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Discovering Johannesburg's Potential as a Water Sensitive City

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Abstract

At the intersection of issues of water scarcity and rapid urbanisation is the need to investigate sustainable urban water management practices in today's cities. This is especially important with the undeniable impact of climate change adding to its complexity. Johannesburg is a prime example of a city facing a myriad of challenges regarding water and is therefore the focus of the thesis. This research focuses on how the city of Johannesburg can pave its way into becoming a Water Sensitive City (WSC)- an aspirational vision of a city that integrates sustainable urban water management practices. To discover this, case study research on Johannesburg is undertaken by exploring the challenges and opportunities in relation to water demand and supply in the city. A few challenges include pollution of water and issues relating to the dependency on surface water. Additionally, an Urban Water Mass Balance (UWMB) analysis was undertaken to explore the potential of alternative water service options in a city that relies predominantly on surface water. It was found that rainwater harvesting had the highest potential to replace the existing centralized system. Based on the results of the case study research and the UWMB analysis a program was proposed to assist Johannesburg's transition into a WSC. The proposal includes proactive recommendations relating to public participation and the protection of the environment.

Keywords: Water Sensitive City, sustainable urban water management, Urban Water Mass Balance, Johannesburg

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List of Acronyms

AMD	Acid Mine Drainage
CMA	Catchment Management Agency
CMF	Catchment Management Forum
COGTA	Department of Cooperative Governance and Traditional Affairs
DALRRD	Department of Agriculture and Land Reform and Rural Development
DHS	Department of Human Settlements
DMRE	Department of Mineral Resources and Energy
DWS	Department of Water and Sanitation
EMP	Environmental Management Plan
GDP	Gross Domestic Product
GI	Green Infrastructure
GPG	Gauteng Provincial Government
IUWSM	Integrated Urban Water Systems Modelling
IVRS	Integrated Vaal River System
LHWP	Lesotho Highlands Water Project
MFA	Material Flow Analysis
MIASA	Mining Industry Association of South Africa
NAFU	National Agricultural Farmers Union
NEMA	National Environmental Management Act
NT	National Treasury
NWA	National Water Act
NWSA	New Water Services Act
SANRAL	South African National Roads Agency Limited
SDF	Spatial Development Framework
SOC	State-Owned-Company
SOE	State-Owned Enterprise
SPLUMA	Spatial Planning and Land Use Management Act
SuDs	Sustainable Urban Drainage Systems
SUWM	Sustainable Urban Water Management
TCTA	Trans-Caledon Tunnel Authority

UWMB	Urban Water Mass Balance
VIP	Ventilated Improvement Pit
WDM	Water Demand Management
WSA	Water Service Authority
WSUD	Water Sensitive Urban Design
WSC	Water Sensitive City
WSP	Water Service Provider
WSS	Water Sensitive Settlements
WWTW	Waste Water Treatment Works
WRC	Water Research Commission

Chapter 1: Introduction

1.1. Background

The proportion of inhabitants globally that will occupy urban areas is expected to rise to 68% in 2050 (United Nations, 2018). This rapid growth in urbanisation has the negative effect of creating an undue strain on natural resources, specifically fresh water (Padowski and Gorelick, 2014) as it has been shown that the urban water consumption (and hence demand) has also increased by five-fold since 1950 (Richter et al. ,2013, p.336, Shiklomanov, 2000). The impact of climate change on the water security (Cook and Bakker, 2012) as well as competing demands from the irrigation and industrial sector (Padowski and Gorelick, 2014) has further compounded the challenges towards creating a sustainable balance between supply and demand. If supply and demand water challenges are not appropriately resolved, scenarios such as the "Day Zero" crisis in which the potable supply in one of South Africa's second most populated cities was under a significant enough threat to warrant severe water restrictions at an unprecedented level of 87 litres per household per day during the 2015-2018 drought (Booysen et al., 2019, p. 6) can occur. South Africa is projected to exceed its water demand and supply gap by up to 17% in 2030 and major cities such as Johannesburg will experience a gap of over 20% (Reddick and Kruger, 2019, p.8).

This therefore begets the importance of the sustainable use of water in today's cities in order to rise up to the water challenges faced across the globe. The United Nations' agenda containing the Sustainable Development Goals (SDGs) establishes that goal 6 is one where "availability and sustainable management of water and sanitation for all" is ensured (United Nations, 2015, p. 20). To succeed in achieving this goal, the transition to sustainable urban water management practices from a traditional water paradigm which focuses on supply only in cities is essential.

The conventional approach to managing the urban water cycle is commonly used in many countries around the world. The concept of the urban water cycle is defined as the combination of both the components of the natural water cycle as well as the anthropogenic factors that have emerged due to urbanisation such as stormwater and wastewater (Marsalek et al, 2017). The conventional approach is focused on the distribution of surface water or groundwater which is treated to reach acceptable requirements for potable use and then reticulated to users with a diverse set of water requirements. The wastewater is collected, treated and discharged back into the environment. The model relies heavily on bulk infrastructure (pipelines, treatment plants, dams) and the expansion of said infrastructure as the demand of water increases

(OECD,2015; McCallum and Boulot, 2015). Furthermore, the factors increasing water demand such as population growth and increased urbanisation, also results in increased development due to urbanisation which correspondingly leads to an increased need in paving for buildings and roads resulting in a reduction in permeable and freely draining surfaces as well as the destruction of vegetation cover which reduces the utilisation of valuable stormwater runoff. An impeded infiltration of stormwater into the underlying aquifers generates larger volumes of surface runoff that can lead to the creation of flood prone regions in low-lying areas (Poleto and Tassi, 2012). This also increases the rate of erosion which directly affects transportation and deposition of sediments. Urban stormwater, therefore, represents an environmental flow problem which can cause deterioration of waterways which in turn leads to a loss of biodiversity (Walsh et al, 2012). The resulting effect is a change in the water cycle which directly affects residents through its negative impact.

The complexity of moving away from the conventional approach and striving towards sustainable urban water management, while simultaneously ensuring the provision of water and sanitation services is immense and requires robust management practices at all levels of government. Common barriers towards sustainable urban water management include institutional limitations such as uncoordinated and irregulated frameworks, lack of clear political and community support and an absence of a long term, strategic approach or vision (Brown and Farrelly, 2009).

As a solution towards addressing the myriad of challenges facing sustainable urban water management, the conceptual framework of a Water Sensitive City (WSC) was developed. This framework is built on creating resiliency within cities and promoting principles of sustainability by focusing on the diversification of water resources, the purveyance of ecosystem services and ensuring communities and other stakeholders as well as governing institutions supports an approach that is rooted in sustainability (Wong and Brown, 2009). The benefits of the WSC framework is that it approaches urban water with an interdisciplinary and holistic lens in an effort to integrate best practices in urban water management and urban design with institutional and social reform (Wong and Brown, 2009).

1.2. Research Focus

Currently, there exists no “example in the world of a Water Sensitive City” (Wong and Brown, 2009, p. 674) with countries such as Australia and Singapore having successfully adapted some practices that generally characterise water sensitive cities and are shifting their existing urban water paradigm (Wong and Brown, 2009). Despite both countries being developed nations, however, and there exists a need to explore at greater detail the application of WSC principles in developing nations (Bichai and Flamini, 2018). Studies from Sholihah et al., (2017) and Fisher-Jeffes et al. (2014) emphasise the need for the water sensitive framework to additionally consider the local scale of developing nations such as Indonesia and South Africa and their respective socio-economic challenges and adapt the WSC model accordingly. The research insights that were borne post the Cape Town "Day Zero" crisis highlighted the importance of planning for water sensitive regions in the country (Taing et al., 2019) and additionally spawned the New Water Strategy that aims to create a WSC by 2040 (City of Cape Town, 2020). A South African city that does not have a clear strategic program to shift towards becoming a WSC is Johannesburg. This thesis will therefore focus on how Johannesburg can transition into a water sensitive city. This can potentially provide a frame of reference and a useful comparison to other cities in developing nations.

Johannesburg is South Africa's most populated metropolitan city (South African Cities Network, 2016, p.344). It is also a spatially fragmented city due to its long history with racial segregation that has morphed into socio-economic segregation. The city is uniquely located on a watershed and hence does not have access to its own water supply and primarily relies on water sources that are hundreds of kilometres away (Dippenaar, 2015; Muller et al., 2019). The city also experiences a number of water challenges including pollution of wetlands and water bodies, groundwater contamination, poor wastewater treatment, water loss from pipe leakages and severe water restrictions to mitigate the high demand in water across the city (Dippenaar, 2015). It is therefore paramount that a proactive rather than reactive approach is taken in Johannesburg in order to prevent a crisis akin to the city Cape Town. A proactive approach justifies an investigation into how water sensitive planning can be incorporated into the development of the city.

A practical approach in planning water sensitive cities is through the concept of an urban water metabolism evaluation which provides and understanding of the urban water cycle of the city which can indicate whether alternate water servicing approaches are practical and applicable (extends the number of water supply options in a city) as well as the type of interventions that can be used to service to these options and inform on land use planning (Farooqui et al., 2016; Renouf et al., 2018, 2017; Renouf and Kenway, 2017; Serrao-Neumann et al., 2017). The urban water metabolism approach stems from the concept of the urban metabolism which is defined in Serrao-Neumann et al. (2017, p. 2) as "a metaphor for conceptualising resource flows through urban systems, as analogous with ecosystems with an inferred intent of emulating the higher resource efficiencies of natural systems." Examples of resource flows include nutrients, energy, greenhouse gases and materials (Kennedy et al., 2007) and water which is the largest material by mass in the urban metabolism (Wolman, 1965; Kennedy et al., 2007). The thesis will be focusing on analysing the urban water metabolism of Johannesburg and its application in creating a WSC.

1.3. Research Aim and Objectives

The main research objective of the thesis is to assess how Johannesburg can transition into a WSC and provide a strategic program that will aid towards this transition. The strategic program will provide specific urban water management interventions and spatial strategies based on an assessment of Johannesburg's UWM, understanding urban water policy and governance and a review of the city's spatial, physical, climate and hydrological characteristics.

The main overarching research question of the thesis will therefore be:

How can Johannesburg potentially transition to a water sensitive city?

The sub-questions and objectives that will aid in answering the questions will be as follows:

1. What are the key characteristics of a WSC and its applicability in South Africa?
    - Define the concept of a WSC to be used in this research
    - Explore the origin and development of this concept
    - Identify its important characteristics
    - Evaluate its applicability in the South African context
    - Identify existing applications of WSC practices and explore what can be learnt
2. Why is a UWM evaluation approach important for transitioning into a Water Sensitive City?
    - Define UWM and its methods of approach
    - Identify the advantages and limitations of using an UWM evaluation
    - Explore how it relates to the WSC concept
3. What are the existing challenges, limitations and opportunities regarding Johannesburg's existing approach to its urban water system?
    - Explore the operational characteristics of the city's urban water system
    - Explore the physical, spatial and climate characteristics of Johannesburg
    - Identify possible areas that require sustainable urban water management interventions

4. In terms of urban water governance, what are the current organisational and policy gaps or provisions that aid towards creating a WSC in Johannesburg?
    - Identify organisational and policy gaps or provisions relating to urban water governance
5. What are the characteristics and implications of an assessment of Johannesburg's urban water metabolism?
    - Analyse the urban water metabolism of Johannesburg
    - Evaluate the urban water metabolism using performance indicators
6. Which urban water management interventions and spatial strategies can form part of a strategic program to guide the water sensitive transition in Johannesburg?
    - Develop a strategic program for Johannesburg's transition to a water sensitive city
    - Identify and explain spatial strategies that can be applied on a city level (macro) and neighbourhood level (meso and micro)

The above research questions and their respective objectives will serve as the foundation of this research.

1.4. Research Methodology

1.4.1. Research Strategy

This section will clarify the methods undertaken to answer the research questions outlined in the previous section. The main methods of approach are qualitative in nature with analysis derived from results from a review of literature and a desktop study involving case study research as well the collection of numerical data from secondary sources.

In order to answer the first and second research question a review of literature will be required pertaining to theory relating to water sensitive cities and urban water metabolism. The applicability of water sensitive cities in South Africa will also be additionally explored. This is important in order to understand the theoretical framework behind the concept and its feasibility in South Africa. The second purpose of the literature review in relation to urban water metabolism theory is to establish the need and justification for implementing an urban water metabolism framework in Johannesburg as part of a potential transition to a WSC.

A desktop study will be used to answer the third and fourth research questions and will require a desktop study of existing spatial, biophysical and climate data in Johannesburg as well as the status quo regarding the urban water cycle. This will enable a deeper understanding of the required urban water management and spatial interventions needed to facilitate a transition towards a WSC city.

With regard to the fifth research question, secondary data will be collected to understand the characteristics of the city’s urban water metabolism. The data will be analysed using a performance indicator assessment derived and outlined in Kenway et al. (2011). The purpose of this assessment is to evaluate which alternative water servicing option provides the most potential in Johannesburg. The complete methodology for this analysis will be explained further in Chapter 4.

Lastly, the sixth research question will be answered through the development of a strategic program that will provide an understanding of the urban water management interventions and the urban water management interventions required for Johannesburg’s water sensitive transition. The program will be based on the findings from the case study review as well as the urban water metabolism analysis.

The need for this multi-layered approach is rooted in the complexity of the context of South African cities which must contend with historic socio-economic injustices that persist even today while aiming towards more sustainable practices.

1.4.2. Scope and Limitations to Research

An investigation into the financial aspects relating to water tariffs and the implementation of projects is outside the scope of this research. One of the limitations in this research is the availability of data in carrying out research for this thesis. It was found that there was a lack of consistent and periodic data for Johannesburg with regard to certain components of the urban water metabolism analysis. Additionally, due to the COVID-19 pandemic, travelling to Johannesburg and further on-site investigation was not possible.

1.5. Significance of Research

This research will contribute towards the larger body of knowledge relating to WSCs in developing nations and thus aim to bridge the gap highlighted in Bichai and Flamini (2018) relating to a lack of research in this area. It will also aid towards a deeper understanding of the urban water metabolism in Johannesburg, by particularly examining the steps required for the city to shift towards more sustainable urban water management practices using this information as well as using an understanding of the unique geographical and socio-economic context of Johannesburg. UWM evaluations in developing countries are required in order to understand its applicability in such nations (Paul et al., 2018) and contribute to a better understanding of UWM. The strategic program developed as a research output will provide urban practitioners such as professionals and other stakeholders in urban, environmental and urban water planning and management with a succinct breakdown of how Johannesburg can build resilience and promote the sustainable use of water.

1.6. Thesis Outline

The thesis is divided into six chapters and are presented in the thesis as follows:

- Chapter 2:

This chapter provides a detailed literature review with the objective of answering the first two research questions relating to WSC and UWM theory. The purpose of this chapter will be to define WSC, its characteristics as well as its applicability in South Africa. The chapter also focuses on the importance of UWM as a tool in planning water sensitive cities and justifies its use in paving the transition towards WSCs.

- Chapter 3:

This chapter provides a detailed investigation into various characteristics of the city that will enable an in depth understanding of water related challenges in the city. It also provides an understanding of the spatial characteristics as well as the climate features that are of importance. The chapter also takes a closer look into the governance structures and policies in Johannesburg that affect the management of water. The purpose of this chapter is to provide an understanding of the types of challenges, limitations and opportunities present in the city.

- Chapter 4

Chapter 4 examines the urban water metabolism of Johannesburg. It explores the methodology employed as well as the associated results. A performance assessment is applied to understand the results and its implication for Johannesburg.

- Chapter 5

This chapter uses the findings from Chapter 2-4 to present a strategic program for guiding the transition of Johannesburg towards becoming a WSC. Examples of interventions that can be applied occur on three different scales and are presented (city, neighbourhood, and street level).

- Chapter 6

The final chapter will present the final conclusions of this thesis. Further avenues of research that can be explored in the area od WSC are also discussed.

Chapter 2: Literature Review

2.1. Introduction

The purpose of this literature review can be divided into two parts: to explore in depth the concept of a WSC as well as its importance and how it can be achieved based on the current research in this area. The second part ascertains the need for a UWM approach and its importance for planning water sensitive cities thus answering the initial research questions as highlighted in Section 1.3.

1. What are the key characteristics of a WSC and its applicability in South Africa?
    - Define the concept of a WSC to be used in this research
    - Explore the origin and development of this concept
    - Identify its important characteristics
    - Evaluate its applicability in the South African context
    - Identify existing applications of WSC practices and explore what can be learnt
2. Why is a UWM evaluation approach important for transitioning into a Water Sensitive City?
    - Define UWM and its methods of approach
    - Identify the advantages and limitations of using an UWM evaluation
    - Explore how it relates to the WSC concept

By exploring the above areas of literature, the background of this study will be laid out and a critical understanding of the concept of a WSC will be understood with added knowledge regarding how a transition towards this is achievable. Additionally, a clear justification regarding using an UWM approach in service of this transition will be understood.

2.2. Water Sensitive Cities

2.2.1. What is a Water Sensitive City?

A tool known as the urban water transitions framework was developed by Brown et al., (2008) as a solution towards addressing the absence of a clearly defined urban water paradigm which provides a reference for urban practitioners towards identifying markers of urban water sustainability as well as make informed decisions related to long term policies. The framework was designed by tracking historical institutional and technological changes in the urban water sector of Australian cities as well as the socio-political drivers of future changes. The tool essentially pointed out different attributes of different stages of the implicit consensus between communities, governments, and various other stakeholders (e.g., businesses) over time. This tool also predicts the target requirements of a future vision of a city that imbibes sustainable urban water management. The aforementioned "agreement" between stakeholders is also known as the hydro-social contract (Brown et al., 2008). The complete urban water management transition framework can be observed in Figure 1.

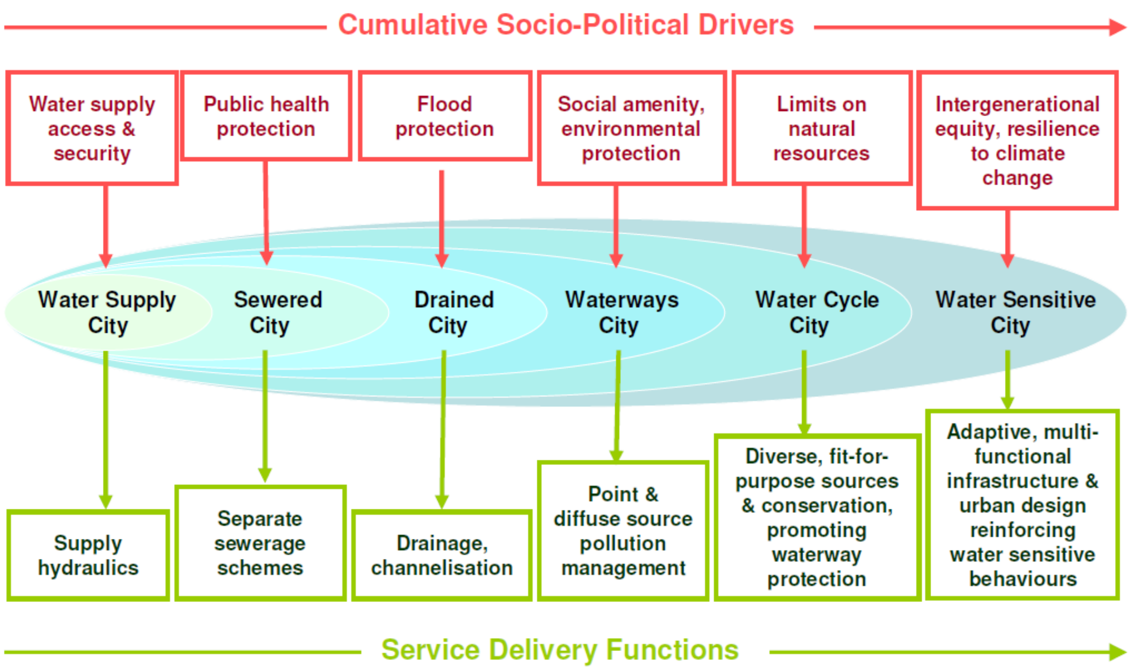


Figure 1: The urban water management transitions framework

Source: Brown et al. (2008, p.5)

The transition framework in Figure 1 maps the socio-political drivers of each phase with its characteristic service delivery functions. The last stage of the transitional framework is the WSC which is the desired future water scenario where a holistic, interdisciplinary approach to urban water planning that requires integration of factors such as health, liveability, economic and environmental sustainability together with water supply security. Active and engaged communities are the hallmark of this stage with continuous engagement allowing for longevity of sustainable urban water management interventions. Technology, infrastructure and policy frameworks would support water sensitive behaviour and be adaptive, flexible and especially resilient. This stage of the framework offers a clear and uniform vision of a the most sustainable version of future cities. According to Wong et al. (2020), it is an aspirational vision (Wong et al., 2020). The intention of the framework was to allow cities to benchmark their current progress with respect to their water sustainability objectives and the type of trajectory the city may be following. The concept is often synonymously used with WSUD (Water Sensitive Urban Design) in Australia (Fletcher et al., 2015) as the definition of WSUD is very similar to that of the WSC idea- "stormwater management within an integrated framework considering the entire urban water cycle" (Fletcher et al., 2015, p. 528). The distinction between the two concepts then becomes less apparent but an important difference can be noted in a study assessing WSUD in Melbourne (Brown and Clarke, 2007) where the concept of WSUD is seen as a collection of methods used to achieve urban water sustainability and as understood from the urban water management transitions framework, WSC is a strategic target or vision for obtaining sustainability in future cities. This definition of WSUD as a means of achieving urban water sustainability is further corroborated in Wong (2006) and Wong and Brown (2009), where both papers clarify the role of WSUD. WSUD is still however very important as it has played a central role in cultivating sustainable water practices in Australia thus servicing the WSC target (Wong and Brown, 2009).

2.2.2. The Key Principles of a Water Sensitive City

But what exactly does this target entail? From the urban water management transitions framework, the broader vision is understood but there are essentially three underlying principles that constitute a WSC, and it is not only limited to implementing WSUD which lacks the much needed community-centric component. Community participation processes are vital in the South African context as evidenced in McEwan (2003) There are three underlying principles that form a WSC (Wong et al., 2020):

a. City as a water supply catchment:
    - This refers to the diversification of water resources in a city where the dependence on surface water is reduced and alternative water sources

are explored such as the collection and treatment of urban stormwater runoff and rainwater, management of groundwater schemes. The idea is that cities within their own boundaries secure a reliable and sustainable water supply (Wong et al., 2020; Wong and Brown, 2009). This also refers to the movement away from conventional urban drainage practices.

b. Cities providing ecosystem services

- At the core of a WSC should be the enhancement and integration of urban landscapes and public open spaces that not only provide amenity but service urban water management, promote biodiversity, protect aquatic environments, provide cooling for microclimates, reduce carbon emissions and can even promote urban food production (Wong et al., 2020). This increased resiliency against climate change impacts are known as “nature based solutions” (Cohen-Shacham et al., 2016).

c. Cities comprising of water sensitive communities

- This principle concerns creating communities that reflect and recognise the importance of sustainable water practices. The values and needs of communities should be included in urban water management projects. This could improve the longevity of the project. It also underpins the need to ensure that industrial, professional and governmental capacity can support these type of projects (Wong et al., 2020). A study by Brown and Farelly (2009) highlighted how socio-institutional capital can be one of the biggest impediments to implementing sustainable urban water management.

Operationalizing these principles to create water sensitive cities is a complex undertaking as one of the key factors towards achieving these principles is that it necessitates the context of the area to be especially understood. This includes the unique characteristics such as the hydrology, topography, geomorphology, microclimate, environmental and urban form as well as the socio-institutional capacity to include alternative water servicing options (Wong et al. 2020).

2.2.3. A WSC and its Applicability in South Africa

Understanding the context of a city in operationalizing principles of a WSC is significantly important. Water sensitive practices have largely been implemented in countries that have far more stable socio-economic and political situations (e.g., Australia and Singapore) with very little infrastructure deficits. Developing nations have to contend with these deficits as well higher unemployment rates, poorer service delivery and high rates of both informality and rapid urbanisation (Mguni et al., 2016). A study on the applicability of Green Infrastructure (GI) based stormwater management solutions in Sub-Sahara cities (Mguni et al.,2016) revealed that any introduction of Sustainable Urban Drainage Systems (SuDS), which is a system of managing stormwater in a sustainable manner, hinges greatly on the method of approach as it is possible that the provision of aesthetic ecosystem services that can provide amenity may increase the value of land, further isolating those in poorer income communities. This indicates that central to an implementation of any type of sustainable urban water management practice requires careful undertaking by all stakeholders that has to include, engage and educate communities as much as possible with the focus on bridging that infrastructure deficit and ensuring that the provision of basic services such as water and sanitation along with enabling sustainable urban development are successfully met.

This multi-dimensional focus is an aspect that is highlighted in South Africa's official guidelines and framework for implementing WSUD (Armitage et al., 2014). Armitage et al. (2014) further proposes that the urban water management transitions framework of a WSC be expanded into Water Sensitive Settlements (WSS) (refer to Figure 2) to uniquely account for the existence of informal and formal settlements within one city boundary and the spatial inequality borne out of the legacy of apartheid, both of which are distinct features of South African cities. The difference therefore between the WSC and WSS framework (see Figure 2) is not the achievable target but rather the stages of transition. There are four components of this newly proposed framework: research, vision, narrative and implementation. The first component refers to research which is the essential building blocks of creating a water sensitive framework in South Africa. Research was carried out by drawing together municipal officials with professionals in industry and academia. The workshops concluded that the implementation of WSUD is not sufficient and requires intentional efforts to engage policy makers and also those who hold an ability to change both national and municipal policy. This justified a need for a Learning Alliance which would be a platform where more discussions can be held and where an input and exchange of ideas can be gathered from industrial and academic professionals and officials. The second component to the framework is the summation of an overall vision that provides a road map towards water sensitivity. A model adapted from Brown et al. (2008) was generated taking into account the unique developmental areas in SA. These areas consist of formally developed areas, informal areas and greenfield developments. Table 1 provides a summary how treating the area according to its context relates to the urban water management transitions framework developed in Brown et al. (2008) as explained in Fisher-Jeffes et al. (2017a, p.8):

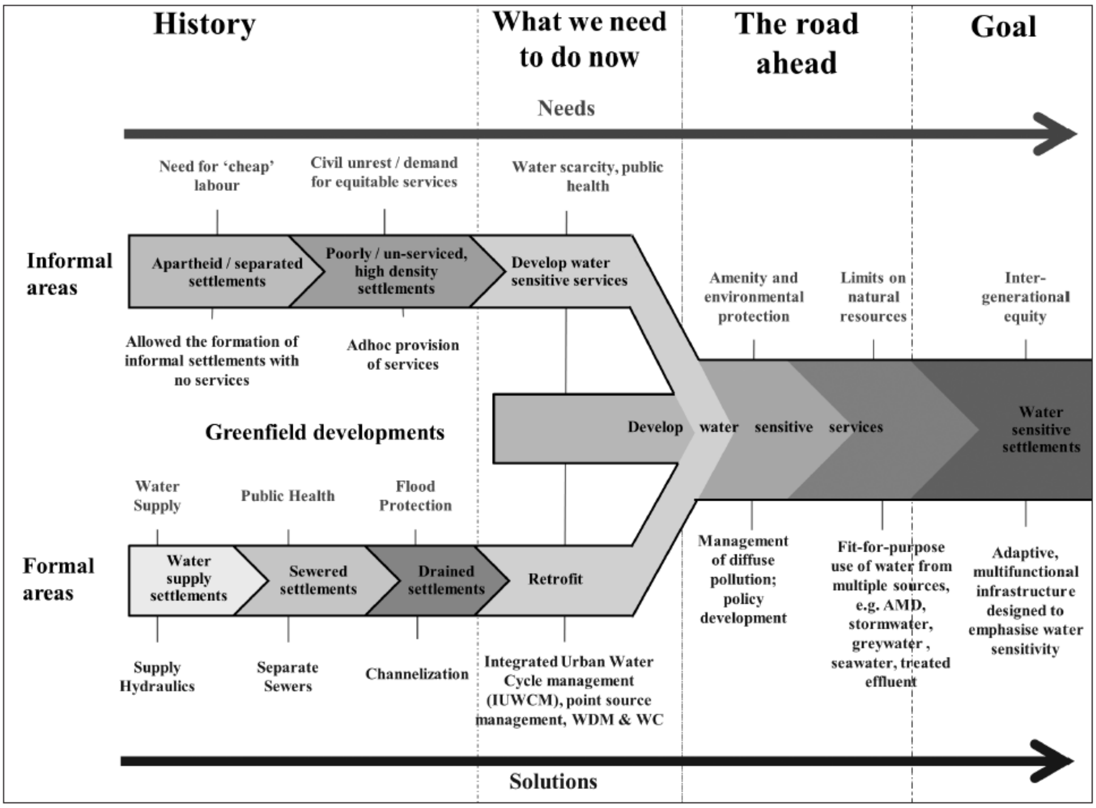


Figure 2: Urban Water Management Transitions Framework for South Africa

Source: Fisher-Jeffes et al. (2017a, p.8)

Table 1: Summary of how the urban context is related to the urban water transitions framework developed by Brown et al. (2008)

Source: Created by author (2021) and adapted from Fisher-Jeffes et al. (2017a)

Formally developed areas	These areas can be related to the "drained cities" component in Brown et al., 2008. A transition towards a water sensitive settlement would require a holistic approach to the urban water cycle management, pollution reduction and management of increasing water demand through retrofit and redevelopment strategies.
Informal areas	Informal areas are considered to be "water supply" cities wherein redevelopment of these particular areas must be based on water sensitive principles from the start using knowledge gained from retrofit strategies in formally developed areas.
Greenfield developments	From the beginning, private developments must adopt water sensitive principles and municipalities must implement adequate approval processes that ensure this.

Fisher-Jeffes et al (2017a, p.8) particularly emphasises that in order for a transition to a WSC to work in South Africa or at least an informal area to transition successfully to a "waterway city", it is important that both informal and formal areas transition together simultaneously as detailed in Figure 2 and Table 1. This is certainly a complex undertaking.

The third and fourth component of the framework includes narrative and implementation aspects. The narrative entails having a clear, communicative vision regarding WSC practices that is understandable for all stakeholders. This narrative component along with the idea of setting forth an explicit vision is echoed in work from Ferguson et al. (2013) that uses strategic thinking to present a coherent program for transitioning to WSCs. According to Ferguson et al. (2013) the success of such a strategic program requires multiple actors to be involved, adaptive thinking according to the context and situation to be implemented and most importantly a cultural shift from the conventional approach has to be adopted at all levels to support the transition. Some of these characteristics are intrinsically built into the water sensitive framework for SA, which is promising and recently in 2020, Fourie et al. (2020) has provide a unifying vision across the country, that has specific guidelines and strategies to plan towards becoming a WSC. The complexity of achieving this is derived from how the country still needs to provide water sensitive services that meet the basic health and service rights of its residents. Additionally, the lower prioritization of sustainable urban water practices in Sub-Saharan cities due to more pressing gaps in provision of water and sanitation services, poverty and inequality is pointed out in Mguni et al. 2016. Implementation with a shortage of capital and resources is therefore recognised as an inherent issue.

One of the ways in which implementation is eliciting progress is through the recognition of WSUD as an approach which is defined in the South African context as a “system-based approach that promotes the development of blue-green infrastructure, including sustainable drainage systems (SuDS), alternative water resources and Water Conservation and Water Demand Management techniques” (Cilliers and Rohr, 2019, p.357). The research on the implementation of WSUD processes is extensive with studies carried out over from the past decade further lending to an increased knowledge base in urban drainage practices and GI based practices towards this new urban water paradigm shift (Armitage et al., 2014; Carden et al., 2016; Fisher-Jeffes et al. 2017a, Fisher-Jeffes et al., 2017b).

These studies also highlight numerous challenges regarding this implementation. Fisher-Jeffes et al. (2012) additionally indicates that water supply and management is not considered as an environmental and economic concern in South Africa and is therefore less likely to be considered under a holistic view due to these aforementioned gaps echoing the study by Mguni et al. (2016). Infrastructure is mainly built with prioritize aim of provision as opposed to sustainability (Cilliers and Rohr, 2019) and as such the country still has service backlogs with an overall water infrastructure backlog of 13 % (Mnisi, 2019). Additionally, Cilliers and Rohr (2019) present the stark issue of wastewater treatment in the country which significantly affects the quality of water bodies. Synchronously, the authors cite the various lessons that can be learnt from the attempted implementation of WSUD processes from various case studies in South Africa within the past decade which can help understand some of the gaps regarding achieving a water sensitive target. These include:

- a need for more context-driven local strategies, that can allow for practical implementation by local governments (Cilliers and Cilliers, 2016)
- the importance of understanding that socio-economic growth can be hampered by reduced water supply security and poor resource quality and management
- WSUD processes must be embedded as the backbone of urban development and a means to achieve socio-economic equity and access to services (Fisher-Jeffes et al., 2012)
- the integration of WSUD into spatial planning at different scales with allowances made for multi-sector and cross-disciplinary work

The last lesson provides an essential justification in this research to present urban water management and spatial interventions in Johannesburg at varying scales which is explored in Chapter 5.

Lastly the importance of a regulatory framework and policy in the implementation of this cannot be undervalued. There are several laws that hinder or enable implementations of a water-sensitive approach in SA and is listed as follows:

- The Constitution of the Republic of South Africa states that the access to adequate drinking water is a basic human right (RSA, 1996, p.11). and delegates local municipalities as a responsible provider of basic service infrastructure requirements including the management, budgeting and planning for the implementation of infrastructure projects and their respective upgrades (RSA, 1996, p. 74). This includes the provision of water, sanitation services and stormwater management within a municipality (RSA, 1996, p.137), however municipalities often have to contend with severe constraints regarding capacity and finance as well as political agendas and corruption which pose extreme obstacles for planning, monitoring and evaluating stormwater management practices (Kanyane, 2014). Additionally enshrined in the constitution is the basic human right of citizens to “an environment that is not harmful to their health or well-being” (RSA, 1996, p.9). The failure of not providing water and sanitation services, can lead to the failure of providing other basic rights such as the one mentioned.
- The National Environmental Management Act (NEMA) (RSA, 1998a) is the framework that aims to uphold the Constitution's listed basic human right for everyone to have access to an environment that is not harmful to their well-being. While being a firm overall law that holds matters that are contradictory accountable. The weakness of the framework reported by Cilliers and Rohr (2019, p. 356) is that municipalities are given less authority regarding the management and jurisdiction of environmental affairs. This despite having significant responsibility regarding the provision of infrastructure. This limits the municipalities' role in managing environmental concerns in relation to infrastructure and other matters. This gap can lead to an oversight regarding these said concerns.
- The National Water Act (NWA) (RSA,1998b) details all the laws relating to the provision of water resources including regulations regarding water use, infrastructure as well classification of catchment areas and catchment forums. It does not yet set forth the need to follow sustainable water practices and supports the conventional approach of stormwater management (Cilliers and Rohr, 2019, p.356) which poses its

own health risks which is an indirect contradiction to the right to a healthy environment NEMA and the Constitution.

- The National Water Services Act (NWSA) (RSA, 1997) reiterates the position of municipalities with regard to water service delivery however it lacks any mention of the holistic and integrated approach required for water sensitive cities. It details the requirement for municipalities for provide a Water Service Delivery Plan every 5 years, indicating some leeway for potential future integration of sustainable urban water management practices. This gap is pointed out by Haigh et al. (2010).
- The Spatial Planning and Land Use Management Act (SPLUMA) 16 of 2013 (RSA, 2013) is arguably very important in that it holds municipalities legally accountable for its spatial development and requires municipalities to create Spatial Development Frameworks (SDFs) that aim towards spatial sustainability, resilience and efficiency which aligns with a vision for a water sensitive city. The law also emphasises the importance of implementing stormwater management in a way that does not cause future hygiene issues (Fourie et al., 2020).

Despite some gaps in regulatory laws, it can be understood that a general awareness of both sustainable urban water practices and the concept of a WSC vision is known in South Africa. Its applicability relies mainly on the local context and its success depends largely on ensuring that basic needs of all people are met. National legislation needs to be more robust and detailed in order to effectively move towards a WSC city.

2.2.4. Examples of Application of Water Sensitive Principles in South Africa

Within the past decade, the move towards sustainable urban water management practices has slowly gained momentum and the Cape Town water crisis was a clear catalyst for championing further research into adopting these practices. This section will focus on two case studies in particular that exemplify the application of water sensitive principles in South Africa. The first case is a study of the introduction of SuDS in an informal settlement called Diepsloot in Johannesburg in order to reduce surface water. The second is a case study of a formal residential development around a wetland in an area called Century City in Cape Town. Both studies offer insights on a micro (neighbourhood) scale regarding the application of the three principles of a WSC as well as insight on how these can be applied within diametrically different socio-economic conditions, a key characteristic of South Africa’s urban landscape.

a. Diepsloot Settlement, Johannesburg

Diepsloot is a settlement developed in the early 1990s on the northern periphery of Johannesburg and began as a temporary resettlement area for those displaced under racially motivated segregation and discrimination laws (apartheid) from the inner-city area of Johannesburg (Bénit, 2002, p.50). The area is characterised by informal and formal dwellings. Informal settlements in the South African context are characterised by predominantly informal dwellings built on land not allocated for housing with limited basic services infrastructure. Informal dwellings are built without any technical specifications and with easily accessible materials. Formal dwellings on the other hand, are built according to very specific building plans on allocated land for housing. These dwellings vary across income level and location (STATS SA, 1998). Informal settlements are often characterised by poor water and sanitation services and additionally stormwater networks are often not prioritised causing surface water stagnation (Bobbins et al., 2019, p.59) and equally erosion is rife causing uneven settlement between informal dwellings and the unpaved lanes between informal dwellings (Fitchett, 2017). Additionally, the settlement undergoes rapid densification and additionally litter and waste are not disposed of adequately and its impact negatively effects the natural environment (Fitchett, 2017, p.312). Two sites were selected in partnership with the residents in the area and interventions were introduced in the area to reduce stormwater runoff and minimise flooding caused by intense rainfall events. The site selection with residents was the first step and is an example of action research which is a collaborative approach that gathers knowledge through action (Koshy et al., 2011, p.3) and the second step involved adaptive co-management which is an approach that seeks to integrate all stakeholders into the evaluation and monitoring aspects of implementing projects (Fitchett, 2017; Fabricius and Currie, 2015). This therefore meant that residents were involved from the beginning of the intervention to its monitoring and evaluation phase. Sustainable drainage interventions such as vegetated and channels and permeable paving which transfer or reduce surface runoff were implemented. The interventions were successful in reducing stormwater runoff and minor improvement of water quality was observed (Fitchett 2017, p.320). Additionally, even though community perceptions were variable between the two sites of interventions, there was significant success regarding engaging the community through action research and adaptive co-management. This indicates that even on a small scale, interventions can prove to be useful and most importantly a bottom-up participatory process is essential for success in not only the planning and design stages, but also in the monitoring and evaluation phases. Even with the complexity that an informal settlement presents, a chance to create water sensitive communities which is one of the main principles of a water sensitive community is possible.

b. Century City Wetland Development, Cape Town

This case study was instrumental to the development of the SuDS guidelines in South Africa (Armitage et al., 2013). The Century city area consists of a multi-use development that is approximately 250 ha in size with medium to high residential areas as well other numerous amenities including shopping malls and commercial areas. Most importantly, it was built around a rare type of wetland and an artificial wetland was subsequently constructed with the purpose of preserving the natural wetland to allow biodiversity in the area to thrive. The constructed wetland ensures that stormwater is treated and retained before it is discharged into the adjoining Atlantic Ocean (Vice, 2011). Additionally, rainwater harvesting systems were included for residential dwellings.

An important stage of the development of the area was the planning phase which aimed to ensure the protection and resiliency of the natural environment and its biodiversity, create opportunities for economic investment (through providing amenity), provide for socio-economic development (through job creation) and facilitate research. The creation of the Blouvlei Environment Management Plan (EMP) was a key driving factor in ensuring that planning of the stormwater management in the area was treated in a holistic fashion (Vice, 2011, p. 131). However, over the developmental period of 15 years, it was observed that the implementation of said planning approach was not consistent enough and certain SuDS options were not well developed which led to some interventions not working to their full potential. This is also possibly due to the complexity of adapting conventional drainage systems to fit more sustainable options. Vice (2011) additionally adds that some SuDS interventions were maintained in isolation with one another and less of a holistic approach was taken. Another key finding of this study was the importance of education in creating awareness and understanding of the importance of the wetland. An eco-centre was built to provide education and awareness on conservation and the importance of using water sustainably. The centre was also used as a management platform to discuss maintenance and operation of interventions in the area (Vice, 2011, p.111). Although it is not known as to which stakeholders were able to participate in these forums. It is interesting to note that this case study does not allude much to its participatory processes in either the planning, operation or maintenance phases of the development. Despite achieving significant progress in adhering to one of the principles of water sensitive cities which is the provision of ecosystem services and alternative water services, the principle of creating water sensitive communities is lacking and could be a possible factor in a number of SuDs interventions not functioning well enough.

The Century City case study reveals the importance of ensuring that there are no gaps in the implementation and maintenance of water sensitive approaches which can be complex in reality despite strong planning initiatives.

The scale and socio-economic conditions of the two case studies are different, however they offer an insight into the momentum of cities in South Africa as they transition to more sustainable urban water management practices.

2.3. Urban Water Metabolism

2.3.1. Understanding Urban Metabolism

The definition of metabolism in natural sciences which is the "precondition of life, along with homeostasis (regulation of the internal environment), structural organization, growth, adaptation, response to stimuli and reproduction" (Van Timmerman, 2013, p.16) crossed over from natural sciences to other various scientific disciplines as early as the 19th century and evolved within industrial ecology as a "core analytical tool to develop an understanding of the energetic and material exchange relations between societies and their natural environments from a macro perspective" (Fischer-Kowalski, 2002, p. 16). It can then be understood as to why this concept has been applied in urban theory as it is a way to understand the interactions between cities and its respective natural environments. However, the theory does not present the city as an organism containing a metabolism but rather as a complex system containing multiple organisms that interact with each other and is therefore more comparable to an ecosystem (Golubiewski, 2012).

The rise of megacities and the resultant challenge of analysing its complexity that is influenced by its urban structure, varying political interests and socio-economic composition has led to more examinations of how cities interact with its environment by tracking the flow and storage of both materials and energy (e.g. energy, air, water, nutrients, etc) (Brunner, 2007; Kennedy et al., 2007). The evolution of urban metabolism studies began with the first quantification study by Abel Wolman in 1965 on a fictional American city with a population of 1 million inhabitants, where energy, waste and water flows were analysed (Wolman, 1965; Kennedy et al 2007; Golubiewski 2012). The analysis was used to indicate how the use of resources and generation of the subsequent waste had an impact on the natural environment (Pincetl et al., 2012).

In the decades that followed Wolman's seminal work, many urban metabolism studies have been carried on different cities throughout the world including Brussels, Tokyo, London and Cape Town (Kennedy et al., 2007). Newman (1999) was the first to suggest that the urban metabolism model can be extended to account for liveability. Additionally, Kennedy et al. (2011) explored the practical applicability of urban metabolism in urban planning and design. Applications of urban metabolism were briefly explored including sustainable indicators and design tools. For the application of design tools, the earliest examples cited were from the MIT School of Architecture in their efforts to redesign New Orleans after Hurricane Katrina and sustainable neighbourhood scale design of campus infrastructure from students at the

University of Toronto. The latter example aimed to produce that were sustainable by its ability to reduce the magnitude of resources flowing into the campus and reduce waste outputs (Kennedy et al. 2011, p.1970). This therefore points to a key positive aspect of urban metabolism studies viz., it can be used to as a transition pathway towards sustainable cities based on the knowledge and analysis of material and energy flows (Kennedy at al. 2011, p.1971). González et al. (2013) further observed that assessing urban planning initiatives through its impact on its urban metabolism can influence both policy and planning and be a key enabler in reducing consumption, which results in increased resource efficiency and increase resource use efficiency. With regard to water, this can prove useful in understanding which aspect of the urban water cycle requires efficient water management as well as provide a useful reference to understand its variations over time (Chrysoulakis et al., 2013). Pamminger and Kenway (2008, p.46) indicate that this type of analysis provides the required context to the type of policies that influence the urban water metabolism and hence changes can be made in line with sustainable practices which reiterates and González et al. (2013) line of reasoning. The need for a specific type of boundary in this type of analysis (Pincetl and Bunje, 2009) also provides a frame of reference which ensures that other components of the urban metabolism can be measured and understood because these are intrinsically linked. For example, the supply of water requires energy which is, as mentioned previously, another component of the urban metabolism (Pamminger and Kenway, 2008, Kennedy et al., 2007). This therefore adds further value to the urban water metabolism as a tool for ensuring sustainable cities and contemporaneously water sensitive cities as a metabolic approach allows one to understand how new water services can be implemented (Farooqui et al., 2016) which is in line with the one of the principles of water sensitive cities that includes the diversification of water resources (Wong and Brown, 2009).

2.3.2. The Link between Urban Water Metabolism and Planning for a Water Sensitive City

With an understanding of the importance of an urban water metabolism study as a tool, its role in planning water sensitive cities must be further investigated. This can be further understood by firstly investigating the how urban water metabolism studies are carried out.

There are two common methods of approach for conducting urban water metabolism studies: Material Flow Analysis (MFA) and Urban Water Mass Balance (UWMB). Material Flow Analysis involves the collection of secondary data on potable water and wastewater flows in addition to other urban resource flows (Renouf and Kenway, 2017, p. 999). This offers an understanding of resource uses in relation to one another in order to work towards the overarching goal of resource efficiency (Newell and Cousins, 2015; Renouf and Kenway, 2017). The limitation of this method is that it is restricted by its use of only accounting only for potable water and wastewater which fails to provide a comprehensive interpretation of the urban water cycle (Kenway et al., 2011, Paul et al., 2018). Flows such as groundwater infiltration, surface runoff and evapotranspiration are significant, thereby making MFA less of a comprehensive and holistic assessment of the urban water metabolism. The UWMB framework was developed by Kenway and fellow researchers (2011) to address the gap that MFA analysis presented (Paul et al., 2018, p.1415) by accounting for all natural and anthropogenic flows through collection of highly aggregated (or top-down approach-based) secondary data. However, what makes this approach appropriate for advancing urban water goals?

Renouf and Kenway (2017) carried out a study examining MFA and UWMB along with several other urban water evaluation approaches, including modelling of urban water systems modelling, complex systems and consumption approaches, and concluded that results of UWMB framework are most aligned with visons and objectives of sustainable urban water management due to its ability to gauge urban water performance of a system through its evaluation criteria.

It is also important to note that there is an understandable critique concerning the overall methodology of urban metabolism approaches. A study of urban metabolism methodologies from Beloin-Saint-Pierre (2017) indicates that there are numerous evaluations for carrying out overall urban metabolism studies and hence a lack of a standardized framework to create meaningful comparisons. Regarding the water component metabolism, this is partially countered by performance assessments derived by Kenway et al. (2011) and later by Farooqui et al (2016). as well as an emerging litany of research that apply UWMB to case studies of various cities across the world (Paul et al. 2018). In the context of the developing world, studies by Paul et al. (2018) for Bangalore and Ffion-Atkins (2021) for Cape Town are slowly adding to the knowledge base and this thesis also aims to contribute to this is body of knowledge by bridging this gap. Another point of contention is pointed out by Newell and Cousins (2015) which explains that while urban metabolism resources flow accounting is useful, it reduces a complex ecosystem to its inputs and outputs, which can lose important nuances in understanding the complexities of a city as an ecosystem.

Nevertheless, Beloin-Saint-Pierre (2017) points out that the simplification of the inputs vs outputs approach still provides merit. In their study, Renouf and Kenway (2017) backs this up as well as concluded that the UMWB method can be complimented by other urban water evaluation approaches such Integrated Urban Water Systems Modelling (IUWSM) and

Ecological Network Analysis (complex systems studies) to provide more robust performance indicators.

Most notably, in the context of this thesis, a UWMB can serve as quantitative assessment that can contribute to the Water Sensitive Cities Index, which is the most comprehensive performance indicator framework for creating water sensitive cities developed by the Cooperative Research Centre for Water Sensitive Cities (Rogers et al., 2020). The Water Sensitive Cities (WSC) index is divided into 6 goals that require a qualitative analysis rating of between 1-5 to fully assess the current performance of a city's transition to a water sensitive city. The assessment is based on feedback from a wide variety of stakeholders brought together via workshops (Rogers et al., 2020). Specifically, goal 4 of the index assesses productivity and resource efficiency contains the following indicators (Rogers et al. 2020, p. 7) in Table 2:

Table 2: Relevant performance indicators for a WSC index

Source: Created by author (2021) and adapted by author from Rogers et al. (2020, p. 7)

Indicator no.	**Indicator**	**Strategic Objectives**
4.1	Optimised resource recovery	The recovery and optimisation of water and other resources flows
4.2	Low GHG emission in water sector	Ensure and maximise the use of alternatives to carbon emissions intensive sources in the water sector
4.4	Low end-user potable water demand	Support cheaper alternatives to drinking water

An UWMB framework can contributes towards providing a specific quantitative assessment that can be used to accurately assess whether a city is moving towards the vision of a water sensitive city. Even more promising is that the trial use of the WSC Index has shown promise in South Africa (Rogers et al., 2020). Finally, to summarize exactly how using a urban water metabolism approach can help create water sensitive cities, Serrao-Neumann et al. (p.1, 2019) lists specific actions that this method of approach can advocate for including: "resource efficiency and hydrological performance benchmarks and targets for urban developments; tailoring programmes for resource efficiency; making a case for regional blue-green space networks for improved hydrological performance; small and large-scale infrastructure innovation; and social and institutional innovation in urban water management''-all of which can push the needle closer to a WSC transition.

2.4. Literature Review Conclusion

The literature review has defined the concept of a WSC which is an aspirational vision of a city that practices three important principles. The first principle is focused on the diversification of water resources and security of supply within a city's own boundaries. The second principle relates to the promote the provision of ecosystem services by integrating nature-based solutions. The final principle emphasises the need for creating water sensitive communities. These are communities that are actively engaged in the value and sustainable use of water. The applicability of the WSC concept was also explored in the South African context and literature suggests that the local context of the country must be especially recognised to transition to a WSC due to its socio-economic conditions. The review also includes an overview of the regulatory laws and policies that enable the WSC transition which are generally broad in nature but are conducive for pushing towards the transition through especially through land use planning using SPLUMA. Examples of how water sensitive principles were explored in two case studies and the use of participatory approaches was recognised as an important tool for success in smaller scale projects. The operation and maintenance of interventions aligned with WSC must be robust and involve the community.

Lastly, the UWM framework was established as an important sustainability transition with UWMB as a tool to inform the planning of WSC through its output of specific quantitative assessments which can be used to benchmark performance progress of cities (using the WSC index). It can additionally be used to compliment other modelling tools to provide even more accurate assessments and be used to champion informed land use planning with regard to planning WSCs.

Chapter 3: Contextual Background: Johannesburg

3.1 Introducing Johannesburg

An important aspect of understanding Johannesburg's potential as a WSC is to understand its water challenges and hence present an in-depth case-study analysis of the city. This chapter will focus on answering the following research questions:

3. What are the existing challenges, limitations and opportunities regarding Johannesburg's existing approach to its urban water system?
    - Explore the operational characteristics of the city's urban water system
    - Explore the physical, spatial and climate characteristics of Johannesburg
    - Identify possible areas for sustainable urban water management interventions
4. In terms of urban water governance, what are the current organisational and policy gaps or provisions that aid towards creating a WSC in Johannesburg?
    - Identify organisational and policy gaps or provisions relating to urban water governance

Johannesburg consists of seven administrative regions (A,B,C,D,E,F,G regions) and is located in the province of Gauteng (see Figure 3 and Figure 4) is considered the economic hub of South Africa with the highest contribution (13%) to the country's Gross Domestic Product (GDP). It is also the fastest growing city (City of Johannesburg, 2021a) with a population of 4.4 million in 2011 (South African Cities Network, 2016, p. 344) and is projected to grow by 84% to reach a population of 8 million in 2050 (Le Roux et al., 2019). The population growth is related to the increase in the urban population of the country which in 2020 was estimated to be 67% and is estimated to reach approximately 80% in 2050 (UN, 2018). A characteristic of urbanisation in Africa is that it is largely driven by the intention of leaving behind poverty-stricken rural areas (WEF, 2015). This, together with population growth and the limited access to affordable housing and inability to cope with the resulting infrastructure demand, contribute to an increase in urban informality which then increases the vulnerability of the poor (South African Cities Network, 2016, pp. 24-25).

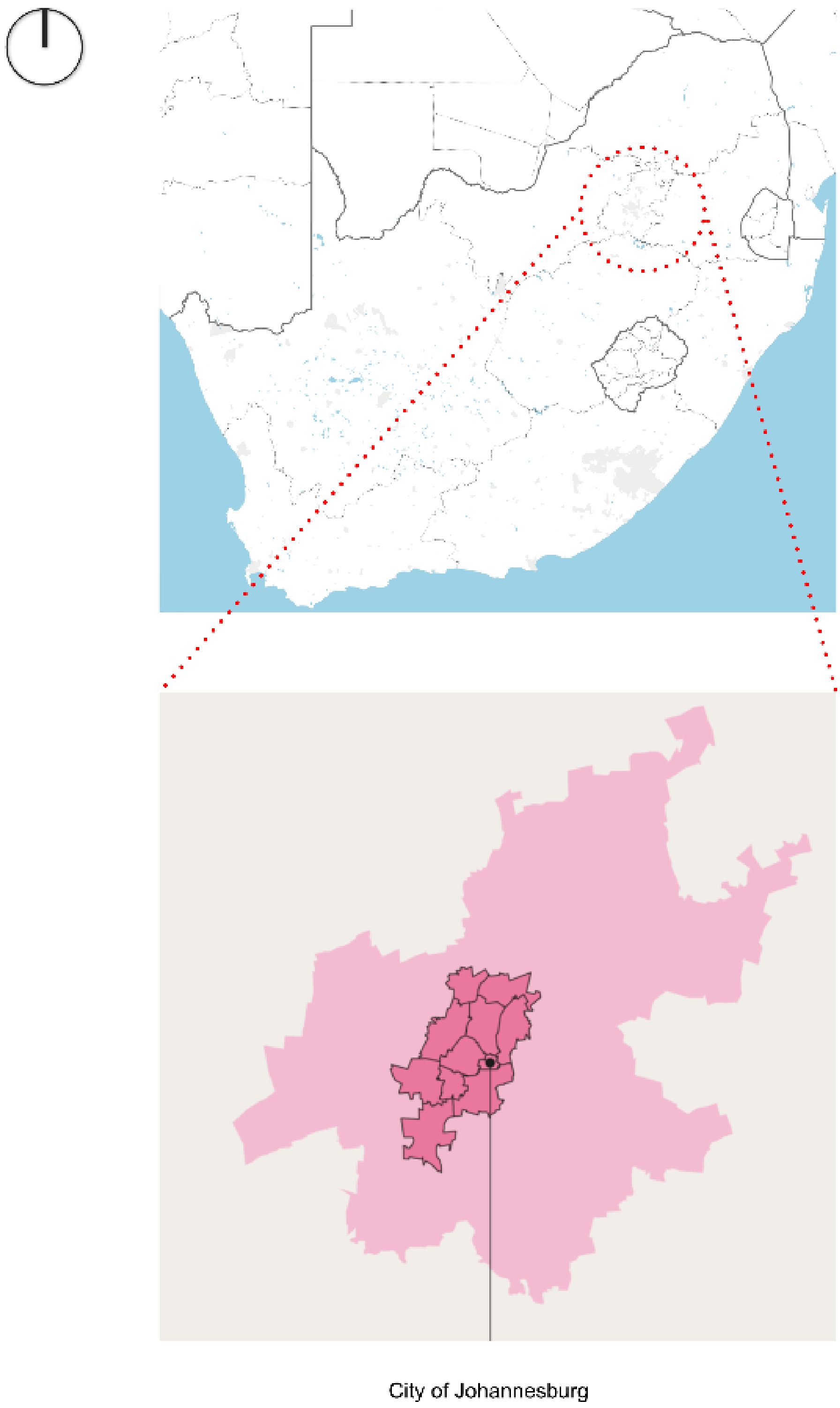


Figure 3: Position of Johannesburg in relation to South Africa and the province of Gauteng

Source: Created by author and adapted from Snazzy Maps (2021)

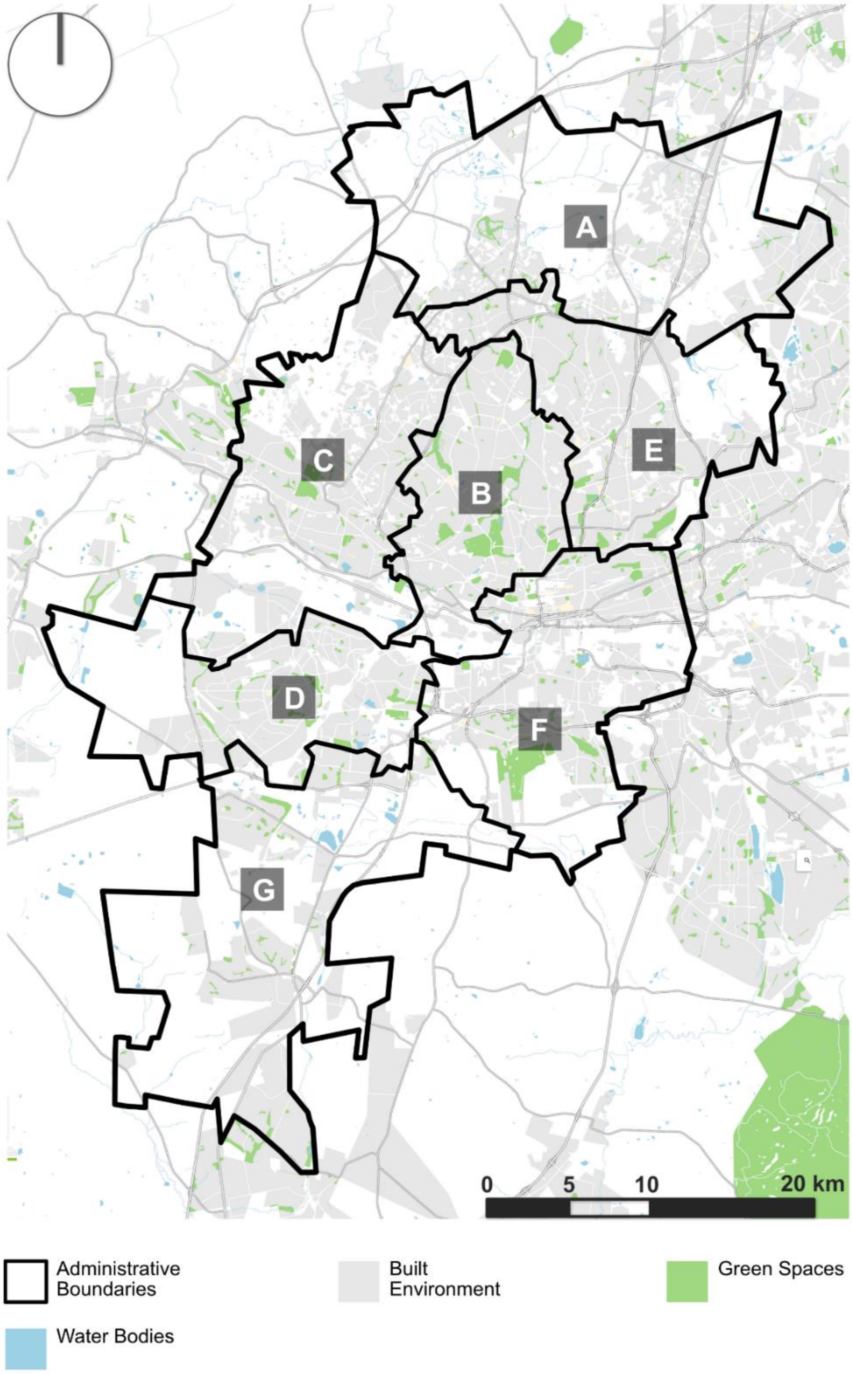


Figure 4: Map of Johannesburg with administrative regions

Source: Created by author and adapted from Snazzy Maps (2021)

3.2. Physical and Spatial Analysis of Johannesburg

3.2.1. Development of Johannesburg in Relation to Water

The origin of Johannesburg's development as a city can be traced to 1886, upon the discovery of gold along the *Witwatersrand* (translated as "Ridge of White Waters"). The city was therefore not built near any major river or lake source like many other cities around the world (Campbell, 2019) and expanded northwards and south bound of the *Witwatersrand* ridge in the decades that followed as seen in Figure 5.

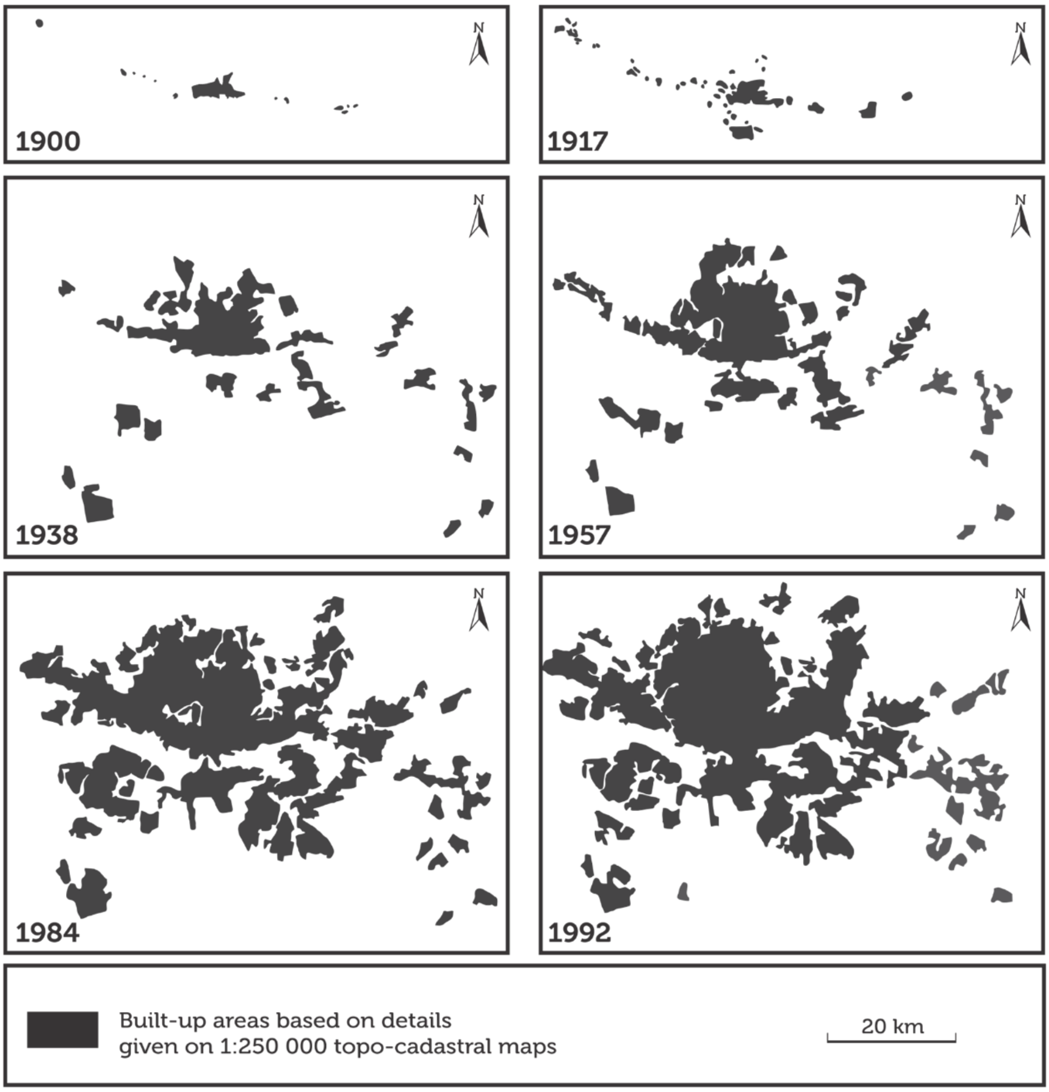


Figure 5: Development from Johannesburg from 1900 to 1992

Source: Created by author and adapted from Beavon (2004, p.7)

The tectonic event that created the *Witwatersrand* ridge exposed gold to the surface which was the catalyst of Johannesburg's development. Additionally, it also formed a continental watershed from which two major river basins were formed-the Senqu-Orange basin to the south of the city and the Limpopo Basin to the north (Turton et al., 2016, p.315). Streams and other tributaries in Johannesburg flowing south of the ridge flow through the Senqu-Orange basin through the Vaal River and into the Atlantic Ocean, whereas streams in the north of the city which are flowing east flow into the Limpopo River and eventually into the Indian Ocean Figure 6 shows the location of the basins with respect to South Africa

The *Witwatersrand* ridge therefore is a headwater for these two basins (Turton et al., 2006, p.316). The city's location on this watershed boundary at a high altitude therefore means that it has a very limited amount of natural water bodies. The topography of Johannesburg can be seen in Figure 7. Parts of the city reach an elevation of 2000 metres above sea level as seen in Figure 7 and the surrounding areas north and south of the city decrease in elevation. A combination of factors such as high altitude, limited water bodies and its location on a watershed present water resources challenges for the city. It therefore relies on inter-basin transfer and these two major basins fall under not just South Africa, but four other southern African nations: Namibia, Botswana, Zimbabwe and Mozambique, thus increasing the complexity of water resource management in the city.

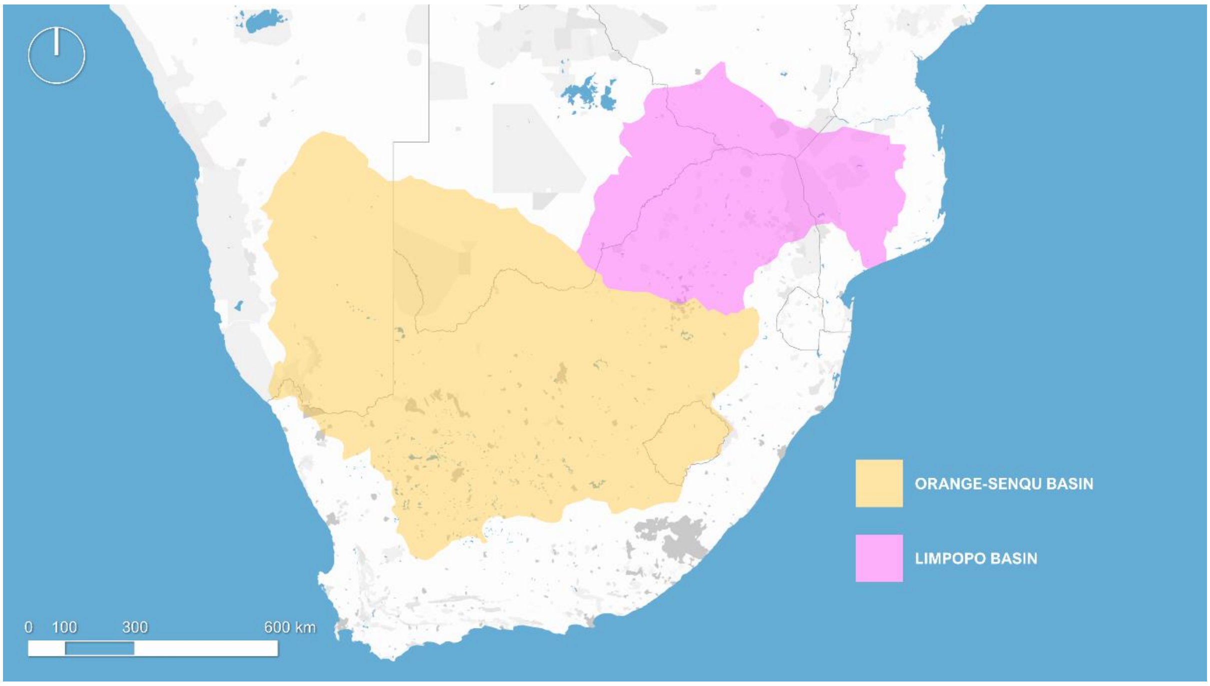


Figure 6: Orange-Senqu Basin and Limpopo Basin

Source: Created by author and adapted from Dippenaar (2015)

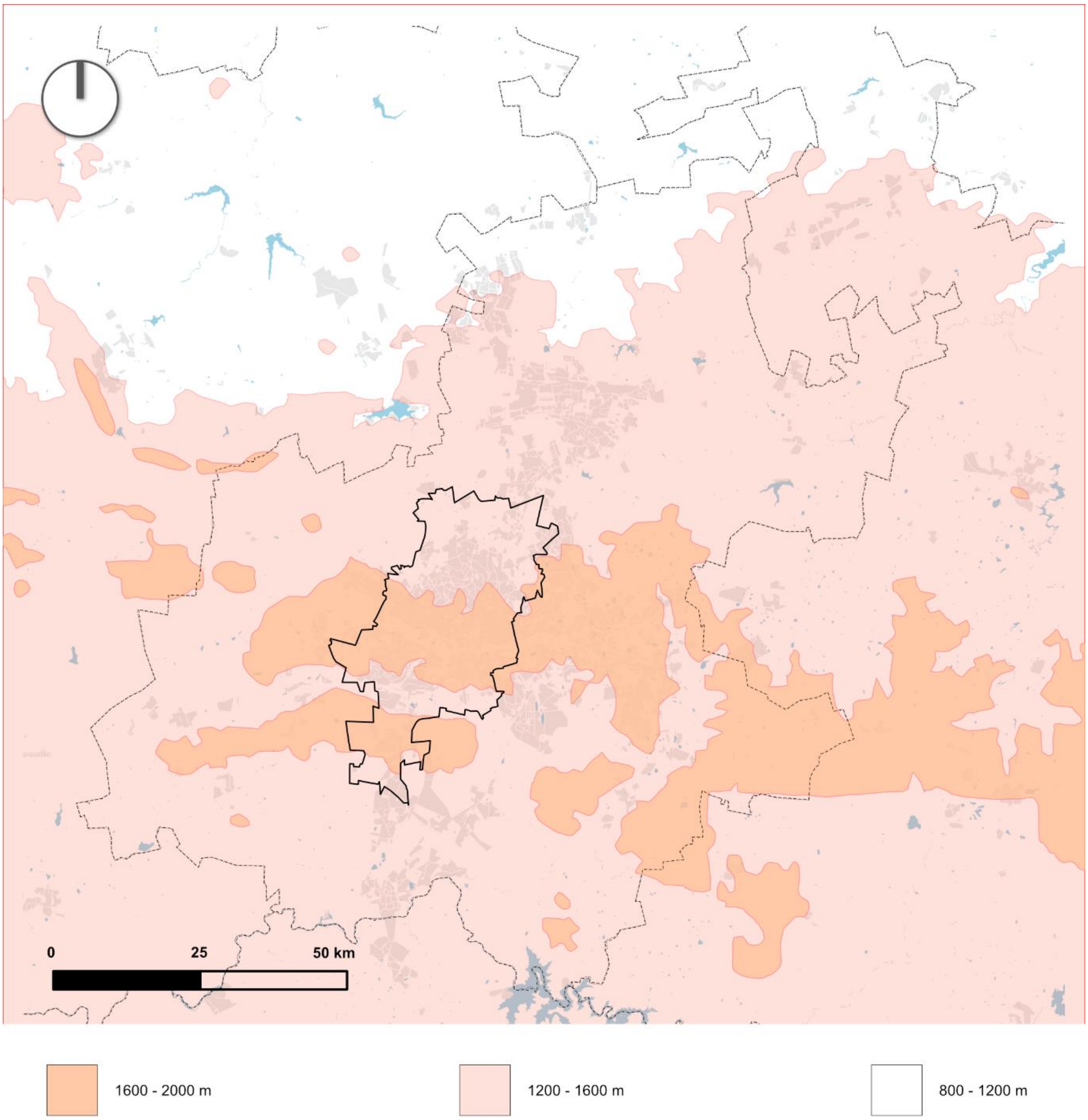


Figure 7: Topography of Johannesburg and the Gauteng province

Source: Created by author and adapted from Department of Water Affairs and Forestry (1999)

Regarding water and wastewater infrastructure, the proportion of households that do not have access to piped water and sanitation in the city in 2011 was reported to be 8.4 % and 10.7 % (STATS SA, 2014, GCRO, 2021b). That gap was reduced to 2.2 % and 3.6% in 2018 (City of Johannesburg, 2021a, p. 15). Figure 8 indicates the map representing the water access in 2011. Further investigation of these areas reveals that these areas contain informal settlements or are in close proximity to informal settlements. There are over 210 informal settlements in the city (City of Johannesburg, 2021a, p. 15). The city also demarcates zones known as deprivation areas where infrastructure backlogs are high and are thus earmarked specifically for development initiatives. A map indicating the informal settlements and deprivation areas can be seen in Figure 9.

A prevalent form of formal dwellings clustered together and protected by walls and fencing and accessible through protected entrances with additional access to public and communal amenities is known as a gated community (Landman, 2004). Gated communities are contentious in South Africa in that while providing safe and secure housing for middle-income and higher income level residents, it is also contributes towards exacerbating the deep socio-economic divide in the city by increasing social and economic isolation (Landman, 2004). The concentration of gated communities is predominantly in the north of the city as seen in Figure 10.

Johannesburg already has to already contend with the legacy of apartheid in which spatial planning was actively used as a tool to disenfranchise non-white groups of people in the city. The legacy can be seen in the disparity in the structuring of the city. This can be observed by comparing Figure 11 and Figure 12. Figure 11 indicates the population density of the city while Figure 12 indicates the zones of economic activity. The economic activity is calculated using the number of businesses within a 2 km radius. Areas characterised by low economic activity are comparatively denser than other areas. The areas of high economic activity contain gated communities and hence higher income earning individuals. Areas towards the south of Johannesburg characterised by a higher number of informal settlements have lower levels of economic activity. A comparison of Figures 8-12 all provide an informative outlook into the spatial structuring of the city. It can be understood that spatial structuring does have an effect on water access and it is therefore important to note in identifying areas that require urban water management and spatial strategic interventions.

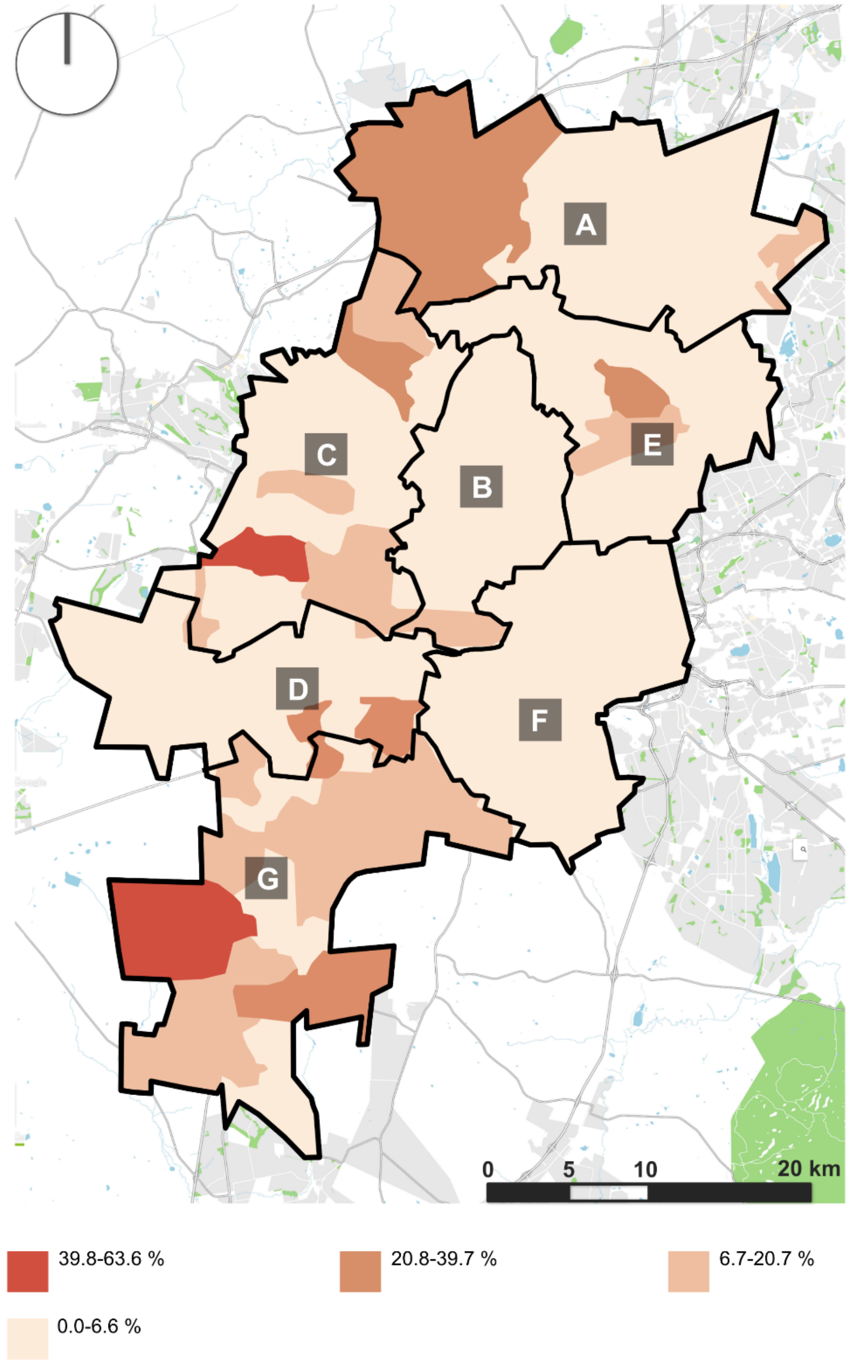


Figure 8: Map illustrating the proportion of inhabitants who do not have access to piped water

Source: Created by author from data sourced from GCRO (2021b)

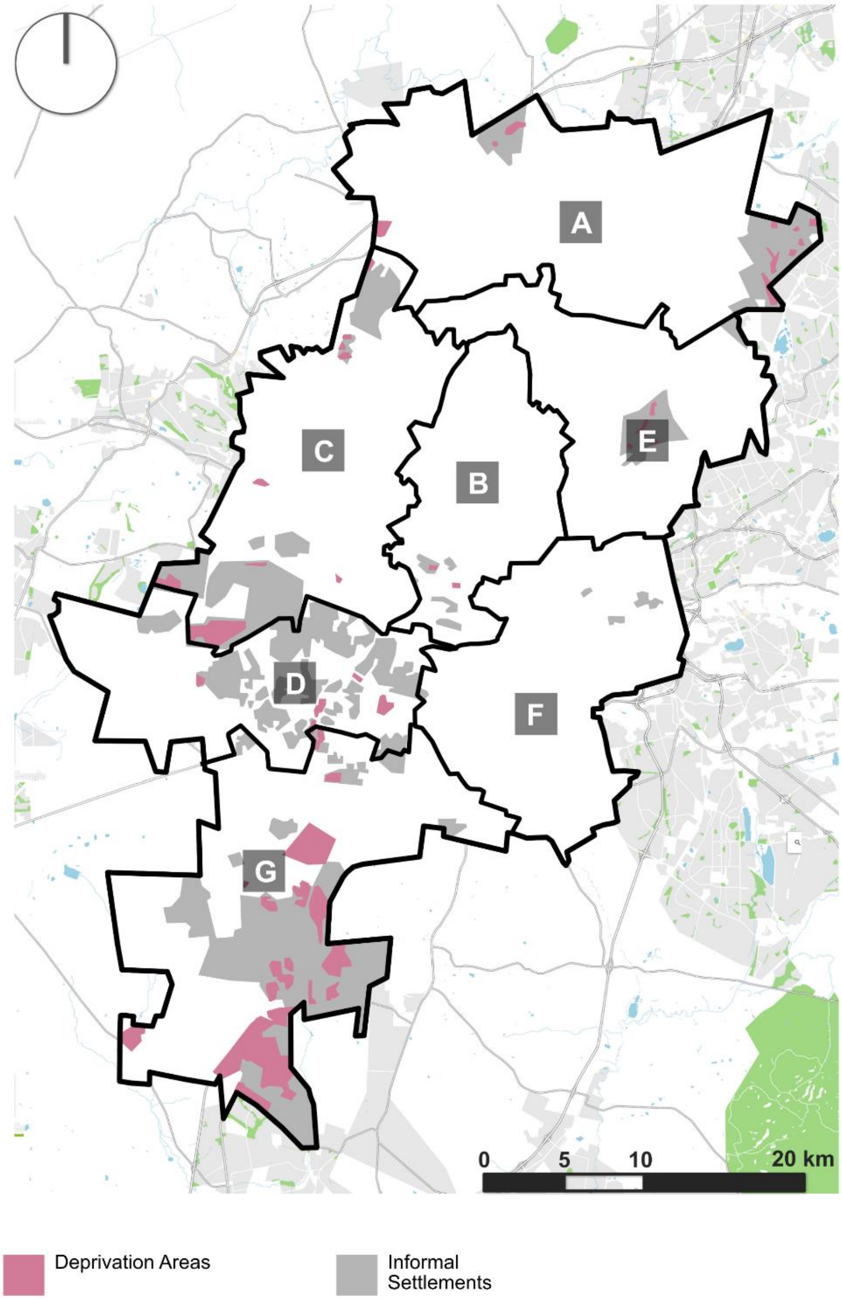


Figure 9: Informal settlement and deprivation areas in Johannesburg

Source: Created by author and adapted from data sourced from City of Johannesburg (2021b)

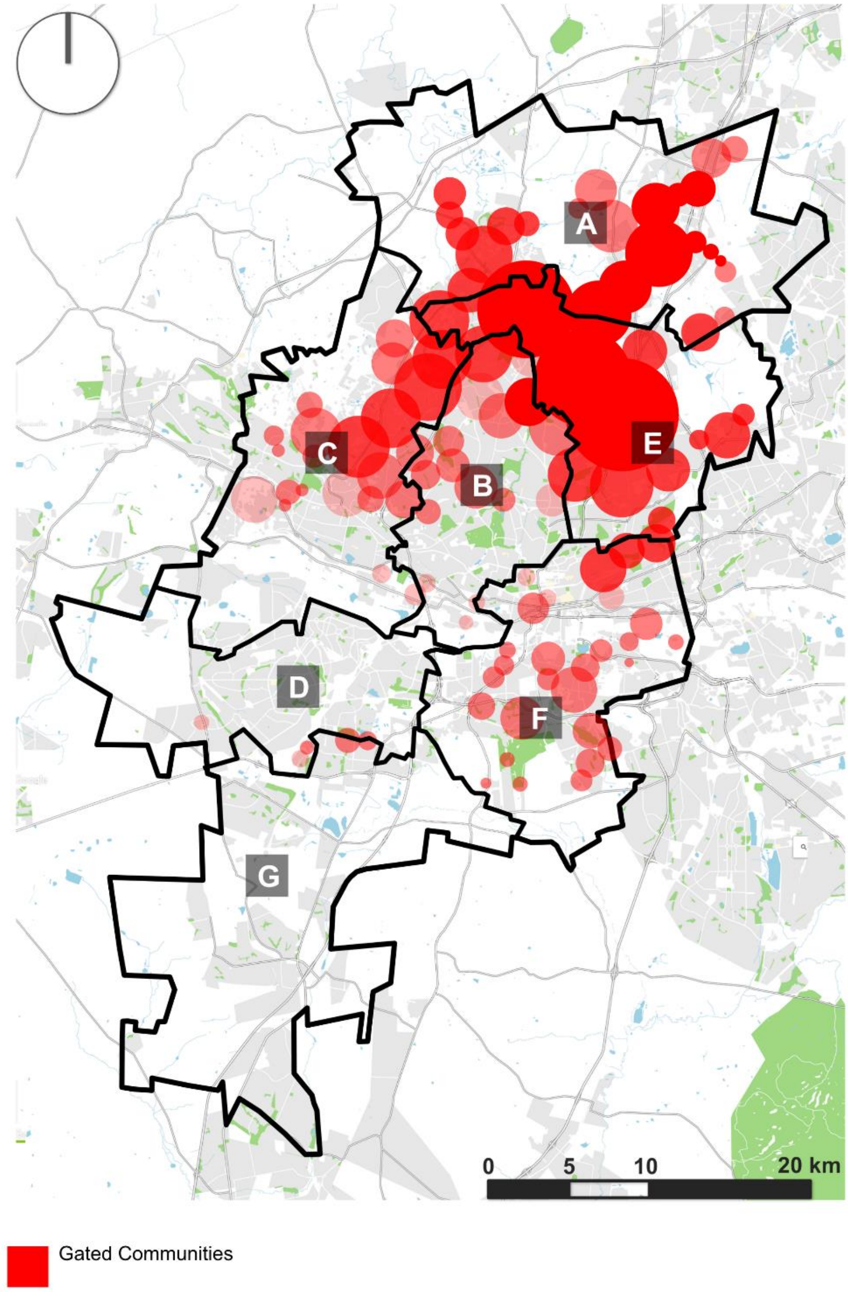


Figure 10: Map of the location of gated communities within the city

Source: Created by author from data sourced from GCRO (2021b)

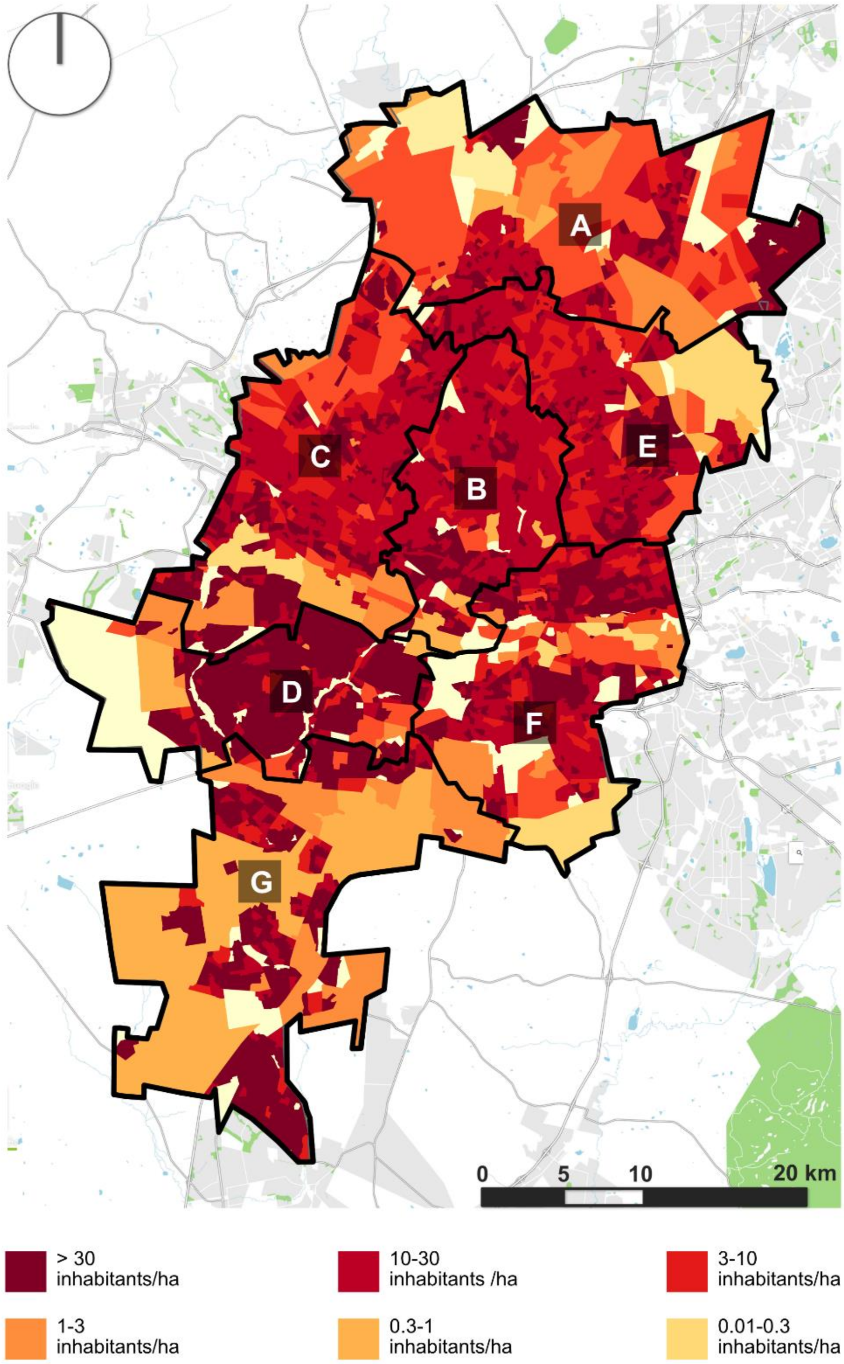


Figure 11: Population density of Johannesburg

Source: Created by author from data sourced from STATS SA (2012)

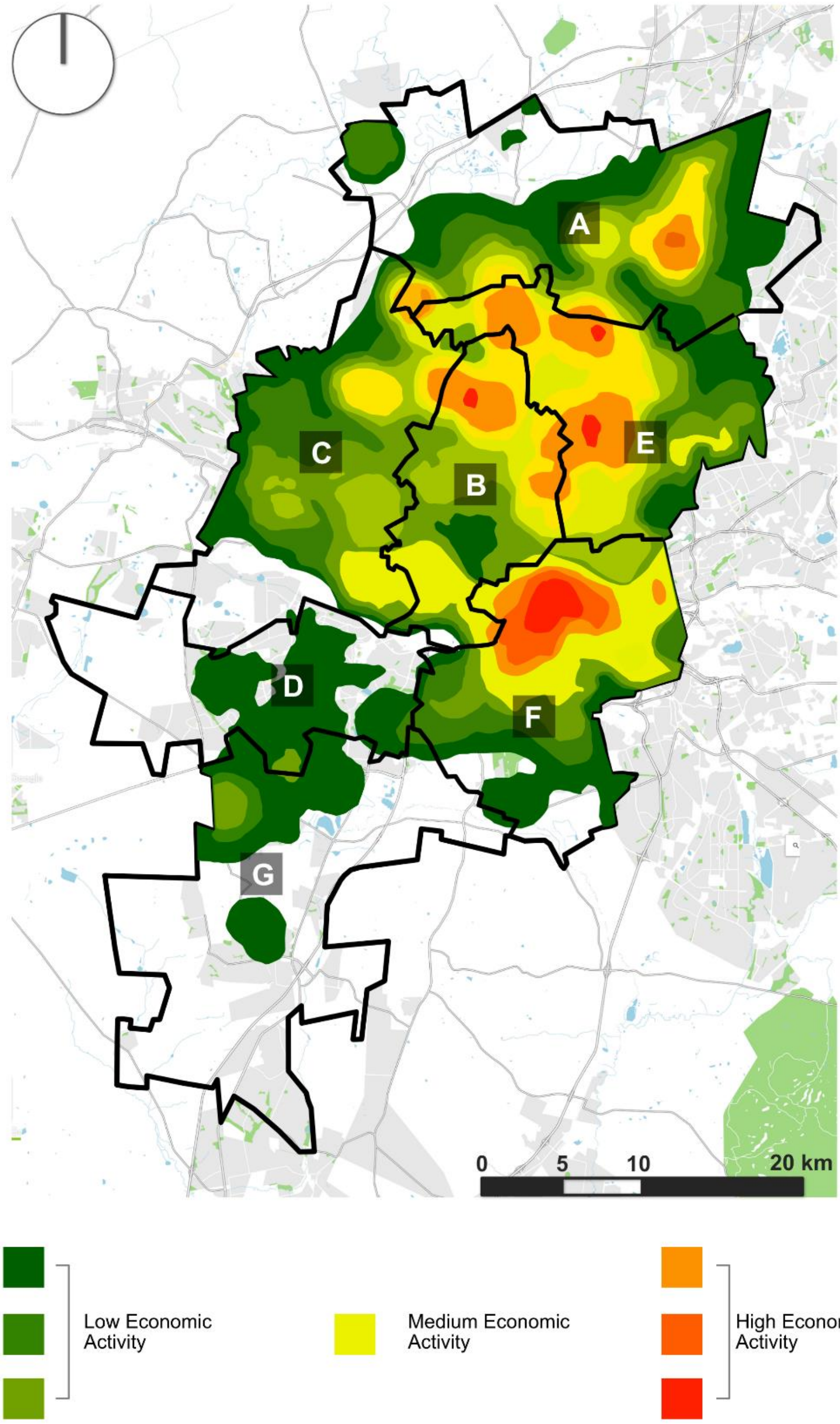


Figure 12: Map illustrating the level of economic activity in Johannesburg

Source: Created by author from data in GCRO (2021a)

3.2.2. Ecological Infrastructure in Johannesburg

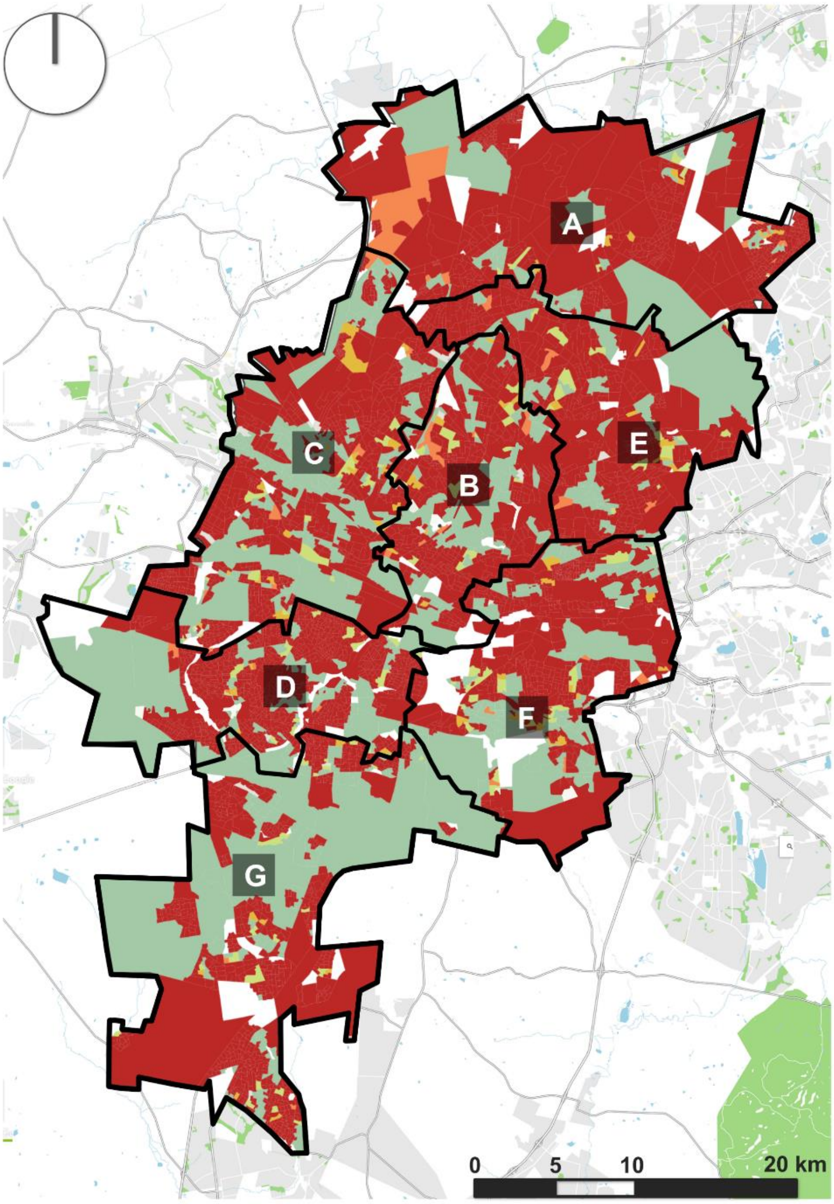
This section aims to shed light on Johannesburg's contemporary situation relating to its ecological infrastructure. There are three types of ecological assets in Johannesburg, viz. green public spaces, trees and vegetation as well as wetlands. The benefits of green, public spaces are numerous and include the improvement of air and water quality, reduction of the urban heat island effect, flood attenuation, the provision of recreational spaces as well as noise reduction (Culwick et al., 2016, Bobbins et al., 2019). Studies by Kondo et al. (2018), Mensah et al. (2016) and Zhang et al., (2017) confirm the positive impact of green spaces in urban environments. It is therefore important to assess all the ecological assets of Johannesburg.

Figure 13 presents the size of park space per capita for the city adapted from Bobbins et al. (2019). The map categorizes green space per capita based on a threshold reported in a report by Siemens known as the African Green City Index. This index presents 60 m^2 of green space per person as a minimum requirement (Economist Intelligence Unit & Siemens, 2012 as cited in Bobbins et al. 2019). Although the validity of this standard could not be verified, it is still worth analysing the park space per capita distribution in Johannesburg. The distribution of parks per capita that meet the minimum requirement is poor with many areas falling below the threshold as seen in Figure 13. It is important to note that the map does not differentiate between private and public green space, therefore some of the areas on the periphery of region D, F and G could be inaccessible and additionally it is important to observe that the population density of these areas is also low (refer to Figure 11) which would impact the representation of park space per capita (Bobbins et al. 2019). The map provides an overall indication that park space per capita in the city is insufficient.

Another aspect of park space that is important to understand is park space accessibility seen in Figure 14. The map was developed using an index based on three factors and by dividing the area into 0.16 km^2 hexagons. The first factor that was considered was the existing road network in the city because most parks in the city are accessible via roads. The second and third factors included a calculation of a walkability score and a score based on how many services are within a 2 km radius using the centre of the hexagon as a reference. Parks that that have been shown on the map are parks that are owned by the municipality and the map does not account for restricted green spaces such as country clubs, golf courses and other privately owned green spaces in gated communities. The index indicates that 0 is the lowest rating which indicates the worst accessibility and 1 is ranked as the highest rating indicating the best accessibility (Bobbins et al., 2019). Areas which indicate the largest proportion of high park accessibility are concentrated in the centre of the city in regions C, B and E. The peripheral areas of the city contain low levels of park accessibility, specifically in the southern portion of the city. A study on green spaces in South African cities (Venter et al., 2020, p. 9) determined that there is severe inequity in the distribution of green assets with most assets concentrated in the north. The park accessibility index and park space per capita maps all indicate a further need to explore options that are green infrastructure (GI) based for the city at large.

Another issue that the city faces with regard to green infrastructure is the presence of alien species. Figure 15 highlights the average density of invasive alien plants within Johannesburg. The average density of invasive alien plants is expressed as a percentage. The colour opacity of each range of percentage increases as it reaches the upper limit. Region A has an average density of alien species between 10-25% distributed throughout the region while the highest density of alien species is present in the southern portion of region C.

Johannesburg also has a high density of trees in the cities in comparison to all the other cities in the province. A high number of trees was planted in the city during the peak mining periods over a 100 years ago (Schäffler et al., 2013, p. 31). The number of non-natural and planted trees in the city cover 14% of the city's surface area which is the highest amongst all the cities in Gauteng (Schäffler et al., 2013, p. 27). The urban forest, however, is not evenly distributed within the city (Venter et al., 2020), with greater portions of trees concentrated in the north of the city.



0-59 square metres

60-65 square metres

66-72 square metres

73-75 square metres

76-100 square metres

101-60 207 square metres

Figure 13: Green space per capita measured in square metres in Johannesburg

Source: Created by author from data in Bobbins et al. (2019)

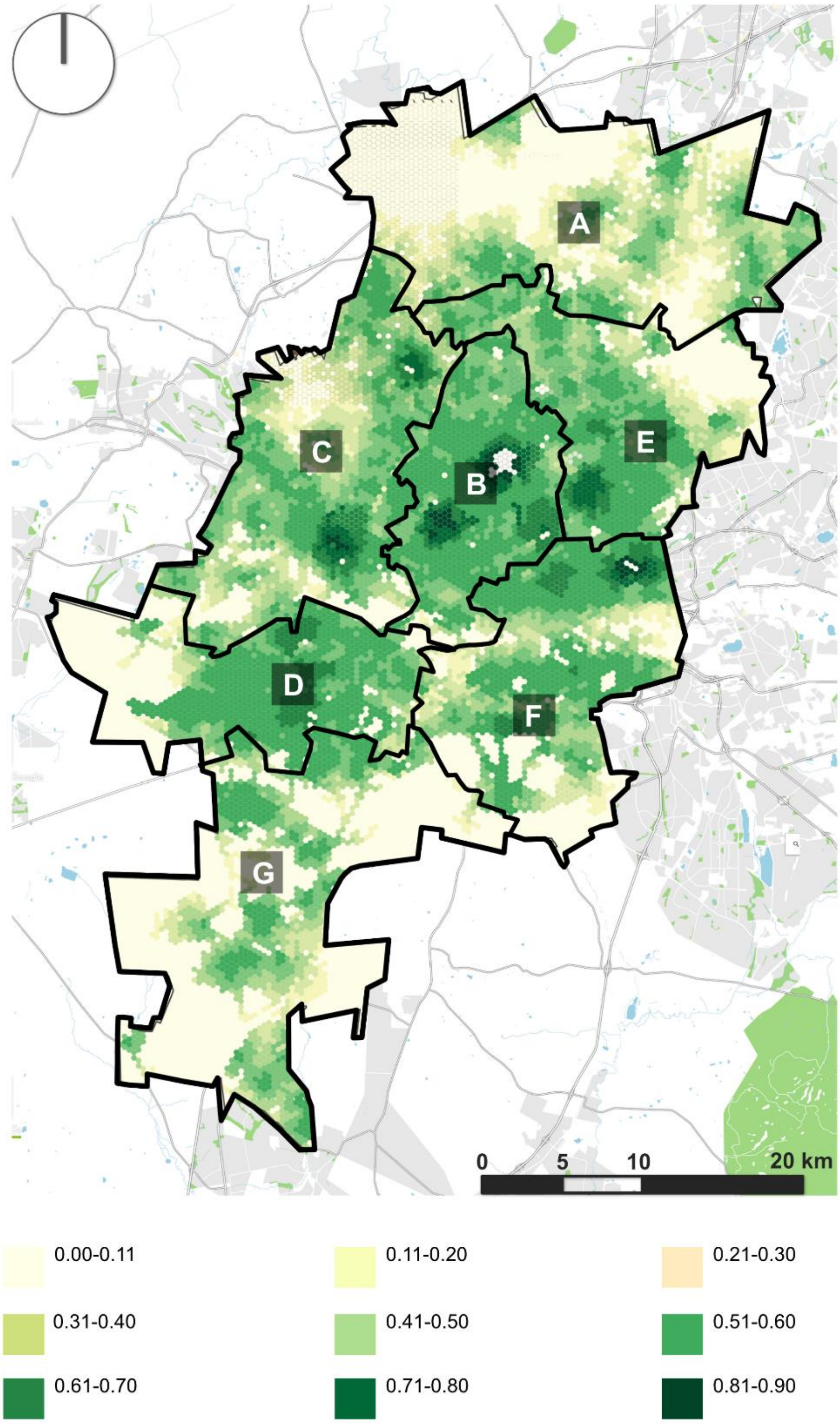


Figure 14: Park accessibility index for Johannesburg

Source: Created by author from data in Bobbins et al. (2019)

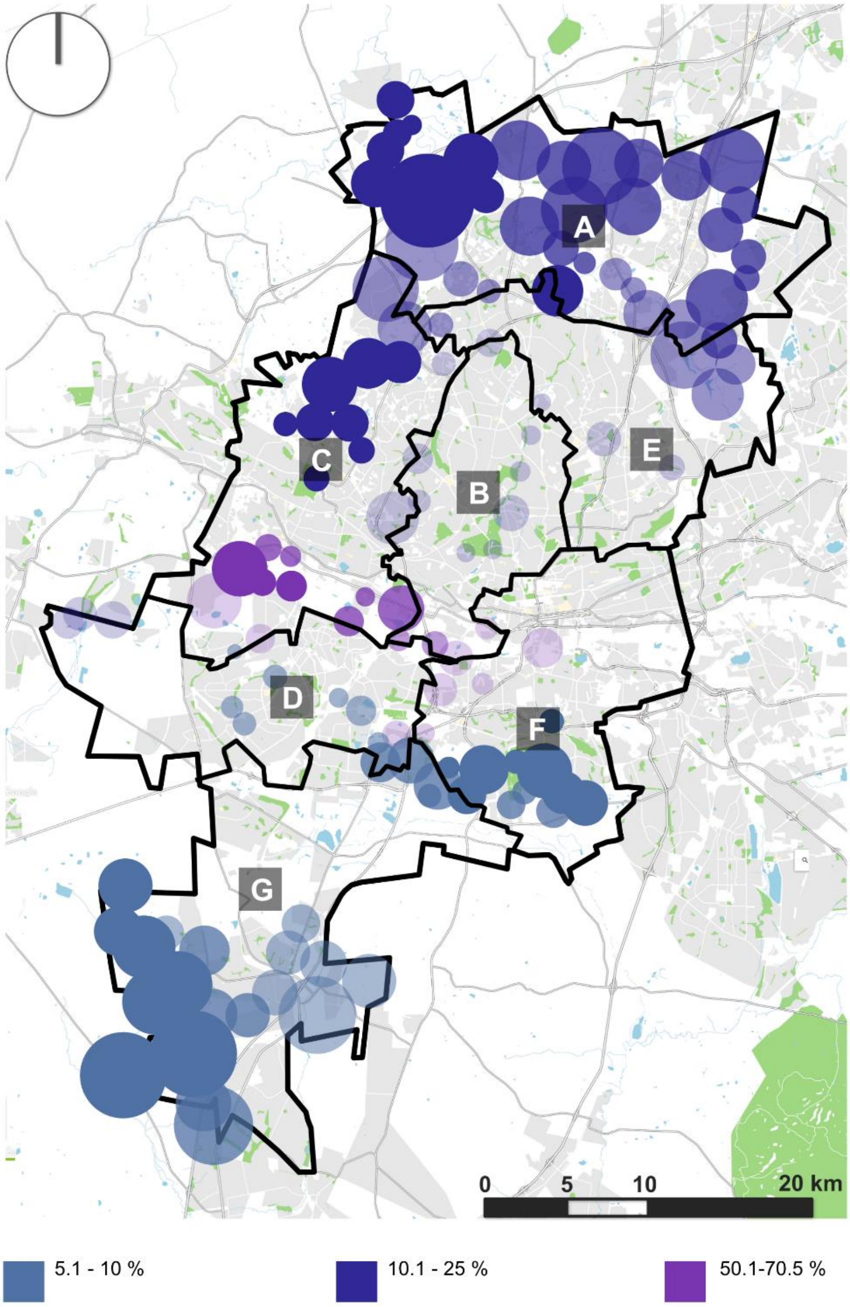


Figure 15: Average percentage density of alien species

Source: Created by author and adapted from data in GCRO (2021a)

Firstly, to understand the situation in the city relating to wetlands, it is important to understand the type of wetlands found in Johannesburg. There are four classifications of wetlands according to Van Deventer et al. (2019) found in Johannesburg namely: channelled valley-bottom wetlands, depression wetlands, seep wetland and unchanneled valley-bottom wetlands. A channelled valley bottom wetland is one that does not have typical features characteristic of a floodplain and has a river or stream passing through it (Ollis et al., 2013, p.24). The second type is an unchanneled-valley bottom which simply does not have a visible stream or river running through it. It is largely characterised by water that may spill over into the wetland from floods or water collected from rain (diffuse water) (Tank, 1983, p. 191) or flow beneath the surface. Groundwater infiltration is high in this type of wetland (Ollis et al., 2013, p. 29). The third type of wetland is known as a depression wetland which is characterised by "closed (or near closed) elevation contours, which increases in depth from the perimeter to a central area of greatest depth and within which water typically accumulates" (Ollis et al., 2013, p. 29). The final type of wetland found in the city is a seep wetland which is distinguished typically by subsurface flowing down a gently steeped slope (Ollis et al., 2013, p.35). Figure 16 and Figure 17 represent conceptual representations of the most common type of wetlands found in Johannesburg, i.e., channelled and unchanneled valley bottom wetland.

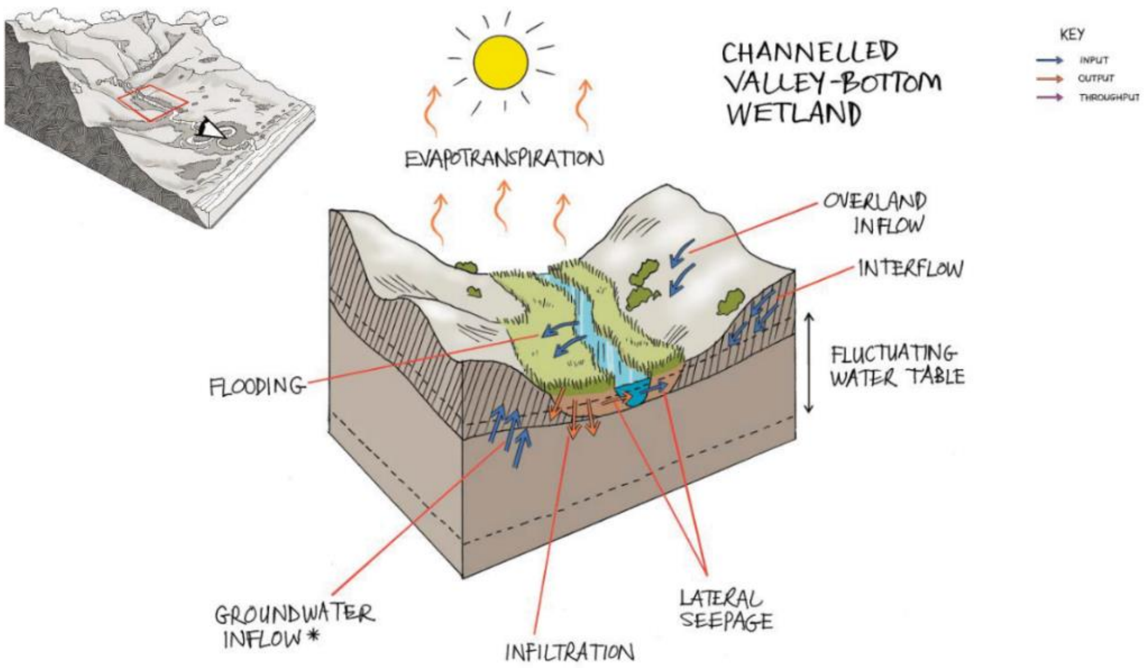


Figure 16: Channelled valley-bottom wetland

Source: Ollis et al. (2013, p.28)

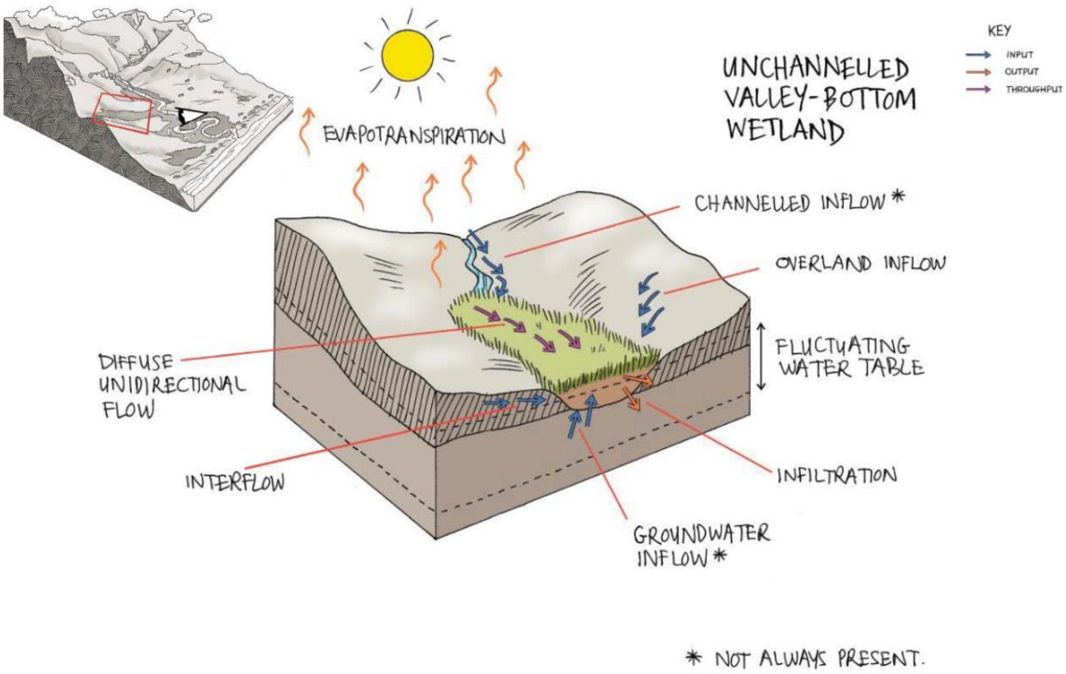


Figure 17: Unchannelled valley-bottom wetland

Source: Ollis et al. (2013, p.30)

The city is largely characterised by unchanneled valley-bottom wetlands and the distribution of which can be seen in Figure 18. This typically indicates that diffuse water can be found in such wetlands and can easily be polluted by contaminants if there is an overflow of stormwater percolating from urbanised areas in the city or if there are poor sanitation services in the area, which means wastewater discharge can easily accumulate in these areas. This could likely infiltrate into the underlying aquifers as well cause issues relating to groundwater. According to an analysis by Bobbins et al. (2019, p.28) the surface area of wetland areas have degraded between 1990 and 2004 by 15% in the Gauteng province and this in turn poses a significant threat to the environment as wetlands are invaluable for the ecosystem as they improve water quality and promote biodiversity. Since there is a clear decrease over time of wetland assets, it is crucial for Johannesburg to protect and rehabilitate its existing wetlands as part of a transition towards a water sensitive city. Figure 19 is a map of the main streams or rivers in Johannesburg, one can see that the classification of primary rivers determined from the Water Research Commission's 2012 Water Resource Study (Water Research Commission, 2021) is very similar to the study by Van Deventer et al. (2019) with a few exceptions. This could be due to the type of satellite imagery used within each study.

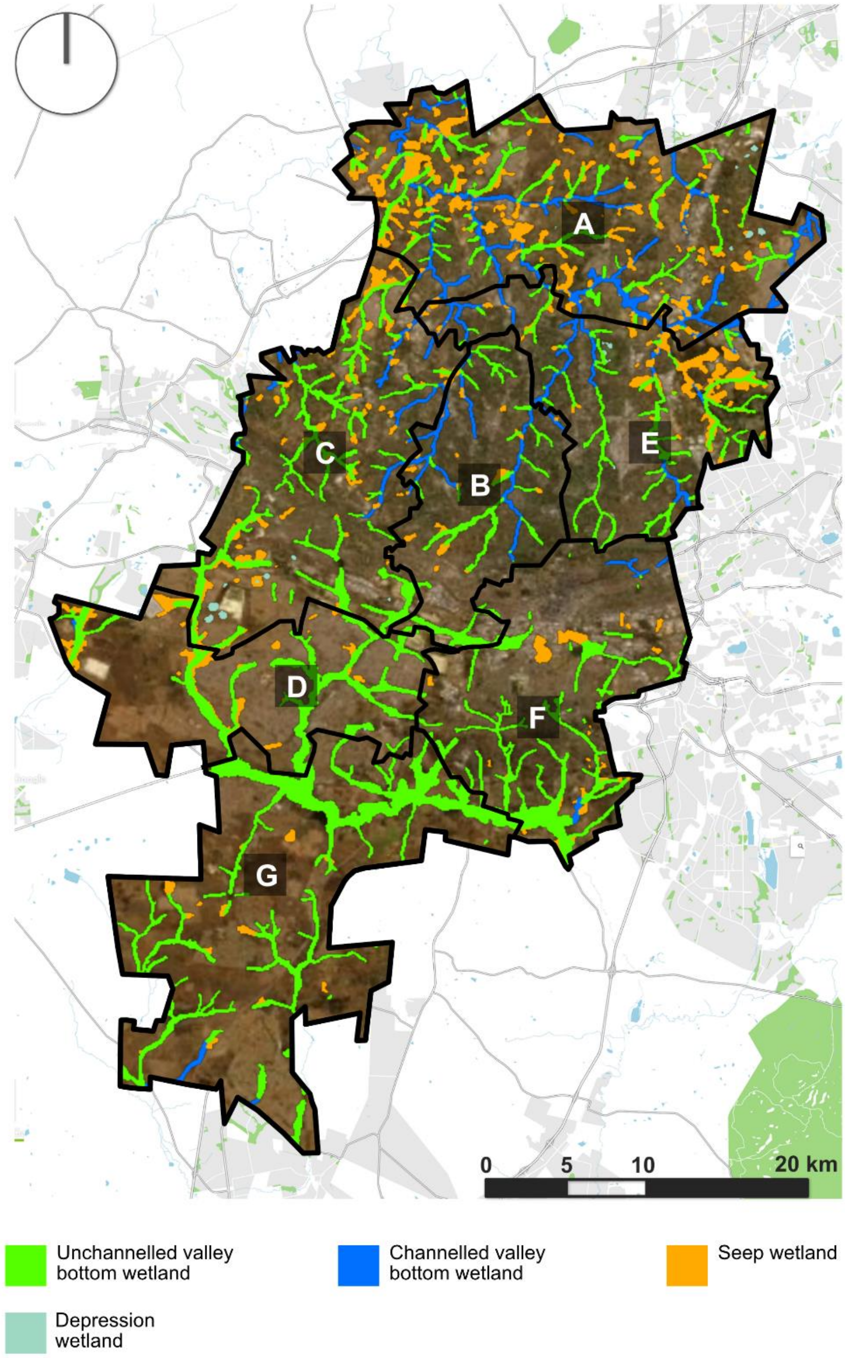


Figure 18: Wetland Distribution through Johannesburg

Source: Created by author and adapted from Western Cape Department of Agriculture (2021) and Van Deventer (2019)

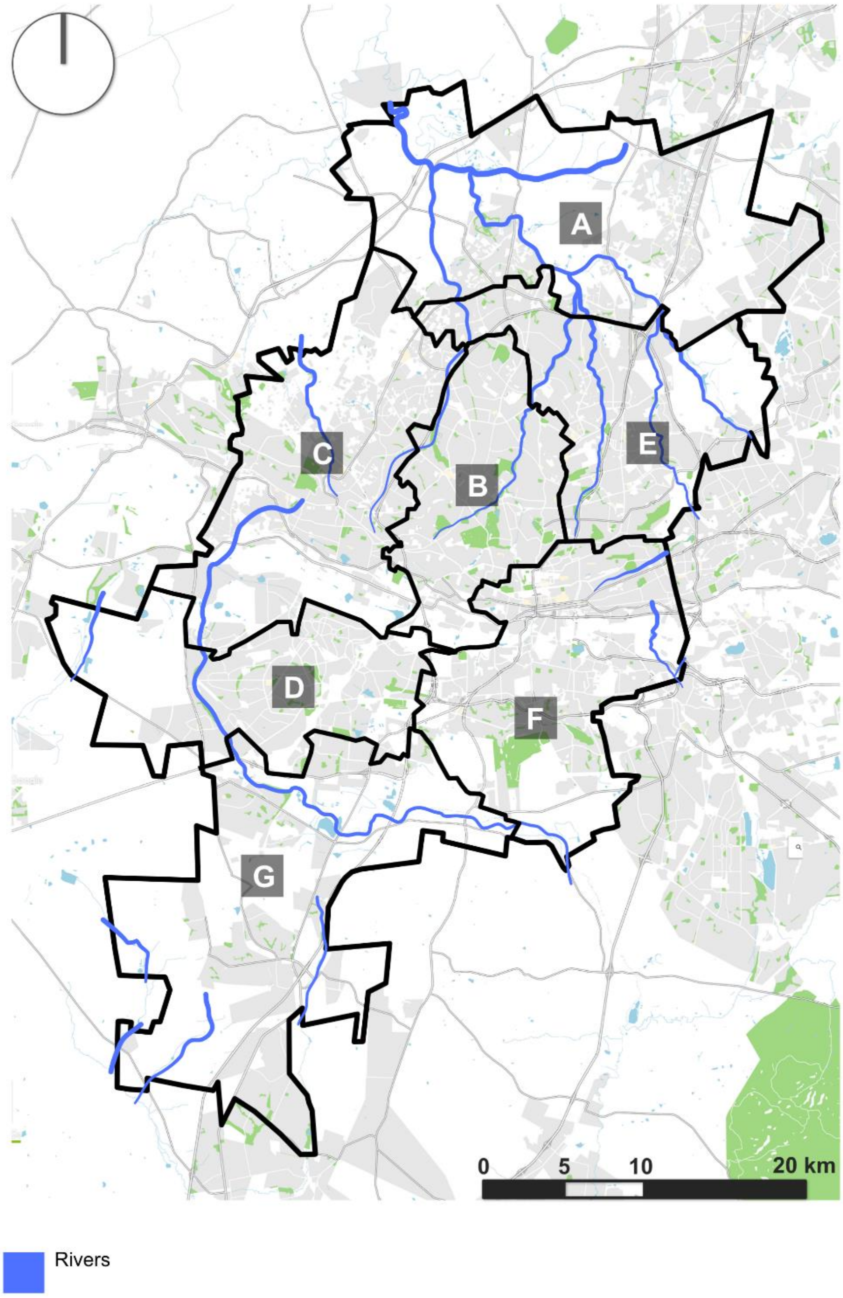


Figure 19: River classification in Johannesburg

Source: Created by author and adapted from data from Water Research Commission (2021)

3.3. Johannesburg: A Hydrological Review

3.3.1. Where does Johannesburg's Water Come From?

Johannesburg's centralized supply system relies on sourcing water from outside the city from what is known as the Integrated Vaal River System (IVRS). This inter-basin transfer system uses natural rivers and tributaries in combination with bulk water transfer infrastructure form other catchment areas to transfer water into the Vaal Dam which supplies water directly to Johannesburg. There are two main transfer schemes that pump water into the Vaal Dam in order to augment supply to Johannesburg and other municipalities in the Gauteng province (Muller et al., 2019).

a. The Thukela-Vaal Transfer Scheme

This water transfer scheme was first completed in 1974 and water is transferred from the Tugela River and originates in the Drakensberg mountains near Lesotho. The scheme ensures that water from the rivers is transferred from Woodstock dam via canals, pipelines and dams into the Vaal River and subsequently the Vaal Dam. A section of the schemes known as the Drakensberg Pumped Storage Scheme is used to generate electricity to the national grid supplier. During non-peak water demand periods, water is stored in the Sterkfontein dam and released into the Vaal Dam when needed.

b. Lesotho's Highlands Water Scheme

This scheme is part of an inter-nation agreement with Lesotho in which water is transferred from the Senqu river in the Lesotho Mountains and from the Katse dam over 200 km to the Vaal Dam through underground pipelines. The project was first proposed in 1954 and comprises of three phases in which four dams were built. The proposed completion date for the second phase of the project is 2026 (Dippenaar, 2015; Muller et al., 2019). The second phase is likely to increase water supply to Johannesburg but delays in construction have tightened the pressure on water security in Johannesburg.

An approximate schematic of the above transfer schemes can be seen in Figure 20.

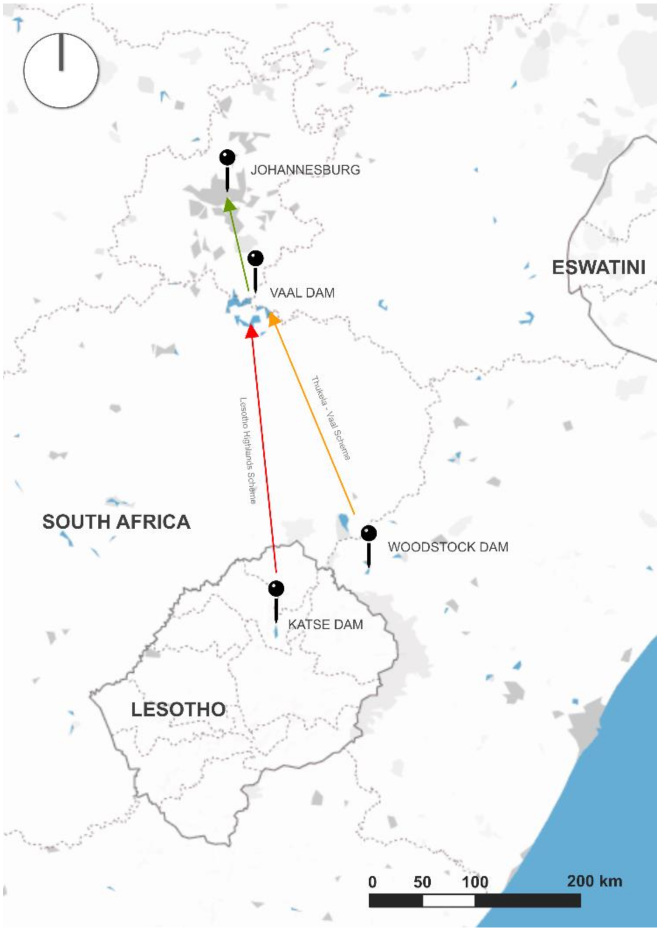


Figure 20: Water transfer schemes supplying the Vaal dam and Johannesburg

Source: Created by author and adapted from Snazzy Maps (2021)

The overall water demand per household in Johannesburg was estimated to be 318 litres/capita/day in 2019 (Cullis and Philips, 2019) with the centralized water supply system relying completely on surface water. The future water demand vs supply vulnerability for Johannesburg under a high population growth scenario indicates that Johannesburg's risk factor for not meeting the demand for water more than doubles in 2050 without any supply augmentation and without experiencing the impact of climate change. Past water supply and demand analysis also indicate this continuous increase in water demand as seen in Figure 21. The graph shows that the past trends have shown that it follows closely with the projected trend which shows the situation under a scenario in which there is no water demand management (WDM) and a high population growth scenario.

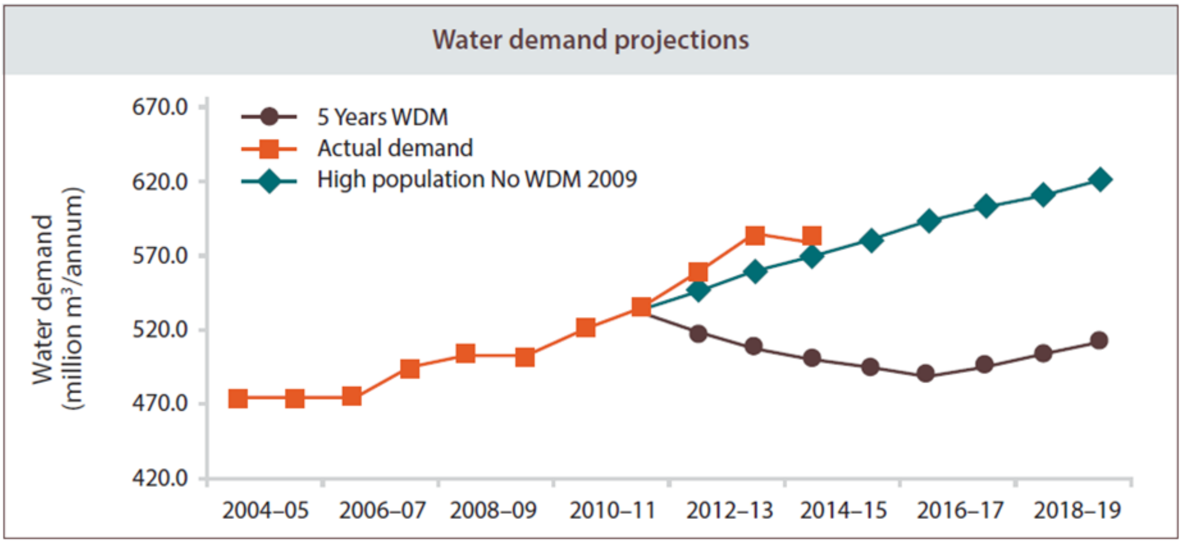


Figure 21: Past water demand trends in Johannesburg

Source: Dippenaar (2015,p.12)

The project demand growth for 2040 in Johannesburg is illustrated in Figure 22. The graph shows projected trends under various scenarios. Both graphs (Figure 21 and Figure 22) also confirm that population growth is intrinsically linked to water demand.

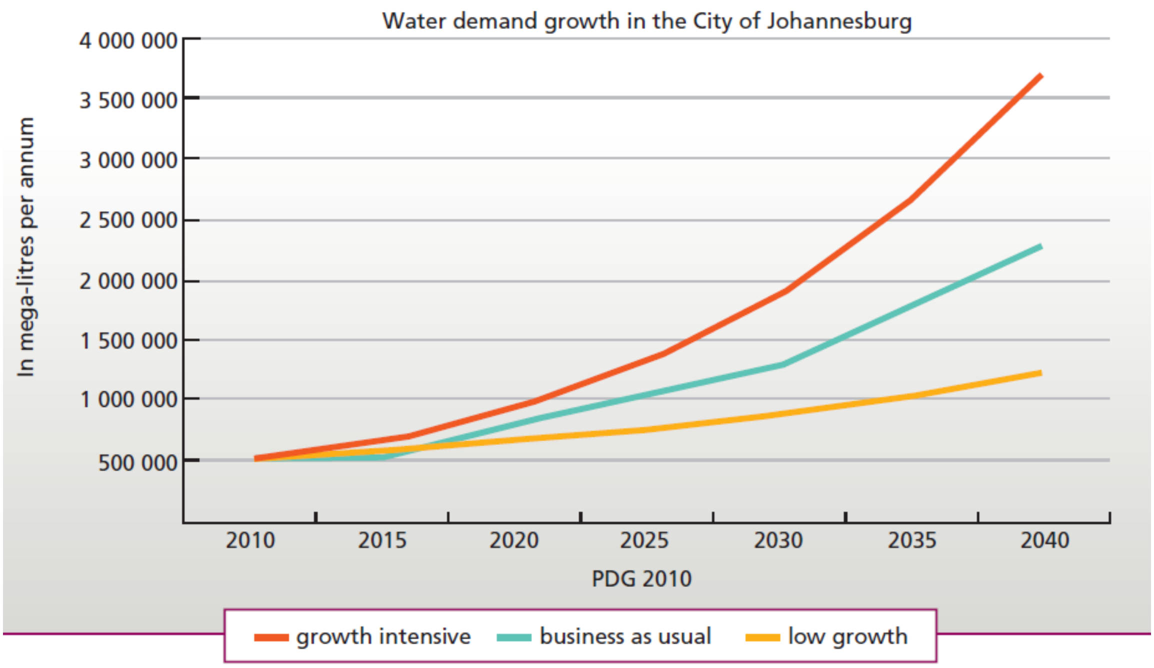


Figure 22: Projected water demand growth 2040

Source: City of Johannesburg (2011, p.57)

Future forecasting and past trends therefore indicate that managing the water demand is of paramount importance for the city. In 2018, the National Department of Water and Sanitation

(DWS) presented targets for municipalities in Gauteng including Johannesburg which receives the highest portion of water in the IVRS System (Department of Sanitation, 2018). The targets have yet to be reached for Johannesburg.

Johannesburg's reliance on surface water is especially risky given that there have been numerous delays with regard to phase II of the Lesotho Highlands scheme as well as the existing climate variability that is only exacerbated by warmer temperatures due to climate change that increase the rate of evapotranspiration (City of Johannesburg, 2021a). Supply restrictions to end users are applied periodically to manage this risk and fall within the targets set by the DWS as well as to compensate for infrastructure failures such as burst pipes and other related operational failures (Muller et al., 2019), which incidentally cause 38% of the bulk supply to Johannesburg to be lost (City of Johannesburg, 2019, p.84). Approximately 4.3 % of residents reported water interruptions in the city in 2018 (STATS SA, 2019, p.45). Additionally, periodic and regular electricity cuts interrupt water distribution throughout the city (City of Johannesburg, 2021a, Johannesburg Water, 2019). There does exist a decentralised water supply system using groundwater, however, there are some issues in relation to that, which will be explored in Section 3.3.4. Additionally, there is a system of free basic water supplied to households below a certain income level. The effect at which this influences water demand does not fall under the scope of the thesis. Overall, it can therefore be understood that there are numerous challenges to contend with regard to water supply distribution in the city.

3.3.2. Wastewater Management and Sanitation

There are six wastewater treatment works (WWTW) in Johannesburg. Wastewater is treated at these plants and discharged into small rivers depending on which side of the watershed the plant is located. On either catchment, there are serious water quality issues downstream of these catchment areas. This is due to the lack of compliance regarding wastewater treatment (Dippenaar, 2015). In 2019, only 78% of wastewater discharged met the required standards (Johannesburg Water, 2019, p.14). Approximately 81% of surface water samples taken downstream from the Gauteng catchment areas were noted to contain above average and potentially dangerous levels of *Escherichia coli* (E.coli) (Muller et al.,2019, p. 23). Muller et al. (2019, p.23) adds that some WWTW receive levels of wastewater beyond their maximum capacity and this is due to misalignment between housing and water services development agendas on a provincial scale. Low-cost housing and other settlements are built without ensuring that WWTWs will be able to meet the demand, and this leads to an overflow of raw, untreated sewage. Adding onto the load of wastewater received by WWTW, is the drainage of stormwater into sewage systems and due to lack of regulations, some stormwater drains are intentionally designed to connect to sewage systems in order to reduce the cost of development.

A positive aspect is that Johannesburg has integrated bio-gas-electricity systems in two WWTWs, i.e. The Northern WWTW and Driefontein WWTW. Anaerobic sludge digestion is used to extract organic matter to produce methane gas which is used to generate electricity to power the operation of the WWTW. This reduces the energy costs of the WWTWs (City of Johannesburg, 2021a, Dippenaar, 2015).

Access to sanitation in Johannesburg is not as comprehensive as water access with a proportion of 3.6% of residents in Johannesburg who do not have access to a flushed toilet (STATS SA, 2019, p.48). In informal settlements, shared sanitation facilities are common, however numerous issues have been experienced by those who use these facilities. Issues include poor lighting and hygiene as well as lack of maintenance, safety and privacy (STATS SA, 2019, p.51). It is common in informal settlements to find Ventilated Improved Pit (VIP) systems (Anaman, 2014, p.32). This is where a ventilated hole in the ground is used to collect waste (Eawag, 2021).

In formal areas, sewage systems are prone to blockages and operational failures which cause overflows and drain into stormwater infrastructure into nearby streams, contributing to an increase in polluted waterbodies (Muller et al., 2019). This has major health implications for both humans and the environment.

3.3.3. Stormwater Management

Johannesburg and most other cities in South Africa follow the conventional approach to stormwater management. Stormwater runoff is drained and redirected to the nearest watercourse away from the built environment (buildings, parking areas, etc) as quickly as possible using gutters and downpipes. The built up-area accounts for at least 32% of the total land area in Johannesburg (Schäffler et al., 2013, p.27). These surfaces are mainly made up of concrete and bitumen and are impervious to absorbing stormwater and usually designed with intention of ensuring stormwater runoff is redirected (Armitage, 2011). An increase in impervious surfaces increase the likelihood of erosion and flooding as the volume of stormwater runoff collected on the surface increases. Stormwater runoff infiltration into the soil also reduces the rate of recharge for the underlying aquifer. When the aquifer does not have enough time to recharge and groundwater is extracted, the water table is lowered which can affect groundwater quality and cause land subsidence (Konikow and Kendy, 2005)This redirection of stormwater the nearest stream increases pollution of water bodies as stormwater can contain many pollutants such as solid waste, silt and heavy metals from car exhausts

(Opher and Friedler, 2010). Added contaminants from sewage discharge can spill over into stormwater drains as well.

According to Mguni (2015) Johannesburg has the potential towards integrating SuDs schemes successfully. The city has attempted to shift to more sustainable stormwater management measures. Mguni's (2015) study also indicates that there are still challenges in ensuring smooth integration of these practices. The main challenges include a lack knowledge and skills on both an operational and policy level in order to ensure implementation, maintenance and monitoring of SuDs schemes. This will require coordination between stakeholders (Mguni, 2015). One of Johannesburg's advantages, however, is in that it is the economic capital of South Africa and therefore has considerably more financial resources than most local governments of other cities (Mguni, 2015) in order to continuously engage with SuDs.

The mean annual surface runoff levels for the city are illustrated in Figure 23. The average levels of surface runoff were recorded over the period between 1920 and 2004 (Middleton and Bailey, 2011). Higher levels of runoff are found towards the central areas of the city. This could possibly be due to watershed.

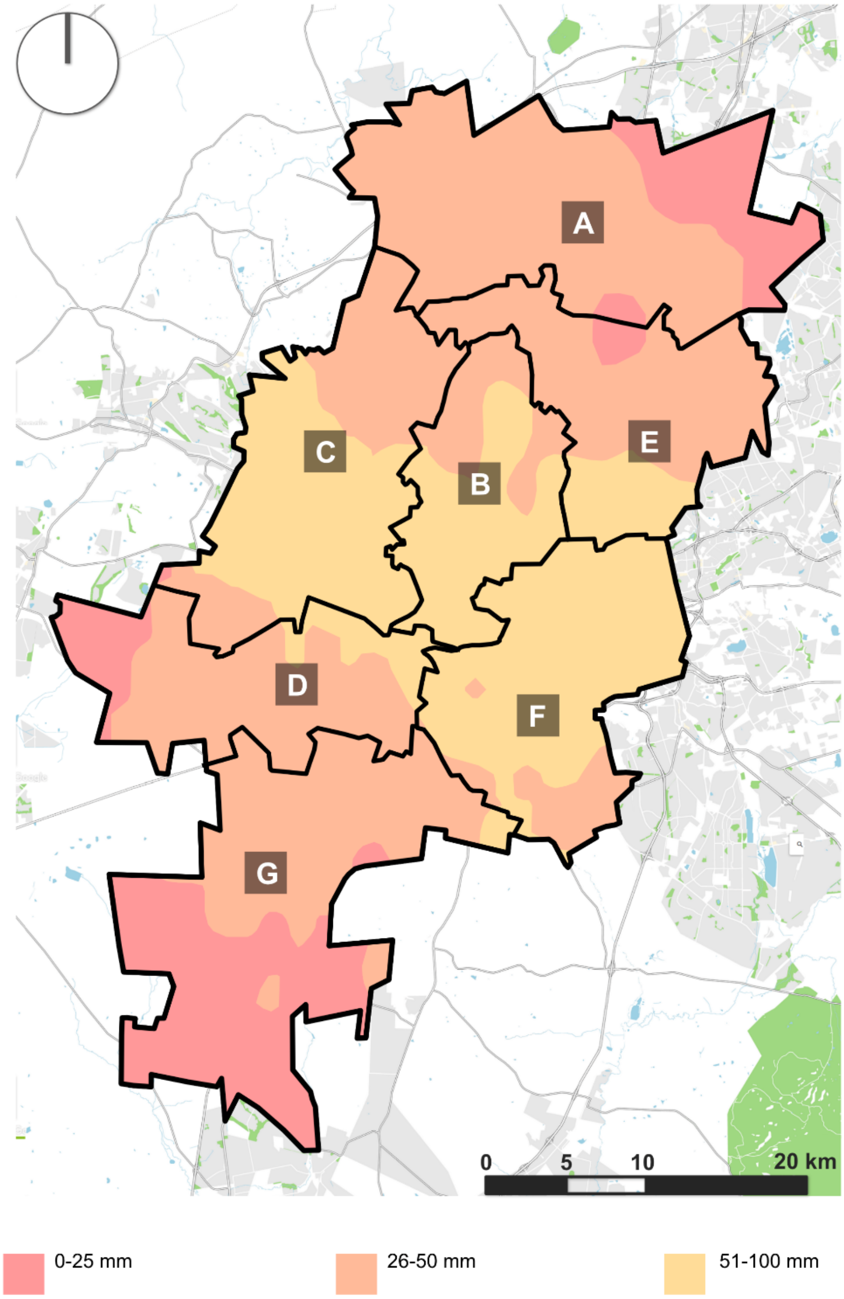


Figure 23: Mean Annual Surface Runoff for Johannesburg

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

3.3.4. Groundwater Resources in Johannesburg

The centralized water supply system in Johannesburg is solely reliant on surface water, however groundwater as a water resource plays an important role in supplying water for domestic and smaller industrial activities (Abiye et al., 2011, p. 99). To further understand the groundwater situation in Johannesburg, it is important to understand the underlying geological conditions of the city. The geology is predominantly composed of hard rock and therefore only small amounts of water can be extracted which in turn cannot form part of the centralized water system of Johannesburg. There are, however, higher volumes of groundwater available specifically in the south of Johannesburg due to the underlying aquifer conditions which are karstic dolomite (Abiye et al., 2018, p.2). The dolomite aquifer is located in the south of Johannesburg and is pivotal in its contribution to base flows for streams and rivers in and around Johannesburg (Anaman, 2014, p.30). The potential recharge depth can be seen in Figure 24 which indicates the depth in mm at which water from infiltration and percolation is received by the underlying aquifer. The dolomitic nature of the aquifer also has potential issues since it is highly permeable and therefore vulnerable to contamination due to improper sanitation and mining related pollution. Sanitation related pollution is likely to occur in informal settlements where nearby watercourses are likely to be polluted by waste or where VIP systems are used, both of which can affect the quality of groundwater (Anaman, 2014; Dippenaar, 2015; Muller et al., 2019). Figure 25 illustrates the groundwater vulnerability risk in the city and it can be observed that the underlying dolomite aquifer is the most at risk due to contamination.

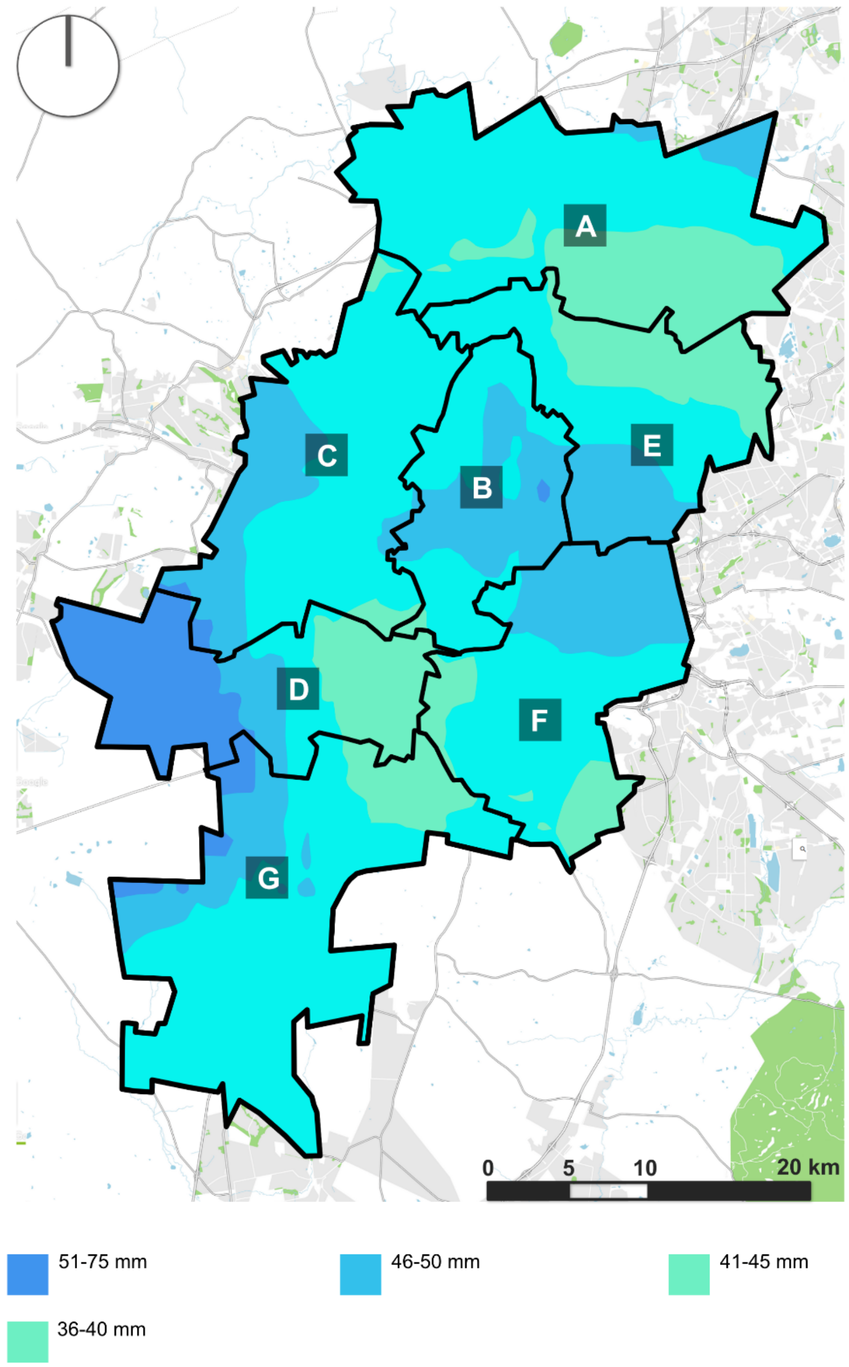


Figure 24: Groundwater recharge depth

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

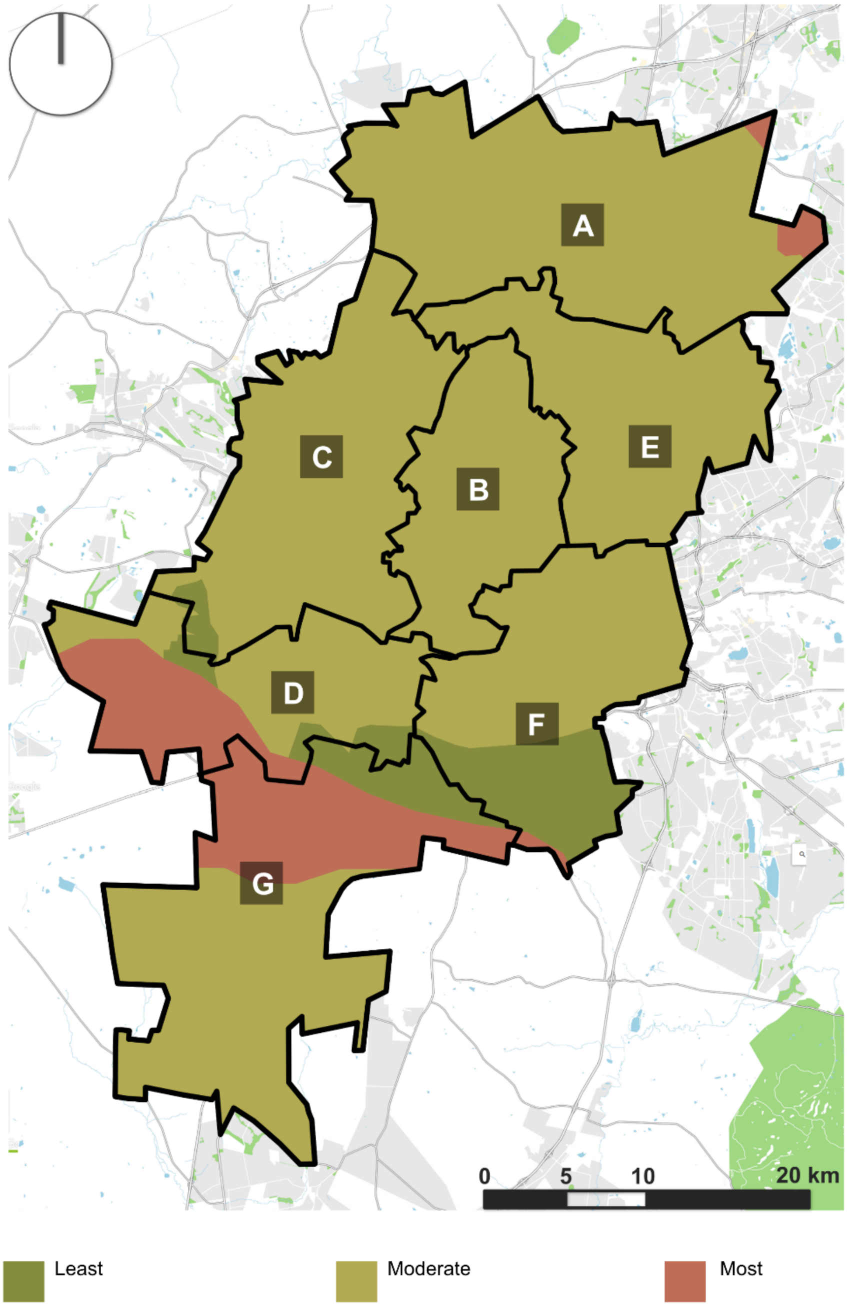


Figure 25: Aquifer vulnerability risk

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

An additional risk relating to the underlying area is with the formation of sinkholes which are as result of water and carbon dioxide dissolving dolomite rock leading to a sudden collapse in the ground. An important challenge to groundwater recharge is the impact of urbanization as it increases the need for hard and therefore impervious surfaces which reduces infiltration of rainwater into the ground to recharge the aquifer (Anaman, 2014; Dippenaar, 2015). Foster (1990, p.190) postulates that low residential development in urban areas can reduce land surface permeability by up to 80%. Discharge effluents generated from various industries can equally contribute to contamination of the soil and hence groundwater (Foster, 1990, p.200). The local government of Johannesburg recognises the potential of groundwater use as a viable water resource, however there are numerous challenges regarding the quality of water including the impact of mining activities which will be explored in the following section. Figure 26 provides a visualisation of the groundwater quality in the area. The map was derived from measuring the electric conductivity and categorises the quality of water accordingly. The values can be correlated with levels of saltiness. At the intersections of region D,G and F are levels of salinity that are concerning. This could be possibly due to exploitation of the available groundwater or contamination.

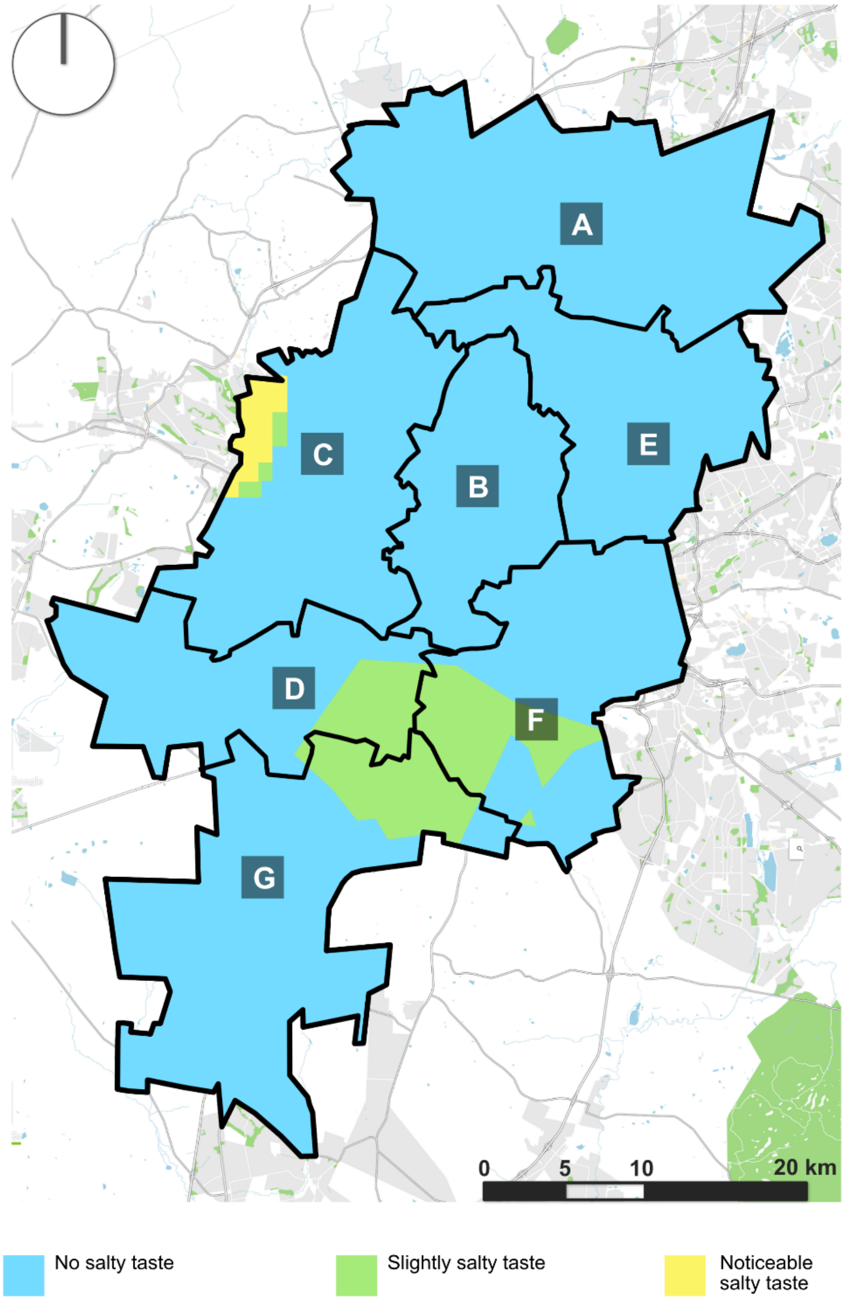


Figure 26: Groundwater quality according to salt levels in the city

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

3.3.5. The Impact of Mining Activities on the Water Cycle in Johannesburg

Pollution of groundwater related to mining activities is directly related to Acid Mine Drainage (AMD) which is a phenomena in which sulphuric acid forms in water due to the weathering of the mineral pyrite. During the process to remove gold and silver, known as cyanidation, pyrite and concentrations of metals such as lead, copper and other sulfide materials which are highly toxic are produced and percolate into both ground and surface water (Humphries et al., 2017). One of the major sources of AMD are the mine tailing storage facilities situated around the Witwatersrand gold mines. These tailing storage facilities are essentially dumps of mining waste material, which are typically not vegetated and therefore produce dust and cause erosion. These mine dumps are also situated in close proximity to residential areas posing a health hazard. The location of mining residual areas can be seen in Figure 27. The residual areas are categorized according to the level of contamination in the area. The map also denotes other key environmental characteristics of the city including the location of the dolomite aquifer highlighted in Section 3.3.4. as well as protected natural areas. Some of these protected natural areas are within close proximity of mining residual areas posing an environmental risk.

Despite a reduction in mining activities over the past two decades, there are some functional mines which contribute to AMD. In these mines, dewatering of deep areas which are flooded can occur and that has a direct impact on the water table by lowering it (Dippenaar, 2015; Humphries et al., 2017). As mentioned in Section 3.3.3, the danger of lowering the groundwater table includes the reduction of already limited water bodies in Johannesburg as well as land subsidence and deterioration of water quality due to the threat of saltwater intrusion into freshwater supplies. Extremely deep groundwater can contain higher levels of saline (Konikow and Kendy, 2005). Overall, it can be understood that the impact of mining activities can disturb both the natural environment as well as harm human health.

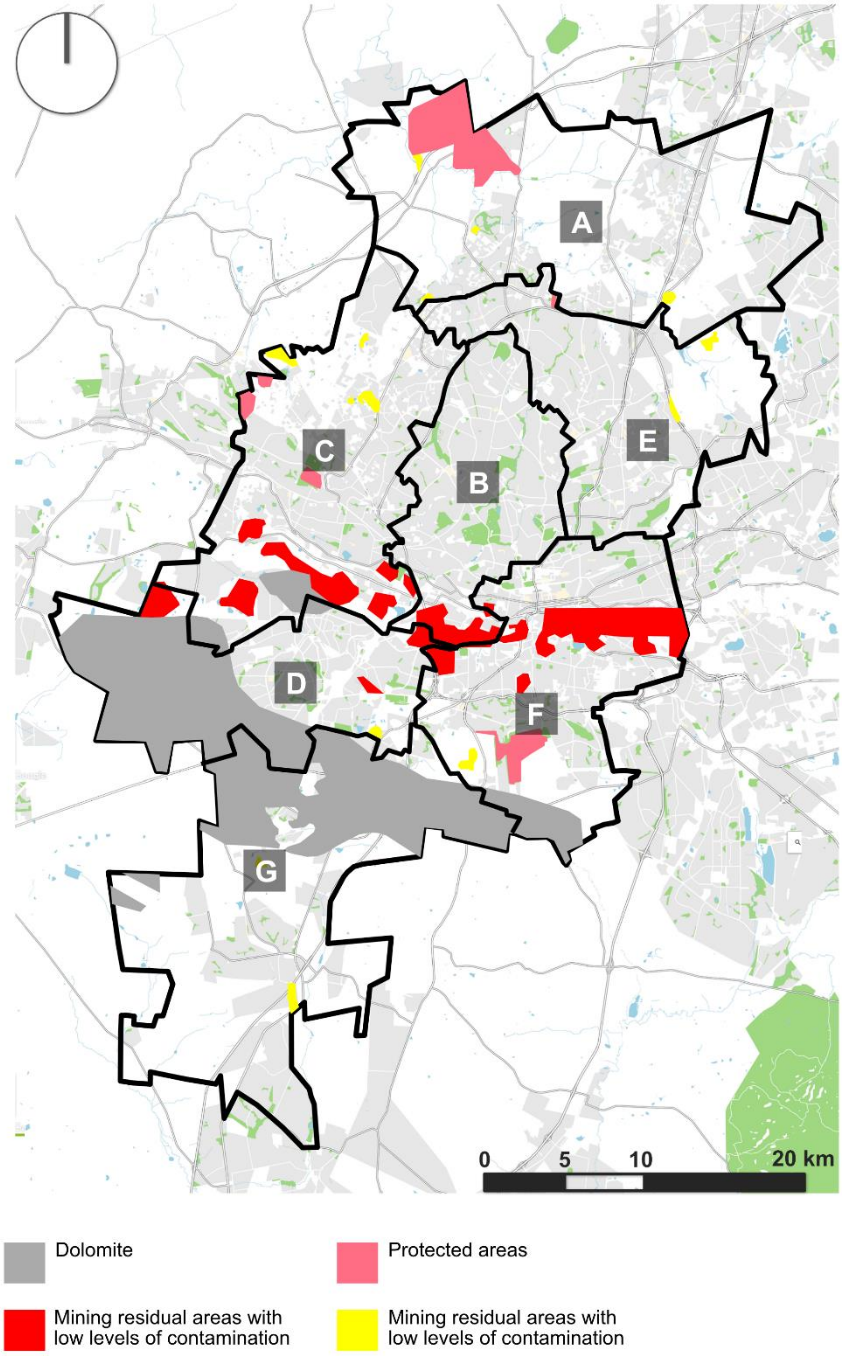


Figure 27: Summary of important environmental characteristics in Johannesburg

Source: Created by author and adapted with data from GCRO (2021a)

3.4. Climate Analysis

This section aims to analyse the climate conditions of the city and understand the risk factors associated to climate change.

3.4.1. Temperature and Rainfall

Johannesburg is a city with a sub-tropical climate that has warm summers and mild, sunny winter periods. The average temperature during summer is 25°C and in winter, the temperatures reach approximately 18°C (City of Johannesburg, 2021a, p.43). Figure 28 shows the mean annual average temperature for the entire city. The map indicates that slightly warmer average temperatures are experienced in the north of the city, particularly in region A. Since 1981, the average temperatures during the mid-day and midnight have increased by 1°C and 1.5°C respectively (City of Johannesburg, 2021a, p.43). Interestingly, a study by Le Roux et al. (2019) indicates that annual heat waves are frequent in the southern parts of the city in region D, G and F, despite experiencing lower average temperatures compared to the rest of the city. Heat waves are classified as three consecutive days in which the average temperature of the warmest month of the year is exceeded by 5°C (Le Roux. et al., 2019). These trends therefore indicate high variability of temperatures over a period of one year. The urban heat island effect adds to this variability as its effect varies around the city as it is directly related to the level of built-up area in the city. On average, due to the urban heat island effect, Johannesburg is 0.15°C higher than the surrounding municipalities (City of Johannesburg, 2021a, p.46).

With respect to rainfall, Johannesburg receives an average of 713 mm of rainfall per year (City of Johannesburg, 2019, p.44). This is significantly higher than the average rainfall in South Africa which is 450 mm per year (Cullis and Philips, 2019). The heaviest rainfall is experienced in the central parts of the city and predominantly in region C, B and F as seen in Figure 29. Rainfall is higher during the months between October and April (Le Roux et al., 2019).

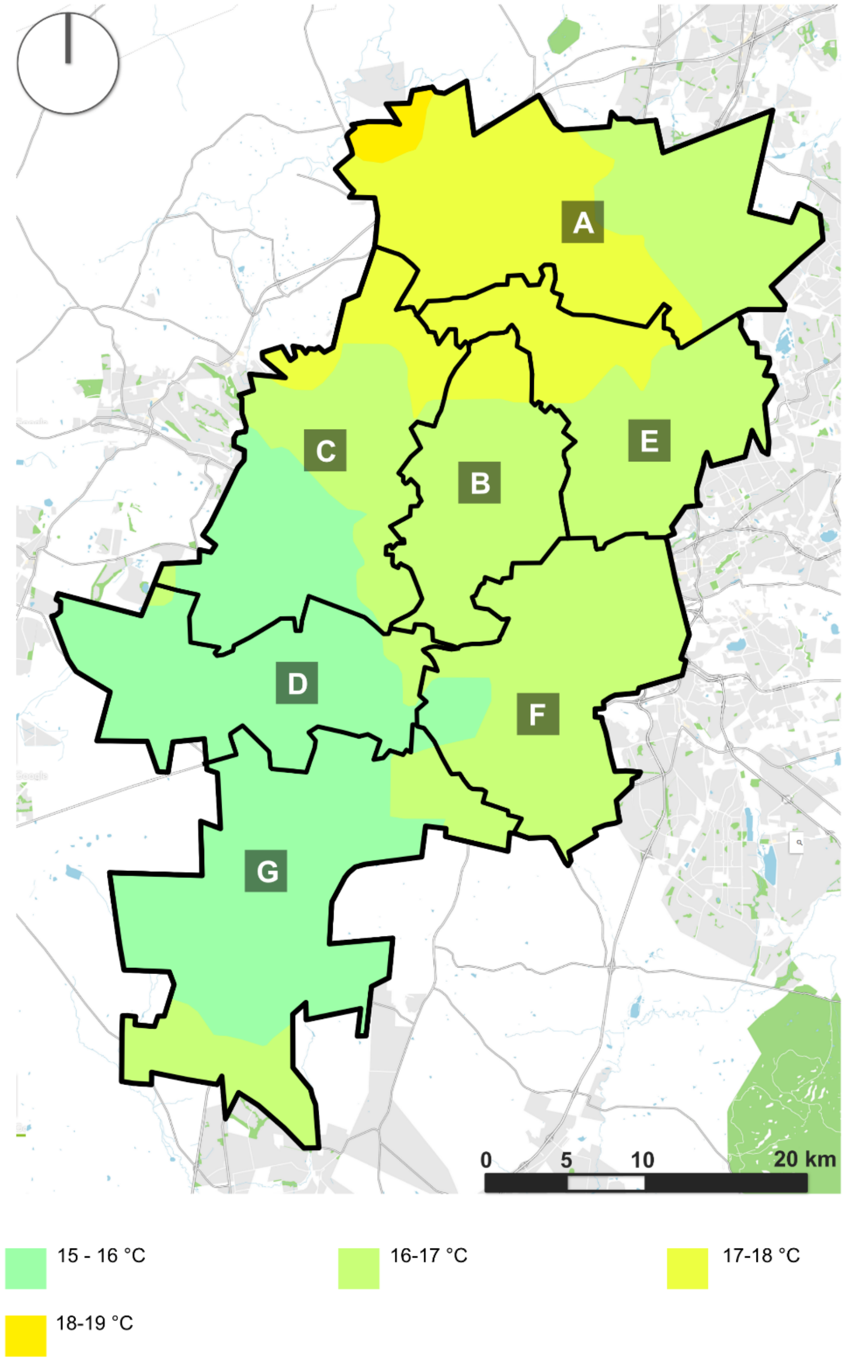


Figure 28: Mean temperatures in Johannesburg

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

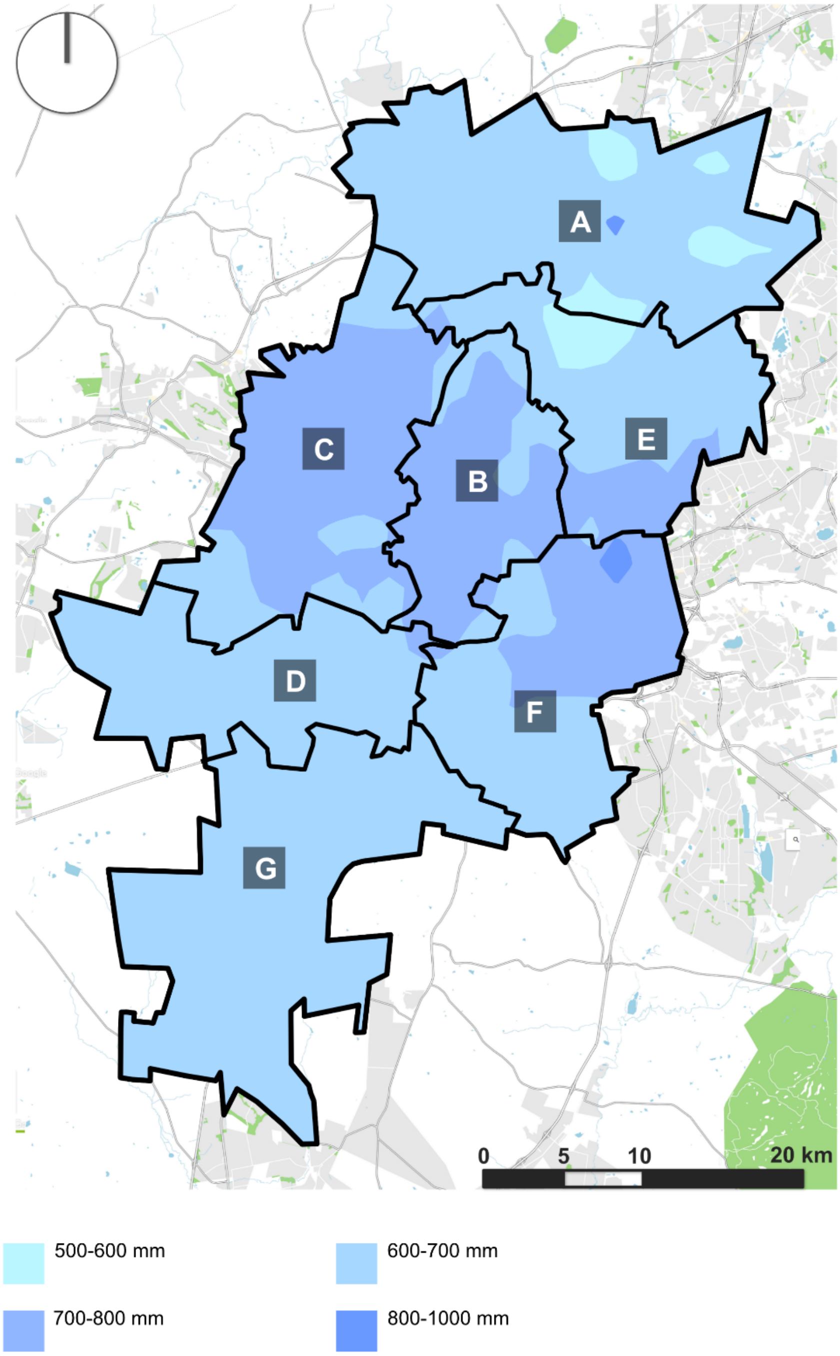


Figure 29: Average rainfall within Johannesburg

Source: Created by author and adapted from Western Cape Department of Agriculture (2021)

3.4.2. Hydro-Meteorological Hazards and Climate Change Impact

There are five types of hazard risks that are identifiable in Johannesburg: flooding, drought, wildfires, heatwaves and extremely hot days. Extremely hot days are categorized as days in which the temperatures exceed 35 °C (Le Roux et al., 2019). The risk of these disasters is exacerbated by the impact of climate change, which within the context of Johannesburg contribute to an increase in rainfall variability, unpredictable rainfall intensity as well as increasing temperatures (City of Johannesburg, 2021a)

Figure 30 indicates the flood hazard risk index for Johannesburg. The index is based on characteristics of the catchment areas and takes into account future rainfall models. The flood hazard index risk is high predominantly in region D, F and especially region G.

According to a vulnerability assessment carried out by the City of Johannesburg, the city will likely experience high interannual rainfall variability, indicating that drought events may be elongated and therefore have a larger impact (City of Johannesburg, 2021a, p.46). An elongated dry season along with windy weather and heat stress can likely cause wildfires (Forsyth, 2019). Figure 31 provides a visualisation the areas that are most vulnerable to heat waves and the urban heat island effect.

Figure 32 depicts the probability of wildfires in the city which is likely throughout the city. This is possibly due to the type of vegetation found in Johannesburg which can be categorised as sour and sweet grassland which is fire dependent. This means that fires are required to renew growth of the vegetation which therefore increase the risk off fires potentially not being managed well and having damaging consequences to the surrounding areas. Many of these areas are located at the intersection between fire-prone vegetation and developed land that comprises of people and infrastructure (Forsyth, 2019).

The aforementioned vulnerability assessment also indicated that annual average precipitation is projected to decrease by 5% in 2050, however the intensity of rainfall is set to increase by 7.5% in the same year. It is therefore predicted that rainfall events will be less frequent, however they will be more intense which may cause flooding.

The combined project climate change vulnerability index scores for Johannesburg for the period between 2030 and 2060 can be seen in Figure 33. The map indicates that region D, the east and west of region A as well as the southern tip of region G are all highly vulnerable to the impacts of climate change, indicating a clear and present need to address these risks in these areas

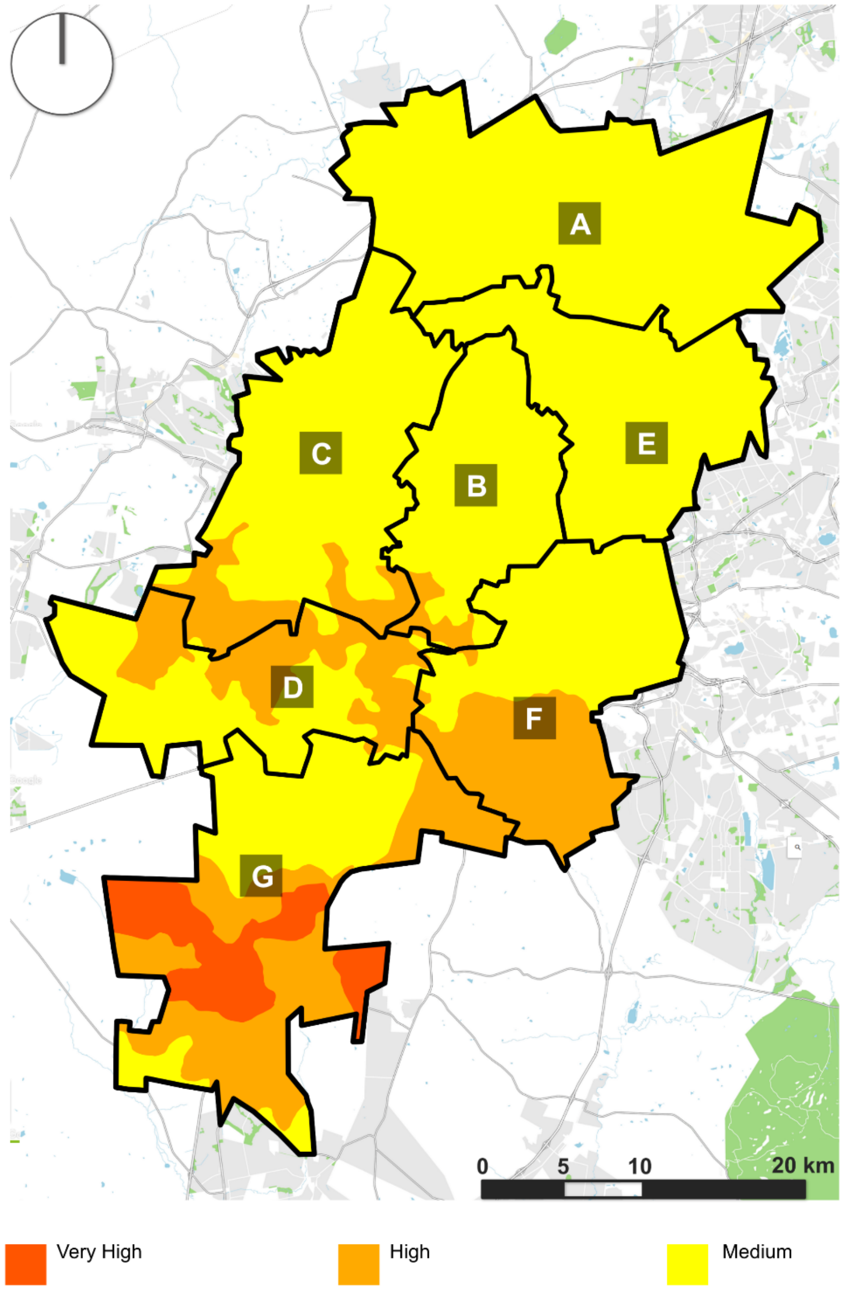


Figure 30: Flood hazard risk index

Source: Created by author and adapted from Le Roux et al. (2019)

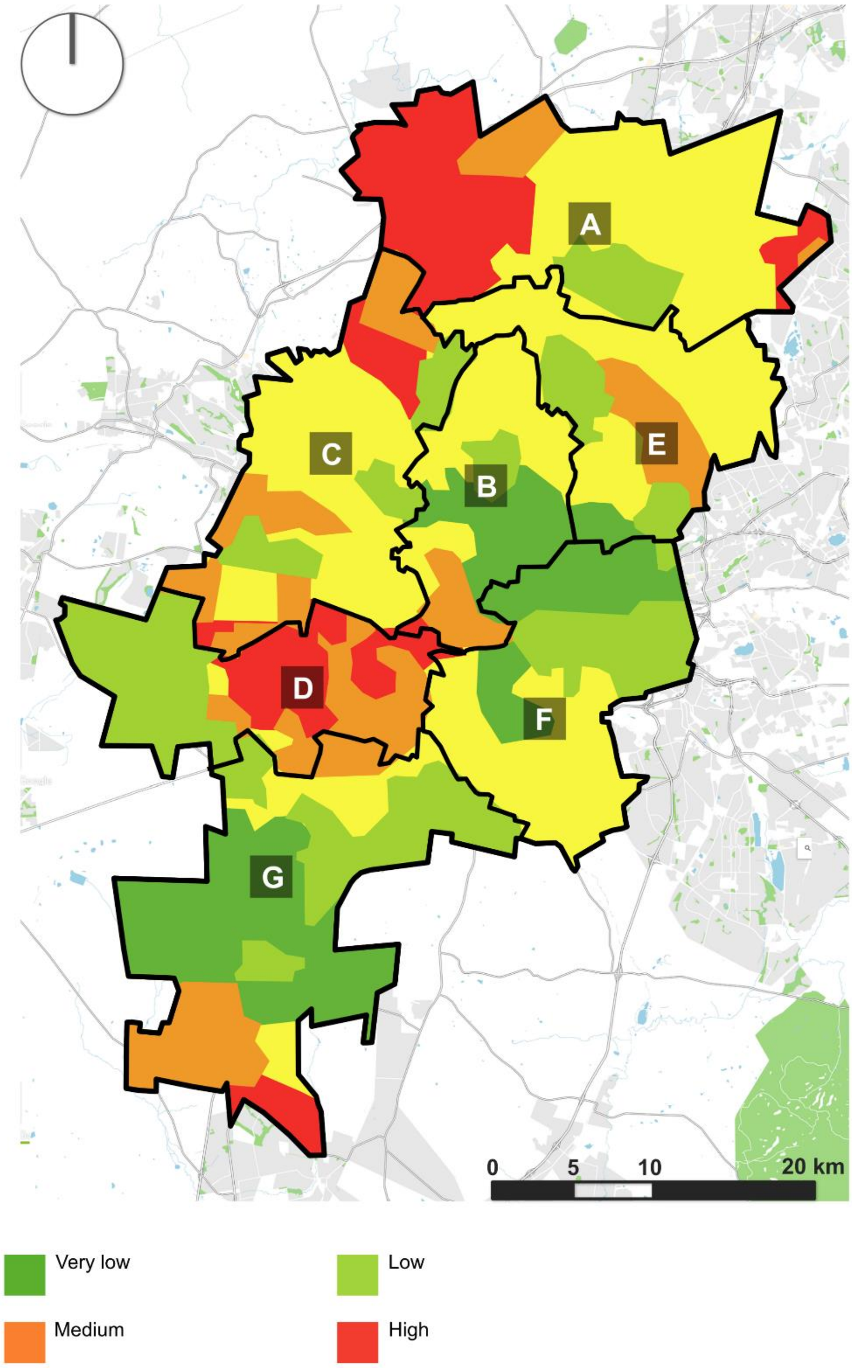


Figure 31: Heat waves and urban heat island impact vulnerability

Source: Created by author and adapted from City of Johannesburg (2021a)

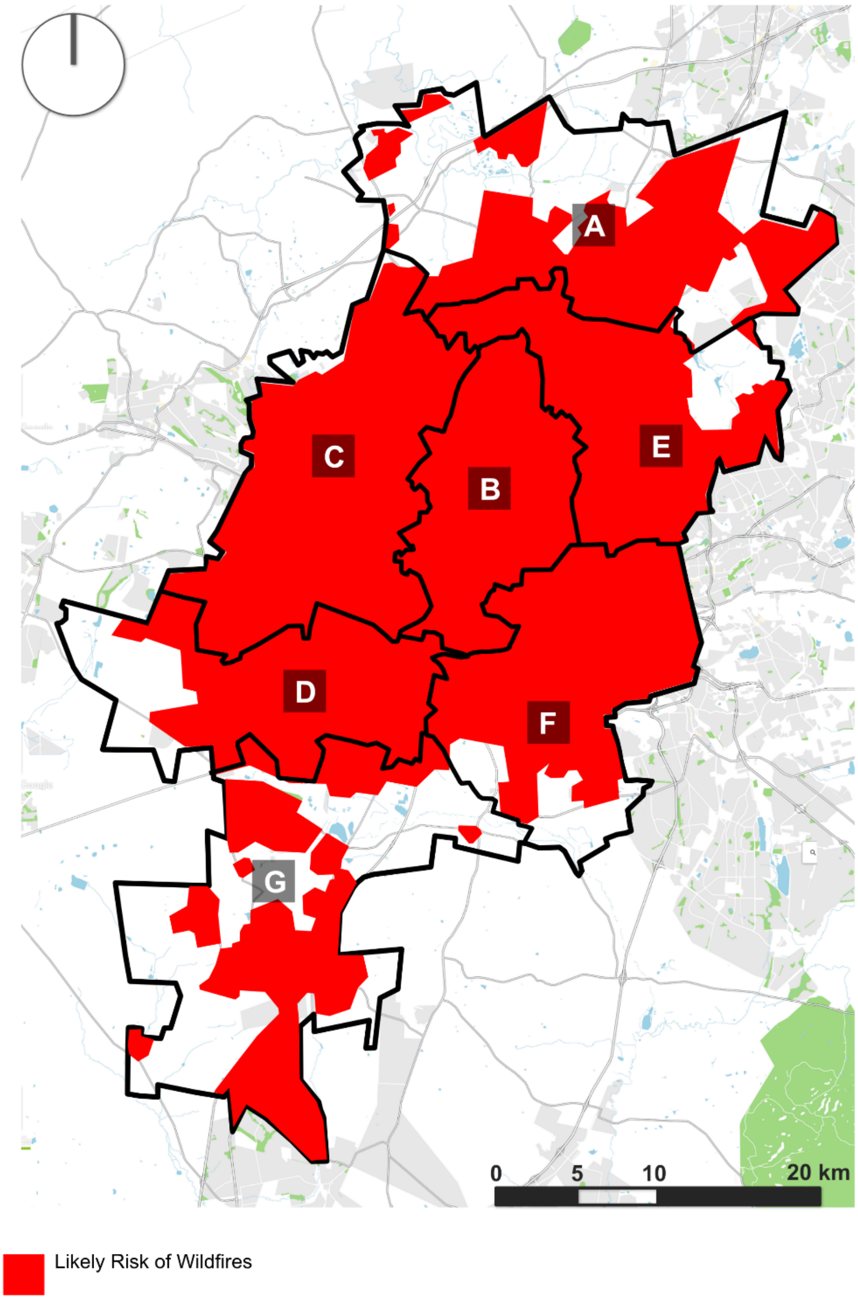


Figure 32: Wildfire risk in Johannesburg

Source: Created by author and adapted from Le Roux et al. (2019)

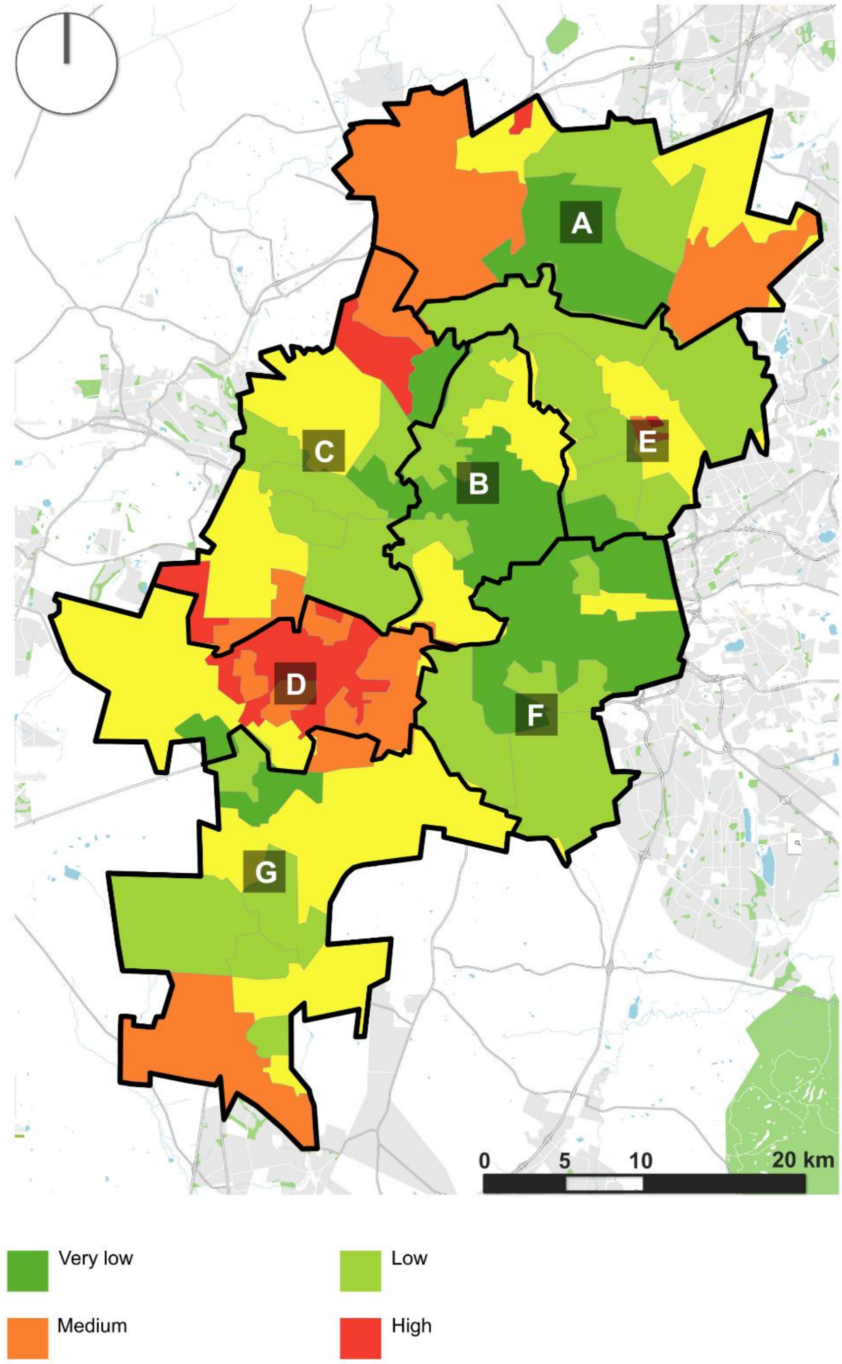


Figure 33: Climate vulnerability risk index

Source: Created by author and adapted from City of Johannesburg (2021a)

3.5. Urban Water Governance in Johannesburg

Section 2.2.3 of the thesis explored the applicability of a WSC in South Africa in terms of its legal framework. This section aims to present the regulatory framework on a city scale (local government) that could possibly enable a shift towards a water sensitive city. Additionally, the organisational arrangement for urban water management relevant to Johannesburg will be explored as well as the enablers and challenges with regard to interdisciplinary coordination and integration.

3.5.1. Regulatory Laws

There are two important provisions made on the local government scale in Johannesburg that are relevant to urban water management in the city: Water Service By-Laws and the Stormwater Management By-Laws. Firstly, the Water Service-By-Laws provides a detailed catalogue of laws regulating the provision of water, construction of infrastructure, quality of water as well as wastewater disposal. It also details materials and substances that are prohibited from entering the sewage and the stormwater systems as well as the responsibilities of property owners (City of Johannesburg, 2008). The by-laws are beneficial in that these provide clear regulations regarding wastewater and water services, and even allow for the implementation of possible recycling of wastewater (Armitage et al., 2014). However, there is a lack of provision made for an integrated and interdisciplinary approach to adopting WSC principles. The by-laws are written with the conventional approach to managing the urban water cycle. This therefore still encourages the use of conventional approaches. The second set of by-laws relating to stormwater management list the management, control and regulation of not only the quantity and the quality, but also the flow and velocity of stormwater runoff. The stormwater by-laws have been updated within the last decade to now include provision of a few SuDs interventions (City of Johannesburg, 2010) which is a promising development in the planning of water sensitive cities. Monitoring

3.5.2. Organisation of Urban Water Management Structure in Johannesburg

An investigation of the organisational structure of the city is important in order to understand how best to improve coordination and integration of stakeholders. Brown and Farrelly (2009) emphasise that a lack of commitment and coordination can be a socio-institutional barrier to implementing sustainable urban water management practices.

In order to first understand the organisational structure of Johannesburg, it is important to understand the national and provincial structure that it forms part of as seen in Figure 34.

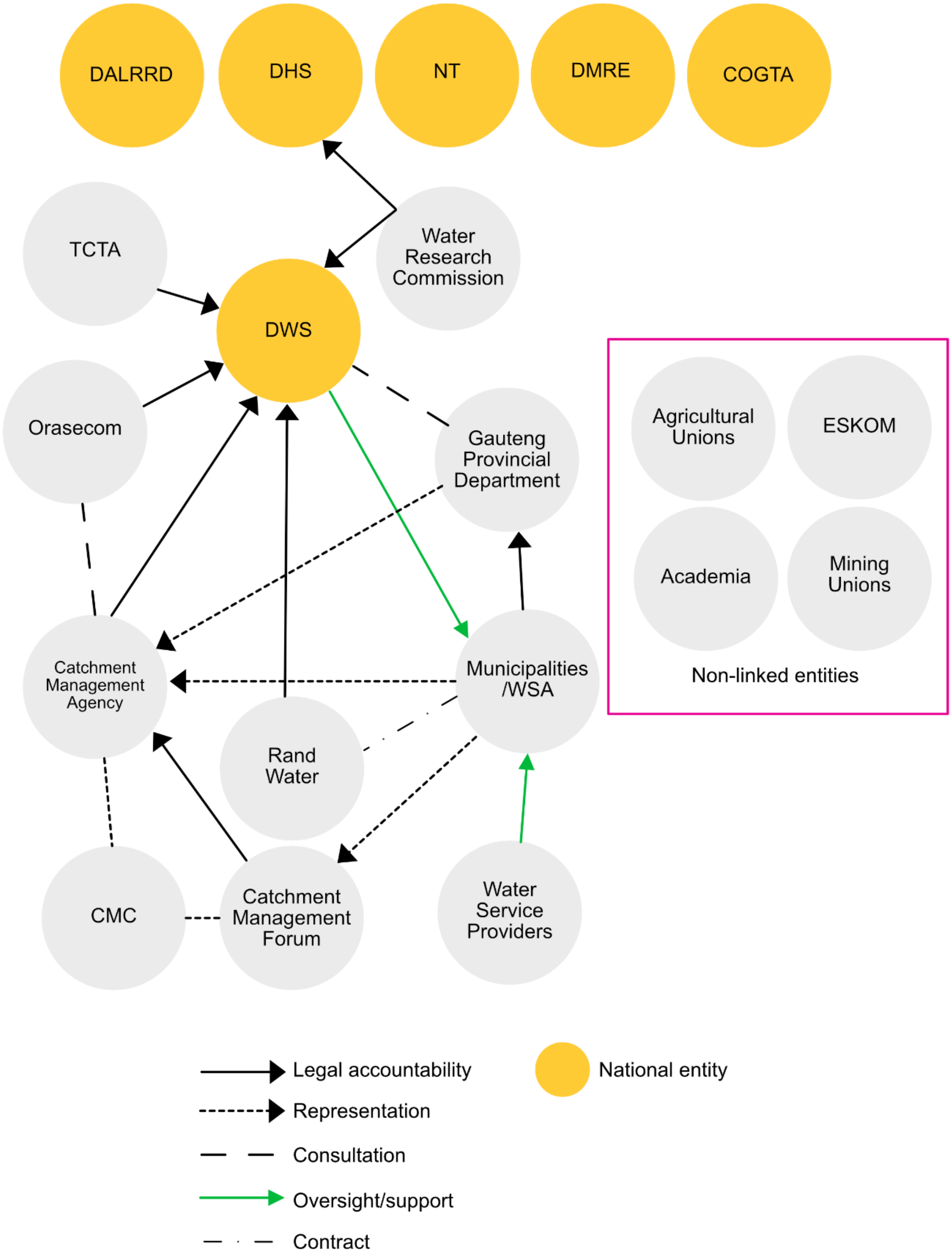


Figure 34: Organisational structure of urban water management

Source: Created by author and adapted from Muller et al. (2019)

The Department of Water and Sanitation (DWS) is the national governing body for the planning, development, operation and maintenance of all national water resources in the country. It is responsible for financing municipalities as well as providing technical support. The responsibility of providing or developing bulk water supply systems also rests with this body(Muller et al., 2019). The Water Services Act and National Water Act uphold the responsibilities of the DWS (RSA, 1998, RSA, 1997). Management of the IVRS rests with the DWS therefore multiple stakeholders across provincial and national boundaries are engaged and coordination between them is essential.

The Gauteng Provincial Government (GPG) is responsible for overseeing municipalities and holds them accountable for management of water resources and services. The GPG also acts as intermediary between the national government and municipalities (Muller et al., 2019)

The Orange-Senqu River Commission (Orasecom) was created in 2000 as a means to facilitate coordination between the four countries that fall within the Orange-Senqu Basin, viz. Namibia, Botswana, Lesotho and South Africa. The commission provides countries with strategies and expertise for water demand management and conservation of water resources in the basin (Water Action Hub, 2021). It also coordinates with Catchment Management Agencies.

Catchment Management Agencies (CMAs) are required to facilitate cooperation between stakeholders on a catchment level and are owned the by the state. The CMAs also monitor financial viability and governance and are responsible for developing catchment level strategies as well as a mandate to engage local communities. The DWS oversees the management of CMAs (Meissner et al., 2016; Muller et al., 2019). Currently, there are 9 CMAs in the country, with the Vaal Catchment and Limpopo Catchment relevant to Johannesburg. The city therefore requires coordination between two CMAs adding to the complexity of catchment management. A Catchment Management Committee (CMC) is used to implement CMA functions in any given area (Palmer et al., n.d., p.16).

Catchment Management Forums are the platform from which water users are engaged and issues of water resource management are discussed. These are inclusive forums that aim to provide a platform to anyone engaged in water issues and have direct engagement with CMAs, thus increasing its importance. These forums are not established under the National Water Act or Water Service Act and are therefore local, informal and more flexible (Palmer et al., n.d, p.17).

Water Boards are public utilities that are legally required to provide bulk-water supply to municipalities and are managed by the minister of the DWS who decides the scope of operations and the type of functions and services that can be carried out. Water Boards are classified as a national State-Owned-Enterprise (SOE) or National Government Business Enterprise (Dippenaar, 2015; Smith, 2006). The relevant Water Board for Johannesburg is Rand Water who is the supplier for majority of the Gauteng Province and supplies water from the IVRS system. Johannesburg takes up the largest portion of water supplied by Rand Water (Muller et al., 2019. p.13.)

The Trans Caledon Tunnel Authority (TCTA) is another SOE tasked with managing and representing South Africa's role in the Lesotho Highlands Water Project (LHWP). It is responsible for managing, funding and implementing projects involved in the LHWP.

Water Research Commission (WRC) was established in 1971 as a research and knowledge hub and is managed by the Department of Human Settlements (DHS) and DWS. The WRC is the key to providing water resource solutions to the country (Watershare, 2020).

Other national government departments include the National Treasure (NT) which regulates funding and grants for municipalities, water boards and the TCTA as well as the Department of Cooperative Government and Traditional Affairs (COGTA) which is the key entity that provides coordination between the three spheres of government and ensures that both local and provincial government carry out their various functions (COGTA, 2021). Additionally, stakeholders from the agriculture and mining sector are important water users. In Gauteng, agricultural irrigation is responsible for 20.2% and the mining sector is responsible for 3.3% of water use (Jovanovic et al., 2020, p.23). With respect to agriculture, the National Department of Agriculture, Land Reform and Rural Development (DALRRD) as well as unions representing farmers such as Agri SA, National African Farmers' Union (NAFU) and the Transvaal Agricultural Union are important. Regarding the mining sector, the National Department of Mineral Resources and Energy (DMRE) as well as Mining Industry Association of South Africa (MIASA) must be engaged especially since this entity contains the chamber of Mines who is responsible for the health and safety aspects of mining. Additionally, the national electricity provider, *Eskom*, is an important stakeholder due its closely intertwined relationship with water provision and additionally, is at the root cause of many water infrastructure failures that occur due to power failures.

The City of Johannesburg Municipality is mandated as a Water Service Authority (WSA) under the National Water Services Act. The municipality is responsible for providing water and sanitation services in the city alongside being responsible for land use planning, housing and stormwater management. Additionally important stakeholders relevant to Johannesburg are private and public enterprises which fall under the category of water users as well as public institutions such as schools, hospitals, and public government offices (Muller et al, 2019, p.16).

The sheer number of stakeholders involved presents a challenge for cross-governmental coordination and therefore the role of COGTA is especially important. Coordination will assist in preventing misalignment of water goals, across the three levels. From the urban water governance structure, it can be observed that the national government holds a significant amount of authority and requires accountability from numerous entities. This therefore means that national government can elicit significant change towards advancing WSC principles through strengthening accountability amongst provincial and more especially municipalities.

In South Africa, a study on four different cities including Johannesburg by Armitage et al. (2014) confirmed a significant and evident characteristic of urban water management-its functions are fragmented. This is quite apparent in Johannesburg where Development, Planning and Urban Management is separate from water supply, wastewater disposal and stormwater management as seen in Figure 35. The city does however seek to integrate water and sanitation with environmental management with its Environment Infrastructure and Services (EIS) entity. Within this entity, water distribution and wastewater are managed and controlled by a State-Owned Company (SOC) called Johannesburg Water which is the Water Service Provider (WSP). The City of Johannesburg municipality owns Johannesburg Water and is the sole shareholder of the company which is managed adhering to laws in South Africa regarding the management of a company (Smith, 2006).

The integration of corporatization into the water service delivery model of dates back to 2002 with the creation of the *iGoli* framework an institutional framework to address the severe financial issues of the city. At the time the municipality agreed to a 5-year contract with a French company in order integrate international experience and expertise into Johannesburg water with the overall goal to ensure the utility could be financially able to continue on its own (Smith, 2006, Armitage et al., 2014).

Another SOC, Johannesburg Roads Agency (JRA), is tasked with management of stormwater management, but its authority falls under the roads and transport department and is separate from EIS. This is further evidence of a fragmented urban water management structure. A positive aspect is that the JRA is intentionally moving towards more water sensitive practices with its design manual, Complete Street Design Guidelines Manual and Stormwater Design Manual. The Stormwater Design Manual elevates the use of SuDS and presents performance assessment criteria which can help form a tangible basis for future projects. However, at present there are no laws that hold the JRA responsible for carrying out stormwater solutions of such projects (Armitage et al., 2014, Cilliers and Rohr, 2019). In an attempt to address the fragmented urban water management, a Water Quality Task Team was created. This brings together the JRA, Johannesburg Water and the city's integrated waste management provider

SOC, Pikitup. to discuss solutions to water quality issues in the city. An added challenge to coordinated management is a lack of technical capacity and expertise.

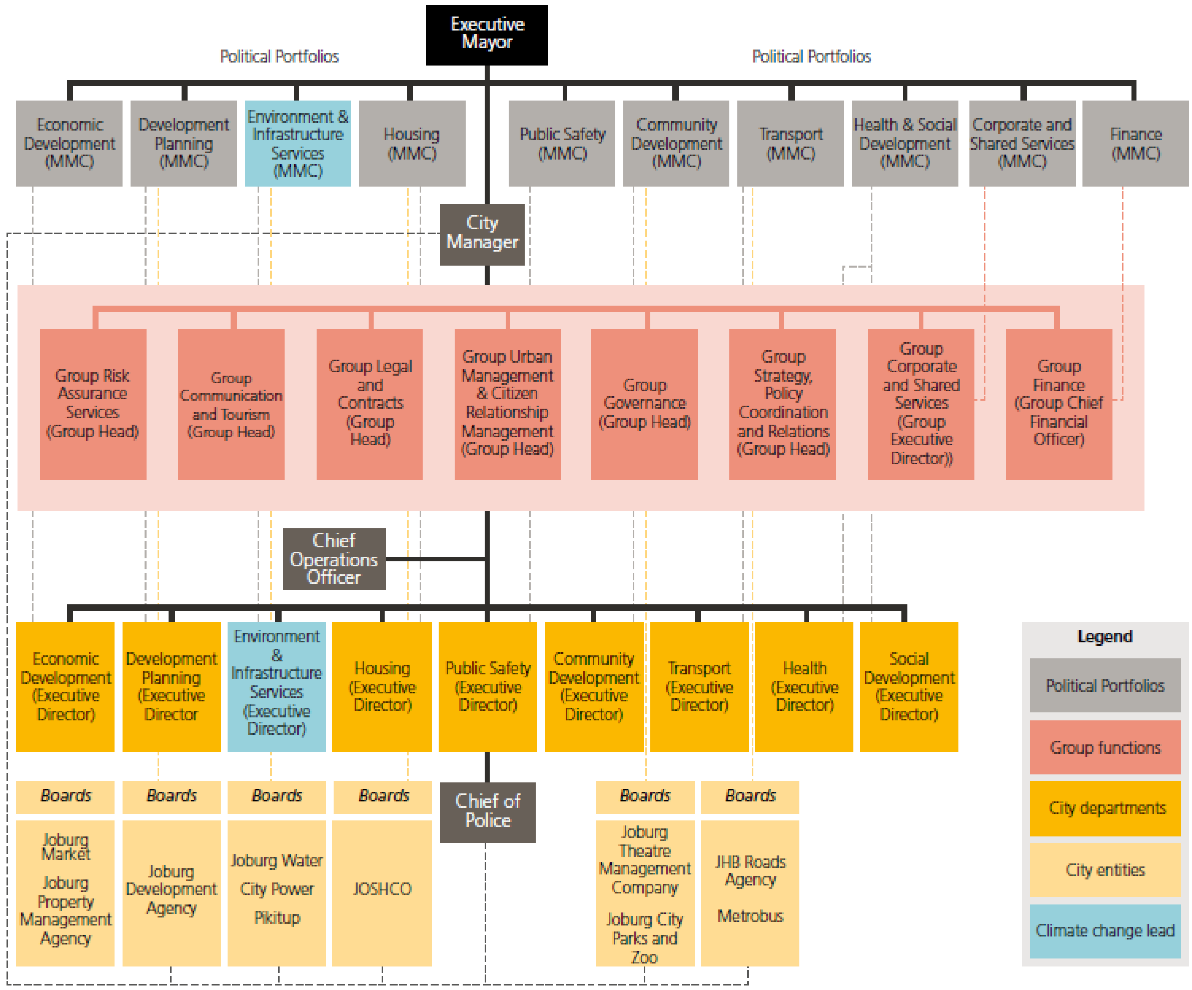


Figure 35: Organisation of management structure of Johannesburg

Source: City of Johannesburg (2021a, p.26)

The stakeholders on a macro level for Johannesburg include all city entities and city departments and additionally representatives from every sphere of government including representatives from municipality sub-areas known as wards. These wards are represented by councillors. Landowners and private stakeholders also play a significant role in the organisation of water in Johannesburg and must be included. Urban water governance in Johannesburg therefore has a number of stakeholders in both the public, private and civic sector

3.6. Discussion

The previous sections have provided a deeper perspective into the physical, spatial, hydrological, climate and urban water management characteristics of Johannesburg. This section provides a summary of the characteristics for each region for the purpose of identifying high priority zones for sustainable urban water management interventions This will enable tailor made solutions to be applied to specific areas. Table 3 highlights a summary of the findings from Chapter 3. As can be observed in the table, there are varied characteristics and concerns in each region. Region D is especially vulnerable due to its proximity to mining residual areas, high climate change vulnerability as well as the socio-economic conditions of the region. The importance of understanding the socio-economic conditions of different regions is important if the application of WSC principles in Johannesburg is to be successful. The results of the case study review of Johannesburg indicate that a strategic program for Johannesburg's transition into a WSC must focus on the following areas of intervention:

- Water supply and demand management due to the vulnerable supply and demand scenario and reliance on water outside of the catchment area
- Prioritisation of improved water and sanitation access based on proportion of inhabitants without access to piped water
- Promotion of green infrastructure (GI) solutions based on the existing GI in Johannesburg which includes wetlands and planted trees
- The removal of species of alien vegetation
- Improvement of wastewater treatment to prevent contamination of downstream environments
- Improvement of treatment of stormwater and reduction in stormwater runoff to prevent pollution of water bodies
- Prevention of groundwater contamination due to AMD and other sources of pollution
- Prevention of groundwater exploitation
- The conversion of mining residual areas due to their health and environmental risks
- The prevention of groundwater exploitation due to the presence of dolomite
- Mitigation of climate change impacts to reduce the risk of hazards
- The creation of stronger legal and regulatory laws (stormwater and water service-by laws) to promote WSC principles
- Accountability and coordination between different levels of governance
- Improvement of fragmentation in organisational structure of Johannesburg
- Capacity building and expertise

Table 3: Summary of key characteristics of each administrative region

Source: Created by author (2021)

	A	B	C	D
Water Access	Low water access	High Water access	Low-medium access	Low-medium access
Economic Activity	Low-medium	Medium-high	Low-medium	Low
Density	Low	Low-medium	Low-medium	High
Ecological Assets	High density alien species; Low park accessibility	Low density alien species; High park accessibility	Medium density alien species; Low-medium Park accessibility	Low density alien species; Low-medium Park accessibility
Settlement Type	Medium density informal settlements; Medium density-gated communities	Low density informal settlements; Medium density-gated communities	Medium density informal settlements; Medium density-gate communities	High density informal settlements
Groundwater Resources	Low-high aquifer vulnerability; High quality; Medium recharge depth	Low aquifer vulnerability; High quality; High recharge depth	Low aquifer vulnerability; Low-medium quality; Medium-high recharge depth	High aquifer vulnerability; Medium quality; High recharge depth
Geological characteristics	Low presence mining residual areas	High presence mining residual areas	High presence mining residual areas	Medium presence mining residual areas Dolomite zone
Flood risk	Medium risk	Medium-high risk	Medium-high risk	Medium-high risk
Wildfire Risk	Likely	Likely	Likely	Likely
Summer heat waves and urban heat island effect	Medium-high vulnerability	Low-medium vulnerability	Medium-high vulnerability	Medium-high vulnerability
Climate Vulnerability Index	Low-high (variable)	Low-medium	Low-high	Medium-high

	E	F	G
Water Access	Low-medium access	High water access	Low water access
Economic Activity	High	High	Low
Density	Low-medium	Low-medium	Low
Ecological Assets	Low-medium density alien species, Low-medium Park accessibility	Low-medium density alien species; Low-medium Park accessibility	High density alien species; Low park accessibility
Settlement Type	Medium density informal settlements; High density gated communities; Multiple-storey buildings	Low density informal settlements; Medium density gated communities; Multiple-storey buildings	High density informal settlements, contains the highest number of deprivation areas
Groundwater Resources	Low aquifer vulnerability; High quality; High recharge depth	Low-medium aquifer vulnerability; Medium quality; Medium-high recharge depth	High aquifer vulnerability; Medium quality; Medium-high recharge depth
Geological characteristics	Low presence mining residual areas	High presence mining residual areas Dolomite zone	Low presence mining residual; Dolomite zone
Flood risk	Medium risk	Medium-high risk	Medium-very high risk
Wildfire Risk	Likely	Likely	Likely
Summer heat waves and urban heat island effect	Medium vulnerability	Low-medium vulnerability	Low vulnerability
Climate Vulnerability Index	Low-medium	Low	Low-high (variable)

Chapter 4: Urban Water Metabolism Analysis of Johannesburg

4.1. Analysing the Urban Water Metabolism of Johannesburg

The purpose of this chapter is to present the methods used to derive characteristics of the urban water metabolism of Johannesburg using a UWMB framework as well the results of a resultant performance assessment. This will assist in answering the following research questions

5. What are the characteristics and implications of an assessment of Johannesburg's urban water metabolism?
    - Analyse the urban water metabolism of Johannesburg
    - Evaluate the urban water metabolism using performance indicators

As mentioned in Chapter 2, the quantitative results of UWMB can assist in a transition to a WSC and will be explained further in this chapter.

4.2. Urban Water Mass Balance Methodology

The basic components of the UWMB method involves both qualitative and quantitative procedures that begin with understanding the parameters of the area that the model will be applied to.

4.2.1. Selection of System Boundary and Parameters

UWMB requires a clearly defined boundary to measure outflows and inflows that are relevant to the city. For the purpose of this study the system boundary will include the whole area of Johannesburg including all administrative regions. Despite Johannesburg's Water role as the WSP for Johannesburg, the extent of service overlaps city boundaries and so the author acknowledges that some flow data from Johannesburg Water will be not accounted for or may be overestimated due to the simplification of this boundary selection. The system boundary extends 1 km underground and excludes bulk water storage outside of the city boundaries or within groundwater aquifers below the city as well as inflows from streams and other tributaries flowing into the city. The justification for this lies in the need to separate the city from the environment in order to understand its interactions with one another (Kenway et al., 2011).

The UWMB framework is based on the principles of conservation of mass and the resultant equation was developed by Kenway and his colleagues' (2011). Outflows (Qo) are subtracted from inflows (Qi) within a defined system boundary (B) where its area (A) can be determined with depth (d) to produce the mass and volume stored within the boundary (ΔS) over a period of time (t1-t2) represented in equation (1) and Figure 36 below:

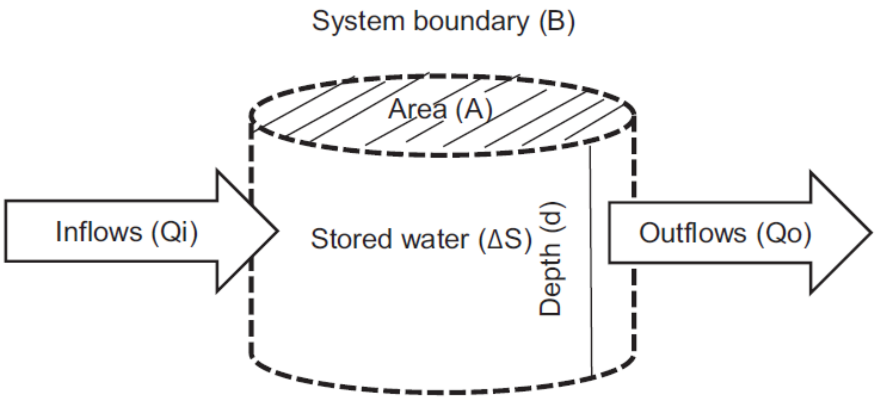


Figure 36: UWMB model

Source: Kenway et al. (2011)

$$\Delta S = (S_{t1} - S_{t2}) = Qi(t1 - t2) - Qo(t1 - t2) \qquad (1)$$

Equation 1 can be simplified as follows to form equation 2 if time intervals (t1-t2) and the boundary (B) is defined:

$$\Delta S = Qi - Qo \qquad (2)$$

From this equation expressed in fluxes of volume or masses moving per unit time, a new equation was developed to expand on inflows and outflows within cities and forms equation (3):

$$\Delta S = C + D + P - (W + R_s + G + ET) \qquad (3)$$

The variables in equation (3) are as follows:

C = flows in the centralized water system (i.e. the major supply system

D = decentralized water from groundwater (D_G) or rainwater tanks (D_R)

P = precipitation (rain, dew)

W = wastewater discharge (including sewage overflows)

R_S = stormwater runoff

G = groundwater infiltration

ET = evapotranspiration

The system boundary excludes bulk water storage outside of the city boundaries or within groundwater aquifers below the city as well as inflows from streams and other tributaries flowing into the city and can be graphically represented as Figure 37:

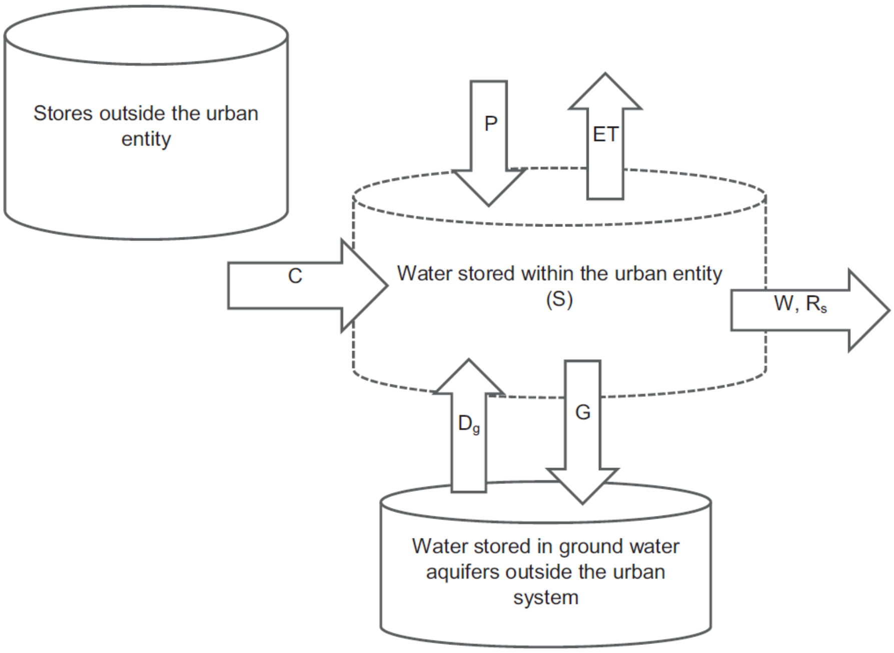


Figure 37: UWMB flows and its relation to the system boundary

Source: Kenway et al. (2011)

Equation (3) was used to determine the urban water metabolism characteristics for five Australian cities: Melbourne, Sydney, Brisbane, Gold Coast and Perth (Kenway et al., 2011). The equation provides provision to be adapted according to the particular context of a city. In research by Farooqui et al. (2016), the equation was adapted to include stormwater harvesting and recycled wastewater. In the case of Johannesburg, no data regarding these two components was available at the time of this study, and additionally no rainwater harvesting data was found for Johannesburg which therefore means that groundwater extraction from boreholes are solely comprises of the decentralized water system for the city. In addition, Johannesburg's location, inland of the country and absence of existing or future plans for desalination plants hence means that the flows from desalinated water in the equation will also not be considered.

A study by Paul et al. (2018) on the urban water mass balance of Bangalore accounted for systems loss from pipe leakages which is a significant component of the hydrological cycle (> 30% in Bangalore) and this is the case in Johannesburg as well (City of Johannesburg, 2021a, p.84). This therefore meant that the equation would be adapted to account for system losses.

The final urban water metabolism equation for the purpose of analysing Johannesburg was determined to be equation (4) and can be graphically represented as Figure 38:

$$\Delta S = C + D + P - (W + R_s + G + ET + Cufw) \qquad (4)$$

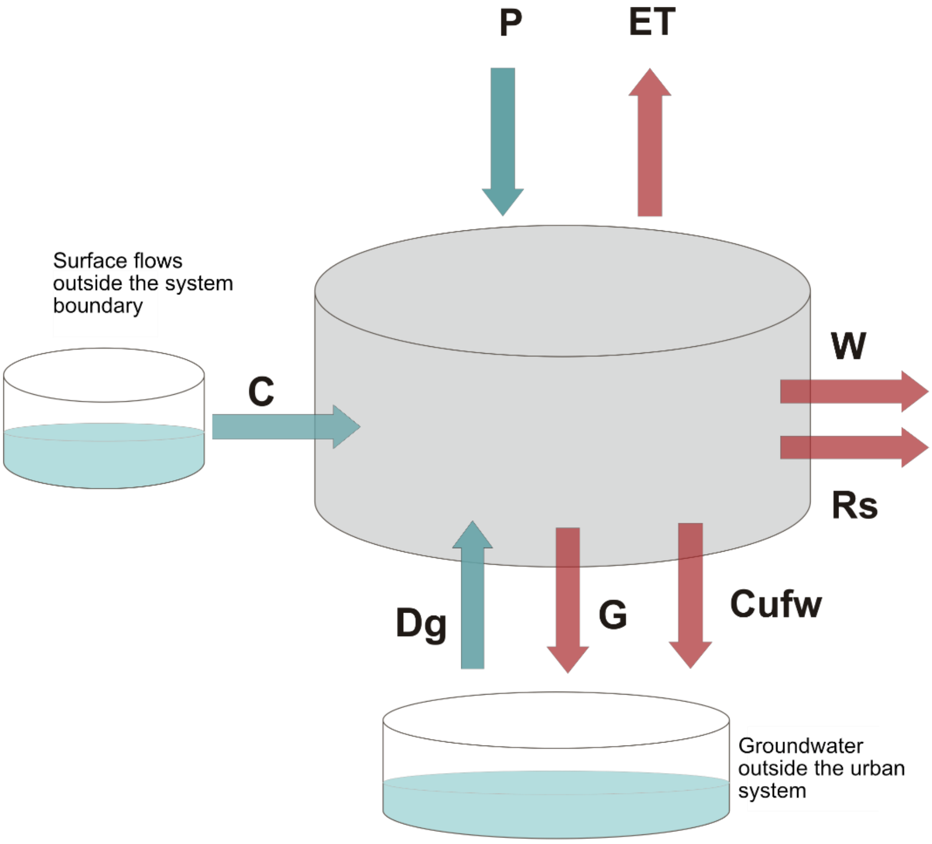


Figure 38: UWMB flow model for Johannesburg

Source: Created by author (2021)

A set of performance indicators was also derived by Kenway et al. (2011) to measure the significance of some of the natural and anthropogenic flows within the boundary. The indicators provide a measure of the extent at which some of these flows could essentially replace the centralized water system. Table 4 shows the full list of indicators used to derive a performance assessment.

Table 4: Performance indicator assessment derived from Kenway et al. (2011)

Source: Kenway et al. (2011)

	Unit	Method	Formula
Water use intensity			
Intensity of water use	(GL/km^2)	Total water use/area	(C + D)/A
Water system centralized			
Supply centralization	%	Centralized supply/total water use	C/ (C + D)*100
Rainfall harvesting	%	Decentralized sources/rainfall	D/P*100
Rainfall potential for water supply			
Centralized supply replaceability	%	Rainfall/centralized supply	P/C*100
Total use replaceability	%	Rainfall/total use	P/ (C + D)*100
Wastewater potential for water supply			
Centralized supply replaceability	%	Wastewater flow/centralized water supplied	W/C*100
Total use replaceability	%	Wastewater flow/water used	W/ (C + D)*100
Stormwater potential for water supply			
Centralized supply replaceability	%	Stormwater flow/water supplied	RS/C*100
Total use replaceability	%	Stormwater flow/water used	RS/ (C + D)*100
Wastewater and stormwater combined potential			
Replaceability of total use with wastewater and stormwater	%	(Wastewater + stormwater flows)/total use	(W + Rs)/ (C + D)*100
Water Loss Recovery Potential of 'total water use replaceability'	%	Water Loss/Total water use	Cufw/(C+D)*100

As far as possible, data was collected using the period between 2018 and 2019 from various different sources. The precipitation (P) value was collected from research conducted by the Council of Scientific and Industrial Research (CSIR) South Africa (Le Roux et al., 2019). The values for centralized water supply (C), wastewater flow (W) and system losses (Cufw) were obtained from an annual report spanning from 2018 to 2019 from Johannesburg Water (Johannesburg Water, 2019). The decentralized water system value consisting of groundwater extraction was obtained from the DWS. The surface runoff (Rs) and groundwater infiltration flows (G) were collected by calculating averages from map data that was compiled in 2005 and 2012 from government sources. Evaporation data was calculated using precipitation, surface runoff and groundwater infiltration flow values as seen in equation (5)

$$Et = P - R_S - G \qquad (5)$$

The data collection from various periods of time are a limitation to this study as it may yield a less accurate representation of annual input and output flows. Data limitations and availability in resource flow analysis was a significant barrier for Culwick et al. (2017) in their urban metabolism study on the Gauteng province citing institutional constraints such as scattered reporting of information amongst the three levels of governments and a lack of understanding in the need to collect data for the purpose of monitoring. Notwithstanding, Culwick et al. (2017) maintains that urban metabolism studies in the region are important for sustainable transitions.

In order to provide a slight reprieve to possible inaccuracies in this study, the values in the UWMB for Johannesburg are compared to UWMB case studies conducted in Cape Town, Sydney and Melbourne to offer some comparisons to the data on Johannesburg. The Australian cities are chosen due to their relative similarities in size and population and Cape Town is chosen by its virtue of being another South African city with several similar challenges as that of Johannesburg. The characteristics of each study are summarised in Table 5:

Table 5: Comparison of characteristics across different cities

Source: Created by author (2021)

City	**Period of study**	**Area**	**Population**	**Population and Area Data**
Johannesburg	2018-2019	1645 km^2	5, 428, 964	(COGTA,2020a p.10)
Cape Town	2015-2018 (Ffion Atkins et al., 2021)	2446 km^2	4, 307,478	(COGTA,2020b, p.13)
Sydney	2004-2005 (Kenway et al. ,2011)	1420 km^2	4, 228, 000	(Kenway et al. ,2011)
Melbourne	2004-2005 (Kenway et al., 2011)	1818 km^2	3, 583, 000	(Kenway et al. ,2011)

Lastly, a scenario analysis to determine how the potential recyclable flows could meet supply and demand deficit gaps in 2019 and 2030 was implemented. This entailed the use of data from Johannesburg Water (2019) and City of Johannesburg (2011) which contained data for the supply and demand deficit and projected deficits in 2030 respectively. The projected deficits are calculated by using an approximate of the projected demand in 2030 and the 2019 water supply, assuming supply will not change. Since it is not realistic to assume that 100% of all recycled wastewater, stormwater and rainwater can be used to meet the gap, flows were calculated using three separate scenarios: 25%, 50% or 75%.

All raw data, data sources and calculations can be found in the Appendix under Tables 23-26.

4.3. Results and Discussion

The results of the UWMB analysis can be seen observed in Figure 39 and was obtained from collection of secondary data. The units of measurement for the components are in either in Gigalitres (GL) or Megalitres (ML) and are calculated using equation (4):

$$\Delta S = C + D + P - (W + R_s + G + ET + Cufw) \qquad (4)$$

$$\Delta S = 1118.44 + 588.38 + 4.02 - (337.99 + 112.19 + 71.06 + 935.19 + 227.11)$$

$$\Delta S = 27.29\ GL$$

The equation is built on the principle that inputs must equate to outputs. A low storage value indicates the accuracy of the balance (Kenway et al., 2011, p. 697). The water balance error for this study is 1.4% indicating that some flows may have been unaccounted for, such as rainwater harvesting (for which there was unavailable data). A further analysis of the storage value falls out of the scope of this study.

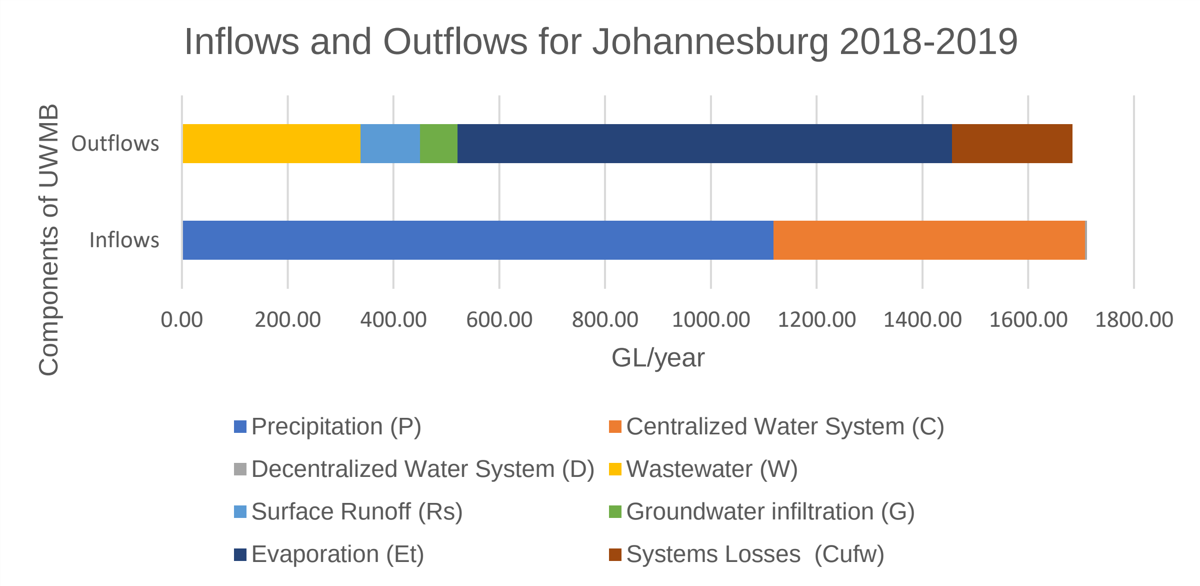


Figure 39: Inflows and outflows for Johannesburg

Source: Created by author (2021)

The resultant components of the balance are compared to Cape Town, Sydney and Melbourne in Table 6:

Table 6: Comparisons of UWMB components across different cities

Source: Created by author (2021) using data from Ffion-Atkins et al (2021) and Kenway et al. (2011)

	Johannesburg	**Cape Town**	**Sydney**	**Melbourne**
Input Flows	GL/year			
Precipitation (P)	1118.44	1471.40	1352.00	1387.00
Centralized Water Supply (C)	588.38	324.90	526.00	431.00
Decentralized Water Supply (D)	4.02	3.30	N/A	6.00
Output Outflows	GL/year			
Wastewater (W)	337.99	234.80	454.00	346.00
Surface runoff (Rs)	112.19	492.30	400.00	300.00
Groundwater infiltration (G)	71.06	0.00	N/A	N/A
Evapotranspiration (Et)	935.18	711.60	1088.00	1251.00
System Loss (Cufw)	227.11			
Storage (ΔS)	27.29	44.50	62.00	72.00

The biggest anomaly in the data from Johannesburg is that surface runoff is significantly lower than calculated in other cities. The reason could be due to the land coverage classification for Johannesburg where approximately 32% consist of the total land area and is classified as built environment (Schäffler et al., 2013, p.27) which has less impervious surface coverage than the other cities. The quality of data could also be a possible reason for this anomaly.

The results of the water performance indicators derived from the formulas in Table 4 are recorded in Table 7.

Table 7: Performance indicator results

Source: Created by author (2021)

	Unit	
Water use intensity	(GL/km^2)	0.68
Water system centralized		
Supply centralization	%	99
Rainfall harvesting	%	0
Rainfall potential for water supply		
Centralized supply replaceability	%	190
Total use replaceability	%	189
Wastewater potential for water supply		
Centralized supply replaceability	%	57
Total use replaceability	%	57
Stormwater potential for water supply		
Centralized supply replaceability	%	19
Total use replaceability	%	19
Wastewater and stormwater combined potential		
Replaceability of total use with wastewater and stormwater	%	76
Water Loss Recovery Potential of 'total water use replaceability' (%)	%	38

The water use intensity is extremely high (0.68) in comparison to Sydney (0.37) and Melbourne (0.24) (Kenway et al., 2011) indicating a much higher water demand in Johannesburg. The supply centralization indicator shows that 99% of the water supply in Johannesburg is centralized which means that almost the whole city depends on surface water. The 1% represents dependency on other sources such as groundwater and rainwater harvesting.

The potential for rainwater to replace the centralized water system was 190% and 189% for total water use replaceability indicating promising potential for rainwater harvesting in the city. This is approximately 10 times higher than the potential centralized and total water use replaceability for stormwater. The low potential for stormwater harvesting is directly related to the lower value of surface runoff determined from the secondary data. Wastewater recovery potential was 57% for both total use and centralized supply system replaceability. The water loss recovery potential replaceability was 38% indicating that 227 GL can be potentially recovered as inputs.

A scenario analysis whereby the supply and demand deficit for 2019 and future gap for 2030 under a "business as usual scenario'' as seen in Figure 22 was calculated in order to see whether augmentation of supply through wastewater, stormwater and rainwater supply could bridge that gap. The full summary of calculations can be found in the Appendix. In 2019, the water supply and demand deficit was 137 ML/day. Under a conservative scenario where only 25% of wastewater and stormwater was recycled, the gap could easily be closed with an extra 10 ML/day to spare. Additionally, if only 75% of system losses were recovered, this would also be sufficient to meet the demand for water in 2019. The projected demand in 2030 under a "business as usual" scenario would see water demand rise to 3425 ML/day with a supply-demand deficit of 1813 ML/day if the supply remained the same as in 2019 (1612 ML/day). In order to meet the demand, only 50% of both stormwater, wastewater and rainfall can be used.

Overall, the results indicate the most promising alternative water servicing option to be rainwater harvesting in the city. This is additionally backed up by studies on rainwater harvesting benefits in South Africa by Mwenga Kabinde and Taigbenu (2011) and Mwenge Kahinda et al. (2010). The UWMB study has provided quantifiable indicators of the possibility of using alternative water servicing options. Alternative water servicing options (i.e., the continued diversification of water resources) are crucial towards becoming a water sensitive city. The findings also give provide a quantifiable reference of which options can be prioritised in Johannesburg. Rainwater harvesting can most importantly form a part of addressing water accessibility in areas in which access to water is poor.

Chapter 5: Solutions for Johannesburg's Water Sensitive City Transition

The purpose of this chapter is to proposes tangible solutions in shifting Johannesburg towards more sustainable urban water management practices. This chapter will answer the final research question of the thesis:

6. Which urban water management interventions and spatial strategies can form part of a strategic program to guide the water sensitive transition in Johannesburg?

- Develop a strategic program for Johannesburg's transition to a water sensitive city
- Identify and explain spatial strategies that can be applied on a city level (macro) and neighbourhood level (meso and micro)

5.1. SWOT Analysis

The literature review of relevant theory, the context-specific analysis of Johannesburg and the urban water mass balance findings provide key findings that can assist in the creation of a strategic program for Johannesburg's potential move to a water sensitive city. The overall SWOT Analysis regarding the implementation of a water sensitive approach for Johannesburg can be described as follows in Table 8:

Table 8: SWOT analysis for Johannesburg

Source: Created by author (2021)

Strengths	• Presence of wetlands and trees • Volume of rainfall
Weaknesses	• Water and sanitation service issues (service delivery, water loss from pipe leakages) • Socio-economic inequality • Urban water governance fragmented • Reliance on surface water and inter-basin transfer scheme • Poor wastewater treatment • Pollution of water bodies and groundwater sources (poor sanitation, solid waste pollution, mining activities) • Inequitable access to GI

Opportunities	• Water service and stormwater by-laws provision • Groundwater resources availability • Rainfall harvesting potential (as determined from UWMB) • Recycling of wastewater and stormwater potential • Mining residual areas as new green space
Threats	• Climate change vulnerability • Rapid urbanisation • Sinkholes from water percolating into dolomite • Floods, heat waves, droughts and urban heat island effect • Water sustainability in developing nations is deemed low prioritization • Future projected demand too high in comparison to supply

5.2. Future Vision for Johannesburg

In order to align with the current water sensitive framework for South Africa as well as the strategic program thinking presented in Ferguson et al. (2013), a new vision unifying the water goals for South Africa can be created, taking into consideration the underlying challenges presented in the SWOT analysis. A vision for Johannesburg can be presented as follows:

"To create a city for you that provides adequate access to water and sanitation for all and also enhances the urban water cycle and promotes and protect the environment"

The vision encapsulates 4 important components. The first component captures the importance of creating a city revolving around its residents, an essential aspect of a WSC is that its citizens are actively aware and understand the role that they play in creating significant change. The second component addresses the importance of ensuring equitable access to the rights of all residents in SA. The third component emphasises the need to promote the natural water cycle in cities as a way of managing the flows of water, in and out of the city. The fourth and final aspect calls for the provision of ecosystem services while simultaneously ascertaining environmental protection. It is especially important that adequate access to services are met as it could counteract the processes if left unaddressed. For example, the purpose of stormwater management systems which may be compromised if these systems, form alternative points of wastewater disposal or even as a potable water source (Fisher-Jeffes et al., 2017b).

These four components can be grouped together according to the challenges in the following way in Table 9:

Table 9: Underlying challenges and its related vision component

Source: Created by author (2021)

Underlying challenges	Vision
• Low prioritization of sustainability due to service delivery challenges • Fragmented urban governance	Water Together
• Water and sanitation delivery • Loss of water from pipe leakages	Water for All
• Reliance on surface water and inter-basin transfer • Inequitable access to GI	Water as a Tool
• Groundwater contamination • Pollution of water bodies and wetlands • Negative impact of mining activities • Climate change impact	Water for the Earth

In order to communicate the vision as clearly as possible, the four components can form the building blocks of the vision and guiding principles for each part of the vision can be derived as seen in Table 10:

Table 10: Vision and guiding principles

Source: Created by author (2021)

Vision		Guiding Principles
Water Together	A vision of a city that sees water as a vital part of society	• Communities are educated, aware and engaged in water-related issues • The value of water promotes economic growth to communities • Communities, governmental institutions, professionals, and academia work together synchronously to find solutions that fit the context of a situation
Water for All	A vision of a city with equitable access to water sanitation	• Everyone has equitable access to clean water and adequate sanitation • Access to these services is long-term and communities are empowered to be self-sufficient and less reliant on governmental bodies • Everyone has access to clean waterways

Water as a Tool	A vision of a city that manages the flow of water in a sustainable manner	• The water cycle is promoted in the best possible way • Water and wastewater infrastructure is operated and managed well • Water supply is reliable and sustainable and from diverse sources • Spatial planning and land use planning supports sustainable urban water practices
Water for the Earth	A vision of a city that promotes social and ecological health	• The environment and its ecosystems are protected, biodiverse and sustainable • The health and safety of communities in relation to the environment are protected • The city has flexible, adaptive climate change resiliency plans • The impact of natural disasters is reduced

The guiding principles provide directives for strategic objectives. These strategic objectives offer a written benchmark towards transitioning to a WSC for the city and can be seen in Table 11.

Table 11: Summary of strategic objectives and actions for a water sensitive transition

Source: Created by author (2021)

Future Vision	**Strategic Objectives to Transition**
Water Together	A- Create public understanding of a water sensitive vision B- Promote cross-sector multi-disciplinary coordination between stakeholders C- Promote participatory engagement D- Create policies and regulatory frameworks that support water sensitive approaches
Water for All	E- Ensure reliable water supply and sanitation for all F- Improve existing water and sanitation services G- Promote economic growth through water
Water as a Tool	H- Reduce demand for potable water I- Educate professionals to build WSC expertise J- Promote systems of accountability, operation and maintenance K- Promote the use of WSUD, SuDs and GI spatial tools on a micro scale

Water for the Earth	L- Improve quality of water bodies and wetlands M- Improve solid waste management N- Improve biodiversity of environment O- Reduce carbon emissions in the water sector P- Increase climate change resiliency

The four components can additionally be communicated to stakeholders using key categories that encapsulate the perceived benefits of implementing them:

- Human and Environmental Health: indicating a positive impact on people, on biodiversity and environmental wellness
- Service Delivery: includes the provision of basic services such as water and sanitation
- Community Unity: engagement with the community is proactive and improves social cohesion
- Climate Change Resilience: lowers climate change vulnerability
- Water Sustainability: projects are in in line with sustainable urban water management practices.

Benefits may not be limited to one component but may overlap and it is important to note that an important benchmark for a micro-scale (neighbourhood scale) project is that it ideally integrates all benefits in its implementation. Additionally, projects can be categorised according to whether the three principles of a WSC are met.

5.3. Water Together: Public Participation and Governance

To achieve the vision defined for "Water Together" component, public participation and awareness, stakeholder engagement and supportive frameworks need to be addressed. Table 12 outlines the strategic actions that can be implemented in order to achieve this vision.

Table 12: Public participation and governance strategic actions

Source: Created by author (2021)

A	Create public understanding of a water sensitive vision
	A1: Create a marketing strategy for mainstream media (tv and radio) as well as social media
	A2: Identify profiles of water engagement in Johannesburg
	A3: Promote benefits of using rainwater harvesting systems
B	Promote cross-sector multi-disciplinary coordination between stakeholders

	B1: Eliminate fragmented governance by creating a joint professional body that represents all relevant governance structures including JW, JRA and urban planning entities in order to deal implementing a water sensitive vision for Johannesburg.
C	Promote participatory engagement
	C1: Adopt adaptive co-management and action research
	C2: Incentivise engagement through water-themed events
	C3: Promote participation in catchment management forums
D	Create policies and regulatory frameworks that support water sensitive approaches
	D1: Strengthen the water service and stormwater management by-laws in the city by increasing the scope of WSUD measures
	D2: On a national scale, enforce laws to implement WSUD in all future projects
	D3: Create an independent water authority or strengthen accountability for national government to hold municipalities accountable for a lack of service delivery as well as monitor compliance of laws pertaining to water use
	D4: Coordinate fragmented entities within Johannesburg

The aim of a marketing strategy (A1) would be to effectively communicate effectively on the key ideas and water vision for Johannesburg. The strategic program needs to be communicated as effectively as possible to raise public awareness and create a sense of ownership for every citizen to work towards this shared vision. The "Day Zero" crisis in Cape Town was partially averted due to a rigorous public campaign that aimed to reduce the water demand of all households. The campaign was fear-based and had negative effects such as deepening racial and economic inequality (Bischoff-Mattson et al., 2020), however the overall impact of a public campaign is worth considering. A proactive, transparent, and well-integrated marketing campaign for Johannesburg can ensure that residents understand and are aware of the role of water in their lives and for society as a whole.

Dean et al. (2016) identifies five types of levels of engagement (A2) in their study on water-related citizen engagement: the disengaged, aware but inactive, active but not engaged, engaged but cautious, and highly engaged. The study also found that levels of engagement depended on factors such as life experience and socio-economic factors. Identifying these groups can allow for more tailor-made educational and engagement interventions to increase the effectiveness and understanding of a water-sensitive approach.

Strategic action C1 is derived from Chapter 2 where the case study of Diepsloot showed the small-scale success of adaptive co-management and action research.

5.4. Water for All: Socio-Economic Equity and Liveability

The "Water for All" component focuses on meeting the basic rights of the city's inhabitants. This will require a focus on improving the quality of life and liveability of the residents of Johannesburg. The research presented in this thesis has highlighted that a small portion of the population residing in Johannesburg do not have access to water and sanitation services. The strategic actions for each objective would therefore focus on improving quality of life (See Table 13).

Table 13: Strategic actions for improving liveability

Source: Created by author (2021)

E	Ensure reliable water supply and adequate sanitation for all
	E1: Enable and strengthen decentralised water supply system in the city
	E2: Invest in mass rainwater harvesting solutions including electrolysis systems for purification
	E4: Conduct wide-scale groundwater potential investigations to find new potential sources of groundwater in areas with poor access to groundwater
F	Improve existing water and sanitation infrastructure
	F1: Created automated systems that detect leakages
	F2: Create an independent body that monitors the progress of phase 2 of the Lesotho Highlands Water Project to ensure that there are no further construction delays
	F3: Strengthen WWTW infrastructure to improve on quality of wastewater treatment
	F4: Lower potable water demand through the use of alternative water service options
G	Promote economic growth through water
	G1: Engage private stakeholders in WSC projects
	G2: Create tourism opportunities in economically inactive zones

One of the main challenges in strategic action E2 is to increase public awareness and understanding of rainwater systems. A strong decentralised system will require the presence of significant incentives to market it as an attractive option to public and private stakeholders. The use of electrolysis and other purification methods can improve the quality of rainwater and possibly transform it into a drinking water option for inhabitants. In informal settlements, decentralised rainwater harvesting stations can be designed and constructed in partnership with the community.

5.5. Water as a Tool: Supporting WSUD Strategies

This component of this vision aims to accommodate strategic objectives related to water sensitive planning and retrofitting strategies into the city. Table 14 outlines the strategic actions needed to successfully realize this objective.

Table 14: Strategies for supporting use of WSUD

Source: Created by author (2021)

H	Reduce demand of potable water
	H1: Create a groundwater database to monitor and track existing boreholes in the city to prevent exploitation
	H2: Impose fines for exceeding daily water consumption limits for high-income earning households and businesses
	H3: Identify new borehole points
I	Educate professionals to build WSC expertise
	I1: Strengthen the Learning Alliance by enabling legal accountability to DWS
	I2: Provide a legal requirement for developers to gain approval from both the municipality and the Learning Alliance
	I3: Implement a water-wise professional certification for all professionals involved in water-related projects
	I4: Create joint partnerships with research institutions in the country across different scales (provincial and local)
J	Promote systems of accountability, operation and maintenance
	J1: Enable the use of multi-value decision support tools
	J2: Provide operational and maintenance budget within the context of each project
	J3: Apply the WSC Index (Wong et al., 2020) to measure progress for the transition to a water sensitive city
	J4: Measure urban water metabolism on a yearly basis
K	Promote the use of WSUD, SuDs or GI spatial tools on a micro scale
	K1: Implement water storage, permeable surfaces and increase vegetated areas

A professional certification body (C3) is a way of educating and ensuring that all professionals have a coherent knowledge and understanding of water sensitive interventions. This promotes interdisciplinary learning and application. A similar program has been successfully applied in Singapore (Centre for Liveable Cities Singapore and Rotterdam Office of Climate Adaptation, 2019). This certification body can be mandated as a legal requirement such that the future approval of tenders require an interdisciplinary team in order carry out projects.

With regard to strategic action J1, a study by Lerer et al., (2015) emphasised the need to use and understand decision support tools in order to develop the best solutions for projects that address water challenges. Ideally, according to Lerer et al., the choice of decision support for any kind of context should firstly have an understanding of the context as well as be driven by the need to address the 12 aspects of water that are valued by stakeholders, a concept derived by Dooyewerd, and adapted by Valkman et al. (2008). The values can be seen in Table 15:

Table 15: Aspects of water valued by stakeholders

Source: Created by author (2021) and adapted from Lerer et al. (2015)

Aspects of Water		**Description**
Bio-Physical Aspects		
1.	Physical	The flow and movement of water (hydraulics)
2.	Chemical	The quality of water
3.	Biotic	Its importance place in the provision of life (human, animal, plant)
Human Aspects		
4.	Psychological	The sensory experience involved in water (e.g., taste, perception)
5.	Logical	Understanding the best possible way to organise the water chain (extraction, distribution, etc)
6.	Historical	The effective use of the existing environment
7.	Linguistic	Its significance with regard to inspiring literary works on water
8.	Social	The role of water in creating connection between people
9.	Economic	The economic value of water
10.	Aesthetic	The ability of water to create beautiful environments
11.	Legal	Law and regulations regarding water
12.	Moral	Creating safety and sustainability

5.6. Water for the Earth: Climate Environmental Health

This component is primarily concerned with long-term actions that can improve the quality of environment as well as building climate resiliency (Table 16).

Table 16: Strategic actions for climate change resilience and environmental health

Source: Created by author (2021)

L	Improve quality of water bodies and wetlands
	L1: Rehabilitate rivers
	L2: Protect and upgrade existing wetlands
	L3: Re-purpose mining dumps
	L4: Enforce strict regulations for industries with regard to dumping of waste
	L5: Invest in AMD treatment technology
M	Improve solid waste management mechanisms
	M1: Prevent illegal dumping
	M2: Create a formal system where waste collection is incentivised
N	Improve biodiversity of environment
	N1: Remove alien species of plants
	N2: Introduce indigenous trees
O	Reduce carbon emissions in the water sector
	O1: Introduce bio-gas conversion in all WWTW
	O2: Use alternative sources of water such as rainwater
P	Increase climate change resiliency
	P1: Reduce the impact of high temperatures through introducing micro-climates through green open space
	P2: Communicate findings in disaster management plans to stakeholders and the public
	P3: Create public systems of warning for hydro-meteorological hazards (using apps and other forms of media
	P4: Create robust evacuation plans in case of hazards

Strategic action P1 relates to the need to increase accessible green space for lower income residents in the city. The spaces need to be accessible and developed in partnership with residents. WSUD tools and urban agricultural initiatives can be combined in these type of projects

5.7. Intervention Areas for Johannesburg

5.7.1. Macro Spatial Strategies

With the overall WSC plan in mind, a macro strategy for Johannesburg involves the enhancement of the existing water cycle in Johannesburg by understanding the catchment area characteristics and harnessing the flows of water through the city in a way that enhances the natural environment using spatial strategies involving WSUD tools. The natural occurring watershed in the centre of Johannesburg means that flows in the northern catchment will flow into the Limpopo basin, while flows to the south will be directed into the Orange-Senqu basin, each leading respectively to the Indian and Atlantic Ocean. The importance of protecting downstream communities and ecosystems by ensuring that discharge flows are treated is of the utmost of importance. From the urban water metabolism analysis, it is also clear that rainwater harvesting is a potential and promising alternative water resource for Johannesburg.

The macro strategy for Johannesburg thus seeks to encapsulate the following actions:

- reusing stormwater and wastewater
- harvesting rainwater
- rehabilitating its rivers and wetlands.
- reducing stormwater runoff
- increasing recharge into the underlying aquifer

The specific spatial and physical qualities of Johannesburg should also be taken into account and the strategy should therefore seek to work within sub-catchment areas as well as ensure that WSUD interventions are prioritised in areas that are disadvantaged. Priority actions are outlined as follows:

1. **Identify**

Areas of intervention must be identified based on spatial, physical and socio-economic characteristics

2. **Restore**

The degradation of water bodies in Johannesburg requires an overhaul of how the city manages its wetlands and water bodies. The restore action will focus on rehabilitating canals, rivers, and wetlands within the city. River regeneration will begin at the source, or the headwater of the main water bodies found in Johannesburg.

3. **Detain, Retain, Recharge (DRR)**

The purpose of detain and retain actions would be to reduce the amount of surface water volume as well as the velocity, especially in informal settlements using water attenuation or infiltration measures. Some detention measures also allow for filtration of pollutants. Retention (retain) actions involve the capturing of water using water storage systems, either long-term or temporarily. These measures potentially allow for water to infiltrate into the groundwater aquifer, thus contributing to its recharge. Additionally, the storage of harvested rainwater through rainwater harvesting storage systems is especially important as an alternative water servicing option due to the urban metabolism analysis results from Chapter 4.

4. **Reuse**

This action involves the reuse of stormwater and wastewater to lower the pressure on the centralized water supply system, by its use by fulfilling non-potable demands such as flushing of toilets and irrigation or parks.

5. **Maintain**

This is a critical action in that all WSUD measures require maintenance in order to uphold the longevity of projects.

Based on the analysis in Chapter 3 and the actions outlined in this section, a map containing priority interventions can be determined based on the following criteria:

- Areas of deprivation/informal settlements:
  From the analysis in Chapter 3, it can be understood that often areas of deprivation and informal settlements are areas which struggle the most with access to water and sanitation and hence must be dealt with accordingly.
- Mining residual areas:
  These areas require redevelopment and specifically with mining tailing dumps, the areas could be redeveloped into vegetated areas to change the landscape. This can be done by operationalizing mining companies to cover the cost and allowing for a culture of urban agriculture to thrive in these places as suggested by Bobbins and Trangoš (2018).
- River rehabilitation:
  To prevent further pollution of downstream environments, it is important that rivers are rehabilitated starting at the source of the river. The city has a number of rivers that begin within its city limits.

Furthermore, the strategy will be implemented by deploying interventions on a sub-catchment level. The different sub-catchments within Johannesburg are depicted in Figure 40. Figure 41 depicts the map containing the priority interventions in which the macro strategy can be applied. Six zones are highlighted. Each zone is in proximity either to mining residual areas, informal settlements or the starting source (headwater) of a river.

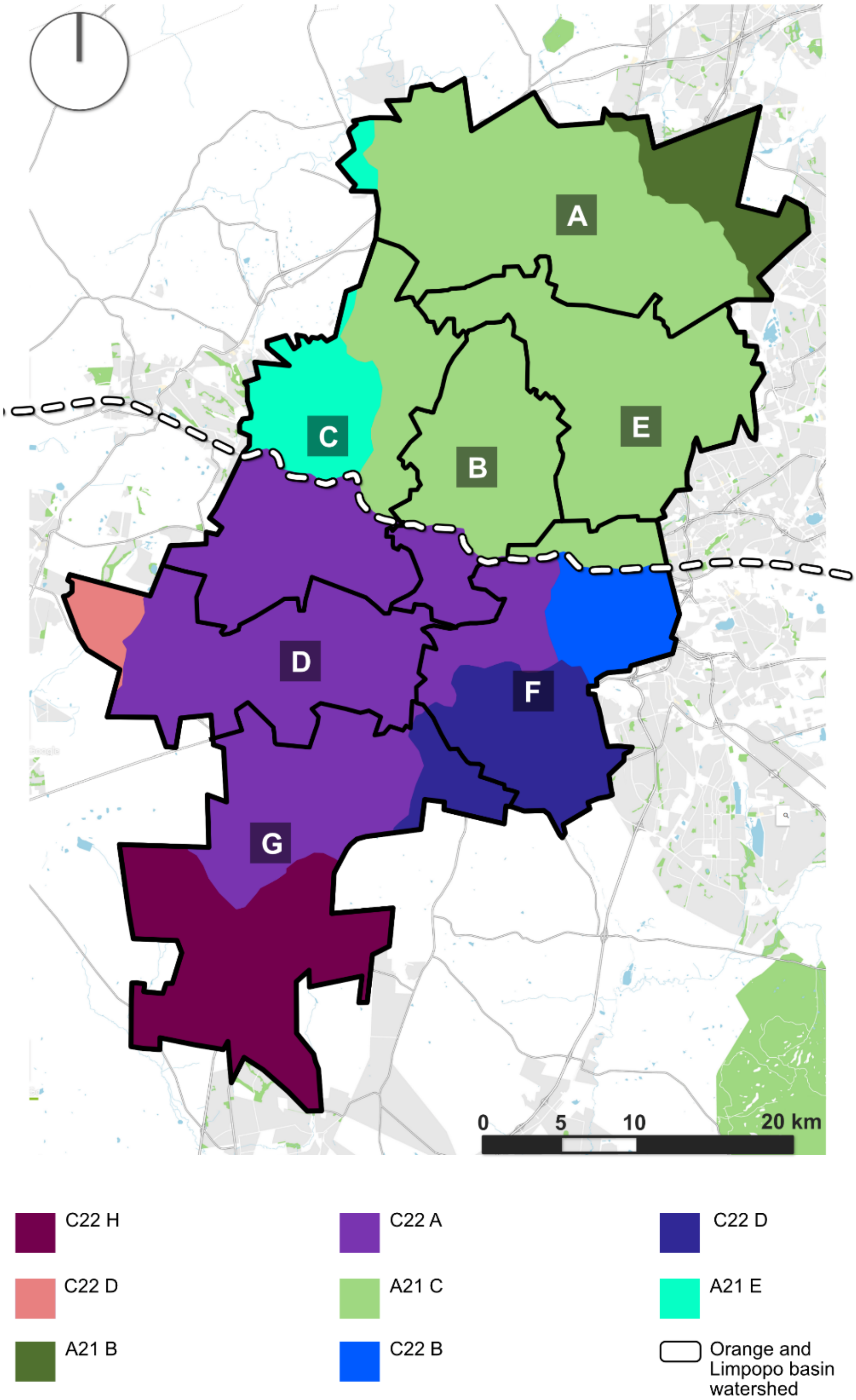


Figure 40: Catchment areas within Johannesburg

Source: Created by author and adapted using data Western Cape of Agriculture (2021)

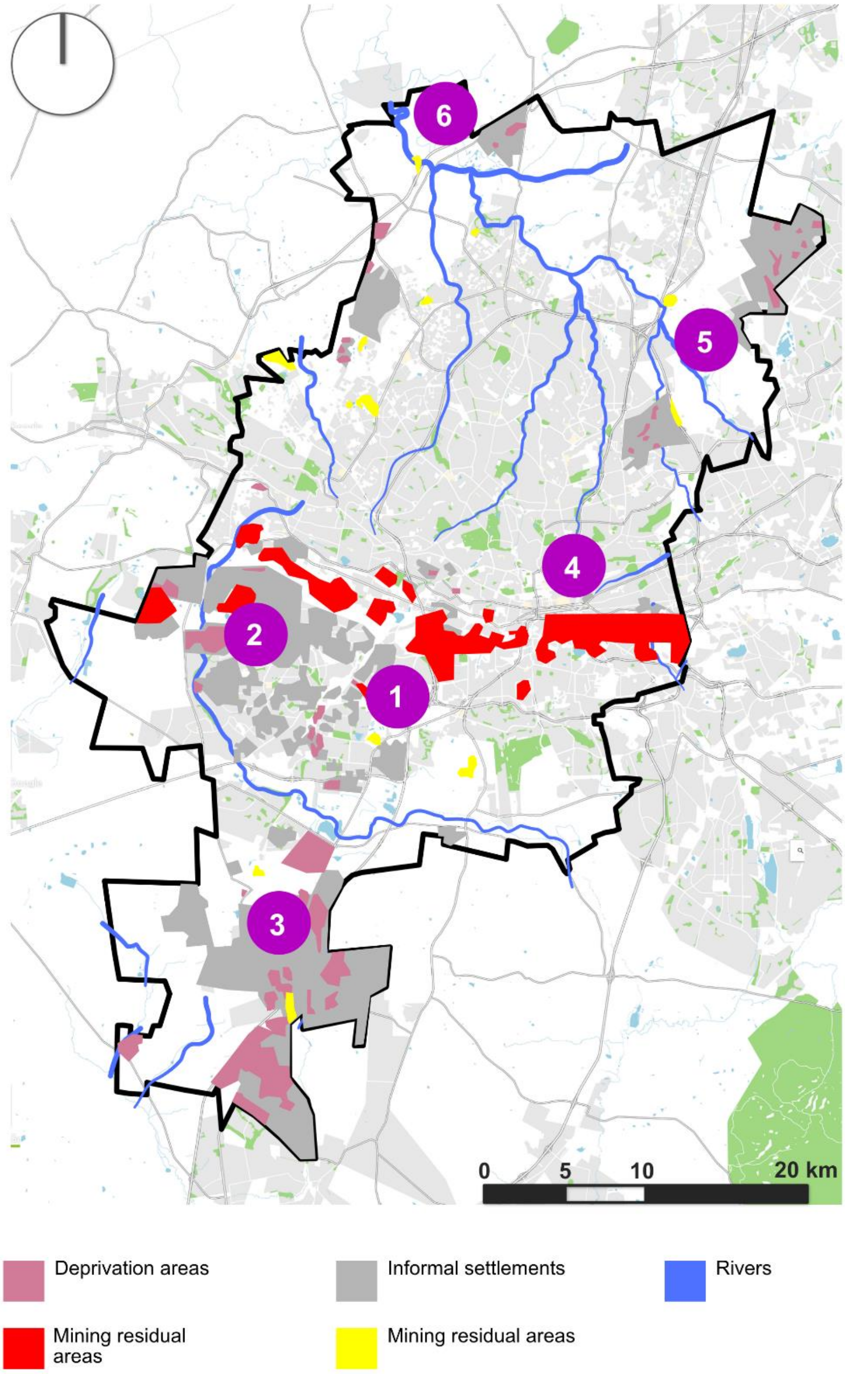


Figure 41: Macro strategy for Johannesburg

Source: Created by author (2021)

5.7.2. Meso and Micro Strategies: Zone 1

This section will present a case study example using intervention area zone 1 (from Figure 41) from the previous section within Johannesburg and seek to showcase how various water sensitive strategies can be implemented at a smaller scale. The selected area (zone 1) is located in Soweto, a sub-area located in region D and is a prime area of intervention due to its intersection of water challenges such as water access and future climate vulnerability (high risk area) as determined in Chapter 3. This area not only contains a high prevalence of informal settlements as well as some deprivation areas, but conditionally contains numerous wetlands areas. Additionally, a case study review of Soweto by Maphela and Cloete (2020) highlighted that Sowetan households have varied perceptions regarding the role they play in relation to water and seeing themselves as catalysts of change. The study also found that the objectives of the National Water Act (RSA, 1998) relating to the municipality's responsibility to provide water has not been met in the area. This highlights the complexity of the area regarding its people.

This thesis seeks to investigate an area approximately 462 ha in size within Soweto as seen in Figure 42. The area contains several amenities as well as both formal housing and informal settlements within the same area. Most notably, the area contains Goudkoppies WWTW, which is one of 6 wastewater treatment plants responsible for Johannesburg's sewage treatment. Within the selected area, is an artificial pond called the Orlando Dam which is located near Soweto Towers, a decommission coal-powered station (see Figure 43) and now has become a popular tourist destination (Gauteng Transport Authority, 2021). The pond is classified as a mining residual area with high levels of contamination (GCRO, 2021a). This is corroborated by a study from Bengu et al. (2017) examining fish health in the dam where it was found that there were high levels of bacteria present in water samples which affected the growth of fish. Two unchanneled valley bottom wetlands (Baileyspruit to the north and Diepkloofspruit meet at Orlando Dam. A land use decision support tool report generated for the area by the South African National Biodiversity Institute (2021) revealed that these wetland ecosystems are under threat. The average rainfall for the area is between 600-700 mm. The underlying aquifer contamination risk is measured to be between least and modest. The saline levels in the groundwater quality present a slightly salty taste. (Western Cape Department of Agriculture, 2021). The area compromises of a portion of three municipal wards (Ward no. 24,25 and 26). In terms of percentage of people who do not have access to water, it was reported in the 2011 national census, that proportions vary greatly within the area. Ward 24 reported that 5% of its inhabitants had access to water while ward 26 reported that 27% of inhabitants did not have access to water (GCRO, 2021b). Access to a flushed toilet followed a similar trajectory with a staggering 41% of inhabitants who did not have access to adequate sanitation. This is indicative of the varying levels of housing in the municipal wards, with specifically the highest percentages from ward 26 due to the inadequate infrastructure available in informal settlements. Stagnant stormwater is also an issue in informal settlements.

Figure 42: Overview of area and areas of intervention required

Source: Created by author using Zoom Earth (2021)

A SWOT analysis for the area in question is presented as follows:

Table 17: SWOT analysis for intervention area 1

Source: Created by author (2021)

Strengths	• Rainfall harvesting potential • Availability of wetland areas for urban agriculture and promoting biodiversity
Weaknesses	• Polluted wetlands • AMD • Poor water and sanitation access
Opportunities	• Tourism • Moderate groundwater availability • Green/open space accessibility • Availability of amenities
Threats	• Lack of public interest • High risk to climate change vulnerability

From this analysis, some key interventions can be implemented in the area:

1- *Orlando dam (wetland rehabilitation and public space)*

The following interventions can be implemented in zone 1, in order to recover the wetland system and additionally offer amenity to the surrounding residents. A snapshot of the area can be seen in Figure 43.

Figure 43: Orlando dam area

Source: Gauteng Transport Authority (2021)

The dam must be upgraded into a constructed or artificial wetland which can be built at the intersection of the two unchanneled valley bottom wetlands (see perspective view of proposals 1 and 2 in Figure 45) that meet at Orlando Dam for purification and retention purposes. These constructed wetlands will consist of shallow, vegetated systems (Bobbins et al.,2019). The vegetated system will act as a bio-remediation zone in order to enable rhizofiltration, which is the process in which plants are used to absorb contaminants. It is therefore specifically useful for treating pollutants from AMD (Abdullahi, 2015). Additionally, the wetland can be used to attenuate stormwater runoff during floods (Bobbins et al., 2019). An example of a constructed wetland is seen in Figure 44.

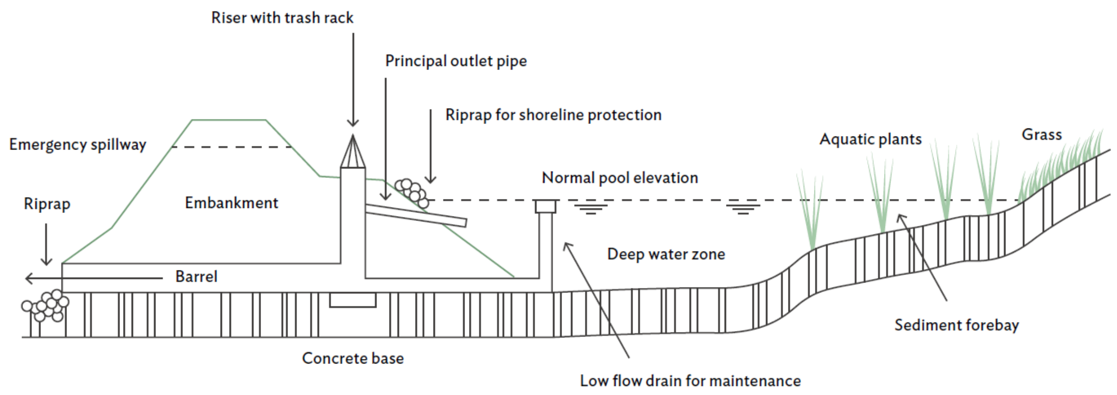


Figure 44: Example of constructed wetlands

Source: Bobbins et al. (2019, p.36)

As mentioned previously, the wetland can offer amenity to inhabitants by providing a space for people to connect and foster connection and value with water. An existing square field adjacent to the wetland can be redeveloped as a semi-permeable surface to prevent stagnation of water in the area. These surfaces would allow water to infiltrate into the surface, which provide natural filtration and help recharge the underlying groundwater aquifers. In addition, alien species vegetation must be removed and replaced with indigenous trees such as knob trees, natal mahogany and umbrella thorn trees (South Africa, 2021).

A full cross section of the area can be seen in Figure 46 to provide a visualization of the proposed strategy.

Table 18 summarises some key aspects of this project and its implementation:

Table 18: Orlando dam key characteristics for implementation

Source: Created by author (2021)

Stakeholders	DWS, DHS, NT, DMRE, DALRRD, COGTA, Gauteng Provincial Department, Water Research Commission, City entities, City departments, catchment forum, catchment management agency, ward councillors, landowners, private stakeholders, agricultural unions, mining unions
Benefits	Human and Environmental Health Community Unity Climate Resilience Water Sustainability
Timeframe	5 years
Water Sensitive Principles	City providing ecosystem services, city comprising of water sensitive communities

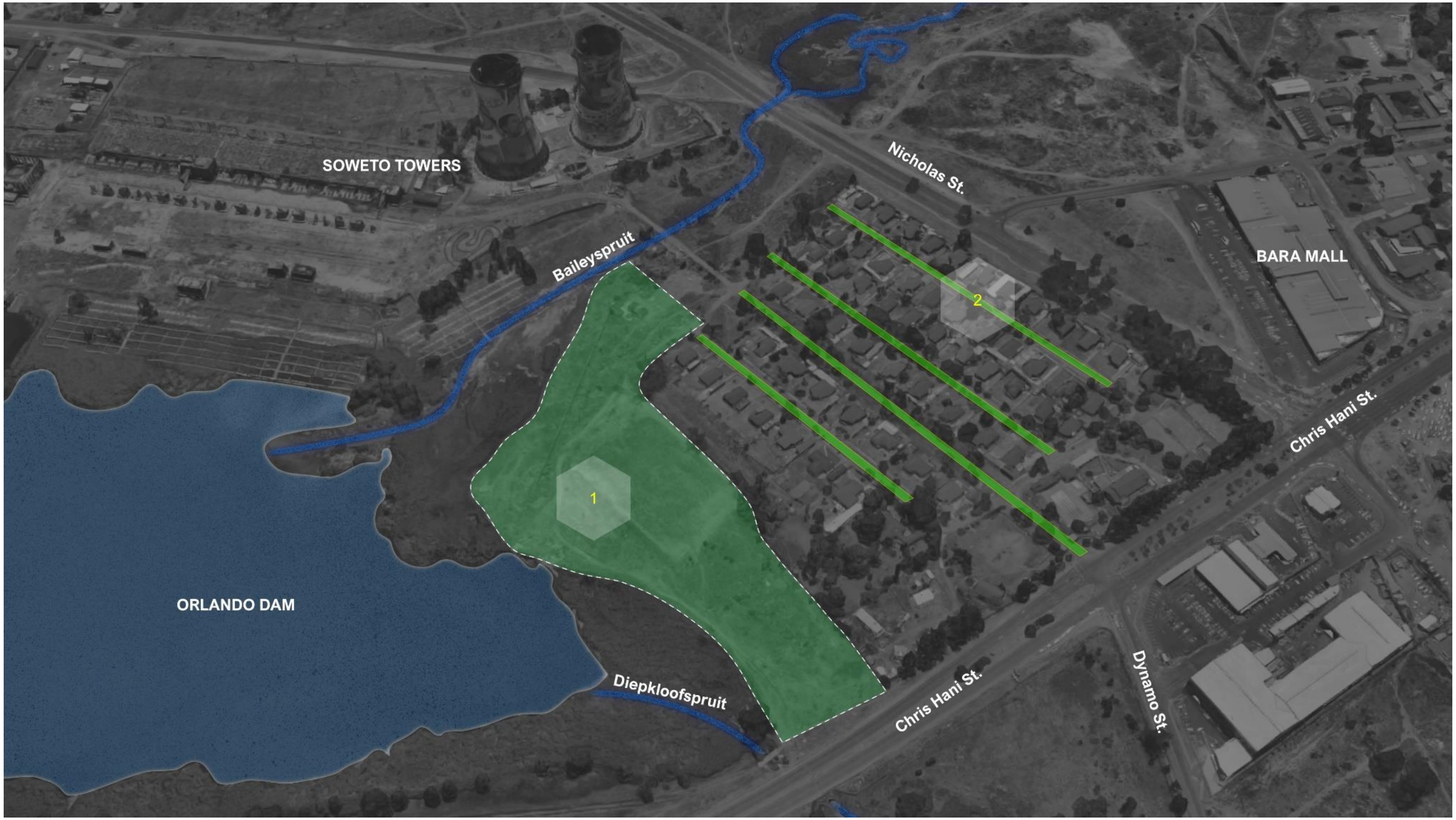


Figure 45: Perspective view of proposals 1 and 2

Source: Created by author and adapted from Google Maps (2021)

Figure 46: Section view of proposal for wetlands

Source: Created by author (2021)

2- Suburban Context a

The area contains scattered blocks of formal housing consisting of single units of housing as pictured in Figure 47.

Figure 47: Street view of suburban context "a"

Source: Google Maps (2021)

The overall area in particular is a gated community which is a typical typology of settlements found in Johannesburg. Streets are approximately 5 m wide and have generally slow-moving traffic with a speed limit of 40 km/h which allow pedestrians to feel generally safe to walk alongside or on them. Retrofitted interventions can include mini-swales and filter strips. Swales are vegetated drainage systems that can slow down runoff and additionally reduce stormwater runoff through infiltration (Bobbins et al., 2019; Woods-Ballard et al.,2011). Filter strips function in a similar way to swales, however these are more concerned with conveyance of stormwater to receiving streams. These can be installed convey stormwater to the north of the community where there is a portion of land gently sloping towards leads the Baileyspruit wetland. This portion of land additionally requires a bio-retention zone and larger vegetated swales as part of ensuring filtration (bi-retention filter) of stormwater runoff and equally allows infiltration into the soil (Bobbins et al., 2019). Litter management in this area is especially important to ensure filtration is not clogged (Brooker, 2011). A bioswale buffer can be used in between the community and the road. Additionally, rainwater harvesting systems can be installed within the community as an alternative source for irrigation, flushing water and drinking water as seen in Figure 48. Storage tanks can be developed above or below ground.

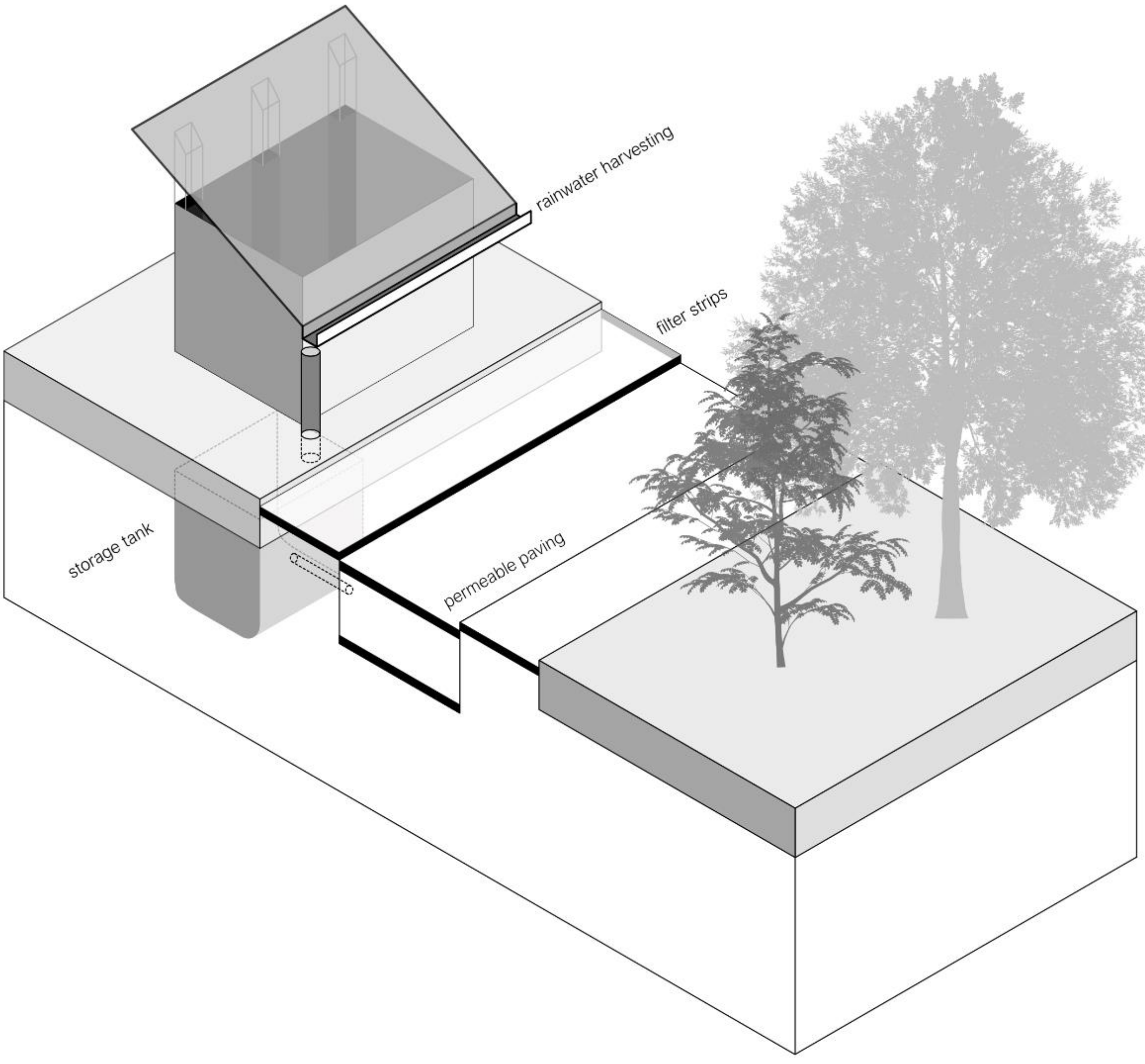


Figure 48: Example of residential rainwater harvesting system

Source: Created by author (2021)

Table 19 provides a summary of key components of the proposal for Suburban context "a":

Table 19: Suburban context 'a' key components

Source: Created by author (2021)

Stakeholders	DWS, DHS, NT, DMRE, DALRRD, COGTA, Gauteng Provincial Department, Water Research Commission, City entities, City departments, catchment forum, catchment management agency, ward councillors, landowners, private stakeholders, agricultural unions, mining unions
Benefits	Human and Environmental Health Community Unity Climate Resilience Water Sustainability Service delivery
Timeframe	5 years
Water Sensitive Principles	City providing ecosystem services, city comprising of water sensitive communities, city as water supply catchments.

Figure 49 indicates a perspective view of the area as well as the location of the filter strips in relation to the adjacent wetland. Figure 50 presents a cross section of the residential street.

Figure 49: Perspective view of suburban context 'a'

Source: Created by author and adapted from Google Maps (2021)

Figure 50: Cross section view of residential street

Source: Created by author (2021)

3- University of Johannesburg Campus

The area contains a university campus (University of Johannesburg) which in itself can be an adequate testing ground for experimental small scale water sensitive strategies for research purposes. Alternative water servicing options can be applied in the university allowing for further research into the effectiveness of options such as rainwater harvesting. The experimental strategies can be more rapidly implemented within a private institution and offer insights into smaller scale interventions. Additionally, the university can be a platform to bring stakeholders together and bring together research partnerships. Table 20 summarises the key components of this proposal.

Table 20: Key components for University of Johannesburg intervention

Source: Created by author (2021)

Stakeholders	DWS, DHS, NT, DMRE, DALRRD, COGTA, Gauteng Provincial Department, Water Research Commission, City entities, City departments, private stakeholders, academics, students
Benefits	Human and Environmental Health Community Unity Climate Resilience Water Sustainability
Timeframe	2-3 years
Water Sensitive Principles	City providing ecosystem services, city as water supply catchments.

4- Informal Settlements

Informal settlements are complex in that retrofitting strategies are difficult to enable without holistic upgrading of the area occurring simultaneously. This proposal will for the purpose of this thesis focus on smaller scale interventions relating to water management. Interventions such as adding a common decentralized rainwater harvesting system for supply of water and permeable paving and soakaways to prevent stormwater stagnation as pictured in Figure 51 which also represents a snapshot of the inner streets of the area.

Figure 51: Informal settlement street view

Source: Google Maps (2021)

The case study on Diepsloot informal settlements indicated the success of permeable paving due to its multifunctional use as not only a means of reducing stormwater runoff through absorption (Bobbins et al. 2019) but providing paving for pedestrians to walk more comfortably through the area. Another strategic intervention to drain water are soakaways and agricultural drains which are shallow, linear excavations which contain materials such as gravel that allows stormwater to percolate into a sub-surface which then infiltrates into the underlying soil. Agricultural drains function in a similar way in that there is a pipe that lies underneath the top layer of filtration to convey water elsewhere (Woods-Ballard et al., 2011).

Another important measure for the area could include the empowerment of the local community through urban agriculture near the Diepkloofspruit (wetland) which can provide a means of food supply to residents in the settlements. Figure 52 provides a perspective view of the area indicating the proximity of the informal settlements to the wetland. Safe urban agricultural practices should go hand in hand with protection of the wetland which will use vegetation that will enable rhizofiltration. Figure 53 provides a cross section of the area identifying where interventions can be placed and Table 21 provides a key summary of the key participants. Additionally, Figure 54 indicates how permeable paving and agricultural drains can be implemented in the area.

Table 21: Informal settlements intervention area components

Source: Created by author (2021)

Stakeholders	DWS, DHS, NT, DMRE, DALRRD, COGTA, Gauteng Provincial Department, Water Research Commission, City entities, City departments, catchment forum, catchment management agency, ward councillors, landowners, private stakeholders, agricultural unions, informal settlement residents
Benefits	Human and Environmental Health Community Unity Climate Resilience Water Sustainability Service delivery
Timeframe	5 years
Water Sensitive Principles	City providing ecosystem services, city comprising of water sensitive communities, city as water supply catchments.

Areas of intervention 1,2 and 4 within this portion of Soweto requires adaptive management and action research to succeed as well as continuous engagement of all stakeholders at every stage of planning.

Figure 52: Perspective view of informal settlement adjacent to wetland

Source: Created by author and adapted from Google Maps (2021)

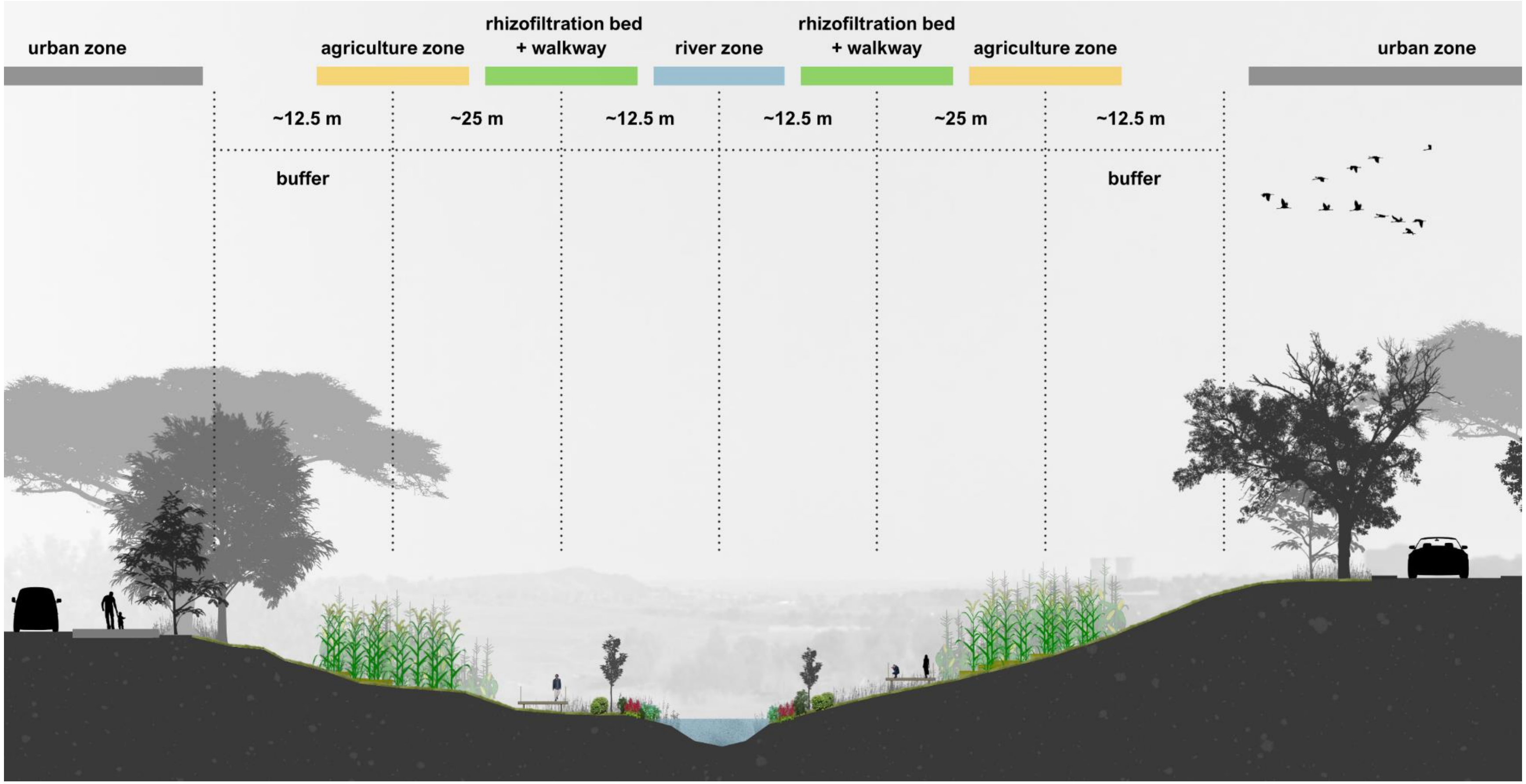


Figure 53: Cross-section of wetland adjacent to informal settlements

Source: Created by author (2021)

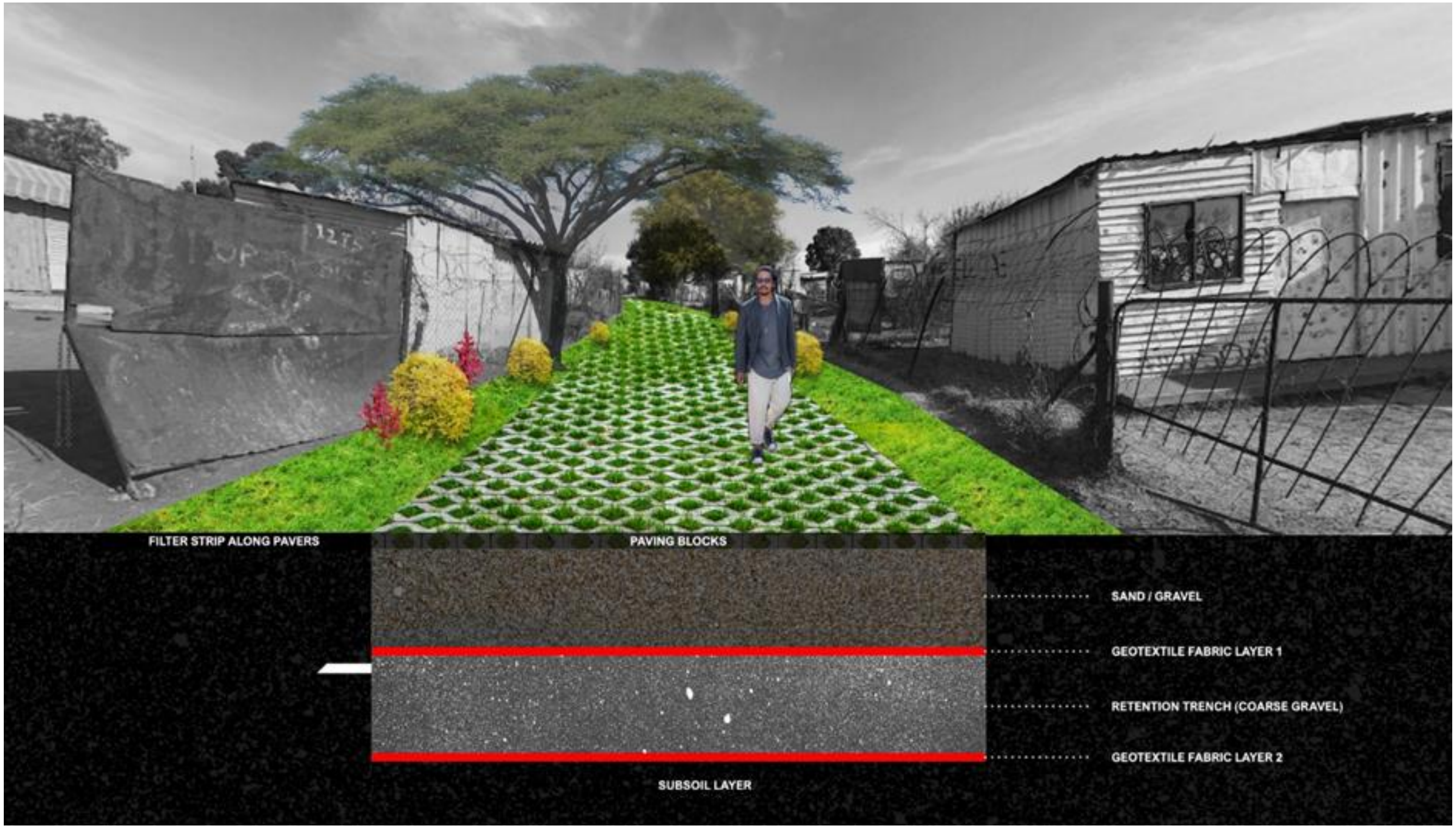


Figure 54: Cross section of inner street view of informal settlements

Source: Created by author and adapted from Google Maps (2021)

5- Goudkoppies Wastewater Treatment Works

In the same approach as the Northern WWTW and Driefontein WWTW, this thesis proposes that bio-gas electricity systems be added to the Goudkoppies Wastewater Treatment Works. The electricity can be used to power the surrounding areas which compensates for the proximity of the WWTW to the surrounding areas.

Table 22: WWTW intervention components

Source: Created by author (2021)

Stakeholders	DWS, DHS, NT, DMRE, DALRRD, COGTA, Gauteng Provincial Department, Water Research Commission, City entities, City departments
Benefits	Human and Environmental Health
Timeframe	2-3 years
Water Sensitive Principles	City providing ecosystem services, city as water supply catchments.

The four proposals offer a glimpse into the possible methods in which small scale interventions can be implemented in priority zones highlighted in the macro strategy.

Chapter 6: Conclusions and Further Recommendations

6.1. Conclusions

This thesis aimed to recommend urban water management interventions and spatial strategies that can be implemented in Johannesburg as part of understanding its potential to transition into a WSC. The analysis was based on three different methods, a review of literature, an analysis of water related characteristics of Johannesburg as well as determining the UWMB balance of the city.

The literature review defined the concept of WSC and its applicability in South Africa. It was determined that any implementation of a WSC transition must be context-oriented by considering the type of development in the area and account for the respective socio-economic conditions. Examples of application of WSC principles were also explored to further understand the practicality of applying WSC principles in different context. It was found that participatory processes in both an informal and formal context are especially important. The policy and regulatory framework supports a WSC transition in some aspects through its spatial land use regulations, however many laws are too broad and require more explicit regulations in order to work at a local level. Additionally, the literature also justified the use of a UWM study in planning a water sensitive transition through its ability to provide quantitative indicators that can champion alternative water services and inform policy guidelines. It can also assist in benchmarking the progress by providing quantitative support to the WSC index which is a measure of tracking progress relating to a city's transition to a WSC.

The case study analysis of Johannesburg revealed challenges relating to the ability to meet the water supply and demand and its reliance on water from other catchments, including challenges regarding pollution of waterbodies, wetlands and groundwater from sources such as wastewater, stormwater and AMD. Accessibility to parks and spatial mismatch between density and economic zones of activity as well as the relationship between informal settlements and lack of water access were highlighted as well. The availability of wetlands presents a key opportunity to apply GI solutions. Organisation gaps in Johannesburg include fragmentation of entities who are responsible for change in the water sector. Regulatory law that needs to be strengthened include the water service and stormwater service by-laws. The threat of the impact of climate change such as the occurrence of hydro-meteorological hazards in the city is another important factor to take into consideration with regard to Johannesburg.

The UWMB analysis further confirmed Johannesburg's reliance on surface water with groundwater sources accounting for a very small portion of the input flows. The performance assessment of the UWMB indicated that wastewater reuse and more especially rainwater harvesting have the potential to form part of alternative water services for the city. A scenario analysis confirmed that alternative options could meet water demand in both 2019 and projected water demand in 2030. The highest potential regarding centralized water supply was found to be rainwater reuse and a WSC transition for Johannesburg can be championed using this as part of a stronger decentralised water system.

Based on the analysis in Chapters 2-4, a strategic program was developed that centred on four key components: public participation and governance, ensuring socio-economic equity and liveability within the area, strengthening the use of WSUD tools and improving environmental health. A macro spatial strategy for Johannesburg indicating 5 action principles to be implemented throughout the city was also described. The strategy based on the analysis in Chapter 3 also identified priority intervention zones. On a micro level, strategies were developed for both informal and formal settlements as well as wetlands using WSUD spatial tools such as permeable paving, rainwater harvesting and swales.

6.2. Further Recommendations

Further avenues of research would include an investigation into the procurement of financing of micro-scale WSC interventions. This would provide a deeper understanding of the level of capacity needed to implement such interventions. This will require an understanding of water tariff pricing and municipality infrastructure budgeting.

The strategic program can further be expanded by predicting and modelling the ideal design flows for each component of the UWMB analysis in Johannesburg if for example, rainwater harvesting systems and recycling of stormwater were part of the inflows and outflows for Johannesburg. The results of this can provide a comparison of the hydrological performance between the current status quo and the ideal urban water metabolism for Johannesburg. This can be used to further champion developments in relation to principles of WSCs.

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Appendix

Table 23: UWMB Components, data sources and calculations

Source: Created by author

2018-2019	**Data Source**		**Unit**	**Conversion**	**l/m²/ year**	**GL/ year**
Precipitation (P)	Cullis and Philips, 2019	679.90	mm/ year	Area x l/m²	679.90	1118.44
2018-2019	**Data Source**		**Unit**	**Conversion**	**Ml/ year**	**GL/ year**
Centralized Water Supply (C)	Johannesburg Water, 2019, p.48	1612	Ml/ day	(Ml*365)/1000	588380	588.38
2011-2012	**Data Source**		**Unit**	**Conversion**	**Ml/ year**	**GL/ year**
Decentralized Water Supply (D)	Fourie, 2012, p.13	11	Ml/ day	(Ml*365)/1000	4015	4.015
2018-2019	**Data Source**		**Unit**	**Conversion**	**Ml/ year**	**GL/ year**
Wastewater (W)	Johannesburg Water, 2019, p.18	926	Ml/ day	(Ml*365)/1000	337990	337.99
1920-2004	**Data Source**		**Unit**	**Conversion**	**l/m2/ year**	**GL/ year**
Surface Runoff (R_s)	Water Resources Study 2005 and 2012 (1920-2009)	68.2	mm/ year	Area x l/m2	68.2	112.189
	Extracted from Western Cape Department of Agriculture (2021)					
2005	**Data Source**		**Unit**	**Conversion**	**l/m2/ year**	**GL/ year**
Groundwater Infiltration (G)	Groundwater Resource Phase Assessment Part 2, 2005, Department of Water and Sanitation	43	mm/ year	Area x l/m2	43.2	71.064
	Extracted from Western Cape Department of Agriculture (2021)					
-	**Data Source**					**GL/ year**
Evaporation (Et)	Et=P-Rs-G					935.19
2018/2019	**Data Source**					**GL/ year**
System loss (Cufw)	Johannesburg Water, 2019, p.48	38.6	%	C*38.6%		227.115
Fixed Values	**km²**	**m²**				
Area of Johannesburg	1645	1645000000				

Table 24: Conversion of UWMB components from GL/year to ML/day

Source: Created by author (2021)

	GL/year	ML/year	ML/day
Precipitation (P)	1118.44	1118436	3064
Centralized Water Supply (C)	588.38	588380	1612
Decentralized Water Supply (D)	4.02	4015	11
Total Input	**1710.83**		
Wastewater (W)	337.99	337990	926
Surface runoff (Rs)	112.19	112189	307
Groundwater infiltration (G)	71.06	71064	195
Evapotranspiration (Et)	935.18	935183	2562
System Loss (Cufw)	227.11	227115	622
Total Output	**1683.54**		
Storage	27.2903		

Table 25: Projected water supply deficits under various scenarios using data from City of Johannesburg (2011)

Source: Created by author (2021)

		Demand	Supply	Gap
		ML/day		
High growth	1950000	5342	1612	3730
Business as usual	1250000	3425	1612	1813
Low growth	800000	2192	1612	580
2019		1749	1612	137

Table 26: Scenario analysis

Source: Created by author (2021)

Recycling Potential	Max	25%	50%	75%
57%	528	131.955	263.91	395.865
19%	58	14.59994	29.19988	43.79982
	586	147	293	440
Loss recovery				
38%	236	59.11204	118.2241	177.3361
	823	205.667	411.334	617.0009
Rainwater 100%	3064	766	1532	2298
TOTAL AUGMENTATION	3887	972	1943	2915

DECLARATION OF AUTHORSHIP

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First Name: Sabena Rajan………………………Surname: Thomas………………………………

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I hereby declare that the Master Thesis, which I am handing in today, is my own work, produced independently, using no other sources and means of support than those specified.

Frankfurt am Main, 01-09-2021.......................... ....

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