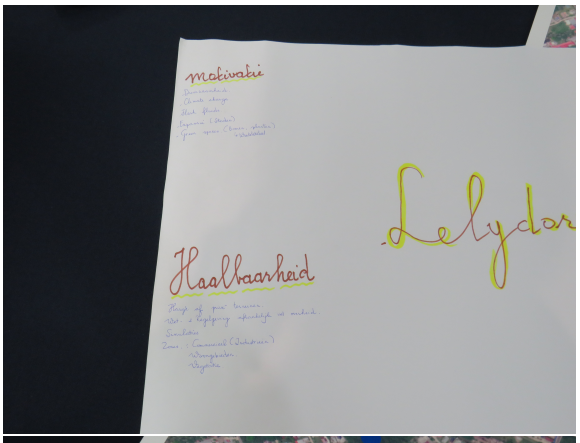
Total Weighted scores							
Criterion	**BS**	**BP**	**TP**	**CW**	**GW**	**GR**	**PP**
Cost	0,7	0,6	0,5	0,5	0,5	0,3	0,2
Resource efficiency	0,4	0,4	0,3	0,4	0,3	0,3	0,2
Effectiveness	0,9	1,0	0,8	1,0	0,7	1,0	0,8
Asset management	0,4	0,5	0,5	0,5	0,5	0,5	0,2
Urban integration	0,5	0,5	0,5	0,4	0,2	0,2	0,3
Private domains	0,2	0,1	0,3	0,2	0,3	0,2	0,2
Co-benefits	0,3	0,3	0,3	0,4	0,3	0,3	0,2
Total	**3,4**	**3,3**	**3,3**	**3,3**	**2,8**	**2,9**	**2,3**

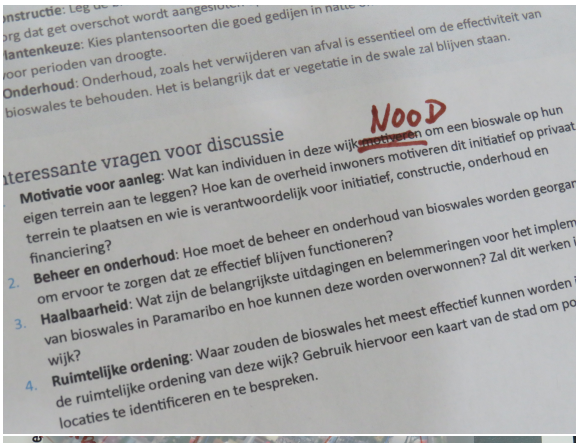
Figure D.1: Scores and their calculations for the MCA.

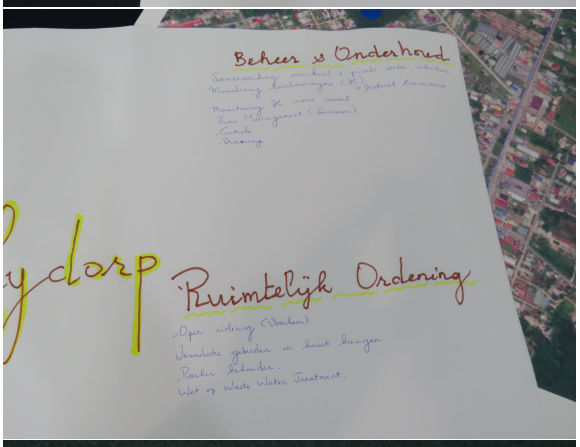
E

Think-tank deliverables

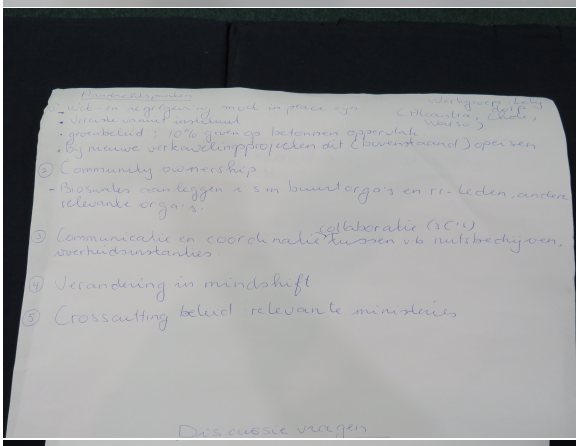


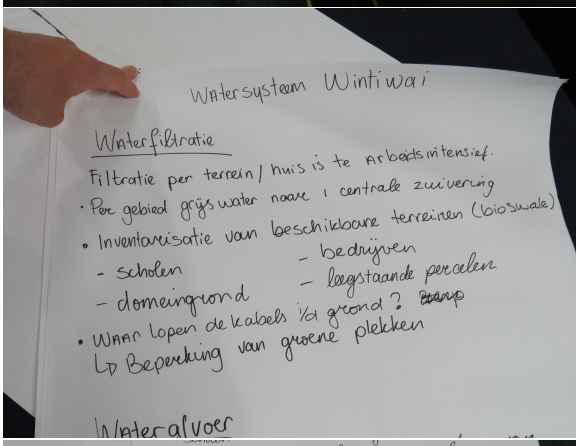

motivatie
Haalbaarheid
Lelydor

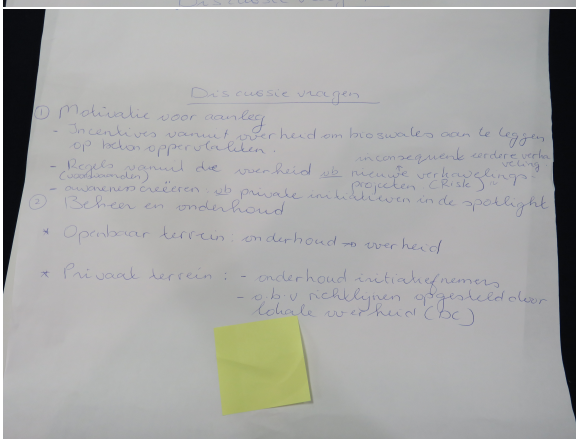

NOOD
Motivatie voor aanleg: Wat kan individuen in deze wijk
eigen terrein aan te leggen? Hoe kan de overheid inwoners motiveren dit initiatief op privaat
terrein te plaatsen en wie is verantwoordelijk voor initiatief, constructie, onderhoud en
financiering?
2. Beheer en onderhoud: Hoe moet de beheer en onderhoud van bioswales worden georgan
om ervoor te zorgen dat ze effectief blijven functioneren?
3. Haalbaarheid: Wat zijn de belangrijkste uitdagingen en belemmeringen voor het implem
van bioswales in Paramaribo en hoe kunnen deze worden overwonnen? Zal dit werken i
wijk?
4. Ruimtelijke ordening: Waar zouden de bioswales het meest effectief kunnen worden i
de ruimtelijke ordening van deze wijk? Gebruik hiervoor een kaart van de stad om po
locaties te identificeren en te bespreken.

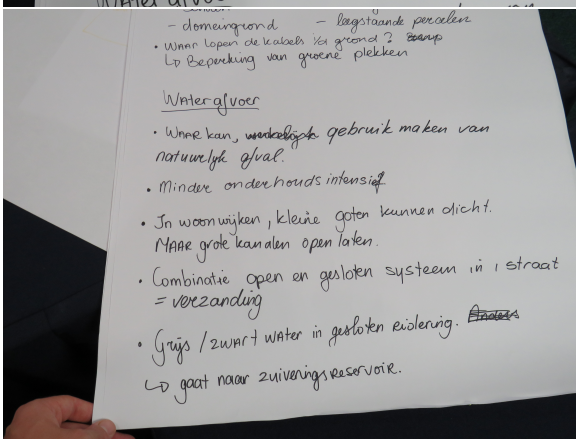

Beheer & Onderhoud
Ruimtelijk Ordening


Watersyste
Delik-tank NBS in Paramaribo 2024


Communicatie en coordinatie tussen v.b. nutsbedrijven, overheidsinstanties
Verandering in mindshift
Crosscutting beleid relevante ministeries
Discussie vragen


Watersysteem Wintiwai
Waterfiltratie
Filtratie per terrein / huis is te arbeidsintensief.
Per gebied grijs water naar 1 centrale zuivering
Inventarisatie van beschikbare terreinen (bioswale)
- scholen
- bedrijven
- domeingrond
- leegstaande percelen
Waar lopen de kabels i/d grond?
Beperking van groene plekken
Watergevoer


Discussie vragen
1 Motivatie voor aanleg
2 Beheer en onderhoud
Openbaar terrein: onderhoud → overheid
Privaat terrein: - onderhoud initiatiefnemers
- o.b.v. richtlijnen opgesteld door lokale overheid (DC)


- domeingrond
- leegstaande percelen
Waar lopen de kabels i/d grond?
Beperking van groene plekken
Watergevoer
Waar kan, gebruik maken van natuurlijk gval.
Minder onderhoudsintensief
In woonwijken, kleine goten kunnen dicht.
Maar grote kanalen open laten.
Combinatie open en gesloten systeem in 1 straat = verzanding
Grijs / zwart water in gesloten riolering.
gaat naar zuiveringsreservoir.

Evaporation in AdeKUS Bioswale using Penman-Monteith

The Penman-Monteith equation for estimating the evaporation rate from an open water surface is given by:

$$E = \frac{\Delta(R_n - G) + \gamma \frac{u_2(e_s - e_a)}{T+273}}{\Delta + \gamma(1 + 0.34u_2)}$$

where:

- E is the evaporation rate (mm/day).
- R_n is the net radiation at the water surface (MJ/m²/day).
- G is the heat flux density to the water (MJ/m²/day).
- Δ is the slope of the saturation vapor pressure curve (kPa/°C).
- γ is the psychrometric constant (kPa/°C).
- u_2 is the wind speed at 2 meters height (m/s).
- e_s is the saturation vapor pressure (kPa).
- e_a is the actual vapor pressure (kPa).
- T is the air temperature (°C).

For Suriname in May, the following meteorological data is used:

- Air temperature (T): 27°C
- Relative humidity (RH): 80%
- Wind speed at 2 meters (u_2): 2 m/s
- Net radiation (R_n): 5 MJ/m²/day

The intermediate calculations are as follows:

$$e_s = 0.6108 \times \exp\left(\frac{17.27 \times 27}{27 + 237.3}\right)$$

$$e_s \approx 3.564\,\text{kPa}$$

$$e_a = e_s \times \frac{80}{100}$$

$$e_a \approx 2.8512\,\text{kPa}$$

$$\Delta = \frac{4098 \times e_s}{(27 + 237.3)^2}$$

$$\Delta \approx 0.215 \,\text{kPa/°C}$$

$$\gamma = \frac{C_p \times P}{\lambda}$$

$$\gamma \approx 0.066 \,\text{kPa/°C}$$

Assuming the net radiation (R_n) is 5 MJ/m²/day and the heat flux density (G) is 0:

$$E = \frac{0.215 \times (5 - 0) + 0.066 \times \frac{2 \times (3.564 - 2.8512)}{27 + 273}}{0.215 + 0.066 \times (1 + 0.34 \times 2)}$$

$$E = \frac{0.215 \times 5 + 0.066 \times \frac{2 \times (3.564 - 2.8512)}{27 + 273}}{0.215 + 0.066 \times 1.68}$$

$$E = \frac{1.075 + 0.066 \times \frac{2 \times 0.7128}{300}}{0.215 + 0.11088}$$

$$E = \frac{1.075 + 0.066 \times \frac{1.4256}{300}}{0.215 + 0.11088}$$

$$E = \frac{1.075 + 0.0003136}{0.32588}$$

$$E = \frac{1.0753136}{0.32588}$$

$$E \approx 3.30 \,\text{mm/day}$$

Therefore, the estimated evaporation rate for Suriname in the bioswale in May is approximately 3.3 mm/day.

G

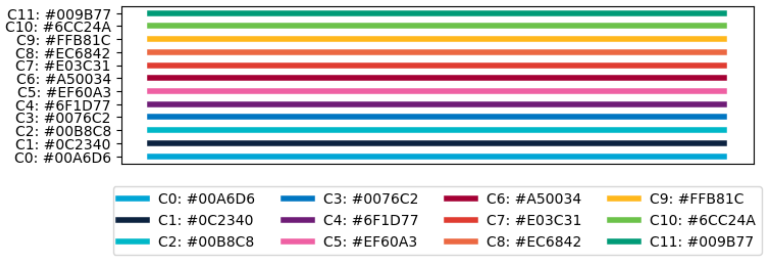
Notebook Full-Scale Test: Bioswale Response

In [1]:
```
import pandas as pd
import numpy as np
import chardet
import matplotlib.pyplot as plt
from scipy import stats
import math
from pathlib import Path
from os.path import basename, dirname, isdir, isfile, join
from matplotlib.widgets import Slider
import mpldatacursor
from matplotlib import rcParams
from scipy.signal import savgol_filter, butter, filtfilt
import matplotlib.colors as mcolors
import matplotlib.dates as mdates
```

```
C:\Program Files\ArcGIS\Pro\bin\Python\envs\arcgispro-py3\lib\site-packages\scipy\__init__.py:138: UserWarning: A NumPy version >=1.16.5 and <1.23.0 is required for this version of SciPy (detected version 1.26.4)
  warnings.warn(f"A NumPy version >={np_minversion} and <{np_maxversion} is required for this version of "
```

TU Delft Color Scheme

In [2]:
```
# Define the custom color scheme
custom_colors = [
    "#00A6D6", "#0C2340", "#00B8C8", "#0076C2",
    "#6F1D77", "#EF60A3", "#A50034", "#E03C31",
    "#EC6842", "#FFB81C", "#6CC24A", "#009B77"
]

# Set the color cycle to the custom colors
plt.rcParams['axes.prop_cycle'] = plt.cycler(color=custom_colors)

# Plot a sample to display the colors
fig, ax = plt.subplots(figsize=(8, 2))

for idx, color in enumerate(custom_colors):
    ax.plot([0, 1], [idx, idx], lw=4, color=color, label=f'C{idx}: {color}')

ax.set_yticks(range(len(custom_colors)))
ax.set_yticklabels([f'C{idx}: {color}' for idx, color in enumerate(custom_colors)])
ax.set_xticks([])

plt.legend(loc='upper center', bbox_to_anchor=(0.5, -0.1), ncol=4)
plt.show()
```



Load and Display Data

Define the File Paths

Set the file paths for the water level CSV and weather station Excel files.

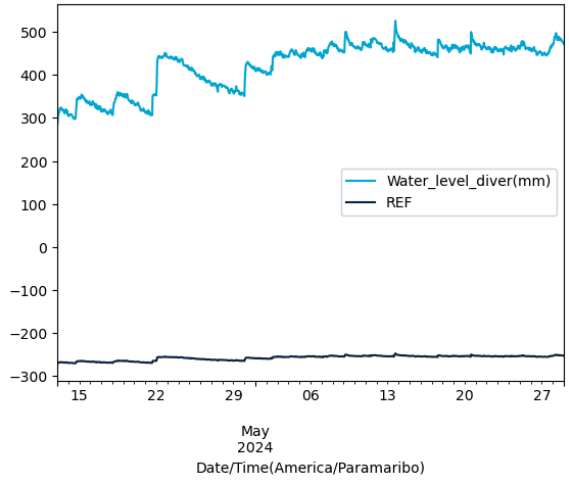
Load the Water Level Data

Read the CSV file into a DataFrame `WL`, parsing dates correctly and setting the first column as the index.

Load the Weather Station Data

Read the Excel file into a DataFrame `WS`, skipping the first row and parsing dates correctly.

In [3]:
```
# Define the file paths
Water_level_path = "Water_level_bioswale_AdeKUS.csv"
xlsx_file_path = "Hydrometcloud_data_Ringharbour.xlsx"

# Read the CSV file into a DataFrame WaterLevel (WL)
WL = pd.read_csv(Water_level_path, sep=';', parse_dates=[0], dayfirst=True, index_col=0)

WL.plot()

# Read the Excel file into a DataFrame WeatherStation (WS)
WS = pd.read_excel(xlsx_file_path, index_col=[0], parse_dates=True)

# Display the head of each DataFrame
# print("WaterLevel DataFrame (WL):")
# print(WL.describe())

# print("\nWeatherStation DataFrame (WS):")
# print(WS.describe())
```



The effect of the constructed bioswale

A reference well was installed near the bioswale to measure the groundwater table using the same equipment as in the bioswale. To maintain consistency, the reference point selected is the bottom of the bioswale. Located 400 meters from the bioswale, the reference well operates under similar conditions. However, it is situated near a small canal on the university campus, where the water flow is negligible but may still cause slight deviations from the steady-state groundwater table.

The precipitation patterns observed in both the bioswale and the reference well are almost identical, with minimal delay. The timing of their responses is considerably equal. The main difference lies in the magnitude of the water level fluctuations. The bioswale exhibits significantly higher increases and decreases in water level, indicating greater inflow and outflow. This suggests that the bioswale effectively captures rainwater and runoff from its surroundings. The higher outflow is likely due to a combination of infiltration and evaporation processes.

Reference Well

Resample Weather Station Data

Resample the weather station DataFrame (`WS`) to a daily frequency and calculate the daily mean values.

```
WS_daily_mean = WS.resample('D').mean()
```

In [4]:
```
# Resample entire weather station DataFrame to daily and calculate mean
WS_daily_mean = WS.resample('D').mean()

# Plotting
fig, ax1 = plt.subplots(figsize=(10, 6))

# Create a secondary y-axis for daily rain
ax2 = ax1.twinx()
bar_container = ax2.bar(WS_daily_mean.index, WS_daily_mean['Daily Rain(mm)'], color='C0', alpha=0.5, label='Precipitation')
ax2.set_ylabel('Precipitation (mm/day)', color='C0')
ax2.tick_params(axis='y', labelcolor='C0')
precipitation_ticks = [0, 10, 20, 30, 40]
ax2.set_yticks(precipitation_ticks)
ax2.set_ylim(0, 60)

# Plot water level and reference water level
line1, = ax1.plot(WL.index, WL['Water_level_diver(mm)'], color='C1', label='Water Level')
line2, = ax1.plot(WL.index, WL.REF, color='C3', linestyle='--', label='Water Level Reference Well')
ax1.set_ylabel('Water Level (mm)', color='C1')
ax1.tick_params(axis='y', labelcolor='C1')

# Add horizontal lines at y = 500 and y = 0
ax1.axhline(y=500, color='C7', linestyle='--')
ax1.text(WL.index[len(WL)//3], 505, 'Bioswale filled', color='C7')  # Adjusted position
ax1.axhline(y=0, color='C7', linestyle='--', label='Bioswale Fill Level')
ax1.text(WL.index[len(WL)//3], 5, 'Bioswale empty', color='C7')  # Adjusted position

# Add label for x-axis
ax1.set_xlabel('Datetime')

# Combine legends
lines, labels = ax1.get_legend_handles_labels()
lines2, labels2 = bar_container.get_children(), [bar_container.get_label()]
ax2_legend = [plt.Line2D([0], [0], color='C0', lw=4, alpha=0.5)]

lines += ax2_legend
labels += labels2

ax1.legend(lines, labels, loc='upper left')

# Show plot
plt.tight_layout()

# Save the plot with grid
plt.grid(True)
plt.savefig('Figures/BS_AdeKUS_grid.png')

# Save the plot without grid
plt.grid(False)
plt.savefig('Figures/BS_AdeKUS_nogrid.png')

# Show plot
plt.show()
```

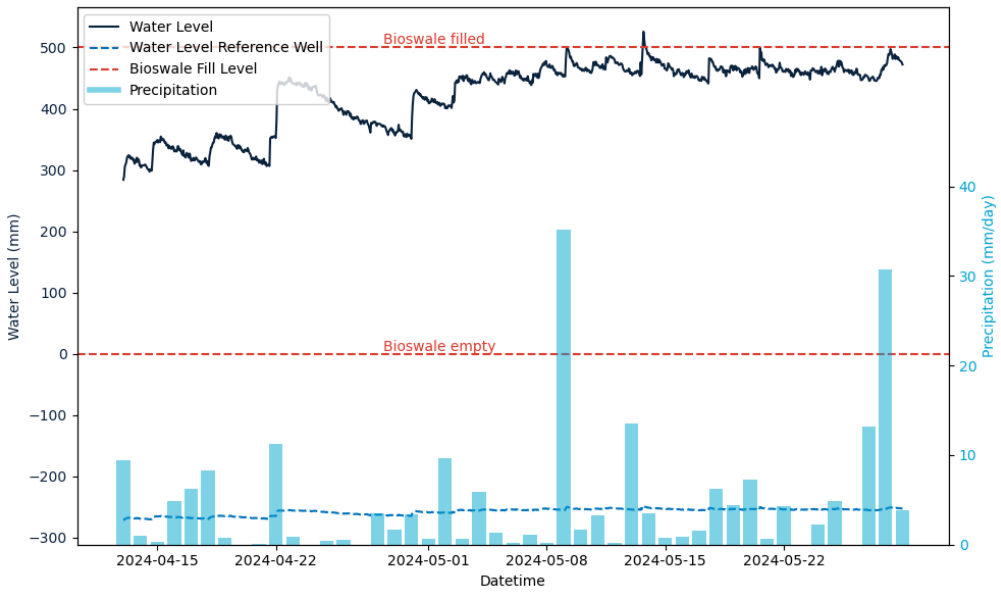
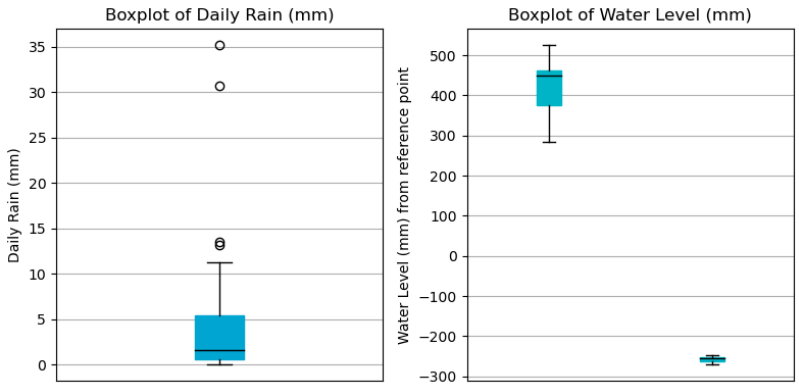


Figure Description

In the figure, we can observe that the bioswale is predominantly filled, suggesting effective water retention. There are discernible responses to rainfall events, evident from fluctuations in water levels, indicating successful infiltration, but because the water levels remain high infiltration seems limited. Notably, around May 15th, there is evidence of a flood event where the water level surpasses the depth of the bioswale, potentially highlighting its capacity limits under extreme conditions.

In [5]:
```
# Create a new figure for the boxplots
fig, (ax_box1, ax_box2) = plt.subplots(1, 2, figsize=(8, 4))

# Plot boxplot of daily rain
ax_box1.boxplot(WS_daily_mean['Daily Rain(mm)'], patch_artist=True,
                boxprops=dict(facecolor='C0', color='C0'), medianprops=dict(color='black'))
ax_box1.set_title('Boxplot of Daily Rain (mm)')
ax_box1.set_ylabel('Daily Rain (mm)')
ax_box1.grid(True)

# Plot boxplot of water level
ax_box2.boxplot(WL, patch_artist=True,
                boxprops=dict(facecolor='C2', color='C2'), medianprops=dict(color='black'))
ax_box2.set_title('Boxplot of Water Level (mm)')
ax_box2.set_ylabel('Water Level (mm) from reference point')
ax_box2.grid(True)

# Remove x-axis labels and ticks
ax_box1.xaxis.set_visible(False)
ax_box2.xaxis.set_visible(False)

# Adjust layout
plt.tight_layout()

# Save the plots
plt.savefig('Figures/WS_WL_boxplots.png')

# Show plot
plt.show()
```



Moving Average Filter

Applies a moving average filter with a window size of 7 days. This filter smooths the data by averaging over a specified number of previous points:

$$MA_t = \frac{1}{N} \sum_{i=0}^{N-1} x_{t-i}$$

Savitzky-Golay Filter

Applies a Savitzky-Golay filter with a window length of 11 and polynomial order of 2. This filter smooths the data by fitting successive sub-sets of adjacent data points with a low-degree polynomial by the method of linear least squares:

$$y_i = \sum_{k=-m}^{m} c_k x_{i+k}$$

where c_k are the filter coefficients obtained by polynomial fitting.

Low-Pass Filter

Applies a Butterworth low-pass filter with a cutoff frequency of 0.1. The filter passes signals with a frequency lower than the cutoff and attenuates signals with frequencies higher than the cutoff:

$$H(s) = \frac{1}{\sqrt{1 + \left(\frac{s}{\omega_c}\right)^{2n}}}$$

where ω_c is the cutoff frequency and n is the order of the filter.

Kalman Filter

Uses a Kalman filter for noise reduction. The Kalman filter operates recursively on streams of noisy input data to produce statistically optimal estimates of the underlying system state. The Kalman filter equations are:

Time Update (Predict)

$$\hat{x}_{k|k-1} = \hat{x}_{k-1|k-1}$$

$$P_{k|k-1} = P_{k-1|k-1} + Q$$

Measurement Update (Correct)

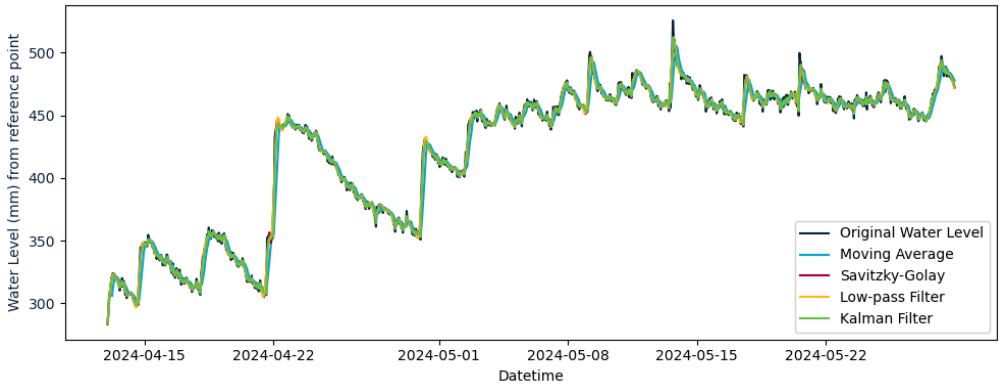
$$K_k = \frac{P_{k|k-1}}{P_{k|k-1} + R}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - \hat{x}_{k|k-1})$$

$$P_{k|k} = (1 - K_k)P_{k|k-1}$$

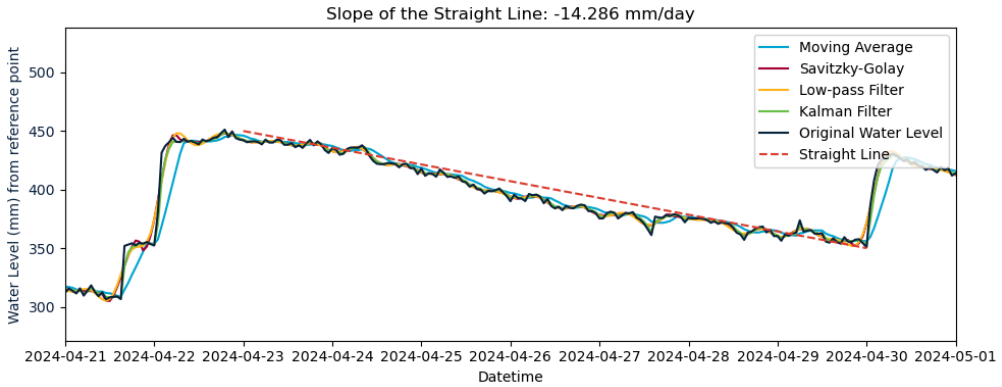
In [6]:
```
# Extract the water level data
water_level = WL['Water_level_diver(mm)']

# Moving average filter
window_size = 7
moving_average = water_level.rolling(window=window_size).mean()


# Savitzky-Golay filter
savgol_filtered = savgol_filter(water_level, window_length=11, polyorder=2)

# Low-pass filter
def butter_lowpass(cutoff, fs, order=5):
    nyquist = 0.5 * fs
    normal_cutoff = cutoff / nyquist
    b, a = butter(order, normal_cutoff, btype='low', analog=False)
    return b, a

def lowpass_filter(data, cutoff=0.1, fs=1.0, order=5):
    b, a = butter_lowpass(cutoff, fs, order)
    y = filtfilt(b, a, data)
    return y

lowpass_filtered = lowpass_filter(water_level, cutoff=0.1)

# Kalman filter
def kalman_filter(data):
    n_iter = len(data)
    sz = (n_iter,) # size of array
    xhat = np.zeros(sz)      # a posteri estimate of x
    P = np.zeros(sz)         # a posteri error estimate
    xhatminus = np.zeros(sz) # a priori estimate of x
    Pminus = np.zeros(sz)    # a priori error estimate
    K = np.zeros(sz)         # gain or blending factor

    Q = 1e-2 # process variance
    R = 0.1**2 # estimate of measurement variance, change to see effect

    # initial guesses
    xhat[0] = data[0]
    P[0] = 1.0

    for k in range(1,n_iter):
        # time update
        xhatminus[k] = xhat[k-1]
        Pminus[k] = P[k-1]+Q

        # measurement update
        K[k] = Pminus[k]/(Pminus[k]+R)
        xhat[k] = xhatminus[k]+K[k]*(data[k]-xhatminus[k])
        P[k] = (1-K[k])*Pminus[k]

    return xhat

kalman_filtered = kalman_filter(water_level.values)

# Plotting
fig, ax1 = plt.subplots(figsize=(10, 4))

ax1.plot(WL.index, WL['Water_level_diver(mm)'], color='C1', label='Original Water Level')
ax1.plot(WL.index, moving_average, color='C0', label='Moving Average')
ax1.plot(WL.index, savgol_filtered, color='C6', label='Savitzky-Golay')
ax1.plot(WL.index, lowpass_filtered, color='C9', label='Low-pass Filter')
ax1.plot(WL.index, kalman_filtered, color='C10', label='Kalman Filter')

# Add label for x-axis
```

```
ax1.set_xlabel('Datetime')
ax1.set_ylabel('Water Level (mm) from reference point', color='C1')
ax1.tick_params(axis='y', labelcolor='C1')

# Combine legends
ax1.legend(loc='lower right')

# Show plot
plt.tight_layout()
plt.savefig('Figures/Filtered_Water_Level.png')
plt.show()
```



In [7]:

```
# Plotting
fig, ax1 = plt.subplots(figsize=(10, 4))

# Plot original water level and filters
ax1.plot(WL.index, moving_average, color='C0', label='Moving Average')
ax1.plot(WL.index, savgol_filtered, color='C6', label='Savitzky-Golay')
ax1.plot(WL.index, lowpass_filtered, color='C9', label='Low-pass Filter')
ax1.plot(WL.index, kalman_filtered, color='C10', label='Kalman Filter')
ax1.plot(WL.index, WL['Water_level_diver(mm)'], color='C1', label='Original Water Level')

# Define the points for the straight line
x1 = pd.Timestamp('2024-04-23')
y1 = 450
x2 = pd.Timestamp('2024-04-30')
y2 = 350

# Draw a straight line from [x=2024-04-23, y=450] to [x=2024-04-30, y=350]
ax1.plot([x1, x2], [y1, y2], color='C7', linestyle='--', label='Straight Line')

# Calculate the slope of the straight line
slope = (y2 - y1) / (x2 - x1).days

# Set the title with the slope information
ax1.set_title(f'Slope of the Straight Line: {slope:.3f} mm/day')

# Add label for x-axis
ax1.set_xlabel('Datetime')
ax1.set_ylabel('Water Level (mm) from reference point', color='C1')
ax1.tick_params(axis='y', labelcolor='C1')

# Combine legends
ax1.legend(loc='upper right')

# Set the x-axis limits to zoom in on the specified date range
ax1.set_xlim(pd.Timestamp('2024-04-21'), pd.Timestamp('2024-05-01'))

# Show plot
plt.tight_layout()
plt.savefig('Figures/Filtered_Water_Level_Zoomed.png')
plt.show()
```



Simplifying Noise Reduction and Infiltration Capacity Analysis

While various sophisticated filters can be applied to reduce noise in the water level signal, such as Moving Average, Rolling Mean, Savitzky-Golay, Low-Pass, and Kalman Filters, they often overcomplicate the problem. These methods can introduce unnecessary complexity and may not provide a clear, intuitive understanding of the infiltration capacity.

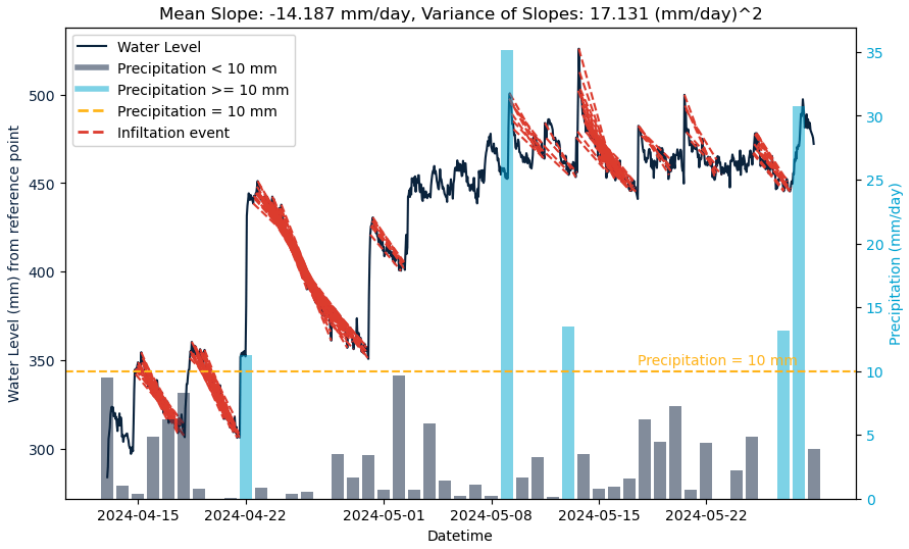
To simplify the analysis and obtain a more straightforward measure of infiltration capacity, I chose to use a straight line from the maximum to the minimum of an infiltration event. This approach offers a clear visual representation and straightforward interpretation of the infiltration rate.

Criteria for Identifying Infiltration Events:

- **No significant rainfall events (>10mm) interrupting the infiltration event.**
- **The event should last longer than two days.**
- **The infiltration rate should exceed 8 mm/day.**

These criteria ensure that the infiltration events are clearly defined and not influenced by external factors such as heavy rainfall. The events that meet these criteria are illustrated in the next figure with a red dashed line.

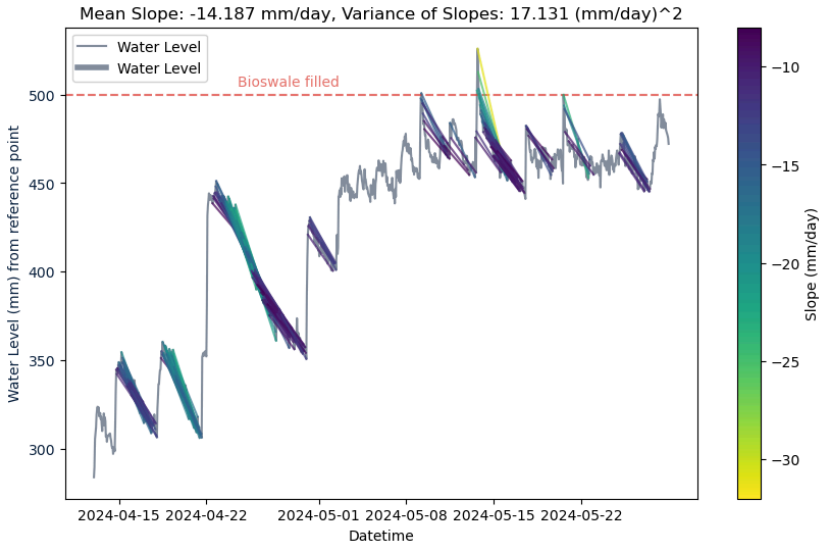
In [8]:
```
# Find all days with under 10 mm precipitation
under_10_precipitation_days = WS_daily_mean[WS_daily_mean['Daily Rain(mm)'] < 10]
over_10_precipitation_days = WS_daily_mean[WS_daily_mean['Daily Rain(mm)'] >= 10]

# Plotting
fig, ax1 = plt.subplots(figsize=(10, 6))

# Create a secondary y-axis for daily rain
ax2 = ax1.twinx()
bar_container_under_10 = ax2.bar(under_10_precipitation_days.index, under_10_precipitation_days['Daily Rain(mm)'], color='C1', alpha=0.5, label='Precipitation < 10 m
bar_container_over_10 = ax2.bar(over_10_precipitation_days.index, over_10_precipitation_days['Daily Rain(mm)'], color='C0', alpha=0.5, label='Precipitation >= 10 mm'
ax2.set_ylabel('Precipitation (mm/day)', color='C0')
ax2.tick_params(axis='y', labelcolor='C0')

# Plot water level
line1, = ax1.plot(WL.index, WL['Water_level_diver(mm)'], color='C1', label='Water Level')
ax1.set_ylabel('Water Level (mm) from reference point', color='C1')
ax1.tick_params(axis='y', labelcolor='C1')

# Add horizontal lines at y = 10
ax2.axhline(y=10, color='C9', linestyle='--')
ax2.text(WL.index[3*len(WL)//4], 10.5, 'Precipitation = 10 mm', color='C9')  # Adjusted position

# Add label for x-axis
ax1.set_xlabel('Datetime')

# Finding negative slopes in the water level plot
valid_slopes = []
rolling_window = 48  # 2 days with hourly data
slope_threshold_min = -8  # mm/day

for start in range(len(WL) - rolling_window):
    end = start + rolling_window
    slope = (WL['Water_level_diver(mm)'][end] - WL['Water_level_diver(mm)'][start]) / (rolling_window / 24)  # Convert to mm/day
    if slope <= slope_threshold_min:
        valid_slopes.append(slope)
        x1 = WL.index[start]
        y1 = WL['Water_level_diver(mm)'][start]
        x2 = WL.index[end]
        y2 = WL['Water_level_diver(mm)'][end]
        ax1.plot([x1, x2], [y1, y2], color='C7', linestyle='--')

# Calculate mean and variance of valid slopes
slopes_mean = np.mean(valid_slopes)
slopes_var = np.var(valid_slopes)

# Set title with mean and variance of slopes
ax1.set_title(f'Mean Slope: {slopes_mean:.3f} mm/day, Variance of Slopes: {slopes_var:.3f} (mm/day)^2')

# Combine Legends
lines, labels = ax1.get_legend_handles_labels()
lines2 = [
    plt.Line2D([0], [0], color='C1', lw=4, alpha=0.5),
    plt.Line2D([0], [0], color='C0', lw=4, alpha=0.5),
    plt.Line2D([0], [0], color='C9', linestyle='--', lw=2),
    plt.Line2D([0], [0], color='C7', linestyle='--', lw=2)
]
labels2 = ['Precipitation < 10 mm', 'Precipitation >= 10 mm', 'Precipitation = 10 mm', 'Infiltation event']

lines += lines2
labels += labels2

ax1.legend(lines, labels, loc='upper left')

# Save the plot without grid
plt.grid(False)
plt.savefig('Figures/BS_AdeKUS_2days.png')

# Show plot
plt.show()
```



These criteria ensure that the infiltration events are clearly defined and not influenced by external factors such as heavy rainfall. The events that meet these criteria are illustrated in the next figure, where the infiltration rate is mapped, differentiating faster infiltration events from slower ones and showing when each event occurred.

In [9]:
```
# Plotting
fig, ax1 = plt.subplots(figsize=(10, 6))

# Plot water level
line1, = ax1.plot(WL.index, WL['Water_level_diver(mm)'], color='C1', label='Water Level', alpha=0.5)
ax1.set_ylabel('Water Level (mm) from reference point', color='C1')
ax1.tick_params(axis='y', labelcolor='C1')

ax1.axhline(y=500, color='C7', linestyle='--', alpha=0.7)
ax1.text(WL.index[len(WL)//4], 505, 'Bioswale filled', color='C7', alpha=0.7)

# Add label for x-axis
ax1.set_xlabel('Datetime')

# Finding negative slopes in the water level plot
valid_slopes = []
rolling_window = 48  # 2 days with hourly data
slope_threshold_min = -8  # mm/day

norm = mcolors.Normalize(vmin=-32, vmax=slope_threshold_min)
cmap = plt.cm.viridis_r  # Reversed colormap to have brighter colors for higher negative slopes

# Variables to track the lowest slope
lowest_slope = np.inf
lowest_slope_start = None
lowest_slope_end = None

for start in range(len(WL) - rolling_window):
    end = start + rolling_window
    slope = (WL['Water_level_diver(mm)'][end] - WL['Water_level_diver(mm)'][start]) / (rolling_window / 24)  # Convert to mm/day
    if slope <= slope_threshold_min:
        valid_slopes.append(slope)
        if slope < lowest_slope:
            lowest_slope = slope
            lowest_slope_start = WL.index[start]
            lowest_slope_end = WL.index[end]
        x1 = WL.index[start]
        y1 = WL['Water_level_diver(mm)'][start]
        x2 = WL.index[end]
        y2 = WL['Water_level_diver(mm)'][end]
        color = cmap(norm(slope))
        ax1.plot([x1, x2], [y1, y2], color=color, alpha=.7)

# Calculate mean and variance of valid slopes
slopes_mean = np.mean(valid_slopes)
slopes_var = np.var(valid_slopes)

# Set title with mean and variance of slopes
ax1.set_title(f'Mean Slope: {slopes_mean:.3f} mm/day, Variance of Slopes: {slopes_var:.3f} (mm/day)^2')

# Add colorbar for slope values
sm = plt.cm.ScalarMappable(cmap=cmap, norm=norm)
sm.set_array([])  # Only needed for matplotlib < 3.1
cbar = plt.colorbar(sm, ax=ax1)
cbar.set_label('Slope (mm/day)')

# Combine legends
lines, labels = ax1.get_legend_handles_labels()
lines2 = [plt.Line2D([0], [0], color='C1', lw=4, alpha=0.5)]
labels2 = ['Water Level']

lines += lines2
labels += labels2

ax1.legend(lines, labels, loc='upper left')

# Save the plot without grid
plt.grid(False)
plt.savefig('Figures/BS_AdeKUS_2days_colored.png')

# Show plot
plt.show()

# Print the lowest slope and the length of the slope in days
```

```
if lowest_slope_start and lowest_slope_end:
    lowest_slope_duration_days = (lowest_slope_end - lowest_slope_start).days
    print(f"Highest negative slope: {lowest_slope:.3f} mm/day over {lowest_slope_duration_days} days")
    print(f"with period: {lowest_slope_start} to {lowest_slope_end}")
else:
    print("No slopes found below the threshold.")
```

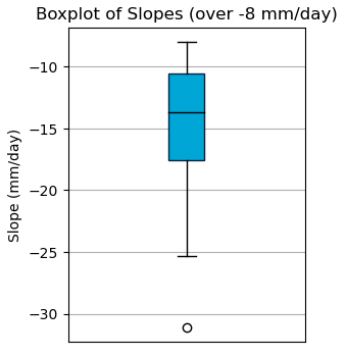



```
Highest negative slope: -31.125 mm/day over 2 days
with period: 2024-05-13 17:00:00 to 2024-05-15 17:00:00
```

Observations on Rainfall Events

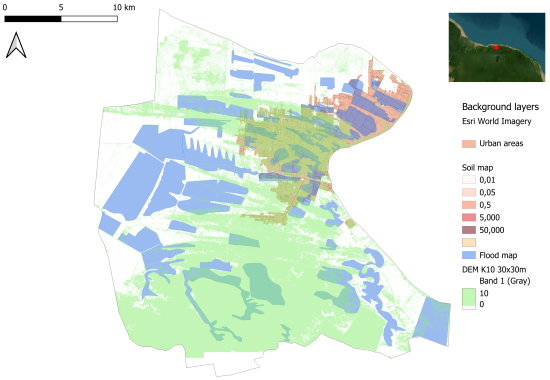
The heaviest rainfall event occurred during the flood event of 13-5 to 15-5 at the bioswale, indicating that the surrounding area of the bioswale is used to infiltrate the water. In this test set-up, this is possible because the swale is surrounded by permeable soil. However, in other applications, bioswales are likely to be surrounded by impermeable soil such as asphalt and concrete. For that reason, the highest value during the flood event might not be reliable for determining the infiltration capacity of the bioswale.

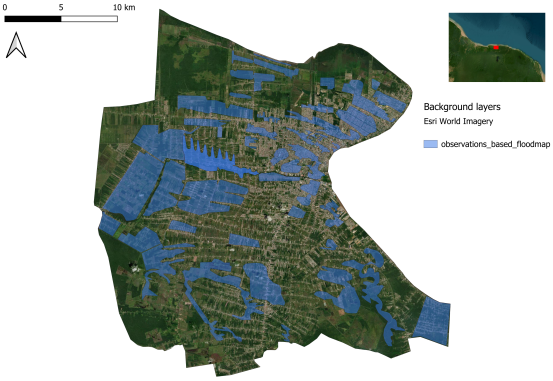
In [10]:
```
# Create a new figure for the boxplot
fig, ax_box = plt.subplots(figsize=(3, 4))  # Swap width and height to accommodate vertical orientation

# Plot boxplot of valid slopes with inverted axes
ax_box.boxplot(valid_slopes, vert=True, patch_artist=True, boxprops=dict(facecolor='C0', color='C1'), medianprops=dict(color='black'))
ax_box.set_ylabel('Slope (mm/day)')
ax_box.set_title('Boxplot of Slopes (over -8 mm/day)')

# Remove x-axis labels and ticks
ax_box.xaxis.set_visible(False)
ax_box.grid(True)

# Save plot
# plt.tight_layout()
plt.savefig('Figures/BS_AdeKUS_slope_boxplot.png')

# Show plot
plt.show()
```

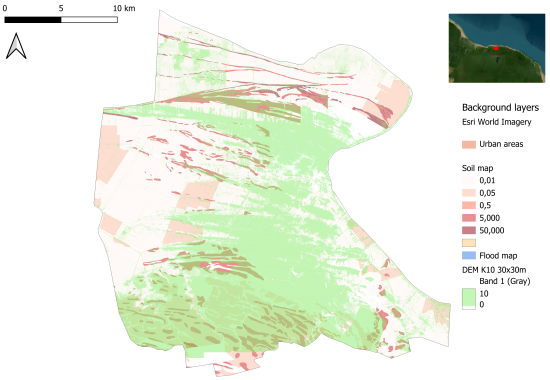


H

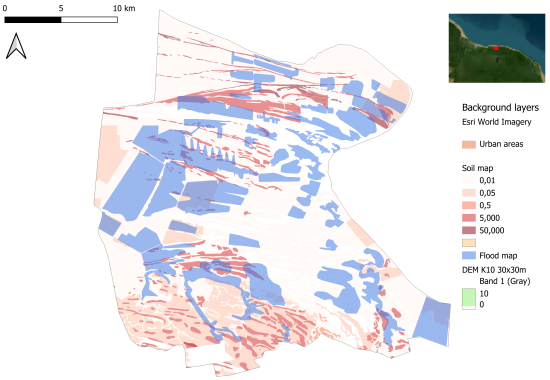
Potential Implementation Maps

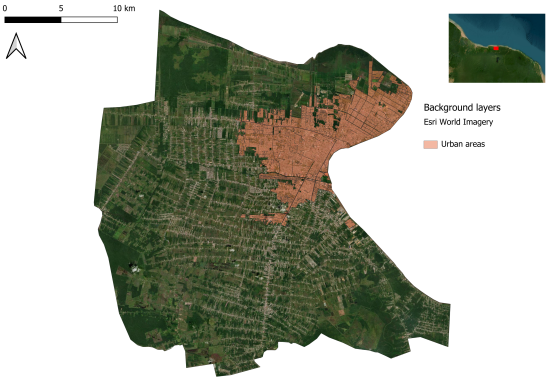

0 5 10 km
Background layers
Esri World Imagery
Urban areas
Soil map
0,01
0,05
0,5
5,000
50,000
Flood map
DEM K10 30x30m
Band 1 (Gray)
10
0

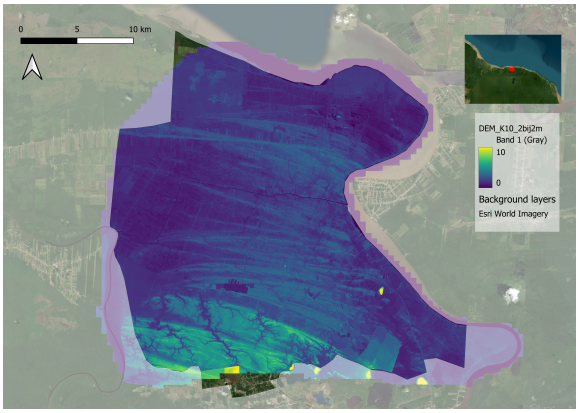

0 5 10 km
Background layers
Esri World Imagery
observations_based_floodmap


0 5 10 km
Background layers
Esri World Imagery
Urban areas
Soil map
0,01
0,05
0,5
5,000
50,000
Flood map
DEM K10 30x30m
Band 1 (Gray)
10
0


0 5 10 km
Background layers
Esri World Imagery
Soil map permeabilities (m/day)
0,01
0,05
0,5
5
50


0 5 10 km
Background layers
Esri World Imagery
Urban areas
Soil map
0,01
0,05
0,5
5,000
50,000
Flood map
DEM K10 30x30m
Band 1 (Gray)
10
0


0 5 10 km
Background layers
Esri World Imagery
Urban areas


0 5 10 km
DEM_K10_2bj2m
Band 1 (Gray)
10
0
Background layers
Esri World Imagery