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Assessing the effectiveness of green infrastructure in urban areas - for mitigation of climate change-induced extreme events in South Africa: a case study of the Johannesburg CBD

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Assessing the effectiveness of green infrastructure in urban areas - for mitigation of climate change-induced extreme events in South Africa: a case study of the Johannesburg CBD

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2025

Declaration

I, Kagiso Thobejane, student number 2901024, declare that this dissertation titled “Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD” is my own work. The information that I have derived from other sources has been referenced accordingly.

Signed,



Kagiso Thobejane

Date: February 10th, 2026

Abstract

The rationale of this research study is to examine the effectiveness of green infrastructure in urban areas for mitigation of climate change, with specific interest in this case study being the Johannesburg Central Business District. The study asserts that green infrastructure should be implemented as a measure to mitigate the effects of the urban heat island effect and urban flooding. The study formulates evidence from municipal authorities, private sector specialists, and local community members to understand the local context and institutional processes influencing the adoption of green infrastructure. The study reveals that the urban heat island effect and flood risk are crucial threats to Johannesburg's urban environment, and that there are vulnerable populations that are disproportionately affected. Through assessing the effectiveness of green infrastructure, such as green vegetation-covered roofs, bioswales, wetlands, permeable pavements, and urban trees, the study demonstrates green infrastructure's ability to provide holistic benefits spanning from urban temperature regulation to stormwater management, to social equity improvement. Furthermore, the study presents notable barriers such as institutional silos, fiscal constraints, and regulatory gaps to the adoption of green infrastructure in the city of Johannesburg. The study concludes with recommendations for integrated policy strategies, clear custodianship, and community engagement in the development of a climate-resilient urban environment in Johannesburg, thus informing future research and broader discussions on urban resilience and climate adaptation in the Global South.

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Acronyms

UHI	Urban Heat Island
GI	Green Infrastructure
CBD	Central Business District
COJ EISD	City of Johannesburg, Environment and Infrastructure Services Department
CO_2	Carbon Dioxide
GDP	Gross Domestic Product
NGO	Non-Governmental Organization
EPWP	Expanded Public Works Programme

1. Chapter 1 – Introduction

In this current era, densely populated metropolitan areas are facing the intensified impacts of climate change. This is an occurrence in which long-term changes in the weather cause drastic effects on the environment in the affected area. A study by Raizada et al. (2022) supports the assertion that climate change is a long-term change in a region's climate or weather patterns over decades or longer. Whereas, Dietz et al. (2020) define climate change as the ongoing pattern of modifications to Earth's overall weather caused by an average rise in the surface temperature of the planet, a phenomenon widely referred to as global warming. The repercussions of this phenomenon leave a daunting mark on the cities and the livelihoods of those who live in these affected areas.

Climate change has major implications in the context of urban areas, particularly for the people residing in densely populated areas in urban settings (Guo et al., 2022). For instance, Guangzhou in China is impacted by urban heat island (UHI), this coastal megacity with high density has 60-year monitoring data showing rising temperatures, and a study reveals strong resident perception of heat-island conditions (Kantamaneni et al., 2023). A similar study by Pappalardo et al. (2023) revealed that in 2022, heatwaves hit densely populated parts of the city of Padua (Italy). The intensifying heatwaves reached 5-8°C above rural surroundings during heatwaves, stressing vulnerable urban residents (Pappalardo et al., 2023). According to Li et al. (2021a), reducing excessive heat from the UHI effect and preventing floods after heavy rains are the two main climate challenges that expanding cities need to address. According to Li et al. (2021b), the UHI effect happens when temperatures are higher in cities than in the countryside. As pointed out by Levermore et al. (2018), when temperatures in cities are higher than their rural counterparts, it's known as UHI. This can be attributed to factors such as engines and machines producing too much heat, or due to natural land cover absorbing less heat than urban construction materials.

As global temperatures continue to rise, heat stress will likely intensify, and the impact of this on livelihoods is detrimental. Consequently, there is a higher chance of heat-related illnesses such as fainting, as well as heat stroke. A study by Li et al. (2015) suggests that the impact of excessive heat exposure results in increased levels of mortality during heatwaves. It can then be understood that cities often experience the UHI effect, which has negative impacts on cities' concentrations of pollutants in the air, consumption of energy, and physical well-being due to localized temperature rises, endangering people, the environment, and the economy (Heaviside et al., 2017).

Events like urban flooding are putting stress on the structure, systems, and functioning of cities. This occurs when a pluvial flood takes place in cities where the surrounding natural environment may have been changed by the construction of roads and pathways, which creates impermeable layers that prevent rainwater from permeating the ground (Agonafir et

al., 2023). Therefore, in urban areas with limited infiltration, rainfall events may instigate a rapid ascent of floodwaters, which is a disaster with severe consequences. For instance, drownings, car accidents, or collapsed buildings may result in loss of life and long-term health consequences (Agonafir et al., 2023). In addition, adverse economic impacts transpire, as transportation services and businesses are damaged and disrupted (Hammond et al., 2015). This is primarily because life in the city is dependent on a variety of services and functions, including electricity and water provision, transportation, and housing (Hammond et al., 2015). Therefore, this demonstrates that urban flooding can cause significant disruption to these services and have broader implications for the population.

The urban footprint of the global north has expanded rapidly because of the growing popularity of major cities like New York and London. These cities are not only the epicenters of energy consumption and waste, but they are also expected to bear the brunt of climate change's consequences. The increase in urban population over the previous century has resulted in significant transformation of the earth's ecosystems, which contributes to climate change (Revi et al., 2014:12). Additionally, large cities account for only a small part of the world's geographical surface, but their physical and ecological footprints are significantly larger (Revi et al., 2014:12). To demonstrate these repercussions, consider the following examples of how the UHI effect and flooding affect cities around the world.

The issue at hand is widespread across all regions of the world. In the USA, the number of heat-related fatalities has steadily risen and now surpasses the number of deaths from other extreme weather events, particularly for vulnerable and underprivileged communities (Meenar et al., 2023). Agonafir et al. (2023) report that 44 people died in September 2021 as a result of the urban flood catastrophe caused by Hurricane Ida's excessive rains in Westchester County, New Jersey, and New York City.

In European cities, especially those in the Mediterranean region, there are substantial disruptions in terms of both increasing seasonal averages and severe weather occurrences (Ingaramo and Negrello, 2024). The country most affected by this catastrophic occurrence is Italy. In May 2023, severe floods struck Bologna, while the country’s north saw extended droughts between 2022 and 2023 (Ingaramo and Negrello, 2024). Flooding is the most common threat from nature in Europe, with over 213 significant catastrophic floods occurring there between 1998 and 2009 (Prokic et al.,2019).

According to a UN report, over 55% of people now reside in cities, with the global south experiencing the fastest rate of urbanization (United Nations, 2018). Meanwhile, in Africa, the combination of climate change and urban growth makes life for citizens particularly difficult in African cities (Li et al., 2021a). East Africa has become more urbanized over the past few years, and this development is anticipated to continue (Li et al., 2021a). Currently, most of the research on the UHI focuses on northern hemisphere mid- latitude cities, with the global south

regions being frequently overlooked (Zhou et al., 2019). Climate change and urbanization brought on by overpopulation will make African cities even more vulnerable to heatwaves in the future (Souverijns et al., 2022). African urban populations are experiencing increased urban heat island impacts as a result of climate change (Li et al., 2021b). An increasing number of people will experience heat stress as metropolitan areas increase and climate change intensifies. According to Li et al. (2021b), in Kenya and Uganda, for example, more than 70 million people faced 20 to 25 days of intense heat per year in 2018. However, by 2090, that number might rise to 125 days, endangering even more people.

There is growing concern that South African towns could be affected by the urban heat island effect, given that between 1997 and 2013, rising temperatures were directly linked to approximately 30,000 deaths in the country (Greenstone, 2023). This calls for greater research into more mitigation measures. Urban heat stress is predicted to become a growing issue because of climate change (Roberts and O'Donoghue, 2013), putting South African cities under double pressure from urbanization and increasingly common and severe high temperatures. South African temperatures are rising far faster than the global average, with forecasts of 3- 6°C by the end of the century, and the country's cities are likely to be hotspots for climate change consequences (Ziervogel et al., 2014). The rise in temperatures is expected to intensify the UHI impact, resulting in extreme weather in South African cities. Meanwhile, in formal areas, densification is frequently viewed as boosting energy efficiency and lowering Carbon dioxide (CO_2) emissions, although it might result in less green spaces and an exacerbated UHI effect locally (Enqvist and Pasquini, 2019).

A study by Hardy and Nel (2015) states that there are UHIs in Johannesburg. At night, the UHI effect is highest over Johannesburg's Northern Suburbs and in places with a high concentration of buildings, and the UHI effect is least strong in regions with a lot of vegetation or water features, including dams and streams (Hardy and Nel, 2015). Given the detrimental consequences of climate change on human populations, mitigating strategies such as green infrastructure may offer prospects to enhance the standard of living in areas where urban heat island and urban flooding effects have the greatest impact (Li et al., 2021 b).

This dissertation presents the argument that climate change is exerting pressure on the sustainability, resilience, and livability of urban areas; furthermore, cities such as Johannesburg must consider implementing green infrastructure as a mitigation measure. The argument is framed in a tripartite approach. Firstly, members of civil society in the Johannesburg CBD provide valuable insights regarding the UHI effect and urban flooding in the city, which helps to underscore the frequency and severity of the climatic issues outlined. Secondly, private sector professionals discuss their technical perceptions regarding green infrastructure as a solution to mitigate the UHI effect and urban flooding. Lastly, policymakers such as government officials emphasize the legislative frameworks that influence the implementation and operation of green infrastructure initiatives in Johannesburg.

1.1. Problem statement

Climatic events are becoming more frequent and intense in large cities because of climate change and urbanization. For instance, Johannesburg is faced with problems such as the UHI effect and urban flooding. The extent of impermeable surfaces is higher while the extent of green areas is lower, which results in localized temperatures and poor water infiltration that aggravate heatwaves and floods (Hardy and Nel, 2015; Agonafir et al., 2023). Climatic effects of this nature cause massive destruction of infrastructure, disruption of service delivery, potential loss of life, and challenges in the realization of sustainable urban development (Heaviside et al., 2017). Nevertheless, there is a research gap in the applicability of green infrastructure as a solution to these challenges in Southern Africa. Green infrastructure, such as green vegetation-covered roofs, parks, and rain gardens, has been identified to mitigate both heat island and stormwater issues in other countries (Li et al., 2021b). However, little has been done to assess its relevance and efficiency in African cities, particularly Johannesburg. This study aims to evaluate the effectiveness of green infrastructure in urban areas, for urban heat islands and urban flooding mitigation, in Johannesburg CBD. In framing this investigation, the study moves away from the generic discourse on climate change and toward the combined effects of environmental stresses and urban development inside a specific African context. While much of the worldwide literature has focused on urban history in the global north, this study focuses on climatic vulnerabilities in Southern Africa, where urbanization and rising temperatures intersect in unprecedented and more critical ways. As the chapters ahead will show, green infrastructure remains a largely untapped yet promising tool for cities like Johannesburg to adapt to a warming world.

In view of these observations, the study will be guided by the following questions:
1. How are the urban heat island effect and urban flooding affecting Johannesburg CBD, and what are the associated implications?

2. To what extent is green infrastructure a solution to mitigate these extreme climatic events, such as urban heat island and urban flooding?

3. What are the key factors that influence the implementation and operation of green infrastructure initiatives?

1.2. Aim and objectives

The study aims to evaluate the effectiveness of green infrastructure in urban areas, for urban heat island and urban flooding mitigation, in Johannesburg CBD. The specific objectives are:

1. To examine the extent of the urban heat island effect and urban flooding in Johannesburg and its associated impacts

2. To assess the role of green infrastructure in mitigating urban heat islands and urban flooding

3. To identify key factors influencing the successful implementation and operation of green infrastructure initiatives

2. Chapter 2 – Theoretical framework and literature review

2.1. Conceptual framework

2.1.1. Urban area

According to Schneider et al. (2010), urban areas include diverse combinations of various kinds of land cover that can include any combination of artificial surfaces and plants. While Cheshire (1999) states that, concerning the definition of "urban area", the entire metropolitan area is the most desirable choice, which constitutes an urban area. Urban areas are defined by a variety of features, including density, land use, and infrastructure. For example, Revi et al. (2014) demonstrate that population density increases with proximity to the city center, implying that urban regions can be classified by their concentrated population density near the city's core. Furthermore, areas that are fragmented and lack natural resources (such as trees, rivers, and wetlands) are more likely to be urban areas, owing to the risk of environmental deterioration caused by urbanization (Revi et al., 2014).

Furthermore, infrastructure is an important aspect that distinguishes urban regions. The global north is renowned for its skyscrapers and cutting-edge infrastructure, whilst impoverished countries in the south have inadequate infrastructure. According to Revi et al. (2014), economically disadvantaged countries struggle to provide basic infrastructure and services, consequently the civilians live in low-quality, overcrowded accommodation. In the context of this study, Johannesburg CBD stands out as a distinct urban region for a number of reasons. For starters, Johannesburg is South Africa's largest metro area by population size. According to Statistics South Africa (2022), this urban area has a population of around 4,803 262, demonstrating its population density. Secondly, Johannesburg is one of the country's financial and economic capitals. Satterthwaite et al. (2010) believe that rapidly urbanized countries demonstrate trends of rapid economic expansion, which may apply to Johannesburg in this situation. To substantiate the claim, Gauteng province consists of two main cities, Johannesburg and Pretoria, and according to StatsSA, Gauteng contributes over 34% to the country’s GDP (Statistics South Africa, 2021). This explains why Johannesburg can be considered one of South Africa's economic strongholds and, as a result, an urban area, or a "World-class African city," as patriots might claim.

Urban areas are pivotal for understanding climate risk because cities are hotspots of climate vulnerability and influence. Due to fast urbanization and expansion, urban areas tend to have warmer temperatures than adjacent rural areas, which is primarily due to insufficient greenery and concrete hard surfaces. Furthermore, this exacerbates heatwaves and allows for air pollution, which worsens as temperatures rise. Additionally, impermeable surfaces in urban areas prevent stormwater from seeping into the ground, posing significant drainage and flooding concerns.

In brief, it is critical to understand and assess climate impacts through an urban lens since cities represent certain risks, but even more so, they have sustainable solutions. Urban areas bear the brunt of climate change the most, which opens an opportunity to foster resilient and sustainable cities. In this study, the urban area was defined using existing administrative boundaries, notably those of Johannesburg, in the

City of Johannesburg municipality. This strategy promotes best practices while remaining in line with official datasets.

2.1.2. Climate change

According to Pielke (2004), climate change is characterized by differences in the average global temperature that arise from human activity, either directly or indirectly, and that complement natural variations in the climate over similar time periods. A more recent study explains that climate change is the long-term change in weather patterns over time (Raizada et al., 2022). Fawzy et al. (2020) reveal that greenhouse gas emissions from the environment and human activities are the main contributors to the shift in climate patterns known as climate change. Literature links these long-term changes in climate/weather to drastic environmental impacts. This assertion is supported by Abbass et al. (2022), highlighting that long-term climate change has led to extreme events such as melting glaciers, increased frequency of droughts, and heavy rainstorms.

This phenomenon typically causes an increase in the average global temperature over extended periods of time. Furthermore, studies reveal that human activity is responsible for the majority of the observed global warming throughout time (Gillett et al., 2021). Warming raises the concentration of a number of trace gases in the atmosphere, known as greenhouse gases. The three most common are carbon dioxide, methane, and nitrous oxide (Filonchyk et al., 2024). According to Intergovernmental Panel on Climate Change (IPCC) assessments, data reports that human actions over the years have been the primary source of the observed increase in global warming (Forster et al., 2024). Jones et al. (2023) reveal that the anthropogenic emissions of greenhouse gases caused by the burning of fossil fuels and changes to the Earth's land surface are mostly related to the extension of agriculture into previously natural habitats.

According to von Storch and Stehr (2006), considerable climate change is caused by anthropogenic activities like industrial pollution and deforestation, which result in CO_2 emissions. Researchers Hansen and Stone (2015) found that almost three-quarters of the consequences seen on continental scales have been mostly caused by anthropogenic climate change.

The main characteristics of climate change impacts are extreme weather patterns, particularly heat waves and rapid rainfall events. According to Kruger and Sekele (2013), for example, a study found that drastic increases in events like heat waves, days with high fire danger, and oppressive temperatures that affect people's comfort and health are already evident in South Africa. In addition, it is predicted that as the world warms further, there will be an increase in the frequency of powerful tropical storms, or hurricanes in categories 4 and 5. Thus, more rainfall is anticipated whenever tropical storms and cyclones occur. Consequently, these aspects of climate change place urban areas at risk.

Due to more frequent and severe droughts, urban floods, and heat waves, climate change makes cities more vulnerable. The UHI impact is exacerbated in inner-city areas due to air pollution, rising energy consumption and resulting greenhouse gas emissions, and exposure brought on by dense populations and expanding urban populations (Rafael et al., 2015).

Climate change is implemented in the current study as the fundamental driving force behind the growing urban challenges, including the UHI effect and urban flooding found in Johannesburg's CBD. Climate change is referenced, rather than assessed directly, through stakeholder impressions gathered through surveys and interviews, as well as related literature. This approach allows the study to analyze how different stakeholders interpret and experience the effects of climate change, as well as how these impacts are related to the city's rising frequency and severity of heat and flood events. By defining climate change as a contextual backdrop, the study emphasizes its critical role in shaping urban vulnerability and justifies the investigation of green infrastructure as a strategic mitigation strategy.

2.1.3. Urban heat island effect

According to Yang et al. (2016), the UHI effect is a type of heat buildup phenomenon brought on by human activity and urban construction within urban regions. However, the UHI effect, which is uncomfortable for urban residents during the summer, is defined by Nuruzzaman (2015) as a high temperature in the city center compared to its surrounding areas.

The urban fabric is continually changing; urbanization has resulted in cities replacing the natural environment with buildings and roads, and it is for this reason (anthropogenic activities) that heat levels in urban areas are always rising. Several factors contribute to the UHI effect, including impermeable surfaces, heat absorption, and low vegetation. For example, urban areas intensify heat because of the concentration of buildings, asphalt surfaces, and limited urban green space (Souverijns et al., 2022). Furthermore, surface alterations cause changes in energy balance, increasing urban temperature as compared to rural areas with no buildings, or even urban areas with fewer buildings that are vegetated (Cristiane de Costa Trindade Amorim et al., 2021).

Urban surfaces such as asphalt and concrete absorb more solar radiation than vegetation, resulting in greater surface temperatures. Furthermore, the absence of flora interferes with evapotranspiration, a process that releases latent heat and helps in cooling. As a result, greater nighttime air temperatures arise from surface cooling caused by energy transfer to the atmosphere (Cristiane de Costa Trindade Amorim et al., 2021). The empirical basis for UHI in this study is clear and supported by GIS- based investigations. For example, Hardy and Nel (2015) used remote sensing data sets and processing techniques to analyze the heat island effect in Johannesburg. The study found that the UHI effect is largest at night in Johannesburg's Northern Suburbs and in places with high building density.

Another study comparing day and night UHI demonstrated that atmospheric heat islands are more severe at night because the surface cools and transfers heat to the atmosphere when there are less wind and no clouds (Cristiane de Costa Trindade Amorim et al., 2021). A separate study by Souverijins et al. (2022) found that the Johannesburg CBD was a few degrees warmer during the day and night than other parts of the city, owing to minimal or no vegetation, substantial volumes of impermeable surfaces, and increased anthropogenic heat fluxes.

Souverijns et al. (2022) discovered that the built-up area of Johannesburg is up to 5°C warmer than rural areas. In addition, a high-resolution land cover map (at 30m spatial resolution) was used to identify roads and small features, such as grouped buildings which had higher air temperatures than the surrounding area. As a result, this study clearly displays evidence in UHI monitoring data, as well as scientific evidence of the occurrence of UHI in Johannesburg CBD, making it relevant to the study setting.

Meter-scale heat stress modeling revealed that urban areas have significantly higher air temperatures than rural areas due to the city's high building density and general design. There is a scientific consensus that heat stress will have a greater impact on human health, necessitating immediate mitigation efforts.

In this study, the UHI impact is viewed as a major urban risk caused by climatic dynamics and the dense, impermeable built environment of Johannesburg's CBD. Rather than being directly evaluated using temperature data, the UHI effect is investigated through the eyes of citizens who live and work in the CBD, based on their perceptions and lived experiences. Secondary data and previous literature reinforce these ideas, providing a richer contextual perspective. The study focuses on how local individuals perceive and are affected by the UHI effect, such as increasing ambient temperatures, discomfort, and health-related difficulties, to highlight the human aspect of urban heat exposure. This conceptualization emphasizes the need for green infrastructure as a mitigation approach in highly populated and heat-stressed cities.

2.1.4. Urban flooding

Urban flooding is a term often used interchangeably; for this reason, it is important to differentiate between urban flooding and flash flooding. Urban flooding is the term used to describe periods of continuous or intense rainfall that last for a short while and cause a buildup of water in urban areas that exceeds the capacity of urban drainage systems (Peng and Zhang, 2022). According to Agonafir et al. (2023), urban flooding is a catastrophic phenomenon that occurs in urban areas with low water infiltration and is caused by rainstorm events that cause floodwater to rise quickly.

According to Kuksina and Golosov (2020), there is no single definition of flash floods; however, flash floods are distinguished by their rapid development and brief duration. Flash floods are most common in the northern hemisphere, subtropical, tropical, and equatorial climate zones due to short-duration intensive rainfall, river basin location in mountainous areas, and small catchment area, resulting in rapid concentration of runoff in river channels (Kuksina and Golosov, 2020). In brief, while both urban and flash floods may share similar characteristics such as excess water, they differ significantly with respect to the cause, duration, and velocity of runoff.

While urban floods are most attributed to natural reasons such as heavy rainfall, it is critical to investigate the human induced causes that allow flooding in urban settings. For starters, urbanization and population density drive up demand for housing and infrastructure, resulting in impermeable surfaces. As a result, drainage systems get overwhelmed, causing surface runoff to accumulate and contribute to urban flooding. Clogged drainage systems fail to separate stormwater and sewage, resulting in floods during heavy rains.

Furthermore, misalignment between constructed and natural systems worsens flooding because urban planners may overlook natural drainage patterns and catchment behavior, disrupting water flow.

Urban flooding can have a tremendous influence on people, the economy, and the environment, as well as cause severe city disruptions. For instance, in poorer settlements, such as Lagos, flooding submerges entire streets, causing traffic jams on main roads (Douglas, 2017). Hammond et al. (2015) describe how flood consequences are typically classified as tangible or intangible. Tangible impacts are losses that may be easily quantified in financial terms, such as property damage or business disruption (Hammond et al., 2015). In contrast, intangible impacts are those that cannot be financially quantified, such as loss of life, psychological suffering, or environmental degradation (Hammond et al., 2015).

Urban flooding is defined in the framework of this study as another important urban risk coming from broader environmental and infrastructure concerns, with a focus on Johannesburg's CBD. Rather than being quantified via hydrological modeling, it is investigated using stakeholders' perceptions and lived experiences. This method enables the study to investigate how various stakeholders experience, perceive, and contextualize urban floods, exposing connections to inadequate drainage infrastructure, impervious surfaces, and climate-related rainfall instability. The study presents urban flooding as a tangible manifestation of urban vulnerability, using it as both a symptom and a reason for the implementation of green infrastructure solutions.

2.1.5. Climate change mitigation

Climate change mitigation, according to Fawzy et al. (2020), is the application of carbon reduction technologies and procedures to lower emissions of CO_2. While Lackner, Chen, and Suzuki (2015) briefly define climate change mitigation as measures to limit the extent of climate change. However, Mi et al. (2019) state that climate change mitigation is a feasible method that was developed for combating CO_2 emissions inventories.

Researchers are divided concerning the terms climate change mitigation and adaptation, which is why it is critical to distinguish between the two. According to Fankhauser (2017), climate change adaptation is the process of making adjustments to climatic changes in order to mitigate negative impacts and/or promote positive outcomes. According to the article, the causes of climate change must be addressed with a significant reduction in greenhouse gas emissions (mitigation), but the effects must be handled through an equal emphasis on investment in climate resilience (adaptation) (Fankhauser, 2017). Eriksen, Nightingale, and Eakin's (2015) study examines climate change adaptation through a social lens, offering a unique perspective. Climate change adaptation is defined as a sociopolitical process that helps individuals and groups manage with various concurrent environmental and social changes (Eriksen et al., 2015). In brief, while the terms climate change adaptation and mitigation are sometimes used interchangeably, mitigation aims to reduce greenhouse gas emissions in order to reduce the severity of climate change. On the other hand, adaptation is centered on coping with the consequences thereof.

To effectively understand climate change mitigation, one must consider its fundamental qualities. For example, carbon sinks, which are systems capable of collecting and storing atmospheric CO_2, are an important component of climate change mitigation. Carbon sinks in this study adopt the form of green infrastructure, such as urban parks, green spaces, street trees, urban forests, and green vegetation-covered roofs. These vegetative elements help to reduce greenhouse gas concentrations by sequestering carbon through photosynthesis. Simultaneously, they serve a vital role in moderating the UHI impact by improving surface albedo, providing shade, and promoting evapotranspiration, which jointly lowers ambient temperatures in urban areas.

According to Schaffler and Swilling (2013), trees assist in managing city microclimates by storing heat and absorbing solar radiation, which is used to reduce temperature in urban areas. A study on urban heat conducted in Johannesburg and Ekurhuleni discovered that having fewer sealed surfaces and more urban green space is an effective way to reduce heat stress and improve living conditions (Souverijins et al., 2022). Furthermore, incorporating green infrastructure into urban development schemes has a dual mitigation advantage, first by addressing climate change on a global scale and then easing regional thermal stress in highly populated cities. Therefore, dual-function positions urban green infrastructure as a key component of building sustainable and resilient cities.

Moreover, another important aspect of climate change mitigation is the promotion of sustainable urban development practices that improve cities' resilience to climate- induced extreme events like urban flooding. This entails integrating green infrastructure technology to better manage stormwater while mitigating the environmental impact of climate change. Green spaces, permeable pavements, bioswales, built wetlands, and rainwater harvesting systems are all examples of ways to improve natural infiltration and runoff filtration after heavy rains. For example, Velita et al. (2023) investigated ways to mitigate and potentially avoid road flooding by the installation of a rainwater gathering and treatment system. Furthermore, the study found that rainwater tanks can collect an average monthly supply of 62.08m^3, which can assist in reducing flooding in the study area (Velita et al., 2023).

The above measures limit the volume and velocity of surface water during heavy rain events, lowering the likelihood and severity of urban floods. To support this, Schaffler and Swilling (2013) explain that trees, vegetated areas, and other biological assets naturally regulate water flow and storm-water runoff by capturing and lowering storm- water runoff from impermeable surfaces. Furthermore, such systems contribute to overall sustainability goals by increasing groundwater recharge, improving water quality, and lowering dependency on energy-intensive grey infrastructure. Green spaces, for example, can serve as effective stormwater management attenuation systems, reducing or eliminating the need to construct large new pipe and channel systems to transport runoff out of the city (Schaffler and Swilling, 2013). Climate change mitigation efforts that incorporate these aspects into urban design not only address immediate flood threats, but also contribute to the long-term objective of constructing more adaptable, habitable, and ecologically integrated environments. Finally, in the context of this study, climate change mitigation is presented through the installation of green infrastructure, which is positioned as a dual-benefit strategy that

reduces both urban heat and urban floods. This dual function emphasizes green infrastructure's position as a comprehensive mitigation strategy for climate threats.

2.1.6. Green infrastructure

Green infrastructure (GI) is a rather broad concept and may be interpreted in many ways, which is why it is important to stress its versatility. Nieuwenhuijsen (2021) defines green infrastructure as a system of green areas that both benefit people and support ecological functions. This emphasizes how crucial ecosystem services are to preserving ecosystems and providing benefits to people. On the other hand, Washbourne (2022) defines green infrastructure as an interconnected network of green spaces that conserves natural ecosystem values and functions and provides associated benefits to human populations.

In the context of this study, GI refers to urban trees, green vegetation-covered roofs, and vegetation that gives insulation to buildings and cool them through evapotranspiration. It also includes built features like bioswales, permeable pavements, and naturalized stormwater ponds designed to prevent urban flooding. It consists of planted and indigenous trees, wetlands, parks, green open spaces, and original grassland and forests, as well as building and street-level architectural interventions that include vegetation (Enqvist and Pasquini, 2019). These features assist in the regulation of stormwater runoff, pollution filtering, and flood control, thus enhancing urban resilience.

GI is fundamentally based on multifunctionality, connectivity, and sustainability. First and foremost, GI is distinguished by its ability to provide various environmental, social, and economic advantages at the same time. Green vegetation-covered roofs, for example, have a plant layer, a lightweight substrate layer, a filter membrane layer, a waterproof layer, and a drainage system to assist reduce stormwater runoff (Kuok et al., 2023). Furthermore, it can assist reduce building energy demands (electricity costs for air conditioning) since the plants absorb sunlight before it reaches the building's roof surface, improving the quality of the air outside and inside the building, as well as the temperature (Kuok et al., 2023). As a result of its multifunctional nature, GI provides a cost-effective and integrated solution to difficult urban concerns.

Green infrastructure connectivity refers to the physical and ecological connections between green spaces that allow species, water, and air to migrate across urban environments. To support this, du Toit et al. (2018) state that GI plays an important role in connectivity by providing regulating services such as temperature regulation, provisioning services such as providing physical goods such as food crops or building materials, cultural services such as recreational parks, and supporting services such as habitat provision. The final fundamental and central element of GI is sustainability, which supports long-term environmental health and resource efficiency. For example, consider bioswales and their well-known potential to reduce urban runoff by combining hydrologic control with water quality remediation (Folorunso, 2020). Folorunso (2020) goes on to say that a well-built bioswale improves water quality, reduces runoff volume, and contributes to ecological and infrastructure resilience.

There is a clear distinction between green and gray infrastructure, which is vital to understand in order to fully realize the benefits of green infrastructure. Folorunso (2020) defines grey infrastructure as systems, including curb-and-gutter conveyance networks and centralized detention basins, which have been historically engineered to move stormwater away from built environments. While these systems are excellent at reducing flooding, they primarily ignore water quality treatment and groundwater recharge, both of which are critical to long-term watershed health. Furthermore, their reliance on large-scale, centralized control frequently lacks flexibility and adaptation, particularly in the face of changing climatic conditions and rising storm intensity (Folorunso, 2020). In a nutshell, grey infrastructure uses traditional, engineered solutions like concrete and steel to manage resources like water and electricity, whereas green infrastructure uses natural systems and processes to achieve the same goals.

The rationale behind GI in this study context, lies within its ability to address climate change-induced impacts in Johannesburg's central business district. According to Wright (2011), green infrastructure is not a solution, and its implementation is determined by the environmental, social, and economic development goals of a specific location. It represents a bio-physical system that combines natural and constructed structures to provide a variety of ecosystem services such as heat island abatement, storm water control, and habitat support.

When incorporating green infrastructure into urban planning systems, there are numerous additional benefits. According to Busayo et al. (2022), green infrastructure can take the shape of rainwater harvesting systems, permeable pavements, canopy trees, and so on, and each has its own set of benefits that can assist tackle certain urban challenges. Rainwater harvesting systems, which collect and store rainwater from roofs for later use, are one example of a combined approach to green infrastructure adopted from a Busayo et al. (2022) study.

Another technique is to build green vegetation-covered roofs, which entail planting flora on the roof's surface to absorb surface runoff. Furthermore, permeable pavements, or pavements that allow water to soak into the soil, could be an effective tool for mitigating urban flooding (Busayo et al., 2022). Additionally, rain gardens and other bioretention systems can temporarily store water before it seeps into the ground and vegetation (Busayo et al., 2022). In addition to capturing rainfall, canopy trees shade green spaces, lowering the UHI effect and protecting the ground from precipitation (Busayo et al., 2022). Retention ponds, wetlands, and swales all store and process runoff, drain it across the area, and promote biodiversity (Busayo et al., 2022). Furthermore, infiltration basins and soak ways facilitate water infiltration and help regulate groundwater discharge.

However, as Wright (2011) has noted, the effectiveness of green infrastructure is in the coordination of these parts in the urban fabric with due regard to the socio-economic and environmental factors that shape the application of green infrastructure. To this end, it is necessary to recognize that green infrastructure has numerous advantages, but its application can have some challenges, including governance, public support, and financing that need to be controlled to achieve sustainable development. Every one of these benefits

should be assessed with certain disadvantages, including the costs of maintenance, conflicts of land use, and the challenge of equal distribution of green areas in cities.

Green infrastructure's theoretical foundation is built on a number of interconnected theories, including urban resilience theory and climate adaptation theory. The following section (theoretical framework) provides a deeper understanding of how these frameworks collectively provide a strong basis for understanding and implementing green infrastructure as a mitigation and adaptation strategy in modern urban areas.

This study frames green infrastructure by examining stakeholder perceptions of its existence, function, and performance in the urban landscape. This approach reflects how different stakeholders, such as municipal governments, community members, and non-governmental organization consultants, understand and evaluate the significance of green infrastructure in tackling urban difficulties. This lens is used to investigate the visibility and perceived effectiveness of green infrastructure as a climate-responsive solution.

2.1.7. Effectiveness

According to Price (1972), effectiveness is the degree of goal achievement, similarly, Farahbakhsh (2015) alludes that effectiveness generally means the extent of target realization. Additionally, Sundqvist et al. (2014), state that effectiveness may also act as the foundation for internal as well as external advancements in terms of time, expenditure, and quality.

In the context of this study, effectiveness is defined as the degree to which GI fulfills its intended goals in minimizing climate-related urban difficulties such as the UHI effect and flooding. This includes the extent to which GI interventions regulate ecological, hydrological, and thermal processes in the urban environment. For example, the effectiveness of a green vegetation-covered roof can be evaluated based on its ability to lower indoor temperatures and reduce building energy use. Studies in the United States found that vegetated rooftops reduced peak temperatures from 0.5 K to 3.5 K, and a green vegetation-covered roof rather than a white roof can further reduce energy savings from 40% to 110% (Yeung and Li, 2024). A bioswale's ability to catch and filter stormwater runoff during significant rainfall events can be used to determine its effectiveness. This is illustrated in Folorunso's (2020) study, which shows that bioswales tailored for infiltration can lower runoff volumes by up to 80%, while field-monitored bioswales have shown peak flow reductions ranging from 20% to 70%.

Similarly, tree-lined roadways or urban parks may be deemed effective if they produce measurable cooling effects and contribute to better air quality. This is demonstrated by a study that assessed the regulation services on urban vegetation in several African cities. In Abeokuta, Nigeria, only 13% of the benefits of the forest were perceived to be regulating services, whereas in Kumasi, Ghana, the three highest rated services were air quality regulation, shade, and temperature reduction (du Toit et al., 2018). In this study, effectiveness is a multidimensional term measured by stakeholder assessments of whether GI features are visible, functional, and provide concrete environmental benefits in Johannesburg CBD.

GI's effectiveness can be measured using various main qualities or components that reflect how well it achieves its goals. To begin, it can be quantified through visible outcomes, such as lower surface and air temperatures in metropolitan areas with vegetation, or lower frequency and severity of flooding in zones

with permeable surfaces and drainage systems. Second, stakeholder perceptions are an important qualitative metric of effectiveness because they capture how communities, officials, and practitioners perceive and assess the functionality and benefits of GI treatments in their daily lives. Finally, policy implementation, such as the inclusion of GI in urban planning frameworks, zoning regulations, and municipal climate policies, demonstrates institutional acknowledgment of its worth and effectiveness as a climate mitigation and adaptation measure. The City of Johannesburg Metropolitan Municipality, for example, has a climate change policy in place and is revising its adaptation strategy, they have also commissioned an external agency to develop a green infrastructure strategy (Enqvist and Pasquini, 2019). Furthermore, the Air Quality and Climate Change section of Johannesburg's Environment and Infrastructure Services department emphasized the importance of reviewing the city's adaptation plan, recognizing the various impacts of heat on the city, they intend on developing a heat management plan, and emphasizing the importance of green infrastructure in heat mitigation (Enqvist and Pasquini, 2019). These components, when combined, provide a thorough framework for assessing how effectively green infrastructure operates in practice.

The concept of effectiveness is highly significant in the study setting because it determines if GI is a realistic solution to the dual concerns of the UHI effect and urban floods in Johannesburg CBD. Given the city's dense built environment and growing vulnerability to climate-related concerns, examining the effectiveness of existing or prospective GI solutions can assist in identifying their feasibility and potential for scale. By concentrating on how effectively GI performs in terms of heat mitigation and stormwater management, the study gives evidence-based insights into whether such nature-based solutions may help the city achieve its overall climate resilience and sustainability goals. This study uses a mixed-methods approach to define the effectiveness of GI, which includes survey responses, stakeholder interviews, and a literature assessment of observed results. In-depth interviews will give further qualitative information about stakeholders' experiences and evaluations of GI performance. Furthermore, references to similar research conducted elsewhere, such as reduced surface water buildup or localized cooling impacts, will be used to back up perceptions and assess the tangible impact of GI interventions.

Figure 1 displays the conceptual framework, which provides a more detailed description of the relationships between the study's primary components. The climate adaptation theory and urban resilience theory are integrated to address the UHI effect and flooding in Johannesburg's CBD. Additionally, GI is emphasized as the strategy that connects the theories, thereby focusing on adaptations that mitigate heat and flood risks, while simultaneously enhancing resilience and offering socio-economic co-benefits.

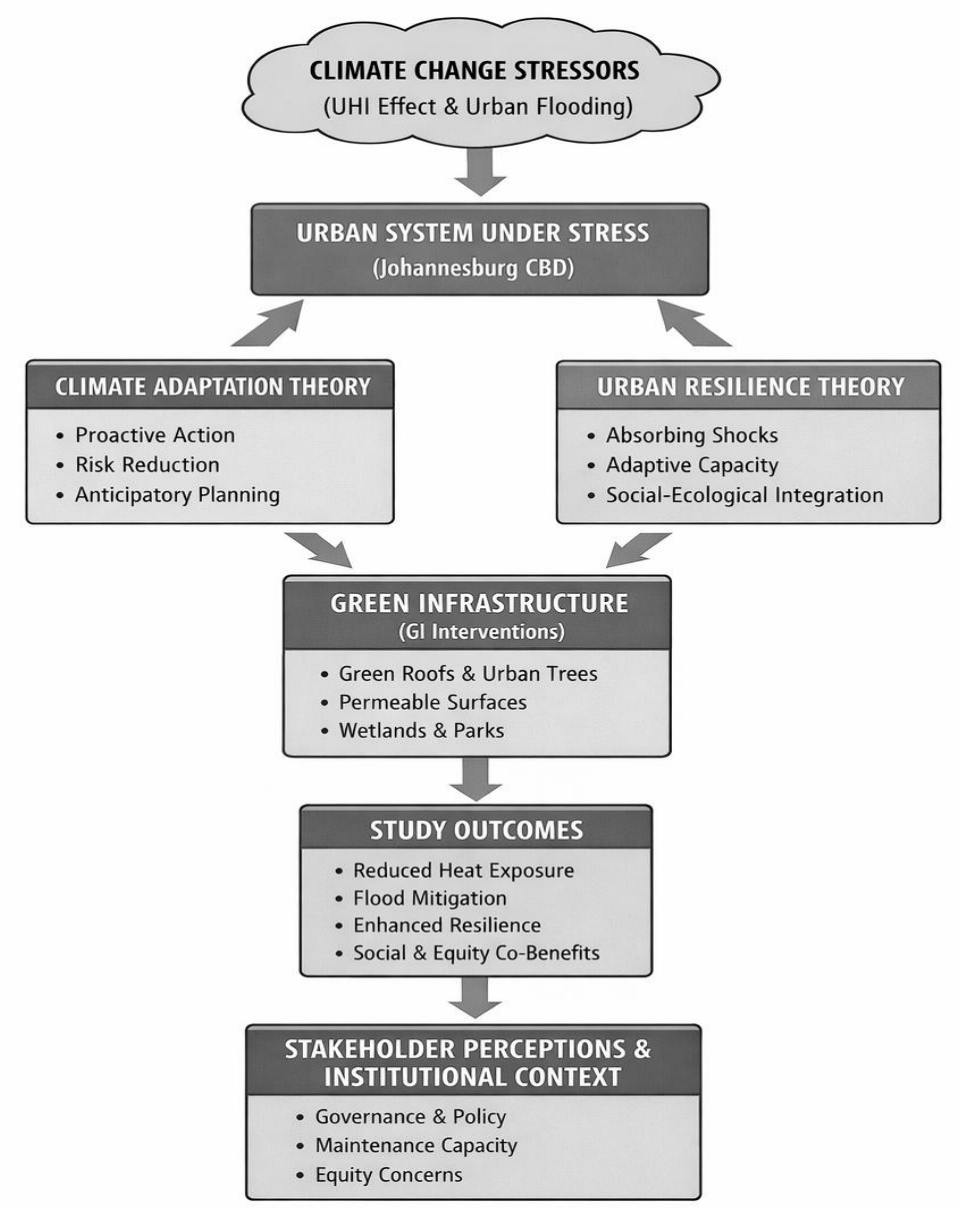


Figure 1: Illustrates the conceptual framework of the study

2.2. Theoretical framework

2.2.1. Urban resilience theory

Early ecological resilience thinking focuses on how ecosystems respond to disturbances, which later served as an extension of the urban resilience theory's origin (Amirzadeh et al., 2022). Given the complexities urban areas face in this modern era, the Urban Resilience Theory has progressed to cater to various stresses that urban areas encounter. The Urban Resilience Theory gained traction in the early 2000's in empirical research, as cities encountered increasing challenges. C.S Holling proposed this theory in 1973 and since then the framework of resilience has been put forward as a fundamental force that works at different levels, due to its emphasis on the relationship between social systems and ecological systems (Masnavi et al., 2018). The Urban Resilience Theory recontextualizes resilience thinking for urban settings, which are interconnected and dynamic, as opposed to similar theories such as ecology and systems theory. At its core, the Urban Resilience Theory refers to a city's ability to withstand, adapt to, and recover from shocks and stresses while maintaining essential functions and overall well-being (Cao, 2023). The theory frames cities as complex and adaptive systems that must be capable of dealing with shocks like the UHI effect and urban flooding. The core principles embedded in this theory are that urban areas are multi-faceted because they include economic, social and environmental systems. Urban resilience encompasses systems like the environment at large, it includes agents such as individuals or communities, and it also includes institutions like governance and policy (Zeng et al., 2022). Another principle of the Urban Resilience Theory is that it stresses the importance of equity, participation, and governance in building resilient cities (Meerow and Newell, 2019). Lastly, the Urban Resilience Theory requires thorough planning and active learning in order to achieve long-term sustainability (Cao, 2023).

This theory is relevant to this study because it provides a theoretical foundation for grasping how urban areas like Johannesburg CBD can withstand the UHI effect and urban flooding. Climate change-induced stressors expose the weakness of current infrastructure and the maintenance thereof. As a result, the theory demonstrates the importance of adaptation and mitigation, which is central to the study for evaluating the effectiveness of green infrastructure as a sustainable adaptation strategy. Sharifi and Yamagata (2018) proposed that urban systems can continuously develop adaptation strategies in response to changing dynamics to mitigate hazards. The Urban Resilience Theory can inform urban development which uses green infrastructure to alleviate crises. Furthermore, the Urban Resilience Theory encourages legislative and regulatory frameworks, risk mitigation methods, adaptation plans, ecologically friendly energy alternatives for fossil fuels, and the incorporation of green infrastructure (Parker and Simpson, 2020). This theory is crucial to this research because it can guide the creation of urban development and community planning that is already geared toward reducing the effects of climate change by implementing green infrastructure.

The Urban Resilience Theory attributes its strength to its holistic systems view. It is for this reason that researchers are encouraged to take into consideration how multiple urban systems (environmental, social, and technical) are integrated and how they interact under stress and shocks. This is highlighted by Giulia (2023), the article offers a comprehensive framework for evaluating urban resilience in planning. In the

context of this study, green infrastructure contributes to environmental resilience due to its cooling of heat islands and flood attenuation capabilities. In addition, green infrastructure contributes to social resilience because green spaces provide access to public recreational areas, which benefits the community. Moreover, green infrastructure provides institutional resilience in terms of policy and planning support. It is worth noting that the Urban Resilience Theory aligns well with the goals of sustainable urban development by ensuring that cities anticipate risks and respond adaptively, as opposed to reactive, ill-prepared interventions.

Notwithstanding the urban resilience theory's functionality, the theory has been criticized for its ambiguity and for being difficult to measure empirically (Kolte et al., 2023). Some critics argue that the theory is applied rhetorically, lacking a distinct operational framework, and in a report titled "Urban resilience thinking for municipalities", Harrison et al. (2014) highlight that resilience planning in the context of South Africa may grapple with institutional fragmentation, institutional silos, and a lack of capacity in local government. Furthermore, Shamsuddin (2020) asserts that barriers such as institutional resistance and divergent stakeholder interests intensify implementation challenges. There is evidence that states that the Urban Resilience Theory is ambiguous and is largely interpreted differently across disciplines, and this creates challenges in implementation (Büyüközkan et al., 2021). Other critics explain how the Urban Resilience Theory prioritizes system recovery over addressing the underlying vulnerabilities and social inequalities (Meerow and Newell, 2019).

In this study, the Urban Resilience Theory is conceptualized as the foundational framework to assess whether green infrastructure is capable of contributing to Johannesburg CBD's ability to withstand, adapt, and recover from the UHI effect and urban flooding. This theory informs the analysis of green infrastructure as a useful tool for cooling heat islands and flood attenuation. Furthermore, the Urban Resilience Theory emphasizes how resilience is inclusive of social and institutional aspects, which helps underpin the study's regard for stakeholder engagement. In brief, this theory serves as a guiding tool for data collection procedures and the understanding of stakeholder perceptions on the subject matter.

2.2.2. Climate adaptation theory

Climate change has harsh effects that make life for citizens difficult; therefore, the causes of climate change must be addressed with significant mitigation strategies. Furthermore, the effects of climate change must be handled through an equal emphasis on investment in climate resilience (adaptation) (Fankhauser, 2017). The realization that mitigation efforts are not enough to address the impacts of climate change, led to the response of developing the Climate Adaptation Theory. It is clear that climate change mitigation focuses on reducing emissions, however, adaptation includes minimizing the harm caused by extreme climatic events by simply adjusting the ecological, infrastructural, and societal systems. Whether actual or expected climatic impacts, the Climate Adaptation Theory addresses how natural systems and humans adjust to these impacts. As climate change intensified and became a pressing issue, social sciences, evolutionary biology, and human ecology started evolving from the early 1970s, and these advancements formed a foundation for the development of this framework (Jones et al., 2021). There were organizations

such as the IPCC, which helped promote adaptation as a key component of climate policy globally, as a result, the concept of climate adaptation gained prominence (Pörtner et al., 2022).

Evidence suggests that at its core, this theory assumes that climate impacts are inevitable, and urban areas need to prepare the most, since they are more vulnerable. Secondly, adaptation is multi-scalar and takes on many forms, for instance, infrastructural, technological, and ecological adaptation. According to an article by Castro and Sen (2022), adaptation takes on many forms and includes individuals, communities, and governments. This theory promotes proactive adaptation over reactive adaptation. In the context of this study, the theory illuminates the importance of green infrastructure designs to reduce future flood risks (proactive and anticipatory), as opposed to a reactive approach of responding after the impact and deploying emergency stormwater upgrades.

In urban areas such as Johannesburg CBD, the Climate Adaptation Theory is relevant because this is where the UHI effect and urban flooding intersect with dense infrastructure, limited natural resources, and socio-economic inequality. Most urban areas struggle with adaptation due to high population density and infrastructural challenges (Bedsworth and Hanak, 2010). This theory is especially relevant to urban climate issues because it supports the integration of green infrastructure into cities as a cost-effective, multifunctional solution that reduces vulnerability and fosters increased adaptive capacity. In addition, the Climate Adaptation Theory informs urban planning by stressing the need for intergovernmental coordination and nature-based solutions (Owens, 2020). A notable contribution of the Climate Adaptation Theory is that it offers a systematic approach to categorize and evaluate adaptation actions and outcomes (Eisenack and Stecker, 2012). The theory's strength is in its flexibility; it makes room for both bottom-up community responses and top-down institutional approaches. For example, this makes it suitable in fragmented urban areas like Johannesburg CBD, creating a shift from institutional silos and allowing adaptation to occur through multiple government-led projects and community initiatives. This encourages urban planners to consider environmental, social, economic, and infrastructural adaptation demands together, thus promoting multi-sectoral integration.

To protect citizens from extreme heat and floods, the Climate Adaptation Theory allows for an assessment of how well green infrastructure is functioning as a proactive adaptation strategy in the context of this study. The Climate Adaptation Theory has been put under scrutiny, despite its breakthroughs in empirical research. Firstly, Arteaga et al. (2023) explain the theory-practice gap by showcasing how robust theoretical frameworks (Climate Adaptation Theory in this case) often fail to translate into effective, practical action on the ground. This is due to issues such as capacity and funding, amongst others. In South Africa, challenges such as budget constraints and policy misalignment can deter the practical implementation of adaptation strategies. Other limitations of this theory include social limits, where adaptation is constrained by values, ethics, and culture. Adger et al. (2009) explain that these societal aspects are often overlooked in technical approaches. Additionally, there is limited evidence of transformational adaptation, this is due to the gaps in adaptation research, which makes it difficult to consolidate findings into a unified theory (Nalau and Verrall, 2021).

Despite its limitations and criticisms, the Climate Adaptation Theory remains an important framework for this study for several reasons. Firstly, this theory is applied in this study to conceptualize green infrastructure as a proactive and nature-based adaptation tool. Secondly, it is applied in this study to evaluate how green infrastructure aids in reducing exposure to UHI effect and urban flooding. Moreover, this theory is applied in this study to guide the analysis of stakeholder perceptions of green infrastructure's adaptation effectiveness. In brief, the Climate Adaptation Theory's application in this study helps integrate technical interventions with issues of climate justice, urban planning, and governance. By focusing on proactive anticipatory interventions, rather than system response under shock, the Climate Adaptation theory complements the Urban Resilience Theory in that manner. The connection between these two theories is that they both address climate issues, adaptation theory is, however, tied closely to policy and urban planning frameworks.

There is widespread vulnerability in urban areas around the world, and this is due to the threats brought by the UHI effect and urban flooding. A notable response is the emergence of green infrastructure, which has been recognized as a global strategy to reduce surface temperatures in cities and improve flood attenuation. The following section presents case studies of the application of green infrastructure in different global contexts. Additionally, the effectiveness, limitations, and various implementation strategies will be highlighted. Bringing these international cases to light will assist in comprehending how similar methods can be implemented or scaled in the city of Johannesburg.

2.3. Literature review

2.3.1. Green infrastructure for UHI and flood mitigation: A global perspective

There are many cities globally that are confronted with high ambient temperatures and have turned to green infrastructure for adaptive and sustainable solutions. A renowned city in the United Kingdom, named Edinburgh, has the highest number of Green Flag parks, and this is a standard showcasing its high-quality green spaces, which reduce emissions. In other cases, Berlin is well renowned for its extensive green spaces, which make up approximately 44% of the municipal area. Thus, living up to its reputation as one of the greenest cities in the European Union (Hansen et al., 2017). According to Connop et al. (2016), actions of architectural modifications like retractable umbrellas, nature-based solutions like green vegetation-covered roofs, and emission reductions are meant to improve ecosystem services. In the same light, there is evidence from a study conducted in Chicago that increasing the city's tree cover by 10% could decrease total energy consumption for heating and cooling by 5 to 10% (Haq, 2011).

There is extensive research on European cities that demonstrates the effectiveness of green infrastructure in mitigating the UHI effect. For instance, a study by Marando et al. (2021) found that in cities like London, green infrastructure can cool urban areas by an average of 1.07°C, with potential reductions up to 2.9°C. The study explains how achieving a 1°C drop in urban temperatures requires at least 16% tree cover. This highlights the need for integration of green infrastructure into urban planning to maximize UHI mitigation. Similarly, China has been implementing various types of green infrastructure to address UHI, these include urban parks, forests, and green vegetation-covered roofs (Shao and Kim, 2022). Other targeted cases that lack literature or effective documentation are urban areas such as the Green Belt of Beijing, the Green Belt of Caracas and the Green Belt of Vitoria Gasteiz, which all provide valuable ecosystem services (Patiño and Garcia, 2015).

As climate change intensifies, heavy rainfall events, which lead to urban flooding, are becoming a challenge, and cities have turned to green infrastructure for flood attenuation. China is presently enacting a policy program known as "sponge cities" in order to address urban pluvial flooding comprehensively and to encourage environmentally friendly, sustainable urban growth (Prokic et al., 2019). A similar study in Beijing, China, by Wang et al. (2024), performed a flood risk assessment using green infrastructure prioritization, and the results proved that green infrastructure is more effective than blue or grey infrastructure in reducing flood risks. Furthermore, a localized study showed that integrated green infrastructure can reduce total runoff by up to 100% in small storms and by up to 92.8% for peak flow (Liu et al., 2014). In the Netherlands, a project called Amsterdam Rainproof is being carried out to improve the city's ability to withstand the increasing frequency of flooding and to make better use of the free rainwater that drains through façade gardens, green vegetation-covered roofs, and water-permeable pavement (Prokic et al., 2019). As part of Belgium's PLUIE Flood Prevention Plan, rainwater tanks are installed to improve evapotranspiration and infiltration for new homes, which is encouraged by regional grants for existing homes (Prokic et al., 2019). Such initiatives can help better adapt the built environment to higher precipitation levels. In Seoul, South Korea, a study that coupled green-grey infrastructure with decentralized network design reduced flood volume by 73.5% and duration by 54.7% (Park et al., 2024). A study by

Ferreira and da Rocha (2023) proved that green vegetation-covered roofs outperform grey technology in flood mitigation. The study's key outcomes were that permeable pavements performed poorly in reducing flood risk as opposed to green vegetation-covered roofs, and that just substituting 24% of the area with green vegetation-covered roofs prevents canal overflow.

Although functional, green infrastructure has limitations, and there are considerations and research gaps that require attention. In some cases, the effectiveness of green infrastructure depends on spatial scale, storm intensity, and integration with existing infrastructure (Green et al., 2021). The contemporary literature cited demonstrates how green infrastructure has been successfully implemented to alleviate the problem of urban floods caused by climate change.

2.3.2. Green Infrastructure for UHI and flood mitigation: A regional perspective

In African cities, green infrastructure has been recognized as a sustainable strategy for mitigating the UHI effect, particularly in overpopulated cities that face urban thermal challenges. There is a study that examined the relationship between land surface temperature and the spatial patterns, composition, and configuration of impervious surfaces/green spaces in four African cities, namely, Lagos (Nigeria), Nairobi (Kenya), Addis Ababa (Ethiopia), and Lusaka (Zambia). The key findings of the study were that high UHI levels are found near city centers, and cities that dominate in impervious surfaces are warmer by 3-4°C (Simwanda et al., 2019). The study explains how cities with more green spaces are cooler because results yield a strong negative correlation between green space and land surface temperature (Simwanda et al., 2019). A notable recommendation from this study is to restore and expand green spaces withinurban footprints to mitigate UHI.

To assess the role and potential of blue-grey infrastructure, the urban thermal environment and vegetation abundance in four East African cities (Khartoum, Addis Ababa, Kampala, and Dar es Salaam) were characterized in a study. This study by Li et al. (2022) revealed that blue-green infrastructure moderates UHI across different climate regions and seasons. Furthermore, increased vegetation is associated with lower land surface temperatures (Li et al., 2022). In semi-arid Africa, Ladan et al. (2023) investigated the potential of urban green infrastructure in semi-arid climates, and the results highlight how increased vegetation is the most efficient method for reducing UHI in semi-arid regions. The vertical greening systems (VGS), which grow plants inside or along the vertical axis of a building façade, are making a comeback as a way to incorporate greenery into the urban fabric (Adegun et al., 2021). High-density polyethylene (HDPE) and bamboo prototypes of VGS were affixed to the empty walls of a Lagos residential building (Adegun et al., 2021). Temperature measurements from May to September 2014 (during both the wet and dry seasons) indicated an average indoor air temperature reduction of 2.3°C, showing that this installation enhanced thermal conditions, according to an assessment (Adegun et al., 2021).

A building's rooftop where plants are grown intensively (on a thin substrate) or extensively (on a thicker substrate) is referred to as a green vegetation-covered roof (Vijayaraghavan, 2016). In Nigeria, green vegetation-covered roofs are not very popular within the built environment, and the research on the pros and cons and implementation strategies of green vegetation-covered roofs is very limited, despite their

potential benefits (Adegun et al., 2021). In addition, an investigation was carried out to bolster this claim. The investigation revealed that although there are prospects for the implementation of green vegetation-covered roofs, their popularity was low in the research region due to several factors, including expense, technical difficulties, a lack of expertise, and constraints resulting from the interpretation of planning regulations (Ezema et al., 2016).

Employing environmentally friendly techniques can effectively manage floods. Green infrastructure is a sustainable and multi-benefit approach to urban flood mitigation. In a study, wetland restoration and urban forests were used to investigate the potential of nature-based solutions for flood management. The study by Enu et al. (2023) revealed that green infrastructure is being implemented for flood mitigation in flood-prone urban areas such as Dar es Salaam, Kampala, and Nairobi. Similarly, storm runoff ponds have been installed in Dar es Salaam's Mbezi Valley, which is likewise fed by a high-water table and is utilized by locals for recreation, washing clothes, and crop irrigation (Douglas, 2016). According to a study by Adegun et al. (2021), gardens can help with runoff infiltration, sunshade, windbreaking, biodiversity preservation, and erosion control. Greenways also decreased flood risk by altering river flows. In Mozambique, a rainwater harvesting facility with an 18m2 catchment area was constructed; Lumbroso et al. (2008) describe this construction as an example of green flood risk management practices. The consensus is that green solutions are feasible for reducing hydrometeorological risk (floods) in Sub-Saharan Africa for several reasons, including their long-term and cost-effectiveness, as opposed to conventional engineering methods (Enu et al., 2023).

It is evident that green infrastructure, although context-specific, is a promising sustainable solution for urban flood management in Africa. Despite the challenges such as land use, governance, or planning, there is a track record of benefits in diverse cities that prove that nature-based techniques can effectively manage floods.

2.3.3. Green infrastructure for UHI and flood mitigation: A local perspective

South Africa is facing rapid urbanization and extreme climate risks in its major cities. As a response to risks like the UHI effect and flooding, cities have turned to green infrastructure for solutions. A case study was conducted in Durban’s CBD to measure the impact of green vegetation-covered roofs on UHI, and the findings were that over seven years, green vegetation-covered roofs were up to 9.2°C cooler than conventional roofs during the summer (Greenstone, 2023). This clearly shows that green vegetation-covered roofs have the potential to reduce city ambient temperatures. Furthermore, it is becoming a trend in Durban to upgrade buildings with rooftop gardens. This is important because property developers are taking a step towards sustainable development initiatives (Greenstone, 2023). However, it can be argued that these greening practices are happening on a smaller scale compared to other urban areas (Greenstone, 2023). Furthermore, some municipalities may find it difficult to mirror Durban’s greening initiatives, and this would be attributed to a lack of resources.

Souverijns et al. (2022) conducted a study on urban heat in Johannesburg and Ekurhuleni, there were spatial differences in the UHI effect of both cities because of their urban design. The study found that the

highest heat stress was found in areas with low vegetation cover and high building density (Souverijns et al., 2022). The study highlighted that meter-scale analysis proves that shade from vegetation is important for reducing heat stress. Furthermore, this demonstrates the importance of integrating urban vegetation into urban planning to mitigate the UHI effect.

A study was conducted by Labuschagne and Zulch (2016) in Johannesburg, where rooftops were analyzed to assess the likelihood of developing green vegetation-covered rooftop systems. Furthermore, interviews were conducted, and evidence shows that there is a gap in knowledge among construction professionals regarding green vegetation-covered rooftop gardens. In Johannesburg, green vegetation-covered rooftop systems have a significant demand despite the evidence of a lack of awareness of these systems (Labuschagne and Zulch, 2016). The following is a list of reasons in support of these green vegetation-covered rooftop systems: a natural and secure environment is provided by green vegetation-covered rooftops; green vegetation-covered rooftops offer better-insulated buildings to conserve electricity; air quality is improved, and this is good since Johannesburg is renowned for air pollution in the CBD and the industrial area (Labuschagne and Zulch, 2016). Akbari (2005) is of the view that green vegetation-covered rooftop systems can help mitigate the urban heat island effect, and this can be achieved through the transpiration process of plants.

Urban trees, green spaces, and other natural resources naturally control storm and water flow-water runoff by decreasing and intercepting stormwater flowing off of impermeable surfaces (Berland et al., 2017). In Johannesburg, for example, trees with a strong vertical anchorage may help to reduce the velocity of fast-flowing storm water, thereby enhancing resilience to erosion damage. This is important because increasingly dangerous flash flooding is being caused by highveld thunderstorms and the covering of natural drainage systems with hard surfaces (Schäffler and Swilling, 2013). According to research by Busayo et al. (2022), South Africa can implement hybrid strategies that use vegetation, porous surfaces, and temporary water storage to reduce combined sewage overflows. Consequently, this would assist cities in distributing less water through the grey infrastructure drainage system, which is frequently overworked by wastewater treatment facilities.

Despite the case studies presented on green infrastructure initiatives in South Africa, there is a need for more research tailored to South African urban contexts. There is potential to implement and scale nature-based technology to achieve urban resilience, however, this requires local empirical research, which will inform policy and urban planning.

2.4. Conclusion

There is much complexity in the concept of green infrastructure, which requires a more standardized approach. In most cases, authors fail to highlight how green infrastructure can be incorporated into urban environments. Similarly, the term green infrastructure is constrained in terms of having a solid, universal definition. Besides standardizing the definition, more effort should be invested in research that helps people understand the benefits of green infrastructure in developing countries and urban areas with varying climates.

Many communities in African cities are missing out on the potential benefits associated with green infrastructure, and this is due to inadequate research in the Global South. Where climate change mitigation strategies are concerned, there is a shortfall in case studies that contextualize the effectiveness of different climate change mitigation strategies in Africa through green infrastructure. Therefore, this creates a gap where long-term studies that assess the impact of mitigation strategies in African cities are needed. This would address the minimal studies conducted in South Africa regarding green infrastructure and climate change mitigation.

The theoretical and conceptual foundations of this study have been established in this chapter. The role of green infrastructure in addressing the UHI effect and urban flooding has been conceptualized, drawing from the Urban Resilience Theory and the Climate Adaptation Theory. A global literature review of green infrastructure applications demonstrates its effectiveness in mitigating the UHI effect as well as urban flooding. The review of literature brought to light gaps in green infrastructure research, particularly in African cities, and it is for that reason that this present study is relevant. In conclusion, the methodological and analytical approach detailed in Chapter 3 is informed by the foundations of Chapter 2, which provide a coherent framework.

3. Chapter 3 - Methodology

The purpose of this chapter is to outline the methodological steps employed in this study. Research methodology is a vital component of the study, as it provides a systematic framework for collecting, analyzing, and interpreting data to address the research problem (Patel and Patel, 2019). This chapter begins by explaining the research design and describes the study area, the sampling procedure, and the data collection tools. The methodological foundation for this study was based on a mixed-methods strategy that combined quantitative and qualitative approaches. According to Turner et al. (2017), a mixed-methods approach is a research methodology that integrates numerical, statistical, and descriptive, interpretive methods within a study. To fully clarify the research issue, mixed methodologies provided an improved comprehension of the phenomenon being studied and better responses to the research questions. Furthermore, this chapter highlights the data analysis methodology as well as the limitations encountered during the study.

3.1. Research design

This study adopted a descriptive and cross-sectional mixed-methods research design. Research design is defined by Patel and Patel (2019) as a framework for addressing the research question, including sampling, data collection, and analysis techniques. The research design is a blueprint that specifies the procedures for obtaining reliable and valid results. Considering this, the integration of both quantitative and qualitative research methods was most appropriate for this study as it enabled the understanding of the multifaceted nature of green infrastructure and its role in combating climate change impacts. An online survey helped gather quantitative data from participants, while individual interviews and a focused group discussion provided qualitative data. The quantitative aspect included online survey data collected from participants in the study area; the data were subsequently used to highlight the perceived occurrence and severity of urban heat and flooding. The qualitative component was utilized to gather crucial insights, experiences, and perceptions from stakeholders on various kinds of issues. Specifically, stakeholders' perspectives on GI, difficulties in implementation, and governance constraints. During the study, the two data strands were merged, with the quantitative data providing empirical evidence on the extent of climate-related impacts. Furthermore, the qualitative data shed light on the underlying social, institutional, and policy processes that influence GI effectiveness. As a result, the mixed-methods approach strengthened the study's validity by connecting measured climate consequences to lived experiences and institutional realities. The mixed-methods approach offered a better understanding of the impact of green infrastructure strategies, especially in the Southern African region. Phenomenology, survey research, and thematic analysis were utilized to guarantee that both the qualitative and quantitative aspects were captured and analyzed effectively. In brief, this well-defined research design translated research questions into a systematic approach for data collection and analysis, ensuring that the study meets its objectives (Bloomfield and Fisher, 2019).

3.2. Study area

The study was conducted in Johannesburg CBD, located in the City of Johannesburg Municipality in the Gauteng Province of South Africa. In the year 2024, the estimated population of Johannesburg was close to 6.3 million (StatsSA, 2024). Johannesburg is the largest metropolitan area in South Africa in terms of population size, and it is the nation's financial and economic hub. Johannesburg occupies approximately 1 645 km^2 of land and is within the Gauteng-City Region with neighboring municipalities such as the City of Tshwane municipality and the Ekurhuleni municipality (Abrahams and Everatt, 2019). Johannesburg is located on the Highveld, which is the wide, grassy plateau that runs through the interior of South Africa. The city is situated on top of the Witwatersrand, a chain of short, rocky hills that serves as the watershed between the drainage basins that empty into the Atlantic and Indian seas (Campbell, 2024). The average summer temperature is approximately 24 °C, whereas the average winter temperature is roughly 13 °C and rarely goes below freezing (Campbell, 2024). Johannesburg is 164,458 hectares large, and from that, a total of 16.1% is covered by trees, both non-indigenous and indigenous forests (Schäffler and Swilling, 2013).

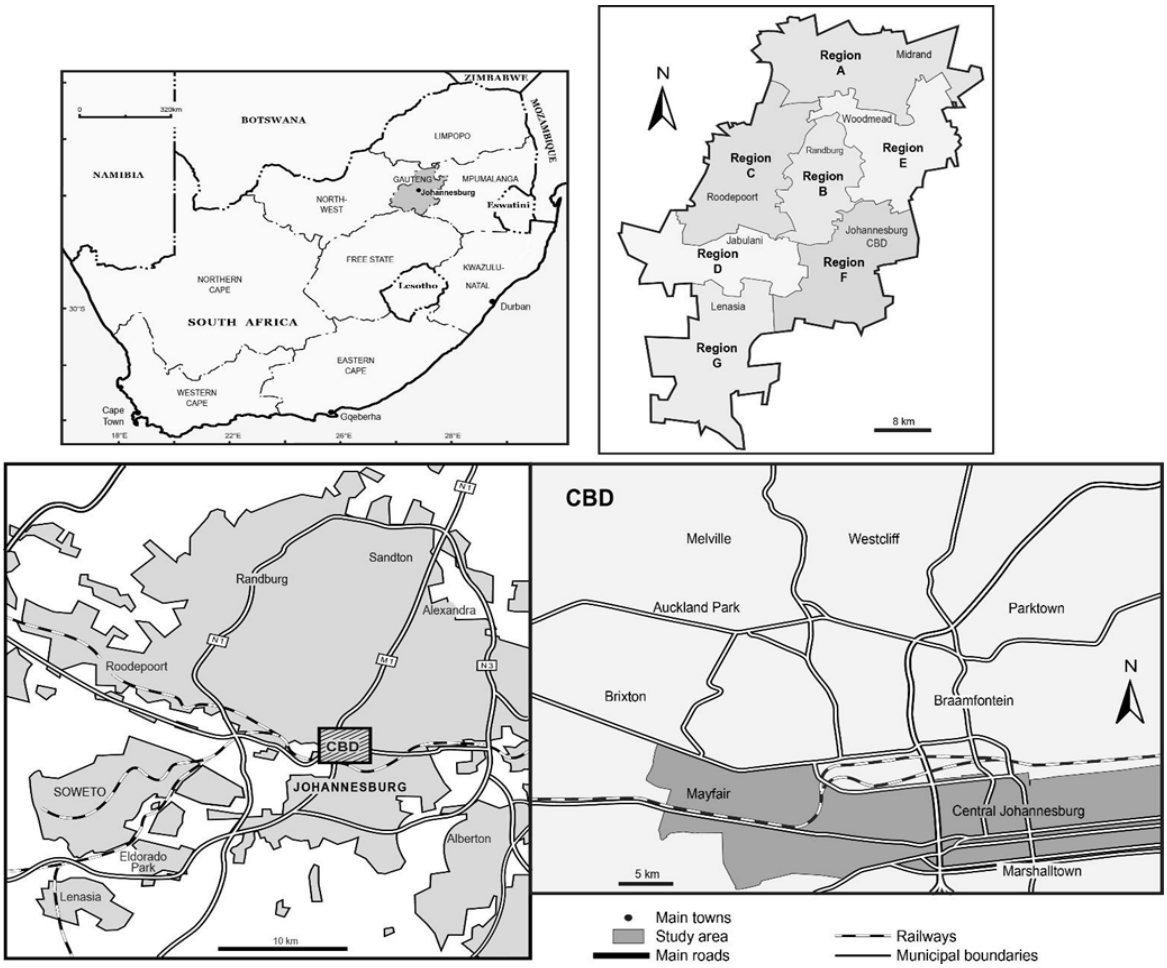


Figure 2: Johannesburg CBD locality map

3.3. Study population and sampling procedure

Johannesburg was selected using purposive sampling, as this city presents rising issues in disaster and risk management in the context of urban resilience and climate adaptation. For this city to be adaptable to climate change, there is a need to investigate green spaces, given the risk of floods and rapid urban growth that contributes to the urban heat island effect (Busayo et al., 2022). Johannesburg has natural features in abundance and needs to adopt innovative, eco-friendly solutions to mitigate the crises brought about by climate change, which is the core function of this study. For instance, Johannesburg's trees, which are surrounded by green open spaces, create a network of soft, natural areas that stand out in an otherwise tense urban setting and demonstrate the intricate and paradoxical nature of the built environment (Schäffler and Swilling, 2013).

Casteel and Bridier (2021) describe a study population as the defined group from which research participants are drawn and to whom study results are intended to apply, making its clear definition crucial for valid, reliable, and generalizable research outcomes. In terms of sampling procedures, a total of 56 respondents were engaged. A sample size of 56 respondents allowed for a sufficient degree of representativeness across the three key stakeholder groups identified (local community, municipal authorities, and NGOs). To fully comprehend the complex effects of green infrastructure on mitigating climate change, a rich range of viewpoints was ensured through this breakdown. The study population was composed of 3 key stakeholders, which were categorized as follows:

- Group A – Local Community
- Group B - Municipal authorities
- Group C – NGOs in the environmental space (private sector specialists)

The sampling procedure of the study was two-fold. Firstly, for the local community members, 1 in every 10 adults was approached in the streets of Johannesburg CBD by interception sampling. These prospective participants were informed about the study and given the opportunity to consent to participate. Upon their approval, the participants scanned a QR code with their phone, which opened a Google Forms survey. For Group A, a total of 50 respondents from the local community were selected.

Secondly, Groups B and C were sampled through purposive sampling. Purposive sampling is a targeted approach to participant selection, widely used in qualitative research to ensure the sample best fits the study's objectives and provides rich, relevant data (Tongco, 2007). The strategy of purposive sampling used in the study was criterion-based. For instance, the selection for Group B (municipal authorities) for the focus group discussion was based on their roles in policy implementation, infrastructure monitoring, and urban environmental governance. The City of Johannesburg's Environment and Infrastructure Services Department (CoJ EISD) was the municipal entity chosen for this study's component. A formal request for permission to participate in the study was sent to the municipal entity, along with an outline of the research project. After their approval, communication was maintained to set a suitable time and date for the discussion. Before taking part in the focus group discussion, each participant was provided with a participant information sheet (Annexure 2) and signed the consent forms (Annexure 3). A total of four municipal authorities volunteered and consented to being part of the study's focus group discussion.

For the semi-structured interviews, NGOs had to be involved in the environmental space to meet the selection criteria. A focused Google search was done to find private companies that work in the fields of climate change, environment, sustainability, and just energy transition. A shortlist of pertinent organizations was created as a result of this search. Following that, a formal request for permission to participate in the study was sent to each of the shortlisted organizations, along with an outline of the research project. Three organizations responded positively and granted permission for the principal researcher to access their premises for data collection. These organizations were Sustainable Energy Africa, the Gauteng City-Region Observatory, and the National Business Initiative. To set up appropriate times and dates for the interviews, constant communication was maintained with these organizations. Informed consent papers and participant information sheets were given to participants on the day of data collection, and they were filled out and signed before the interviews, attesting to their willing involvement in the research. The Gauteng City-Region Observatory later stopped responding to follow-up communication, despite the signed agreement, and this was acknowledged as an unexpected withdrawal. For Group C (NGO's), there were two respondents from local NGOs who participated in the study, one representative from the National Business Initiative, and one representative of Sustainable Energy Africa.

Finally, 56 respondents were selected to find an acceptable balance between the need for a variety of in-depth insights and practical viability. This figure was supported by methodological considerations and the requirement to include a variety of viewpoints within the setting of the Johannesburg CBD. While this sample size was not statistically representative of the entire population, it was a deliberate decision based on practical considerations. The scope of this research was constrained by limited time, financial resources, and logistical capabilities. Given these constraints, a smaller sample size allowed for more manageable data collection and analysis within the available resources, while still providing valuable insights for the study's objectives. These key informant groups provided a well-rounded and contextually relevant sample for this study, ensuring diverse perspectives across sectors.

Table 1: Overview of research questions, corresponding objectives, data collection tools, and key informant groups for the study

Questions	Objectives	Data Collection Tool	Key Informant Group
Q1 - How are the urban heat island effects and urban flooding affecting Johannesburg CBD, and what are the associated implications?	Ob1 - To examine the extent of the urban heat island effect and urban flooding in Johannesburg and its associated impacts	Google Forms survey Literature review	Local community members
Q2 - To what extent is green infrastructure a solution to mitigate these extreme climatic events?	Ob2 - To assess the role of green infrastructure in mitigating urban heat islands and urban flooding	Phone recorder	NGO's
Q3 - What are the key factors that influence the implementation and operation of green infrastructure initiatives?	Ob3 - To identify key factors influencing the successful implementation and operation of green infrastructure initiatives	Phone recorder	Municipal authorities

The following section outlines the research technique in detail.

i) Question 1 and Objective 1

To explain why online surveys were used here, it was because surveys can be used in data collection with a large number of people. The benefit of this tool is collecting quantitative data about how these groups perceive and experience the effect or the existence of the UHI effect and urban flooding through the responses of closed-ended and Likert scale questions. This approach allowed comparing the responses, which in turn made it possible to determine the degree and variation of these climatic impacts within different demographic groups. A thorough analysis of journal publications on UHI and floods in Johannesburg's CBD was conducted. To look for journal papers on related subjects, web-based search engines like Google and Google Scholar were used. This approach was to discover contemporary research in the study area on the existence of the UHI effect and urban flooding. The rationale for including online surveys with the literature review is the cross-checking of the results obtained. The self-completed surveys revealed current perceptions and experiences of the stakeholders as needed, whereas the literature review enabled the researcher to go beyond the perceptions of the study's participants and place the research findings in a broader context, often organizing the material according to how it has been discussed in the existing literature. The rationale is that, through consulting literature, reports, and other official records, the researcher was better placed to put meaning to the responses obtained.

ii) Question 2 and Objective 2

The rationale for the use of semi-structured interviews was that these enabled describing how the interviewed stakeholders perceive and assess green infrastructure as a solution. This tool was suitable because it was flexible in leveraging the participants' knowledge, beliefs, and/or experiences on green infrastructure in their practice. It made use of an open-ended response that was very useful for a topic where perception may not be easily defined and may have some measure of complexity, and it allowed the identification of the impediments and the enablers to put in green infrastructure.

Moreover, although surveys yielded numerical results that facilitate comparisons, semi-structured interviews yielded qualitative data that complement those gathered from the surveys. On the one hand, the use of data collected during interviews strengthened the information obtained from literature reviews, highlighting both global standards and local peculiarities. Similarly, the interview responses were compared to global case studies, which helped in determining whether the conclusions support or contradict existing research. The rationale for the inclusion of a literature review was that, through documenting the literature of the study, Johannesburg could be compared with other countries' green infrastructures. Furthermore, it enhanced the ability to identify best practices and an appreciation of the level of effectiveness exhibited by these solutions in tackling similar problems in other countries.

iii) Question 3 and Objective 3

The rationale for a focus group discussion was to get selected authorities in the municipality to engage in issues relating to the technical, political, social, and economic prospects of green infrastructure. As opposed to structured methods such as surveys or individual interviews, focus group discussions allowed a profound

discussion and identification of key issues that may be overlooked by one person in an interview. Consequently, the policies, regulatory frameworks, funding mechanisms, and technical capacities of green infrastructure implementation are complex matters, thus requiring focus group discussions to obtain specific information from experienced officials. This approach enabled one to identify crucial factors like government policies, funding limitations, and community participation, which are vital for the projects to be carried out.

3.4. Data collection

This section highlights the tools applied to collect data during the study. The process of data collection, as outlined by Mazhar (2021), is the essential process of systematically gathering information to answer research questions, with its quality directly impacting the validity and usefulness of research findings. This study adopted a mixed-method approach, which included quantitative and qualitative data collection. The quantitative data were in the form of online surveys, and the qualitative data included individual interviews, focus group discussions, and a review of the literature.

i) Online surveys

An online survey was developed to collect data that would inform the first objective and the first observation of this study. The participants scanned a QR code with their phone to access the Google Forms survey. The Google Forms survey platform saved the participants' answers in an Excel spreadsheet, which was exported during the data analysis phase. This survey contained 20 questions (Annexure 808.4.1), which were tailored to provide data specifically on the extent and impacts of the UHI effect and urban flooding in Johannesburg CBD. A total of 50 respondents from the local community completed the survey. The questions on the survey were closed-ended, Likert scale questions, which required participants to rate their level of agreement with a statement or a question using a pre-defined scale. This method of data collection was better suited to gather insights regarding the frequency and severity of heat stress and flooding, which was pivotal in assessing the existence and intensity of the issues outlined in the first objective.

ii) Individual semi-structured interviews

Regarding the second objective and observation, individual interviews were the primary data collection method. The interview had 10 questions (Annexure 8.4.2), which were tailored to explore stakeholders' perceptions and experiences with green infrastructure as a solution to mitigate the UHI effect and urban flooding in Johannesburg CBD. There were two respondents from local NGOs who participated in these interviews. These questions were designed to be open-ended, which allowed participants to elaborate more on their insights and the nuances of their experiences.

iii) Focus Group Discussion

The third objective and observation were informed by collecting data from a focus group discussion. This discussion contained 10 questions (Annexure 8.4.3), which helped identify key factors that influence the implementation and operation of green infrastructure initiatives. A total of four municipal authorities consented to being part of the study’s focus group discussion. The questions focused on the technical, political, social, and economic dimensions, and they encouraged participants to provide detailed responses based on their expertise and experiences in the public municipal sector.

iv) Review of literature

Four journal publications about UHI and flooding in Johannesburg were found through Google searches. A thorough understanding of local concerns on the state of UHI and flooding in South Africa was attained by engaging with additional literature from a different metropolitan area. The systematic review procedure used

in this study began with the formulation of a set of inclusion criteria, followed by an article search employing operative keywords, as shown in Table 2.

Table 2: Systematic literature review process to inform research objective 1

Inclusion criteria	Keywords
Documents that focus on answering the research question/achieving research objective 1.	"Urban heat island" "Urban flooding" "Johannesburg" "Heat stress" "Flood"
Documents that analyze the urban heat and flood challenges in Johannesburg.	

3.5. Data analysis

Data analysis is a structured process that transforms raw data into meaningful insights, supporting scientific discovery and informed decision-making through a combination of exploration, modeling, and interpretation (Angelov et al., 2018). Quantitative data were analyzed using software for statistical computing and data visualization. This involved converting the raw data into statistics for ease of interpretation. On the contrary, thematic analysis was utilized to interpret the qualitative data of this study. This approach allowed the data to be described and gain insight into its meaning. The following section outlines the data analysis procedure employed in this study.

i) Quantitative data analysis

The quantitative data from the online survey were preprocessed and stored in Microsoft Excel. The data was imported into R, which is software for statistical computing and data visualization. The data was analyzed by means of a well-structured workflow that combined descriptive (Annexure 8.5.2) and inferential statistics. To determine whether participant responses were equally distributed across response categories, a chi-square goodness-of-fit test was conducted. Section 4.1.3 presents a detailed overview of the inferential statistics used for the study, as well as the null hypothesis tested. To ensure consistency, data cleaning and coding of categorical responses were conducted after importing the dataset. Vetter (2017) explains that descriptive statistics in research involve techniques that help condense large amounts of data into simple summaries, making it easier to understand patterns, trends, and relationships within a dataset. Different types of descriptive statistics were calculated, namely, the mean, median, mode, and standard deviation. This was meant to explore the dispersion and the central tendency.

Each response category was used to generate frequency distributions and percentage counts to reveal overall patterns. The output results were used for data visualization, pie charts, bar graphs, and line plots were generated to enable pattern identification and cross-comparison. By utilizing this R-based approach, a seamless and transparent framework for quantifying the perceptions of the participants was enabled. In brief, the descriptive statistics provided an essential foundation before making inferences about the Johannesburg CDB population from the sample data. Inferential statistics enable researchers to make generalizations, predictions, or inferences about a larger group (the population) using information collected from a smaller subset (the sample) (Khakshooy and Chiappelli, 2018). In brief, inferential statistics were essential for making evidence-based decisions and generalizations in this study, moving beyond the data collected to broader scientific conclusions.

ii) Qualitative data analysis

Braun and Clarke (2016) define thematic analysis as a method, not a methodology, for systematically identifying, analyzing, and reporting patterns (themes) within data. It is not tied to any specific theoretical framework, making it adaptable across various research paradigms. The qualitative data analysis in this study followed an inductive thematic analysis approach, meaning that themes, categories, and codes (Annexure 8.5.1) were derived from the raw interview data itself rather than being imposed from pre-existing theories or frameworks. The process involved engaging closely with the transcripts, allowing patterns and meanings to emerge naturally from the participants' responses. The first step involved transcribing all the

audio recordings from the interviews that were conducted. These transcripts were used to identify insightful observations and common themes. The initial codes were conducted by highlighting valuable insights, which were categorized under a specific definition, and this was substantiated by examples in the raw data for the compact codebook. To ensure consistency and coherence, the analysis was reviewed and repeated several times, which ensured the relevance of the findings to inform the research objectives.

3.6. Ethical considerations

In research, ethics is defined as adherence to a set of moral principles that guide researchers in conducting research responsibly and with integrity (Ajemba and Arene, 2022). Ethical clearance (Annexure 8.1) was obtained from the ethics committee at the University of the Witwatersrand. The Human Research Ethics Committee (Non-Medical) protocol number for this study is [H25/02/24].

Ethics not only applies in the data collection phase, but it is also applied throughout the research value chain to ensure honesty, objectivity, and accountability. In the context of human research ethics, the moral duty to conduct good deeds and refrain from harming others is known as beneficence (Brear and Gordon, 2021). Guided by beneficence, the principal researcher used risk-benefit analysis at individual and group levels to protect the subjects' well-being as part of the researcher's duty of care to human subjects. Additionally, non-maleficence, another principle that refers to the moral duty to avoid causing harm (Brear and Gordon, 2021). The study was guided by the non-maleficence principle because the study did not involve any physical contact with human participants and did not include any line of questioning that negatively affected the emotional well-being of participants.

Detailed consent forms were provided, clearly explaining the scope of the study and participants' rights. Furthermore, informed consent is a prerequisite that was considered for this research study as per ethical principles. In the process of this study, all participants were fully informed about how the data would be collected, used, and stored. Furthermore, the participants were informed about their right to withdraw from the study. To protect the identity of the participants, all personal information collected was anonymized, ensuring that individual identities cannot be linked to specific data points. Access to this data was restricted to the principal researcher and the supervisor

3.7. Limitations

Research studies are often confronted with limitations, and this research study encountered several methodological constraints. The first notable aspect was the time constraint, the data collection was undertaken within a two-month period, which limited opportunities for follow-up interviews and surveys. Secondly, the proposed sampling strategy proved to be counterproductive in the field. The intention was to approach one in every ten adults in the CBD, and this area is densely populated and widely perceived as unsafe, consequently, rendering street-level sampling a risk. In addition, some prospective participants were understandably reluctant to engage with the principal researcher; this may have been due to personal safety concerns, such as fear of theft or being scammed, which is a harsh reality. As a result, participation rates from the local civilians were lower than anticipated.

Another methodological constraint was that the online survey did not allow the participants to document their demographics (sex, ethnic group, etc.). The only inclusion-exclusion criteria that were applied were asking each prospective participant whether they lived or worked in the study area before they could participate in the study. Therefore, the results do not allow for the disaggregation of responses across socio-demographic groups but rather represent aggregated perceptions of climate-related impacts. As a result, the study's ability to evaluate equity and differences in vulnerability is limited, and the results' applicability

to certain population subgroups within the study area is also limited. To enable deeper analysis, future studies could overcome these limitations by including demographic profiling. These limitations should be taken into account when evaluating the results.

In the context of qualitative data collection, some individuals and organizations initially agreed to be interviewed and even signed formal permission letters granting access for interviews. However, some participants later withdrew, and others stopped responding to follow-up communication, despite these signed agreements. Although other interviews were completed, these unexpected withdrawals limited the depth of qualitative insights that could be captured. It is worth noting that the reduced number of participants does not compromise the integrity or objectives of this research study. In fact, the changes emphasized quality over quantity. In closing, these limitations do not invalidate the findings, however, they should be considered when interpreting the results and assessing their broader applicability.

4. Chapter 4 – Findings

This chapter covers the results of the study, and it is a vital part of the research process since it provides evidence that can be used to test the study's hypothesis and conclusions. The findings given in this chapter are based on data collected during the data collection phase, and these are linked to the strategic themes indicated in the research questions in Chapter 1.

This chapter presents the findings from the quantitative and qualitative analyses in an integrated approach. The mixed-methods data, which was analyzed, includes online surveys, interviews, and focus group discussions conducted with stakeholders in Johannesburg CBD. The findings are structured around the study objectives, with thematic analysis, descriptive, and inferential statistics providing a synthesis of perspectives from participants. The first results, which are presented, are in line with the investigation into the extent of the UHI effect and urban flooding in Johannesburg. This is followed by exploring the role of green infrastructure in mitigating the UHI effect and urban flooding. The perceptions of the role of green infrastructure in mitigating the UHI effect and urban flooding are also presented in this chapter. The chapter concludes by presenting the participants' perceptions of key factors influencing the successful implementation and operation of green infrastructure initiatives, as well as feasible measures that could be implemented.

4.1. Extent and impacts of the UHI effect and urban flooding in the CBD

Following the comprehensive literature review of journal articles on climate change-related impacts, Table 3 presents the findings of the data.

Table 3: Studies assessing UHI and urban flooding in Johannesburg

Study author	Key finding
Hardy and Nel (2015)	Johannesburg remote sensing research reveals that vegetation cover affects intra-urban temperature variations: residential neighborhoods with more trees have cooler surfaces, while impoverished regions with less vegetation have a greater surface than urban heat island.
Souverijns et al. (2022)	The most heat-stressed locations in Johannesburg and Ekurhuleni are densely populated, low-vegetation, and low-income districts, according to high-resolution modeling and community monitoring.
Fatti and Vogel (2011)	According to preliminary data for the years 1960–2009 revealed that Johannesburg's heavy rainfall events were increasing in frequency and intensity, which was consistent with predictions of climate change.
Tyson et al. (1972)	An outline of the Johannesburg Urban Heat Island Project's goals is provided. The development of heat islands above South African cities is discussed, along with a brief overview of the literature on vertical

	temperature structure above cities and an illustration of the complexity of the structure developing over Johannesburg.
*Greenstone (2023)	The urban heat island effect (UHI) and temperature of green roofs, as well as control locations, were measured over a seven-year period for this study's quantitative analysis. Over the course of seven years, one green roof's average summer temperature (January/February) was 9.2 degrees Celsius lower than the control roof. The aim of this study was to provide evidence in favor of the advantages of green roofs in reducing the rise of inner-city heat islands in the Central Business District (CBD) of Durban.

*Search expanded to urban areas locally, and Greenstone's study was appropriate since it investigated the potential role green roofs can play in mitigating the urban heat island effect: a case study of the Central Business District, Durban.

4.1.1. Urban heat island effect

Participants described the UHI effect as a growing and under-acknowledged problem in Johannesburg's CBD. The phenomenon is largely attributed to the expansive paved surfaces, high-rise buildings, limited vegetation, and intense vehicular traffic that dominate the inner city. One city practitioner explained: ***"The CBD is a heat trap; there is concrete everywhere, vehicles idling, and hardly any trees. It is unbearable for people walking or trading on the streets."***

The effects of heat are not distributed evenly across the population. Pedestrians and informal traders, who spend prolonged periods outdoors, were identified as particularly vulnerable. Participants noted that there are few shaded areas or cooling refuges for these groups. A focus group participant remarked: ***"We talk a lot about floods, but the heat is just as dangerous. People faint, vendors pack up early, and it affects productivity. It's a silent stressor."***

The lack of adequate shading infrastructure, such as street trees, awnings, and cooling corridors, was emphasized as a major gap. Informal traders, many of whom operate without permanent shelters, bear the brunt of this exposure. Equity concerns were repeatedly raised, with participants observing that those least able to adapt financially are the most affected. Another focus group stakeholder noted: ***"You find the poorest people: vendors, security guards, cleaners, outside all day in 30-plus degrees, with no shade. That's an equity issue the city cannot ignore."***

i) Perceived temperature difference

Additionally, with regard to the UHI effect, participants were asked to express their views on how noticeable the temperature difference between Johannesburg CBD and nearby areas was. The survey results are shown in Figure 3.

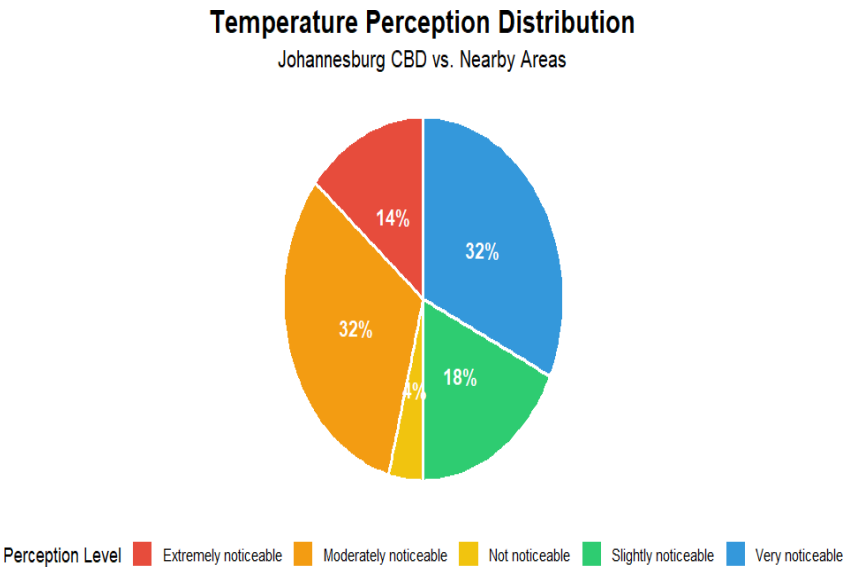


Figure 3: Perceived temperature distribution amongst participants

Figure 3 indicates that most respondents (83.3%) perceive a temperature difference of some level between the Johannesburg CBD and its surrounding areas. Only 16.7% report no noticeable difference, indicating that the UHI effects are perceptible to most respondents.

The frequency analysis displayed the distribution of replies in counts and percentages, emphasizing salient trends. Pie charts and line graphs were used as visual aids to assist with pattern detection and interpretation, ensuring that both numerical and graphical viewpoints guided the outcomes.

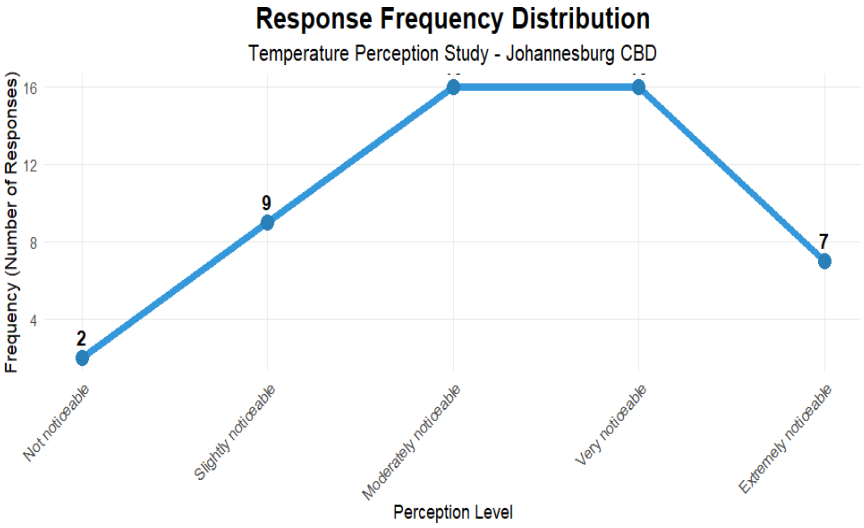


Figure 4: Perceived temperature difference frequency distribution patterns

Figure 4 shows frequency patterns. The peak at “Moderately noticeable” (16 responses, 33.3%) (Figure 4) suggests this is the most common perception level. The distribution is right-skewed, with fewer people reporting extreme temperature differences.

ii) Perceived high night-time temperatures

Participants were asked to express their views on how often they notice temperatures in Johannesburg CBD remaining high during nighttime. The survey results are shown in Figure 5. Figure 5 shows distinct frequency patterns in temperature perception. The peak occurs at "Often" (20 responses, 40%), representing the modal response, followed closely by "Sometimes" (18 responses, 36%), indicating these are the most common experience levels. Only 18% report "Rarely" noticing high temperatures, indicating that the UHI effect during nighttime hours is perceptible to most CBD residents. The dominance of positive responses ("Sometimes" + "Often" + "Always" = 94%) provides strong visual evidence that the UHI phenomenon is a widely experienced reality rather than an isolated occurrence.

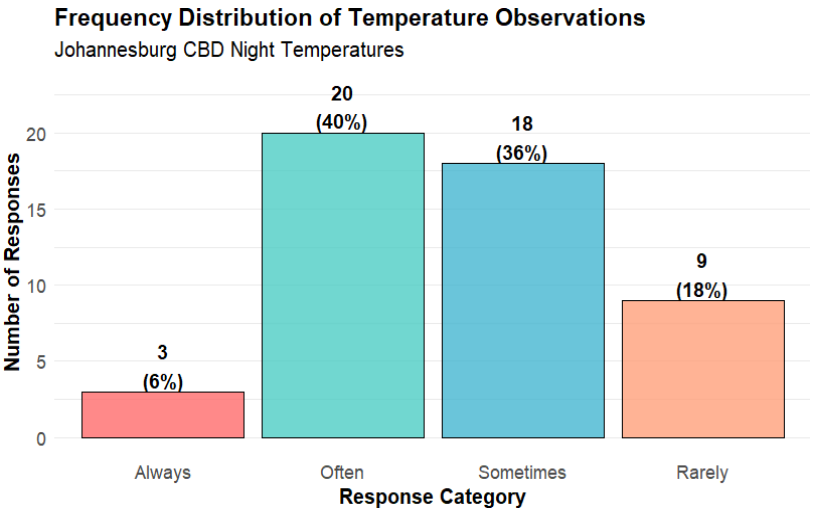


Figure 5: Perceived night temperature frequency distribution patterns

The distribution shows a right-skewed pattern (Figure 5), with the frequency declining sharply from "Often" to "Always" (3 responses, 6%), suggesting that while most residents notice elevated temperatures regularly, fewer experience them constantly. The relatively low frequency of "Rarely" responses (9 responses, 18%) compared to the combined frequent responses (38 responses, 76% for "Often" + "Sometimes") demonstrates that regular perception of nighttime heat is the dominant pattern among Johannesburg CBD residents.

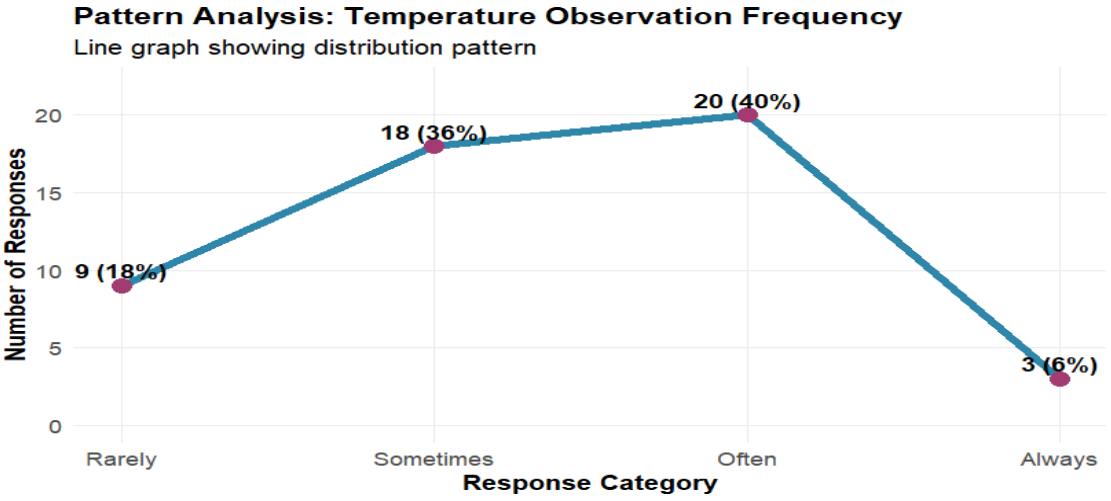


Figure 6: Perceived temperature pattern analysis

Overall, participants painted a picture of a CBD exposed to compounding climate stressors such as chronic heat stress during hotter months. These stressors not only undermine grey infrastructure functionality but also place a disproportionate burden on the urban poor, exacerbating existing inequalities in the city.

4.1.2. Urban flooding

Alongside the UHI effect, participants consistently highlighted seasonal flash flooding as one of the most pressing climate-related challenges facing the Johannesburg CBD. Specific areas such as Market Street, Sauer Street, and the Park Station precinct were repeatedly mentioned as high-risk zones. These areas experience recurrent inundation during heavy rainfall events, leading to significant disruption of urban life. As one interviewee from Sustainable Energy Africa noted: ***"Seasonal flash flooding around Market, Sauer, and Park Station is now common. The stormwater system was designed for one-in-five-year events, but we are increasingly seeing one-in-twenty-year events."***

The inadequacy of stormwater infrastructure was a dominant theme. Infrastructure that was once considered sufficient is now overwhelmed by the intensity and frequency of rainfall events, resulting in ponding on roads, overflow of drainage systems, and damage to nearby businesses and properties. The Sustainable Energy Africa respondent explained: ***"When those storms hit, the roads turn into rivers. Taxis and buses can't move, and even emergency services are forced to wait until the water subsides."*** Beyond physical damage, flooding was described as a serious socioeconomic hazard. Street vendors lose stock, commuters are delayed, and formal businesses suffer operational losses. These impacts extend beyond immediate disruption to create ripple effects on livelihoods and economic productivity in the CBD.

i) <u>Perceived flooding frequency/impact</u>

Participants were asked to express their views on how frequently they have noticed or been impacted by flooding in Johannesburg CBD after heavy rainfall. The survey results are shown in Figure 7. The pie chart indicates that flooding impacts in Johannesburg CBD show a mixed distribution, with 74% of respondents experiencing flooding impacts at least sometimes (17 'Sometimes', 18 'Often', and 2 'Always'). However, 26% report minimal impact ('Never': 5 responses, 10%; 'Rarely': 8 responses, 16%), suggesting that while flooding affects most CBD residents to some degree, the severity and frequency vary considerably across the population.

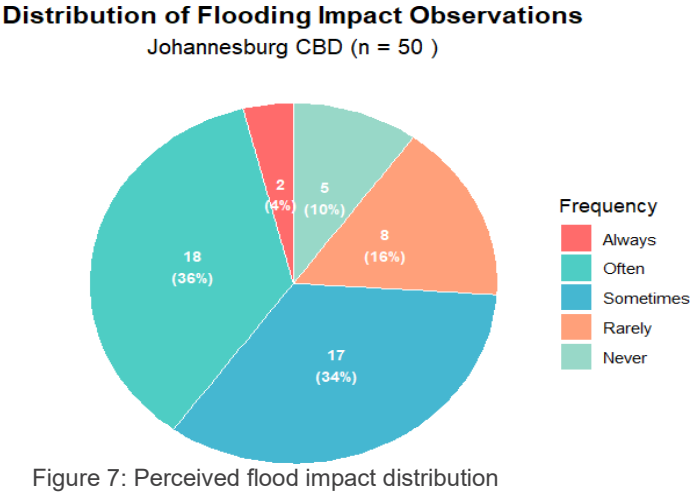


Figure 7: Perceived flood impact distribution

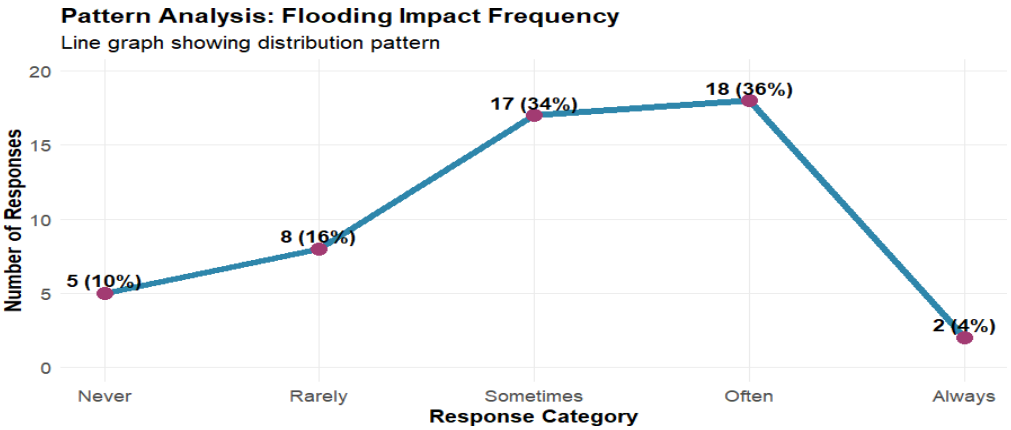


Figure 8: Perceived flood impact pattern analysis

The distribution appears slightly left-skewed (Figure 8), with a concentration of reactions in the middle-to-upper frequency categories. The substantial representation across multiple categories (Never: 5, Rarely: 8, Sometimes: 17, Often: 18, Always: 2) demonstrates that flooding experiences vary significantly among Johannesburg CBD residents, reflecting diverse geographic locations, building types, or individual sensitivity to flooding events.

ii) Perceived disruption of excessive heat and flooding to livelihoods

In line with the first objective, participants were given the platform to express their views on whether the UHI effect and urban flooding are issues. The survey results, shown in Figure 9 reflects the responses to how disruptive flooding and excessive heat are to daily life in Johannesburg CBD.

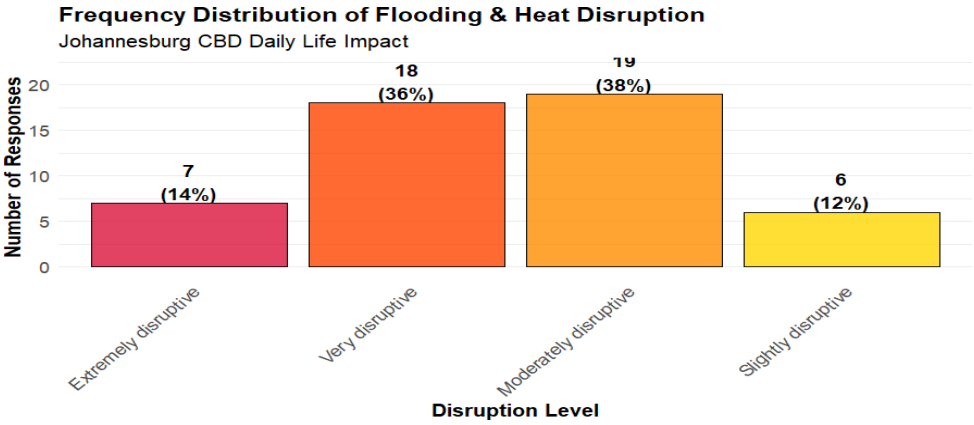


Figure 9: Perceived urban flood and UHI disruption frequency distribution

Figure 9 reveals that flooding and excessive heat severely disrupt daily life in Johannesburg CBD, with 88 % of respondents experiencing moderate to extreme disruption (38 % 'Moderately disruptive', 36 % 'Very disruptive', and 14 % 'Extremely disruptive'). Only 12 % report minimal disruption ('Slightly disruptive': 6 responses, 12%), indicating that climate-related events are a major livelihood challenge across the CBD, with the vast majority of residents experiencing significant daily disruptions from flooding and excessive heat.

The distribution in the graph below shows a concentration in higher disruption categories, with significant representation in 'Very disruptive' (18 responses, 36 %) and 'Extremely disruptive' (7 responses, 14 %). The minimal frequencies in lower categories ('Slightly disruptive': 6 responses) demonstrate that flooding and excessive heat consistently disrupt daily life across Johannesburg CBD, suggesting systemic climate challenges that affect the majority of residents within the CBD.

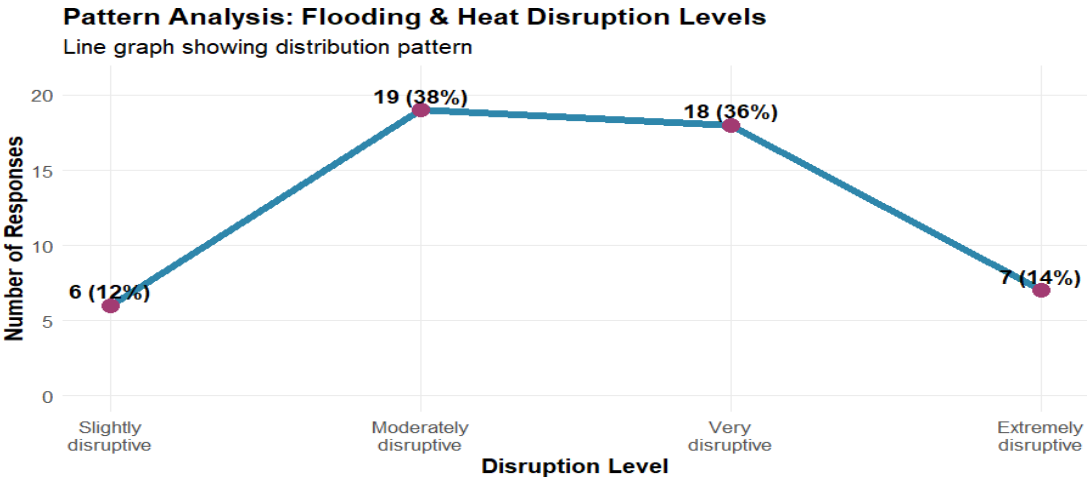


Figure 10: Urban flood and UHI disruption pattern analysis

Participants painted a picture of a CBD exposed to compounding climate stressors, namely, acute flooding during storms and chronic heat stress during hotter months, according to the pattern analysis in Figure 10. Both stressors not only undermine infrastructure functionality but also place a disproportionate burden on the urban poor, exacerbating existing inequalities in the city.

4.1.3. Inferential statistical analysis

To determine whether participant responses were equally distributed across response categories, a chi-square goodness-of-fit test was conducted. Table 4 unit Table 6 present the findings.

Table 4: Chi-square goodness-of-fit test results of participant response distribution (Hypothesis 1)

Hypothesis 1:

- H_0: Responses are equally distributed across all categories
- H_1: Responses are not equally distributed

Test: Chi-square goodness of fit test (non-parametric)

Results:

Response Category	Observed	Expected	Difference	Chi-square Component
Always	3	12.5	-9.5	7.22
Often	20	12.5	+7.5	4.50
Sometimes	18	12.5	+5.5	2.42
Rarely	9	12.5	-3.5	0.98

Test Statistics:

- Chi-square statistic: $\chi^2 = 15.12$
- Degrees of freedom: df = 3
- Critical value ($\alpha = 0.05$): 7.815
- P-value: p = 0.0017

The decision for the test results in Table 4 is that the null hypothesis was rejected ($\chi^2 = 15.12$, df = 3, $p = 0.0017$), indicating that responses were not equally distributed across categories. The observed distribution shows that participants responded "Often" and "Sometimes" more frequently than expected under a uniform distribution (20 and 18 observed vs. 12.5 expected, respectively), while "Always" responses occurred less frequently than expected (3 observed vs. 12.5 expected). This provides strong statistical evidence of systematic response patterns among participants.

Table 5: Chi-square goodness-of-fit test results of participant response distribution (Hypothesis 2)

Hypothesis 2:

- H_0: Responses are equally distributed across all categories
- H_1: Responses are not equally distributed

Test: Chi-square goodness of fit test (non-parametric)

Results:

Response Category	Observed	Expected	Difference	Chi-square Component
Always	2	10	-8	6.4
Often	18	10	+8	6.4
Sometimes	17	10	+7	4.9
Rarely	8	10	-2	0.4
Never	5	10	-5	2.5

Test Statistics:

- Chi-square statistic: $\chi^2 = 20.6$
- Degrees of freedom: df = 4
- Critical value ($\alpha = 0.05$): 9.488
- P-value: $p < 0.001$

The decision for Table 5 is that the null hypothesis was rejected ($\chi^2 = 20.6$, df = 4, $p < 0.001$), indicating that responses were not equally distributed across categories. The observed distribution shows that participants tended to respond "Often" and "Sometimes" more frequently than expected, while "Always" responses occurred less frequently than would be expected under a uniform distribution. This suggests systematic patterns in participant perceptions rather than random or uniform response tendencies.

Table 6: Chi-square goodness-of-fit test results of participant response distribution (Hypothesis 3)

Hypothesis 3:

- H_0: Responses are equally distributed across all categories
- H_1: Responses are not equally distributed

Test: Chi-square goodness of fit test (non-parametric)

Results:

Response Category	Observed	Expected	Difference	Chi-square Component
Always	11	10	+1	0.1
Often	18	10	+8	6.4
Sometimes	14	10	+4	1.6
Rarely	4	10	-6	3.6
Never	3	10	-7	4.9

Test Statistics:

- Chi-square statistic: $\chi^2 = 16.6$
- Degrees of freedom: df = 4
- Critical value ($\alpha = 0.05$): 9.488

- P-value: p = 0.0023

The decision for Table 6 is that the null hypothesis was rejected ($\chi^2 = 16.6$, df = 4, p = 0.0023), indicating that responses were not equally distributed across categories. The observed distribution reveals that participants responded "Often" and "Sometimes" more frequently than expected (18 and 14 observed vs. 10 expected, respectively), while "Never" and "Rarely" responses occurred less frequently than expected (3 and 4 observed vs. 10 expected, respectively). This provides strong statistical evidence of systematic response patterns, with participants tending toward more positive response categories.

4.2. Role and effectiveness of green infrastructure

4.2.1. Decentralized green infrastructure

Participants consistently emphasized the importance of small-scale, decentralized GI interventions that can be embedded within the highly built-up environment of the CBD. Rain gardens, bioswales, permeable paving, biodiverse sidewalks, and rooftop gardens were highlighted as both practical and effective. These measures were described as “retrofit-friendly” and adaptable to constrained spaces. As one interviewee from the National Business Initiative explained: ***“Most effective forms in the CBD are decentralized, retention gardens, bioswales, and permeable paving. They provide both hydrological and thermal solutions without demanding large tracts of land.”*** Green vegetation-covered roofs were also raised as valuable, though with recognition of structural limitations on older buildings. Where feasible, they were seen as important for both runoff reduction and additional green space in the vertical urban landscape.

4.2.2. Upstream buffering and wetland

While decentralized GI was seen as essential within the CBD, participants also pointed to the role of upstream wetlands and buffer zones in flood mitigation. These natural systems function as sponges, absorbing and delaying stormwater before it overwhelms the inner-city drainage network. A stakeholder from the National Business Initiative stressed this dual approach: ***“You can’t only focus on the CBD, you need designated green zones upstream to slow the water. That way, by the time it gets downtown, the drainage system can cope”.*** The combination of decentralized interventions within the CBD and upstream buffers was framed as a complementary strategy, where one reinforces the effectiveness of the other.

4.2.3. Conditions of Effectiveness

Stakeholders were clear that the effectiveness of GI is conditional on governance and planning integration. Participants pointed to the need for GI to be embedded in water- sensitive urban design (WSUD) standards, incorporated into capital planning, and supported by reliable maintenance regimes. One COJ EISD practitioner noted: ***“It’s not enough to have pilot projects. GI must be written into the engineering manuals, the zoning codes, and the capital budgets. Otherwise, you get isolated successes but no systemic impact.”***

The example of Paterson Park was often cited. This project demonstrated how GI could deliver lower operating costs and avoid flood damages exceeding R100 million over twenty years. However, participants lamented that similar approaches had not been replicated more widely across the city. As another COJ EISD participant put it: ***“We know it works, Paterson Park is proof. The problem is uptake. Until it’s mainstreamed, we’ll remain in pilot mode.”***

4.2.4. Co-Benefits of Green Infrastructure

Beyond its hydrological and thermal functions, GI was praised for its multi-dimensional co-benefits. These include reducing flood risks and associated economic losses, mitigating heat stress for commuters and informal traders, improving urban biodiversity, and enhancing air quality. Several participants highlighted

the social justice dimension, noting that GI can improve the dignity and safety of public spaces in the CBD. The participant from Sustainable Energy Africa explained that: ***"Green infrastructure is not just about water. It's about reclaiming the dignity of public spaces, especially for people who live and work outdoors."***

Employment and livelihood opportunities were another recurring theme. Participants observed that GI could be tied to the Expanded Public Works Programme (EPWP) to create jobs in installation, operation, and maintenance. A COJ EISD official revealed that: ***"If you design it properly, GI creates livelihoods — not just temporary work, but skills in landscaping, horticulture, and maintenance."***

This framing of GI as a multi-benefit investment rather than a narrow environmental intervention was seen as critical to building political and institutional support.

4.3. Factors influencing implementation and operation of green infrastructure

4.3.1. Barriers

The study found that several barriers are inhibiting the implementation and operation of GI. Figure 11 shows the multiple and interconnected barriers that hinder the effective implementation and long-term operation of green infrastructure (GI) in the Johannesburg CBD. At the center lies the concept of "barriers," which branches into six key dimensions: budgeting challenges, regulatory gaps, institutional silos, political priorities, procurement and Expanded Public Works Programme (EPWP) constraints, and physical constraints.

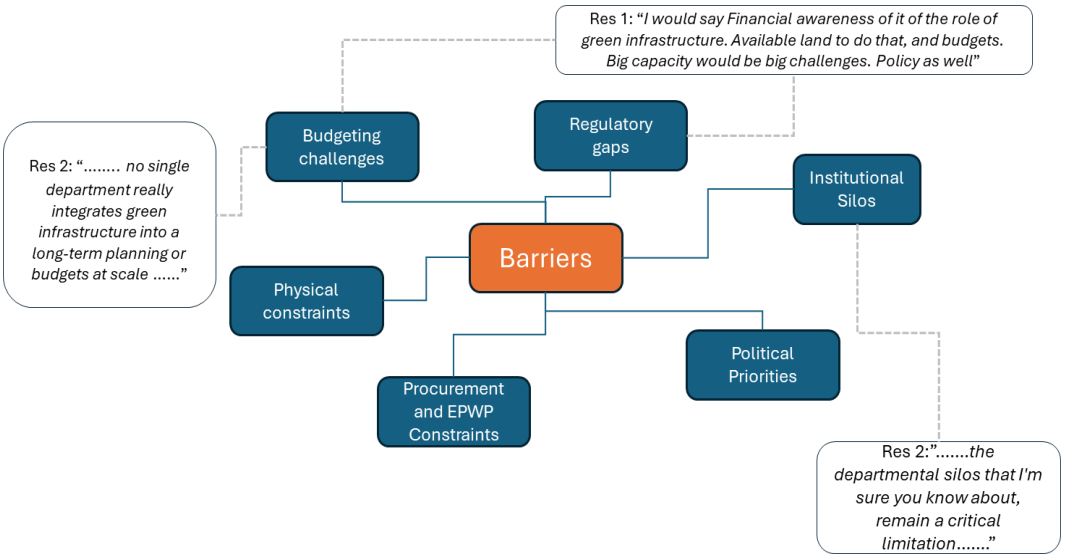


Figure 11: Barriers to the implementation and operation of GI

As shown in Figure 11, there are budgeting challenges which relate to the insufficient allocation of resources and the failure to account for life-cycle costs and avoided damage. The respondents indicated that GI is often misclassified as a recurring expense rather than as an infrastructure investment capable of generating long-term economic savings.

Regulatory gaps emerge from the absence of binding requirements for GI in zoning regulations, engineering codes, and development approvals. It emerged from the interviews that the current policies largely encourage GI uptake but fall short of mandating it, thereby limiting its integration into mainstream urban development practices. Besides regulatory gaps, institutional silos are another challenge which reflect the fragmentation of responsibilities across municipal departments such as City Parks, the Johannesburg Roads Agency, and environmental management units. The lack of a designated custodian for GI assets leads to poor coordination, inconsistent funding streams, and unclear accountability for maintenance.

Political priorities shape decision-making processes in ways that often disadvantage GI. Grey infrastructure projects, which are more visible and politically expedient, tend to be prioritised over less conspicuous but equally vital GI interventions. This creates a bias in resource allocation and undermines long-term sustainability goals. In addition, procurement and EPWP constraints capture operational inefficiencies, including bureaucratic procurement processes and rigid EPWP regulations, which delay implementation and reduce the effectiveness of GI-related employment schemes. These constraints also discourage innovation and adaptability in project delivery. Also, physical constraints arise from the dense, highly built-up nature of the CBD. Limited open space restricts the installation of large-scale GI features, necessitating innovative approaches such as small-scale, decentralised interventions (e.g., permeable paving, green vegetation-covered roofs, and rain gardens). Collectively, the results highlight that the barriers to GI are not solely technical but also institutional, political, and structural in nature. Addressing these barriers requires systemic reforms, including regulatory integration of GI into planning frameworks, cross-departmental coordination, dedicated long-term budgeting, and alignment of political priorities with sustainability objectives.

4.3.2. Enablers

The study identified several factors that enable the implementation and operationalization of GI. Figure 12 presents the key factors that enable the successful implementation and long-term operation of GI in Johannesburg's CBD. At the center is the theme "Enablers of GI Implementation and Operation," connected to four critical dimensions: policy integration, clear custodianship, community value, and targeted implementation.

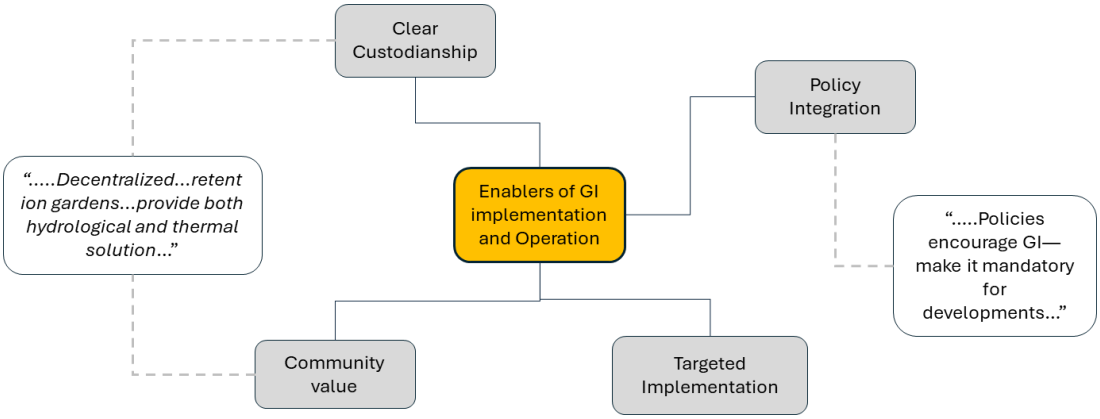


Figure 12: Enablers of GI implementation and operationalization

As shown in Figure 12, policy integration is one of the enablers highlighting the importance of embedding GI into statutory planning frameworks, engineering standards, and development approval processes. By

making GI a mandatory requirement rather than an optional feature, municipalities can ensure consistent adoption and mainstream it into everyday urban development practices. In addition, clear custodianship was stated as another enabling factor. It refers to the assignment of explicit responsibility for GI assets to a lead department, supported by service-level agreements and adequate maintenance budgets. Custodianship ensures accountability, reduces fragmentation, and provides clarity on long-term operation and upkeep.

Community value underscores the role of GI in delivering tangible social benefits, such as shading, seating, recreational opportunities, and cooling spaces for vulnerable groups like pedestrians and informal traders. By aligning GI projects with community needs, municipalities can secure greater public support and encourage stewardship. On the other hand, targeted implementation emphasizes the need to prioritize GI in locations where it can deliver the highest impact. These include flood-prone nodes, heat-stressed pedestrian corridors, and upstream buffer zones. Targeting ensures efficient allocation of resources while maximizing both environmental and social outcomes.

Overall, the qualitative results indicate that the effective implementation of GI is not only dependent on technical design but also on governance, institutional clarity, and social responsiveness. Enablers such as policy integration and custodianship create the institutional foundation, while community value and targeted implementation enhance legitimacy and ensure that GI delivers equitable and context-specific benefits.

5. Chapter 5 - Discussion

This chapter highlights the implications of the findings presented in Chapter Four, aligning them with existing literature and the broader debates on climate-resilient urban development. The findings are presented through the lenses of the Urban Resilience theory and the Climate Adaptation Theory, evaluating how GI can mitigate the UHI effects and flooding in the Johannesburg CBD. Chapter Five begins by examining the participants' perceptions of the UHI effect and urban flooding. By analyzing and interpreting these results, a precedent is set, enabling the reader to comprehend that the aforementioned climatic effects are pressing issues that warrant investigation. This is followed by the discussion that highlights the role of GI in addressing UHI and flooding while identifying key institutional and policy considerations for Johannesburg.

5.1. Prevalence of UHI and flooding in Johannesburg CBD

This study has found that UHI and flooding are significant contributors to Johannesburg's climate-induced extreme events. According to the findings (presented in section 4.1), both visualizations converge on the same conclusion that UHI effects are widely perceptible to Johannesburg CBD residents during nighttime hours. The nighttime perception of UHI was significant based on buildings absorbing and retaining heat during the day, and releasing it at nighttime, inducing warmer conditions. This builds on existing evidence by Hardy and Nel (2015) that the UHI effect is largest at night in Johannesburg's Northern Suburbs and in places with high building density.

With approximately 4 out of 5 residents reporting regular awareness of elevated temperatures. This indicates that the intensity and persistence of UHIs are quite clear, hence there is widespread awareness amongst residents. To that end, the residents of this city bear the brunt of the UHI effect, which is why their lived experiences (perception data) validate the need for intervention. The Urban Resilience Theory frames cities as complex and adaptive systems that must be capable of dealing with shocks. Therefore, this aligns and emphasizes system vulnerability due to Johannesburg CBD's inadequacy to address urban heat stress.

Johannesburg CBD's built-up environment has little to no vegetation, substantial volumes of impermeable surfaces, and increased anthropogenic heat fluxes, which exacerbate the UHI effect. Additionally, heat levels in metropolitan areas are constantly rising due to anthropogenic activities that affect and alter the natural environment through the construction of roads and buildings. This confirms the results of the study that demonstrate that regular perception of heat is the dominant pattern among Johannesburg CBD residents. A contributing factor is the changes in the surface of Johannesburg CBD, which lead to changes in energy balance, raising the temperature in the city relative to rural areas devoid of structures or even vegetated urban areas with fewer buildings. This occurs when absorbed solar radiation and heat storage are increased by an altered urban fabric, reduced greenery, and heat-absorbing materials. These results highlight the increased heat concerns in Johannesburg's CBD, which is in line with research from China that shows a connection between increased urban heat and dense built form and impermeable surfaces (Hua et al., 2020). The study investigates the impacts of the expansion of impermeable surfaces on UHI and finds that each 10% increase in impervious surface area is associated with an increase in surface

temperature of 0.41 to 0.91K (Hua et al., 2020). This evidence strengthens the claim that impervious surfaces increase urban heat.

Where flooding is concerned, the data revealed that 72% of participants experienced flooding impacts. This suggests that flooding is a significant issue in the Johannesburg CBD, affecting nearly three-quarters of residents, though with varying degrees of impact and frequency. Due to the increased demand for housing and infrastructure brought on by urbanization and population density in the CBD, impermeable surfaces were created. Consequently, surface runoff built up and contributed to urban flooding as drainage systems were overloaded. Floods occur during periods of high precipitation because clogged drainage systems are unable to separate sewage and rainfall. To that effect, this study reveals a significant waste management crisis during flooding events in Johannesburg CBD, where 86% of participants observe waste accumulation during flooding. The high mean score (likely to be around 3.6-3.8 on a 1-5 scale) indicates this is a severe and persistent problem. This demonstrates that in addition to disrupting cities, urban flooding can have a profound impact on people and the environment. This suggests an urgent need for improved flood-related waste management systems and debris collection protocols in the CBD area.

According to climate adaptation theory, participants' high knowledge of UHI and floods (4 out of 5 for heat, 72% for flooding) indicates that crucial information is readily available, which is a crucial factor in determining adaptive capacity. This research reveals that although people living in the central business district of Johannesburg have the knowledge to encourage adaptation, the city's adaptive capacity is still lacking. Adaptive capacity in climate research refers to an organization's or system's ability to adapt to climate change, minimize harm, take advantage of opportunities, or react to impacts (Mortreux and Barnett, 2017). It becomes clear from this analysis that institutional, financial, and political constraints limit the adaptive capacity of Johannesburg CBD.

In conclusion, increased urban runoff and heat are mostly caused by impermeable surfaces and dense built form. Therefore, in order to lessen the effects of UHI and urban flooding, permeable materials and green infrastructure are essential components of urban planning. By defining UHI and flooding as urban risks coming from broader environmental and infrastructure concerns, this justifies the investigation of green infrastructure as a strategic mitigation strategy.

5.2. Effectiveness of green infrastructure in the context of Johannesburg CBD

Green infrastructure is not only theoretical but has demonstrable potential in practically mitigating both UHI and flooding. Evidence from the findings that demonstrate the potential of GI is the renowned Paterson Park project, which avoided flood damage exceeding R100 million over twenty years. This is explicitly stated in the Sustainable Asset Valuation (SAVi) report by Copernicus Climate Change Service (2021) that the biggest extra advantage of nature-based stormwater infrastructures is the reduction in the expense of flood damage. Over the course of 20 years, the complete renaturalization of the stream prevented flood damage expenses of about ZAR 103 million (Copernicus Climate Change Service, 2021). The climatic issues in Johannesburg CBD are acute and compounding, which makes GI well-suited to mitigate impacts.

The effectiveness of permeable pavements, rooftop gardens, and street trees in regulating surface runoff and temperature was repeatedly cited by participants during the interviews. Johannesburg CBD needs to incorporate GI by harnessing green vegetation-covered roofs, bioswales, permeable pavements, wetlands, and urban trees, because their combined use offers the greatest benefits for urban climate resilience and stormwater management. Mechanisms such as evapotranspiration make GI effective because of the vegetation in urban gardens that gives insulation to buildings and cools them through evapotranspiration. There is empirical evidence across multiple cities that demonstrates that integrating urban trees and green vegetation-covered roofs significantly reduces UHI intensity within the city. For instance, in Guilford, UK, the GI measures that were implemented were trees, grasslands, and green vegetation-covered roofs, and Tiwari et al. (2020) found significant UHI reduction outcomes. The best green infrastructure for lowering urban heat islands is trees, with green vegetation-covered roofs serving as an extra mitigation strategy for a city- wide decrease (Tiwari et al., 2020). The mechanism of infiltration within the GI is effective because it facilitates water infiltration and helps regulate groundwater discharge. Based on the findings of similar studies, a more plausible explanation is that bioswales tailored for infiltration can lower runoff volumes by up to 80%, while field-monitored bioswales have shown peak flow reductions ranging from 20% to 70% (Folorunso, 2020). One National Business Initiative participant noted that: ***"uMngeni-uThukela Water, which operates in eThekwini Municipality, is doing work upstream in their river system to prevent downstream flooding. It's an effective example of sustainable stormwater management that the city of Johannesburg can emulate."***

Decentralized GI interventions are particularly suitable for the CBD, where space is limited. Since Johannesburg has a dense built environment that is spatially deprived, large-scale centralized systems may prove less effective than decentralized systems. This supports the statement made by one participant from Sustainable Energy Africa that: ***"Johannesburg CBD is hyper urbanized now and so the most effective forms of green infrastructure would obviously have to be decentralized."*** For instance, green vegetation-covered roofs and permeable pavements are decentralized GI interventions that are scalable and adaptable to the specific needs and spatial constraints of various urban areas. By incorporating these at a local level, there is quick deployment, cost effectiveness, as well as ecological services that the city will stand to benefit from.

Upstream wetland and buffer restoration can complement CBD-level measures by reducing peak flows. Upstream interventions, such as wetlands and buffers, can be effective for the study area due to volume attenuation during heavy rainfall events. This statement verifies the claims of Nauta et al. (2024) that wetland restoration in the Kylldal catchment, Germany, reduces peak and base flows by 12–24%, and mitigates flood risks, addressing challenges posed by climate change and land use changes. Similarly, this is in line with the findings of Wu et al. (2020) that there was a 24% reduction in peak flows, 17% in the flow of volume when upstream wetland restoration actions were adopted in the Nenjiang River, China. The city of Johannesburg should draw inspiration from global case studies and implement them due to the core benefits, like reducing downstream flooding. Johannesburg CBD is in a downstream position relative to the surrounding suburbs, so during heavy rainfall events, water flows towards the CBD, and as cited by a participant from Sustainable Energy Africa: ***"there is seasonal flooding affecting Market Street, Sauer***

Street, and Park Station." This validates the implementation of upstream interventions such as wetlands, natural vleis, and buffers to absorb storm runoff.

5.3. Institutional and regulatory dynamics

Institutional silos and regulatory gaps are major constraints in implementing GI in Johannesburg CBD. Respondents noted fragmented responsibilities across municipal departments, echoing findings by Enqvist and Pasquini (2019) that institutional silos impede GI mainstreaming. One COJ EISD official noted that: ***"Green infrastructure lacks a clear institutional custodianship. So, for example, City parks may maintain a green space, but they don't do stormwater infrastructure; that's JRA's job. And while JRA may manage stormwater, they don't do vegetated systems. That's more social development's job under the food resilience unit with the food gardens. So, you can see that there's a sense of non-ownership where no single department really integrates green infrastructure into long-term planning or budgets at scale."*** The problem of institutional silos reflects the division of duties among municipal departments. It is difficult to plan for and maintain green infrastructure solutions since policies and visions established by various agencies have distinct obligations.

In terms of regulatory framework gaps, a pertinent issue is that GI is encouraged and not mandated in the regulations of the City of Johannesburg Municipality. For example, a COJ EISD official noted that: ***"With the spatial development framework, in terms of densification, they're trying to introduce mixed-use developments, and if you apply to develop a block of flats, they encourage you to include nature-based solutions. This is ineffective; the policies need to move from encouraging and just enforcing it, to make it mandatory for developments to adopt such infrastructure."*** Johannesburg's current policies encourage GI but fall short of making it mandatory, limiting widespread adoption. The results of these interviews are in line with the notion that GI must be a legally binding regulation and performance standard, which will reinforce sustainable development. Johannesburg's municipality needs to adopt this approach, which uses legal requirements to ensure GI is implemented. In the United States, for instance, local governments have increasingly resorted to GI in response to federal initiatives and enforcement measures, especially under the Clean Water Act, and federal restrictions have contributed to the acceleration of GI adoption for stormwater management (Kim, 2024). The key driver of GI adoption is embedding it within regulations and decrees. This will help the city of Johannesburg to successfully integrate nature-based solutions into the CBD to mitigate the UHI effect and urban flooding.

5.4. Financial and political considerations

Several participants framed GI as an extra financial burden on already tight municipal budgets, viewing it as a cost rather than an investment. This view frequently results from misconceptions that, as opposed to conventional grey infrastructure, GI does not produce immediate, tangible benefits. Consequently, GI is not prioritized, and pilot projects are restricted to demonstration areas rather than widespread adoption, causing delays in its implementation. Evidence, however, contradicts this "cost" framing. For example, the Paterson Park project in Johannesburg shows that an initial investment in GI can avert significant long-term losses, such as the avoided flood damage, which is estimated to be worth over ZAR 103 million over 20 years (Copernicus Climate Change Service et al., 2021).

In terms of the reality of budget constraints, participants acknowledged real municipal budgetary constraints, even though perception issues are important. Funding is frequently directed toward immediate, perceived service delivery issues like response to emergencies, road maintenance, water and electricity supply, leaving little space for longer-term initiatives like GI. The practical potential of GI implementation is shaped by this reality, necessitating innovative funding options and phased deployment plans to maintain continuity in the face of financial constraints. Cost-benefit evaluations conducted in international contexts reinforce the economic case for GI. According to Alves et al. (2019), Melbourne's urban greening initiatives showed high benefit-to-cost ratios through energy savings and decreased flood damages, while Philadelphia's USD 2.4 billion, 25-year GI investment is expected to capture 85% of stormwater entering the sewer system, with direct and indirect economic benefits including increased property values and job creation (Christman et al., 2018). These incidents highlight the need to change municipal viewpoints toward long-term economic and environmental benefits by framing GI as an investment with demonstrable returns rather than as a discretionary expense.

The decisions about infrastructure investment are influenced by political motives. For instance, when allocating municipal resources, GI is frequently overshadowed by projects with obvious short-term effects, including street lighting or road repairs. Additionally, the election cycles impact the political economy, as governments give priority to projects that show constituents immediate advantages, therefore ignoring long-term measures like GI. One COJ EISD official noted that: ***"there are competing socio- economic needs, you find that initiatives such as GI are not well funded. But the basic services like water, electricity are the ones that normally get more attention because of people's needs, given the socio-economic conditions and past injustices of South Africa. In South African politics, GI support is not like in Europe, where green issues are at the top of the agenda."***

Some participants proposed that political manifestos might change if GI were linked to socioeconomic advantages. By presenting GI as a means of improving urban amenities, creating jobs, and enhancing public spaces, local leaders might concurrently fulfill the goals of economic development and climate adaptation. Johannesburg may learn from the effective use of co-benefits in GI projects such as the Green Mark Incentive Schemes in Singapore, which have leveraged political and financial support, with a dramatic increase in green buildings from fewer than 20 in 2005 to over 2,100 by 2014 (Shan et al., 2017). The relationship between political backing and financial incentives is emphasized by climate adaptation theory.

The political will required for long-term adaptation measures is more easily generated when local governments understand that GI can improve local lives, lower urban temperatures, and lessen flood damage. Therefore, matching GI initiatives with social and economic goals can increase adoption and guarantee sustained dedication to climate-resilient urban growth.

5.5. Social and equity dimensions

Participants' perceptions revealed that the effects of climate change in Johannesburg's CBD are not uniformly spread, with pedestrians and informal traders being especially at risk from flooding and heat stress. The significance of operating in open, exposed public spaces and the dependence on street-level

infrastructure for transportation and trade are examples of disproportionate exposure. In keeping with the emphasis of Urban Resilience Theory on unequal exposure and adaptation capability, socioeconomic position, housing quality, and access to alternate shelter all contribute to increased vulnerability. Since informal traders work in areas with little shade, poor drainage, and frequent pedestrian traffic, they are more vulnerable to intense heat and flooding. The risks faced by pedestrians are comparable since they depend on walking or public transportation during periods of extreme heat or flooding. The vulnerability of these individuals is further exacerbated by a lack of alternatives, such as sheltered pathways or robust transit options, which increases their exposure and potential injury.

There are equitable benefits to GI. For example, in places where a lot of people walk and trade informally, urban trees, shaded walkways, and bioswales alleviate heat and surface runoff. According to participants, tree-lined pathways and shaded marketplaces would improve comfort, lessen economic disruption, and safeguard livelihoods. One participant from Sustainable Energy Africa emphasized how: ***"A green vegetation-covered roof on top of a private development does have environmental benefits, but it's not equitably accessible. In contrast, a biodiverse sidewalk in a dense walkable area creates shared public value. I think we also need to shift thinking from asking which green infrastructure is effective, to asking what green infrastructure produces equitable, co-beneficial, and systemic outcomes here in Johannesburg's terrain."*** Therefore, GI interventions in Johannesburg CBD can reduce exposure, enhance adaptive ability, and give equitable, co-beneficial advantages that traditional gray infrastructure by itself cannot, especially for vulnerable populations.

The public space dignity of Johannesburg CBD needs to be reclaimed. Currently, heat stress and flooding compromise dignity by making pedestrian zones and roadways hazardous, unpleasant, and uninhabitable. Therefore, by enhancing environmental conditions and developing inclusive, easily accessible, and aesthetically pleasing urban areas that promote social interaction and human well-being, GI will reclaim and promote dignity. Cities like Jakarta and Medellín have shown that certain GI initiatives can promote climate justice. In Medellín, park modifications and urban greening decreased exposure in informal settlements (Meninato and Marinic, 2024). While the boundaries of major flood canals, such as the Banjir Kanal Timur in Jakarta, integrated pedestrian-friendly green areas with flood prevention (Wardiningsih et al., 2023). These lessons can be applied in Johannesburg, where interventions should focus on social justice and environmental risk in crowded metropolitan areas.

6. Chapter 6 – Conclusion and recommendations

6.1. Conclusion

Green infrastructure presents a viable, equitable, and multi-benefit approach to addressing urban flooding and UHI in Johannesburg's CBD. Local case studies and global precedents show that GI is feasible due to its ability to leverage long-term environmental and socio-economic rewards, despite perceived cost and institutional constraints. Equitability is attained by focusing on vulnerable groups, such as pedestrians and street vendors, and making sure that interventions improve access to safe and respectable public areas, decrease exposure, and increase adaptive capacity. Moreover, GI offers a number of advantages, including lowering temperatures, managing stormwater, creating jobs, and enhancing public facilities, demonstrating its value as a comprehensive approach to urban adaptation.

However, GI's effectiveness depends on systematically removing important obstacles. For instance, the fragmented municipal responsibilities, a lack of funding, and a lack of regulatory mandates are important barriers. These must be addressed first; otherwise, initiatives run the risk of discontinuity or an unfair benefit distribution. The first steps in a logical implementation pathway are clear custodianship and regulatory integration. Then, finance and the incorporation of participatory mechanisms follow. The city would be exposed to growing climate hazards if these issues were not resolved, undermining the sustainability and resilience of GI efforts. A redesigned urban landscape with protected vulnerable populations, restored public areas, and efficient environmental services is the long-term goal of a climate-resilient Johannesburg CBD. This would entail inclusive urban landscapes, improved livelihoods, lowered flood risk, and cooler streets, which are all signs of success. Johannesburg can improve the general standard of living in the city and establish a socially and environmentally sound model of urban sustainability by putting GI first, which will also help to alleviate climate stresses. Lastly, the strategy used in Johannesburg has wider ramifications for urban adaptation in Africa and around the world. This study serves as a model for other rapidly urbanizing communities dealing with comparable climatic and socioeconomic issues. By demonstrating how GI, its multi-benefits, coordinated policy, institutional leadership, funding, and community participation, locally contextualized policies can concurrently promote resilience, equity, and urban livability throughout the Global South, the findings add to the body of knowledge on climate adaptation.

6.2. Recommendations towards sustainable implementation

In Johannesburg, integrating GI into citywide planning tools and coordinating efforts across municipal departments is crucial to achieving sustainable GI deployment. Operationally, this coordination entails coordinating the duties of the parks, engineering, and stormwater management departments, defining custodianship, and integrating GI goals into urban development plans. In the absence of this alignment, implementation initiatives are scattered and ineffective. In fact, participants underlined that overlapping responsibilities and unclear roles often lead to uneven monitoring, duplication, and decreased long-term efficiency. Thus, the first and most important step in maintaining GI interventions is to create a coordinated institutional structure.

To incorporate GI into the city's development criteria, regulatory integration is crucial in addition to institutional cooperation. One COJ EISD official stated that: ***"The Climate Action Plan, Spatial Development Framework, and the CAPEX framework of the city all reference green infrastructure's value. But this is fragile because it's not really embedded in service delivery mechanisms. For instance, green infrastructure is not standard in development calculations, nor does it consistently appear in municipal budget line items. Municipalities need to incorporate green infrastructure in their development criteria."***

Municipalities can go beyond voluntary or ad hoc implementation by integrating GI requirements into engineering codes, zoning schemes, and building laws. By using regulatory mainstreaming, developers may make sure that elements like vegetated drainage systems, permeable pavement, and green vegetation-covered roofs are consistently incorporated into their designs. This change guarantees compliance and uniformity across projects, moving from an optional improvement to a standard procedure. This strategy is best illustrated by cities like Singapore, where GI standards have been mandated and have clearly improved urban livability, microclimate regulation, and stormwater management (Lim and Lu, 2016). Thus, Johannesburg can use these examples to create legally binding structures that ensure quantifiable environmental results.

The establishment of a specialized custodial authority in charge of GI supervision is equally crucial. In addition to developing precise performance standards and coordinating activities across departments, such an entity would oversee the entire GI lifecycle, from design and implementation to performance review. By guaranteeing a single vision and operational coherence, a custodial authority would successfully bridge institutional silos in contrast to the current fragmented setup, where tasks are divided among several municipal divisions. This authority would streamline maintenance activities around the city, improve monitoring, and increase accountability by acting as both a coordinator and a regulator. Moreover, long-term GI performance continues to depend on financial sustainability. Due to inconsistent funding and a lack of restricted financing, many projects never make it past the pilot stage. To that end, reliable finance sources that guarantee project continuity can be created by creating specific municipal budget lines, enacting environmental taxes, or encouraging public-private collaborations. Planned interventions run the risk of being abandoned in the absence of fixed finance, which could result in the degradation of tangible assets and a decline in public trust. Thus, restricted finance structures are essential for shielding GI investments from shifting urban priorities and budgetary swings.

Furthermore, to foster community and political support, GI must also be in line with socioeconomic interests. It is more likely that projects that offer observable co-benefits, like the creation of jobs through neighborhood maintenance initiatives and the improvement of public areas, will gain support from a variety of stakeholders. A participant from Sustainable Energy Africa explained that: ***"Economically, I think green infrastructure offers more than just beautification or aesthetics. I think it enables green livelihoods as well. If tied to structured maintenance contracts and integrated into systems like the EPWPs, the expanded public works program."*** Therefore, the linkage strengthens GI's long-term validity and support

within the community by transforming it from a strictly environmental program into a catalyst for urban growth and social inclusion.

When combined, these insights show that policy integration, dedicated custodianship, a finance framework, and alignment with socio-economic co-benefits are critical implementation pillars necessary for Johannesburg's sustained GI deployment. Green infrastructure must be acknowledged as important infrastructure, on par with conventional grey systems, to bring about a paradigm shift. The success of all other implementation techniques will be unlocked by granting GI comparable status through maintenance procedures, regulatory protection, and specific budget allocations. By doing this, Johannesburg may advance toward a future in which socially just and climate-resilient infrastructure is woven into the very fabric of the city's growth plan.

7. References

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8. Annexures

8.1. Annexures 1 - Ethics clearance certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Thobejane

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER: H25/02/24**
PROJECT TITLE	Assessing the effectiveness of green infrastructure in urban areas - for mitigation of climate change-induced extreme events in South Africa: A case study of the Johannesburg CBD
INVESTIGATOR(S)	Mr K Thobejane
SCHOOL/DEPARTMENT	Geography, Archaeology and Environmental Studies/
DATE CONSIDERED	14 February 2025
DECISION OF THE COMMITTEE	Approved Risk Level: Minimal
EXPIRY DATE	13 May 2028

DATE 20 June 2025 **CHAIRPERSON** _____
(Professor J Watermeyer)

cc: Supervisor : Dr S Kubanza

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **A SIGNED COPY** returned to the Secretary electronically. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure be contemplated from the research procedure as approved I/we undertake to submit an amendment of the protocol to the Committee. **I/we agree to completion of a regular progress report. For Minimal and Low Risk studies, this is due annually on 31 December. For Medium and High Risk studies, this is due twice annually on 30 June and 31 December.**

_____ 20 / 06 / 2025
Signature **Date**

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

8.2. Annexure 2 – Participant information sheets

8.2.1. Online survey

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Sir/Madam

My name is Kagiso Thobejane. I am a Masters student in Environmental Sciences at the University of the Witwatersrand, Johannesburg. My supervisor is Dr. Nzalalemba Serge Kubanza. I am conducting a research study about green infrastructure as sustainable solutions for climate change mitigation. The study title is Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

I am inviting you to take part in an online survey where you are required to answer a few questions. If you decide to take part, your participation in this research study will last no more than 10 minutes. The online survey will take place once you proceed below, after confirmation of your consent to participate.

This data will be stored on a password-protected personal computer with restricted access and destroyed 5 years after completion of the study. Only the researcher and the supervisor will have access to the data.

The online survey will be confidential and anonymous. When I share the results of the research study, I will not include your name or anything else that could identify you.

If you decide to take part in the research study, it should be because you want to volunteer. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will not cost you anything. You will not be paid for being in this research study.

The risks for this research study are no more than what happens in everyday life.

This research study will be written up as a research report. The report will be available on the university library website. If you would like to receive a summary of this report, I will be happy to send it to you.

This research study has received ethical clearance from the University of the Witwatersrand [H25/02/24].

If you have any questions during or afterwards about this research study, feel free to contact me or my supervisor on the details listed below. If you have any concerns or complaints about the ethical procedures of this research study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za.

Yours sincerely,
Kagiso Thobejane

Researcher:
Kagiso Thobejane, 2901024@students.wits.ac.za, 074 837 5538

Supervisor:
Dr. Nzalalemba Serge Kubanza, serge.kubanza@wits.ac.za, 011 717 6515

8.2.2. Interview

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Sir/Madam

My name is Kagiso Thobejane. I am a Masters student in Environmental Sciences at the University of the Witwatersrand, Johannesburg. My supervisor is Dr. Nzalalemba Serge Kubanza. I am conducting a research study about green infrastructure as sustainable solutions for climate change mitigation. The study title is Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

I am inviting you to take part in an interview where you are required to answer a few questions. If you decide to take part, your participation in this research study will last no more than 20 minutes. The interview will take place in person, after confirmation of your consent to participate.

With your permission, I would like to audio record the interview. This data will be stored on a password-protected personal computer with restricted access and destroyed 5 years after completion of the study. Only the researcher and the supervisor will have access to the data.

The interview will be confidential and anonymous. When I share the results of the research study, I will not include your name or anything else that could identify you.

If you decide to take part in the research study, it should be because you want to volunteer. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will not cost you anything. You will not be paid for being in this research study.

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Yours sincerely,
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Researcher:
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Supervisor:
Dr. Nzalalemba Serge Kubanza, serge.kubanza@wits.ac.za, 011 717 6515

8.2.3. Focus group discussion

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Sir/Madam

My name is Kagiso Thobejane. I am a Masters student in Environmental Sciences at the University of the Witwatersrand, Johannesburg. My supervisor is Dr. Nzalalemba Serge Kubanza. I am conducting a research study about green infrastructure as sustainable solutions for climate change mitigation. The study title is Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

I am inviting you to take part in a focus group interview where you are required to answer a few questions. If you decide to take part, your participation in this research study will last no more than 20 minutes. The focus group interview will take place in person, after confirmation of your consent to participate.

With your permission, I would like to audio record the focus group interview. This data will be stored on a password-protected personal computer with restricted access and destroyed 5 years after completion of the study. Only the researcher and the supervisor will have access to the data. When I share the results of the research study, I will not include your name or anything else that could identify you.

If you decide to take part in the research study, it should be because you want to volunteer. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will not cost you anything. You will not be paid for being in this research study.

The risks for this research study are no more than what happens in everyday life.

This research study will be written up as a research report. The report will be available on the university library website. If you would like to receive a summary of this report, I will be happy to send it to you.

This research study has received ethical clearance from the University of the Witwatersrand [H25/02/24].

If you have any questions during or afterwards about this research study, feel free to contact me or my supervisor on the details listed below. If you have any concerns or complaints about the ethical procedures of this research study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za.

Yours sincerely,
Kagiso Thobejane

Researcher:
Kagiso Thobejane, 2901024@students.wits.ac.za, 074 837 5538

Supervisor:
Dr. Nzalalemba Serge Kubanza, serge.kubanza@wits.ac.za, 011 717 6515

8.3. Annexure 3 – Consent forms

8.3.1. Online survey

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

Kagiso Thobejane

I, ……., agree to participate in this research project.

By clicking **next** and clicking **submit** at the end of this survey, you agree to the following:

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study	YES	NO
I agree that data from the survey may be used by the researcher in their research report	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report	YES	NO
I agree that other researchers may use the information I provide in my survey (depending on their own ethics clearance being obtained) but my name and any personal information will not be used or passed on	YES	NO

…… (signature)
…… (name of participant)
…… (date)

…… (signature)
…… (name of researcher/person seeking consent)
…… (date)

8.3.2. Interview

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

Kagiso Thobejane

I, ..., agree to participate in this research project.

I agree to the following:

(Please circle the relevant options below)

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that direct quotations from my interview may be used by the researcher in their research report	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report) OR I acknowledge that my participation in this interview during data collection cannot be anonymous or confidential, but that anonymity and confidentiality can be guaranteed when the researcher is reporting the data.	YES	NO
I agree that other researchers may use the information I provide in my interview (depending on their own ethics clearance being obtained) but my name and any personal information will not be used or passed on	YES	NO

..... (signature)
..... (name of participant)
..... (date)

..... (signature)
..... (name of researcher/person seeking consent)
..... (date)

8.3.3. Focus group discussion



Assessing the Effectiveness of Green Infrastructure in Urban Areas - for Mitigation of Climate Change-Induced Extreme Events in South Africa: A Case Study of the Johannesburg CBD.

Kagiso Thobejane

I, ..., agree to participate in this research project.

I agree to the following:

(Please circle the relevant options below)

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study	YES	NO
I agree that the focus group may be audio recorded	YES	NO
I agree that direct quotations from my focus group may be used by the researcher in their research report	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report) OR I acknowledge that my participation in this focus group during data collection cannot be anonymous or confidential, but that anonymity and confidentiality can be guaranteed when the researcher is reporting the data.	YES	NO
I agree that other researchers may use the information I provide in my focus group (depending on their own ethics clearance being obtained) but my name and any personal information will not be used or passed on	YES	NO

..... (signature)
..... (name of participant)
..... (date)

..... (signature)
..... (name of researcher/person seeking consent)
..... (date)

8.4. Annexure 4 – Question sheets

8.4.1. Google forms survey

Survey Questions

Is the urban heat island effect and urban flooding affecting Johannesburg CBD and what are the associated implications?

1. How noticeable is the temperature difference between Johannesburg CBD and nearby areas? *

- Not noticeable
- Slightly noticeable
- Moderately noticeable
- Very noticeable
- Extremely noticeable

2. How often do you feel discomfort due to high temperatures while in Johannesburg CBD? *

- Never
- Rarely
- Sometimes
- Often
- Always

3. To what extent do high temperatures in Johannesburg CBD affect your ability to carry out your daily activities comfortably? *

- Not at all
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent

4. How frequently do you experience the need for cooling (e.g., fans, air conditioning) when spending time in Johannesburg CBD?

- Never
- Rarely
- Sometimes
- Often
- Always

5. How often do you notice temperatures in Johannesburg CBD remaining high, during night times? *

- Never
- Rarely
- Sometimes
- Often
- Always

6. To what extent do you feel that the heat in Johannesburg CBD affects air quality (e.g., feeling of smog or poor ventilation)? *

- Not at all
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent

7. How significantly does the urban heat in Johannesburg CBD impact the availability and usability of outdoor spaces (e.g., visiting parks, using walkways)?

- Not at all
- Slightly
- Moderatetly
- Significantly
- Extremely

8. During the hottest months, how often do you notice the temperature in Johannesburg CBD to be higher than in surrounding areas? *

- Never
- Rarely
- Sometimes
- Often
- Always

9. To what extent do you believe heat levels in Johannesburg CBD impact public health (e.g., cause heat-related discomfort, fatigue, heat stress)? *

- Not at all
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent

10. How frequently have you noticed or been impacted by flooding in Johannesburg CBD after heavy rainfall?

- Never
- Rarely
- Sometimes
- Often
- Always

11. How disruptive is flooding to transportation within Johannesburg CBD during the rainy season (e.g., road closures, public transport disruptions)? *

- Not disruptive
- Slightly disruptive
- Moderately disruptive
- Very disruptive
- Extremely disruptive

12. How significantly does flooding impact your access to businesses and services in Johannesburg CBD (e.g., including situations where walking or commuting to shops, clinics, or public buildings becomes unsafe or impossible due to heavy rain or flooding)? *

- Not at all
- Slightly
- Moderately
- Significantly
- Extremely

13. To what extent does flooding damage infrastructure (e.g., roads, sidewalks) in Johannesburg CBD?

- Not at all
- Slightly
- Moderately
- Significantly
- Extremely

14. How frequently do you encounter damage to your personal property or vehicles due to flooding in Johannesburg CBD? *

- Never
- Rarely
- Sometimes
- Often
- Always

15. How often do you experience delays or problems getting to places like work, school, or shops because of flooding in Johannesburg CBD?

- Never
- Rarely
- Sometimes
- Often
- Always

16. How often do you see waste or debris accumulating in flooded areas within Johannesburg CBD?

- Never
- Rarely
- Sometimes
- Often
- Always

17. How significantly does flooding impact outdoor public areas (e.g., parks, recreational spaces) in Johannesburg CBD? *

- Not at all
- Slightly
- Moderately
- Significantly
- Extremely

18. To what extent does flooding pose a safety risk to pedestrians in Johannesburg CBD? *

- Not at all
- Slightly
- Moderately
- Significantly
- Extremely

19. How concerned are you about potential health risks (e.g., water contamination, mold, mosquito breeding) associated with frequent flooding in Johannesburg CBD?

- ○ Not concerned
- ○ Slightly concerned
- ○ Moderately concerned
- ○ Very concerned
- ○ Extremely concerned

20. Overall, how disruptive would you say flooding and excessive heat are to daily life in Johannesburg CBD? *

- ○ Not disruptive
- ○ Slightly disruptive
- ○ Moderately disruptive
- ○ Very disruptive
- ○ Extremely disruptive

8.4.2. Interview questions

1. What types of green infrastructure (e.g., green roofs, permeable pavements, urban trees) do you think could most effectively address urban heat island and flooding in Johannesburg CBD? Why?

2. What challenges or limitations do you foresee in implementing green infrastructure in Johannesburg CBD?

3. Can you describe any specific social, economic, or environmental benefits that you think green infrastructure could bring to Johannesburg CBD?

4. Have you seen any examples (locally or globally) where green infrastructure has been successfully used to address similar urban issues? What lessons could Johannesburg learn from these cases?

5. How would you describe the level of public and institutional support for green infrastructure initiatives in Johannesburg CBD? What could be done to improve this support?

6. In your view, how has Johannesburg CBD been impacted by urban heat and flooding in recent years, and what specific examples come to mind?

7. How do you believe green infrastructure could help manage rainfall and reduce the frequency or severity of flooding in urban spaces like the CBD?

8. What would you consider the main obstacles to integrating green infrastructure solutions within Johannesburg's current urban planning and development practices?

9. What challenges do you foresee in maintaining green infrastructure in an urban setting like Johannesburg CBD, and what measures could help ensure its sustainability?

10. How do you think green infrastructure projects in Johannesburg CBD might influence or inspire other parts of the city or similar urban areas facing heat and flooding challenges?

8.4.3. Focus group discussion questions

1. What roles do government policies and regulations currently play in the implementation of green infrastructure projects in Johannesburg CBD?

2. How would you assess the level of political will to support green infrastructure initiatives at both the municipal and national levels?

3. In your opinion, how does access to funding and financial resources impact the feasibility of green infrastructure projects?

4. What are the primary technical challenges faced when implementing green infrastructure in urban environments like Johannesburg CBD?

5. How significant is the role of community participation in the success of green infrastructure projects in the CBD?

6. What level of collaboration exists between the public and private sectors in supporting green infrastructure projects, and how could this collaboration be improved?

7. What social factors, such as public awareness or cultural attitudes, do you think impact the acceptance and success of green infrastructure in Johannesburg?

8. How does the availability of technical expertise, such as skilled designers and maintenance professionals, affect the implementation of green infrastructure?

9. What barriers do you think exist within the current regulatory framework that might hinder green infrastructure projects?

10. How do you think economic conditions, such as local economic priorities or competing interests, impact the focus on green infrastructure in Johannesburg CBD?

8.5. Annexure 5 – Codebook and statistics table

8.5.1. Compact codebook

Code	Definition	Example signal in data	Outcome link
Decentralized GI in dense CBD	Preference for small, distributed, retrofit-friendly GI (rain gardens, bioswales, pocket parks, sidewalks)	"Most effective forms…decentralized…retention gardens…provide hydrological and thermal solution."	Feasible GI portfolio for CBD
Buffering & catchment logic	Upstream wetlands/green belts to delay runoff before CBD	"Designated green zones/buffer zones…limit volume going into the CBD…"	Flood mitigation
WSUD / nature-based standards	Call to embed water-sensitive urban design & GI into standards	"Updated stormwater guidelines and CAP call for WSUD…uptake hindered…"	Institutionalisation
Institutional silos	Fragmented custodianship (City Parks vs JRA vs EISD)	"No single department really integrates GI into long-term planning/budgets."	Barrier to scale & O&M
Regulatory gap	GI absent from zoning/site plans/engineering standards	"Zoning codes and site plans often overlook green components…"	Barrier to mainstreaming
Life-cycle & avoided-cost logic	GI seen as Opex liability vs investment; evidence of avoided flood losses	"Paterson Park…lower costs and >R100m avoided flood damages/20 yrs."	Economic case for GI
Political salience & competing needs	"Visible" grey projects outcompete GI; socio-economic pressures	"Environmental sustainability not at the top…basic services get attention."	Prioritisation barrier
Community co-benefits & dignity	Heat relief for vendors/commuters; skills/jobs via EPWP	"Reclaim dignity of public space…green livelihoods if tied to maintenance contracts…"	Social licence & equity
Capacity & procurement friction	EPWP rules, procurement delays, partner constraints	"Procurement holding projects…EPWP red-tape undermines intent."	Delivery risk
O&M custodianship & KPIs	Need for named owner, budgets, SLAs, and KPIs	"Embed GI into performance metrics…multiyear O&M budgeting."	Sustainability of assets

8.5.2. Descriptive statistics tables

Case 1: How noticeable is the temperature difference between Johannesburg CBD and nearby areas?

Statistic	Value	Interpretation
Sample size (n)	50	Adequate for basic descriptive analysis
Mean Score	3.4	Average between “Moderately” and “Very noticeable”
Median	3.5	Central tendency slightly above moderate
Mode	Moderately noticeable	Most common response category
Standard Deviation	1.2	Moderate variability in responses

Case 5: How often do you notice temperatures in Johannesburg CBD remaining high, during nighttime?

Statistic	Value	Interpretation
Sample size (n)	50	Adequate for basic descriptive analysis
Mean Score	2.34	Average between “Often” and “Sometimes”
Median	2	Central tendency at the middle value
Mode	Often	Most common response category
Standard Deviation	0.848	Moderate variability in responses

Case 10: How frequently have you noticed or been impacted by flooding in Johannesburg CBD after heavy rainfall?

Statistic	Value	Interpretation
Sample size (n)	50	Adequate for basic descriptive analysis
Mean Score	3.08	Average response in the middle range
Median	3	Middle value when ordered
Mode	Often	Most frequently occurring response
Standard Deviation	1.047	Moderate to high spread around the mean

Case 16: How often do you see waste or debris accumulating in flooded areas within Johannesburg CBD?

Statistic	Value	Interpretation
Sample size (n)	50	Adequate for basic descriptive analysis
Mean Score	3.6	Average response in the middle range
Median	4	Middle value when ordered
Mode	Often	Most frequently occurring response
Standard Deviation	1.107	Moderate to high spread around the mean

Case 20: Overall, how disruptive would you say flooding and excessive heat are to daily life in Johannesburg CBD?

Statistic	Value	Interpretation
Sample size (n)	50	Adequate for basic descriptive analysis
Mean Score	3.52	Average response in the middle range
Median	3.5	Middle value when ordered
Mode	Moderately disruptive	Most frequently occurring response
Standard Deviation	0.886	Moderate to high spread around the mean