Integrating Nature-Based Solutions in Informal Settlements:

A Case Study of Climate-Resilient Urban Planning in Philippi, South Africa

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Title: Integrating Nature-Based Solutions in Informal Settlements: A Case Study of Climate-Resilient Urban Planning in Philippi, South Africa

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Abstract

Cities worldwide face major environmental and sustainability challenges in an era characterised by increasing urbanisation and the intensifying impacts of climate change. This thesis explores the integration of Nature-Based Solutions into the urban structure of informal settlements to enhance climate resilience. Due to its unique challenges and vulnerable community, it uses Philippi in Cape Town, South Africa as a case study. The research aims to assess the viability and effectiveness of Nature-Based Solutions in improving urban water management and reducing vulnerability to climate-related risks. The study employs a mixed-methods approach, combining qualitative review of local reports and literature with quantitative data on hydrology, geology and socio-economic conditions, to ultimately provide a conceptual design and recommended strategy to increase climate resilience in this vulnerable urban structure.

The research identifies key environmental challenges in Philippi, including frequent flooding and inadequate stormwater drainage, exacerbated by poor infrastructure, blocked drainage systems and socio-economic vulnerabilities. The main results indicate that Nature-based solutions interventions, such as bioswales, permeable pavements, and bioretention areas, offer cost-effective and sustainable alternatives to traditional infrastructure while contributing to better quality stormwater. It is suggested that the solutions discussed in this study, contribute to effective stormwater management while enhancing urban resilience and community well-being.

The conclusions emphasise the necessity of context-specific designs and strong community engagement for NBS project success. The study suggests a participative approach to designing and implementing NBS to ensure cultural relevance and sustainability. Based on past research, it is obvious that institutional support and coordination among local governments, NGOs, and community groups are critical to the long-term viability of these initiatives.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CBA - Community-Based Adaptation
CCA - Climate Change Adaptation
CFA - Cape Flats Aquifer
CFR - Cape Floristic Region
CoCT - City of Cape Town
CSIR - Council for Scientific and Industrial Research
DIY - Do It Yourself
ES - Ecological Services
FGD - Focus Group Discussions
ISN - Informal Settlement Network
NBS - Nature-Based Solutions
NGO - Nongovernmental Organisation
PCBP - Permeable Concrete Block Pavers
PHA - Philippi Horticultural Area
SDG - Sustainable Development Goals

SES - Socio-Ecological Systems
SuDS - Sustainable Urban Drainage System
TEK - Traditional Ecological Knowledge
UCT - University of Cape Town
UNFCCC - The United Nations Framework Convention on Climate Change
WQV - Water Quality Volume

1. Introduction

Cities around the world are dealing with significant environmental and sustainability difficulties in an era marked by growing urbanisation and the escalating challenges of climate change. Water, an indispensable resource for urban life, is currently at the forefront of urban resilience and sustainability discussions, highlighting its central importance in addressing these concerns (Roaf et al., 2009; Swatuk et al., 2021).

Managing urban water in Cape Town, South Africa, presents unique challenges due to the region's Mediterranean climate, which features wet winters and dry summers (Lionello et al., 2006). The city narrowly escaped a "Day Zero" situation that would have resulted in cutting off the supply of municipal water in 2017-2018 due to a severe water crisis. This highlights another critical need: better management of urban waters to improve resilience and mitigate the effects of increasing droughts and floods (Taing et al., 2019).

Cape Town will be increasingly vulnerable to extreme weather events such as increased storm activity as a result of anthropogenic pressures, poor drainage, and soil degradation, as well as intense cut-off lows and cyclones (Dube et al., 2021). Urbanisation and climate change, including the El Niño-Southern Oscillation, contribute to increased coastal as well as pluvial flooding (see Figure 1). Furthermore, Figure 2 demonstrates both how serious the problem is and how concerning the seasonal water fluctuations in dams are. The red line depicts the estimated point at when the taps would be shut off, sometimes known as "Day Zero". All of this appears to point to the critical need for new urban solutions that imitate nature's efficiency in urban water management (Dube et al., 2021).

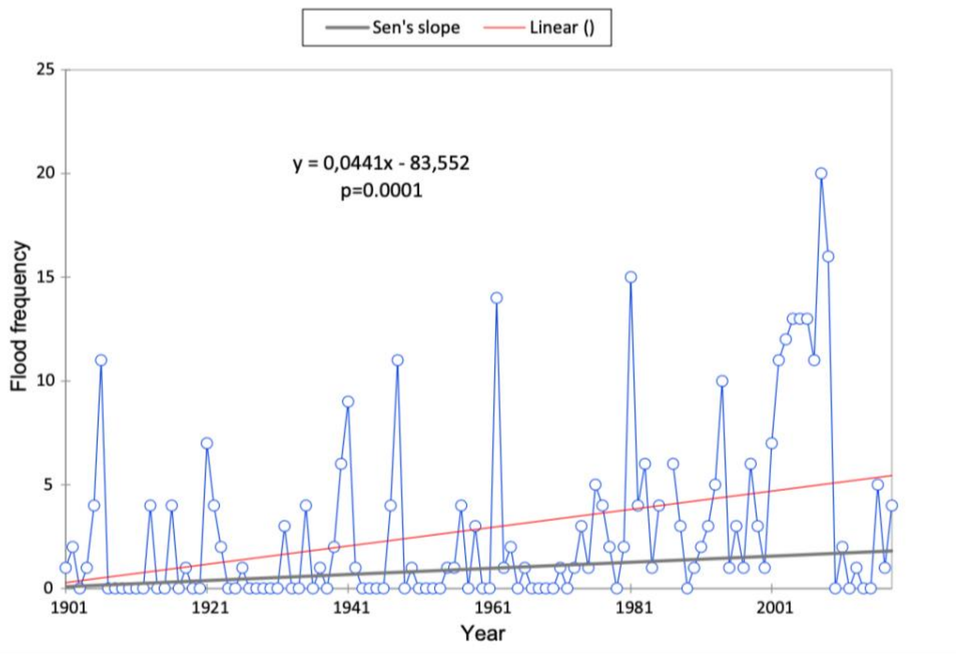

Figure 1. Flooding frequency and trends in Western Cape province 1900–2018. (Dube et al., 2021)

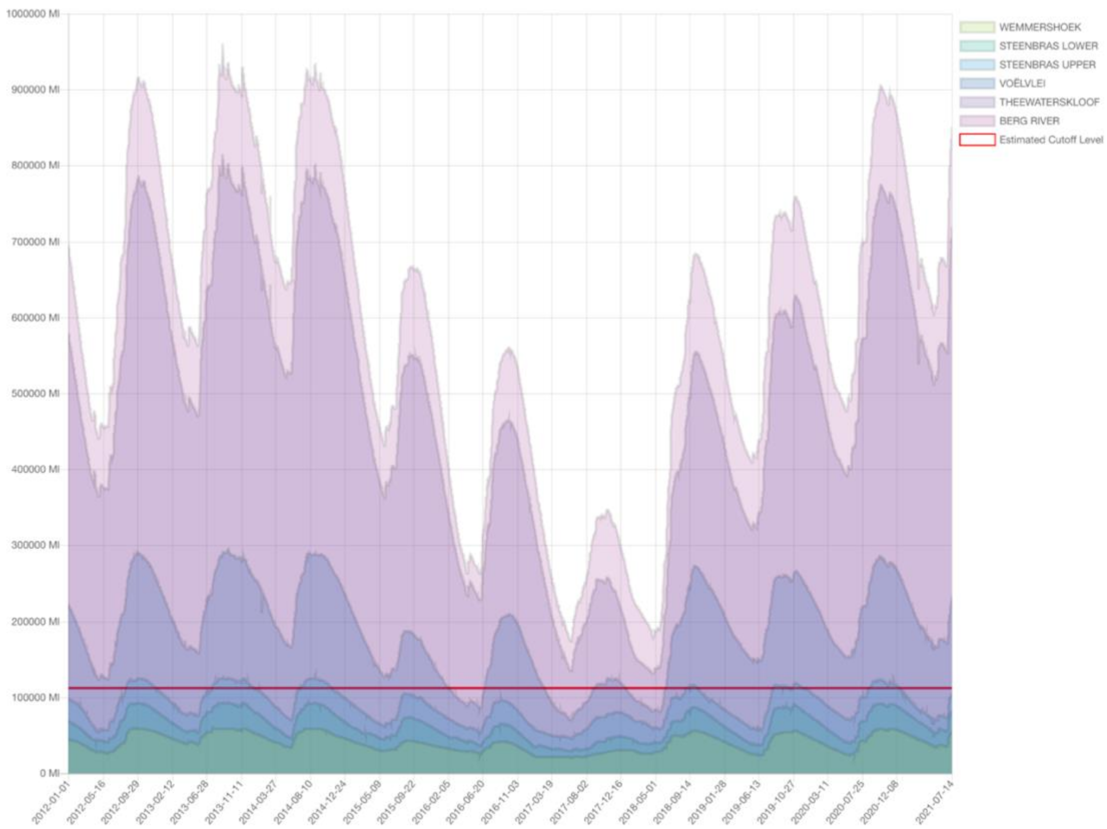

Figure 2. Historical Dam Levels for the Cape Town Region: 2012—2021. (www.capetowndrought.com, 2021)

In response, the report by Swatuk et al. (2021) looks into the use of nature-based solutions (NBS) as comprehensive approaches to resolving Cape Town's water-related risks. These initiatives aim to improve urban water security and sustainable development, which is especially important for cities facing water scarcity as a result of climate change and urbanisation. Particularly, the informal settlements in the Cape Flats area such as Philippi, prone to winter flooding due to a high-water table and heavy rainfall, exhibit the acute vulnerabilities of these communities. These vulnerabilities are intensified by inadequate infrastructure, poor housing quality, and economic disparities, thereby emphasising the need for effective water management and climate resilience strategies. Such climate resilience strategies are vital not only for low-income communities but also for affluent areas that face the compounded impacts of sea-level rise and storm activity (Dube et al., 2021; Drivdal, 2015).

The study focuses on the viability of integrating the NBS into Cape Town's informal settlements while addressing the areas' unique environmental and socio-economic challenges. Furthermore, this study contributes to the discussion of sustainable urban development in the age of climate change by providing insights into developing resilient, water-sensitive cities capable of navigating the difficulties of urbanisation and climate change inequities, thereby improving the quality of life for their residents. Moreover, the research will consider the role of community involvement and its contribution to sustainable development and community upliftment. It is suggested that engaging residents in planning and implementation ensures cultural relevance and sustainability, while collaborative governance between local authorities, NGOs, and community groups is crucial for long-term success (Diep et al., 2022). This integrated approach is essential for effectively addressing informal settlements' complex water management and environmental challenges.

1.1. Context of the research

According to UN-Habitat (2022), urban areas house more than 55% of the world's population and are anticipated to grow to 68% by 2050. This urban development is predominantly occurring in rising Asia and Africa, which are seeing the fastest rates of urban population growth and an increase in natural disasters. According to United Nations (2019) figures (see Figure 3), informal settlements are home to nearly 1 billion people worldwide, a figure that is anticipated to rise as urban areas grow. The communities around Cape Town are no different, and because these settlements are frequently located in disaster-prone locations, residents are more vulnerable to the effects of climate change, such as flooding and extreme weather events (Dube et al., 2021).

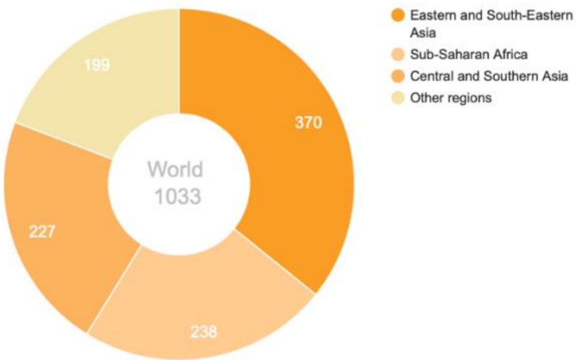

Figure 3. Urban population living in slums or informal settlements, 2018 (millions of people). (United Nations, 2019)

The City of Cape Town (CoCT), with its fast urban expansion, embodies these developmental issues. The extensive region known as the Cape Flats (Figure 4), known for its low elevation and vulnerability to floods, has experienced a significant expansion in informal settlements (Mtuleni, 2016). According to recent research, many settlements in this region, including Philippi, are particularly vulnerable to winter flooding as a result of severe rainfall and insufficient drainage systems. According to Dube et al. (2021), nearly 60% of CoCT's informal settlements are located in flood-prone locations, threatening the health and safety of thousands of residents.

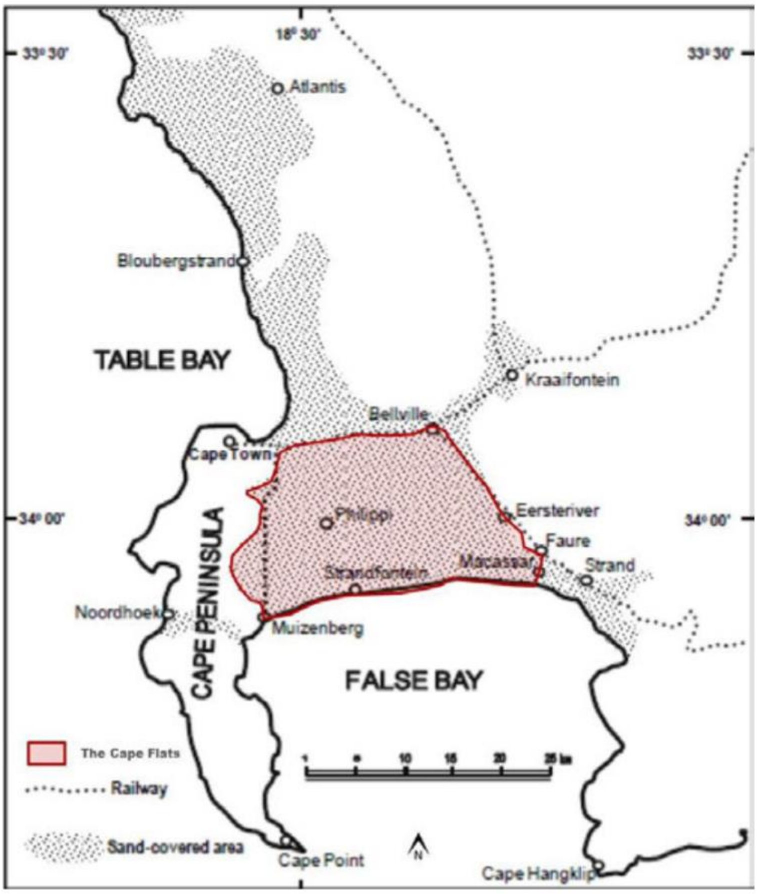

Figure 4. Location of the Cape Flats area in the Cape Town Metropolitan Area (Adelana et al., 2010)

In terms of the study's scope, Philippi Township (see Figure 5) is a prominent urban region in the south-east of Cape Town, South Africa. Philippi, represents the problems and opportunities posed by growing urbanisation, climate change, and informal settlement growth (Mtuleni, 2016). Furthermore, Philippi's geographical location on the Cape Flats makes it prone to flooding. The area is characterised by flat, low-lying topography with a high water table and mostly sandy soils, which naturally predispose it to waterlogging during the winter rainfall season (Mtuleni, 2016).

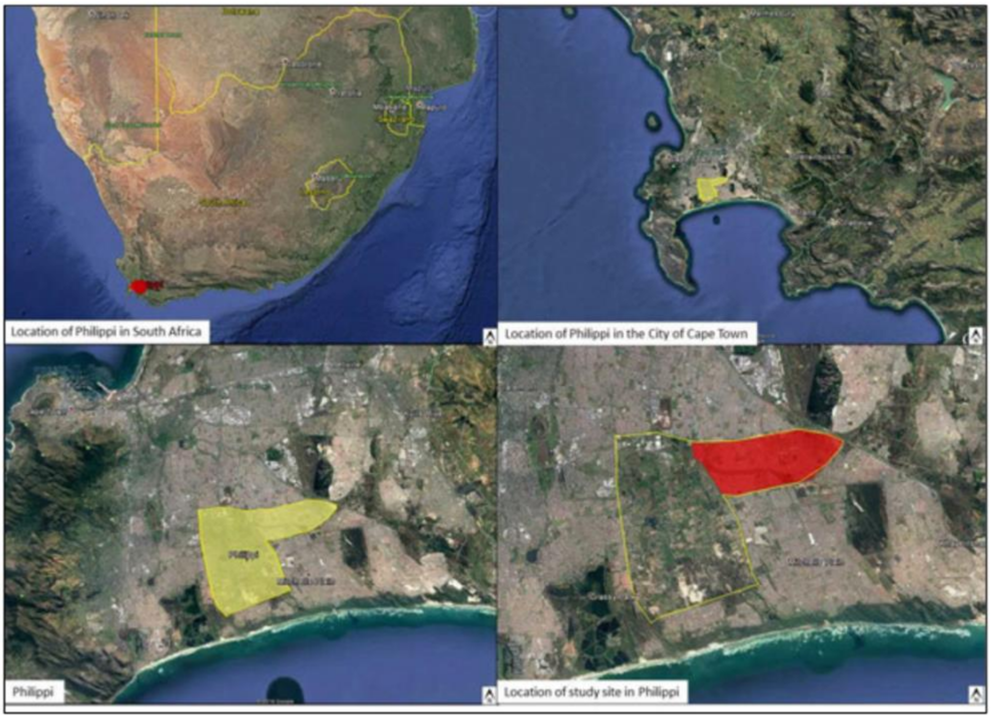

Figure 5. Contextualising the study area. (Mtuleni, 2016)

Furthermore, the Cape Flats Aquifer (see Figure 6), presents both a challenge and an opportunity for water resource management, as it has the potential for sustainable groundwater extraction while also being susceptible to contamination and overexploitation (Mtuleni, 2016).

Figure 6. Aquifers beneath the Cape Metropolitan Area. (CoCT, 2018)

Philippi, with its rapidly growing population, worsened by in-migration from rural regions seeking better chances in Cape Town, is at the forefront of this urban issue (Mtuleni, 2016). During 2016-2021, the Western Cape received 468,568 in-migrants and 178,013 out-migrants, leading to a positive net migration of 40,8%. The CoCT is the largest recipient of migrants in the province (Stats SA, 2021). According to the Cooperative Governance and Traditional Affairs (COGTA) (2020), the township's population has been gradually increasing, with a substantial percentage living in conditions that do not fulfil basic housing standards, hence increasing their vulnerability to extreme events such as flooding.

Furthermore, climate projections for the Western Cape indicate that high-intensity rainfall events would become more frequent (see Figure 7), exacerbating existing flood hazards in the region (Dube et al., 2021). At the same time, dry summer periods would continue to become drier, leading to severe droughts.

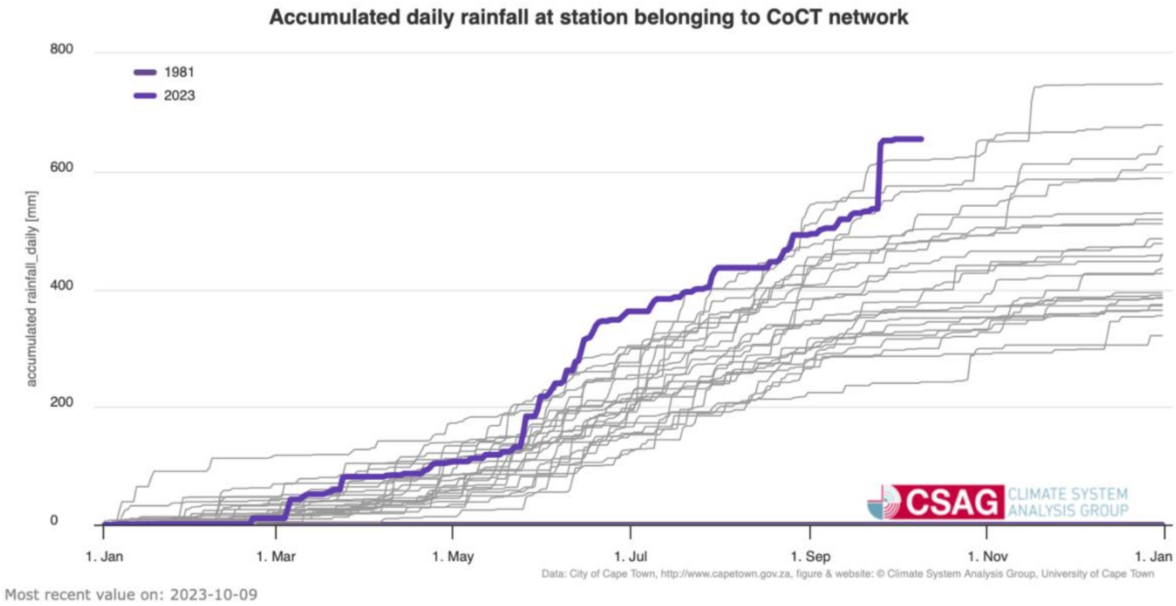

Figure 7. Year-by-year accumulated daily rainfall from 1981 to 2023 in CoCT (Tygerberg collection point). (CSAG, 2023)

The city's approach to flooding has frequently been reactive rather than proactive, with short-term emergency measures preceding long-term, permanent solutions (Mtuleni, 2016). The Water Research Commission's (2021) report, Towards the Blue-Green City: Building Urban Water Resilience, recognises the need for more holistic approaches to water management, highlighting the importance of incorporating NBS into urban planning to improve flood resilience and adapt to changing climate conditions.

1.2. Main Objectives

The problem statement emphasises aforementioned previously, that urbanisation and climate change present significant challenges globally, with informal settlements being particularly vulnerable. Effective water management strategies are crucial for creating sustainable and resilient urban structures in these areas (Drivdal, 2015). NBS offer a promising approach to sustainable climate adaptation, aiming to mitigate extreme events and build resilience (World Bank Group, 2021).

Initial examinations of documents like the "Philippi Opportunity Area Local Spatial Development Framework" by the City of Cape Town (CoCT) (2022) and "Towards the Blue-Green City: Building Urban Water Resilience" by Swatuk et al. (2021) reveal a reliance on broad governmental strategies that often overlook the unique challenges of specific underprivileged areas within Philippi, such as Brown Farms. These areas frequently lack basic infrastructure, making traditional solutions both expensive and difficult to maintain (Mtuleni, 2016). Additionally, broad NBS strategies often fail to consider the socioeconomic constraints, governance issues, and infrastructural deficiencies prevalent in informal settlements (Hanson et al., 2020). This study also acknowledges the unique challenges posed by the socio-economic conditions in informal settlements, particularly the community's reluctance to maintain these measures, and issues such as vandalism and theft.

Moving to the main objectives, the purpose of this study is to assess the applicability of NBS for increasing climate resilience and reducing human vulnerability in informal settlements. By evaluating a conceptual NBS design, the research will analyse its viability in terms of efficacy, community engagement, cost-effectiveness, and local adaptability. Focusing on the Philippi informal settlement, the study will explore the feasibility and implementation potential of NBS within this challenging urban setting. In addition, it seeks to address the research gap due to the absence of detailed case studies and proposed design solutions in existing policy documents.

The objectives include examining existing plans and policies and conducting a literature review on NBS. This study will critically evaluate the application of NBS principles within the specific constraints and opportunities of informal settlements like Philippi, thereby contributing to sustainable urban development and resilience.

Furthermore, the study proposes practical design solutions that utilise NBS principles to reduce flooding, enhance water security, and improve living conditions in the Philippi. These solutions will be tailored to local conditions and unique challenges while remaining scalable and replicable in similar urban contexts. Finally, the research findings and recommendations will advocate for sustainable and resilient urban development practices. These practices will prioritise the integration of NBS, community involvement, and adaptive planning to address the challenges of climate change and urbanisation in informal settlements.

Discussing the social relevance of the research. Addressing challenges in informal settlements directly contributes to several United Nations Sustainable Development Goals (SDGs). It supports SDG 11 (Sustainable Cities and Communities) by promoting urban resilience and water management through NBS, aiming for safer, more sustainable, and inclusive urban environments. It also supports SDG 6 (Clean Water and Sanitation) by increasing access to clean water and sanitation in underserved communities, and SDG 13 (Climate Action) by offering adaptive methods to mitigate climate change effects on vulnerable populations.

Overall, this research enhances both societal and academic understanding of NBS in informal settlements, providing evidence for their validity and effectiveness. It offers insights for customising and scaling solutions, enriching scholarly discourse on ecosystem services and urban biodiversity, and serving as academic case studies for teaching and future research.

1.3. Central Research Question(s)

The study aims to answer the following research questions:
Main Research Question: "Could NBS be viable and effectively implemented in the Philippi informal settlement to improve urban water resilience and environmental sustainability?"
Sub-Question 1: “What are the specific water management, environmental challenges and opportunities in the Philippi informal settlement?”
Sub-Question 2: “What design solutions can be proposed to incorporate NBS principles effectively within Philippi’s landscape and built environment?”
Sub-Question 3: ”How does community involvement in the planning, decision-making, and implementation phases impact the minimisation of vandalism, the effectiveness and sustainability of NBS in urban environments?”
Sub-Question 4: “What lessons can be learned from the Philippi case study that applies to other informal settlements facing similar water management challenges?”

1.4. Reading Guide

Chapter 1 – The Introduction will provide information on the research background, problem statement, and aims. This part offers the groundwork for recognising the need for implementing NBS in informal settlements and establishes the framework for the inquiry.

Chapter 2 – Theoretical Framework. The framework summarises available information about NBS and pertinent climate adaptation theories. It is critical to grasp the theoretical foundations of the study and identify the research gap that this work seeks to fill. Concentrate on the discussions about the social, economic, and environmental challenges of using NBS in informal communities.

Chapter 3 – Methodology. This section outlines the research design, data collection techniques, and methods of analysis. Understanding this process is crucial for appreciating the depth of research and the approach taken to develop tailored NBS design solutions for informal settlements. It includes a comprehensive case study of Philippi Township, delving into its background to better understand the specific challenges and opportunities related to the research. This section is vital for grasping the complexities of implementing NBS in real-world scenarios and highlights the importance of context-specific solutions.

Chapter 4, 5 – Design Proposal and Discussion. The chapter proposes tailored NBS for Philippi's particular difficulties, with a focus on urban water resilience and community well-being. This chapter assesses the feasibility and impact of various options in Philippi's setting, addressing limits and potential for implementing NBS to ensure sustainable urban growth and climate adaptation.

Chapter 6 – Conclusions and Recommendations. The study ends with conclusions and recommendations, which summarise the study's important findings and suggest areas for further research, policymaking, and urban planning practices. This section summarises the research findings and their practical implications for promoting sustainable urban development.

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2. Theoretical Framework

This research is grounded in a robust theoretical framework that synthesises insights from urban resilience theory (section 2.1.), the ecosystem services (ES) framework (section 2.2.), socio-ecological systems (SES) theory (section 2.3.), and sustainable urban drainage system (SuDS) (section 2.4.). These theoretical underpinnings offer a holistic, multidisciplinary approach to comprehending, crafting, and overseeing urban spaces. They underscore the importance of bolstering resilience, advancing sustainability, and nurturing well-being through the deployment of NBS (section 2.5.), with a particular focus on informal settlements.

The research will make use of the following definition of informality, as described by Huchzermeyer et al. (2014):

> *"An 'Informal Settlement' exists where housing has been created in an urban or peri-urban location without official approval. Informal settlements may contain a few dwellings or thousands of them and are generally characterised by inadequate infrastructure, poor access to basic services, unsuitable environments, uncontrolled and unhealthy population densities, inadequate dwellings, poor access to health and education facilities and lack of effective administration by the municipality"*

Crucially, this framework acknowledges the diverse contexts across various informal settlements, recognising that each presents unique socio-economic, environmental, and infrastructural challenges and opportunities.

2.1. Urban Resilience Theory in Informal Settlements

Resilience, within the urban context, particularly concerning informal settlements, encompasses the capacity of these communities to withstand, adapt to, and recover from hazardous events, trends, or disturbances such as climate change, socio-economic instability, and urbanisation pressures (UN-Habitat, 2022). This concept emphasises the ability of informal settlements to maintain their core functions, identity, and structural integrity amidst challenges, ensuring the sustainability of their social fabric and physical infrastructure (UN-Habitat, 2022).

In the context of climate change, resilience takes on new dimensions of complexity. All parties, including governments, local communities, NGOs, and the commercial sector, must work together to develop adaptation strategies to deal with unavoidable climate consequences, as well as mitigation steps to decrease future risks. The United Nations Framework Convention on Climate Change (UNFCCC, 2020) emphasises six important factors for creating climate resilience, which are especially relevant to informal settlements. These are briefly described below:

1. Awareness-Raising and Advocacy: Educating residents about climate risks and resilient practices. For instance, in informal settlements, this involves tailored communication strategies that consider literacy levels, cultural norms, and accessible media to ensure widespread understanding and engagement.

2. Climate Risk Assessments and a Systems Approach: This might include conducting detailed analyses of specific vulnerabilities and exposure to climate hazards within informal settlements. This requires a holistic understanding of the socio-ecological and infrastructural systems that underpin these communities, identifying points of resilience and fragility.

3. Appropriate Implementation: This entails developing and executing adaptation and mitigation strategies that are suited to the unique characteristics of informal settlements. Presuming culturally sensitive, community-led initiatives that leverage local knowledge and practices, ensuring interventions are both effective and socially acceptable.

4. Resource Mobilisation: Securing and allocating financial, human, and technological resources to support resilience-building activities. In the context of informal settlements, innovative financing models and partnerships are essential to overcome economic constraints and ensure the long-term sustainability of resilience efforts.

5. Monitoring of Progress: Establishing mechanisms to track the effectiveness of resilience strategies, adaptively managing and refining approaches based on feedback and changing conditions. In informal settlements, participatory monitoring involving community members can enhance ownership and responsiveness of resilience measures.

6. Sharing Knowledge, Experiences, and Solutions: Facilitating the exchange of insights and best practices both within and beyond informal settlements to foster a collective learning process. Peer-to-peer learning platforms, workshops, and digital forums can help disseminate successful resilience strategies, fostering a culture of innovation and mutual support.

These elements underscore the importance of community-centred, adaptable, and resource-sensitive approaches to enhancing resilience, recognising the inherent strengths and addressing the specific vulnerabilities of informal settlements (UNFCCC, 2020).

Moving from the social side of resilience to the more technical side. Against the backdrop of increasing extreme weather events, the limitations of existing water infrastructure have become glaringly apparent (Brown et al., 2020). These systems, often designed on outdated assumptions of climate stability, are ill-equipped to handle unexpected conditions presented by today's changing climate, leaving communities exposed to heightened risks (Brown et al., 2020). The "Resilience by Design" framework mentioned in the article by Brown et al. (2020) emerges as a response to this challenge, advocating for a systemic approach. This approach is defined by three fundamental capacities:
- Persistence: The system's ability to continue its core functions despite disruptions and shifts, retaining its essential identity.
- Adaptability: The system's capacity to modify its operations and, if necessary, its identity, to align with changing circumstances.
- Transformability: The system's potential to fundamentally change and stabilise around a new functional baseline when existing conditions make it impossible to preserve its original state (Brown et al., 2020).

The "Resilience by Design" framework offers a methodical way to assess the resilience of systems, examining their persistence, adaptability, and transformability in anticipation of future challenges. This analytical perspective is vital for devising systems that remain coherent under evolving stressors, ensuring the long-term provision of essential services in the face of climatic and environmental changes (Brown et al., 2020).

By adopting a "Resilience by Design" approach, tailored to the complexities of informal settlements, this research aims to bridge the gap between theoretical resilience strategies and practical, on-the-ground implementation needs. It focuses on developing adaptable, sustainable, and transformative solutions that ensure the longevity and efficacy of water management systems amidst the uncertainties of climate change. This integrated theoretical framework provides a comprehensive basis for exploring, designing, and managing urban environments in ways that enhance resilience, sustainability, and well-being through the implementation of NBS, particularly in the challenging contexts of Philippi informal settlement.

2.2. Ecosystem Services Framework

2.2.1. Definition

Another concept, Ecosystem Services (ES), will be widely used and discussed throughout the research to illustrate the advantages (see Table 1) and disadvantages that NBS could hold in informal settlements such Philippi. The ES will be used in this research as the cornerstone of NBS, SuDS, and SES, guiding the integration of natural processes into urban planning in Philippi informal settlement. The definition of ES will follow from the work by Gómez-Baggethun and Barton (2013) who state that ES refer to the array of advantages that humans derive from the natural functioning of ecosystems, including their direct and indirect contributions to our well-being. The focus is on 'urban ecosystem services,' which are the benefits emanating from ecosystems within urban environments and their elements. Such ecosystems typically feature extensive built infrastructure or support densely populated areas. They encompass the urban 'green and blue spaces,' like parks, cemeteries, residential gardens, communal allotments, urban woodlands, wetlands, rivers, lakes, and smaller patches of vegetation, including trees, shrubs, and grass (Gómez-Baggethun and Barton, 2013). This network of green and blue spaces alongside "productive natural landscapes" such as home gardens or allotments, and small-scale innovations for stormwater management, are key elements of NBS (Adegun, 2017). The concept of what constitutes an urban area, including its limits, differs across different countries and regions, influenced by factors like land use, population size and density, the spacing between homes, and the share of the population working in sectors other than agriculture (Gómez-Baggethun and Barton, 2013).

Informal settlements frequently link with NBS by occupying unused or ecologically valuable lands, such as those near bodies of water, in wetlands, or on steep slopes. This pattern is noticeable in the biodiversity-abundant regions of developing nations, where many informal settlements, including those in Mexico City, are situated on lands designated for conservation due to their ecological significance (Adegun, 2017).

Table 1. Summary of key ecosystem services in informal urban areas. (Adegun, 2017).

Service Type	Example	Description	Source(s)
Provisioning	Food	Food and vegetable production in wetlands, communal/private open spaces used as gardens; Fish production and harvesting in blue spaces	Van Averberke (2007); Honning (2009); Rau *et al.* (2011); Hennings *et al.* (2012); Singh *et al.* (2013); Coelho and Raman (2013)
	Water	Groundwater from shallow wells and Surface water from streams/rivers – for domestic use and irrigation	Kimani-Murange and Ngida (2007); Ochieng *et al.* (2011); Vollmer and Gret-Regamey (2013); Phukan (2014)
	Others	Timber from trees – for household fuel and construction; Ttherapeutic flowers, medicinal items, broom making and incense stick from plants and trees	Ballantyne and Oelofse (1999); Gopal (2011); Nagendra *et al.* (2013); Kaoma and Shackletion (2014); Epule *et al.* (2014)
Regulatory	Water Management	Runoff control management and flood mitigation; Greywater treatment	Adegun (2013); Button *et al.* (2010); O'Farrell *et al.* (2012); Douglas (2016)
	Moderating Micro-climate	Trees with canopy provide shade (decreasing ambient air temperature by 3–5 °C in summer in Bangalore urban area/slums)	Jabeen *et al.* (2010); Gopal (2011); Sudhira and Negrada (2013); Oluwafiyekemi and Julie (2015)
	Air Quality Regulation	Cleaning the air through removal of pollutants such as SO_2 and suspended particulate matter.	Sudhira and Nagendra (2013)
Socio-cultural	Aesthetic	Pleasant views of nearby natural environment	Ballantyne and Oelofse (1999)
	Recreation	Mountain climbing, tree climbing, horse riding, fishing, green open spaces used for other games/sports	Ballantyne and Oelofse (1999); Graham and Ernstston (2012)
	Religious/ Cultural fulfilment	Mountainous/lowland areas and other natural areas used for religious activities or cultural rites; Wetlands and other water-bodies as object of worship	Ballantyne and Oelofse (1999); Gopal (2011); Nagendra *et al.* (2013)
	Educational	Green Spaces used for demonstrative teaching and Cognitive development, especially for children	Dubbeling *et al.* (2009)
Supporting	Soil formation/retention; Critical Infiltration; Groundwater Recharge		O'Farrell *et al.* (2012)

2.2.2. Provisioning Ecosystem Services

Water, an essential resource, is often sourced from natural environments like streams, wetlands, and wells in informal settlements due to the lack of adequate municipal water supply. In Nairobi's Langas settlement, for example, a vast majority (89%) of households rely on well water (Adegun, 2017). Talking about food, including plants with edible and medicinal properties, significantly contributes to the sustenance and health of residents in low-income urban informal settlements. Studies highlight the critical role of farming within these communities in bolstering food availability and security. In Pretoria, South Africa, more than half the informal settlement households engage in gardening, with communal farming providing approximately a quarter of their yearly food needs (Adegun, 2017). However, individual gardens yield considerably less, indicating that communal gardens are more productive. Timber serves multiple functions in these communities, especially where there is no access to electricity. It is used for cooking, heating, and as a material for construction and furniture (Adegun, 2017). In Cape Town, Nissing and Von Blottnitz (2007) estimated that 142,000 tonnes of timber, gathered from local vegetation or as waste, is utilised for energy and building materials in informal settlements each year.

2.2.3. Regulatory Ecosystem Services

Residents of informal settlements gain from NBS through environmental regulatory services in three key ways. Initially, micro-climate control is significant, with an experimental green wall in Lagos, Nigeria, reducing the surrounding temperature by about 0.5°C (Adegun, 2017). The presence of vegetation, including trees and plants, not only lowers the air temperature by 3 to 5°C during summer but also enhances air quality by filtering pollutants (Gómez-Baggethun and Barton, 2013). The shade provided by these green elements offers a cooler environment for both domestic and livelihood activities, as well as recreational spaces (Gómez-Baggethun and Barton, 2013). Moreover, informal settlements, along with traditional housing areas, often feature a rich mix of green structures, leading to the lowest recorded land surface temperatures in urban settings (Adegun, 2017). Another regulatory benefit involves the management of water through natural and semi-natural solutions. For instance, rooftop gardens help control runoff, while wetlands and areas alongside rivers play a crucial role in flood mitigation and the purification of greywater (Adegun, 2017). An innovative approach was tested in CoCT's Monwabisi Park informal settlement, where a SuDS (see section 2.4.), comprising artificial swales and infiltration trenches linked to a wetland, efficiently managed stormwater by using vegetation to channel runoff away from critical areas (Adegun, 2017). Lastly, while the literature provides limited evidence on the role of NBS in moderating wind and controlling erosion, it's noteworthy that windstorms pose significant challenges in low-income urban regions. This gap highlights an area for further exploration of how NBS can mitigate such adverse climatic effects (Adegun, 2017).

2.2.4. Socio-cultural Ecosystem Services

Socio-cultural benefits from NBS include aesthetically enriching environments and spaces for recreation, socialising, transportation, provision of food and cultural or inspirational activities within informal settlements. Water bodies and natural areas often become focal points for worship and cultural or religious events (Adegun, 2017). For example, residents near Mandela Park in CoCT appreciate the beauty of their surrounding mountains and trees, particularly for rituals, highlighting these natural settings as perfect ceremonial spots (Oelofs, 1999). Similarly, the Macassar community in the Western Cape engages in activities like horse riding and fishing, reflecting their historical and cultural connection to the local dune (Graham and Ernstson 2012). Moreover, green areas facilitate cognitive growth, as seen in Rosario's La Lagunita settlement, where gardens and paths are used for educational purposes, aiding in children's cognitive development (Dubbeling et al., 2009). Communal gardening efforts not only bolster food security but also strengthen community bonds, fostering social capital that is often deemed more valuable than the direct food output of these gardens (Kornienko, 2013).

2.2.5. Supporting Ecosystem Services

The literature review identifies ambiguity in the specific benefits of ecosystem services (ES) provided to informal settlements (Adegun, 2017). However, O'Farrell et al. (2012) highlight the crucial role these settlements play in supporting ES, even if they do not directly benefit. Their study, including an expert analysis of ES in Cape Town, reveals that decreased plant diversity in informal settlements results in fewer roots for soil stabilisation and less organic matter to enhance soil structure, water-holding capacity, and essential water infiltration and groundwater recharge.

2.2.6. Disadvantages of NBS Experience in Informal Settlements

Exploring the negative impacts that NBS may have on informal settlements offers a comprehensive view of how natural ecosystems affect human well-being (Adegun, 2017). These negative impacts, known as ecosystem disservices, arise either from the inherent characteristics of untouched ecosystems or from human-induced environmental degradation. Both actual harm and perceived issues contribute to these disservices (Adegun, 2017). Health concerns, often tied to natural environments, include increased exposure to diseases and physiological issues. For instance, Douglas (2012) noted adverse effects on health within informal settlements due to environmental factors such as limited green spaces, exposure to hazardous materials in standing water, often due to poor drainage. Studies in Dakar revealed that vegetation, coupled with poor sanitation and waste management, heightened the risk of infectious diseases like diarrhoea (Adegun, 2017). Wetland-proximate settlements frequently battle mosquito infestations and related diseases due to favourable breeding conditions in these damp areas, pieces of evidence of this come from Kumasi (Campion, 2012), Ouagadougou (Baragatti *et al.* 2009) and Kampala (Isunju *et al.* 2016). In Ouagadougou, malaria risk correlates with ecological strata (proximity to hydrographic network) and living in informal settlements (Adegun, 2017). Additionally, urban farming practices, while beneficial for food supply and community cohesion, pose health risks when crops are irrigated with contaminated water, as seen in Nairobi's Kibera settlement (Adegun, 2017).

Negative perceptions of natural ecosystems often stem from fears associated with densely vegetated areas. Concerns include the potential for these spaces to conceal wrongdoers or encourage criminal activity (Adegun, 2017). Additionally, there's apprehension about wildlife, like snakes and scorpions, invading living spaces, contributing to safety fears (Stretha, 2010). Such fears (fear of being mugged or raped in an unlit vegetated space), even when perceived, can lead to significant adverse effects, including anxiety, depression, and hypertension, illustrating how psychological worries can manifest into physical health issues (Adegun, 2017). Concerns are exacerbated in informal settlements due to factors like poor layout, lack of infrastructure, and insecure land tenure, which complicate efforts to address these challenges. For example, the lack of lighting makes it hard to secure areas against crime at night, making densely vegetated spaces particularly problematic (Adegun, 2017). This issue is exacerbated by the country's lack of sufficient and stable electricity supplies resulting in regular load-shedding.

This section provides a comprehensive discussion of the potential environmental benefits and cons of applying such solutions. This theoretical framework is useful for future conceptual design, as significant aspects influencing safety and health hazards have to be acknowledged.

2.3. Socio-Ecological Systems (SES) Theory

This section delves into why it is important to focus on the social side while considering implementing NBS. Particularly, this section will look at the Socio-ecological systems (SES) which are complex, integrated systems where humans and nature co-exist. Informal settlements, often a by-product of rapid urbanisation and rural-urban migration, are critical components of urban SES (Oskam et al., 2021).

Furthermore, the concept of SES will highlight intricate details about community engagement and empowerment, the integration of traditional ecological knowledge (TEK), and effective governance and institutional contexts which encounter their challenges but are very beneficial to potentially enhancing the liveability and sustainability of communities in informal settlements through the application of NBS.

Communities in informal settlements, which are generally distinguished by a lack of formal infrastructure and services, sometimes emerge in ecologically sensitive or dangerous regions, rendering them especially vulnerable to the effects of climate change and environmental degradation (Diep et al., 2022). This creates a unique mix of difficulties and opportunities that highlight the necessity of approaching urban development through a SES lens, as the SES framework recognises communities' roles in maintaining their local ecosystems. It encourages community participation and empowerment by incorporating locals in decision-making processes, acknowledging their traditional ecological knowledge (TEK), and capitalising on their unique insights and capacities for environmental stewardship. This participatory method assures that urban development interventions are culturally relevant, generally accepted, and more efficiently implemented (Diep et al., 2022).

2.3.1. Community Engagement and Empowerment

The consensus is clear: nature-based adaptation planning necessitates a collaborative, transdisciplinary methodology that includes public participation and innovative ways of coordinating the efforts and resources of various stakeholders (Wamsler et al., 2019). NBS have earned recognition for their ability to address multiple urban concerns at the same time (Diep et al., 2022). However, attempts to adopt NBS and similar concepts in Africa's informal settlements have encountered substantial challenges, demonstrating that several obstacles prevent their practical application, such as the "fear of unknown" (Diep et al., 2022). These constraints are especially critical in urban informal settlement environments where land conflicts, urban poverty, and intra-city inequality appear physically and spatially (Diep et al., 2022).

Recent analyses of community-led adaptation efforts in African metropolises, including CT, South Africa (Fox et al., 2021), Windhoek, Namibia (Wijesinghe and Thorn, 2021), and Mombasa, Kenya (Suleiman Haji, 2021), underscore the crucial role of civil society's engagement in project planning and governance for achieving sustainable and inclusive results. Wijesinghe and Thorn (2021) stress that the absence of cooperative governance in comprehensive informal settlement renovation projects has left community needs unaddressed, breeding dissatisfaction and conflict. They also point to the ambiguous responsibilities regarding the upkeep of NBS as a critical concern.

Research on NBS within African urban contexts has revealed with representation of the potential for "niche innovations" to catalyse sustainability transitions by challenging entrenched systems “regime” (see Figure 8) and their established institutional frameworks, networks, and operational norms. Macro-level developments correspond to slow, broad sociocultural processes. The regime determines meso-level dynamics. The regime represents the dominating pattern of actors, objects, and structures in the social system. At the micro-level, individuals, organisations, or innovations are distinguished (Geels and Kemp 2000).

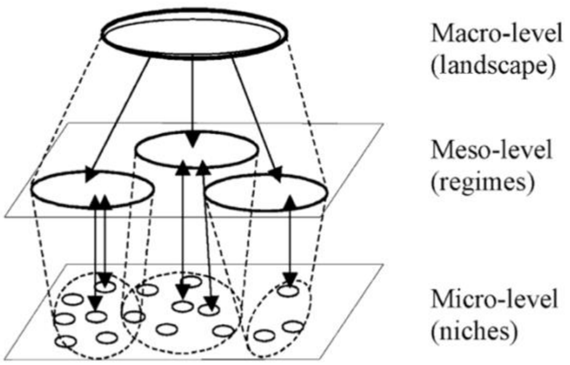

Figure 8. The multilevel concept. (Geels and Kemp 2000)

However, Herslund et al. (2018) and Diep et al. (2019) question the longevity and impact of these localised innovations on broader planning and design paradigms. A deeper understanding is needed regarding the obstacles to implementing and scaling up NBS, identified by Kabisch et al. (2016) as including misalignments between immediate actions and overarching goals, compartmentalised operational silos, and prevailing growth models that compromise urban ecological spaces, alongside a generalised apprehension towards novel uncertainties and perceived risks. Such challenges are acutely relevant in the setting of urban informal settlements, where land disputes, poverty, and disparities manifest vividly.

The role of community involvement in environmental projects is widely acknowledged as crucial, yet the definition of meaningful participation remains a topic of debate. According to Kiss et al. (2022), while NBS projects claim to involve community engagement, this involvement is often superficial, failing to significantly improve ecological outcomes. In contrast, genuine engagement strategies have been shown to foster a range of positive social impacts, such as social learning, a stronger community connection, stewardship of the environment, and greater inclusivity and equity (Kiss et al. 2022). These more impactful forms of community involvement manifest in various activities, including collaborative design sessions, targeted meetings, and educational site visits (Kiss et al. 2022).

The approach of co-producing solutions offers a way to navigate the complexities of human-nature dynamics, potentially minimising negative socio-ecological impacts (Palomo et al., 2016). This is particularly relevant in informal settlements, where the interplay between humans and nature is intricately linked to broader issues of environmental justice, socio-economic disparity, and the pressures of urban growth. Here, the risk of flooding and other environmental hazards is often intensified by historical injustices and the rapid pace of urban development (Diep et al., 2022).

To leverage NBS for enhancing community services, promoting fairness, and addressing power imbalances and environmental injustices, engaging communities in meaningful ways where they hold or share decision-making power is essential, as emphasised by Kiss et al. (2022). In the case of Dar es Salaam city, during the co-design stages, efforts were made to involve community members actively by utilising practical NBS examples and tools to explore multifaceted risk mitigation strategies alongside meeting other local needs. Workshops facilitated a platform for communal learning, idea generation for plan integration, and queries. A participant in the research shared

> *"The children, adults and youth came up with different ideas, and afterwards we all sat down, looked at the different ideas and discussed the most appropriate ones. Every design that was implemented had previously been discussed and agreed upon."* (Diep et al., 2022, p.11)

The realisation of NBS projects witnessed the collective action of community members, highlighting the importance of "unity" in these endeavours (Diep et al., 2022). In St. John's community Silanga Village in Southeast Kibera, for instance, during the construction of local NBS saw equal participation from both genders as paid workers, allowing each person to contribute according to their capability (Diep et al., 2022). One community member noted how NBS in water management extended benefits beyond just flood control, explaining:

> *"With the installation of gutters and drums, rainwater now serves domestic uses and irrigates our gardens. This not only prevents my home from flooding but also provides water for laundry and watering plants."* (Diep et al., 2022, p.12)

Similarly, residents in Nairobi recognised NBS for enhancing aesthetics and aiding in groundwater recharge, while in Dar es Salaam, the focus was on recreational spaces for children, pollution reduction, and soil restoration (Diep et al., 2022). Notably, the Kidarajani project in Dar es Salaam was lauded for revitalising local riverbanks, demonstrating NBS's potential for broader socio-environmental impacts, such as river basin rejuvenation and public space development as observed by participants from both Nairobi and Dar es Salaam (Diep et al., 2022).

Moreover, NBS has been shown to deter environmental waste dumping, driven by their effectiveness in flood risk mitigation and the communal commitment to their upkeep (Diep et al., 2022). The involvement in NBS projects has also fostered educational opportunities for children and youth engagement in community initiatives, with teachers integrating these projects into environmental education (Diep et al., 2022). These multifaceted benefits underline the critical role of deep community engagement in the successful implementation and sustainability of NBS initiatives, highlighting the transformative potential of such projects in addressing environmental challenges and fostering community resilience (Diep et al., 2022).

Community perceptions and appraisals of NBS evolved positively over the project's duration (Diep et al., 2022). Certain individuals in the research by Diep et al. (2022) articulated a shift in their views on NBS, influenced significantly by their involvement in co-creating these projects. This evolution in perspective was particularly noted among those initially sceptical or more trusting of conventional infrastructure solutions (Diep et al., 2022).

Diep et al. (2022) found that participation in the construction phase in informal settlements was pivotal in acquainting community members with NBS practicalities. This stage was instrumental in deepening the understanding of NBS, underscoring the importance of hands-on engagement in transitioning from abstract concepts to tangible applications (Diep et al., 2022). This insight is critical for NBS participatory processes, highlighting the necessity of translating theoretical ideas into real-world implementations, as discussed by Schröter et al. (2014).

Focus Group Discussions (FGDs) and surveys revealed during Kidarajani project in Dar es Salaam that integrating hybrid systems combining green/blue and grey infrastructure facilitated adapting projects to their specific contexts, especially in overcoming spatial limitations (Diep et al., 2022). Grey infrastructure, often requiring less physical space, was merged with green/blue elements early in the design phase, addressing immediate needs identified by the community. This integration was achieved through the collaborative efforts of intermediary organisations and community members, discussing non-NBS elements to fulfil urgent requirements that solely green/blue infrastructure might not meet quickly (Diep et al., 2022).

NBS "niche experiments" provide insights into socio-technical transitions beyond traditional governance frameworks, suggesting that these initiatives foster new partnerships and configurations. They have shifted community perceptions towards valuing urban nature for its multifaceted benefits, with intermediary organisations acting as crucial knowledge brokers (Diep et al., 2022).

The challenge of maintaining NBS projects, given resource constraints within communities, underscores the importance of participatory approaches for inclusivity and effective decision-making. Yet, sustainable and just outcomes necessitate additional governance solutions beyond community engagement to ensure NBS's long-term efficacy (Diep et al., 2022).

2.3.2. Integration of Traditional Ecological Knowledge (TEK)

NBS enhance human well-being by harnessing natural processes to address environmental, social, and economic issues holistically (Yu and Mu, 2023). One of the key elements of effective NBS is Traditional Ecological Knowledge (TEK), valued for its comprehensive and adaptive approach to environmental management (Yu and Mu, 2023). TEK, created over generations by indigenous cultures, encompasses a vast range of activities, beliefs, and social standards. It includes significant knowledge of the local flora and fauna, as well as sustainable ecosystem management, which is passed down through oral traditions and shared experiences (Berkes et al., 2000). However, not all traditional practices are viable; some may become maladaptive in response to changing circumstances (Diamond, 1993; Chapin, 1988; Redford and Stearman, 1993).

Despite these complexities, TEK is crucial for developing adaptable, context-specific NBS that promote social justice (Yu and Mu, 2023). Effective NBS integrate scientific findings with traditional knowledge, requiring thorough data collection and analysis. Given the dynamic nature of environmental and socio-political landscapes, NBS strategies must be flexible, regularly updated, and monitored for effectiveness (Yu and Mu, 2023). An example of TEK in action is sustainable forest management by indigenous groups in India, which uses traditional rainwater harvesting systems to capture and store water, recharge groundwater, and prevent rivers from drying up, thus promoting ecological balance (Martin et al., 2010).

Continuing, TEK's significance extends to urban areas, where it addresses challenges like climate change mitigation, biodiversity conservation, and urban planning (UGEC, 2011). Local communities often lead the implementation of strategies for global environmental changes, including infrastructure improvements, disaster planning, and innovative, cost-effective responses through participatory methods (UGEC, 2011; Nyong et al., 2007). Challenges to local actions include limited technical capacities, lack of transparency, inadequate accountability mechanisms, weak information dissemination, unclear disaster preparedness mandates, and conflicts between government levels (UGEC, 2011). To overcome these, governments must support community resilience by empowering local governance structures, including community-based organisations, farmer and fisherman groups, housing cooperatives, and NGOs (UGEC, 2011).

Moreover, excluding TEK from decision-making or failing to engage indigenous communities in NBS implementation undermines fairness and social justice (Yu and Mu, 2023). Incorporating and safeguarding TEK can prevent biopiracy and support indigenous communities, contributing to comprehensive environmental, social, and economic benefits (Yu and Mu, 2023). However, many studies have not fully explored the dynamic interplay between scientific knowledge and TEK, often treating them as separate or competing sources of information, the study ensures that the proposed NBS interventions are not only scientifically robust but also culturally relevant and more likely to be embraced and maintained by the community, thereby enhancing the overall resilience and sustainability of the urban environment.

2.3.3. Effective Governance and Institutional Context

Local governments are essential in embedding climate change adaptation (CCA) into existing policy frameworks due to insufficient international efforts. Municipalities play a crucial role in integrating localised solutions, strategically fostering citizen involvement to enhance democratic planning and overcome obstacles to sustainability goals (Wamsler et al., 2022; McEvoy et al., 2023). Despite these efforts, challenges such as insufficient municipal capacity, entrenched power structures, and a lack of integration frameworks persist, affecting citizen engagement and support for sustainability initiatives (McEvoy et al., 2023).

In urban environments, community-based adaptation (CBA) strategies are slowly developing, but meaningful community engagement remains limited (Archer et al., 2014; Chu et al., 2016). Often, community participation is superficial, undermining the effectiveness of these actions. More inclusive governance approaches are therefore needed to address the needs of the urban poor (Fox et al., 2021; Ziervogel, 2019).

The Informal Settlement Network (ISN) in CoCT exemplifies a proactive, community-based approach to urban resilience, particularly in dealing with flooding in informal settlements (Fox et al., 2021). ISN's activities include mapping water pipes, organising drainage excavations, and leading community reblocking efforts to improve living conditions (Fox et al., 2021; SDI Alliance, 2012a, 2013). Despite these grassroots efforts, urban governments must also reduce citizens' vulnerability to climate change impacts through integrated approaches involving various stakeholders (Vedeld et al., 2015).

However, the CoCT often engages in token inclusivity, where minorities often being excluded, maintaining power imbalances and relying on short-term, techno-managerial solutions that fail to address underlying vulnerabilities (Fox et al., 2021; Pharoah, 2014). This superficial engagement, described as "domination through inclusion" (Miraftab, 2009), does not facilitate sustainable urban development and perpetuates a cycle of vulnerability. Insurgent groups like ISN advocate for transformative urban planning, emphasising genuine community-driven initiatives and local involvement in shaping urban policies (Fox et al., 2021; SDI Alliance, 2012). Researchers call for a paradigm shift towards transformative adaptation to achieve resilient and inclusive urban development. This shift requires moving beyond tokenism to truly accommodate community needs and aspirations (Charlton, 2018; Colloff et al., 2017; Fox et al., 2021).

2.4. Sustainable Urban Drainage System (SuDS)

This section on Sustainable Urban Drainage Systems (SuDS) is critical for the research on NBS in informal settlements because it explores innovative strategies for managing stormwater in ways that align with environmental sustainability and community well-being. By integrating SuDS into the broader context of NBS, the research aims to provide actionable insights that could transform the quality of life in Philippi through enhanced environmental planning and management.

2.4.1. Basic Understanding of SuDS

In urban South Africa, traditional stormwater management has primarily focused on collecting and channelling runoff to the nearest watercourses, prioritising flow volume over environmental conservation (Armitage et al., 2013). This approach has resulted in significant environmental degradation, evidenced by increased erosion, siltation, and pollution (Armitage et al., 2013). To counter these issues, an alternative strategy known as Water Sensitive Urban Design (WSUD) has been developed, which incorporates stormwater as a crucial component of the urban water cycle through SuDS (Armitage et al., 2013).

SuDS are designed to manage surface water drainage comprehensively, aligning with sustainable development goals by addressing water quantity, enhancing water quality, improving amenities, and maintaining biodiversity (Armitage et al., 2013). This strategy mitigates the negative environmental impacts traditionally associated with stormwater management while also providing additional benefits (Armitage et al., 2013). SuDS differ from conventional drainage practices by mimicking the natural hydrological cycle through a series of strategic interventions called a 'treatment train' (Armitage et al., 2013). These interventions organise stormwater management into hierarchical levels that aim to enhance quantity, quality, amenities, and biodiversity effectively (Armitage et al., 2013). The foundational principle of this approach is that improvements to biodiversity are contingent upon first ensuring the safety of life and property (Armitage et al., 2013).

Researchers like Woods-Ballard et al. (2007) highlight the vital role of the water cycle in sustaining life, noting that urbanisation often leads to the degradation of essential water resources such as wetlands, rivers, and groundwater. This degradation results from pollution, resource depletion, and construction activities within natural floodplains (Woods-Ballard et al., 2007). Additionally, urban development tends to reduce the land's natural permeability (see Figure 9) by replacing porous surfaces with impermeable materials like roofs, roads, and pavements, typically drained through rigid infrastructure such as pipes and lined channels (Woods-Ballard et al., 2007).

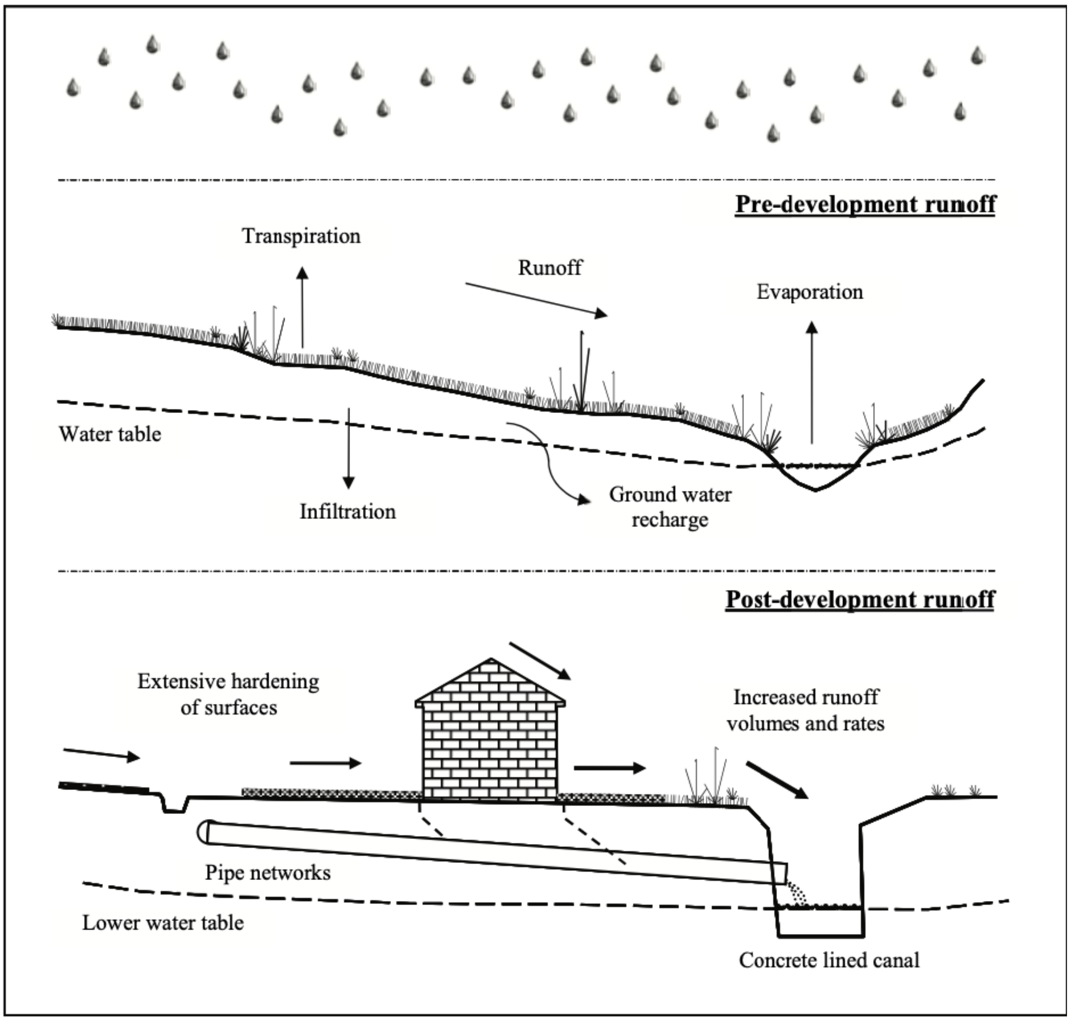

Figure 9. Typical pre- and post-development runoff scenarios with the conventional approach to stormwater management. (Wilson et al., 2004)

Moreover, development frequently results in the loss of native vegetation, which diminishes the landscape's capacity to manage stormwater through natural processes like ponding, interception storage, and evapotranspiration. The compaction of subsoil layers during development further decreases their ability to absorb water, reducing infiltration capacity.

Traditional drainage systems often focus solely on mitigating local flooding issues, largely ignoring the preservation or enhancement of water quality and other environmental and recreational benefits (Armitage et al., 2013). These systems can exacerbate flooding in broader areas and fail to recognise stormwater as a potential resource (Armitage et al., 2013). Illustrations such as those in Figure 9 depict typical pre- and post-development scenarios using conventional stormwater management practices, while associated hydrographs in Figure 10 demonstrate that post-development conditions significantly increase the risk of severe flooding and downstream erosion (Armitage et al., 2013). The reduced infiltration impacts aquifer recharge, decreasing baseflow to watercourses, and surface runoff typically carries more contaminants, further harming aquatic environments and biodiversity (Armitage et al., 2013). The urban heat island effect prevalent in large cities may amplify these challenges by increasing stormwater runoff (Armitage et al., 2013).

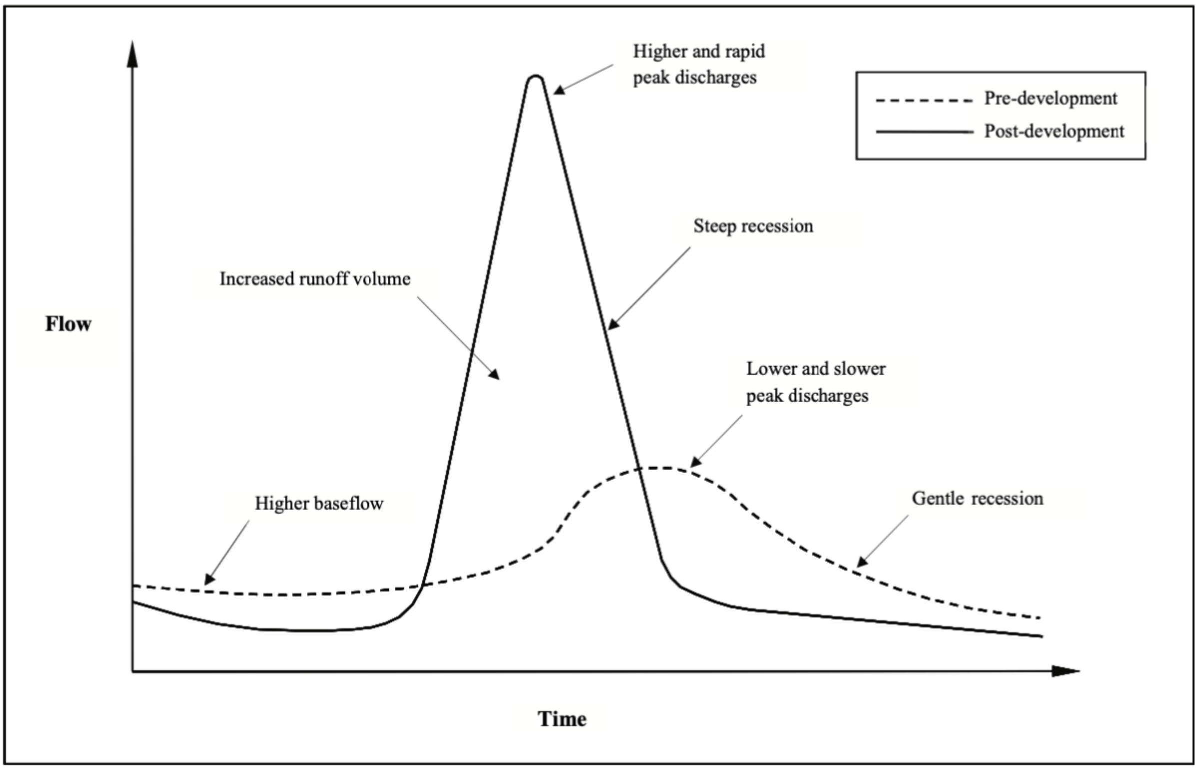

Figure 10. Typical hydrographs associated with pre-and post-development with the conventional approach to stormwater management. (Reed, 2000)

According to Armitage et al. (2013), SuDS emphasises a natural approach to drainage that incorporates various processes which align with core design principles. These principles aim to manage flow and volume to control the quantity of stormwater, improve water cleanliness to enhance quality, enhance environmental and aesthetic amenities for better amenities, and promote diverse ecological habitats to support biodiversity.

In terms of managing stormwater quantity, SuDS techniques include rainwater harvesting, which captures runoff from structures like rooftops for onsite reuse, reducing the volume of water that needs to be managed. Other methods include infiltration, which allows stormwater to seep into the ground, reducing surface runoff, and detention, which involves temporarily storing water to slow runoff rates before it is released. Additional practices include conveyance, which transfers stormwater from one location to another, long-term storage to control stormwater in designated areas that drain slowly, and extended attenuation storage to retain stormwater during floods when other options are not viable (Armitage et al., 2013).

For water quality management, SuDS employs techniques such as sedimentation, which slows water flow to allow sediments and pollutants to settle. Filtration and biofiltration use vegetation, soil, or geotextiles to trap pollutants carried by sediment. Adsorption involves binding pollutants to the surface of aggregate particles through processes like cation exchange and chemisorption. Biodegradation breaks down organic pollutants via microbial action, while volatilisation converts pollutants into gases or vapours. Precipitation removes soluble metals from stormwater by chemical reactions that form insoluble precipitates, and plant uptake and nitrification processes help remove nutrients and convert ammonia to less harmful substances. Photosynthesis also plays a role by breaking down organic pollutants through exposure to ultraviolet light (Armitage et al., 2013).

Finally, biodiversity management under SuDS involves the protection of native species and their habitats, maintenance by removing invasive species, and regular monitoring to ensure timely intervention for ecological preservation. These comprehensive strategies collectively enhance urban resilience through thoughtful integration of natural processes and informed management practices (Armitage et al., 2013).

2.4.2. SuDS Selection

Understanding SuDS involves recognising that stormwater management employs a series of sequential unit processes, much like wastewater treatment in a treatment facility (Armitage et al., 2013). SuDS are structured as a series of treatment options, or "treatment trains," (see Figure 11) where various processes are linked together to effectively manage stormwater (Armitage et al., 2013). This methodology is detailed in twelve distinct families of SuDS options, each comprising various overlapping treatment processes (Armitage et al., 2013). The appropriate selection of these options is tailored to the unique characteristics of each site, recognising that not all options are applicable or effective in every scenario. Evaluating the advantages and limitations of each option during the planning and design phases is crucial, especially in sensitive areas like informal settlements (Armitage et al., 2013).

The literature, including works by Wilson et al. (2004) and Woods-Ballard et al. (2007), outlines seven primary criteria for selecting the most suitable SuDS options: current and future land use, site characteristics and utilisation, catchment characteristics, stormwater runoff quantity and quality requirements, and the needs for amenity and biodiversity enhancement (Armitage et al., 2013).

According to Armitage et al. (2013), the treatment train model outlines four key intervention points for effective stormwater management. The first point, Good Housekeeping, focuses on minimising the release of pollutants like solid waste into the environment, it clogs current stormwater infrastructure, reducing discharge capacities and leading to greater flooding. Following this, Source Controls involve techniques such as green roofs, rainwater harvesting, permeable pavements, and soakaways to manage stormwater runoff close to its origin. The third point, Local Controls, manages stormwater locally using bio-retention areas, filter strips, infiltration trenches, sand filters, and swales, typically within road reserves. Lastly, Regional Controls address stormwater runoff from multiple developments through larger-scale implementations like constructed wetlands, detention ponds, and retention ponds.

Each of these control points offers slightly different combinations of SuDS options, which are chosen based on criteria including site suitability, lifecycle costs, amenity and biodiversity value, and the capacity to manage both the quantity and quality of stormwater (Armitage et al., 2013).

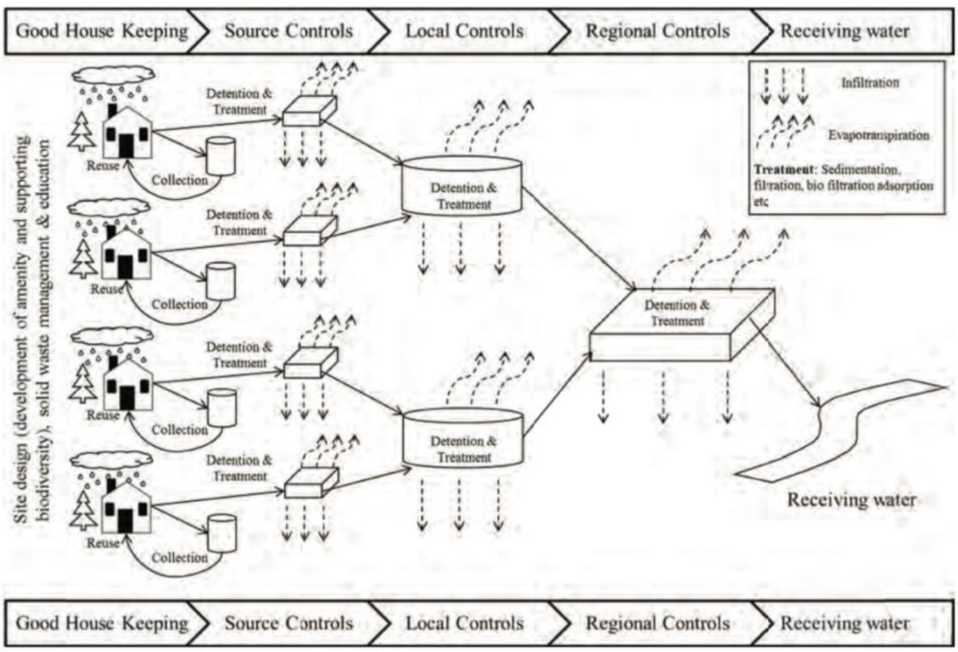

Figure 11. SuDS treatment train schematic. (Armitage et al., 2013)

2.4.3. Design and Management of SuDS

This section outlines a comprehensive framework for the design and management of drainage systems, established by the CSIR in 2000. The framework's primary goals focus on enhancing public health and safety by protecting individuals and properties from flood hazards through effective stormwater management. Additionally, it aims to improve community well-being, conserve water resources for public use, preserve the natural environment through sustainable practices, and maintain a balance between economic development and environmental sustainability. In addition, the intention is to provide the most effective techniques of reducing runoff in such a way that the primary beneficiaries pay in proportion to their prospective benefits.

An essential strategy in achieving these objectives involves managing and treating stormwater runoff as close to its source as possible to emulate pre-development hydrological conditions. This method typically incorporates processes such as collection, storage, use, infiltration, and evapotranspiration (Armitage et al., 2013). When onsite management is not feasible, local SuDS controls are employed to manage stormwater within localised areas. Natural pathways like filter strips or swales are preferred over pipes and concrete canals, which tend to accelerate flow and degrade water quality. Additionally, regional SuDS controls serve as a final measure before stormwater is discharged into natural water bodies (Armitage et al., 2013).

Design strategies for SuDS include preparations for various 'design storms,' with each type of storm requiring a tailored management approach. For instance, for urban areas engineers use the 1:5-year return period to calculate run-off and stormwater capacities. However, due to climate change, the calculations may need to be adjusted according to new conditions and regular check-ups should made as well to ensure relevance of the technologies. Moreover, small storms should ideally be completely infiltrated onsite, while larger storms necessitate management practices that minimise environmental impacts (Armitage et al., 2013). This approach is detailed in the SANRAL 'Road Drainage Manual' (2006). Urban development often leads to increased runoff rates by 20-50%, and in extreme cases, the peak flow can increase up to 6.8 times higher than pre-development levels, posing risks of flash flooding and ecological damage. By implementing controls that mimic natural hydrological conditions post-development, these adverse effects can be effectively mitigated (Armitage et al., 2013).

2.4.4. Aesthetic Impact and Amenity Benefits

According to Armitage et al. (2013), the visual and recreational qualities of SuDS are crucial for ensuring their public acceptability and effective integration into local environments. To achieve this, several strategies are employed, including educational and awareness campaigns that inform the public about the benefits and functionalities of SuDS. Enhancing the aesthetic appeal of these systems through thoughtful landscaping that harmonises with the local environment is also vital. Additionally, developing and adhering to comprehensive maintenance plans ensure that SuDS remain visually appealing and functional throughout the year. Another important aspect is the integration of SuDS features with recreational areas to manage health and safety risks effectively, thereby creating multifunctional landscapes that serve both ecological and recreational purposes.

Ecological diversity is a critical component of SuDS, supporting local biodiversity and ecological balance. This is facilitated by planting native vegetation and pre-treating water to reduce pollution levels before it enters natural bodies, thus preserving water quality (Armitage et al., 2013). Maintaining and enhancing existing natural watercourses and drainage patterns also contribute to ecological health. Moreover, creating diverse habitats supports a variety of wildlife populations, and designing wildlife-friendly features, such as shallow aquatic benches in wetlands and ponds, provides habitats for different aquatic species (Armitage et al., 2013).

Lastly, while implementing SuDS, it is essential to recognise and mitigate potential unintended effects, such as the attraction of water birds whose waste may increase nutrient levels in water bodies. Effective community engagement strategies are critical for the successful implementation of SuDS. These strategies include involving the public in the design process, providing detailed information about the benefits of SuDS, and marking SuDS facilities. This not only educates the community and maintenance teams about their purpose but also ensures proper maintenance practices, enhancing the overall functionality and sustainability of SuDS (Armitage et al., 2013).

2.5. Nature-based Solutions (NBS)

2.5.1. Definition

NBS employ natural processes to tackle societal challenges and enhance urban resilience, improving public health, climate change resilience, and community well-being (Word Bank Group, 2021). These strategies include both structural and non-structural measures to protect, manage, restore, or create natural elements and are often termed “ecosystem-based adaptation,” particularly in urban African contexts (Diep et al., 2022).

The37 definition of NBS is subject to debate; some experts assert that NBS should only involve functional ecosystems, excluding technologies like wind, wave, or solar power that lack direct ecological interaction (Diep et al., 2022). However, in informal settlements where immediate ecosystem services are vital, the effectiveness of purely green NBS can be constrained (Diep et al., 2022). As a result, hybrid systems that integrate natural elements (green or blue) with engineered (grey) infrastructure are becoming recognised as effective under these conditions, although they present classification and management challenges (Diep et al., 2022)

Globally, NBS are supported by international frameworks such as the Sendai Framework for Disaster Risk Reduction, the SDGs, and the Paris Climate Agreement, which promote a unified approach to managing environmental and climate risks while boosting the adaptive capacities of at-risk populations (Word Bank Group, 2021).

NBS are implemented at various scales (see Figure 12), from green roofs and bioswales in small urban spaces to larger green infrastructures like urban parks and extensive ecosystems such as wetlands and coastal forests (Word Bank Group, 2021). These solutions mitigate urban hazards like floods, erosion, and extreme temperatures, often proving more cost-effective and sustainable than traditional grey infrastructure (Raymond et al. 2017). By bridging different sectors and fostering cross-sectoral partnerships, NBS effectively address urban resilience challenges, enhancing both the quality of urban life and environmental health (Word Bank Group, 2021).

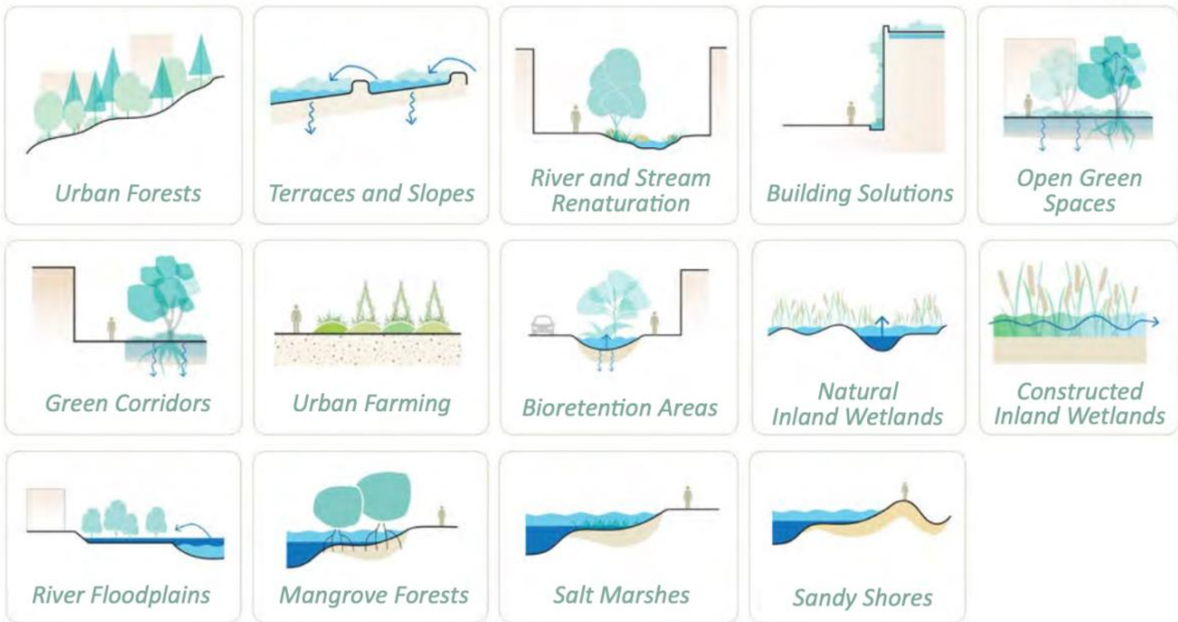

Figure 12. Diversity of NBS for urban application. (Word Bank Group, 2021)

2.5.2. The Framework of Potential Investment into NBS

Figure 13 illustrates a decision-making framework for investing in Nature-Based Solutions (NBS). Each NBS operates through processes like infiltration, evapotranspiration, water storage, and aquifer recharge, which establish its functional abilities such as flood regulation, heat regulation, soil stabilisation, and water retention. These functions, in turn, deliver various benefits to people, including reduced flood risk, decreased heat stress, enhanced outdoor recreation, improved human health, and increased biodiversity.

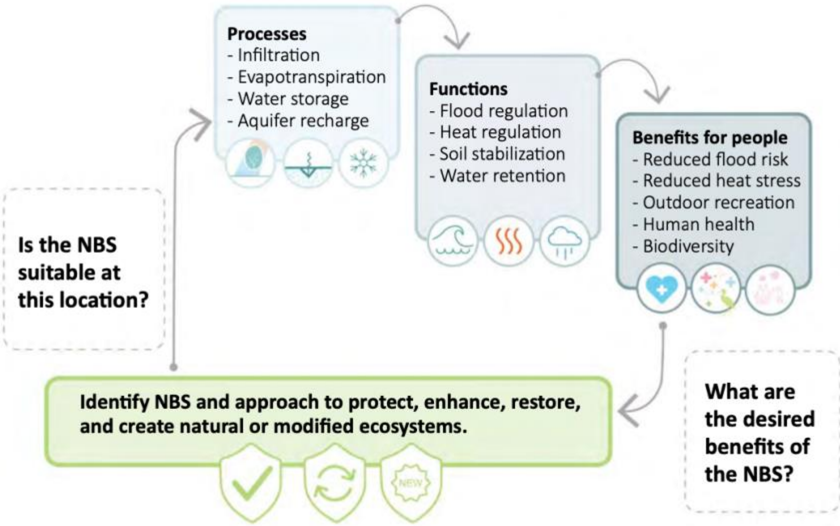

Figure 13. A framework to support the first identification of potential investments in NBS. (Word Bank Group, 2021).

Compared to traditional grey infrastructure, NBS provide a variety of societal benefits that are critical in urban planning and development. It is critical to assess the feasibility of NBS for specific places, taking into account aspects such as local temperature, geography, available space, and maintenance requirements. This step is debatable, especially in the setting of informal settlements, but there are persuasive arguments supporting NBS's viability in these places.

Informal settlements often face significant environmental challenges, including flooding, poor water quality, and limited green spaces. NBS can address these issues by providing natural water management and improving living conditions. For example, stormwater management through green infrastructure can mitigate flood risks, while green roofs and urban forests can reduce heat stress and enhance biodiversity.

Moreover, NBS are typically more adaptable and cost-effective than grey infrastructure, making them a practical solution for resource-constrained informal settlements. They can be designed to integrate with existing community structures and require less maintenance, leveraging local knowledge and participation. This community-driven approach not only ensures sustainability but also empowers residents, fostering a sense of ownership and stewardship over their environment.

Therefore, by carefully assessing local conditions and engaging the community, it is possible to implement NBS effectively in informal settlements, achieving the desired benefits and contributing to sustainable urban development (World Bank Group, 2021).

2.5.3. Implementing an Integrated Systems Approach to NBS for Urban Resilience

To effectively boost urban resilience, NBS must be integrated using a holistic systems approach, particularly in complex urban settings. This approach involves initially adopting a systems-based perspective to address both resilience and biodiversity challenges and subsequently integrating NBS into various urban planning and policy frameworks (Word Bank Group, 2021).

This integration entails designing NBS not in isolation but as complements to existing risk management strategies. For example, NBS can augment existing grey infrastructure, thereby enhancing the system's overall capacity and efficiency in risk reduction and providing additional environmental benefits (see Figure 14). This integration proves essential both at a broader system level and locally, where hybrid solutions combining nature-based and grey infrastructure elements can deliver optimal results (Word Bank Group, 2021).

NBS can also be woven into comprehensive programs such as risk management plans, structural design plans, proactive urban and land use planning, evacuation management, and sustainable maintenance practices. Due to their versatile nature, NBS can fulfil diverse functions across different scales, addressing various urban resilience needs like flood management and heat reduction (see Figure 14). For instance, a water management NBS could protect cities from floods and droughts alike, while a slope stabilisation project in erosion-prone areas could control runoff and enhance water distribution (Word Bank Group, 2021).

Furthermore, as urban areas experience significant biodiversity loss, aligning with global biodiversity restoration and enhancement efforts becomes critical. This involves protecting important biodiversity zones, managing them effectively, and improving ecological networks that facilitate wildlife movement, which is crucial for maintaining genetic diversity and species health. NBS can provide essential supplementary habitats within these networks, necessitating a deep understanding of local ecological conditions, such as climate and soil types, and the selection of appropriate native plant species (Word Bank Group, 2021).

Beyond environmental impact, NBS contribute to urban aesthetics and cultural benefits, enhancing the appeal of urban areas and offering recreational opportunities. The success and sustainability of NBS also hinge on community engagement. Incorporating local needs and aspirations into planning processes ensures community support and the long-term viability of these interventions, thereby reinforcing the comparative advantages of NBS over traditional grey infrastructure (Word Bank Group, 2021).

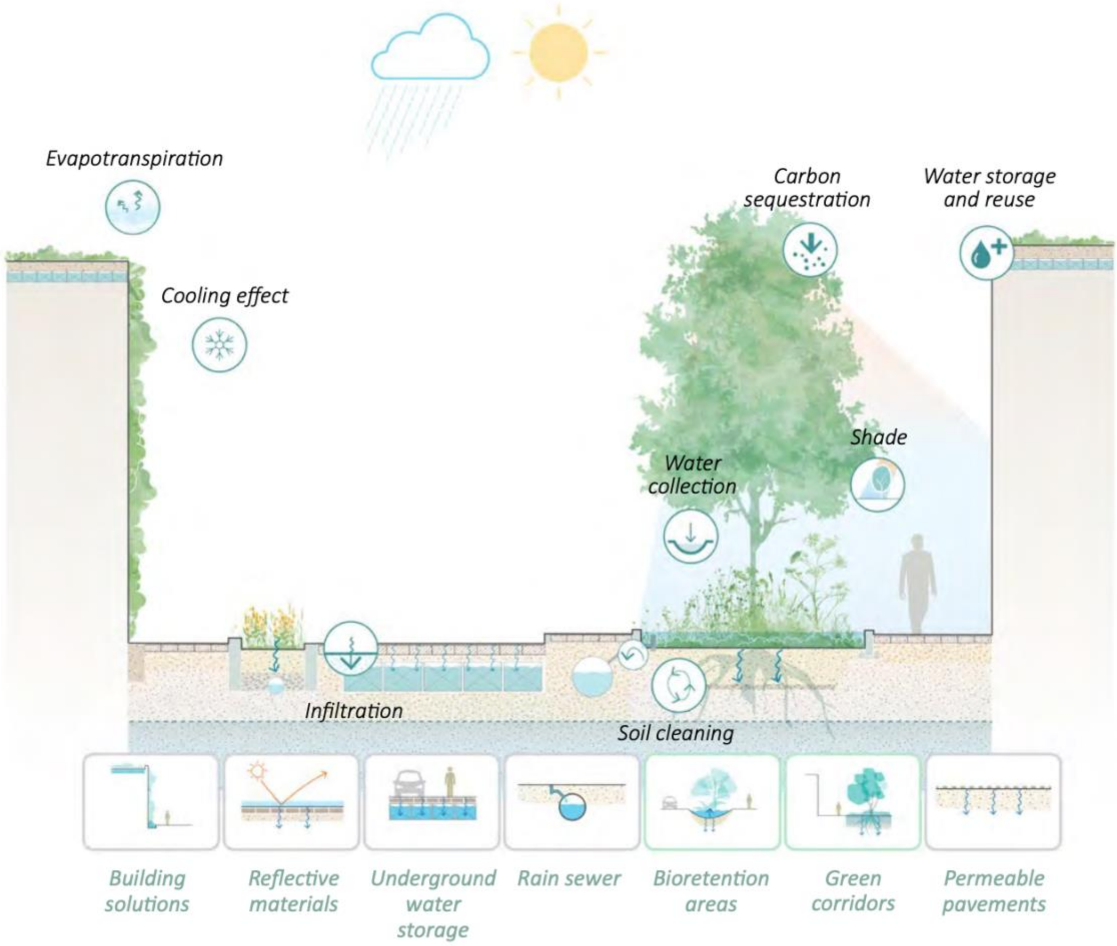

Figure 13. Example of a hybrid solution integrating green and grey infrastructure. (Word Bank Group, 2021).

2.5.4. Implementing a Hierarchy of Ecosystem-Based Approaches for Ecosystem Conservation

NBS encompass a broad spectrum of ecosystem-based strategies including the protection, sustainable management, restoration, and creation of natural or green infrastructure. These strategies are organised hierarchically (see Figure 15), prioritising the protection of existing ecosystems, followed by their enhanced management, restoration, and finally, the creation of new NBS (Word Bank Group, 2021).

This hierarchical approach is particularly important for strategic urban planning and evaluating investment opportunities at various scales, including neighbourhood, city, and river basin levels. It involves comprehensively assessing each component to develop an effective NBS strategy. The focus of the research is specifically on the Creation of New NBS within this hierarchical model (Word Bank Group, 2021).

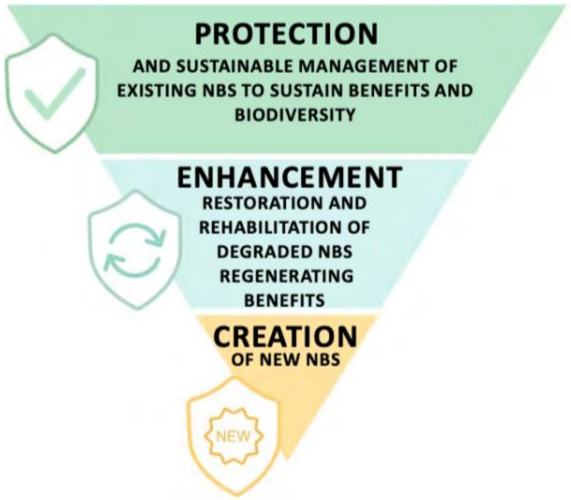

Figure 14. A hierarchy of approaches under the NBS umbrella. (Word Bank Group, 2021)

Adopting a hierarchical structure for NBS supports strategic urban planning and emphasises the need to protect existing natural infrastructure to preserve its functional and biodiversity values. Crucial ecosystems such as wetlands, grasslands, floodplains, urban forests, and mangroves should be integrated into zoning and planning to prevent degradation (Word Bank Group, 2021).

While protection is paramount, restoration and rehabilitation are critical as urban lands face impacts that diminish ecosystem services. Reforestation, stream restoration, and coastal habitat recovery (e.g., mangroves, and salt marshes) can revive ecological functionality. Productive lands benefit from terracing, slope stabilisation, and sustainable farming, while urban green spaces improve through design and replanting (Word Bank Group, 2021).

The creation of new NBS, the third hierarchy layer, aims to mitigate impacts and enhance urban resilience. Interventions such as green roofs, vegetated facades, constructed wetlands, and bioretention areas help build resilience and offer various co-benefits to urban communities (Word Bank Group, 2021).

2.5.5. Integration of NBS Across Various Spatial Scales

NBS should be considered at various spatial scales to effectively address urban resilience. The Catalogue identifies three main scales: the river basin scale, the city scale, and the neighbourhood scale, with each scale presenting distinct NBS opportunities. For instance, floodplain restoration can enhance natural hydraulic and hydrological connectivity at the river basin scale, managing flood hazards effectively, while bioswales may be more applicable at the neighbourhood level (Word Bank Group, 2021). This research will focus on the neighbourhood scale due to the scope of the research project.

Neighbourhood-scale interventions focus on local resilience, addressing challenges through measures in buildings, streets, and public spaces. These smaller-scale interventions can greatly increase stormwater retention and mitigate heat island effects. According to Word Bank Group, (2021) examples include:

- Green roofs, green facades, and private gardens integrated with green streets to regulate temperature and store water.
- Retention basins, rain gardens, or green water squares for water storage.
- Bioswales for localised rainwater catchment and drainage.

In the context of Philippi informal settlement, the implementation of NBS will be held in arid or semi-arid urban environments and requires special planning to accommodate the harsh conditions. Critical factors such as sunlight intensity, rainfall patterns, and surface and groundwater levels need careful analysis Indigenous plant species with suitable tolerances should be selected for these conditions. Ensuring the survival and establishment of plant life in these NBS projects also necessitates adequate resources for maintenance and watering (Word Bank Group, 2021).

2.6. Conceptual Model

The conceptual model (see Figure 16) illustrates the relationships between various elements contributing to urban resilience for vulnerable communities in informal settlements. Urban resilience, the dependent variable, is the ultimate goal, achieved by enhancing the capacity of informal settlements to withstand and adapt to environmental stresses.

The model addresses the impacts of extreme climate events such as floods, heat waves, and storms, which pose significant threats to vulnerable regions. Implementing mitigation and adaptation strategies is crucial to effectively manage these risks.

Central to the model are the independent variables, which encompass ecosystem services and include NBS, SES, and SuDS. NBS employs natural processes and green infrastructure, such as bioretention areas, to manage stormwater, thereby reducing flood risk. SES focuses on the interactions between communities and ecological systems, promoting social cohesion and adaptive governance. SuDS implements innovative drainage solutions, such as permeable pavements and swales, to control and treat stormwater effectively. Together, these independent variables enhance ecosystem services, providing essential benefits like water regulation, flood mitigation, and biodiversity support.

These ecosystem services directly impact vulnerable communities, improving living conditions and reducing vulnerabilities. Ultimately, these efforts contribute to urban resilience, ensuring that informal settlements can effectively adapt to and thrive amidst the challenges posed by climate change.

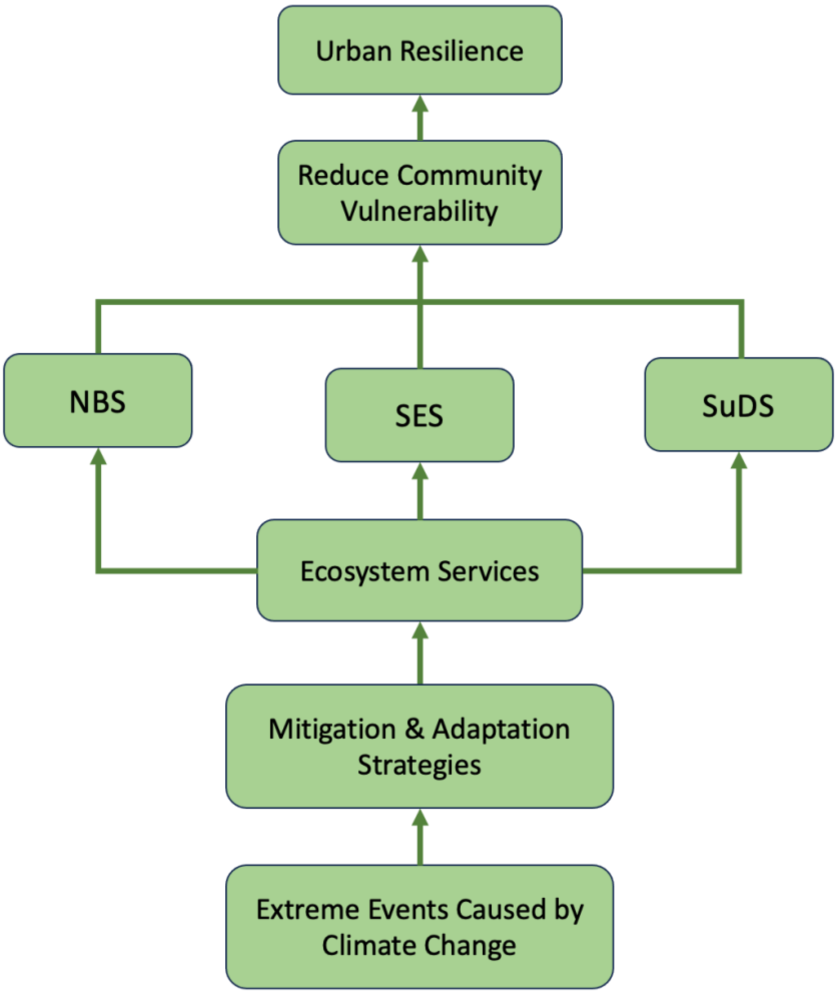

Figure 16. Conceptual model. (Author's own)

3. Methodology

3.1. Research Strategy

The research conducted on the Philippi informal settlement aims to assess the feasibility and practical implementation of NBS within a complex urban environment, addressing the research gap created by the lack of detailed case studies and proposed design solutions in policy documents. The study's multifaceted nature necessitates a diverse array of research methodologies and techniques, ensuring a comprehensive and reliable foundation of sources and evidence to address the posed research questions.

The research adopts a mixed-methods approach to data collection and discussion, integrating quantitative and qualitative data to offer a well-rounded perspective on the implementation challenges and opportunities for NBS. Additionally, a case study methodology is consciously employed to provide a detailed contextual analysis of the Philippi informal settlement, facilitating a deeper understanding of the specific environmental, social, and infrastructural dynamics relevant to the area. The research is structured through several interconnected phases that include a Literature Review, Secondary Data Collection, Case Study Development, Design Proposal and Discussion.

By utilising these methodologies, the research seeks to provide insightful and actionable outcomes to inform future urban planning and development efforts in Philippi and similar urban areas. Table 2 connects the various strategies used to address each research question.

Table 2. Approach to operationalise theory and research questions

Title	Description
Main RQ	Literature Review, Secondary Data Collection, Design Proposal
Sub-Question 1	Literature Review, Secondary Data Collection
Sub-Question 2	Literature Review, Design Proposal
Sub-Question 3	Literature Review, Discussion
Sub-Question 4	Literature Review, Discussion

3.2. Data Collection and Analysis

3.2.1. The Mixed Method Approach

The mixed method approach integrates both quantitative and qualitative research methodologies within a single study to leverage the strengths of each method of data acquisition. This approach is particularly advantageous as it addresses the inherent biases and limitations present in any single research method. Each research technique is typically suited to answer specific kinds of questions and may fall short in other areas. By employing both qualitative and quantitative methods, this approach helps to reduce or eliminate biased findings of individual methods, enabling a more comprehensive analysis through cross-validation of data (Creswell, 1999).

Qualitative Research Methods: Qualitative methods primarily focus on subjective analysis, utilising text or image-based data. For this study, qualitative research includes an extensive document analysis of local government reports, NGO publications, and various research papers specific to Philippi and Cape Town. This approach is uniquely tailored to capture the lived experiences and environmental challenges faced by Philippi residents. By engaging with these diverse sources, the research gains a nuanced understanding of how NBS can specifically enhance environmental resilience in this informal settlement. Incorporating both local insights and international perspectives ensures a comprehensive and context-sensitive analysis, enriching the research's depth and reliability (Yin, 2009).

Quantitative Research Methods: These methods emphasise objective, numerical data that provide precision and are generally more straightforward to replicate (Yin, 2009). The quantitative strategies in this study involve the detailed examination of socio-economic statistics and spatial-temporal data, such as rainfall patterns, slopes, elevation, evaporation rates population density, etc. Such methods are essential for accurately delineating the flood risks in Philippi and underpinning the study with robust, quantifiable data.

3.2.2. The Case Study Method

The case study method is ideal for investigating specific phenomena within real-life contexts. Yin (2009) describes it as "*an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, particularly when the boundaries between phenomenon and context are blurred*." This method provides detailed insights into particular instances, essential for this research's focus on Philippi.

In this study, the case study method examines Philippi's unique environmental, social, and economic dynamics. By analysing elements like drainage systems, biodiversity, and geographical conditions, it offers an in-depth look at how NBS can be implemented effectively in this informal settlement. Detailed document research, development plans, and site analysis using Google services (Street View and Google Earth) have revealed how various factors shape Philippi's challenges and opportunities to implement resilience strategies.

This approach effectively explores the interplay between environmental conditions, infrastructure deficits, and socio-economic vulnerabilities, providing insights into causality and potential interventions. By examining these factors, the study aims to contribute to the development of practical planning practices and policies tailored to Philippi, enhancing urban resilience and community well-being.

Despite its strengths, the case study method's main limitation is its limited generalisability (Yin, 2009). To address this, the research incorporates diverse evidence sources, including local government reports, community narratives, and international NBS studies. This approach extends the study's scope and reinforces its conclusions, ensuring the findings are robust and applicable to similar urban settings (Yin, 2009).

3.3. Research Stages

3.3.1. First Stage

The research process was structured into four distinct stages. The initial stage involved a detailed literature review of scholarly articles and publications to establish a solid foundation in the concepts and theories outlined in Chapter 2. For the identification of pertinent academic literature, databases such as SmartCat, Google Scholar, and Scopus were employed. Key search terms including "Informal settlements," "flood resilience," "NBS," "ecosystem-based adaptation," "SES," "climate adaptation," and "SuDS" were strategically used to pinpoint relevant studies. Additionally, specific policy documents were examined to understand the existing institutional framework in Cape Town (see Table 3).

The analysis of these documents involved a thorough and detailed review, specifically aimed at identifying solutions for improving flooding problems in informal settlements and implementing NBS. Each document was meticulously examined to understand the current strategies related to flood protection, stormwater management, and plans for informal settlements.

Particular attention was given to sections detailing flood protection measures and stormwater management, focusing on how these policies addressed the needs of informal settlements. The review aimed to identify specific solutions and strategies within the documents that could be applied to enhance flood protection and incorporate NBS in these areas.

The identified solutions were then compared against other practices in NBS implementation in informal settlements to highlight deficiencies and areas for improvement. Opportunities for better integration of NBS were pinpointed, with proposals for realistic improvements based on successful examples and established best practices.

An online consultation meeting was conducted with Dr. John Okedi, a researcher from the University of Cape Town (UCT), to obtain first-hand information and enhance the research's depth. This discussion with an expert from the Department of Environmental and Geographical Science, provided additional perspectives on local environmental challenges and potential NBS interventions. Furthermore, the recommended guidebook "Alternative Technology for Stormwater Management: The South African Guidelines for Sustainable Drainage Systems" by Armitage et al. (2013) was extensively utilised during the literature review and the development of the conceptual design.

Table 3. Overview of reviewed policy documents

Title	Author/Year of Publication	Description
WATER OUTLOOK 2018 REPORT	City of Cape Town (2018)	This document was analysed for its sections on water supply, demand management, and long-term water resilience strategies to understand how current practices align with potential NBS implementations. However, it was focused on general municipal water difficulties rather than Philippi-specific issues, and there was little information supplied concerning NBS.
CITY OF CAPE TOWN STATE OF THE ENVIRONMENT 2022	City of Cape Town (2022)	Key sections on environmental health indicators, biodiversity, and ecosystem services were reviewed to assess the current state of natural resources and the potential for integrating NBS. However, it didn't contain a lot of specific solution to the informal settlements.
Khayelitsha Mitchells Plain Greater Blue Downs District Plan Volume 2	City of Cape Town (2023b)	This plan provided insights into urban development and spatial planning policies, particularly relevant sections on land use and infrastructure development. However, it was focused on the transportation-oriented development (TOD), rather than NBS.
PHILIPPI OPPORTUNITY AREA LOCAL SPATIAL DEVELOPMENT FRAMEWORK	City of Cape Town (2022)	This framework was critical for understanding the specific local context of Philippi, focusing on land use planning, infrastructure needs, and environmental management as well as the scale of the development area, to identify overlooked places. The "opportunity area" does not encompass the entire area of Philippi, thus the research focused on underserved communities (Brown Farms) inside Philippi.
PROFILE: CITY OF CAPE TOWN	(COGTA) (2020)	This profile offered a comprehensive overview of socio-economic and governance structures, highlighting areas of vulnerability and opportunity for NBS integration.
Climate Resilience Nature-based Solutions to Build in	UN-Habitat (2022)	This strategy paper provided international best practices and recommendations for implementing NBS in informal

Informal Areas Strategy Paper		settlements, offering a benchmark against which local strategies were assessed.
Towards the Blue-Green City: Building Urban Water Resilience	Swatuk et al. (2021)	This study from the Water Research Commission was examined for recommendations on urban water management and resilience-building through NBS. However, while the paper is fairly detailed, it lacks context-specific recommendations, particularly for Philippi.

3.3.2. Second Stage

The second stage of the research process entailed an extensive collection of secondary data to assess the specific environmental and infrastructural needs and challenges of the Philippi informal settlement. This phase involved the analysis of various key socio-economic, environmental and hydrological characteristics, including:

a) **Socio-economic analysis:** Analysing the socio-economic situation of Philippi is essential for designing an effective NBS that address the community's specific needs. This study utilised a literature review and data analysis to understand the socio-economic conditions and the impacts of flooding on residents' livelihoods and the environment. Data collection involved examining developments at national, city, and local levels, focusing on how these factors influence Philippi. Sources such as the CoCT's planning documents and Census 2011 data were critical in providing insights. This comprehensive socio-economic analysis is crucial for tailoring NBS to improve living conditions and resilience in Philippi, ensuring that interventions are effective and equitable.

b) **Rainfall Patterns and Intensity:** Data on precipitation levels, measured in millimetres per event or aggregated over months or years, were analysed to assess water availability and potential flood risks. This quantitative analysis is crucial in understanding how rainfall variability impacts the area. Although detailed analysis would be required to further facilitate accurate estimations, prevailing and historical rainfall patterns were analysed to obtain an initial indication of the occurrence of extreme events. The information was mainly sourced from the website of the Climate Systems Analysis Group which is part of the University of Cape Town (CSAG, 2023).

c) **Geomorphology and Geology:** Understanding the geomorphology and geology of Philippi, including soil type, elevation, slope percentage, and depth, is crucial for designing effective NBS. Soil type affects water infiltration and retention, influencing flood risk and the viability of certain NBS. Elevation and slope percentage determine water flow patterns, critical for managing stormwater. The depth of soil impacts the potential for vegetation growth and the stability of green infrastructure. This study used data from CapeFarmMapper 3 (n.d.) and reports from CoCT (2023) to analyse these factors, ensuring that NBS designs are appropriately tailored to the local physical environment.

d) **Hydrology:** Hydrological analysis is essential for understanding the freshwater dynamics and flood risks in Philippi. In this study, data on hydrological patterns, pollution sources, and the interaction between stormwater infrastructure and natural water bodies were analysed, by using secondary data sources, to assess flood risks and water quality challenges. Data collection and analysis were based on sources such as the CoCT's environmental reports and hydrological maps (CapeFarmMapper 3, n.d.), ensuring a comprehensive understanding of the local hydrological context.

e) **Biodiversity:** Analysing biodiversity and vegetation is crucial for understanding the ecological dynamics of Philippi, which is part of the Cape Floristic Region (CFR), a global biodiversity hotspot. This study focuses on the predominant vegetation types, including the FS 6 Cape Flats Dune Strandveld and the fynbos biome. Key aspects of this analysis include identifying native and invasive plant species, understanding their ecological roles, and assessing the impact of urban expansion on habitat loss. Identifying Invasive species was critical for ecological restoration and conservation. Data for this analysis was sourced from CapeFarmMapper 3 (n.d.) and various local environmental studies. This information was used to evaluate the current state of vegetation, identify critical areas for conservation, and propose enhancements to NBS.

f) **Climate Change Impacts:** Analysing the climate of CoCT was essential for designing effective NBS in the Philippi. This study aimed to understand how the Mediterranean climate influences ecological functionality, water resource management, and groundwater recharge. Key climatic aspects were analysed by reviewing graphs and comparing them with other literature to assess future development impacts, including temperature ranges, seasonal wind patterns, and evaporation rates. Data collection involved examining historical climate records, current weather patterns, and climate projections to evaluate the potential impacts of climate change. Sources such as Ziervogel et al. (2014) and CapeFarmMapper 3 (n.d.) provided comprehensive and reliable data crucial for developing resilient NBS tailored to Philippi's specific conditions.

By integrating these diverse sets of data, the study aimed to provide a comprehensive understanding of the current state of Philippi's environment and infrastructure. This enabled the formulation of tailored strategies that leverage the existing natural assets and address the identified challenges. Additionally, urban development plans, previous environmental assessments, and reports from local NGOs and government agencies were scrutinised to enrich the understanding of the local context and ongoing initiatives, providing a solid foundation for future planning and intervention in the Philippi.

3.3.3. Third Stage

The third part of the research entails creating a conceptual design after obtaining all relevant data and creating a comprehensive picture of local conditions. This design will take into careful consideration the suitability factors outlined in the World Bank Group's report "Catalogue of Nature-Based Solutions for Urban Resilience" published in 2021 (see Figure 17). These factors encompass essential environmental, technical, and urban aspects for effective NBS implementation. Environmental considerations include understanding the local climate, water flow, and soil conditions, and managing pollutants to ensure safe water quality. Evaluating hydrologic connectivity and landscape integration is also crucial. Technical aspects guide the design in selecting appropriate species, analysing terrain, combining natural and engineered solutions, ensuring structural capacity, and making the solutions accessible and inclusive. Urban considerations address planning NBS in harmony with existing land uses, considering population density, and integrating NBS into broader urban development plans for sustainable growth.

Furthermore, the implementation of NBS techniques is mentioned in Armitage et al.'s (2013) report. "An alternative technology for stormwater management. South African Guidelines for Sustainable Drainage Systems". Each part of the design will be adjusted to effectively answer the specific needs and challenges identified in Philippi, following the concepts and guidelines outlined in the reports.

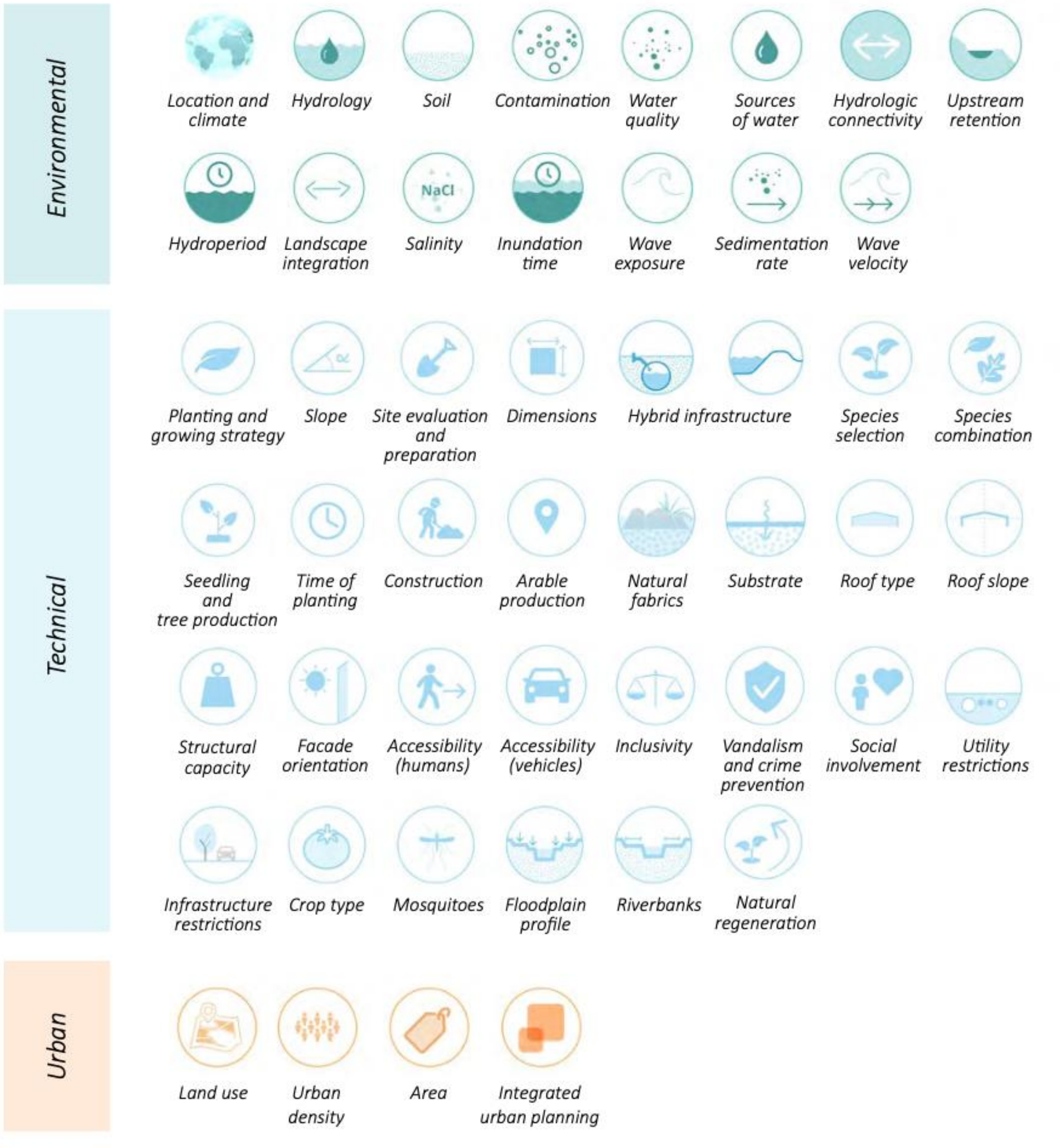

Figure 15. Suitability considerations icons. (Word Bank Group, 2021)

To bring the design proposal to life, advanced digital tools will be employed. The primary software applications used will include SketchUp for 3D modelling and various Adobe programs for detailed graphic design and layout presentations. These tools will enable the precise visualisation of the proposed interventions and allow for the meticulous planning of NBS implementations that enhance urban resilience.

3.3.4. Fourth Stage

Stage 4 of the research focuses on the formulation of critical discussion and conclusions. The objective of this stage is to reflect on the conceptual design that was developed according to the research findings. Additionally, this stage aims to draw meaningful conclusions about the research process and main findings.

The method employed in this phase involves a thorough analysis of the case study and design proposal outcomes. By evaluating the results of these elements, the study will extract key insights and lessons learned. These findings will then be used to support the approach employed in the conceptual design and recommend ways to integrate NBS into the urban planning of informal settlements, with a particular focus on adapting these strategies to the unique challenges and opportunities of informal settlements like Philippi.

Moreover, this stage includes a reflective component, where the research process itself is examined. This examination will highlight the strengths and achievements of the study, discuss any limitations encountered, and suggest areas for further research. This reflective analysis is crucial for understanding the efficacy of the research methodology and for improving future studies in similar contexts.

3.4. Ethical Considerations

The research on implementing NBS in the Philippi adhered to stringent ethical standards, ensuring data integrity, privacy, and environmental respect. Since there was no direct contact with the local population, concerns related to informed consent, confidentiality, and potential harm were not applicable.

Despite the lack of direct interaction, the study was conducted with sensitivity towards the local culture and environmental context, ensuring a respectful representation of the community's socio-economic and environmental conditions. Research methodologies minimised negative environmental impacts, considering how data collection and interventions might affect the local ecosystem and advocating for sustainable practices.

Data integrity was maintained by using accurately represented, reliable, and credible secondary data. Misrepresentation was strictly avoided, and findings were reported transparently. Public communications avoided stigmatisation, aiming to inform and improve urban planning and resilience strategies beneficial for similar communities globally.

The study primarily used publicly available data or data obtained with appropriate permissions, ensuring no encroachment on proprietary data or intellectual property rights. The research aimed to contribute constructively to urban resilience and sustainable development, offering insights and strategies valuable both academically and practically.

3.5. Case Study Analysis

3.5.1. Socio-Economic Analysis

Philippi, a township within the economically disadvantaged Cape Flats area southeast of CoCTs metropolitan region, has been significantly influenced by various developments at the national, city, and local levels. The PHA, which lies to the township's west, remains an essential agricultural zone that is largely undeveloped, providing substantial agricultural output to the city due to its strategic position and size (Mtuleni, 2016). However, these agricultural areas and subsequent food production are at risk, particularly due to stressors like urbanisation and climate change (Mtuleni, 2016).

The township comprises several neighbourhoods including Browns Farms, Heinz Park, Kosovo Informal, Philippi East, Philippi Park, Philippi SP1, Sweet Home, and Weltevreden Valley North 1 and 2, as detailed in Figure 18. Located centrally on the Cape Flats, Philippi is bordered by key arterial roads like the N2, M7, M9, and R300 and is accessible via six main routes, enhancing its role as a distribution node (Mtuleni, 2016).

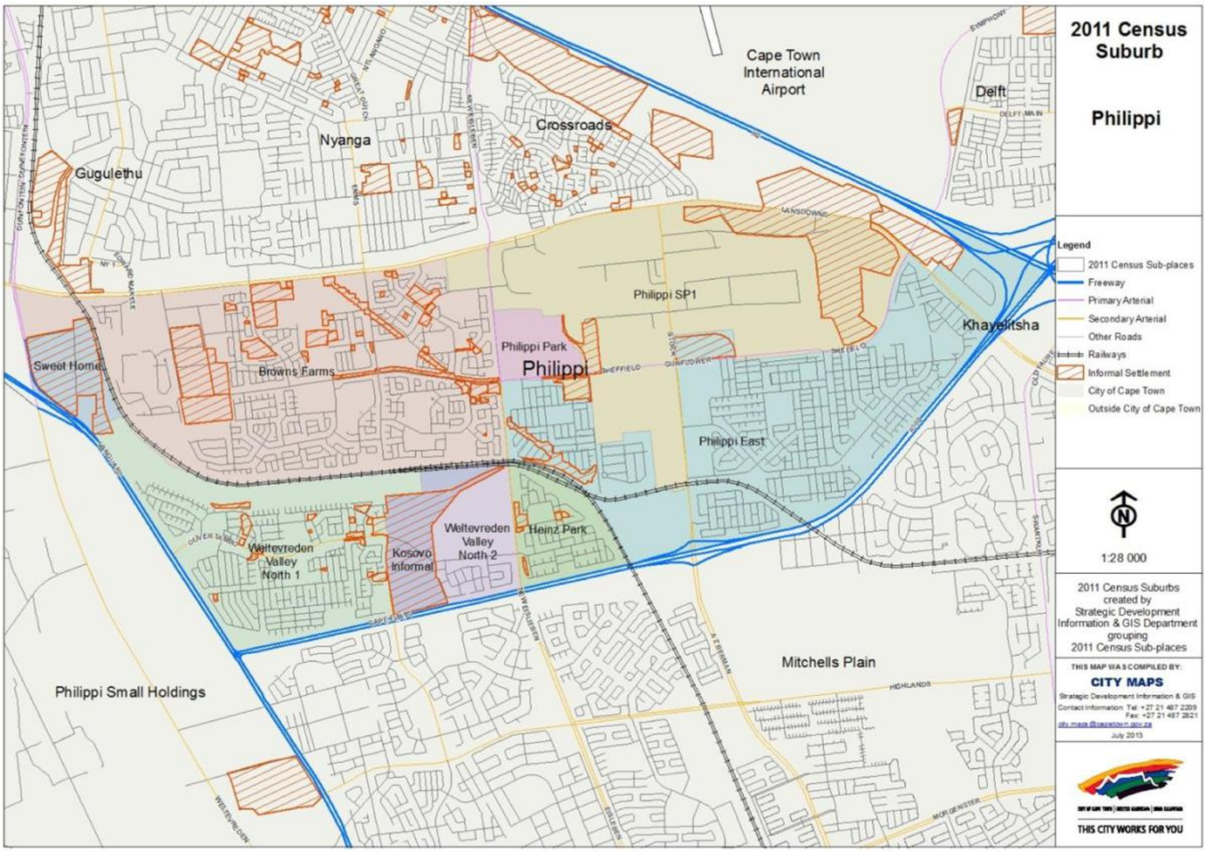

Figure 16. Philippi settlements and surrounding neighbourhoods. (CoCT, 2013)

Philippi's geographical location offers numerous opportunities despite facing challenges such as unemployment, poverty, crime, food insecurity, overcrowding, and exposure to environmental risks like fires and flooding. The study focuses on Philippi due to the significant urban development observed in the area, particularly concerning the impacts of flooding on residents' livelihoods and the environment. This site provides a critical perspective on managing human-environment interactions in informal settlements around CoCT (Mtuleni, 2016).

Data from the 2011 census reveals that Philippi had a population of 200,603 residents, spread across 64,411 households, with an average size of 3.09 persons/household (CoCT, 2013). The majority of the population are Black Africans, making up 94% of the township's residents. Infrastructure access is relatively high, with 77% of the population having access to a flush toilet connected to a sewage system, and 67% having piped water in their homes or yards (CoCT, 2013). Financially, nearly 80% of households earn R3,200 (±€150) or less per month, and only 44% reside in formal housing structures (CoCT, 2013).

3.5.2. Land Use

The township of Philippi displays diverse land uses, predominantly residential as illustrated in Figure 19. A section of Philippi is allocated for industrial activities. This area is experiencing rapid development and is poised to become a key economic hub in the southeast of the CT metropolitan area. The types of land use influence the nature and quantity of pollutants entering the water systems. Residential areas like Philippi often see water systems contaminated with household and sewage waste. Additionally, water systems in industrial areas may contain chemical pollutants. These pollutants could have serious repercussions for the health of both surface and underground water systems, posing substantial risks to human and environmental health (Mtuleni, 2016).

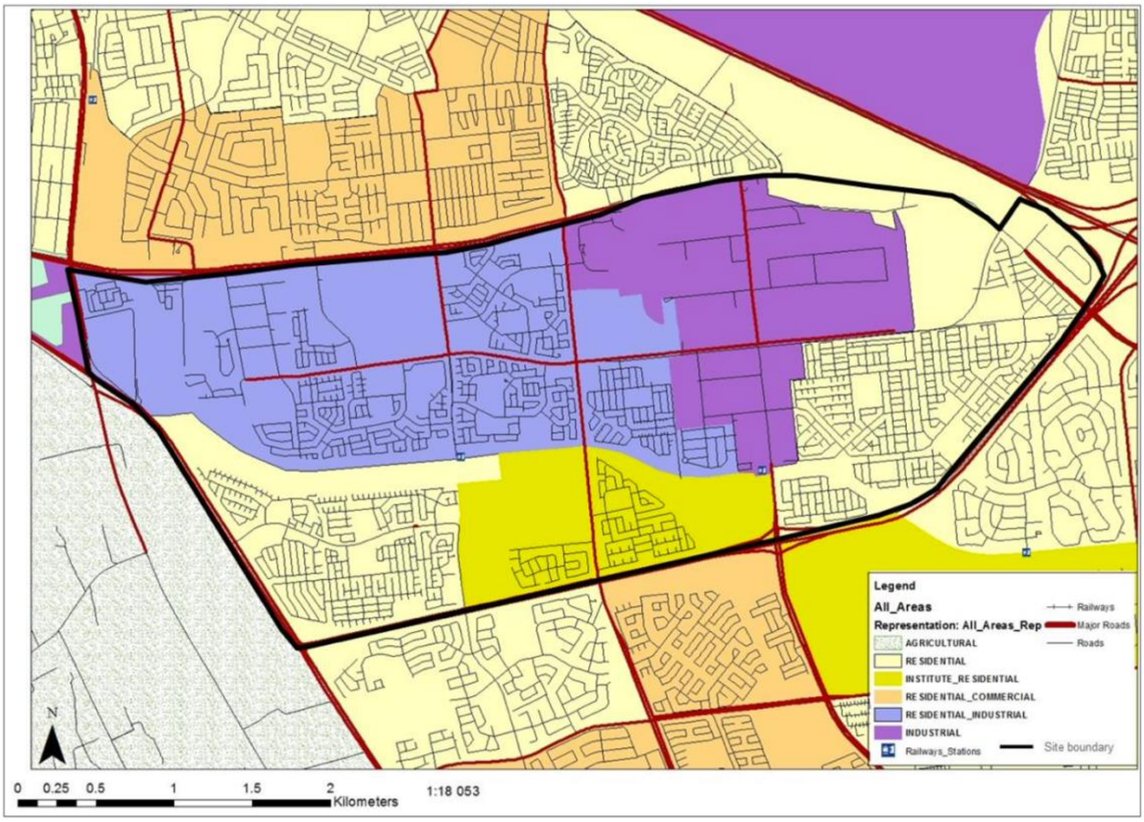

Figure 17. Land Use in Philippi. (Mtuleni, 2016)

3.5.3. Geomorphology and Geology

The landscape of the Cape Metropolitan area is largely shaped by ongoing weathering and hydrological processes. This region's geology consists of various rock formations, predominantly the Cape Granite Suite, the Malmesbury Group, the Klipheuwel, the Quarternary Sands, and the Table Mountain Sandstone. These geological features contribute to the rich and varied soil types that underpin the distinctive species and landscapes unique to Cape Town (CoCT, 2023).

Philippi is located on the Cape Flats, a coastal plain set amidst the mountainous regions of the Cape Town metropolitan area, covering an area of 630 km². The Cape Flats are primarily composed of sands derived from the weathering of quartsite and sandstones from the Malmesbury Formation and the Table Mountain Group, as well as Aeolian sands from nearby beaches (Adelana et al., 2010). In Philippi, the geology includes tertiary to recent calcareous sands featuring limestone outcrops, particularly near the False Bay coast, identified as part of the Sandveld Group. The soils in this area are broadly classified as Grey regic sands and are considered highly erosive with less than 15% clay content, depths ranging from 450 mm to less than 750 mm, and slopes varying from 0-5 degrees (CapeFarmMapper 3, n.d.). Furthermore, due to the high porosity of the sandy soils, there is a risk that water will infiltrate rapidly without being adequately filtered from pollutants, potentially leading to aquifer contamination. This combination of geology, topography, and biodiversity plays a vital role in the urban planning and development considerations for CoCT, where these accessible lowlands are often targeted for urban development due to their ease of access compared to the more rugged, mountainous areas (Adelana, et al., 2010)

Additionally, Philippi is predominantly flat, ranging from 32 meters to 42 meters above sea level, highlighting its vulnerability to flooding and the importance of improving resilience, possibly through the implementation of NBS.

3.5.4. Biodiversity

Philippi, part of the Cape Town metropolitan area, is located within the Cape Floristic Region (CFR), one of the world's six floral kingdoms and a globally renowned area. This region, characterised by a Mediterranean climate, supports diverse plant and animal life across various hilly terrains. Many species unique to this region are found here, though urbanisation and other human activities have led to significant habitat loss (CoCT, 2023). In the informal settlements, much of the indigenous vegetation has been removed to make way for development. However, plans for green areas include reintroducing this native vegetation to restore some of the region's natural biodiversity (CoCT, 2023).

In Philippi, the predominant vegetation type is the FS 6 Cape Flats Dune Strandveld, unique to the coastal lowlands around CoCT (CapeFarmMapper 3, n.d). Furthermore, the Philippi is situated within the fynbos biome which spans flat to slightly undulating dune fields and is characterised by shrublands of tall, evergreen, hard-leaved shrubs mixed with grasses, annual herbs, and succulents. Notable plant species which lay under fynbos include Euclea racemosa, Metalasia muricata, and Olea exasperata (Fynbos Corridor Collaboration, n.d.).

Furthermore, invasive plant species in the Philippi area of CoCT, such as the Port Jackson, pines (Pinus spp.), eucalyptus (Eucalyptus spp.), and various acacias (Acacia spp.) (CapeFarmMapper 3, n.d.), significantly impact the local ecology, water resources, and fire hazards. These invasive plants outcompete native vegetation, reducing biodiversity and altering the natural habitat. They consume large amounts of water, exacerbating the region's water scarcity issues. This is particularly concerning in an area like CoCT, which has faced severe droughts in recent years (Gaertner et al., 2016).

Moreover, invasive species like eucalyptus and pines are highly flammable, increasing the risk and intensity of wildfires. These plants can form dense stands that burn hotter and spread more rapidly than native vegetation, posing a greater threat to both natural and human communities. Efforts to manage and remove these invasive species are crucial for restoring the native ecosystem, conserving water resources, and reducing fire risks in Philippi and the greater Cape Town area (Gaertner et al., 2016).

The Cape Flats Dune Strandveld faces considerable ecological challenges, primarily from urban development, leading to significant habitat transformation. Over half of its original area has been modified, categorising it as an endangered habitat (Fynbos Corridor Collaboration, n.d.; Fynbos Life, n.d.).

Despite these challenges, the Cape Flats Dune Strandveld remains critical for biodiversity conservation in CoCT, significantly contributing to the region's ecological diversity. The biome supports a wide range of flora adapted to its sandy, nutrient-poor soils, including various fynbos and Strandveld species, with key adaptations to drought and wind. This high level of biodiversity and endemism underlines the importance of conservation efforts in the area (Fynbos Corridor Collaboration, n.d.).

Philippi possesses some green infrastructure such as wetlands, open fields, and small-scale greenery, with potential for enhancement, serving as a critical asset in a flood-prone region like the Philippi Horticultural area (CoCT, 2022b).

3.5.5. Climate

Cape Town has a Mediterranean climate, with wet winters and dry summers. Annual rainfall varies according to geography, with lowlands and coastal plains receiving an average of 515mm/year and mountainous areas receiving around 1500mm/year (Ziervogel et al. 2014). As a result, the Cape Flats suffer drier circumstances, whereas the Table Mountain Range is wetter (Cameron, 2014), with average rainfall of 619mm/year (Adelana et al., 2010) and an annual evaporation mean of 2200-2400mm (CapeFarmMapper 3, n.d.). The north-westerly winds, common during the winter months, often bring rainfall, intensified at times by large cold fronts from the Atlantic Ocean, which increase precipitation (Ziervogel et al., 2014). While regional climate forecasts predict a trend towards drier conditions overall, they also indicate a likely rise in the frequency and intensity of extreme rainfall events in Cape Town (Ziervogel et al., 2014). However, this data has already been affected by climate change and is expected to continue changing in the future, leading to more extreme events.

The winter season, spanning June to August, sees temperatures averaging a maximum of 18°C and a minimum of 8.5°C. In contrast, the summer months from November to March are warmer and drier, with average maximum and minimum temperatures of 26°C and 16°C, respectively. These climatic patterns significantly influence the ecological functionality of the city's natural systems, affecting the survival of plant and animal species, water resource management, and groundwater recharge (Ziervogel et al., 2014).

Understanding the local climate patterns and their implications allows for the design of context-specific interventions that enhance urban resilience and sustainability, addressing both current challenges and future climate projections.

3.5.6. Hydrology

The primary source of freshwater pollution in Cape Town is inadequately treated wastewater, with additional pollutants from raw sewage in informal settlements, contaminated urban stormwater, and deficient or aged urban water infrastructure (CoCT, 2022a). Pollution effects are exacerbated by flooding, negatively impacting human and environmental health (CoCT, 2022a). Despite recent improvements in ecosystem health and water quality in 2022, many freshwater systems still fall short of recommended standards due to urbanisation-driven inflows (CoCT, 2022a).

To address water shortages, CoCT has explored using groundwater, including the Cape Flats Aquifer (CFA), to supplement its water supply. The CFA has sufficient storage capacity to meet up to two-thirds (about $18Mm^3/a$) of the city's basic water needs (Adelana, 2010). However, the CFA's largely unconfined nature makes it vulnerable to surface pollution from industrial and agricultural chemicals, untreated human waste, high nitrate levels from wastewater treatment, and toxic materials from landfills and cemeteries (Giljam & Waldron, 2002). This necessitates groundwater protection measures in the city's development plans (Adelana et al., 2010).

In the Philippi area, despite sparse natural vegetation, the southwest PHA and north near the airport maintain crucial biodiversity. Philippi, a flood-prone lowland, benefits from man-made retention ponds that manage runoff, especially from higher elevations along Sheffield Road. These ponds are part of the stormwater infrastructure, coping with up to a 10-year storm. However, an additional 14 hectares of detention pond capacity is needed to handle more severe storms and support full development scenarios (CoCT, 2022b). Large-scale developments, such as shopping centres with extensive parking areas, exacerbate flooding risk, highlighting the need for enhanced stormwater management (CoCT, 2022b).

3.5.7. Flood Risk in Philippi

Cape Flats, within which Philippi informal settlement is located are defined by rapid urban development, including industrial, and agricultural activities, and dense human settlements. Such urban expansion on the Cape Flats poses a significant threat to groundwater quality as surface activities contribute both directly and indirectly to the recharge of the CFA (Hay et al., 2015). Flooding in the Cape Flats typically arises from high water tables, insufficient stormwater infrastructure, and the inundation of low-lying areas like wetlands and retention ponds where informal settlements are often established without regulations in place (Ziervogel et al., 2014). Flooding is exacerbated by natural and urban water recharge from informal settlements located in these vulnerable areas (Hay et al., 2015). Additionally, contributions from wastewater treatment works and stormwater, combined with the flat topography and compact nature of the environment, lead to frequent winter flooding, compounded by contaminated water entering the aquifer and often inadequate stormwater drainage infrastructure (Hay et al., 2015).

Despite evidence of flooding's significant impacts in Philippi (Armitage et al., 2010), current geospatial data does not classify Philippi as a flood-prone area (Mtuleni, 2016). However, areas identified as flood-prone are typically associated with areas located around major natural watercourses (Mtuleni, 2016). During periods of intense or prolonged rainfall, wetlands and other large water bodies within Philippi fill up, posing risks to human and environmental health. The flat terrain prolongs the duration of flooding events as water drains slowly, making it difficult for water levels to recede quickly (Bouchard et al., 2007). Once the soil reaches saturation capacity, infiltration ceases and ponding occurs.

Although wetlands (see Figure 20) in Philippi are recognised as flood-prone, many remain natural and undeveloped (CoCT, 2023b).

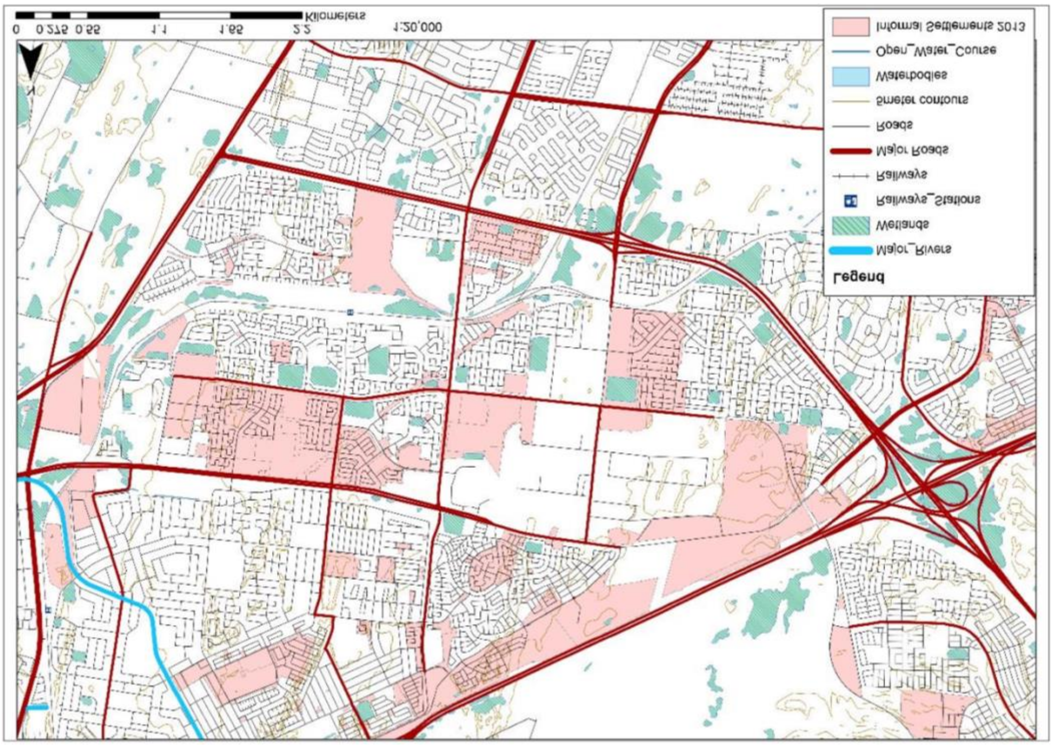

Figure 20. Wetlands and waterbodies in Philippi. (Mtuleni, 2016)

However, developments around these wetlands and sections of informal settlements encroaching upon them increase flood exposure (see Figure 21). The CoCT provides basic water-related services such as stormwater drains, formal trenches, and retention ponds, but their effectiveness is often compromised by blockages from trash build-up, silt accumulation, and man-made obstructions (Bouchard et al., 2007). Many settlements in Philippi lack proper drainage systems, largely due to their origins in illegal land invasions where the local government has limited control, and resources, and because increasing density complicates upgrading and retrofitting (Armitage et al., 2010). This inadequate infrastructure significantly contributes to flooding, which combines standing water with waste from sewers and drains, spreading bacteria and diseases in densely populated areas (Bouchard et al., 2007). Standing floodwater, when not drained quickly, also becomes polluted and emits odours (Drivdal, 2011).

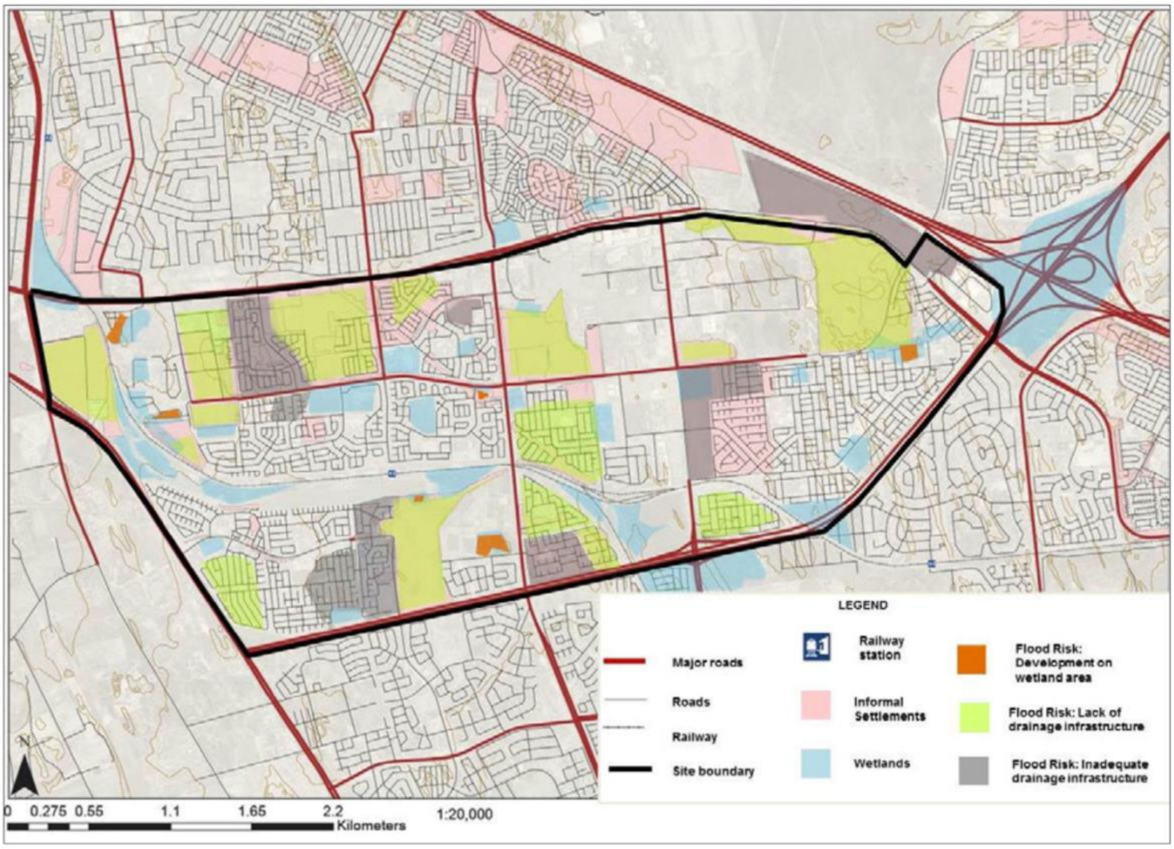

Figure 21. Flood risk in Philippi. (Mtuleni, 2016)

Figures 22 and 23 illustrate the state of stormwater and sewer drainage systems in Philippi, highlighting areas with inadequate or disconnected infrastructure. Compared to neighbouring areas like Nyanga and Mitchells Plain, Philippi has significant gaps in its water infrastructure network (Bouchard et al., 2007). Flood risk management is often not prioritised at the household and community levels. Many residents view their homes as temporary, hoping for relocation or formal housing provision, leading them to settle in high-risk areas as space within the city becomes scarcer (Drivdal, 2011). This overcrowding increases flood risks due to the greater number of people potentially affected by extreme events (Bouchard et al., 2007; Drivdal, 2011). High exposure rates to extreme events also increase community vulnerability.

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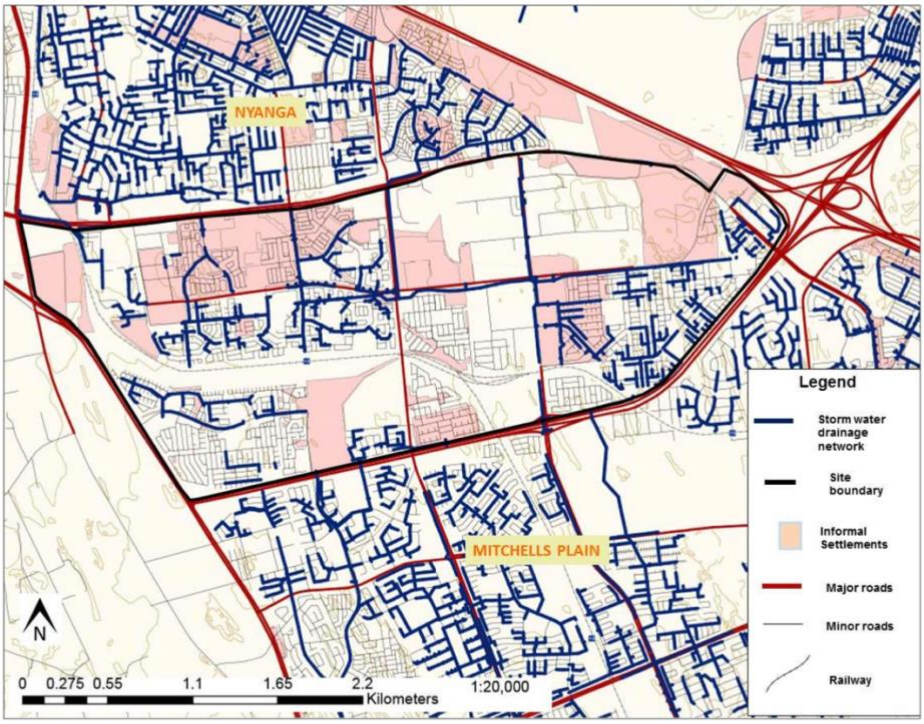

Figure 18. The stormwater drainage system in Philippi. (Mtuleni, 2016)

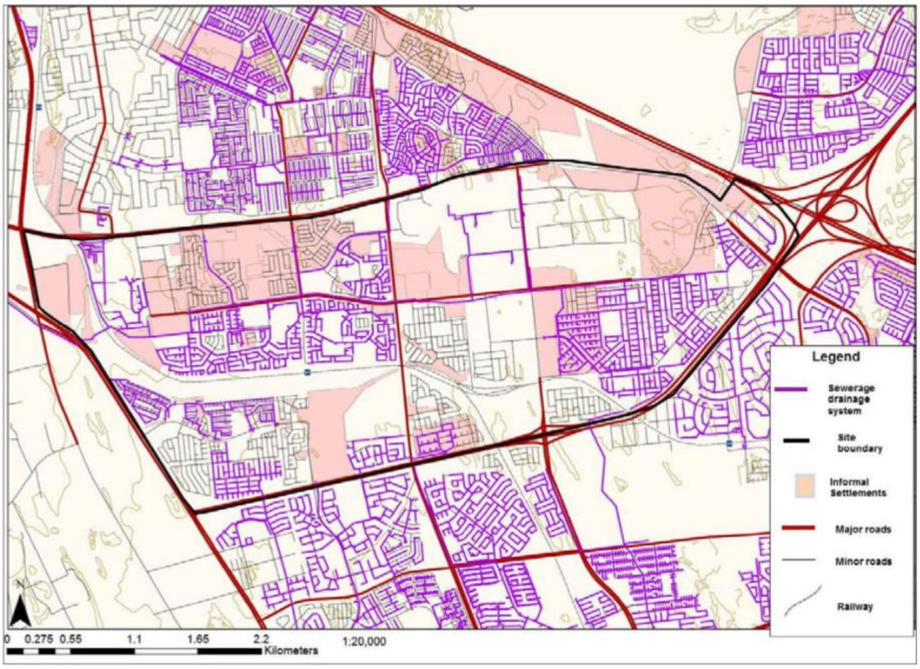

Figure 19. Sewerage drainage system in Philippi. (Mtuleni, 2016)

The effects of flooding in Philippi are evident, especially during the winter. Impacts include health risks, physical damage, and broader social and economic repercussions. Despite the challenges, many residents remain due to financial constraints (Bouchard et al., 2007). Public and shared spaces also suffer from flooding, affecting nearly all residents (Drivdal, 2011). The CoCT has undertaken efforts to mitigate flood risks through infrastructure and housing initiatives, though some measures have unintentionally increased vulnerabilities (Bouchard et al., 2007). For instance, the relocation of residents from Phola Park to the lower-lying Graveyard Pond has resulted in worse living conditions. Due to the terrain, water often fails to drain for extended periods, accumulating beneath the floors of the shacks and posing a potentially significant health hazard (Drivdal, 2011).

As winter approaches, residents brace for the impacts of expected flooding by implementing practical improvements to their homes and community spaces (Drivdal, 2011). Coping strategies include elevating belongings, covering homes with plastic, and enhancing drainage around homes, though many still choose to endure the conditions in their current homes (Drivdal, 2011).

3.5.8. Public Space/ Utilities

Open and public spaces play critical roles in urban environments but are often misunderstood as interchangeable terms. Public spaces are specific areas accessible to the public, such as parks, sports fields, urban agricultural spaces, and sidewalks. In contrast, open spaces can include any undeveloped land, whether publicly accessible or not. Within the Philippi area, the network of open spaces is fragmented and constitutes around 15% of the land area, which is significantly less than in more established suburbs. Almost half of these open spaces remain unused, leading to prevalent issues like dumping and littering. To combat these challenges, the City's Urban Waste Management department has developed a waste management and recycling policy, initiating several pilot recycling programs (CoCT, 2022b). Community involvement in these initiatives shows potential for expanding to other areas, aligning with suggested improvements such as transforming unused open spaces into community gardens or recreational areas. This approach not only addresses waste management issues but also fosters a sense of ownership and stewardship among residents, contributing to the overall enhancement of public and open spaces in the area.

Despite these measures, public spaces within the Philippi are scarce and generally in poor condition, failing to enhance the public realm effectively. Additionally, the area faces several infrastructure challenges. The eastern parts of Philippi and Crossroads experience a slight shortage of electrical capacity, affecting residential and some industrial areas. The bulk water infrastructure, however, shows adequate spare capacity across most of the district. On the other hand, there is a notable deficiency in wastewater infrastructure, especially on the western and eastern fringes of Philippi, which needs urgent attention. Moreover, while the 2017 MTIIF data suggests that stormwater infrastructure is adequate, evidence indicates significant challenges, exacerbated by informal settlements and illegal dumping (CoCT, 2022b).

4. Conceptual Design

The study area for the conceptual design focuses on a particularly vulnerable section of Brown Farms in Philippi, identified as highly susceptible to flooding due to inadequate stormwater drainage and sewage systems and a lack of NBS and being overlooked in most policy reports.

Link Road has been identified as a flood-prone area by Mtuleni (2016), presenting an opportunity for redesign with efficient water flow management in mind (see Figures 24 and 25). It is important to note that the road begins near the M9 highway, which means runoff accumulates from this point toward the study area. Although the M9 is equipped with stormwater infrastructure such as sewage systems and bio-retention zones, a glance at Google Earth's Street view (2022) reveals that these infrastructures are littered, significantly reducing their efficiency.

Thus, the conceptual design (see section 4.1) aims to reduce water flow speed, and run-off volume and redirect it from a main artery, alleviating pressure on the drainage system. Water accumulated in the bioswale will flow southward to a lower elevation, ultimately reaching the wetlands, where it will infiltrate the groundwater in detention ponds (see Figure 26).

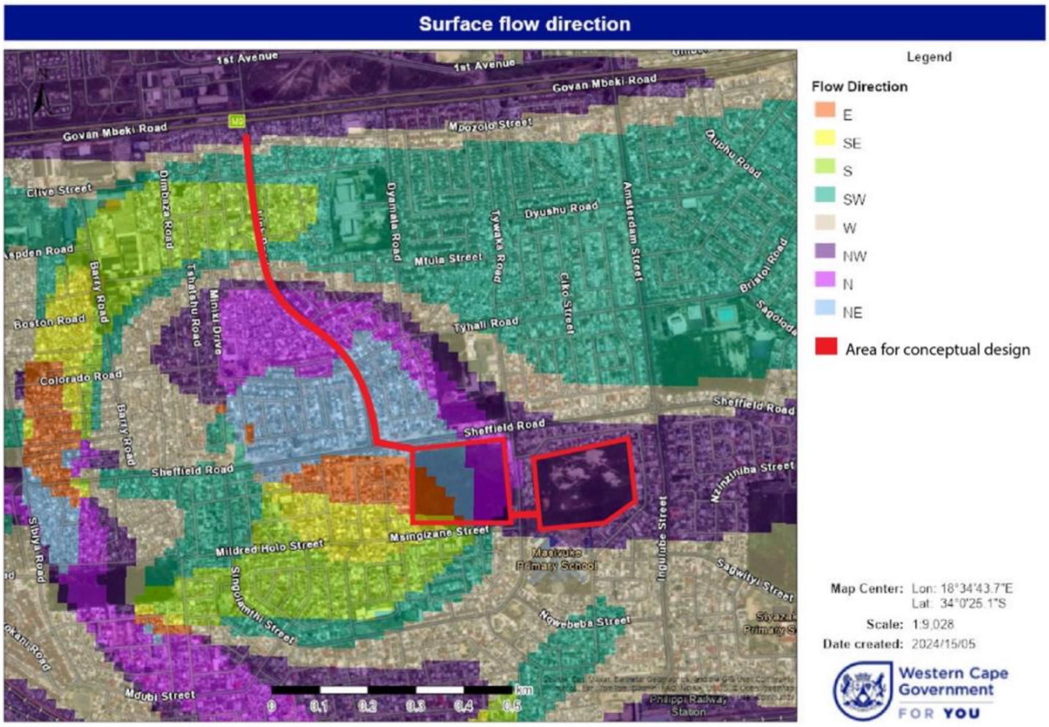

Figure 20. Surface Flow Direction. (CapeFarmMapper 3, n.d.)

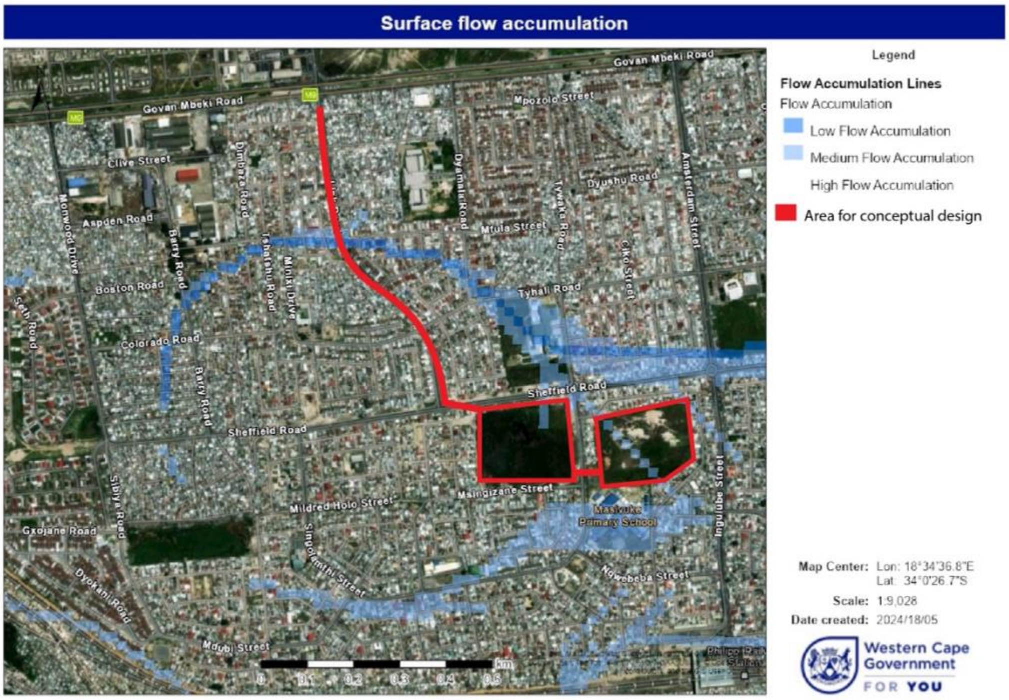

Figure 21. Surface flow in the study area. (CapeFarmMapper 3, n.d.)

The design demonstrates how Link Road can be redeveloped to incorporate NBS, enhancing resilience to climate change. Proposed features include permeable pavements, bio-retention areas, and bioswales along Link Road, effectively managing stormwater and reducing flood risk.

Additionally, the design proposes transforming the open area in the southeast part of Brown Farms with NBS elements (see section 4.3.) like wetlands, detention ponds, and recreational green spaces. These interventions aim to improve water management, biodiversity, and community well-being, creating a comprehensive plan that addresses immediate flooding issues and contributes to the long-term sustainability and liveability of Brown Farms. Furthermore, the combination of these systems will prevent stagnant water, which may be the epicentre of mosquito breeding as well as unpleasant odours.

Moreover, the design at the individual level (see section 4.2.) was developed to show what residents of the informal settlement can do with their homes to harness the benefits of ecosystem services (see Table 1)

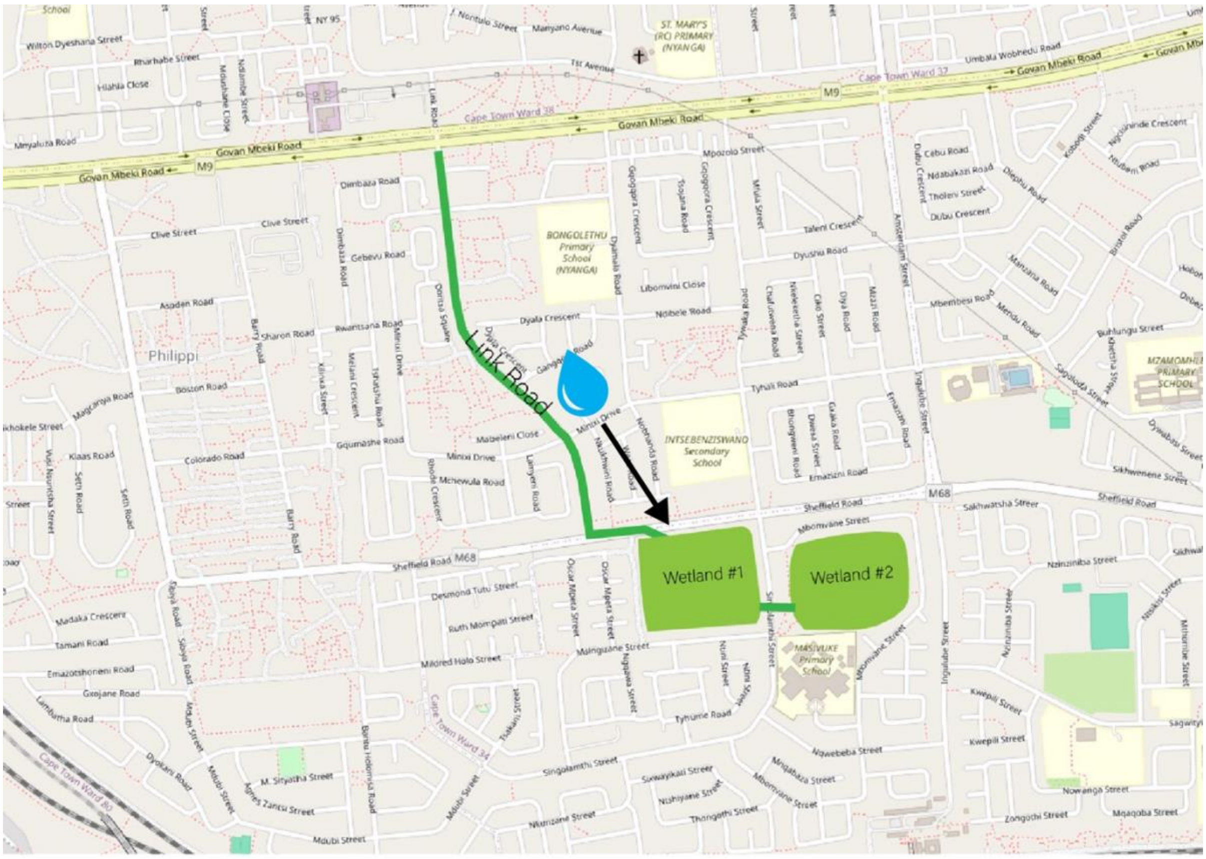

Figure 22. Design study area Brown Farms. (Author, 2024)

4.1. Link Road Conceptual Street Design

The cross-section design of Link Road in Brown Farms (see Figure 27), Philippi, features an overall street width of 8.2 meters. This includes 0.7 meters for sidewalks on both sides, ensuring pedestrian accessibility and safety. Incorporating water-wise indigenous vegetation such as Metalasia muricata, Olea exasperata, Fynbos flowers, Ficinia nodosa (Knotted Club-rush), Stenotaphrum secundatum (Buffalo Grass), Juncus kraussii (Dune Rush), and Elegia tectorum (Cape Thatching Reed) into the bioswale design is an ideal choice due to their native resilience and ecological benefits. These plants are well-adapted to local conditions, promoting water filtration and soil stabilisation within the bioswale. Metalasia muricata and Olea exasperata provide robust foliage and erosion control, while Fynbos flowers enhance biodiversity and aesthetic appeal. Ficinia nodosa and Juncus kraussii excel in wet conditions, aiding in water absorption and purification. Stenotaphrum secundatum offers durable ground cover, and Elegia tectorum contributes to water management and habitat creation. Together, these plants create a functional, sustainable, and visually pleasing bioswale, while simultaneously promoting biodiversity and ecosystem services (see Table 1).

The design of the bioswale measures 1 meter in width and 0.75 meters in depth, effectively capturing and infiltrating stormwater runoff to mitigate flooding risks and enhance water quality, for detailed technical aspects see section 4.1.2.

The road itself spans 5.8 meters, adhering to the minimum road width standard of 5.5 meters as specified by Kuilsrivier Municipality (1984), ensuring it can accommodate vehicular traffic without disrupting movement, with provisions for adequate root space and the use of permeable materials (see section 4.1.1.) to promote groundwater recharge and reduce surface runoff. The height of the dwelling was difficult to measure because of the absence of standardised design principles in the informal settlements. Therefore, an average height of 2.5 meters was assumed to ensure that people could stand at full height. Dimensions for this design were measured using Google Earth, ensuring accuracy and relevance to the specific site conditions. This holistic approach ensures that the infrastructure supports both ecological and social benefits, fostering a resilient urban environment.

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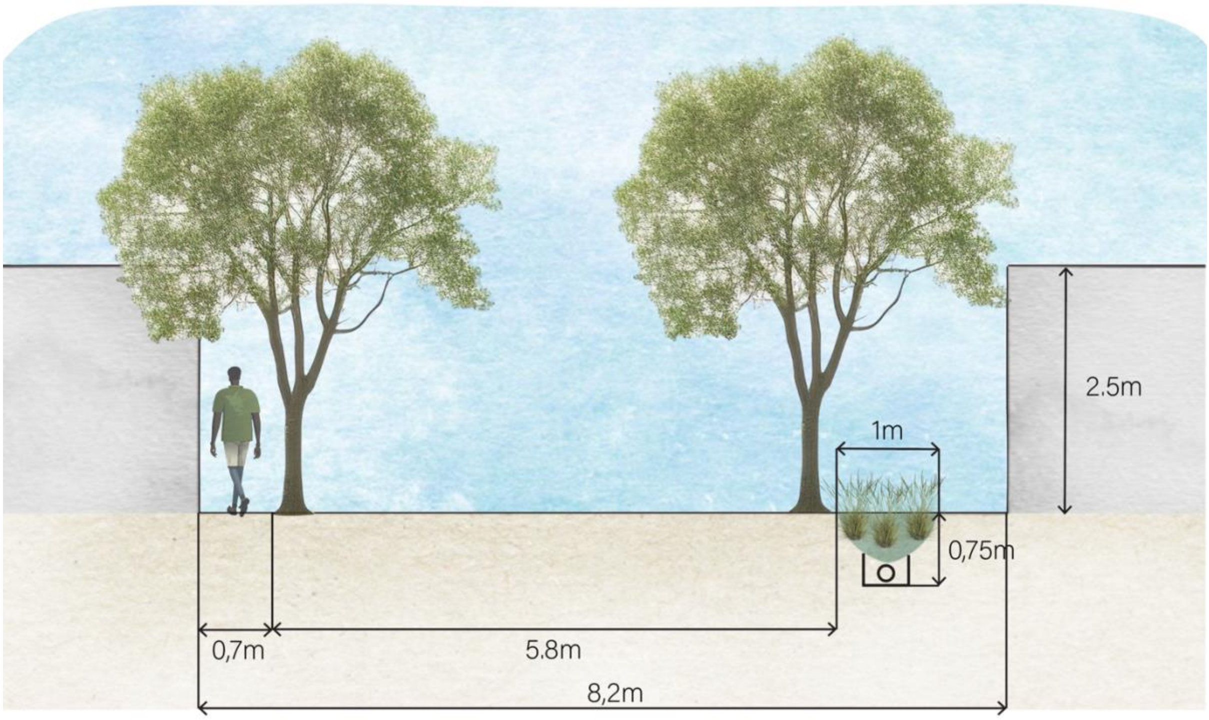

Figure 23. Cross section Link Road. (Author's own)

The conceptual street design provides an aerial view of the Link Road (see Figure 28) as well as to scale street view (see Figure 29), highlighting various elements that enhance both functionality and safety. Brachylaena discolour trees stand out as a great choice for the Brown Farms due to their tolerance to the local temperature and drought-resistant qualities, which require little watering once planted. They provide substantial shade, reducing temperatures, which is beneficial in urban heat islands. In shaded locations, tree canopies may reduce temperatures by 1 to 5°C (33.8 to 41°F). It is possible to lower daytime air temperatures by around 1°C (33.8°F) with a 10% increase in tree canopy cover (Thorne and Soar, 2001).

According to Eisenberg and Polcher (2020) a root space that is 12 m^3 and at least 1.5 m deep is optimal as well there must be a minimum of 1.8 metres between the edge of the tree pit and the roadway curb or any structures, these requirements were complied with in the conceptual design. Moreover, tree selection acknowledged the presence of overhead power lines and underground utilities.

Furthermore, proper clearance must be maintained from infrastructure, and trees must withstand urban conditions, including pollution and vibration. Periodic trimming is necessary (Eisenberg and Polcher 2018). These trees also stabilise soil, prevent erosion, and support local biodiversity by providing habitat for birds and insects.

The trees are strategically planted within bio-retention ruts (see Figure 28) along the road. They are small vegetated pits typically 1 to 10 m^2 in size, are filled with sand or coarse aggregate, topped with soil, and planted with vegetation, allowing runoff to infiltrate. A subsurface drainage network may be used if local infiltration rates are insufficient (Armitage et al., 2013). The ruts, which are half-circle in shape, not only aid in water management but also serve to narrow the road, thereby naturally slowing down traffic and increasing overall safety by discouraging high vehicle speeds and reducing traffic volume.

The pedestrian paths adjacent to the road are covered with gravel, promoting water permeability and reducing surface runoff. To ensure that pedestrians can comfortably navigate these areas, small wooden bridges are installed at regular intervals across the bioswales. These bridges provide convenient crossing points, enhancing accessibility while maintaining the integrity of the bio-retention system.

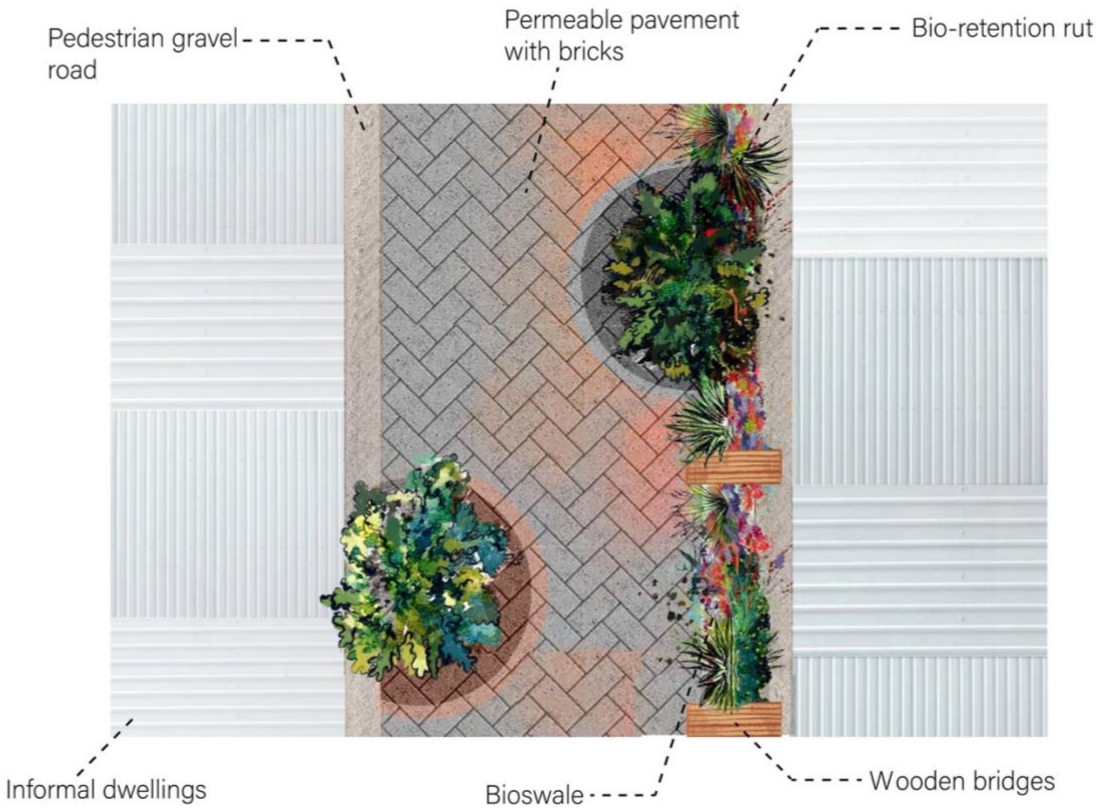

Figure 24. Arial view of the Link Road. (Author and Filippova, 2024)

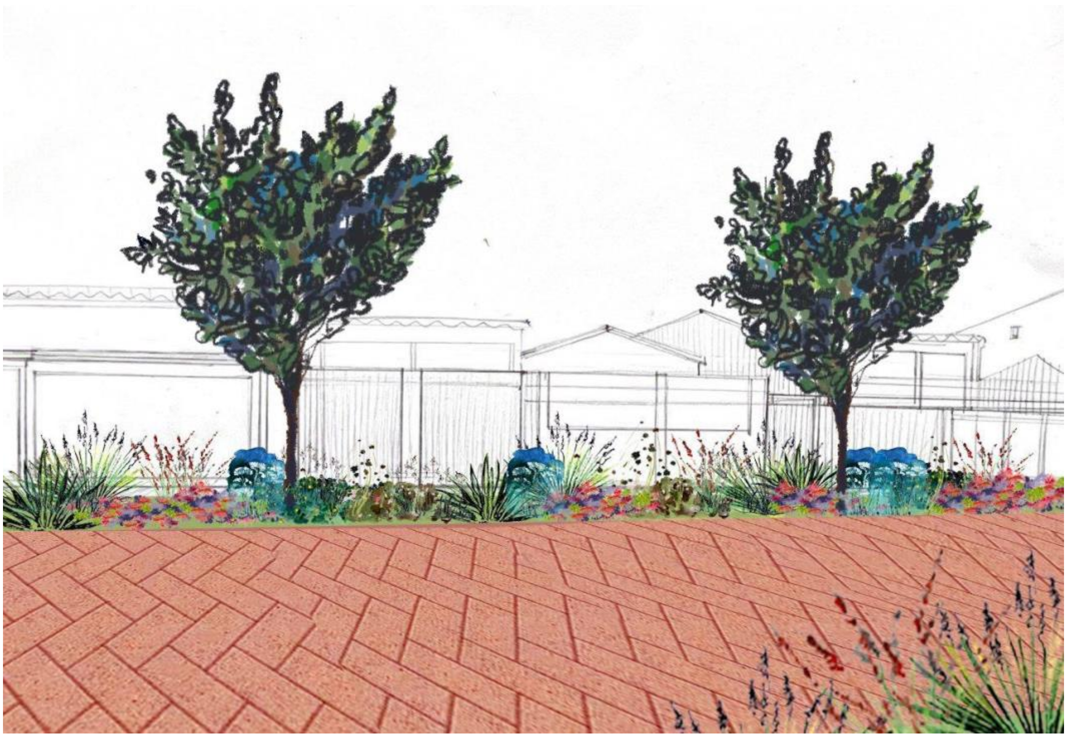

Figure 25. Conceptual design, street view. (Author and Filippova, 2024)

Further discussion will cover the detailed design elements, focusing on their advantages, disadvantages, design guidelines and maintenance requirements ensuring a comprehensive understanding of the implementation and long-term sustainability of the proposed solutions.

4.1.1. Permeable Pavements

Permeable pavements facilitate stormwater infiltration through surfaces into sub-layers (see Figure 30), which is planned for the study area. Materials will include permeable concrete block pavers (PCBP), brick pavers, stone chips, gravel, porous concrete, and porous asphalt. Grass can be used in low-traffic areas. Suitable for pedestrian and vehicular use, they can handle heavier loads with design modifications. Typically built on coarse gravel sub-bases, they allow stormwater infiltration and promote groundwater recharge. Soluble pollutants pass through (see Appendix 1), while debris remains on the surface for collection (Armitage et al., 2013). It should however be mentioned, that maintenance is required to remove sediment and ensure infiltration capacities are maintained.

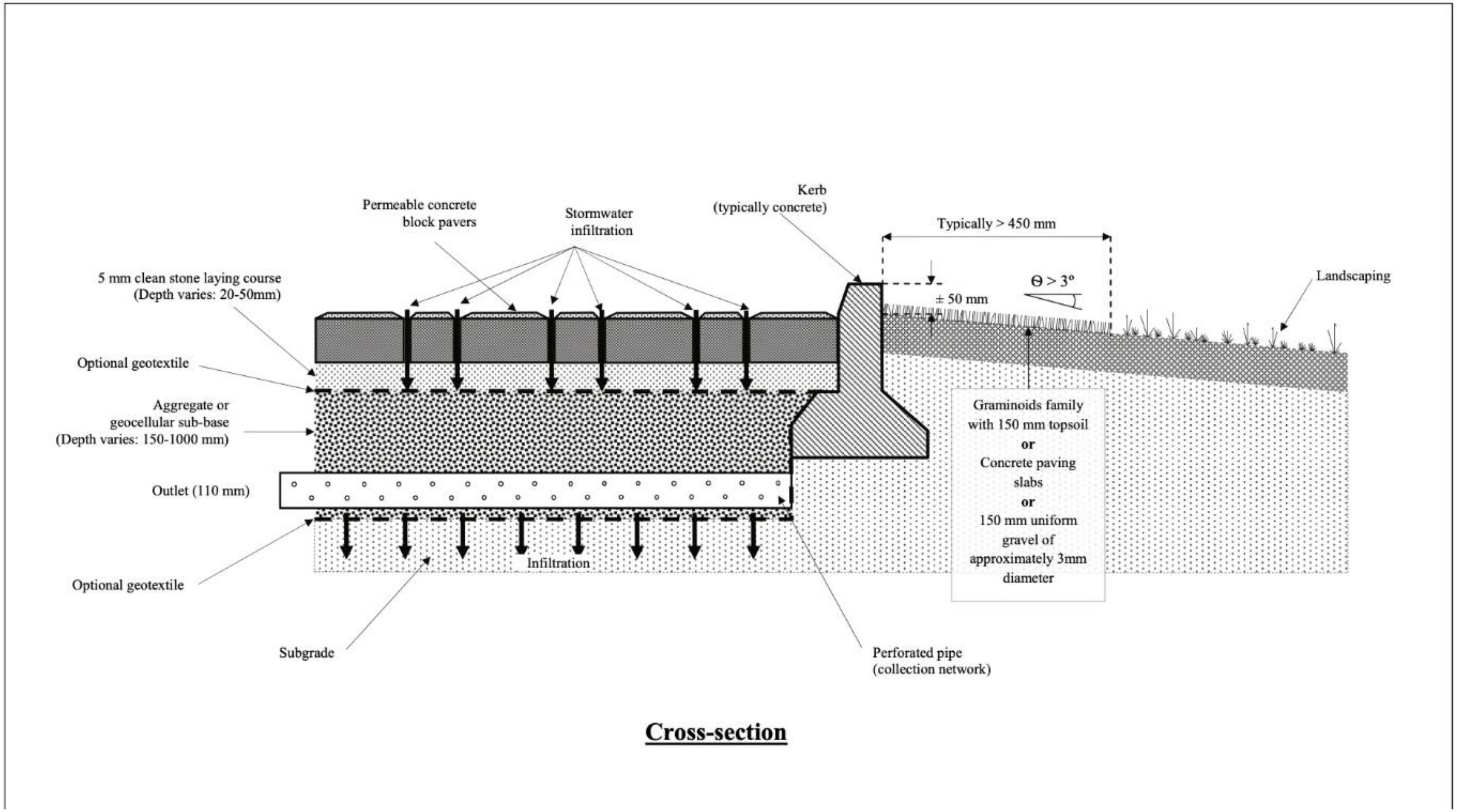

Figure 26. General design for permeable pavements and adjoining landscaped areas. (Armitage, 2013)

4.1.1.1. General Design Guidelines

Permeable pavements must capture the minor design storm's Water Quality Volume (WQV) and discharge additional flow in a controlled manner. They should withstand expected loads and be protected from sediment during construction to prevent clogging. Not suitable for slopes over 5%, in the case of the study area, the slope varies from 0% to 5%. Constructed with compacted stone base layers, they should have a graded filter to avoid using geotextiles. Good workmanship is crucial, and perforated drainage pipes may be needed if infiltration is insufficient. PCBPs are strong and resistant to chemicals, oils, and fuels (Armitage et al., 2013).

According to Armitage et al. (2013), there are several advantages of permeable pavements which will be beneficial to the study area. They can reduce stormwater discharge rates and volumes, thereby mitigating the impact on local water bodies. Another advantage includes the marked increase in usable area by integrating drainage solutions directly into roadways and parking lots, making efficient use of available space. Additionally, these systems can recharge groundwater and store stormwater for domestic use, providing a sustainable water resource. They are particularly suitable for areas with limited infiltration capacity. Moreover, when properly designed, these systems can prevent surface ponding and address freeze-thaw issues effectively.

However, Armitage et al. (2013) identified several limitations of permeable pavements. These systems are limited to slopes less than 5%, making them unsuitable for steeper areas. They cannot be used as fill materials due to the risk of soil failure when the soil becomes saturated. Additionally, they are not recommended for areas with high traffic volumes, speeds exceeding 50 km/hr, or for supporting heavy vehicles. Proper management is crucial, as these systems can clog with fine sediment if not maintained correctly. Furthermore, they have a lower pollutant removal capability compared to other SuDS options.

4.1.1.2. Operation and Maintenance

Maintenance should be planned and include regular inspections. This includes the periodical replacement of fine stone aggregate in PCBPs to prevent blockage. Typical maintenance involves vacuum-sweeping or high-pressure jet-washing every three months. In case of failure, geotextile filters are removed and replaced. Many systems do however operate successfully with minimal maintenance due to high initial infiltration capacity (Armitage et al., 2013).

4.1.2. Bioswales

Swales are shallow, grass-lined channels with flat and sloped sides, serving as alternatives to curbs and gutters in residential areas. They reduce runoff volumes and peak flows but require surface area to be constructed. Swales are often used with buffer zones and bio-retention systems, employing infiltration and bio-infiltration to remove pollutants. They function as open drainage systems, offering pre-treatment for larger SuDS options, and providing aesthetic and landscape enhancements, as well as ecosystem services and improved social interaction (Armitage et al., 2013, Ruangpan et al., 2020).

4.1.2.1. Advantages and Limitations

According to Armitage et al. (2013), bioswales offer several advantages, which would potentially improve the situation for the study area. They are cost-effective and visually appealing, making them appropriate for a variety of contexts. By enabling on-site infiltration of runoff, bioswales aid in local water management. Additionally, they retain particulate pollutants (see Appendix 1) near their source, reducing the spread of contaminants see Appendix 3 for types of contaminants). Bioswales also collect polluted stormwater runoff, removing, trapping, and degrading organic contaminants. Nitrogen contaminants are converted into gas and returned to the atmosphere, while inorganic contaminants are captured and immobilised (Kennen and Kirkwood, 2015). Bioswales also reduce runoff volumes (see Appendix 2 for formulas to calculate runoff rates) and delay peak flows, resulting in enhanced water management. According to Khan et al. (2013), bioretention areas can reduce runoff volume by up to 90%, as seen in Calgary, Canada. This is comparable to a peak flow drop of up to 41.65% observed in the Hai He Basin of China (Huang et al. 2014).

Furthermore, they help regulate heat by decreasing surface and air temperatures via vegetative evapotranspiration. This process involves the uptake of water by plants and its release into the atmosphere, which cools the surrounding environment. This cooling effect is particularly beneficial in urban areas where heat islands are common (World Bank Group, 2021). Additionally, bioretention areas enhance biodiversity by providing habitats and supporting ecological connectivity. They improve the Brown Farms' environment by linking it to surrounding natural areas and providing food and pollination opportunities for wildlife (Kim and Song, 2019). These areas can also be integrated with traffic control and regulation measures, enhancing the safety and usability of public spaces (Kim and Song, 2019). Moreover, added greenery encourages physical activities and reduces stress, contributing to overall well-being. Proximity to tree canopies can also reduce mortality rates in the elderly (Gehrels et al. 2016).

However, Armitage et al. (2013) report that these systems have several shortcomings. They need greater land area than typical drainage systems, which can be an issue in space-constrained settings which is the case for informal settlements, however, the Link Road is wide enough for such development. Their ability to remove soluble contaminants and fine particles is restricted. Furthermore, they are impracticable for steep slopes, which is not the case for the study area. Standing water can promote mosquito breeding and produce unpleasant odours. For the proposed conceptual design, quick infiltration is suggested. Finally, unless properly maintained, these systems are prone to failure.

4.1.2.2. General Design Guidelines

According to Armitage et al. (2013), swales are particularly suitable for road medians, parking areas, parks, and recreational spaces. The design of swales should prioritise both flow conveyance and stormwater pre-treatment. The process begins by determining the treatment performance, appropriate plant species, and their densities. Native floodplain species that tolerate variability in soil saturation and inundation and are resilient to environmental stress are often best suited, the examples of plant species for the study area can be seen in section 4.1. Next, the design should consider flows and dimensions concerning site constraints. It is important to optimise design inflow, ensuring it accounts for scour velocity and treatment needs. Additionally, overflow areas should be sized with traffic considerations in mind. Finally, drafting a comprehensive maintenance plan is essential to ensure the long-term effectiveness of the swale. All of these aspects were addressed in the explanation of the Link Road conceptual design (section 4 and 4.1.).

Bioswales on Link Road should be located above the water table to prevent groundwater from intersecting the filter bed, which would reduce infiltration capacity. A minimum distance of 0.6 meters should be maintained between the bottom of the bioretention area and the seasonally high groundwater table unless an impermeable liner is installed (World Bank Group, 2021). In Brown's Farm, the depth of groundwater ranges between 3-5 meters deep according to CapeFarmMapper (n.d.). However, Water Stories (n.d.) indicates that the water table can be notably high, often around one meter from the surface in some areas. For the conceptual design, almost the most extreme case was considered, resulting in a 0.75-meter depth for the bioswale as mentioned in Figure 27.

Examining Link Road, the soil is predominantly sandy, which is unsuitable for effective water treatment (see Appendix 4). Therefore, areas like these typically utilise mixed soils or engineered media with high infiltration rates to enhance water treatment capabilities (World Bank Group, 2021).

Swales will manage minor flood designs, ensuring low flow velocities and adequate freeboard to prevent flooding. Along the Link Road, grassed swales will be constructed with gentle slopes in the south direction (the direction of flow), with side slopes maintained at a gentle angle—typically less than 30°—to allow for easy cutting with mechanical grass cutters. Also, a longitudinal slope of >2.5% will be maintained to avoid standing water. Healthy grass cover is crucial for pollutant removal. Dense grass and proper vegetation enhance effectiveness, with recommended types including groundcovers, shrubs, trees, and Indigenous plants (Armitage et al., 2013)

Bioretention areas on the Link Road can be effectively combined with sewer systems through an overflow outlet or underdrains that connect to the sewer system. By attenuating runoff, they relieve pressure on sewer systems and contribute to integrated stormwater management, blending green and grey infrastructure (World Bank Group, 2021).

Furthermore, effective swale management depends on quality maintenance, including regular mowing, weed control, watering, re-seeding, and debris removal. The first two years are crucial for plant establishment. Inspect swales twice a year, addressing erosion and sediment build-up. Remove sediment when it exceeds 100 mm in depth (Armitage et al., 2013).

Moreover, according to Armitage et al. (2013), there are two notable technology derivatives (see Figure 31). Enhanced dry swales are vegetated systems equipped with prepared soil beds and under-drain systems, which enhance filtration. Wet swales, on the other hand, retain stormwater and create marshy conditions suitable for wetlands. However, wet swales are not recommended for residential areas due to the potential for odours and mosquito breeding.

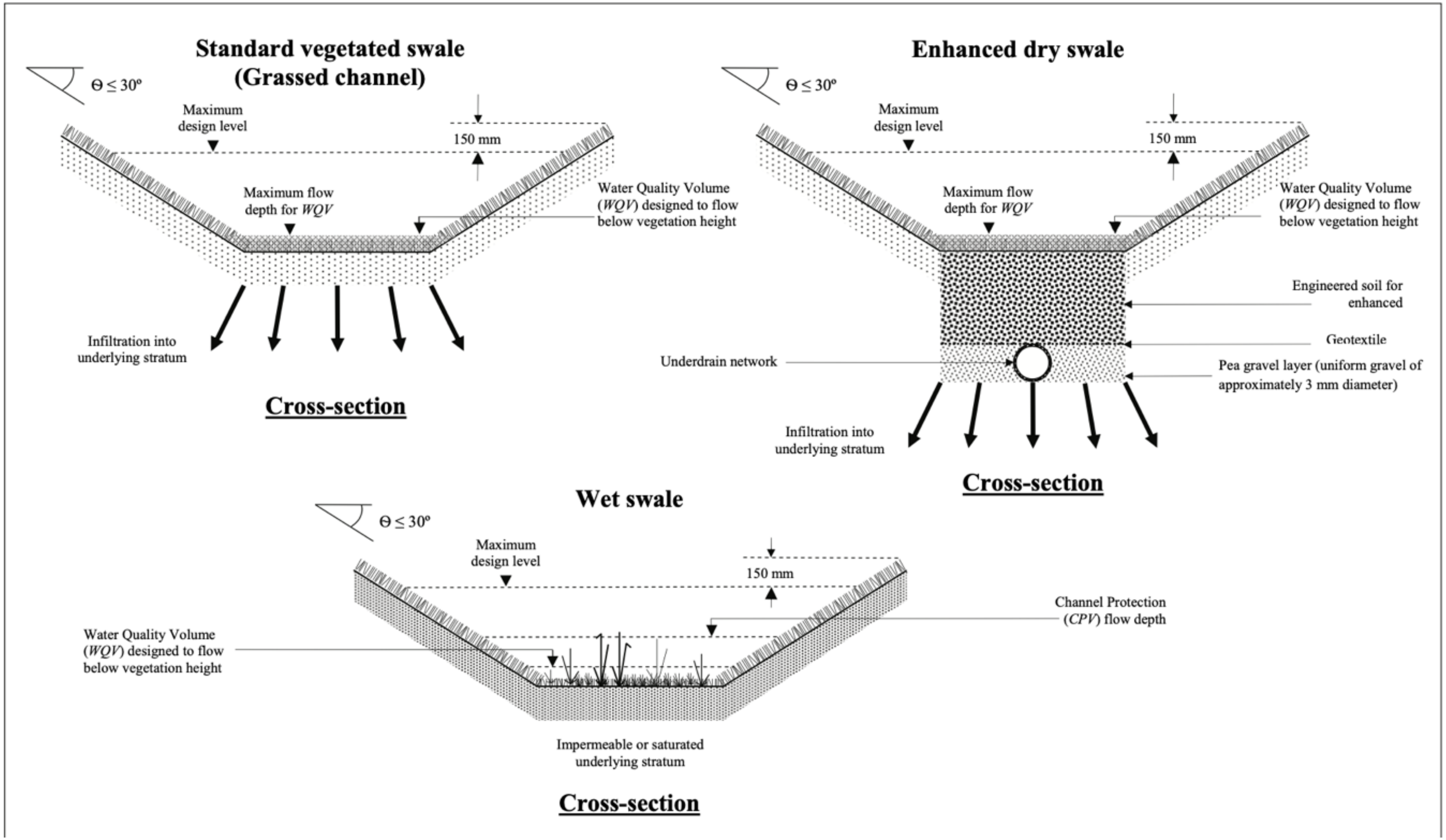

Figure 27. General design for swales. (Armitage, 2013)

4.2. Individual-level Conceptual Design

The conceptual design at the individual level (see Figure 32) showcases practical solutions for residents of informal settlements in Philippi, Cape Town to harness ecosystem services. Vertical gardens are integrated into walls to maximise limited space. These gardens use modular panels, hanging pots, or trellises where various plants can be grown. Suitable plants for vertical gardens in this context include herbs like basil, mint, and parsley; vegetables such as lettuce, spinach, and cherry tomatoes; and flowers like nasturtiums and marigolds. These plants are well-suited to the local climate and not only provide food but also contribute to improving air quality, reducing urban heat, and adding aesthetic value to the homes.

It is suggested that raised garden beds be placed near dwellings, to encourage local food production, ultimately improving food security and biodiversity. Vines that grow on home facades, such as Senecio tamoides (Canary Creeper) or Thunbergia alata (Black-eyed Susan), assist manage internal temperatures by providing shade and cooling through evapotranspiration.

These small-scale urban farms may improve local economies and job creation by providing fresh produce and proteins, thus enhancing food security and maybe creating work opportunities. They may improve human health by increasing social well-being and nutritional health, as well as providing physiological and psychological benefits. Educationally, they may teach children and adults about the importance of food and the environment while also imparting new skills. Urban farms can promote social cohesiveness, build community hubs, and reduce crime and vandalism (see Figure 33).

Soakaways (see section 4.2.1.) are incorporated as underground structures to manage rainwater runoff, reducing flooding risks and facilitating groundwater recharge for future use. To direct water from the rooftop into the soakaway, a drainage pipe should be installed, channelling the water underground. Furthermore, water filters with gravel and sand are proposed as a simple yet effective system for filtering rainwater and greywater, making it safer for domestic use and irrigation.

These individual-level interventions empower residents with practical means to contribute to sustainable water management and improve their living conditions by utilising natural processes and resources. The choice of plants is specifically tailored to thrive in the Mediterranean climate of Cape Town, ensuring their viability and effectiveness in this environment.

Regarding feasibility and implementation, the materials used in the conceptual design can be sourced from second-hand construction materials, which could be found around the informal settlements making them cost-effective. soakaways can be constructed using a DIY approach, utilising readily available materials such as crates from products, such as vegetables, milk, etc.

Similar solutions have been successful in other informal settlements, as mentioned in the theoretical framework. This includes Mtshini Wam settlement and Dar es Salaam. Additionally, local government can initiate programs aimed at improving local living conditions at the individual level. Such programs could provide financial support, resources, and training to residents, ensuring the sustainable implementation and maintenance of these bioretention systems. This collaborative approach, involving residents, local authorities, and possibly NGOs, can ensure the long-term success and scalability of these interventions.

Involving the community is crucial for the success of these interventions. Incentives such as offering free workshops on urban gardening and water management can encourage participation. The use of the Extended Public Works Program (EPWP) can be complemented with more localised initiatives such as community-led garden projects, where residents are given tools and resources to start their gardens. These initiatives have succeeded in places like the Khayelitsha community garden project, where residents received training and materials to grow their food, improving food security and community engagement.

By providing tangible benefits such as food, improved living conditions, and economic opportunities, these interventions can align with the immediate priorities of the residents. Collaborating with local NGOs and community leaders to facilitate these projects ensures that the interventions are grounded in the community's needs and are more likely to be embraced and sustained.

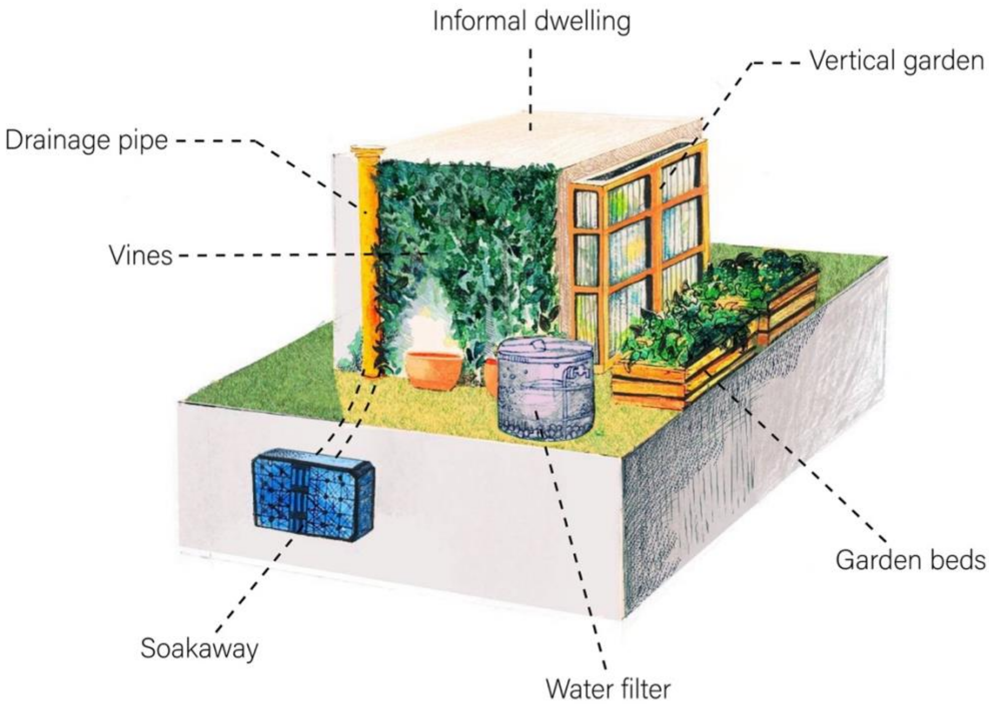

Figure 28. Conceptual design on an individual level. (Author and Filippova, 2024)

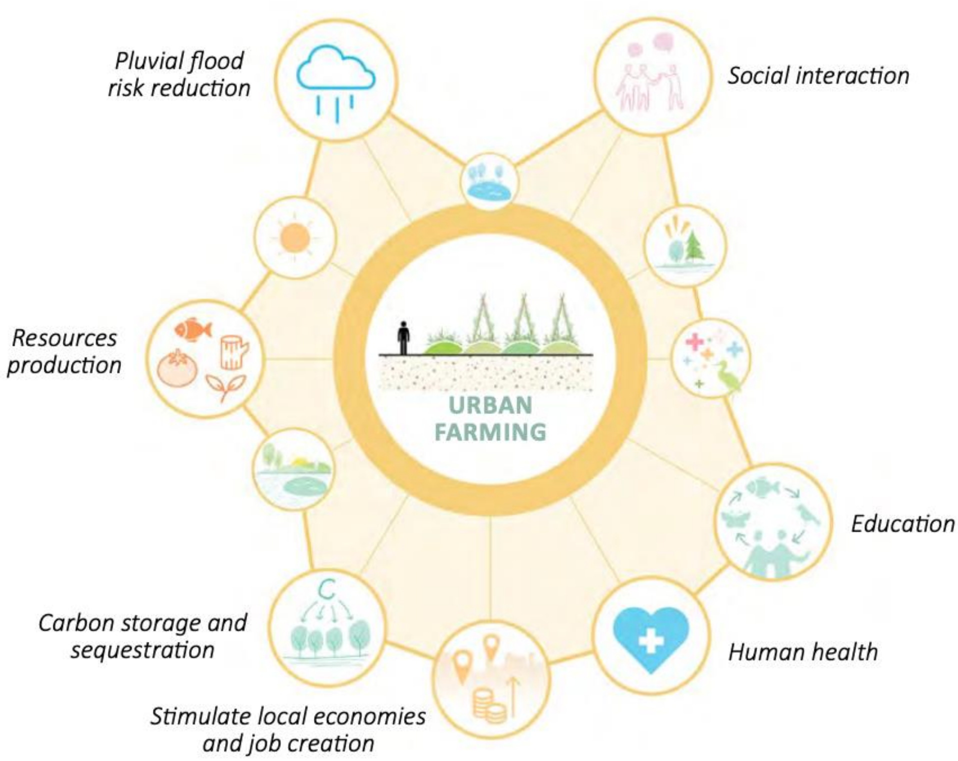

Figure 29. Sampling of important benefits that urban farming can provide to people. (World Bank, 2021)

4.2.1. Soakaways

Soakaways, which will be utilised for individual use in informal dwellings, are underground storage areas filled with coarse aggregate or porous materials that release stormwater into the surrounding soil (see Figure 34). They handle roof runoff from individual buildings and can be extended to manage larger areas such as highways or roads. Modular geo-cellular structures can enhance stormwater treatment and groundwater recharge. However, rapid water movement increases groundwater contamination risk, necessitating upstream stormwater pre-treatment, which will be provided with other NBS such as bioswale or trees. Pollutant removal processes of soakaways (see Appendix 1) beneficial for the study area include volatilisation, sedimentation, biodegradation, and filtration (Armitage et al., 2013).

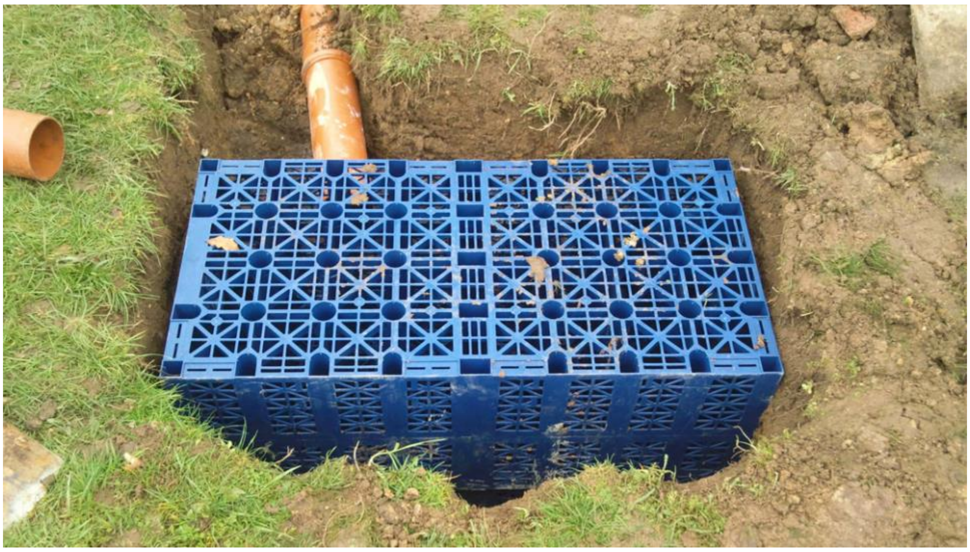

Figure 30. Soakaway. (www.southwestdrainageservices.com)

4.2.1.1. Advantages and Limitations

According to Armitage et al. (2013), soakaways offer several advantages. They have a long design lifespan when regular maintenance is performed. They significantly reduce both the volume and rate of runoff. Additionally, they are effective in removing particulate and suspended pollutants (see Appendix 3). However, these systems have several limitations. They are unsuitable for use near structural foundations or areas that affect drainage. However, in informal settlements where foundations are often lacking, this limitation is less relevant. Their application is limited to small connected areas, which is ideal for high-density informal settlements. They are ineffective on steep slopes, which is not the case for Brown Farms, or in unstable areas. In regions with fine silt and clay strata, sub-drain piping is necessary due to low infiltration rates. Additionally, sedimentation can reduce their storage capacity over time. Conversely, soakaways have the distinct advantage of not requiring connection to a larger infrastructure system, thereby avoiding additional costs.

4.2.1.2. General Design Guidelines

According to Armitage et al. (2013), the size of a soakaway depends on the porosity of the fill material and drains stormwater into the underlying soil or through perforated sub-drains. To prevent fine-grained material from entering, measures during construction and maintenance are necessary (see Figure 35). A geotextile liner is necessary for soils with fine grains. Soakaways should store the entire design storm volume and infiltrate at least half within 24 hours. They typically serve areas less than 1000 m² but can manage up to 100,000 m² with groups. Depth ranges from 1 to 4 meters, with residential ones usually less than 1.5 meters. They are typically constructed made making use of polyethylene or precast concrete rings, with diameters between 1 and 2.5 meters. To prevent groundwater contamination, soakaways should be 1.5 meters above the groundwater table.

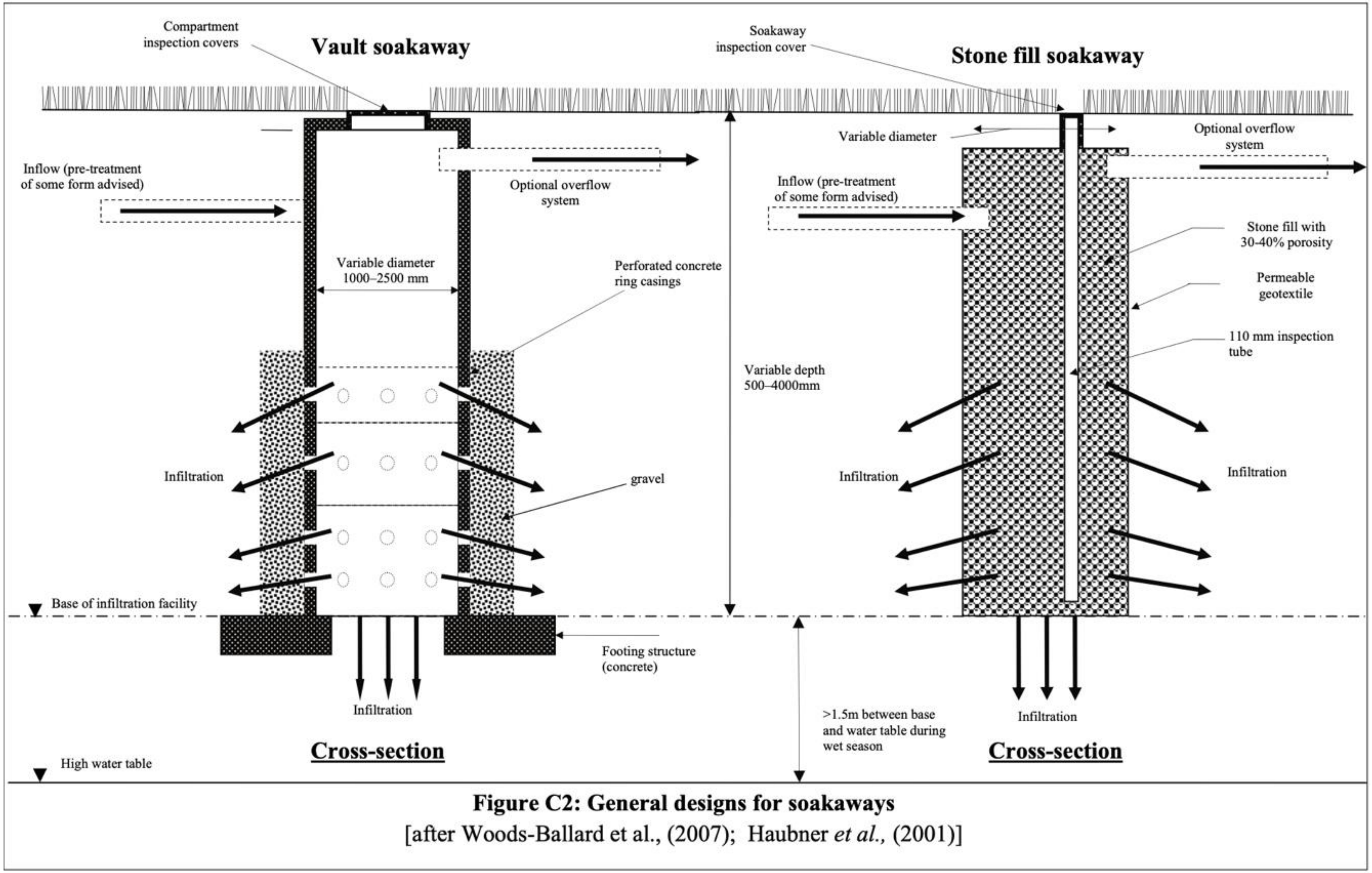

Figure 31. General design for soakaways. (Armitage, 2013)

Furthermore, the lifespan of soakaways depends on inspection and maintenance frequency. For example, in areas containing more fine-grained soils, frequent inspections could be necessary. Inspection openings facilitate maintenance, debris removal, and sediment build-up checks. Regular sweeping of adjacent areas prevents silt intrusion. Clogged soakaways may attract mosquitoes and produce foul odours, necessitating backfill replacement (Armitage et al., 2013).

4.3. Wetland Conceptual Design

The conceptual design for the wetland area in Brown Farms, Philippi, integrates two main elements: a shallow constructed wetland (see section 4.3.1.) and detention ponds (4.3.2.). This design showcases how such spaces could be transformed into multifunctional parks, providing both ecological benefits and community amenities tailored to the unique needs of the Philippi area.

The shallow-constructed wetland serves as a critical ecological feature, filtering stormwater runoff and enhancing biodiversity by creating habitats for local flora and fauna. This is particularly important in Philippi, where effective water management is crucial due to frequent flooding. The detention pond plays a key role in managing stormwater, reducing flood risks, and facilitating groundwater recharge in an area prone to heavy rainfall and poor drainage.

The design incorporates wooden paths and gazebos (see Figures 36, 37, 38, 39, 40), creating a recreational and educational space where locals can interact with nature. The wooden paths ensure easy access throughout the park, allowing residents to explore the wetland safely. Gazebos provide shaded spots for rest and community activities, making the park a hub for social interaction and environmental education.

By transforming this area into a park with educational and recreational features, the design not only addresses environmental resilience but also enhances the quality of life for residents of Brown Farms. This approach promotes sustainable urban planning, integrating ecological health, ES with community well-being, and offering a valuable green space for the people of Philippi to enjoy and learn from.

Figure 32.. Wetland 1, 2 design, aerial view. (Author's own)

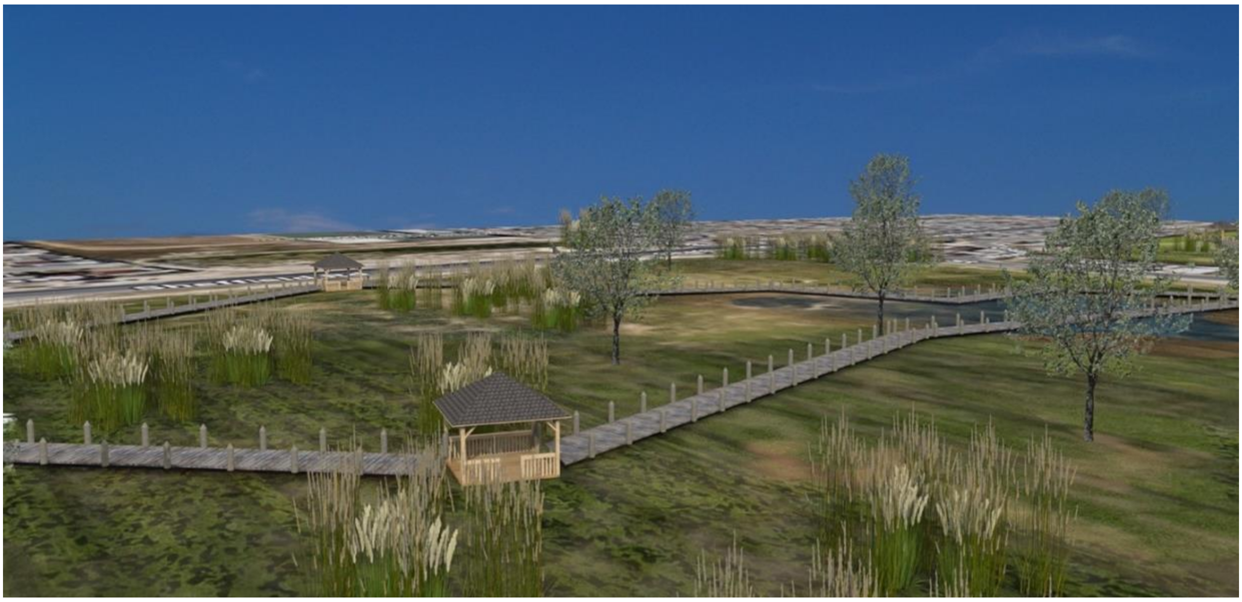

Figure 33. Design render for Wetland 2. (Author's own)

Figure 34. Design render for Wetland 1. (Author's own)

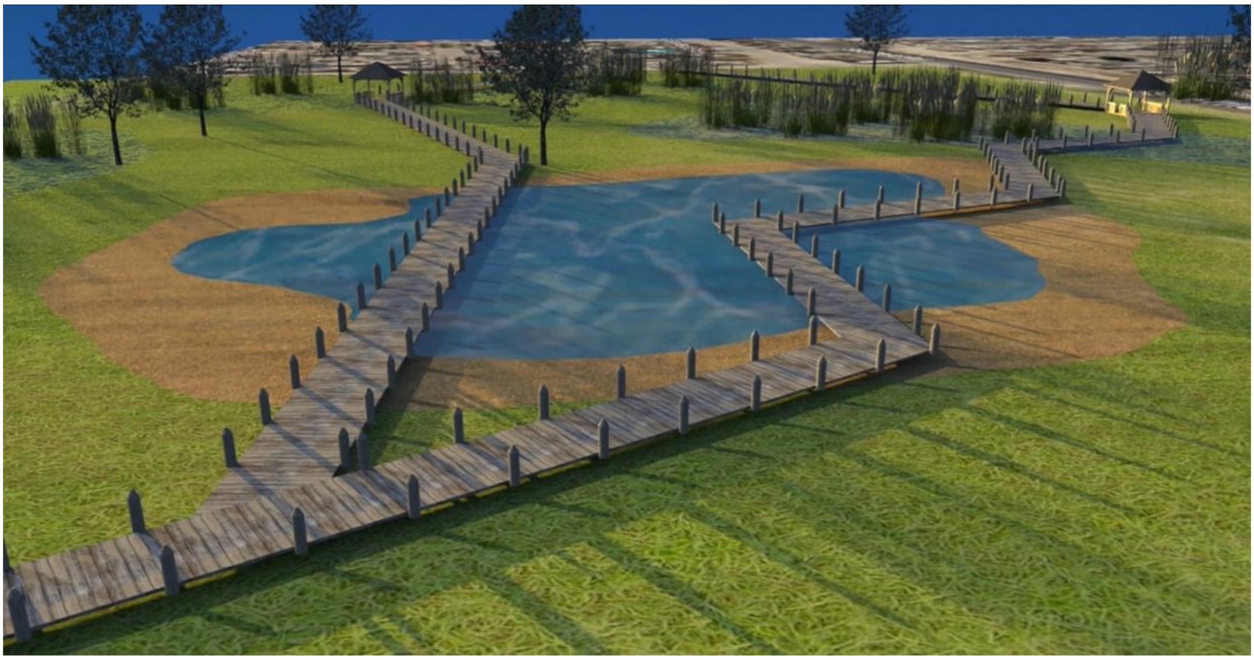

Figure 35. Design render #2 for Wetland 1. (Author's own)

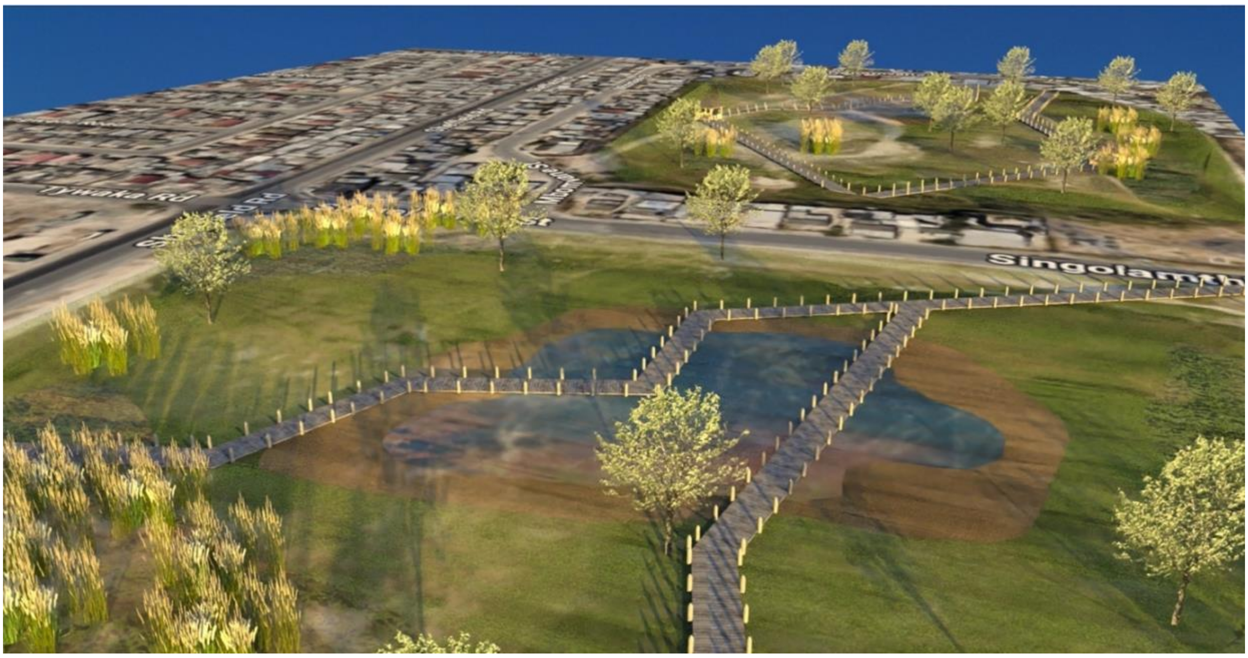

Figure 36. Design render for wetlands 1 and 2. (Author's own)

4.3.1. Constructed Wetland

Constructed wetlands are man-made systems designed to mimic natural wetlands, improving their efficiency, functionality, and aesthetics. In the study area, existing wetlands are in poor condition and require such enhancements. These systems cater to catchments larger than 10 hectares, like the study area, and effectively reduce stormwater flood peaks while treating runoff from residential zones.

For estimating water storage in constructed shallow wetlands, the formula used in the research by Gleason et al. (2007) is employed. This surface storage formula, V = A x D, includes key elements:
Surface Area (A): The wetland's area in square meters (m^2).
Average Depth (D): The average water depth in meters (m).

The area size for Wetland 1 (see Figure 22) is around 39,000 m2 and for Wetland 2 – 31,000 m2 (Google Earth Pro, 2024). The surface layer mainly consists of Grey regic sands with less than 15% clay content, with depths ranging from 0.45 m to less than 0.75 m (see section 3.5.3.). An average of 0.6m will be taken for the calculation.

The calculation for Wetland 1 follows: V = 39,000 x 0,6
V = 23,400 m3

The calculation for Wetland 2 follows: V = 31,000 x 0,6
V = 18,600 m3

Moreover, wetlands will provide lively habitats for animals and visual appeal for recreational purposes. Pollutant removal in artificial wetlands is aided by sedimentation, fine particle filtration, and biological nutrient and pathogen elimination (Armitage, 2013). However, constructed wetlands may need supplementary water during dry periods to support dense vegetation. In addition, pollution control characteristics are detailed in Appendix 1.

4.3.1.1. Advantages and Limitations

According to Armitage et al. (2013), constructed wetlands offer several advantages, which will significantly mitigate climate change impacts and improve living conditions in the study area. They have a high efficiency in removing pollutants (see Appendix 1) and can enhance the aesthetics of properties. Additionally, they have the potential to produce food in small aquaculture wetlands and can be retrofitted into existing flood control basins. However, Armitage et al. (2013) note that these systems have limitations, such as potentially attracting mosquitoes and requiring relatively flat land. The study area, which will include a constructed shallow wetland, addresses these limitations and is discussed in further sections. Bird faeces can increase phosphorus levels in the water, and clean water can pick up pathogens from sediment. High inflows can damage the wetland, and during dry periods, supplementary water may be required. Additionally, wind can re-suspend solids in shallow water.

4.3.1.2. General Design Guidelines

Successful wetland implementation in Brown Farms, Philippi, requires careful integration into local landscape design and management (see Figure 41). Ensuring public and maintenance access is crucial, and involving local interest groups is encouraged. Installing trash racks helps prevent litter accumulation. Effective pollutant removal is achieved by regulating water levels and designing meandering flows. Using indigenous vegetation is recommended to protect biodiversity and enhance pollutant removal processes (Armitage, 2013). According to Armitage et al. (2013), vegetation should rapidly establish, be low in disease or weed risk, suit the local climate, tolerate waterlogged conditions, and effectively remove pollutants. These considerations ensure the vegetation's effectiveness and sustainability in Brown Farms.

Furthermore, constructed wetlands require frequent inspections and maintenance, especially for sediment and debris removal. Healthy vegetation and adequate flow conditions are essential. Vegetation may need periodic harvesting, and invasive species should be controlled. Mosquito breeding should be managed naturally, and nutrient reintroduction from plant die-offs must be monitored (Armitage et al., 2013).

Moreover, according to Armitage et al. (2013), there are several technology derivatives in stormwater management. Pocket wetlands are small wetlands that serve areas up to 40,000 m² and require a baseflow to support the ecosystem. Submerged gravel wetlands use rock or gravel to keep water below the surface, promoting nitrogen removal through anaerobic conditions. However, the optimal choice for the conceptual design, considering the climatic conditions, is shallow wetlands. These wetlands are designed to manage and treat large volumes of stormwater by using plants that can withstand both wet and dry conditions. This design helps minimise standing water, thereby reducing mosquito breeding as well as unpleasant odours.

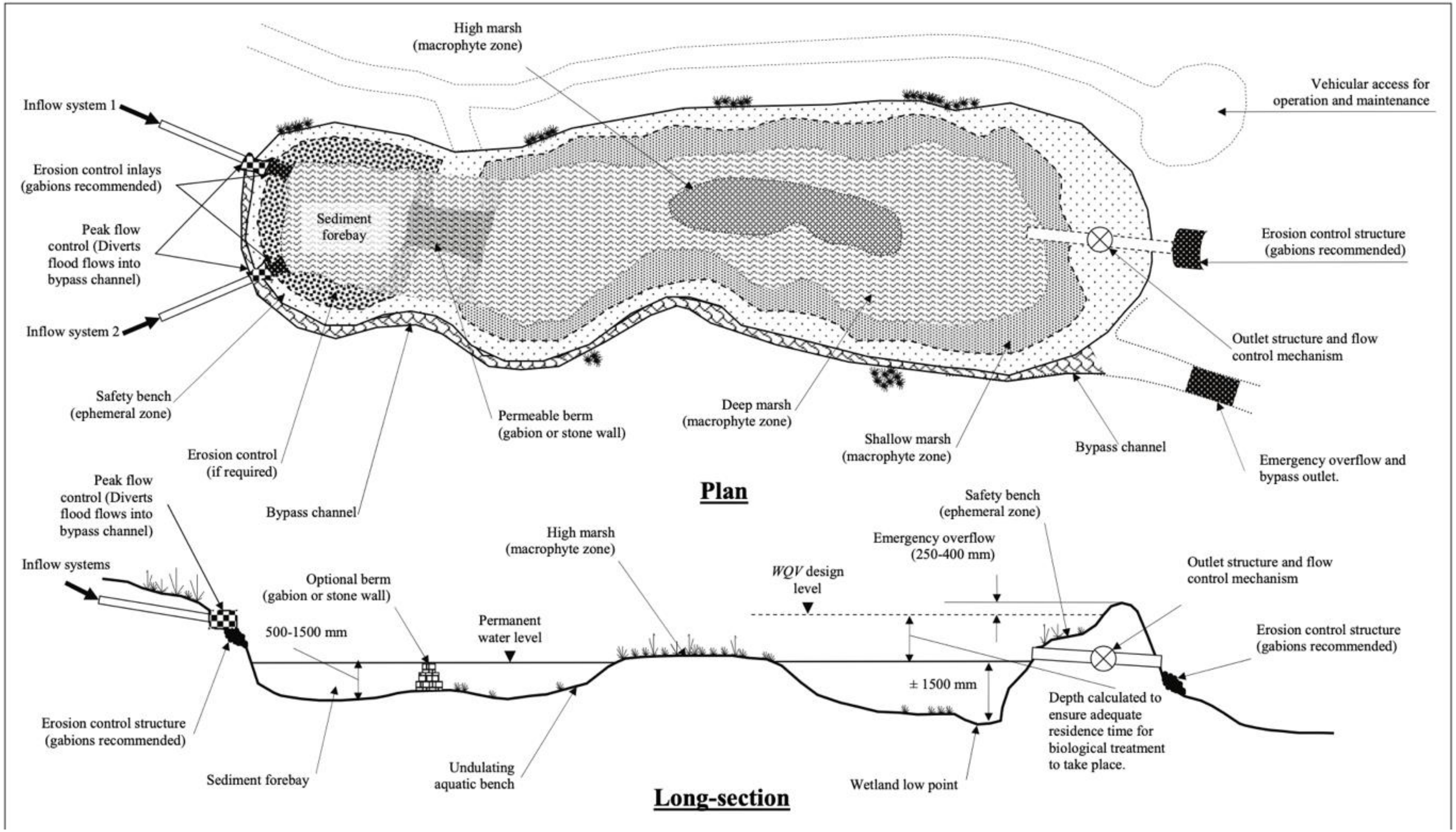

Figure 37. General design for constructed wetlands. (Armitage, 2013)

4.3.2. Detention Ponds

Detention ponds are temporary storage facilities for stormwater runoff, designed to manage flow by allowing water to infiltrate the soil or drain into downstream watercourses. Typically dry, they regulate flow and pollutant removal (see Appendix 1) through sedimentation. Larger ponds are more effective at removing pollutants. Detention ponds are best for small, frequent storms and require adequate space (Armitage, 2013). This will be a valuable addition to the planned constructed shallow wetlands in the study area, as it will provide an additional method to accumulate and drain stormwater, functioning like a siphon in shower drainage systems.

4.3.2.1. Advantages and Limitations

According to Armitage et al. (2013), detention ponds offer several advantages that could benefit the study area. These ponds temporarily store large volumes of stormwater, helping to reduce downstream flood peaks. Inexpensive to construct and maintain, detention ponds can also serve as recreational areas during dry seasons. Additionally, they enhance property aesthetics and are considered safer than wet ponds. However, these systems have several limitations. They are ineffective at removing dissolved pollutants and fine materials, and they are less effective at eliminating pathogens. Detention ponds are prone to siltation and can become swampy after rainfall. Furthermore, they require large areas, occupy valuable land, and are unsuitable for areas with high water tables due to the risk of groundwater contamination. The conceptual wetland design acknowledges these limitations and addresses them by combining constructed shallow wetlands with detention ponds. This approach aims to minimise unwanted effects, while enhancing the system's overall effectiveness.

4.3.2.2. General Design Guidelines

Designed for the study area, detention ponds must store water for 24-72 hours while ensuring safety, preventing erosion, and incorporating features such as inlet structures and emergency spillways (see Figure 42). Drought-tolerant vegetation is recommended for arid regions. They can double as sports facilities. Pre-treatment systems or sediment traps at the inlet can enhance pollutant removal. Ponds should be at least 2% of the contributing impervious area. For safety, ponds should be fenced and able to drain quickly if needed (Armitage, 2013). Precautions for ponds can include providing gentler side slopes, such as less than a 1 in 3 gradient, creating shallower depths around the edges, and strategically placing vegetation to act as a barrier, helping prevent unsupervised children from accessing the water.

Furthermore, Proper maintenance is essential for performance, including regular inspections, especially after major storms. Vegetation management and periodic de-silting (every 5 years) are necessary to maintain functionality and aesthetics (Armitage et al., 2013).

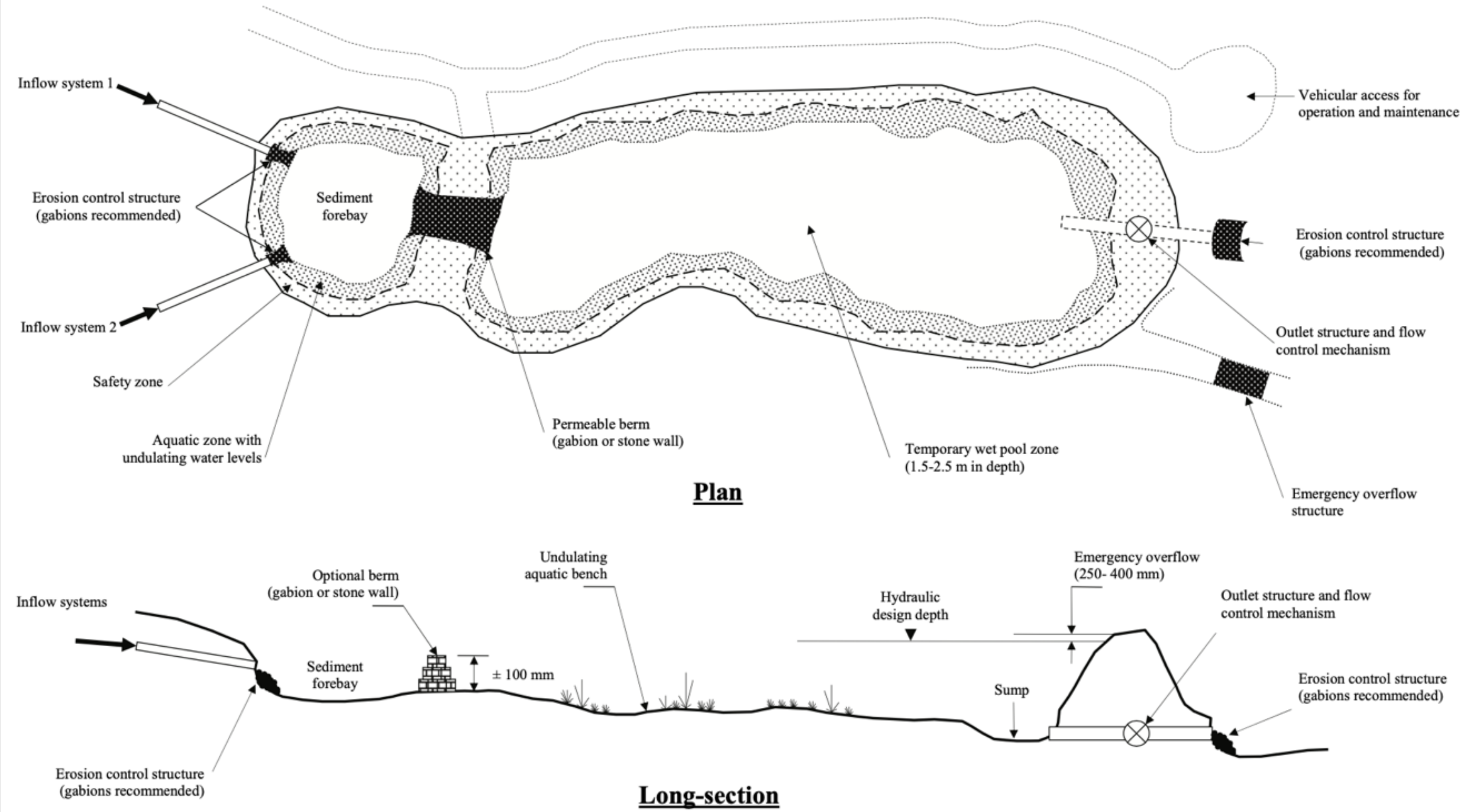

Figure C9: General design for detention ponds

[after Wilson *et al.,* (2004); Woods-Ballard *et al.,* (2007) and Others]

Figure 38. General design for detention ponds. (Armitage et al., 2013)

5. Discussion

Cape Town, particularly community members of informal settlements such as Philippi in the Cape Flats area such as Brown Farms, face significant vulnerabilities due to climate change and rapid urbanisation. Issues such as increased flooding, extreme weather events, and water scarcity are exacerbated by the region's Mediterranean climate. The informal settlements in Philippi highlight the socio-economic challenges prevalent in many urban areas of the Global South, where inadequate infrastructure, housing, and basic services leave residents especially vulnerable to environmental stresses. According to the extensive literature review and case study development, innovative, cost-effective solutions like NBS seem to offer feasible and sustainable alternatives to traditional infrastructure. NBS in Brown Farms have significant potential to address urban resilience challenges in resource-constrained settings. By leveraging natural processes NBS can provide multiple ES benefits, including stormwater management, flood risk reduction, enhanced biodiversity and temperature regulation. Their adaptability and low effort make them ideal for informal settlements where traditional infrastructure solutions may be prohibitively expensive.

However, implementing NBS must be tailored to the specific environmental, social, and economic contexts of the area, as generic solutions are often inadequate for the unique challenges of informal settlements. Furthermore, community involvement (see section 2.3.1, 2.3.2.) is critical for the success and sustainability of urban solutions in these areas. Local knowledge and participation ensure that NBS projects are culturally appropriate and widely accepted, reflecting a broader trend in urban planning where community-driven approaches are essential for addressing complex socio-environmental challenges.

Moreover, despite their potential, practical implementation of NBS encounters challenges like governance, funding, and the technical capacity of local institutions (see section 2.3.3.), requiring strong institutional frameworks and sufficient resources for effective deployment. At the individual level, the viability of this solution may be limited, as disadvantaged residents often prioritise essential expenses like food over gardens, which are considered a luxury. From a government perspective, funds are more likely to be directed towards essential services such as running water and flushing toilets. NGOs may be better suited to manage these types of programs.

The research validates the conceptual model's premise that integrating NBS, SES, and SuDS under the umbrella of ecosystem services may impact vulnerable communities positively. By enhancing water regulation, flood mitigation, and biodiversity support, these ecosystem services contribute to the ultimate goal of urban resilience, providing a sustainable and adaptable solution to the environmental and socio-economic challenges faced by communities like Philippi.

Discussing the proposed conceptual design, despite its robust foundation provided by handbooks and guidelines by the World Bank (2021) and Armitage et al. (2013), a significant limitation remains. The strategies have not yet been empirically tested in Philippi. While the design aligns well with documented successes elsewhere, its effectiveness and practical challenges in this specific environment are speculative. Pilot projects and ongoing monitoring are essential to validate these designs and adapt them to real-world conditions. Empirical data from pilot projects would provide insights into the performance of these solutions in Philippi's unique context.

Lastly, the theories used in this study are largely valid and useful, but there are areas where adjustments could enhance their applicability. Explicit strategies for sustained community engagement and education should be incorporated, such as continuous workshops and hands-on activities related to NBS maintenance to mitigate risks of lack of ownership. Moreover, integrating economic incentives for residents, like hiring locals for NBS maintenance, provides job opportunities and ensures regular upkeep, addressing both environmental and socio-economic challenges. Emphasising adaptive management within the theoretical frameworks is crucial, with continuous monitoring and flexibility to adjust strategies based on real-time data ensuring that NBS remain effective under changing conditions.

6. Conclusion

Amid climate challenges, integrating NBS into urban planning has become a promising strategy to enhance flood resilience and promote sustainable development. This research on the Philippi informal settlement aimed to evaluate the feasibility and practical implementation of NBS in a complex urban environment, addressing gaps due to a lack of detailed case studies and design solutions in policy documents. The achieved objectives included analysing existing plans and policies, reviewing NBS literature, critically assessing NBS applications in informal settlements, and proposing practical, scalable design solutions tailored to local conditions.

Through an in-depth case study of Philippi in Cape Town and a review of literature and policy reports, this research provides valuable insights into the critical role of NBS and answers the research questions. The study's hypothesis—that despite the potential benefits of NBS, their implementation in informal settlements may not significantly enhance urban water resilience or community well-being due to prevailing socio-economic, infrastructural, and environmental challenges—could not be fully supported due to a lack of empirical evidence. However, arguments based on academic sources, previous research, and personal impressions suggest that the hypothesis is likely valid.

Addressing the main research questions, the Philippi informal settlement faces significant water management and environmental challenges due to its flat, low-lying geography, high water table, and inadequate drainage infrastructure, which lead to frequent flooding and contamination of the Cape Flats Aquifer. Socio-economic vulnerabilities further exacerbate these issues. However, NBS such as wetland restoration, bio-retention areas, and permeable surfaces can effectively manage stormwater and enhance urban resilience.

To address these challenges, proposed design solutions include street-level interventions like permeable pavements and bioretention areas with bioswales to reduce runoff, promote groundwater recharge, and enhance biodiversity. Individual-level interventions, such as vertical gardens and raised garden beds, improve water utilisation and local food production. Transforming open areas into multifunctional parks with constructed wetlands and detention ponds provides recreational spaces and boosts biodiversity. Integrating NBS with existing infrastructure further enhances resilience.

Community involvement in planning and implementing NBS is essential for their effectiveness and sustainability. Educational workshops and campaigns can reduce pollution and misuse while engaging residents in building and maintaining NBS fosters a sense of ownership and responsibility. Municipal, provincial, and national governments, along with community programs, play significant roles in facilitating partnerships, developing skills, and sustaining adaptation measures for long-term perspective.

Returning to the main research question, NBS can be viable and effectively implemented in the Philippi informal settlement to improve urban water resilience and environmental sustainability. This requires a comprehensive approach involving community participation, tailored design solutions, integration with existing infrastructure, and careful planning for maintenance. Raising awareness and educating the community about the benefits of NBS fosters support and proper maintenance to avoid vandalism. Integrating NBS into broader urban planning and policy frameworks ensures a holistic approach to improving resilience and sustainability. By adopting these strategies, Philippi can manage its water-related challenges and serve as a model for other informal settlements.

One of the recommendations, the study might highlight is that there is a need for risk-informed local plans to reduce disaster risk in CoCT. Collaborative governance is crucial in the planning and implementation processes for flood risk reduction, integrating different actors to work towards a common agenda. Prioritising cooperative relationships between planning, flood risk management, and sustainable water and infrastructure development can enhance clarity, thoroughness, and efficiency. An integrated approach to building adaptive capacity to flood risk is essential in flood-prone areas like Philippi.

Future research could benefit from different approaches to enhance outcomes. Firstly, securing more comprehensive and recent environmental data through partnerships with local environmental agencies or universities could have provided a more precise basis for analysis. Additionally, incorporating more advanced GIS and remote sensing technologies early in the research would have improved the accuracy of spatial data and the identification of specific flood-prone areas.

Secondly, prioritising establishing structured and ongoing communication with community members and stakeholders from the outset via local organisations or educational institutions is essential to provide validity for conceptual design options. Regular workshops and feedback sessions would ensure continuous and inclusive participation.

Lastly, expanding the scope of the literature review to include more case studies from other regions with similar socio-economic and environmental conditions could have provided additional insights and comparative perspectives, strengthening the theoretical framework and practical recommendations.

Concluding, this research contributes to urban resilience theory by providing practical insights and design solutions addressing environmental and socio-economic challenges in informal settlements.

7. Reflection

Throughout this research, several aspects went well, contributing significantly to the overall success of the thesis. The mixed-methods approach proved effective in capturing a comprehensive understanding of the challenges and opportunities associated with integrating NBS in informal settlements. The combination of qualitative insights with quantitative data provided a robust foundation for the case study.

However, some challenges emerged during the research. One significant issue was the limited availability of up-to-date and detailed environmental data specific to informal settlements. This gap sometimes necessitated reliance on older data or broader regional information, which might not fully capture the unique conditions in Philippi.

The outcomes of the research appear convincing, particularly in demonstrating the potential of NBS to address urban resilience challenges in informal settlements. The findings align well with existing literature and case studies, underscoring the benefits of NBS. However, the proposed design solutions are not well-supported by empirical data and community feedback, lacking credibility in their feasibility and effectiveness.

I should highlight that AI such as ChatGPT was employed as an assistance tool while writing this thesis. In several cases, I utilised it as a paraphrasing tool, with prompts such as 'Rewrite', 'Make it cohesive', 'Rephrase the text', and 'Summarise the text'. Also, in the early stages of the research, I used prompts like 'Define vulnerable locations in Cape Town' and 'Tell me about NBS in informal settlements?' as inspiration to create the thesis. The generated material was thoroughly and critically evaluated for factual accuracy and adjusted to be as objective as possible.

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Appendix

Appendix 1 – Pollutant Removal Capacities

Measured pollutant removal capacities of selected SuDS options and technologies
(after Debo & Reese, 2003; Minton, 2002; NCDWQ, 2007; Wilson *et al.*, 2004, Woods-Ballard *et al.*, 2007)

Option / Technology	Pollutant Removal (%)					
	TSS	Hydro-carbons	TP	TN	Faecal Coli Forms	Heavy Metals
Source controls						
Green roofs	60-95	-	-	-	-	60-90
Sand filters	80-90	50-80	50-80	25-40	40-50	50-80
Underground sand filters	75-90	-	30-60	30-50	40-70	40-80
Surface sand filters	80-90	-	50-60	30-40	-	-
Filter drains	50-85	30-70	-	-	-	50-80
Soakaways	70-80	-	60-80	25-60	60-90	60-90
Oil and grit separators	0-40	40-90	0-5	0-5	-	-
Modular geocellular structures	PS	PS	PS	PS	PS	PS
Stormwater collection and reuse	PS	PS	PS	PS	PS	PS
Local controls						
Bioretention areas	50-80	50-80	50-60	40-50	-	50-90
Filter strips	50-85	70-90	10-20	10-20	-	25-40
Infiltration trenches	70-80	-	60-80	25-60	60-90	60-90
Permeable pavements	60-95	70-90	50-80	65-80	-	60-95
Swales	60-90	70-90	25-80	30-90	-	40-90
Enhanced dry swales	70-90	70-90	30-80	50-90	-	80-90
Wet swales	60-80	70-90	25-35	30-40	-	40-70
Vegetated buffers *	50-85	70-90	10-20	10-20	-	25-40
Regional controls						
Constructed wetlands	80-90	50-80	30-40	30-60	50-70	50-60
Extended detention shallow wetland	60-70	-	30-40	50-60	-	-
Pocket wetland *	80-90	50-80	30-40	30-60	50-70	50-60
Submerged gravel wetland	80-90	-	60-70	10-20	-	-
Detention ponds *	45-90	30-60	20-70	20-60	50-70	40-90
Extended detention ponds	65-90	30-60	20-50	20-30	50-70	40-90
Infiltration basins	45-75	-	60-70	55-60	-	85-90
Retention ponds	75-90	30-60	30-50	30-50	50-70	50-80
Floating islands	-	-	-	-	-	-

PS - Product Specific; TSS - Total Suspended Solids; TP - Total Phosphorous; TN - Total Nitrogen
* Estimated values based on similar SuDS options

Appendix 2 - Runoff rates and volumes

A rapid evaluation of the anticipated runoff rates from small catchments, typically those less than 15 km², can be achieved using the Rational Method (Armitage, 2013):

$$Q = \frac{C\,i\,A}{3.6}$$

Where:

Q = design peak runoff rate (m^3/s)
C = runoff coefficient (0 – 1)
i = rainfall intensity (mm/hr)
A = catchment area (km^2)

The runoff volume may be estimated from (Woods-Ballard *et al.*, 2007):

$$RV = PR \times A \times d$$

Where:

RV = runoff volume (m^3)
PR = coefficient of runoff (0 – 1)
A = catchment area (km^2)
d = rainfall depth (mm)

Appendix 3: Stormwater pollutants (Armitage, 2013)

Pollutant Group	Pollutant	Source	Impacts
Nutrients	Nitrogen & Phosphorus	Fertilisers	Excessive nutrients result in eutrophication. They are commonly associated with algal plumes, reduced clarity resulting in decreased bio-diversity.
		Animal waste	
		Organic matter	
		Septic tanks	
Sediments	Suspended & settable solids	Erosion of landscaping	Increased turbidity, sedimentation, smothering of aquatic plant and animal life.
		Erosion of construction sites	
Organic Material	Plant litter	Landscaping	Increased nutrients & sediment.
Pathogens	Bacteria, viruses and protozoa	Failing sewer/sewage systems	Public health risk. Contaminated recreational areas. Threat to downstream irrigation water and edible crops. Decreased economic value of natural recreational areas.
		Animal waste	
Hydrocarbons	Oils & grease & others	Motor vehicle emissions and wear	
		Industrial processes & waste	
Metals	Lead, copper, zinc and others	Motor vehicle wear	
		Industrial leaks	
		Construction materials-galvanised	
Toxic chemicals	Pesticides and herbicides	Agriculture	
		Landscaping	
Solids	Debris & rubbish	Littering	Threat to wildlife. Aesthetic appeal decreased
		Dumping	

Appendix 4. Typical soil texture permeability coefficients (Armitage, 2013)

Soil texture	Permeability coefficients (mm/h)	Adequacy
Gravel	10,000 – 1,000,000	Generally inadequate treatment
Sand	100 – 100000	
Loamy sand	10 – 1000	Yes
Sandy loam	50 – 500	
Loam	1 – 100	
Silt loam	0.5 – 50	
Sandy clay loam	1 – 100	
Silty clay loam	0.05 – 5	No
Clay	< 0.1	
Unstratified soil	0.01 – 10	
Rock	0.01 – 100	