



**COLLEGE OF SCIENCE AND TECHNOLOGY**  
**SCHOOL OF ARCHITECTURE AND BUILT ENVIRONMENT**

**MSc in Geo-Information Science for Environment and Sustainable Development**

**Harnessing nature to Advance Sponge City in Rwanda: Empirical Analysis of the  
Impacts of Restoration of Nyandungu Urban Wetland on Flood Risk Reduction**

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**March 2025**

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### Declaration

I declare that this thesis entitled "**Harnessing Nature to Advance Sponge City in Rwanda: Empirical Analysis of the Impacts of Restoration of Nyandungu Urban Wetland on Flood Risk Reduction**" submitted for the award of the Degree of Master of Science in Geo-Information Science f or Environment and Sustainable Development is my original work that has never been submitted to any university or other higher learning institution.

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### Approval

It is hereby confirmed that this thesis entitled "**Harnessing nature to Advance Sponge City in Rwanda: Empirical Analysis of the Impacts of Restoration of Nyandungu Urban Wetland on Flood Risk Reduction,**" submitted by Fidele MWIZERWA, was assessed in relation to the fulfillment of the requirements for the award of the Degree of Master of Science in Geo-Information for Environment and Sustainable Development in the School of Architecture and Built Environment.

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## Abstract

In Rwanda, Kigali's urban wetlands have been degraded by agriculture, settlements, and commercial activities, which have been exacerbated by increased flooding. This degradation has diminished the wetlands' ability to mitigate floods and provide other ecosystem services. To address this issue, Kigali initiated a citywide wetlands restoration plan, converting major urban wetlands into parks. In this line, Nyandungu Eco-Park, was the first wetland to be restored as a pilot project using Sustainable Urban Design (SUDS) and ecosystem-based adaptation interventions where those approaches were expected to be replicated in the restoration of Gikondo, Rwampara, Rugenge-Rwintare, Kibumba, and Nyabugogo wetlands. This study evaluates the flood control benefits of the restored Nyandungu wetland and recommends further interventions based on the Sponge City approach. An intensive literature review, spatial data analysis, and field observations were conducted to assess the restoration's impact on flood risk reduction and to identify suitable Sponge City infrastructures for the Nyandungu catchment. Results show a significant reduction in flood susceptibility in the area where interventions were established. Area which was highly susceptible to flooding reduced from 26 hectares in 2010 to 2 hectares in 2023 and areas less susceptible to flooding increased from 30 hectares to 119.7 hectares. The Normalized Difference Vegetation Index (NDVI) analysis showed an increase in vegetation health in Nyandungu Wetland, with values rising from 0.351 in 2010 to 0.495 in 2023. This indicates that previously degraded vegetation areas have significantly recovered, with higher vegetation density observed in 2023. The Normalized Difference Water Index (NDWI) analysis of Nyandungu from 2014 to 2023 shows a slight increase in areas with higher water content, which is equal to 1.23 ha. Area with low water content decreased by 0.76 ha. These shifts indicate improved water content and vegetation moisture in areas where interventions were established. Regarding the analysis conducted on the whole catchment, the analysis of Land use Land cover (LULC) revealed that built area increased from 149 Ha to 239 ha in a total of 3149 Ha for the whole catchment. Normalized Difference Built-up Index (NDBI) of 2023 was found to be high with where 239 Ha were found to be in area with high NDBI, Sediment Transportation Index (STI) analyzed for the whole catchment indicated that this index ranges from 0 to 204.368 which is very high. Results from flood susceptibility analysis conducted for the whole catchment was found to be high where 60 % of the catchment were found to be highly susceptible, 21 % moderate, 10% low and 9% very low. In this line, the study recommends implementing additional Sponge City infrastructures in the whole catchment, such as green roofs, vegetated swales, rain gardens, rainwater harvesting, detention basins, and porous pavements. In the whole catchment. Other sponge city infrastructures such Bioswales, grass swales, and infiltration ponds/basins should be established at runoff entry points to further mitigate flooding impacts on the restored wetland. These measures can contribute to reduce future flood risks by addressing runoff from the catchment area

**Key Words:** Urban wetlands, Ecosystem based Adaptation, Flood, Geographic Information System.

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### Acronyms and abbreviations

ADB	Asian Development Bank
AHP	Analytic Hierarchy Process
ARCOS	Albertine Rift Conservation Society
BMPs	Best Management Practices
CGIS-UR	Center for GIS and Remote Sensing
EbA	Ecosystem-based Adaptation
EO	Earth Observation
FONERWA	Fund for Environment and Natural Resources for Rwanda
GGGI	Global Green Growth Institute
GGGI	Global Green Growth Institute
GIS	Geographic Information System
GIS	Geographic Information System
GoR	Government of Rwanda
GPS	Global Position System
IFRC	International Federation of Red Cross and Red Crescent Societies
IPCC	Intergovernmental Panel on Climate Change
LDCF	Least Developed Countries Fund
LID	Low Impact Development
LULC	Landuse Landcover
masl	meters above sea level
MINEMA	Ministry in charge of Emergency Management
MININFRA	Ministry of Infrastructures
NAP	National adaptation planning Process
NbS	Nature based Solutions
NDVI	Normalized difference vegetation index
NIR	Near Infra-red
NISR	National Institute of Statistics of Rwanda
NLA	National Lands Authority
NUWEP	Nyandungu Urban Wetland Ecotourism Project
RDB	Rwanda Development Board
REMA	Rwanda Environment Management Authority
RNRA	Rwanda Natural Resources Authority
RUDP	Rwanda Urban Development Project
SCME	Spatial Multiple Criteria Evaluation
SUDS	Sustainable drainage systems
TWI	Topographic Wetness Index

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## CHAPTER I INTRODUCTION

### 1.1 Background of the study

With the emerging climate change, the risk of floods is becoming a threat for urban dwellers across the world (UN-Habitat, 2018). The occurrence of this climate change-induced disaster has caused devastating impacts in urban areas, such as loss of lives, damage to infrastructure, displacement of people, and loss of property and businesses, among others (Hammond et al., 2015). This has led to significant economic losses and environmental damage in different cities, causing approximately \$175 billion in economic losses worldwide in 2021 (AL-Hussein et al., 2023).

Urbanization and climate change have been recognized as major causes of urban flooding (Feng et al., 2021; X. Sun et al., 2021). In one hand, Urbanization which is associated with the increase in impermeable paved built-up areas have been decried to reduce the soil infiltration rate and cities sponginess during rainy seasons. This, in turn, increases surface water runoff, causing flooding downstream (C. Xu et al., 2020). On the other hand, climate change has led to increased precipitation (Tabari, 2020). Consequently, these two factors have been causing devastating flooding that affects several cities (Pariartha et al., 2023; Salike, 2017).

With the continuous growth of urban areas and the persisting climate change (Trenberth, 2011), different urban stormwater management and urban flood adaptation approaches have been developed and adopted by different countries (Griffiths et al., 2020). These approaches include Sustainable Drainage Systems (SUDS), Low Impact Development (LID), Best Management Practices (BMPs), Water-Sensitive Urban Design (WSUD), Sponge City, and many more (Ahmed et al., 2022). These approaches provide several benefits, such as improved stormwater management, enhanced water quality, reduced flooding, and increased biodiversity (EPA, 2012). However, with the continuous steady growth of urbanization coupled with the impacts of climate change, there are some limitations in addressing the emerging problems of the constant changes in runoff, as well as flood intensity and frequency (Ahmed et al., 2022; Le et al., 2024). It is in this context that a paradigm shift has been initiated, where scholars recommend the use of more Nature-Based Solutions or hybrid approaches that combine Blue and Green infrastructures in urban stormwater

management and urban flood adaptation (Ruangpan et al., 2020). One of these approaches is the sponge city, which is a new Ecosystem-Based Approach (EbA) initiated in China in 2014 (Boncheva, 2022; Chan et al., 2018a; Ma & Jiang, 2023b; United Nations Environment Programme, 2022). Since that time, Sponge city has been ranked the best in the context of restoring wetland for flood adaptation and provision of other associated co-benefits (Fennessy & Lei, 2018; Ma & Jiang, 2023b).

The sponge city approach, which is an emerging nature-based solution for urban flood adaptation, was initiated in China to help Chinese cities adapt to devastating floods that have affected their cities for so long (Boncheva, 2022; Ma & Jiang, 2023b). The term “sponge cities” is used to describe urban areas with abundant natural features such as trees, lakes, and parks, or other well-designed elements intended to absorb rain and prevent flooding (Hamidi et al., 2021; Harrisberg, 2022; Y. Peng & Reily, 2021). This approach was inspired by the LID and SUDS approaches. However, it has proven to have more flood adaptation functions than those of the above-mentioned approaches, as it was developed primarily for urban flood adaptation under climate change (J. Liu et al., 2021a). For example, a 2019 study found that sponge city projects in Beijing reduced flood risk by 10-20% in some areas (Shao et al., 2016). Since its emergence, the sponge city approach has been regarded as a new viable solution for urban flood adaptation during this time of climate change crisis (Ma & Jiang, 2023c).

The idea of implementing the sponge city concept in Africa has been widely suggested by various scholars (Ayad & Rasheed, 2022; Kongjian, 2021; Thoms & Köster, 2022a). So far, some studies have been conducted to indicate the sponginess of some African cities, where Cairo was found to be 20% spongier, Durban 40%, Lagos 39%, Nairobi 34%, and Kigali 43% (Arup, 2022). Currently, studies are being conducted to assess the applicability of this approach in different African countries and its associated benefits and potentials (Ayad & Rasheed, 2022; Z. Li et al., 2018a; Singh & Bwalya, 2018; Thoms & Köster, 2022a). Moreover, countries like Kenya have already adopted this approach, where Kajiado, Kwa VONZA, and Kitui have been transformed into sponge towns, while their urban degraded wetlands were among the restored areas using this approach (Bosma, 2019).

Urban wetlands in Rwanda have been prone to severe degradation as a result of anthropogenic activities and climate change (Alikhani et al., 2021; Desta et al., 2012; Gitay et al., 2011; Z. Li et al., 2022). Since the 1960s, the city of Kigali has grown steadily from 200 hectares to 73,800 hectares in 2018 (Nduwayezu, 2015; Umuhire, 2014). This

rapid growth of Kigali and the associated human activities have been putting significant pressure on the city's existing green spaces (RDB, 2023). As a result, some areas of wetlands in Kigali were converted to agriculture, human settlements, and commercial and industrial activities, which decreased their flood abatement capacity (Bayizere et al., 2022; Rwanyiziri et al., 2020b). With the continuous occurrence of flooding in the city of Kigali, the Government of Rwanda initiated wetland restoration aimed at reducing flood impacts in the city (Sabiiti, 2022). In this context, Nyandungu urban wetland, which has been impacted by flooding, was the first wetland to be restored using SuDS approaches and other Ecosystem-Based Adaptation interventions to reduce its risk of being affected by floods (REMA, 2022d).

## **1.2 Problem statement**

Wetlands in the City of Kigali have undergone substantial degradation over the past years, primarily due to the increasing pressure driven by agricultural activities and the encroachment of human settlements, which have replaced wetland species with crop plants and buildings from 80 Ha to 120 Ha respectively (ARCOS, 2021b; Kalisa, 2020). The degradation of these wetlands was aggravated by flooding whose intensity and frequency have increased due to climate change which reduced 80% of the ecosystem services provided by the wetlands in the city of Kigali (ARCOS, 2021a; Ingabire et al., 2020). In line with the vision of the city becoming a green and resilient urban area (Habishuti, 2022), the city of Kigali initiated the restoration of its major wetlands, converting them into parks. (Sabiiti, 2022). As part of this initiative, a master plan for the restoration of Gikondo, Rwampara, Rugenge-Rwintare, Kibumba, and Nyabugogo wetlands were developed. These wetlands cover 15.76 Km<sup>2</sup>, accounting for 20% of the total area of Kigali (730km) (Sabiiti, 2022). The main purpose of this restoration is to reduce the impacts of flood which have been impacting the city of Kigali (Sabiiti, 2022).

Similar to other cases of wetland degradation in Rwanda, Nyandungu wetland was encroached upon by human activities and was also highly impacted by flooding (FONERWA, 2016; REMA, 2022c). In this respect, in 2015, the City of Kigali initiated the restoration of the wetland into an eco-park using Sustainable Urban Drainage Systems (SUDS) interventions based on Ecosystem-based Adaptation. As part of this project, benches were installed, 1,100 meters of road, two parking areas, an information center, a restaurant, lavatories, a maintenance house, two gates with

green power (solar-powered lighting), sewage treatment systems, a pop-up garden, and 8,574 meters of walkways and bicycle lanes were constructed. Moreover, five catchment ponds, three recreational ponds, drainage channels, and a stream crossing the wetland were rehabilitated. Other established interventions included planted infiltration plants, 17 trees, including 55 indigenous trees, three lawns, a medicinal garden, vegetated swales, check dams, and bioretention basin (Gakuba, 2012; REMA, 2022d). In this regard, different benefits, such as flood attenuation among others, were expected (Habakubaho, 2021; Kyanga, 2021; REMA, 2019a).

The restoration of Nyandungu urban wetland has been undertaken on 121.89 hectares of the total wetland area, which covers 243.92 hectares within the Nyandungu subcatchment, which itself spans 3,149.37 hectares (REMA, 2022f). However, according to REMA (2010) and USEPA (2000), it is recommended that while restoring wetlands, the areas of intervention to be restored should be taken into consideration. This means that a design should be conducted for the entire watershed, not just a part of the wetland. This is required to understand the potential of the whole watershed/catchment and its impact on the wetland (Dooley & Stelk, 2021; Fabian, 2021). Moreover, in its 13th article, the Ramsar COP8 Resolutions state that, "Whenever possible, the minimum acceptable scale for wetland restoration planning should be at the catchment level." In this context, individual, relatively small restoration projects targeting a single wetland can be valuable if they are planned within the context of the catchment. The same article states that wetland restoration planning should not ignore the value of upland habitats and the linkages between upland and wetland habitats (Ramsar Convention on Wetlands, 2002). However, the landscape plan for Nyandungu wetland restoration was developed at the wetland level, not at the catchment level (Habakubaho, 2021; Ssinabulya, 2015). This might hinder the ability of this wetland to manage floods, given that the Nyandungu catchment is becoming more urbanized, with many buildings and paved areas. When coupled with changes in rainfall patterns due to emerging climate change, this urbanization may increase surface water runoff from the catchment (Quang et al., 2023).

Although implementing interventions at the wetland level can pose challenges, the choice of wetland restoration approach is also important, as some methods may yield greater benefits than other (Muthukrishnan & Field, 2004; Sullivan et al., 2018; Turenscape, 2015). This is where the Sponge city has emerged as an outstanding

approach enabling the development of more Blue-Green Infrastructures during the wetland restoration process (Liu et al., 2021a). Moreover, sponge city approach recommends restoring the whole catchment which is proved to be a viable solution for flood risk control downstream (Peng et al., 2022; Qi et al., 2023; Ye et al., 2018; Yin et al., 2022). Moreover, because of having more Nature-based interventions, sponge city approach was found to have more flood risk reduction benefits under climate change than SuDS, which is the approach used in Nyandungu wetland restoration (Liu et al., 2021a). Therefore, this study intends to evaluate the flood control benefits of the approach used in the restoration of Nyandungu urban wetland and recommend other types of interventions grounded in sponge city approach that may be applied for enhanced restoration of Nyandungu wetland with consideration to its catchment as well as other urban wetlands.

### **1.3 Research objectives**

#### **1.3.1 Main objective**

To examine the potential of sponge city functions on flood risk reduction in Nyandungu urban wetland, a half-decade after restoration.

#### **1.3.2 Specific objectives**

To attain the general objective, the present study specifically:

- i. Examine functions of sponge city in relation to flood risk reduction in wetlands.
- ii. Examine outcomes of the restoration of Nyandungu urban wetland in relation to flood risk reduction
- iii. Suggest other interventions for flood risk reduction in Nyandungu urban wetland in relation to sponge city approach.

### **1.4 Research questions**

This research will attempt to respond to the following research questions:

Table 1 Specific research objectives and research questions

Specific Objectives	Research Questions
1. Examine functions of sponge city in relation to flood risk reduction in wetlands.	1. What are functions of sponge city in relation to flood risk reduction in wetlands?

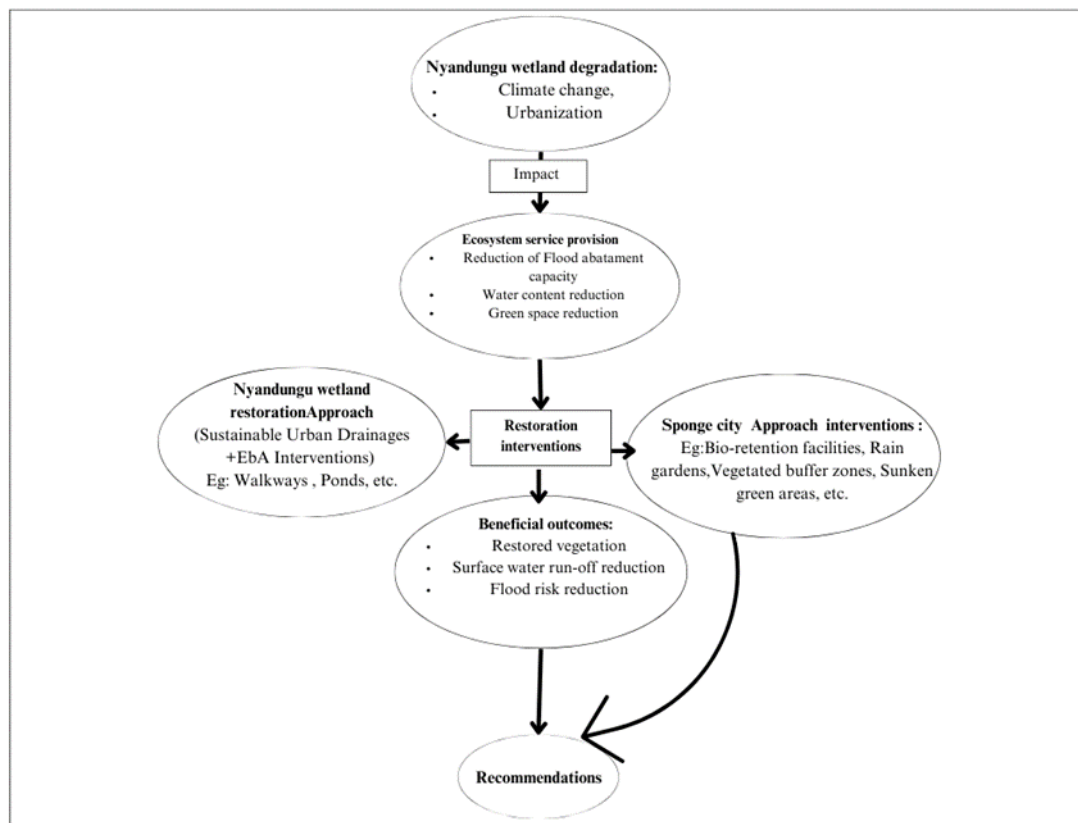
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|---|--|
| <ol style="list-style-type: none"><li>2. Examine outcomes of the restoration of Nyandungu urban wetland in relation to flood risk reduction</li><li>3. Suggest other interventions for flood risk reduction in Nyandungu urban wetland in relation to sponge city approach.</li></ol> | <ol style="list-style-type: none"><li>2. What are the outcomes of the restoration of Nyandungu urban wetland in relation to flood risk reduction?</li><li>3. What are the other interventions for flood risk reduction in Nyandungu wetland in relation to sponge city approach?</li></ol> |
|---|--|
- 

### **1.5 Motivation and Significance of the Research**

Urban Wetland degradation as a results of urbanization and climate change have been a major concern around the world (Mondal et al., 2017; Rwanyiziri et al., 2020a). With the continuous occurrence of deadly climate change-induced flooding and the reduction of green spaces in urban areas, wetland restoration using different approaches such LID, BMPs ,SUDS and many more has been carried out worldwide to help wetland regain their giant sponge effect and help cities adapt to flood (Kim et al., 2011). To date, the Sustainable Urban Drainage System (SUDS), which is the approach used in the Nyandungu wetland restoration, has been regarded as an older method that is outperformed by the sponge city approach (Ahmed et al., 2022, Liu et al., 2021a). The sponge city approach, an emerging method in wetland restoration, has been widely accepted by various scholars as the most effective strategy for transforming degraded wetlands into parks, as it has been shown to offer more functions than SUDS, as it treats polluted water bodies, enhances ecological conditions, mitigates climate risks, and promotes sustainable urban construction (Liu et al., 2021a). Results from this study will reveal whether the approach used contributed to flood risk reduction in the Nyandungu wetland and will recommend other types of interventions grounded in the sponge city concept for its effective restoration. If successfully completed, this study will be the first of its kind conducted in Rwanda and the region. As the government intends to restore all wetlands in the City of Kigali into parks, the findings of this study will provide a basis for enhancing the restoration of other wetlands in the City of Kigali.

## 1.6 Conceptual and analytical frameworks

The conceptual framework outlining the key elements for the degradation and restoration of the Nyandungu wetland has been developed. The key indicators are divided into four components within a causal chain. The first component includes indicators that demonstrate the causes of wetland degradation in the study area. The second component covers indicators that assess the impact of degradation on the wetland's functions. The third component encompasses indicators that facilitate a comparison of the flood control benefits of the various intervention approaches in relation to the sponge city approach. The last component comprises indicators related to recommendations for enhancing the restoration of the Nyandungu wetland. Figure 1 below summarizes the indicators in the conceptual framework.



Source: Oates et al., 2020b; RDB, 2022; REMA, 2022f, 2022d; World Bank, 2021.

Figure 1 Conceptual and Analytical Framework

All these indicators were used to understand the causes of Nyandungu Wetland degradation and their impact on various components of the wetland. They also helped

evaluate the benefits of the implemented restoration approach compared to the Sponge City approach. Lastly, recommendations were derived based on the insights gained from these indicators.

### 1.7 Research design

To attain the results, a research design presented in Figure 2 below was adopted. The first step involved conducting a literature review to understand the research topic, formulate the research objectives and research questions, and identify the data needed to answer the research questions of this study. It was through the literature review that the differences between SUDS and the sponge city approach were investigated, and the potential of the sponge city concept in restoring degraded wetlands was discovered. The next step was data collection, followed by data cleaning and analysis. This research adopted a mixed-methods research approach, which was chosen because the study required answers to research questions that necessitate both quantitative and qualitative data.

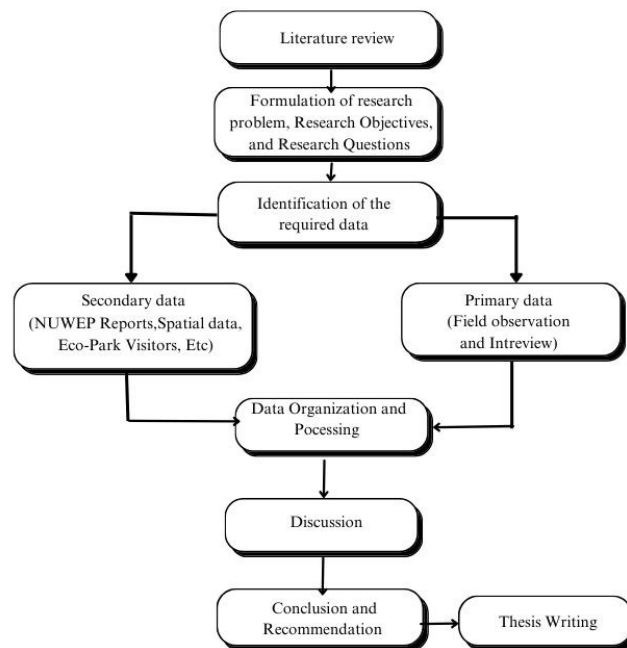


Figure 2 Research design

Quantitative data consist of numerical data, whereas qualitative data consist of categorical and textual data. Secondary data, which are mainly spatial data, were

collected from different sources, and other non-spatial data were collected from various institutions. Primary data were collected through field observation. To easily obtain the information, these data were converted into charts, maps, images, and graphs. Eventually, the thesis report was written.

### 1.8 Research Matrix

The table below shows the research matrix, which indicates how the research was operationalized. This matrix illustrates the relationship between the research objectives and research questions in relation to the collected data. In addition, the methods used to collect these data, as well as the sources, are indicated. To achieve accurate results, both qualitative and quantitative data were collected, as shown in Table 2 below. Both types of data helped to find results that respond to the objectives of this research.

Table 2 Research Matrix

Research Objective	Research Questions	Methods and data sources	Expected data
1. Examine functions of sponge city in relation to flood risk reduction	a. What are functions of sponge city in relation to flood risk reduction?	<ul style="list-style-type: none"> <li>Review of literature about the functions of sponge city interventions for flood control under flood event.</li> </ul>	<ul style="list-style-type: none"> <li>Summary of sponge city infrastructures functions for flood control and flood risk reduction</li> </ul>
2. Examine outcomes of the restoration of Nyandungu urban wetland in relation to flood risk reduction	b. What are the outcomes of the restoration of Nyandungu urban wetland in relation to flood risk reduction?	<ul style="list-style-type: none"> <li>Review documents on NUWEP interventions for flood risk control and their functions</li> <li>Collection of spatial data to perform flood susceptibility before and after the wetland restoration (LULC, Soil, River shapefile, DEM, Rainfall), NDVI and MDWI.</li> </ul>	<ul style="list-style-type: none"> <li>Summary of NUWEP interventions for flood control and their functions</li> <li>Maps, figures and charts</li> </ul>

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<p>3. Suggest other interventions for flood risk reduction in relation to sponge city approach.</p>	<p>c. What are the other interventions for flood risk reduction in relation to sponge city approach?</p>	<ul style="list-style-type: none"> <li>• Spatial data to perform SMCE for suitable sponge city for flood risk reduction in Nyandungu catchment (Hydrologic soil groups (HSGs), LULC, River, Soil and DEM)</li> </ul>	<ul style="list-style-type: none"> <li>• Summary of suitable sponge city intervention for flood control</li> <li>• Maps, charts and figures</li> </ul>
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## 1.9 Thesis structure

The thesis structure consists of five sections with a list of appendices, figures, and tables.

**Chapter 1: Introduction** - Chapter one consists of the general background of the research, the research problem, the research motivation and its significance, the research objectives, the research questions, the conceptual framework, and the research design.

**Chapter 2: Literature review**- Chapter two discusses the background related to the topic by reviewing the literature in order to enhance understanding of the topic.

**Chapter 3: Methods, Materials, and Procedures** - Chapter three describes the overview of the case study area, the methods and approaches used for data collection and processing. Data processing methods, tools, and approaches, as well as data processing stages, are described. Finally, a chapter summary is provided at the end of this chapter.

**Chapter 4: Results and Discussion** – Chapter four presents the main findings and discussion of the results of the study. These results were presented in form of maps, tables and charts. It also discusses the results and revealing the relationships, trends and generalizations among them

**Chapter 5: Conclusion and Recommendations** - Chapter five is the last section of the thesis and concludes with recommendations based on the findings and the research objectives and questions. Recommendations for further research are provided in this chapter.

## CHAPTER II LITERATURE REVIEW

The literature review under this chapter was conducted in a bid to understand the impact of urbanization and climate change on urban wetlands. It also shed light on the different urban wetland restoration approaches and policies supporting the use of those approaches and their relevance in line with the country's development goals.

### 2.1 Climate change and Urban wetland degradation

Climate change has been identified as a major threat to urban wetlands (Barros & Albernaz, 2014). It affects wetland structure, functions, and ecological balance. The key components of wetlands that are greatly affected by climate change are briefly discussed below.

#### 2.1.1. Hydrology

Climate change significantly alters the hydrology of wetlands, which is critical to their functioning (Bergkamp, 1999). Variability in precipitation patterns can lead to increased flooding during intense rainfall events or prolonged drought conditions when precipitation is scarce (Trenberth, 2008). These fluctuations in water levels disrupt the balance necessary for wetland ecosystems to thrive, leading to challenges such as habitat loss for aquatic and terrestrial species (Erwin, 2009; Salimi et al., 2021). Additionally, changes in evaporation rates and the timing of runoff can affect the hydrological connectivity of wetlands with surrounding ecosystems, further impacting their capacity to filter pollutants and provide essential water quality benefits (Karim et al., 2016).

#### 2.1.2. Vegetation

Wetland vegetation is highly sensitive to climate change, which can lead to shifts in plant species composition and distribution (Y. Li et al., 2024). Rising temperatures and altered moisture availability can favor certain species, often resulting in the proliferation of invasive plants that outcompete native vegetation (Short et al., 2016). These changes not only affect the biodiversity of wetland areas but also impact the habitat quality for wildlife that depend on specific plant communities for food and shelter (Chang et al., 2023). Moreover, the alteration of plant communities can influence the wetland's ability to perform critical functions such as carbon sequestration, nutrient cycling, and providing shelter for aquatic life (Y. Chen et al.,

2023).

### **2.1.3. Soil**

The soil in wetlands plays a vital role in their ecological health, and climate change poses threats to its integrity (Jackson et al., 2014). Variations in water levels can lead to changes in soil moisture and nutrient availability, impacting the types of vegetation that can thrive in these environments (van der Valk et al., 1994; Wilcox & Nichols, 2008). Moreover, climate change can affect the chemical composition of soils, potentially disrupting essential processes such as decomposition and nutrient cycling (B. Biswas et al., 2018). Wetland soils are also crucial carbon sinks, and changes in temperature and hydrology may reduce their capacity to store carbon, thus contributing to increased greenhouse gas emissions (Were et al., 2019).

### **2.1.4. Biodiversity**

Climate change has profound implications for the biodiversity of wetland ecosystems (Mitchell, 2013). Changes in habitat conditions, such as altered hydrology and vegetation shifts, can lead to declines in species populations and even local extinctions (Lucas & Lloréns, 2008). Many wetland species, including amphibians, birds, and aquatic organisms, rely on specific environmental conditions for their survival and reproduction (Sievers et al., 2018). As these conditions change, species may struggle to adapt or migrate, leading to changes in community composition (Muluneh, 2021). The loss of biodiversity not only diminishes the ecological resilience of wetlands but also reduces their capacity to provide essential ecosystem services (Ingabire et al., 2020).

### **2.1.5. Ecosystem Functions**

Wetlands provide numerous ecosystem functions, including water purification, flood regulation, and habitat provision (Alikhani et al., 2021). Climate change can disrupt these critical functions by altering hydrology, nutrient cycling, and species interactions (Gómez-Baggethun et al., 2019). For instance, increased flooding or drought can impair the ability of wetlands to regulate water flow, resulting in higher flood risks for surrounding communities (Xiong et al., 2023). Additionally, changes in nutrient dynamics can affect the productivity of wetland ecosystems, leading to declines in fish and wildlife populations (Wrona et al., 2006).

The overall disruption of these functions not only affects the ecological integrity of

wetlands but also has significant implications for the communities that rely on them for various services.

## **2.2. Impact of climate change induced flood in urban areas**

Globally, the frequency and severity of urban flooding events has increased due to climate change, which has had devastating effects on urban wetland ecosystems and urban dwellers (Sun et al., 2021). Flooding alters structure, functioning, and biodiversity of urban wetlands (Lucas & Lloréns, 2008). As a key abiotic pressure flooding leads to changes in plant population characteristics and hydrological processes in the wetlands. This affects many urban wetlands plants populations (M. Zhang et al., 2022). A study by Pricope & Shivers (2022) indicated that increased frequency of flooding caused by climate change hastens the loss of wetland cover and plants. These factors also diminish the ability of wetlands to deliver ecosystem services.

According to the United Nations Office for Disaster Risk Reduction, over 200 million people are impacted by floods annually, making flooding the most prevalent natural disaster worldwide (UNDRR, 2020). With 1.5 billion people affected, Asia has experienced 41% of all flooding incidents and 93% of all flood-related deaths worldwide, making it the region with the greatest impact. Significant flooding consequences are also felt in the Americas with 680 flood occurrences and Africa with 763 flood events between 2000 and 2019, the same report revealed (UNDRR, 2020, 2021). As wetlands have proved to reduce the risk of flood impacts, this indicates the need for more solutions to promote flood adaptation in urban areas where urban wetland restoration can be a viable solution.

## **2.3 Importance of urban restored wetland in flood risk reduction**

Urban wetlands play a critical role in flood risk reduction by acting as natural sponges that absorb and store excess rainfall and surface runoff (Mwizerwa et al., 2023). Restored Urban wetlands have the capacity to slow down water flow and spread it across a wider area, which reduces the intensity and velocity of floodwaters (Gato-Trinidad et al., 2022). This process helps to mitigate the impact of heavy rainfall events, thereby protecting urban infrastructure and communities from flood damage (EPA, 2016).

One significant fact is that wetlands can reduce peak flood levels by up to 60%, as demonstrated in numerous studies (Acreman & Holden, 2013). For example, the

United States Environmental Protection Agency (EPA) notes that a single acre of wetland can store approximately 1.5 million gallons of floodwater (EPA, 2016). This capacity for water retention is crucial in urban settings where impervious surfaces such as roads, buildings, and parking lots prevent water infiltration, leading to increased runoff and heightened flood risks (Barnes et al., 2000). Furthermore, healthy urban wetlands contribute to groundwater recharge by allowing water to percolate slowly into the ground, replenishing aquifers and maintaining the base flow in rivers and streams during dry periods (Rafiei et al., 2022; Wisconsin Wetlands Association, n.d.). This natural regulation of water flow is essential for maintaining the hydrological balance in urban areas.

Urban wetlands also provide crucial ecological benefits that support flood risk reduction (Dooley & Stelk, 2021; Ming et al., 2007). Vegetation in wetlands stabilizes soil with its root systems, reducing erosion and sedimentation in waterways. This stabilization helps maintain channel integrity and reduces the likelihood of riverbanks collapsing during flood events (EPA, 2022). Additionally, wetlands improve water quality by filtering pollutants, sediments, and nutrients from runoff before it reaches downstream water bodies. This filtration process helps to maintain the health of urban waterways, ensuring they are better equipped to handle floodwaters without becoming overwhelmed by contamination (Dordio et al., 2008).

In summary, healthy urban wetlands are vital for flood risk reduction, offering significant water storage capacity, groundwater recharge, soil stabilization, and water quality improvement. Their preservation and restoration are essential for enhancing urban resilience to flooding and protecting communities from the adverse impacts of climate change-induced extreme weather events.

#### **2.4. Approaches used in restoration of urban Wetland for flood adaptation**

From the 1990s, wetland restoration and rehabilitation have been the major options adopted by the international community for wetland conservation (Maleki et al., 2018; REMA, 2023). This initiative emerged while seeking for solutions to the deadly floods that occur as a result of climate change and urbanization among others (Fennessy & Lei, 2018; Gubic & Baloi, 2020; WWT Consulting, 2018). Due to climate change and rapid urbanization, urban areas have been facing with deadly flooding which ravages cities and disrupt the welfare of urban dwellers (Chai et al., 2022; Tang et al., 2024). Rapid urbanization contributes to the increase in surface water run off because of increased paved areas and lack of or poor infrastructure for urban storm water

management (Bajracharya et al., 2016). On the another hand, climate change has aggravated this due to increased rainfall frequency and intensity (Huong & Pathirana, 2013). Moreover, rapid urbanization has been putting pressure on city's green spaces which are often needed by urban dwellers for different purposes such as recreation, education and beautification of the city (Ben Messaoud et al., 2024; Nshimiyimana et al., 2023; Rehman et al., 2023; Siddique & Uddin, 2022).

As a solution, different urban storm water management approaches which consider wetlands as their primary infrastructure were combined with other interventions to restore degraded urban wetlands, helping regain their flood control capacity while also providing other ecosystem services (Brien, 2009; Clearwater, 2013; Environment Agency, 2003; WWT Consulting, 2018). Those approaches include the Best Management Practices (BMPs), Low Impact Development (LID), in the United States of America (USA), Sustainable Urban Drainage system (SUDS) in the United Kingdom of Great Britain and Northern Ireland (UK) and Europe, Water-sensitive urban design (WSUD) in Australia, Sponge City in China (Rodríguez-Rojas & Grindlay Moreno, 2022; Xiang et al., 2019; Zhao et al., 2021) and many more. It is worth noting that, approaches have primarily the objective of managing urban storm water using different infrastructure such as Bioswales, Permeable pavement, Retention basins, Green roofs, Rain gardens, constructed wetlands, just to mention few (Environment Agency, 2003; Fletcher et al., 2015). Those stormwater management approaches are combined with other practices such as the restoration of wetlands natural vegetation, widening existing rivers channel, just to mention few to restore those wetlands and the Catchment or sub Catchment in which the wetland is located (SusDrain, 2018).

With the emergence of climate change, different scholars recommended the use of Nature based solutions in which Ecosystem Based Adaption is categorized to restore urban degraded wetlands (Pricope & Shivers, 2022; J. Sun et al., 2024; Wamsler et al., 2016). However, NbS were regarded by scholars not to be a standalone approach, in some cases an hybrid approach which is the combination of Blue infrastructure and selected EbA were found to be effective under some cases (W. Chen et al., 2021; Depietri & McPhearson, 2017). Some of those approaches and their origin are discussed below:

#### **2.4.1. Best Management Practice (BMP)**

BMPs are strategies designed to minimize the impact of urban development on water quality and quantity (Muthukrishnan & Field, 2004). They include practices such as

sediment control, stormwater management, and pollution prevention (Pickford, 2022). BMPs are implemented to reduce runoff and improve water quality through methods like green roofs, permeable pavements, and constructed wetlands (Wilson et al., 2006). BMPs include a variety of techniques, such as sediment control and structural practices designed to mitigate the impacts of urban development on water quality and quantity (Nilsson, 2018).

#### **2.4.2. Low Impact Development (LID)**

LID is an innovative approach to land development that manages stormwater at its source (Liaw et al., 2000). It emphasizes the use of natural systems and processes to maintain the hydrologic cycle (Shafique & Kim, 2015). Techniques include bioretention areas, rain gardens, and green infrastructure that promote infiltration and reduce runoff, helping to protect water quality and promote biodiversity (Putri et al., 2023). LID emphasizes integrating natural processes into urban design to manage stormwater at its source, using features like bioretention areas and permeable pavements to promote infiltration and reduce runoff (T. Liu et al., 2021).

#### **2.4.3. Sustainable Urban Drainage System (SUDS)**

SUDS are designed to mimic natural drainage systems to manage rainfall and surface water sustainably (Sirishantha & Rathnayake, 2017). This includes techniques such as swales, detention basins, and permeable surfaces that manage stormwater and reduce flooding while enhancing biodiversity and improving water quality (Ferrans et al., 2022). SUDS mimic natural drainage systems to manage surface water sustainably through techniques like swales and green roofs, enhancing biodiversity while controlling flooding (Scholz, 2015).

#### **2.4.4. Water-Sensitive Urban Design (WSUD)**

WSUD integrates urban planning and water management to create sustainable urban environments (Patil & Anbalagan, 2023). It focuses on managing the urban water cycle (stormwater, groundwater, and potable water) using practices like rainwater harvesting, vegetated swales, and green roofs to promote ecological health and resilience against climate change (Fumero, 2020; Matto et al., 2017). WSUD combines urban planning with water management strategies to create sustainable urban

environments, utilizing rainwater harvesting and green infrastructure to support ecological health (Hurlimann & Wilson, 2018).

#### 2.4.5. Sponge City

Sponge City initiatives aim to enhance urban resilience by improving the city's ability to absorb and reuse rainwater (J. Wang et al., 2021). This includes using permeable materials, green roofs, and rain gardens to increase infiltration, reduce runoff, and manage flooding while promoting ecological functions within urban landscapes (Oates et al., 2020a).

Table 3 Main Approaches used in restoration of urban Wetland for flood adaptation

Approach	Origin/Region	Focus	Key Characteristics
BMP	USA	Pollution control	Structural practices for runoff management
LID	USA	Source control	Natural systems for stormwater management
SUDS	UK/Europe	Sustainable drainage	Mimics natural drainage systems
WSUD	Australia	Water cycle integration	Combines urban planning with water strategies
DUD	Germany	Localized solutions	Small-scale, community-based interventions
Sponge City	China	Urban resilience	Increases capacity for rainwater absorption

Source: Fletcher et al., 2015.

These concepts are essential for promoting sustainable development and resilience in urban environments by leveraging nature's capabilities. Best Management Practices (BMP), Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), and Water-Sensitive Urban Design (WSUD) all emphasize managing stormwater and improving water quality through sustainable practices. They often incorporate Nature-Based Solutions (NbS), which leverage natural systems to enhance these strategies (Ruangpan et al., 2020).

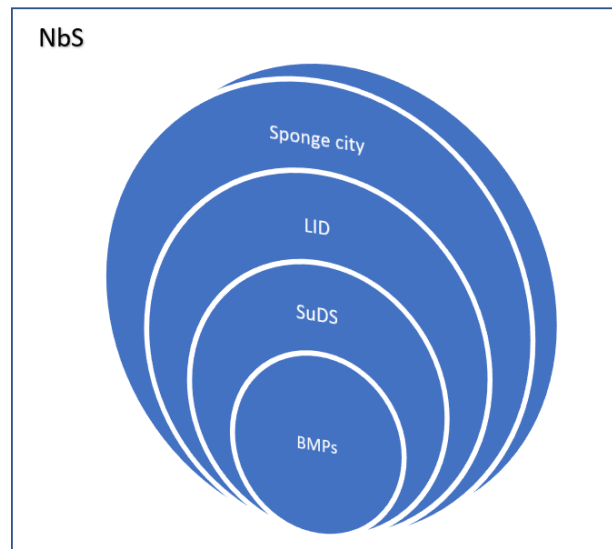


Figure 3 Relationship of Nature-Based Solutions concepts

Source: Ma & Jiang, (2023a); Qi et al., (2020)

Sponge City in China directly integrate NbS to enhance urban resilience and adapt to climate impacts (Ma & Jiang, 2023b). In terms of functions and scope, sponge city has far more functions than of the remaining approaches (Q. Li et al., 2019)

### 2.5. Genesis of sponge city-An EbA for urban flood risk reduction

The concept of a "sponge city" originated in China in 2000 as a response to urban flooding, water scarcity, and the need for sustainable urban development (Turenscape, n.d.). Chinese scientists introduced the idea, aiming to mitigate flooding by absorbing, capturing, and purifying rainwater, then storing it for later use (Y. Peng & Reily, 2021). In 2013, the Chinese government formally endorsed the idea and launched the Sponge City Pilot Program, selecting 30 pilot cities to implement sponge city techniques and technologies (Chikhi et al., 2023; Oates et al., 2020a; Rau, 2022; Zheng et al., 2022). These cities, chosen for their diverse geographical and climatic conditions, included regions such as Beijing, Shanghai, and Wuhan (X. Li et al., 2016; Oates et al., 2020a; Yin et al., 2022; Zhao et al., 2021). From 2015 to 2020, the pilot cities implemented various sponge city techniques, including green roofs, permeable pavements, and wetland parks, refining strategies and technologies. By the early 2020s, the sponge city initiative had gained global attention, with other countries showing interest in adopting similar strategies for sustainable urban development and flood management. Today, the concept continues to evolve, incorporating new technologies and strategies, and has become an integral part of China's urban development strategy and a model

for sustainable urbanization worldwide (Dahmke & Bohm, 2023; OECD, 2023; Thoms & Köster, 2022b; UNEP, 2018) (Ayad & Rasheed, 2022; Thoms & Köster, 2022a; Zeng et al., 2023).



Figure 4 Schematic diagram of the Sponge city concept

Source: Pattinson, 2016

Sponge city was inspired by the urban storm water management approaches mentioned above Such BMP, LID, GI, and SUDS and is built almost on similar principles (Zhao et al., 2021). However, the Chinese sponge city has more types and functions than those of BMP, LID, GI, and SUDS. Sponge city is composed of three complementary and interdependent systems: LID measures, pipeline drainage system and excessive stormwater runoff drainage system, because it is required to treat the polluted water bodies, enhance ecological conditions, mitigate climate risks, and promote sustainable urban construction (J. Liu et al., 2021b). After the emerging of this approach, different countries across the world have implemented it to cope with flooding (Ayad & Rasheed, 2022; Thoms & Köster, 2022a; Zeng et al., 2023).

The sponge city is composed with ensembles of infrastructures such as urban green spaces, constructed wetlands, rain gardens, green roofs, recessed green spaces, grass ditches, ecological parks and many more (Qi et al., 2021)). Some of those infrastructures are explained in detail below:

### **2.5.1. Urban green space**

The urban green space is an open space in urban areas reserved for parks and green spaces (Knobel-Guelar, 2020). The urban green space helps to ensure that urban residents have adequate opportunities for exposure to nature; urban biodiversity is maintained and protected; environmental hazards such as air pollution or noise are reduced; the impacts of extreme weather events such as flood are mitigated; the quality of urban living is enhanced; the health and well-being of residents is improved (de la Salud, 2017). The urban green spaces consist of roadside greenery, playgrounds; green roofs and facades; parks and urban meadows; greenways and corridors (such as green trails for walking/cycling); coastal, riverside or lakeside trails, linking green with blue spaces; recreational and urban gardening facilities (such as community gardens, sport and play areas and school grounds).

### **2.5.2. Constructed wetland**

Due to industrial development and mining, the disruption of nature is taking place; in this way, the constructed wetland is required for creating an artificial wetland to treat sewage, greywater, storm water runoff or industrial wastewater (Choi et al., 2021). Storm runoff from urban areas has been recognized as a major contributor to pollution of the corresponding receiving urban watercourses. The constructed wetlands play a great role, because when the polluted water flows through the wetland, it can be purified efficiently through filtration, adsorption, sedimentation, ion exchange, plant uptake and microbial decomposition (Vymazal & Kropfelova, 2008).

### **2.5.3. Rain garden**

Every time it rains, water runs off impermeable surfaces, such as roofs or driveways, collecting pollutants such as particles of dirt, fertilizer, chemicals, oil, garbage, and bacteria along the way (Ground Water Foundation, 2022; National Resource Conservation Service, 2005). As a solution, the rain garden acts as water holder to catalyze water run-off. Rain garden, which is different from pond or water garden, is a garden of native shrubs, perennials, and flowers planted in a

small depression, which is generally formed on a natural slope(Woelfle & Uncapher, 2021). It is designed to temporarily hold and soak in rainwater runoff that flows from roofs, driveways, patios, or lawns. Rain gardens are effective in removing up to 90% of nutrients and chemicals and up to 80% of sediments from the rainwater runoff (Dripps & Bressler, 2013) Compared to a conventional lawn, rain gardens allow 30% more water to soak into the ground.

#### **2.5.4. Green roofs**

Apart from being a viable option for reducing the urban heat effects, green roofs reduce flood, because they are able to retain some water (Köhler et al., 2003). Green roofs have deeper, more organic growing medium or soil capable of supporting a wide variety of plants, often including shrubs and small trees. In fact, the green roofs contribute to flood control by storing rainfall in the soil substrate and delaying the runoff peak generation (Fasnacht, n.d.).

#### **2.5.5. Ecological Parks**

The ecological parks are considered in designing the sponge city as they offer the role of flood management because they possess the trees, plants, and other grass that facilitate the slow water run-off (Xing, 2019).

The figure 6 below indicates the sponge city infrastructure established on-site.



Figure 5 Sponge city infrastructures on-site

Source: Köster, 2021

## 2.6 Sponge city as an EbA approach for to restore degraded urban wetland for flood control

A study of Y. Ma & Jiang (2023) and Mei et al.(2018) has unveiled a sponge city to be an Ecosystem-based adaptation Approach that was initiated by China to address the impacts of urbanization and climate change by primarily focusing on flood mitigation and adaptation. Currently, this approach is being replicated worldwide (Ayad & Rasheed, 2022; Ferreira et al., 2022a, 2022b; Rothwell, 2022; Thoms & Köster, 2022a). This approach was given too much attention by different scholars, researchers, and planners to assess its applicability as it is believed to incorporate all aspects necessary to make a city resilient and livable in the changing climate (Ayad & Rasheed, 2022; Boncheva, 2022; Chan et al., 2018b; Chao, 2021; Z. Li et al., 2018b; Thoms & Köster, 2022b; Zeng et al., 2023).

Sponge Cities is built on principles Ecosystem-Based Adaptation (EbA) (Ma & Jiang, 2023a; Qi et al., 2020). It recognizes the importance of integrating nature-based

solutions into urban planning to address the challenges posed by climate change and other environmental stressors (Pan et al., 2021). Ecosystem based adaptation consists with the use of nature to combat environmental challenges that occur as a result of climate change impacts. Those solutions should not only designed to combat those effects of climate change but also to provide other co-benefits that improve community livelihood (Scarano, 2017).

## **2.7 SuDs and Sponge city: A review on differences and Similarities**

SUDs and sponge city are both concepts related to sustainable urban development and water management, but they refer to different approaches and strategies (Esmail & Suleiman, 2020; Lashford et al., 2019). SUDs (Sustainable Urban Drainage Systems) SUDs are a set of practices and techniques designed to manage surface water runoff in urban areas in a sustainable and environmentally friendly manner. The goal of SUDs is to mimic natural drainage processes, reduce flood risk, and improve water quality by controlling and treating stormwater at its source (Environment Agency, 2003; susdrain, 2024). Sponge city on the other hand, focuses on urban planning and design strategies that allow cities to absorb, capture, and manage rainwater like a sponge. It emphasizes the use of permeable surfaces, green infrastructure, and water-sensitive urban design to enhance the natural water cycle and reduce the impact of urbanization on water resources (Rau, 2022; Yin et al., 2022). SUDs mainly focus on preventing flooding, reducing erosion, and improving water quality by managing stormwater runoff in a sustainable way (S. S. Chen et al., 2021). Sponge city aims to create cities that function like sponges, absorbing and utilizing rainwater for various purposes, including recharging groundwater, supporting urban ecosystems, and promoting overall resilience to climate change (Y. Sun et al., 2020).

In terms of scope, SUDs and sponge city have some differences. SuDS primarily address the management of stormwater runoff, aiming to prevent flooding and improve water quality by controlling the flow of water through urban areas but Sponge City encompasses a broader range of strategies beyond stormwater management. It includes a holistic approach to urban planning that considers water supply, flood control, water quality, and ecological preservation (H. Liu et al., 2017; Srishantha & Rathnayake, 2017).

For the case of components, SuDS may include permeable pavements, green roofs, rain gardens, detention basins, swales, and other engineered systems to capture and treat stormwater close to its source (Dickie & Construction Industry Research and

Information Association., 2010; Duffy & Berwick, 2013; Ferrans et al., 2022; Jiménez Ariza et al., 2019). For the case of Sponge City, in addition to the stormwater management techniques used in SUDs, Sponge City strategies may involve the integration of natural features such as constructed wetlands, parks, and green spaces to enhance the city's ability to absorb and retain water (Hermaputi & Hua, 2017; Y. Sun et al., 2020; Yin et al., 2022).

SuDS (Sustainable Drainage Systems) manages surface water runoff through techniques like green roofs and permeable pavements to reduce flooding and improve water quality. Sponge Cities integrate SuDS with broader urban planning to absorb, store, and reuse rainwater, enhancing resilience and ecological health. While SuDS focuses on project-level interventions, Sponge Cities apply these principles city-wide, promoting multifunctional landscapes. Below there is a list of infrastructures applied to in both sponge city approach and SUDs approach. Table 4 clearly indicated that sponge city has more functions than those of SUDs which make it more beneficial.

Table 4 Comparison of SuDS infrastructure vs Sponge city infrastructure

<b>SUDS Infrastructure</b>	<b>Sponge city Infrastructure (NbS)</b>
Trenches	Green roofs,
Swales	Sunken green areas
Bioretention	Infiltration ponds
Pervious pavements	Bio-retention facilities
Geocellular/modulars	Grass swales
Sand filters	Rain gardens
Infiltration basins	Storm and constructed water wetlands
Detention basins	Wet ponds
Ponds	Retention basins
Stormwater wetlands	Detention basins
Inlets and outlets	Vegetation buffer zones
	Bioswales
	Constructed Wetlands
	<b>Sponge city Infrastructure Grey Solutions</b>
	Permeable pavements and green ways
	Underground rainwater tanks
	Water storage modules
	Seepage wells, seepage pipes, seepage canals
	Rainwater drainage facilities
	Rainwater purification facilities
	Green Area irrigation
	Artificial soil filtration

Source: Biswas et al., 2019 and Woods-Ballard et al., 2007.

Table 4 which compares the SuDS infrastructure versus Sponge city infrastructure indicate that Sponge city has more functions than those of SuDS. Sponge city has more nature-based solutions for flood adaptations which SUDS lack. This makes it an outstanding approach for urban flood adaptation.

## **2.8 Successful stories of urban wetland restored into sponge parks using sponge city approach**

Since when sponge city was introduced, different wetland was restored worldwide into parks using this approach. Some of the successful projects of those parks are discussed below:

### **2.8.1. Harbin Cultural Center Wetland Park**

Harbin Cultural Center Wetland Park is in Harbin, one of the major cities in northeastern China. The city is prone to flooding due to its proximity to the lower reaches of the Songhua River (Turenscape, 2015). The wetland habitat was deteriorating due to the lack of water supply. Meanwhile, the rapid urban development in the northern part of the site caused severe storm-water inundation while the discharge of the contaminated stormwater caused the water quality of the river to decline (Turenscape, 2014).



Figure 6 Harbin Cultural Center Wetland Park

Source: Turenscape, 2014

As a solution, this damaged wetland was restored into urban wetland park was created in Harbin to manage storm runoff and wastewater from a local treatment plant. In addition to the productive wetland, active recreational uses, pedestrian paths and resting groves were incorporated into the design. The park design transforms a degraded wetland into a cherished urban park that is intensively used by urban residents year-round (Turenscape, 2015).

### **2.8.2. Loucun Wetland Park**

Located in In Sanya, Hainan Province, the Dong'an Wetland was designated as the site for one of Sanya's first pilot projects of urban environmental remediation and ecological restoration because of its key position in the regional ecological pattern, especially for urban stormwater management (Bai et al., 2018).



Figure 7 Loucun Wetland Park

Source: Shanghai Municipal Engineering Design Institute 2022.

The project aims at integrating leisure and recreational functions with landscape elements including ponds, forest on water, terraced vegetable garden, and trail loop, while promoting water circulation, improving water quality, and retaining rainwater and regulating water reuse, acting as a resilient urban sponge for rainwater management (Turenscape, 2021). The newly built project transforms an ignored grey place into a new home for egrets, an outdoor classroom for children's nature education, and a destination for citizens to evoke their memories (Bai et al., 2018).

### **2.8.3. Wetland Park around River Besòs in Spain**

This park is one of the most important green areas in the metropolitan area of Barcelona, spanning 115 hectares across the municipalities of Barcelona, Santa Coloma de Gramenet, Sant Adrià de Besòs, and Montcada i Reixac. It features two distinct sections: the wetlands, known for their high environmental, biological, and scenic value, which are not open to the public, and a public area stretching over 5 km.



Figure 8 Ideal for shootings: Besòs river park  
RVD Media Group, 2016.

The public space includes green areas, paved paths, and a bike track. Visitors can observe more than 200 bird species from viewing points located in the north and south. The Sant Andreu area has three park entrances: one in Baró de Viver and two in the Bon Pastor neighborhood (Miller, 2008).

### **2.9 Current status of urban wetland degradation in City of Kigali**

The City of Kigali contains 37 wetlands covering an area of more than 9,160 hectares (ARCOS, 2019). Wetlands have seen substantial alteration over the years, primarily because of being drained by agricultural activities and human settlement encroachment, which have replaced wetland species with crop plants and buildings.

#### **2.9.1. Review on urban degradation in the city of Kigali**

In 2020, Kigali urban wetlands covered 10.6%, this percentage reduced from of 14% in Kigali Master Plan of 2013. Studies indicate that 50% of Kigali wetlands have lost their ecological character mainly due to high population density that put pressure on agriculture productivity and urban wetlands wise use (Kalisa, 2020). A study conducted by ARCOS (2021b) indicated a great change in land use land cover change in Kigali city urban wetlands since 2008. This study highly considered the classes of cropland,

natural vegetation, water bodies and others. Due to their study interest, they never indicated the encroachment of wetlands by human settlements. So far, their study, revealed a great change in Land Use Land Cover (LULC) in the Kigali city's wetlands.

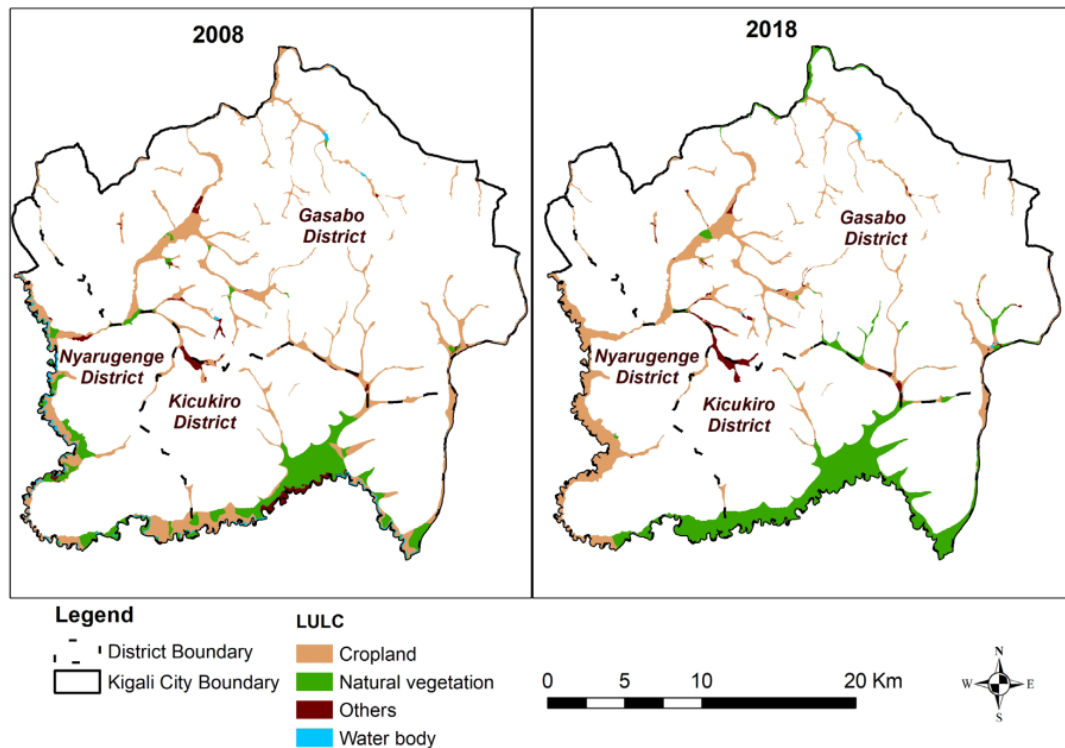


Figure 9 Land cover/use and changes in Kigali City's wetlands from 2008 to 2018

Source: ARCOS, 2021b

Figure 7. indicates the change in LULC. The class of cropland and other are highly changing and at high rate. ARCOS(2021b) revealed that cropland accounts for 11.24% as an annual rate of change in the wetlands located in the City of Kigali. Followed by grassland (grass & crops) 85.95%, built-up areas (commercial buildings, public facilities, and residences) 27.45% and green spaces (parks and river) 27.25% between 2012 and 2018.



Figure 10 Gikondo wetland after relocation of human activities

Source: Nkurunziza, 2022

The conversion of Kigali's wetlands to farmland, human settlements, commercial, and industrial uses has reduced their flood and pollution abatement ability (Bayizere et al., 2022; GGGI, 2022; Rwanyiziri et al., 2020b). Urbanization is highly regarded as the major cause of wetland degradation in the City of Kigali (Baloi, 2014). The findings of the study conducted by (Rwanyiziri et al., 2020b) shown that Kigali city has grown dramatically at the expense of Rwampara wetland during the past four decades. Over the last 31 years (1987-2018), the built-up area has increased by 77%, reducing the wetland surface area from 24 ha to 7.7 ha. Nyabugogo is still experiencing effects of humans activities that change it in terms of LULC (ARCOS, 2021b). In addition the wetland is heavily being affected by heavy metals (Bayizere et al., 2022; Nhapi, 2011). (Sekomo et al., 2011) The table below summarizes the major cause of wetlands degradation in the City of Kigali. Note that some of them were removed from the wetland as results of the ongoing relocation of anthropogenic activities in the wetlands in Rwanda.

Table 5 Categories of activities damaging wetlands in the City of Kigali

Activity	District			Total	Legal	Without legal Documents
	Gasabo	Kicukiro	Nyarugenge			
Residential home	1177	306	146	1629	703	926
Commercial activities	61	3	37	101	79	22
Industrial activities	6	73	5	84	78	6
Parking	10	4	25	39	3	36
Garages	9	6	15	30	4	26

Warehouses	12	1	17	30	23	7
Carpentry/Welding workshop	8	0	6	14	0	14
Dumping sites	4	2	10	16	0	16
Petrol Stations	4	1	19	24	22	2
Carwash	2	0	4	6	0	6
Schools	2	2	2	6	2	4
Health centers	2	0	0	2	2	0
Worship houses	7	1	3	11	5	6
Domestic animal rearing	97	7	12	116	0	116
Playgrounds	9	3	4	16	0	16
Garden centers	6	4	43	53	5	48

Source: Nizeyimana, 2021.

Despite the facts that anthropogenic activities are the lead cause of wetland vulnerability in the City of Kigali, the situation is still worsened by climate change which is causing high evaporation in the wetlands, drought and flood inundation that destroy the wetlands life (Ingabire et al., 2020; Umugwaneza et al., 2021). Kigali's tropical wet and dry climate, shaped by its high elevation, experiences average temperatures of 20°C and annual rainfall of about 900 mm annual, concentrated in two rainy seasons (March-May and September-December). However, Climate projections under the RCP8.5 scenario indicate significant increases in rainfall: 15-36 mm more during the short rainy season and 28-115 mm more in the long rainy season over the 21st century, along with an increase in the variability of monthly rainfall and extreme precipitation events. The intensity of rainfall on the heaviest days will rise by 12% between 2040–2059 and by 53% between 2080–2099, heightening the risk of damaging floods (Habakubaho, 2021). These changes are expected to exacerbate urban flooding and further degrade wetlands.

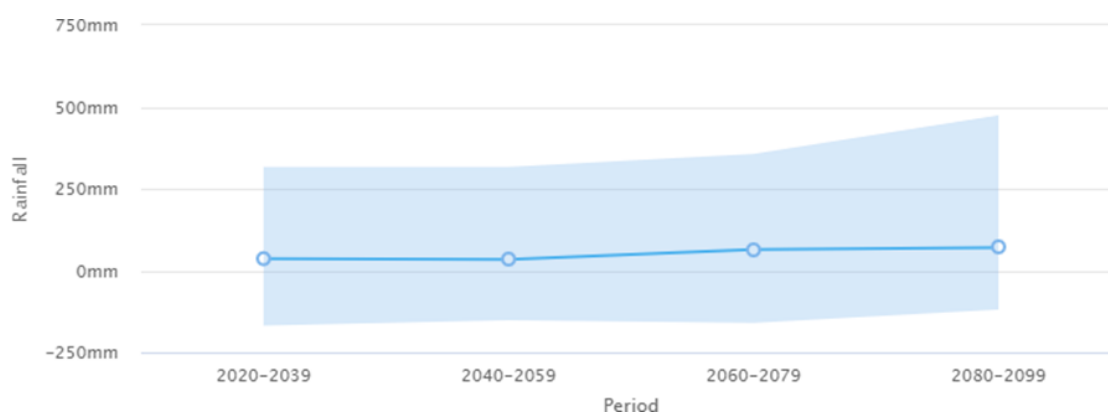


Figure 11 Projected change in monthly rainfall range for the Nyandungu pilot area from 2020–2099  
Source: Habakubaho, 2021.

In conclusion, climate change poses multifaceted challenges to urban wetlands worldwide, threatening their ecological integrity and the essential services they provide to urban communities (Trading et al., 2021). Understanding these impacts and implementing effective mitigation and adaptation strategies are essential steps toward ensuring the resilience and sustainability of urban wetlands in the face of ongoing environmental changes.

### **2.9.2 Existing plans for restoration of urban degraded wetland in the city of Kigali**

In 2017, the president of Rwanda emphasized that wetlands should be protected and preserved. He insisted that the relocations of human settlements and industries should be done as quickly as possible. Special attention directly was given to the wetlands located in the city of Kigali (KT Press Staff Writer, 2017; Ngabonziza, 2017; The EastAfrican, 2017). Since that time, relocation activities started but so far, there are still some human activities located in the wetlands and the impacts left by the relocated one is still visible. Currently, the government is interested in restoration of the wetlands located in the city of Kigali mostly by transforming the major wetlands into eco-parks (Sabiiti, 2022). In addition, a Kigali urban wetland master plan published in September 2021 revealed that 15.76 hectares (20%) of Kigali's 730 square kilometers were designated as wetland and marshland areas that must be reclaimed due to human and industrial encroachment (Sabiiti, 2022).

In line with the implementation of this masterplan, Nyandungu wetland have been restored into Nyandungu Eco-Park under second Rwanda Urban Development (RUDP II) project started in 2021 (Gakuba, 2012). The country is still undergoing the wetland restoration process, some studies were concluded for the whole wetland or parts of it, others are still underway. In November, 2022, the city of Kigali received a wetland city accreditation award during the 14th meeting of the conference of the contracting parties to the Ramsar Convention on Wetlands (COP14) in Geneva (Ramsar, 2022; REMA, 2022a).

Generally, all the afore-mentioned facts indicate the countries great move and willingness to conserve and restore wetlands.

## **2.10 Restoration approaches for flood adaptation in the degraded wetland in the City of Kigali**

The Rwandan government has recognized the importance of wetland management through policies emphasizing conservation and sustainable development. Initiatives in Kigali involve collaborative efforts from government agencies, NGOs, and community groups to focus on restoring wetland areas affected by urban expansion (REMA, 2020, 2023). Before 2015, there were no clear approaches used in the restoration of urban wetland in the City of Kigali. Some taken action was only to prohibit all activities related to wetland degradation including the dumping of waste in the wetland, planting trees alongside the rivers located in the wetland and widening of water channels crossing the wetland (Kyanga, 2021). Since 2015, Nyandungu wetland was restored using Sustainable Urban Drainage Systems (SUDs) under the fund of Nyandungu Urban Wetland Ecotourism Project (NUWEP), and co-finance of National adaptation planning Process (NAP) and Least Developed Countries Fund (LDCF) II project (Gakuba, 2012; REMA, 2022d; Ssinabulya, 2015). Currently the next phase is the restoration of other five wetlands which are Gikondo, Rwampara, Rugenge-Rwintare, Kibumba, and Nyabugogo wetland using the approaches used and lessons learned in restoring Nyandungu Wetland (Muhozi, 2024; REMA, 2021).

## **2.11 Legal framework for wetlands management and Ecosystem based Adaptation in Rwanda**

Rwanda has established the Policies, laws and guidelines and legal frameworks to support wetland protection and restoration, and management of flood risks in line with its vision 2050. Some of those policies, laws are discussed below:

### **❖ The Rwandan Constitution**

The Constitution of the Republic of Rwanda was introduced in 2003 following approval by a referendum held on the 24th of May 2003 and amended in 2015. The Constitution incorporates the articles of environment protection. For instance, article 22 and 53, states that each citizen has the right to healthy and satisfying environment; each person has the right to protect to conserve and promote the environment (GoR, 2015) Thus, the restoration of Nyandungu wetland for flood risks control falls in the constitution plan.

**❖ Law N°48/2018 OF 13/08/2018 on environment**

The Organic Law on Environmental Protection, Conservation, and Management is highly relevant and indicates activities which are prohibited in wetlands areas and provides that wetlands should be protected from all forms of degradation. Its article 42 indicates that acts prohibited in wetlands and protected areas, Article 47 clearly stated what Polluting and damaging the wetlands and the article 48 indicate fine to be given to someone who change of the nature of wetland. This legislation sets out the general legal framework for wetlands protection and management and on avoiding and reducing negative impact on the wetlands. The policy seeks to conserve, preserve, and restore ecosystems and maintain ecological and systems functions, particularly the conservation of national biological diversity; optimize utilization of resources to attain a sustainable level of resource consumption; and create awareness among the public to understand and appreciate the relationship between environment and development, ensuring participation of individuals and the community in the activities for the improvement of environment. The successful restoration of the NUWEP wetland and the conservation of the natural resources in NUWEP are entirely consistent with the Environmental Policy and any management activity will need to follow this policy (GoR, 2018)

**❖ National environment and climate change policy**

The National Environment and Climate Change Policy provides strategic direction and responses to the emerging issues and critical challenges in environmental management and climate change adaptation and mitigation. The statement 2 of this policy emphasizes on “promote sustainable management of wetlands”. The recommended action under this policy includes the restoration of wetlands in which NUWEP falls in. This policy emphasizes that wetlands must be protected. The policy emphasizes that to promote sustainable management of wetlands several actions must be taken, those actions include the development of a wetlands master plan, develop guidelines for the use of wetlands, just to mention a few (MoE, 2019a).

**❖ National Land Policy**

Land use and management law determines how land should be used in Rwanda. It also establishes the principles that are respected on land rights as well as all other appendages natural or artificial. One of the objectives of the policy is to promote

conservation and sustainable use of wetlands. The reference to master plans is relevant for the development and conservation of NUWEP (MoE, 2019b).

❖ **Rwanda biodiversity policy and *National Biodiversity Strategy and Action Plan***

Rwanda biodiversity policy acknowledges the importance of biodiversity in wetlands. It stresses the protection and conservation of wetlands. One of the main objectives of this policy is to ensure that wetlands and freshwater systems areas are sustainably managed. The National Biodiversity Strategy defines the objectives and priorities for the conservation and sustainable management of biodiversity. The Strategy includes hillsides and wetlands and protected areas as some of the areas that need to be conservation (GoR, 2016).

❖ **National disaster risk reduction and management policy**

The ultimate goal is to increase the resilience of vulnerable groups to disasters. This policy presents the institutional structures, roles, responsibilities, authorities and key processes required. This study is coherent with this policy as it is being conducted in disaster prone-area (MINEMA, 2023).

❖ **Ecosystem-Based Adaptation Guidelines for Climate Resilient Restoration of Savannah, Wetland and Forest Ecosystems of Rwanda**

This guideline detailed steps and restoration plans aimed at enhancing climate resilience. The guidelines are divided into three main ecosystem types: wetlands, savannahs, and forests. For each ecosystem, the document proposes four steps for intervention: planning, ecosystem assessment, development of EbA (Ecosystem-based Adaptation) intervention measures, and monitoring/evaluation of implementation. The primary goal is to achieve sustained recovery of these ecosystems by enhancing resilience to climate change and improving human well-being (REMA, 2019b).

## CHAPTER III METHODS, MATERIALS AND PROCEDURES

### 3.1 Introduction

This section provides an overview of the approaches and methodologies used in this study to investigate research problems and answer the research questions. The methods included the use of Geographical Information System and remote sensing techniques, along with on-site data, field observations, and interviews. These methods provided information to address the research question and achieve the objectives mentioned earlier. Primary and secondary data were collected using a variety of techniques and tools, including literature review, field data observation, interview and GIS Technology. After collecting the data, it was processed, analyzed, and interpreted using various tools and software such as ArcGIS Desktop, ArcGIS Pro, Google Earth, QGIS, MS Excel to determine the benefits of Nyandungu wetland restoration and identify suitable sponge city infrastructure that may be established to enhance the restoration of Nyandungu Urban wetland.

### 3.2 Study area description

#### 3.2.1. Location

The Nyandungu site is in the valley of Masoro-Bumbogo hill in Ndera, Gasabo District and Kanombe-Nyarugunga hill in Kicukiro District between 1°57'30.81"S and 30° 8'42.20"E. It stretches 3.6 Kilometers along the KK 3 Road and intersected by the KK 15 Road and the road towards the Adventist Central Africa University. The wetland park is divided into five Sectors, starting below La Palisse Hotel and ends at the road to Ndera (REMA, 2019a). It is bordered to the south by the Kigali-Kayonza Road (RN3) and the road to the Adventist University to the west and the road to Ndera to the east. Kigali's industrial zone abuts Nyandungu to the north. It is located in Kimironko, Ndera and Nyarugunga sectors of between the Gasabo and Kicukiro District (REMA, 2019a, 2022b, 2024). This Eco- Park is part of Nyandungu wetland, which is extended to Kimironko, Remera and Ndera sectors of Gasabo and Kicukiro District and covers an area of 243.92 Ha (Habakubaho, 2021). The restored wetland area covers 121.7 Ha (REMA, 2019a).

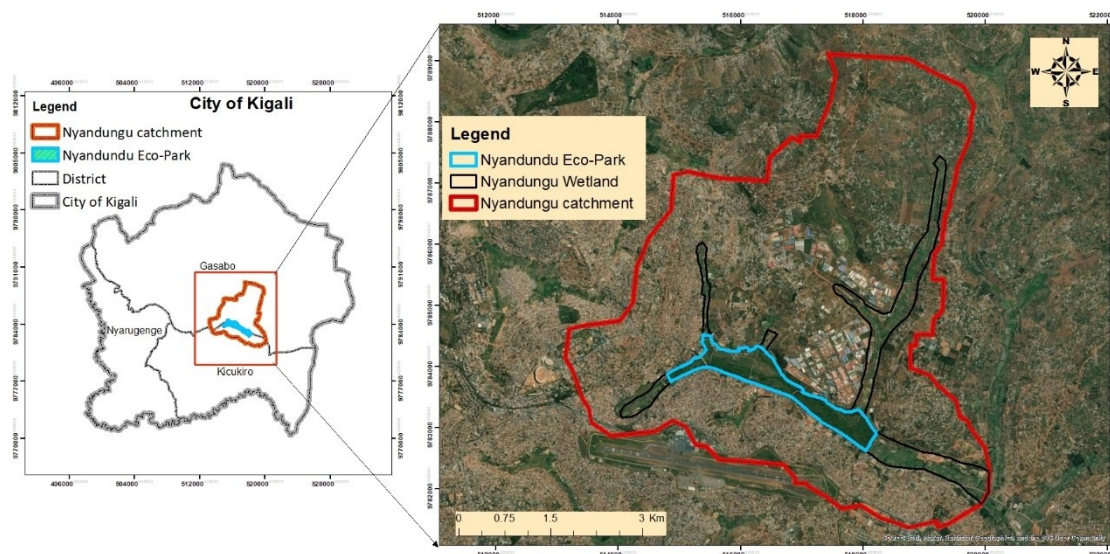


Figure 12: Location of Nyandungu Eco-Park

Source: <https://geodata.rw/portal/home/>

The study area was selected purposively because it is the first restored wetland among the degraded wetlands in the City of Kigali. It will be followed by the restoration of five wetlands namely Rwampara, Gikondo, Rugenge-Rwintare, Kibumba and Nyabugogo Wetland under the Second Rwanda Urban Development Project (RUDP II) funded by World Bank (REMA, 2022e).

### 3.2.1.1. Topography of Nyandungu wetland

Nyandungu Wetland is in a low area of 1360 meters altitude, and it is surrounded by hills that reach at altitudes of 1,480 masl (Habakubaho, 2021). Anthropogenic action has changed the landscape by various constructions. The site has had flood-prone area due to three main reasons: The area is a low land which receives water from the densely populated surrounding hills, the soil is clayey which have low infiltration rate (Kyanga, 2021).

### 3.2.1.2. Climate of Nyandungu wetland

Nyandungu wetland is characterized by a tropical wet and dry climate, which is modified by its high elevation. Its tropical climate is characterized by long wet seasons and relatively low temperatures because of its altitude. Its relatively low pluviometric annual module (between 1000-1300 mm) and clayey sandy soils. The average temperature is 20°C with an average minimum of 16°C and an average maximum of 28°C. More than 75% of the annual rainfall occurs during the short

rainy season (March to May) and the longer rainy season (September to December). Average rainfall during the short rainfall season is 360 mm and during the long rainy season is 338 mm<sup>85</sup>. (Gakuba, 2012).

### **3.2.1.3. Hydrology**

Nyandungu valley is drained by two streams: Mwanana and Kabagenda. Both flow into the Mulindi stream, a tributary of the Nyabarongo River. The Mwanana Kabagenda system contributes to the Mugesera-Rweru freshwater lakes and wetland system that is a major contributor to the Nyabarongo wetland-river system which has national and international significance (Habakubaho, 2021).

## **3.3.2 Secondary data collection**

### **3.3.2.1 Literature Search and Review**

A systematic literature review was conducted to gather information relevant to the study's objectives, which focused on understanding the functions of sponge cities, evaluating the outcomes of the Nyandungu Urban Wetland Restoration, and proposing additional interventions for flood risk reduction. The review began by defining research questions and objectives, followed by developing a review protocol with clear inclusion and exclusion criteria. The literature search targeted peer-reviewed articles, reports, and case studies from databases such as Google Scholar, PubMed, Scopus, and Web of Science, using specific keywords related to "sponge city approach," "wetland restoration," "urban flood risk," and "nature-based solutions." The inclusion criteria were studies published within the last 15 years (2009–2024), as this time span ensured coverage of both foundational research and recent advancements, relevant studies providing empirical data or case studies, and materials written in English. Exclusion criteria involved non-peer-reviewed studies, research outside the geographic or thematic scope, and documents lacking empirical evidence or accessible full texts. Titles and abstracts of search results were screened for relevance, and selected studies underwent a full-text review to extract detailed information on methodologies, outcomes, and themes.

In addition to the database search, various published materials were consulted through a comprehensive desk review. These materials included web documents and other records obtained from libraries and documentation units of public organizations such as the Rwanda Environment Management Authority (REMA), the City of Kigali, the Ministry in Charge of Emergency Management (MINEMA), the Ministry of Infrastructures (MININFRA), the Global Green Growth Institute-Rwanda (GGGI), the Rwanda Green Fund-FONERWA, and local administrative units like the Nyarugunga and

Ndera sectors in Gasabo and Kicukiro districts. The analysis emphasized empirical findings related to wetland functions and urban flood resilience, structured into frameworks and visualized through tables and figures. The review considered research detailing the ecological, social, and economic impacts of similar interventions while excluding overly theoretical or unrelated studies. This systematic approach ensured the literature's relevance to the study, providing comprehensive insights into proven practices and informing evidence-based recommendations for enhancing urban climate resilience through the restoration of Nyandungu Wetland.

### 3.3.2.2 Geographical Information Systems (GIS)

GIS and Remote Sensing was utilized to obtain different geospatial data which used in spatial analysis. A summary of sources of GIS data is in Table 3.1. below.

Table 3. 1 GIS data source

Data type	Format and Resolution	Year	Source
Nyandungu Landscape plan	Shapefiles,	2017	REMA, RDB
Drainage systems	Vector	2020,	REMA
Aerial Orthophoto	Image of 30 of resolution	2010, 2023	NLA, Google Earth, QGIS
DEM	10 m Raster	2023	USGS Earth Explorer
Landsat 4,7,8	Raster		USGS Earth Explorer/ESA
Landuse/Landcover	Raster		RCMRD Open data
Soil data	Shapefiles	2020	CGIS-UR
Administration boundary	Shapefiles	2024	National Lands Authority (NLA)
River	Shapefiles	2020	CGIS-UR
Rainfall data	Excel /Shapefiles/Raster	2010,2023	Mateo Rwanda
Road	Shapefile	2010,2023	Google Earth
Wetland	Shapefiles	2010	REMA

Source: (RCMRD, 2022; Stratford et al., 2011; Verisk Maplecroft, 2014).

Those data were collected to acutely understand the level of degradation that Nyandungu wetland has undergone in the past as well as understanding the NUWEP project aspirations. Those secondary data acted as a baseline of concluding whether the project objectives were or were not met.

### **3.3.3 Primary data collection**

#### **3.3.3.1 Field observations**

Field observation, and photo taking was conducted in the area understudy, to observe the established interventions. Current Land Use Land Cover and Impact of the catchment on wetland were observed. The used checklist can be found in Annex IX. Other information such the information associated with those interventions was recorded for further analysis. A camera was used to take pictures. Through field observation, current land use land cover of the Nyandungu wetland Eco-Park was observed and information related to wetland restoration interventions made during the implementation of NUWEP project were jotted down. Moreover, the visible challenges from the neighborhood of the park as well as in the whole catchment of Nyandungu that may have impact on the wetland were observed and relevant information were recorded including pictures which indicates the current status. GPS Garmin e-Trex 20 devices were used to captured coordinates of entries of drainage channels from neighboring area of the Watershed

#### **3.3.2.2. Interview**

Interviews were conducted with the Environmental Officer and Disaster Management Officer of Gasabo and Kicukiro Districts, as well as Social Affairs Officers of Nyarugunga and Ndera sectors. The Environmental Officer and Disaster Manager highlighted changes in environmental conditions and a reduction in disaster occurrences within the restored Nyandungu Wetland area. Meanwhile, the Social Affairs officers discussed the various benefits that the wetland restoration has brought to the local population. Moreover, four wetland experts, two EbA experts and five flood experts were interviewed. Both of those interviewees helped in choosing the main criteria and their weighting for flood susceptibility analysis as well as in weighting criteria used in suitability analysis of sponge city infrastructure for flood control in Nyandungu catchment.

### 3.3 Data processing and analysis

#### 3.3.1. Spatial data analysis

In this study, GIS data were used to reveal the benefits of Nyandungu wetland restoration and in suitability analysis of recommended sponge city infrastructure. This was done through flood susceptibility analysis, Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) analysis. Both flood susceptibility, NDVI and NDWI were analyzed for the years of 2010 and 2023 using ArcGIS 10.4 and QGIS Software. Those years were selected based on the available spatial data. Moreover, the time in which the wetland protection and restoration started as well as the time in the wetland were restored under NUWEP project and opened to the public was considered in the selection of those years. Suitability analysis was conducted based on current data.

#### 3.4.1. Flood Susceptibility analysis

Flood susceptibility analysis was done using Landuse LandCover (LULC), Precipitation, Slope, Soil texture, Distance from River and Topographic Wetness Index (TWI) to reveal an area which might be flooded once a heavy rain occurs (Mind'je et al., 2019). Those above mentioned factors were selected based on an intensive literature review and consultation of flood experts (Hirwa et al., 2023; Kaya & Derin, 2023; Mind'je et al., 2019; Samanta et al., 2018).

Flood susceptibility analysis require considering different factors that contribute to flooding hazards in certain area (Bora et al., 2022; Sakmongkoljit et al., 2021). Those biophysical factors, also called geo-environmental factors which helped to analyses the change in flood susceptibility of Nyandungu Urban Wetland eco-park were selected after an intensive literature to understand their contribution to the likelihood of flood occurrence and the help of experts. Moreover, weight assigned to those indicators (criteria or factors) is based on their level of influence as well as their contribution to susceptibility of the area. A Table describing the used factors and their relevance can be found in Annex I.

Table 6 Factors used in flood susceptibility analysis

Factors	Weight (%)
TWI	10 %
Slope	20%,
Elevation	10%,
Precipitation	15%,
LULC	20%
Proximity to river	10%,
Soil type	15 %

CR= 3.9%.

Those weight were obtained based on the use of AHP approach and consultation of experts from REMA, Gasabo and Kicukiro District and in Ndera and Nyarugunga sectors and university of Rwanda. The analytical hierarchy process (AHP) is one of the most widely used and effective methods in disaster modeling, such as flood monitoring, mapping, and problem analysis (Hirwa et al., 2023; Hussain et al., 2021; Nsangou et al., 2022).

### 3.4. 3. Spatial Multiple criteria analysis for sponge city infrastructure

Geospatial data also supported in suitability analysis of suitable location of sponge cities infrastructure. To come up with relevant information different literature were consulted (Asare et al., 2024; Christiana, 2023; Maleki et al., 2018), hence LULC, Distance to rivers, Soil texture, Soil Hydrological group, Elevation, and Slope were used as criteria for suitability analysis of location of sponge city infrastructures using Weighted Linear combination(WLC).

Weighted Linear combination or simple additive weighting, which is one of GIS-based Multi-attribute Decision Analysis is based on the concept of a weighted average in which continuous criteria are standardized to a common numeric range, and then combined by means of a weighted average (Drobne & Lisec, 2009). In this approach the decision makers assign the weights of relative importance directly to each attribute map layer. The total score for each alternative is obtained by multiplying the importance weight assigned to each attribute by the scaled value given for that attribute to the alternative and then summing the products over all attributes (Mendas & Delali, 2012).

$$S = \sum w_i x_i \quad (1)$$

In this formula  $S$  stands for suitability,  $W_i$  is weight of factor  $i$ , and  $x_i$  is the criterion score of factors. This approach was combined with Analytical hierarchical process (AHP) and consultation of experts to determine the weight of each factor. The selection of suitable location of sponge city interventions for Urban Flood Mitigation in Nyandungu catchment was done based on five criteria indicate in table 6 below.

Table 7 Weighting of factors used in Suitability analysis

Factors	Weight (%)
LULC	19
Distance to rivers	15
Soil texture	16
Soil Hydrological group	14
Elevation	20
Slope	16

CR = 2.8 %.

Those factors were weighted using the same weighting approach (AHP) as well as the consultation of experts. Relevance of the selected factors can be found in annex II.

### 3.4.2. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is the most used vegetation index for observing greenery globally. High reflectance in NIR and high absorption in red spectrum, are the two bands that are used to calculate NDVI. So, the following formula gives Normalized Difference Vegetation Index (NDVI).

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \dots\dots\dots (2)$$

The NDVI value varies from -1 to 1. Higher the value of NDVI reflects high Near Infrared (NIR), means dense greenery. This Index was analysis in years of 2010 and 2023 to understand the change in wetland after wetland restoration. NDVI Maps can be found in Annex IV.

### 3.4.4. Normalized difference built-up index (NDBI)

The Normalized Difference Built-Up Index (NDBI) is a spectral index used in remote sensing to identify urban and built-up areas. It leverages the difference in reflectance between built-up surfaces and vegetation, using specific bands from satellite imagery.

$$\text{NDBI} = (\text{SWIR} - \text{NIR}) / (\text{SWIR} + \text{NIR}) \dots\dots\dots (3)$$

This index was analyzed to understand the ration of built-up area in the catchment. High NDBI is associated with high runoff which cause flooding downstream (Hoang &

Liou, 2024).

#### **3.4.5. Sediment transport Index (STI)**

The Sediment Transport Index (STI) is a measure used in soil erosion studies to quantify the potential for sediment transport by water. The STI, or Sediment Transport Index, is a crucial tool for obtaining essential information about the sediment movement in each basin. Its map can be found in Annex IV.

#### **3.3.2. Non-spatial data analysis**

Non-spatial data were prepared and analyzed using Microsoft Excel 2019. This software was used to turn those data into charts and tables. Those data include historical data of wetland visitors, historical data extracted from ArcGIS, data collected from interview as well as data collected from field observation and counting.

## CHAPTER IV RESULTS AND DISCUSSION

This chapter presents and describes the findings derived from the comprehensive analysis of the data collected, in line with the research objectives outlined in Chapter I. An interpretation of these findings is provided, addressing the research questions and incorporating insights from existing scientific literature. The chapter explores key aspects, including the established flood risk reduction interventions implemented during the restoration of Nyandungu Wetland into a park. It further reveals the benefits of these restoration efforts on flood risk reduction, defines the functions of Sponge City concepts in relation to mitigating flood risks, and recommends specific Sponge City infrastructures to enhance the Nyandungu wetland Eco-Park

### **4.1. Overview of key interventions for flood risk reduction in Nyandungu wetland**

To understand the benefits of established flood control benefits after Nyandungu wetland restoration the first step was to review the established interventions during the wetland restoration into park and their contribution to flood risk control. The literature review conducted revealed that during the restoration of Nyandungu wetland different interventions were established. Those intervention were established through established Sustainable Urban Drainage interventions and restoration of degraded vegetation using EbA interventions primarily for flood curbing (REMA, 2024). Those interventions include planted filtration Plants (vegetated swales or biofiltration basin), rehabilitated attenuation Ponds such as Pond Muhazi, Pond Kivu, Pond Ruhondo and Pond Ihema (REMA, 2024). Widened channels of Mwanana and Kabagenda River's to increase their capacity to transport water. Those interventions were restored to slow down the run off ,infiltrate and purify water in the wetland (Habakubaho, 2021; REMA, 2022b)

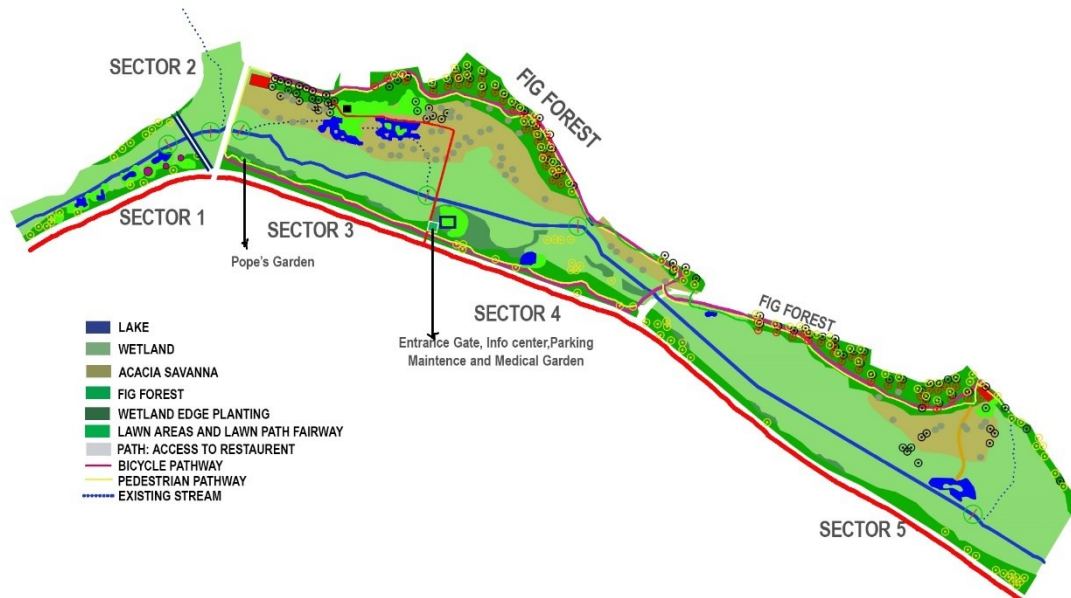


Figure 13 Interventions established in Nyandungu wetland restoration

Source: REMA, 2024.

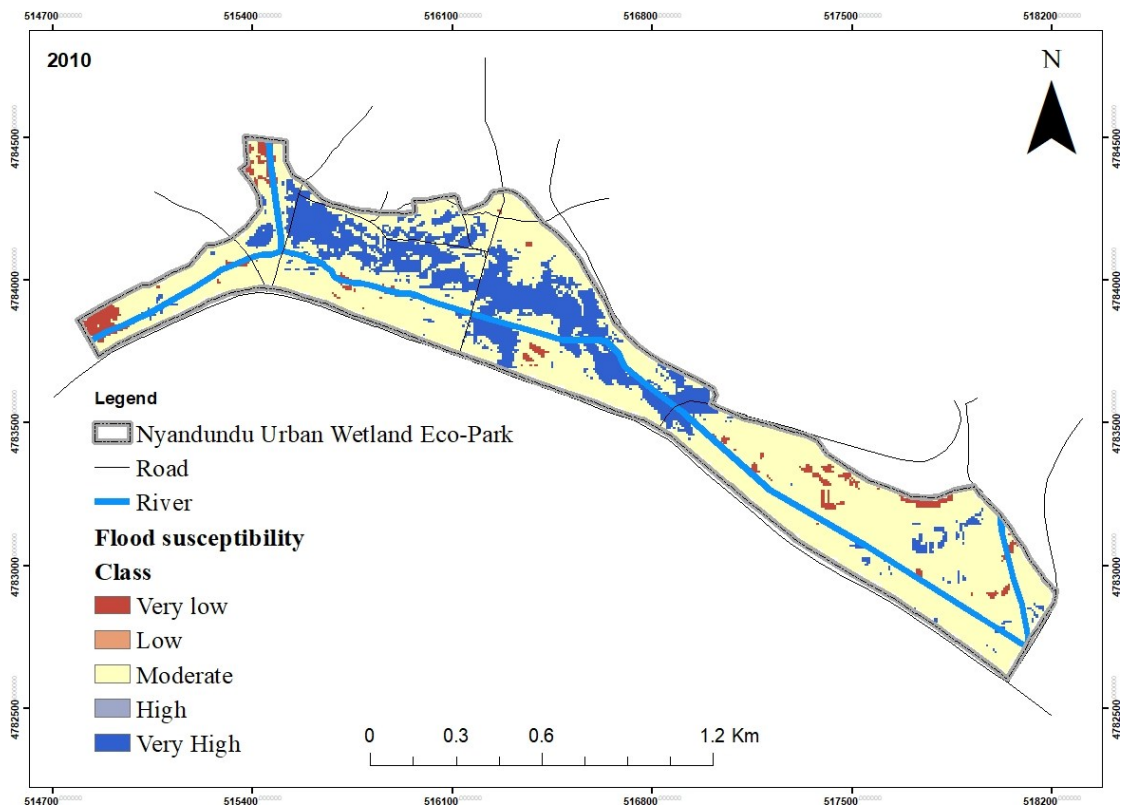
As indicated in figure 12 above, the park was designed into five sectors (zones) which have different interventions. Sector one is comprised of filtration plants and actuation ponds. This sector is full of nature in terms of filtration plants and attenuation Ponds. Its main function is to reduce the speed of the water as it filters into the rest of the wetland. Sector two which is the smallest of all the sectors is comprised with filtration plants. It also has species of filtration plants to further slowdown and clean the water. Sector three which the Sector three is the center of the ecotourism activities in the park is comprised with walkaways and bicycle lane, pond Muhazi, pond Kivu, pope's garden, recreation area, and parking. Sector four is comprised with walkways and Bicycle lanes, medical gardens, pond Ruhondo and recreation area. The sector is a mix of light ecotourism activity as well as natural processes including filtration and slowing down of water. Last but not least, is the sector 5 is comprised with walkways and pond Ihema. Sector 5 which is the biggest of all sectors is the final processing point for the wetland. It hosts the Ihema pond Ihema and plenty natural forests and filtration plants (REMA, 2024).

## 4.2. Benefits of Nyandungu wetland restoration on flood risk reduction

Benefits of Nyandungu wetland restoration was analysed to assess the impact of the established interventions in reducing the flood risk and other associated impacts which have been affecting this wetland for a long time. Results from the conducted analysis are discussed below.

### 4.2.1. Change in flood susceptibility in the restored area

The analysis conducted revealed that the flood risk has reduced as outcome of the interventions undertaken. This analysis revealed that very high susceptibility area reduced from 26 Ha in 2010 before wetland restoration to 2 Ha in 2023. Area that is less susceptible to flooding increased from 30 Ha to 119.7 Ha in the park. This indicate that the flood curbing objective was achieved from the established interventions. Based on the figure 14 below, results indicate that flood has reduced in interventions area especially in sector 1 up to sector 4 where interventions like pond Muhazi, Pond Kivu, Pope’s Garden, pond Ruhondo and many others were established. Moreover, it’s in this area where the highly degraded vegetation was restored (REMA, 2024).



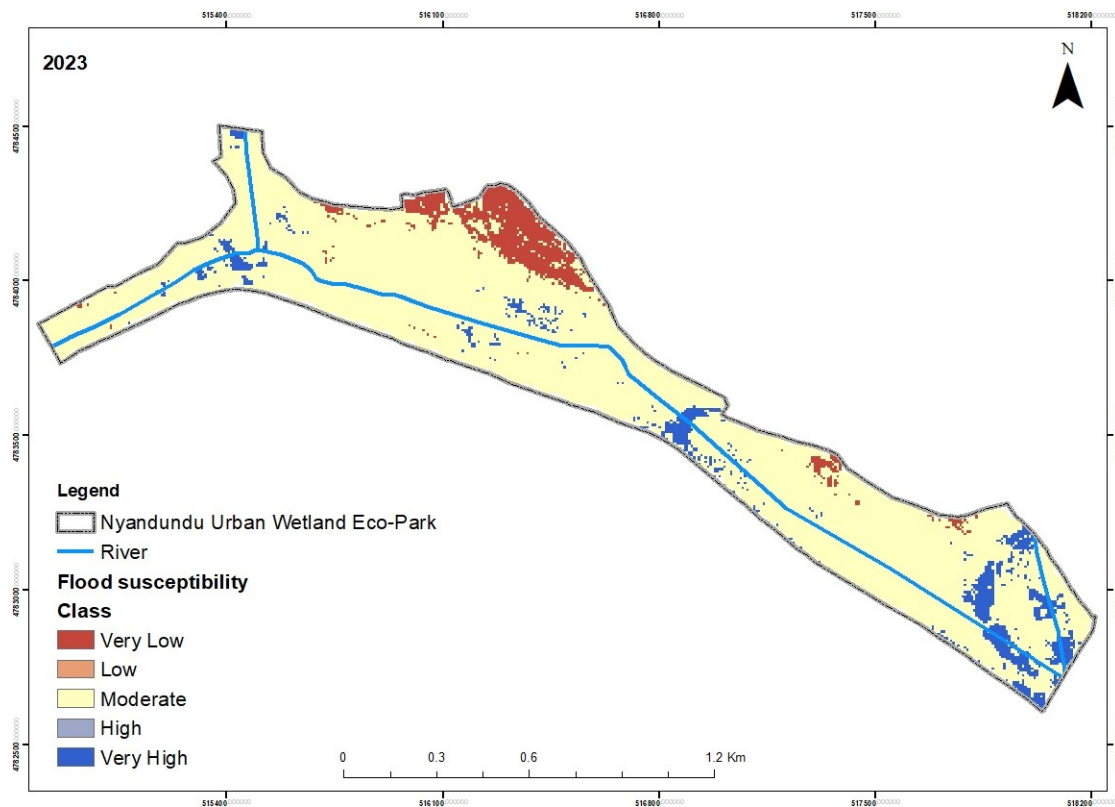
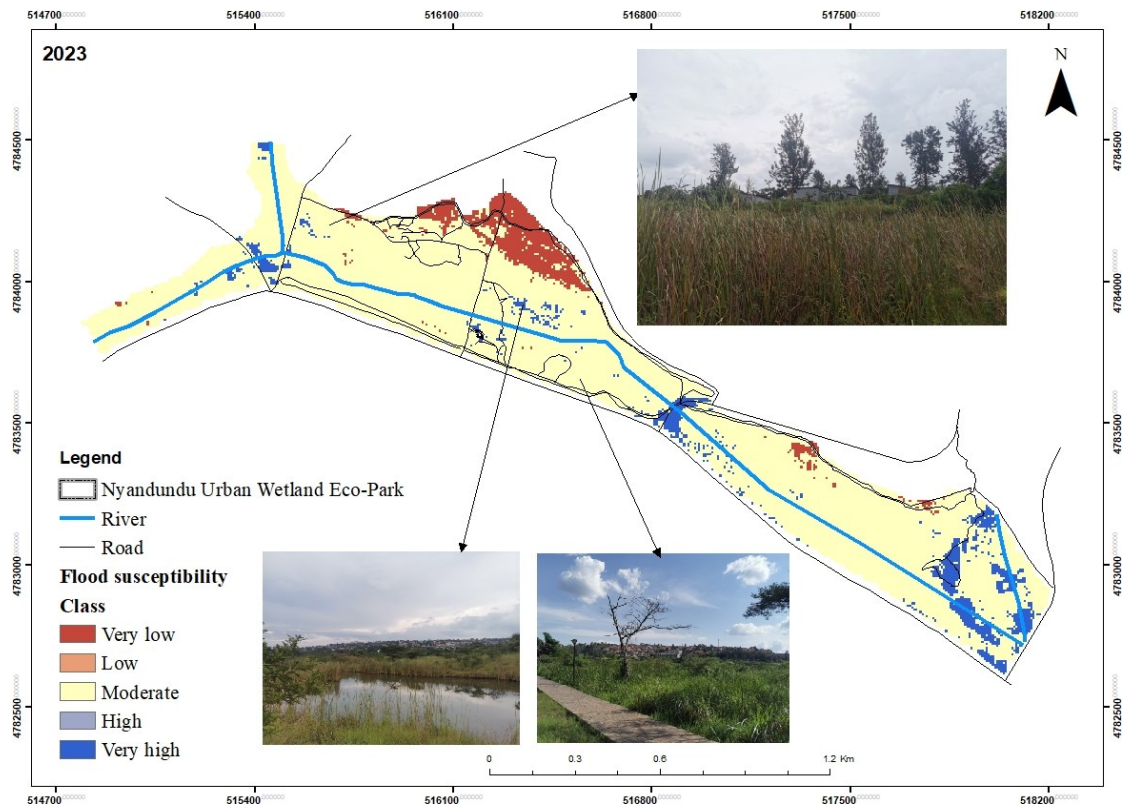


Figure 14 Flood Susceptibility in 2010 and 2023

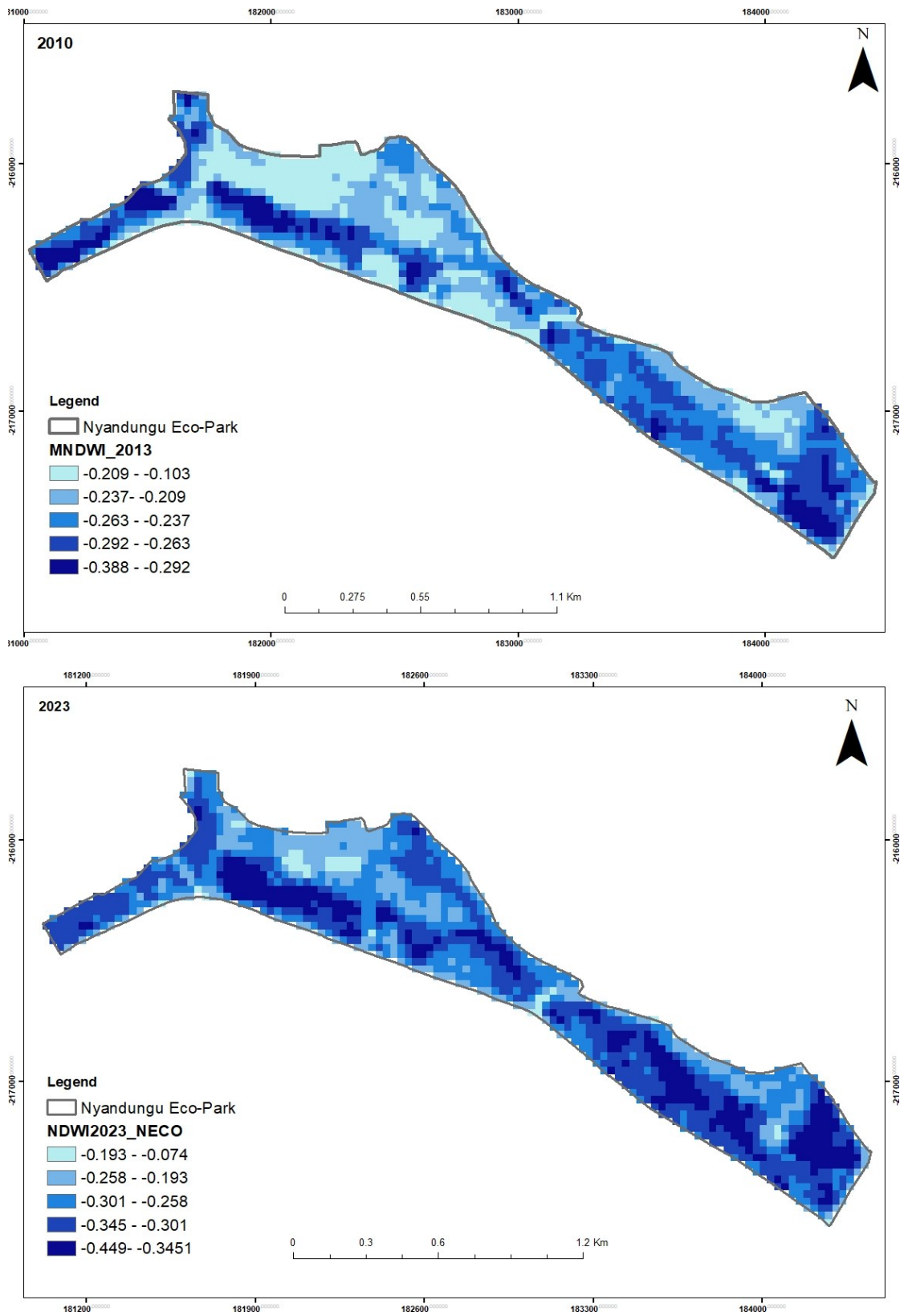
Source: <https://earthexplorer.usgs.gov/>

Conserved and restored urban wetlands have the potential to reduce urban flooding while buffering storm surges, since they act as sponges, potentially shielding urban dwellers from extreme weather impacts such as flooding (Dooley & Stelk, 2021; Nzuve, 2023). The reduction in flood susceptibility in Nyandungu wetland as a result of its restoration is similar to the outcomes of the study conducted by (Zhang & Kondolf, 2024) which indicated that established interventions such as ponds has reduced flood in Lower Yellow River wetland in China.



#### 4.2.2. Increase in wetland water content

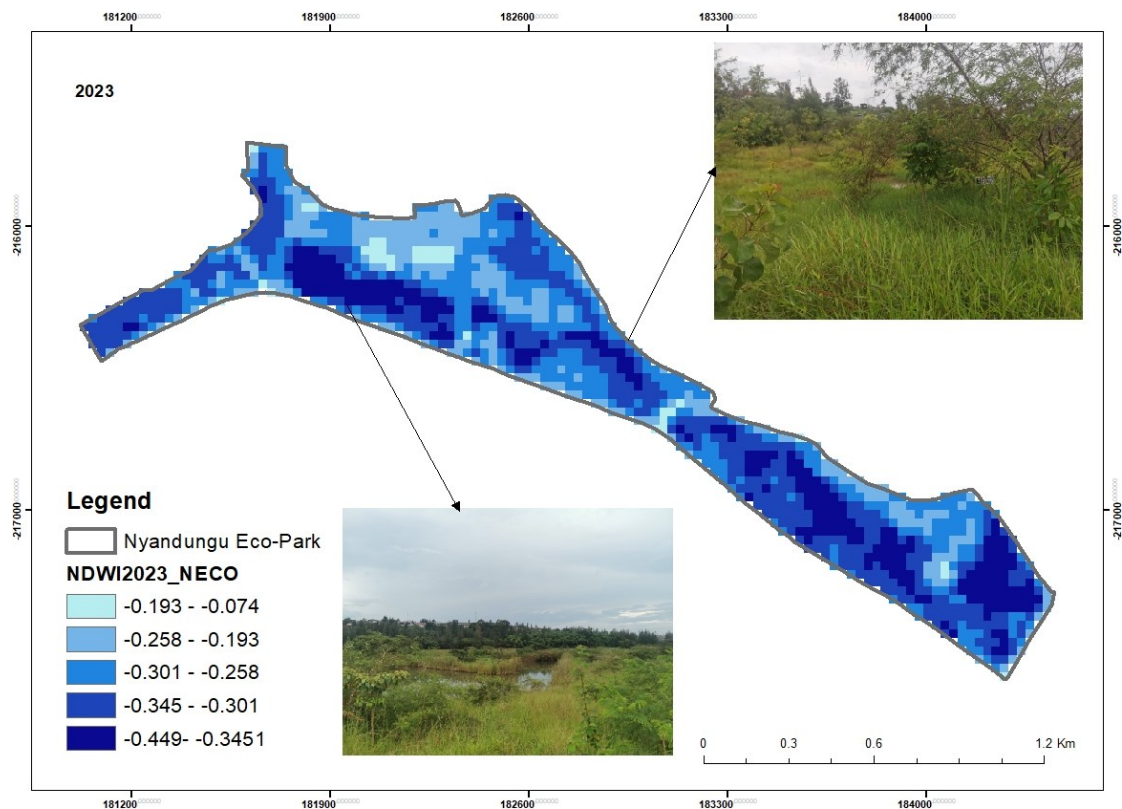
Despite the facts that the flood susceptibility has reduced, it worth noting that the wetland sponginess was increased because of restoration interventions. The analysis of Modified Normalized Difference Water Index (MNDWI) revealed that the wetland capacity to restore water has increased.



Source: <https://earthexplorer.usgs.gov/>

Figure 15 Modified Normalized Difference Water Index

Results from the analysis revealed that the area with high water content increased from 2014 to 2024. The comparison of NDWI values between 2014 and 2023 for the Nyandungu area reveals significant changes in water content and vegetation moisture. The are of NDWI in 2014 are as follows: Range 1: 12.17 hectares which accounts for (10.0%), Range 2: 18.24 hectares (15.0%), Range 3: 24.34 hectares (20.0%), Range 4: 30.42 hectares (25.0%) and Range 5: 36.50 hectares (30.0%). For the case of NDWI 2023, Range 1: 13.40 hectares (11.0%) Range 2: 17.87 hectares (14.7%) Range 3: 24.57 hectares (20.2%) Range 4: 30.14 hectares (24.8%) and Range 5: 35.74 hectares (29.4%). The shift in areas covered by different NDWI ranges indicates changes in water content and vegetation moisture in the Nyandungu area from 2014 to 2023. The area in which the water content increases is the area in which the interventions have taken place.



Restoring urban wetlands using nature-based solutions has proved to increase its sponges by holding more water (USEPA, 2000) The restoration of Nyandungu wetland increased its capacity to hold water by acting as sponge during and after flood events. Ponds are among the major interventions that contributed to flood reduction in Nyandungu wetland. A study conducted by Fennessy & Lei (2018) revealed that wetland restored using Nature based Solutions including the restoration and creation of ponds reduced flooding risk in the area of interventions. Wetland vegetations has been regarded as one of the best ways to slow down and prevent flooding in the

wetland. In addition, it increases water content in the wetland which make a Wetland a sponge (Acreman & Holden, 2013).



Figure 16 Flood curbing interventions

Source: REMA, 2024

The picture in figure 16 above indicate some of the ponds established in the wetland. Moreover, restored vegetation and widened river channel were vital in increasing water content in the wetland.

#### 4.2.3 Change in vegetation cover in restored Area

The analysed Normalized Difference Vegetation Index (NDVI) of 2010 and 2023 revealed that this index has steadily increase between the analysed years. Generally, NDVI increased from 0.351 to 0.495, this indicate that the vegetation in the wetland became healthy in 2023. In 2010, the NDVI values, ranging from 0.092 to 0.351, show relatively sparse vegetation with large areas dominated by lower NDVI values, indicating a degraded ecosystem. However, by 2023, the NDVI values, now ranging from -0.006 to 0.495, reflect a substantial increase in vegetation density, with higher NDVI values covering a larger portion of the wetland.

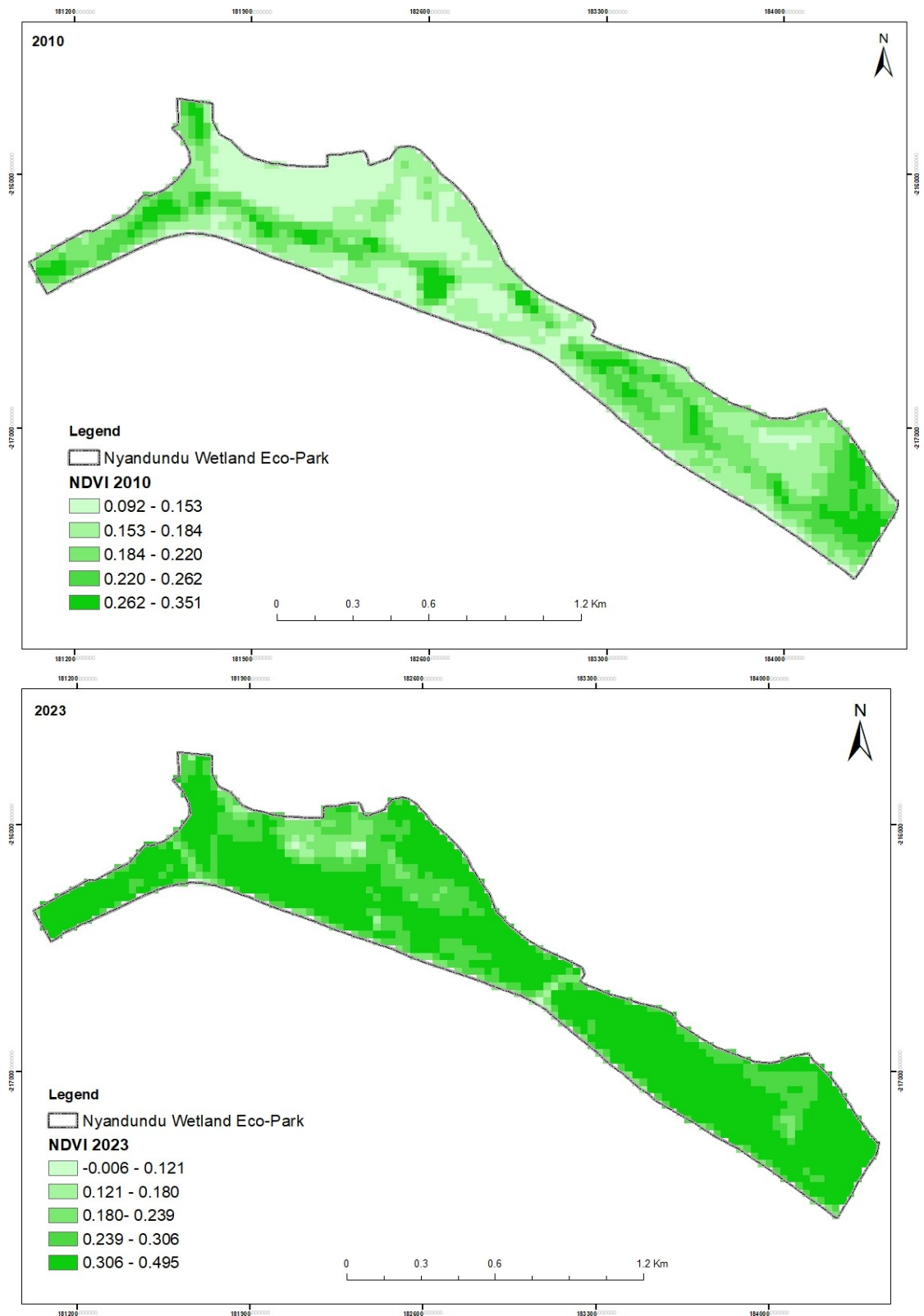


Figure 17 Normalized difference vegetation index

Source: <https://earthexplorer.usgs.gov/>

This shift suggests that restoration efforts, including the use of nature-based solutions such as pond construction and the reintroduction of native plant species, have successfully revitalized the wetland. The overall improvement in vegetation health is a clear indicator of the wetland's ecological recovery and enhanced ability to function as a natural sponge, contributing to flood control and increased biodiversity. However, it is worth noting that the lowest value of NDVI is found in 2023. This value is from Building and Paved Road established in wetland. The increase in NDVI value indicate that vegetation in the wetland was restored as planned under the project (REMA, 2022f).



Figure 18 (a) and (b) Degraded vegetation before restoration (c) and (d) Vegetation after wetland restoration

Destroyed vegetation were cleared as a result of quarrying activities (Habakubaho, 2021). Those destroyed vegetations were restored under NUWEP project.

### **4.3. Nyandungu wetland restoration in light with wetland and storm water management principles**

The second step was to understand the effectiveness and sustainability of the above-mentioned benefits from the established interventions during Nyandungu wetland restoration. This was achieved through the analysis of the used approach, wetland design principles, storm water management principles considered as well as the current and future impacts of the catchment LandUse change on the restored wetland.

Results from a literature review conducted revealed that Nyandungu wetland restoration has undoubtedly generated great benefits in terms of flood curbing (REMA, 2024). However, after several trips conducted to the park in different rainy seasons and literature review conducted to both Nyandungu Urban Wetland Eco-Tourism Park (NUWEP) project and wetland restoration principles, some of the observation found resulted in the idea of conducting a study to recommend other flood control interventions to establish in Nyandungu catchment to prevent future impacts that may affect the park.

The conducted review on NUWEP Project revealed that Nyandungu wetland was restored on wetland level and not catchment level (REMA, 2024; Ssinabulya, 2015). This is different from the wetland restoration principles suggested by Ramsar Convention on Wetlands, United States Environmental Protection Agency (US EPA). Besides, this restoration do not comply with the 13<sup>th</sup> resolution taken in COP 8 (Ramsar Convention on Wetlands, 2002; USEPA, 2000) .which suggest that “While restoring urban wetland, the impact of the watershed/catchment on the wetland which is going to be restored should be considered. Similar to the principles of wetland restoration; scholars and experts indicate that urban storm water management should be done at catchment level in order to avoid flooding in downstream (Harris, 2022; Wong et al., 1999; H. Xu et al., 2023). According to the literature review and field survey conducted, the afore-mentioned principles were not considered during the designing process of Nyandungu wetland restoration. In this line, to shed a light on the future impact of the catchment, various analysis indicated below were conducted to reveal the impact that the catchment may exert on the restored part of the wetland and to later recommend action to be undertaken

### 4.3.1. Change in LULC, NDBI, NDVI and Status of Sediment Transportation Index (STI) in the catchment

The analyzed change of Land use Landcover of 2010 and 2023, Normalized Difference Built-up Index (NDBI), Normalized Difference Vegetation Index (NDVI) and flood susceptibility of 2023 indicated a need to establish interventions in Nyandungu catchment to capture water before their reach downstream. The analysis conducted indicated that the Land use Land cover (LULC) is increasingly changing in Nyandungu Catchment due to its urbanization. Results from this analysis revealed that built area increased from 149 Ha to 239 ha in a total of 3149 Ha for the whole catchment. The analyzed NDBI Normalized Difference Built-up Index (NDBI) of 2023 was found to be high where an area that is equal to 239 Ha were found to be in area with high NDBI

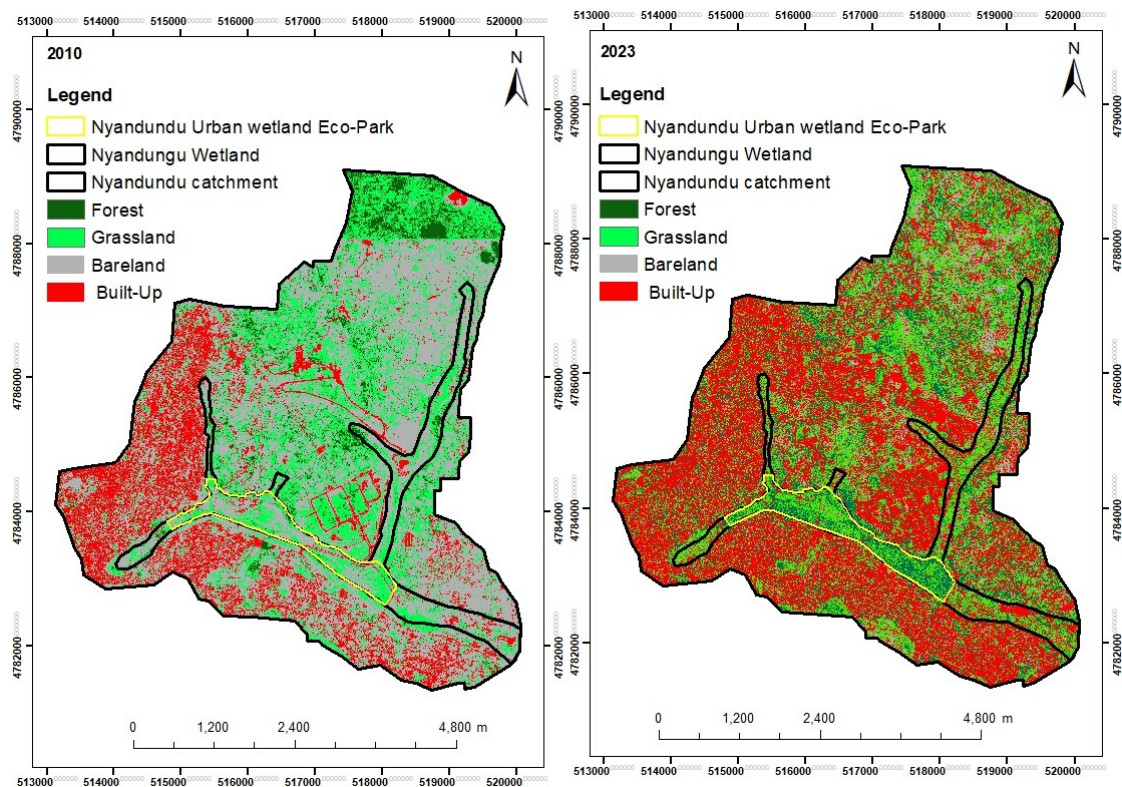


Figure 19 LandUse LandCover Change

This change is worth considering because it has a direct impact on the Nyandungu as it is in the lowland. Several studies revealed that the change in built up area has a direct impact on runoff generated by the catchment (Chilagane et al., 2021; Sajikumar & Remya, 2015; Waikhom et al., 2023). Based on the finding from the analyzed data,

Nyandungu Catchment might experience high run-off in the future due to increase in built up area as indicated in figure 19 above.

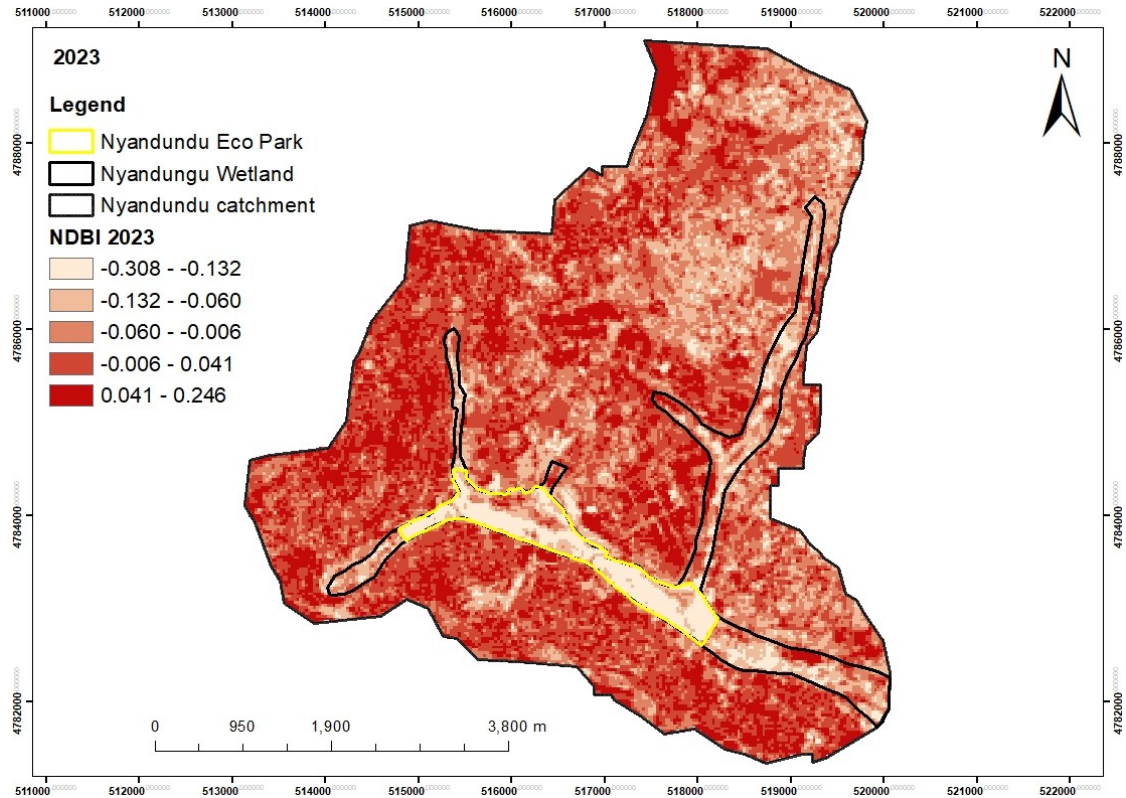


Figure 20 Normalized Difference Built up Index

This indicates that if the catchment continues to urbanize more there will be an increase in run-off from the catchment that flows towards the wetland. In addition, a Sediment Transportation Index (STI) analyzed for the whole catchment indicated that this index ranges from 0 to 204.368 (See annex IV). Moreover, the NDVI change detection of 2010 a 2023 conducted revealed that the vegetation reduced a lot in the catchment replaced by built up area (See figure 20). This may hinder the ability of this wetland in managing the flood, given that Nyandungu catchment is becoming more urbanized with a lot of buildings and paved areas, together with the change in rainfall pattern due to the emerging climate change, it might increase the surface water run-off running towards the wetland.

#### 4.3.2. Floods susceptibility in Nyandungu catchment

In terms of floods susceptibility, the catchment was found to have an area which is highly susceptible where 60 % of the catchment were found to be highly susceptible,

21 % moderate, 10% low and 9% very low.

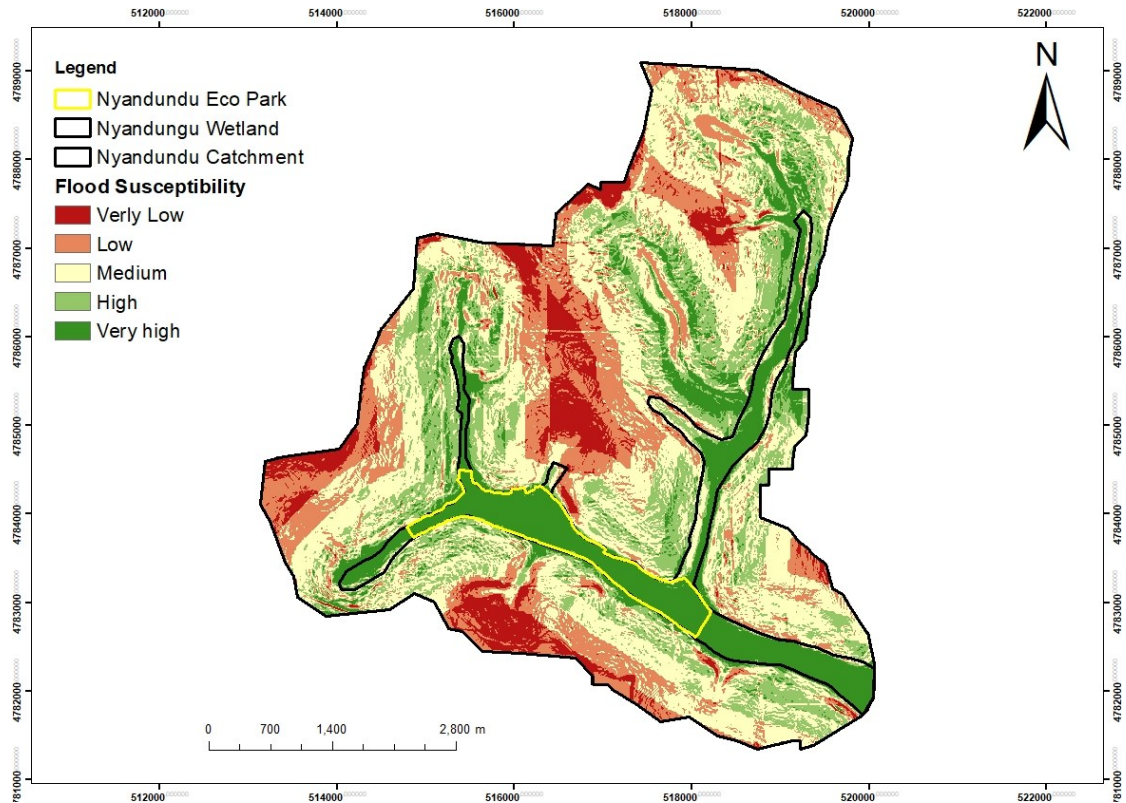


Figure 21: Flood Susceptibility in Nyandungu Catchment

Based on all the above information an analysis was conducted to recommend suitable sponge city infrastructure that can be added to the catchment to enhance the restoration of Nyandungu catchment by making catchment a sponge.

#### 4.2. Functions of sponge city in relation to flood risk reduction

Since its emerging sponge city have been regarded as the best Ecosystem based Adaptation approach for urban flood adaption under climate change (Ma & Jiang, 2023b). This approach uses its infrastructures such as green roofs and walls, permeable pavements, rain gardens and bioretention areas, permeable surfaces, infiltration trenches and basins, detention and retention ponds, constructed wetlands, vegetated swales to reduce flood risk through retention and absorption of Stormwater; increase Infiltration and Groundwater Recharge; Runoff Reduction and Delay (Bah et al., 2023; Rau, 2022).

#### **4.2.1. Retention and absorption of Stormwater during flooding**

In retention and absorption of Stormwater during flooding sponge city uses different of its infrastructure to retain and absorb run off and rain water (Han et al., 2023). A Study conducted by Liu et al.(2020), revealed that permeable pavement tested under low- and high-intensity rainfall cases recorded approximately 52.5% and 42.5% average runoff retention, respectively. United state-Environmental Protection Agency (EPA) revealed that green roofs can retain 70-90% of rainfall during moderate storms and up to 40% during heavier rainfall events, thereby reducing stormwater runoff and mitigating flood risks (US-EPA, 2013). Rain gardens and bioretention areas can reduce runoff volume by 30-70%, depending on design and site conditions, Detention ponds can reduce peak flow rates by up to 20-40%, downstream during heavy rain event, Vegetated swales can reduce peak flow rates by up to 65% and decrease runoff volume by 30% (Malaviya et al., 2019; L. Zhang et al., 2020). The reduction of run off helps to manage stormwater and reduce flooding downstream.

#### **4.2.2. Infiltration and groundwater recharge**

Studies revealed that sponge cities can increase infiltration rates by up to 50% compared to conventional urban areas. Moreover, groundwater recharge rates in sponge cities can be significantly higher, with some studies reporting up to 70% improvement in recharge capacity. Xiamen implemented a Sponge City pilot project covering about 4.2 square kilometers in 2015. By 2019, the project had seen an increase in green space by 16.3%, with over 163,000 square meters of newly added green areas. The Sponge City project in Xiamen managed to increase the city's rainwater utilization rate to 70%, up from the previous rate of 35%. As a result of the green infrastructure implemented, Xiamen now retains up to 60% of stormwater runoff, compared to only 20% before the project's implementation. Groundwater levels in Xiamen have shown a consistent rise since the initiation of the Sponge City project, with an average recharge rate of 25,000 cubic meters per day (Jiahong & Chao, 2023)

#### **4.2.3. Runoff Reduction and Delay**

Sponges, through their porous and absorbent structure, significantly contribute to runoff reduction and delay. When integrated into green infrastructure, they capture

and retain rainwater, reducing the volume of immediate surface runoff. For example, a study by (J. Wang et al., 2021) found that green infrastructure practices mimicking sponge-like properties can reduce surface runoff by up to 30% in urban areas with high impervious surfaces. This absorption not only helps to mitigate flooding by reducing the volume of runoff but also slows the rate at which water enters drainage systems. Moreover, research conducted by (Rodríguez-Rojas & Grindlay Moreno, 2022) demonstrated that green infrastructure features acting as sponges can delay the peak flow of stormwater by up to 50%, providing valuable time for drainage systems to cope with excess water and reducing the risk of urban flooding. Overall, sponges act as a buffer, balancing water flow during and after precipitation events. A table 5 below indicate some of the identified uniqueness of sponge city interventions and their contribution to flood risk reduction based on their functions

**4.2.4. Relationship between functions of sponge city infrastructure and their outcome**

It is worth noting that most of the sponge city infrastructures are multi-functional. These functions are interrelated as one contribute to another and for some case an infrastructure has two or more functions (Y. Peng & Reily, 2021). This makes the sponge city a powerful approach to urban flood adaptation.

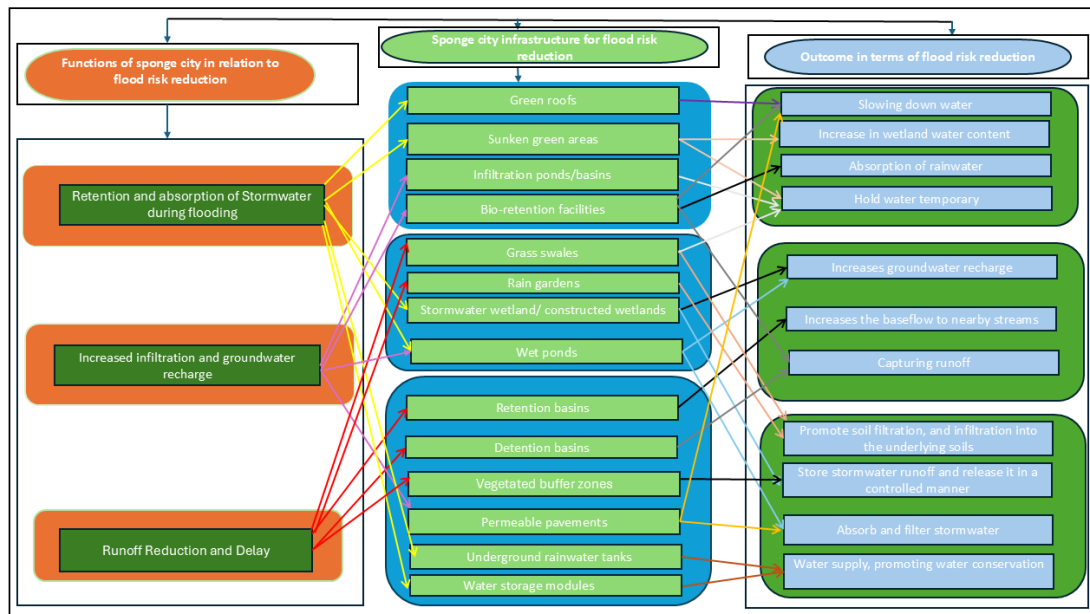


Figure 22: Relationship between different aspects of sponge city approach in flood risk reduction

The above figure illustrates the relationship between the functions of a sponge city for flood risk reduction, the corresponding infrastructure, and the resulting outcomes. Sponge cities aim to retain and absorb stormwater during flooding, increase infiltration and groundwater recharge, and reduce and delay runoff. To achieve these functions, sponge city employs various infrastructures such as green roofs, sunken green areas, infiltration ponds, bio-retention facilities, grass swales, rain gardens, and stormwater wetlands, among others. Several Sponge City infrastructures share similar functions related to flood risk reduction. For the retention and absorption of stormwater during flooding, elements such as infiltration ponds/basins, bio-retention facilities, grass swales, stormwater wetlands/constructed wetlands, and rain gardens are crucial. These systems work to slow down and absorb rainwater, effectively managing stormwater retention and mitigating flooding. In terms of increased infiltration and groundwater recharge, infrastructures like wet ponds, infiltration ponds/basins, bio-retention facilities, rain gardens, vegetated buffer zones, and permeable pavements facilitate the infiltration of water into the ground, promoting the recharge of groundwater sources. For runoff reduction and delay, structures such as retention basins, detention basins, underground rainwater tanks, and water storage modules play a significant role. These systems are designed to store excess water temporarily and release it in a controlled manner, helping to delay and manage stormwater runoff, thereby reducing flood risks. Overall, many of these infrastructures are multifunctional, contributing to various aspects of flood risk reduction by combining stormwater absorption with controlled release.

### **4.3 Recommended Sponge city infrastructures**

#### **4.3.1. For the whole catchment area**

The analysis results identified areas within the catchment, including the restored wetland area, where specific Sponge City infrastructures can be implemented. Figure 22 below presents four categories Type 1, Type 2, Type 3, and Type 4. Each category represents specific types of Sponge City infrastructure recommended for particular areas of the catchment. These recommendations were made based on the distinct

characteristics of each area considered during the analysis.

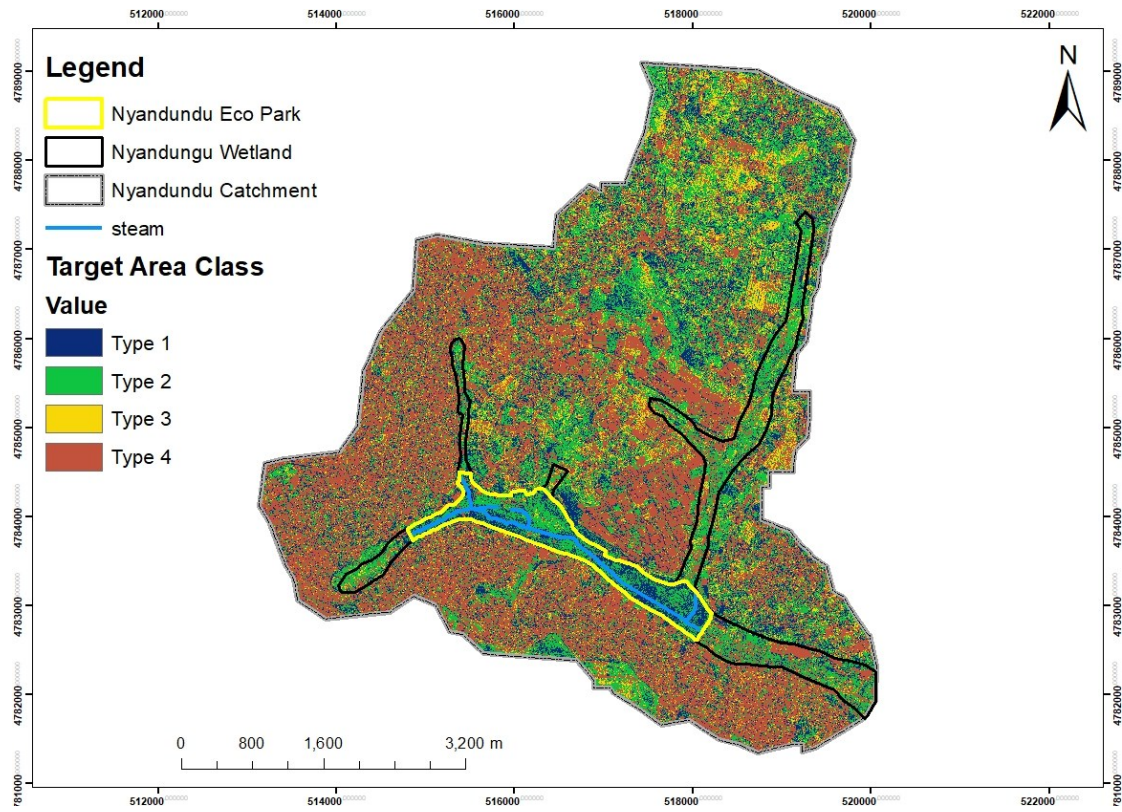


Figure 22: Area for specific intervention in Nyandungu catchment

Major infrastructure recommended infrastructure that can be established in the catchment includes green roofs, vegetated swales, rain gardens, underground rainwater tanks, detention basins, Sunken green areas and porous pavements. The restored part of the wetland can be enhanced by adding Vegetated swales, Infiltration ponds/basins, Sunken green areas, Bioswales and Wet ponds. The non-restored part of the wetland can be restored using similar infrastructures of Nyandungu wetland eco-park and add almost all the sponge city infrastructure in table 8 below. Those infrastructures were selected based on literature review, characteristics of the catchment, field observation, geospatial analysis and consultation of experts. A table 8 below describes in the details the selected infrastructures.

Table 8 Characteristics of the different target areas

Target area	Characteristics	LULC	Distance to rivers	Soil	Elevation	Slope	Suitable infrastructure	Sponge city
Type 1	Made up of 65% forest and grassland, 25% built-up	83% of the area is outside a buffer of 400 m to the nearest river	Made up of 78.5% sandy-loamy soil	Made up of 57% moderate to high elevation areas	72% of the area falls within high slope	*Green roofs *Porous pavements *Vegetated swales *Sunken green areas *Infiltration ponds/basins		
Type 2	Made up of 72% built-up	65% of the area is outside a buffer of 400 m to the nearest river	88% sandy and sandy-loamy soils	Made up of 69.5.7% moderate to high elevation areas	Made up of 70% high slope area	*Green roofs *Porous pavements *Underground rainwater tanks *Rain gardens *Bioswales *Wet ponds *Stormwater wetland/		
Type 3	78 % of this area is built-up	57% of the area is outside a buffer of 400 m to the nearest river	Made up of 86.4% sandy and sandy loamy soils	About 40% of low elevation areas	Made up of 72.8% low slope areas	*Green roofs *Porous pavements *Vegetated swales *Detention basins *Bio-retention facilities		
Type 4	The area is 82%builtup	70% of the area is within a buffer of 400 m close to rivers	More than 67% of the area is made up of sandy and loamy soils	82% of the area is relatively low land	88% of these areas are generally low slope	*Green roofs * Underground rainwater tanks * Permeable pavements * Water storage modules * Retention basins * Detention basins * Sunken green areas		

### 4.3.3. Specific interventions at the entry point of water from catchment

To effectively manage runoff at the entry points where water from Nyandungu catchment flows into the Nyandungu Urban Wetland Eco- Park, a flow accumulation map that shows where water from the catchment drains towards the wetlands was analyzed and is indicated below. The red dots indicate where water drains in the restored area of the wetland either through natural channels or created drainages

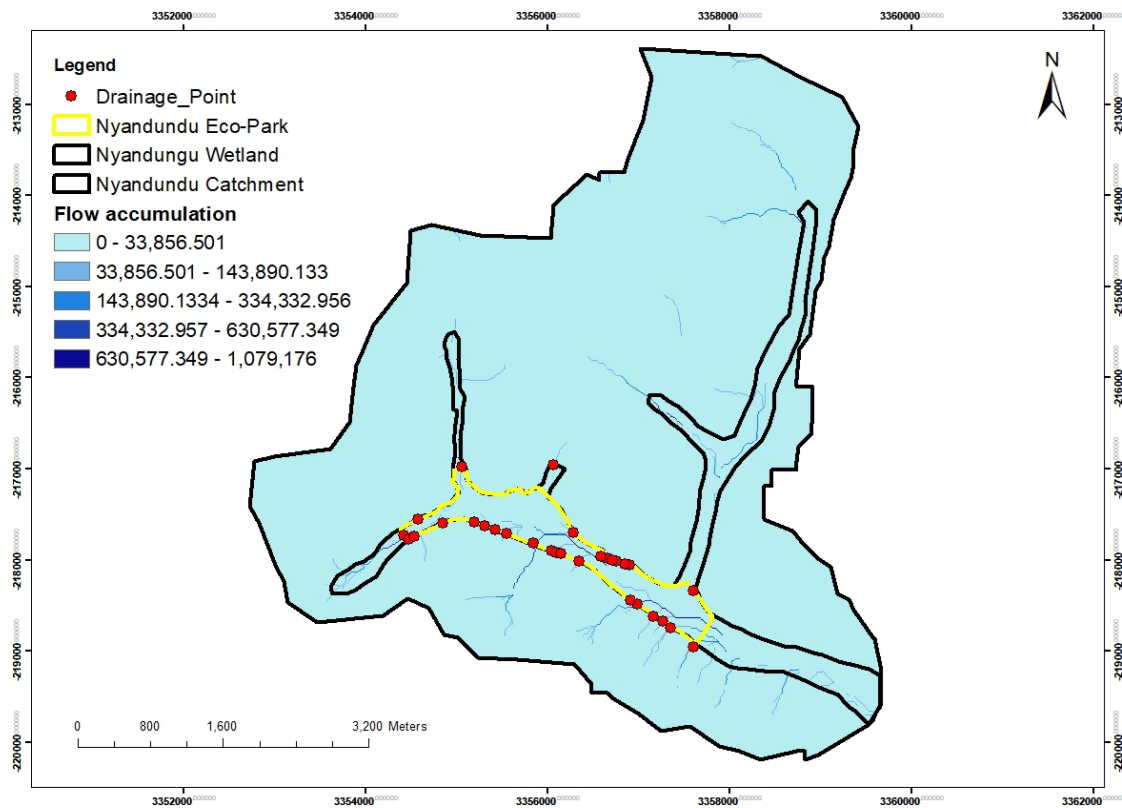


Figure 23 Run-off entry point

This analysis was conducted to propose sponge city infrastructure that can be established at those entry points. The recommended sponge city infrastructures include bioswales, Grass swales and Infiltration ponds/basins. As Nyandungu catchment is becoming more urbanized which increases runoff from the catchment towards the wetland, these infrastructures will capture, filter, and infiltrate stormwater right at the entry points, reducing the volume of water that reaches the wetland and improving the quality of water entering the wetland.

In summary, Nyandungu urban wetland restoration have reduced the flood risk on the wetland via the established interventions. Those interventions have restored vegetation at wetland level and increased water content in the wetland. However, the wetland was restored at wetland not catchment level where the continuous urbanization of the catchment coupled with climate change may increase the run off from the catchment. This run off may deteriorate the restored area. In this line, the sponge city interventions were recommended to be established in the catchment as well as in entry points of the water which flow from the catchment towards the wetlands.

## CHAPTER V CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusion

Urban wetlands have been greatly affected by urban expansion and climate change. As cities continue to face frequent flood events, countries have directed their efforts towards the restoration of urban wetlands as a strategy to enhance city resilience. Various approaches, including Sustainable Drainage Systems (SUDS), Low Impact Development (LID), Best Management Practices (BMPs), Water-sensitive Urban Design (WSUD), and Sponge City, have been employed in urban wetland restoration. However, given the escalating intensity and frequency of floods resulting from climate change, along with the growing interest in the implementation of Blue Green Infrastructure for flood adaptation in urban areas, Sponge City has emerged as the most efficacious approach to assist cities in adapting to flooding in the context of climate change.

Urban wetland in the city of Kigali have been encroached by human activities as well as being impact by flooding. The city initiated the restoration of urban wetlands in the city of Kigali make the cities of Kigali resilient to flooding. Nyandungu wetland was the first wetland to be restored. The restoration of the Nyandungu Urban Wetland in Rwanda has shown promising results in demonstrating the potential urban wetland restoration for flood risk reduction in the city of Kigali. An Empirical analysis conducted revealed that over the past five years indicates that the wetland's restoration has contributed to significant reductions in flood incidents and their severity.

However, due to the impact of catchment on the wetland and the emerging use of more nature-based solutions, sponge city infrastructures were recommended to be established at Nyandungu catchment to reduce run off flowing into the wetland. The examination of the functions of the sponge city approach, revealed that this approach that use natural infrastructure, plays a critical role in mitigating flood risks through enhanced water absorption and storage capabilities. To reduce, the future impact that might be caused by the increased run off as a result of increased built up in the catchment, some of infrastructures grounded in sponge city were recommend being established in Nyandungu catchment.

## 5.2 Recommendations

Based on the findings of this study, it has been necessary to formulate some recommendations as follow:

- ❖ Given that Nyandungu Urban Wetland restoration have generated flood risk benefits, it is recommended that similar projects could be implemented in restoring other urban wetland in Rwanda to mitigate flood risks and enhance urban resilience. Rwanda Environment Management Authority should plan the restoration of other urban wetlands in the city of Kigali, or in the secondary and satellite cities of Rwanda to help those cities become resilient to flooding.
- ❖ The restoration of Nyandungu wetland conducted at wetland level have generated different benefits, however based on the impact of the Catchment to the wetland, it is recommended to establish sponge city interventions in Nyandungu catchment. This will ensure that the restored area of the wetland is protected from future impacts from the catchment. Rwanda Environment Management Authority should plan how those interventions should be established in the catchment.
- ❖ REMA and the City of Kigali should increase public awareness and involvement of community in wetland restoration projects through educational programs and participatory activities. Engaging local communities ensures the sustainability and success of such initiatives.
- ❖ REMA should also Monitor and Evaluate Impact of human activities on wetland. Establishing a robust monitoring and evaluation mechanisms to assess the long-term impacts of human activities on restored wetland may increase the suitability of the project and promote accountability.

## 5.3. Research limitations

While conducting this research some limitations were encountered. The first challenge was to find accurate spatial data. Currently, geospatial data are being widely disseminated across different platforms to make them open and readily available to use but those free data have some limitations. Spatial resolution, lack of data for some years when you are conducting research that needs time series data and data covered with clouds are among those limitations. For this study, only spatial resolution and financial limitations were encountered. Currently the free Landsat available data has

15-meter panchromatic and 30-meter multi-spectral spatial resolution. For, sentinel data has spatial resolution that ranges from 10 meters to 60 meters. Where the main visible and near-infrared Sentinel-2A bands have a spatial resolution of 10 meters, while its “red-edge” (red and near-infrared bands) and two shortwave infrared bands have a 20-meter spatial resolution. The coastal/aerosol, water vapor, and cirrus bands have a spatial resolution of 60 meters. Generally, this resolution is good but not enough when you are conducting your study on a small area. This may partially affect the accuracy of the results and in research, conducting a study on small area is always recommended to find accurate and meaningful results. Additionally, some data of interest were not available. For instance, in the beginning, flood extent was expected to be analyzed to indicate the change using distinct flood event. However, due to lack of SAR and Landsat data of the period in which flood occurred, flood susceptibility was found to be an alternative methodology to use. Last but not least, the lack of research permit to collect data in Nyandungu Eco- Park and in companies and institutions involved in NUWEP Project planning and implementation as well as in its management made some key interesting points of the research not covered.

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## Annexes

### Annex I: Classification and weighting of flood Susceptibility analysis factor for 2010 and 2023

Factors	Unit	Class	Susceptibility class	Class ratings	Weight (%)	Relevancy of the selected factor	Calculation/Computation
TWI	Level	3.69- 6.44	Very low	1	10	The TWI map illustrates the influence of topography on the magnitude of wet areas that produce runoff, and serves as a valuable metric for assessing the flood susceptibility of a watershed (Fatah et al., 2022).	$TWI = Ln\left(\frac{\text{flow accumulation scaled}}{\text{Tan slope}}\right)$
		6.44- 8.51	Low	2			
		8.51- 10.69	Moderate	3			
		10.69- 13.33	High	4			
		13.33- 18.32	Very High	5			
Slope	%	0- 2.453	Very High	5	20	The slope of the land is a significant factor in causing floods in urban areas. This is because the slope affects water flow characteristics, such as velocity and discharge (Tariq et al., 2022).	Calculated from DEM using ArcGIS Desktop software
		2.45- 6.27	High	4			
		6.27- 10.20	Moderate	3			
		10.204- 15.79	Low	2			
		15.79- 25.02	Very low	1			
Elevation		1,364- 1,368.91	Very High	5	10	The elevation plays a crucial role in influencing both the direction and volume of surface runoff and	Calculated from DEM using ArcGIS Desktop software
		1,368.91-	High	4			

		1,375.92					subsurface drainage velocity. Specifically, low-lying plain areas exhibit heightened vulnerability to flooding due to the rapid flow of water from higher, elevated regions towards these flat plains(Dekongmen et al., 2021).	
		1,375.92-1,382.92	Moderate	3				
		1,382.925-1,388.88	Low	2				
		1,388.886-1,402	Very low	1				
Precipitation	Mm/year	964.16-974.52	Very low	5	15		Flooding commonly occurs because of significant precipitation. The incidence and attributes of urban floods have increased in severity over the last five decades due to climate change and other human-induced factors(Sun et al., 2021).	Rainfall data and Interpolation in ArcGIS
		974.526-985.94	Low	4				
		985.945-997.15	Moderate	3				
		997.15-1,006.87	High	2				
		1,006.87-1,018.08	Very High	1				
LULC	Level	Settlement	Very High	5			Land use has a substantial influence on the infiltration capacity and runoff coefficient of water. Surface roughness, which is regulated by land use, plays a pivotal role in determining surface flow characteristics, such as depression storage capacity and velocity (Endreny, 2006).	Supervised classification in ArcGIS Desktop and Goggle Earth Image
		Wetland	High	4				
		Annual Cropland	Moderate	3	20			
		Closed and Open Shrubland	Low	2				
		Sparse Forest	Very low	1				
Proximity to River	m	0- 47.175	Very High	5			Rivers play a significant role in the occurrence of floods in urban areas. Particularly during periods of prolonged rainstorms, rivers serve as natural channels for the	Euclidian distance in ArcGIS Desktop
		47.175-101.339	High	4	10			
		101.339-171.229	Moderate	3				

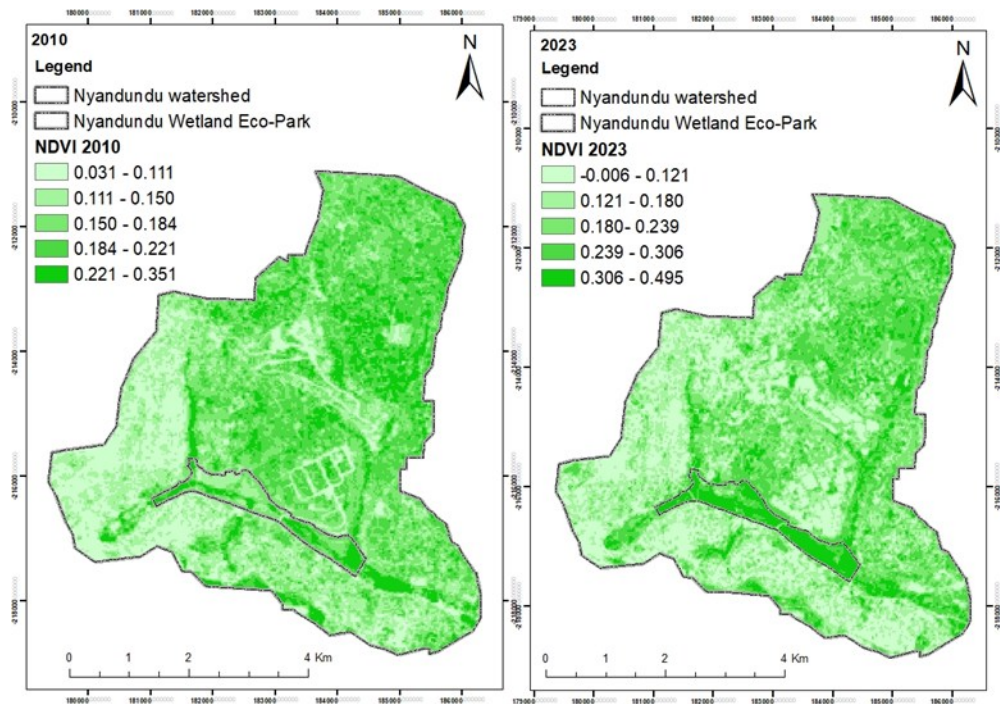
	171.229-269.074	Low	2	gradual or sudden release of excessive floodwaters into adjacent riverside regions, thereby subjecting these areas to riverine inundation (Z. Wang et al., 2019).  The clay content of the soil is a vital factor in flood analysis. Soils that contain a high proportion of clay exhibit a reduced capacity for infiltration, leading to an elevated occurrence of runoff or overland flow in comparison to soils with a lower clay content (Prachansri, 2007).	Existing data
	269.074-445.546	Very low	1		
Soil type	Clay	Very High	5		
	Clay loam	High	4		
	Sandy clay loam	Moderate	3		
	Silty clay	Low	2		
	Sand clay	Very low	1		

### Annex II: Classification and weighting of factors used in suitability analysis of sponge city infrastructure in Nyandungu Catchment

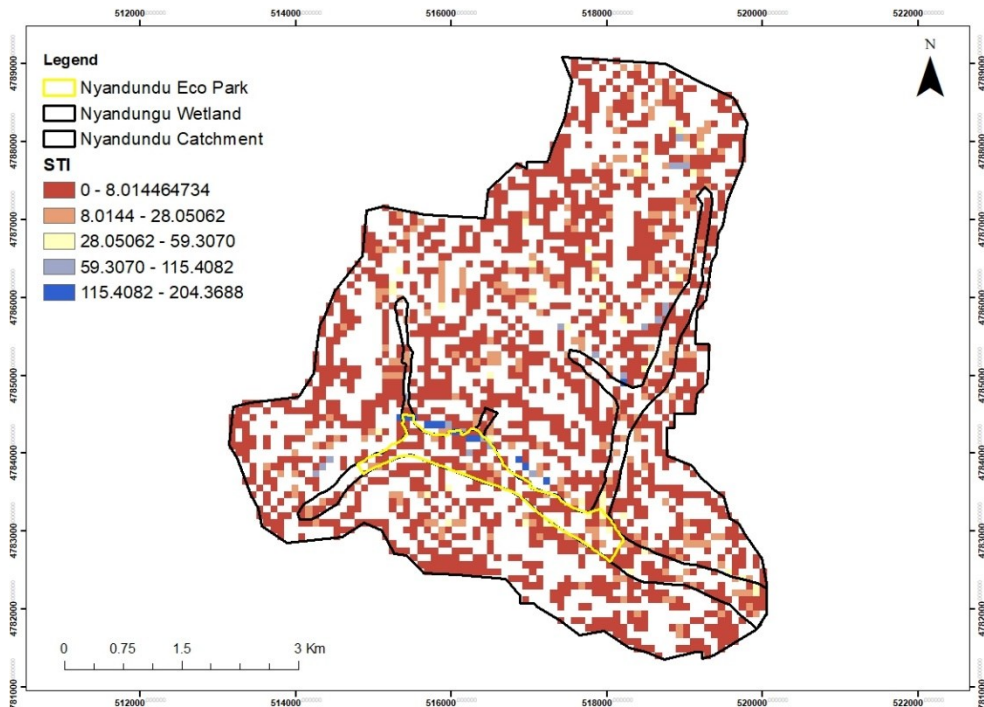
Criteria	Class	Classified value	Final weight	Relevancy of the selected factor
Hydrologic groups (HSGs)	soil HSG-C	1	14	Global Hydrologic Soil Groups (HYSOGs250m) are a classification system that categorizes soils based on their hydrologic behavior, specifically their capacity to transmit water. This classification aids in assessing soil water retention, infiltration, and runoff potential on a global scale at a resolution of 250 meters (ROSS et al., 2018).
	HSG-D	2		
	HSG-C/D	3		
	HSG-D/D	4		
LULC	Forest	1	19	This analysis considered areas in the municipality that have been covered with hard surfaces, such as roads, pavements, and buildings. Built-up areas are typically sealed, making it less likely for water to penetrate. As a result, these areas are more vulnerable to surface runoff and inundation, requiring specific sponge city interventions to effectively minimize urban flooding (Wilson St., Baffoe-Bonnie B., 2009).
	Grassland	2		
	Bareland	3		
	Built-Up	4		
Distance to rivers	0- 217.918	5	15	Areas near rivers or located within river buffers are deemed significant due to the increased likelihood of flooding during heavy storms. Such areas are particularly
	217.918- 448.289	4		

	448.289- 684.887	3		vulnerable to inundation, primarily due to their shallow water tables and susceptibility to river overflows (Tariq et al., 2022).
	684.887- 958.842	2		
	958.842- 1,587.693	1		
Soil texture	Sandy loam	1	16	Soil texture, which is the composition and size of soil particles, is a factor that affects runoff by influencing the soil's ability to absorb water. Soil with larger particles can absorb more water compared to soil with smaller particles. As a result, areas with mostly fine particles, such as clay soils, are more prone to flooding during intense storms, particularly if the slope and other factors are unfavorable. Therefore, soils, with a fine texture are more at risk for surface runoff and flooding. Based on those variations, specific sponge city interventions can be used to adapt to flooding(Guo et al., 2022).
	Silt loam	2		
	Sandy clay loam	3		
	Clay loam	4		
	Clay	5		
Elevation	1,351- 1,417.047	1	20	Elevation was selected as one of the key variables, pertaining to highland and lowland regions. This criterion was considered due to the documented evidence that indicates floods typically exert a more pronounced influence on low-lying areas. Consequently, lowland areas are more susceptible to escalated runoff and inundation. Given that water naturally flows from higher to lower elevations, it is imperative to implement tailored sponge city infrastructure strategies for distinct elevation zones to effectively mitigate urban flooding (Mind'je et al., 2019).
	1,417.047- 1,468.941	2		
	1,468.941- 1,531.843	3		
	1,531.843- 1,612.043	4		
	1,612.043- 1,752	5		
Slope (Percentage rise)	0- 7.602	5	16	The analysis included consideration of the slope, which is defined as the degree of steepness of landforms in each area. This is because the slope of a terrain directly influences its water carrying capacity. Steeper slopes generally facilitate faster water flow, whereas relatively gentle and flat areas tend to accumulate water or experience stagnation. Consequently, areas with horizontal slopes are particularly vulnerable to inundation (Veerappan & Sayed, 2020)
	217.918- 448.289	4		
	448.289- 684.887	3		
	684.887- 958.842	2		
	958.842- 1,587.693	1		

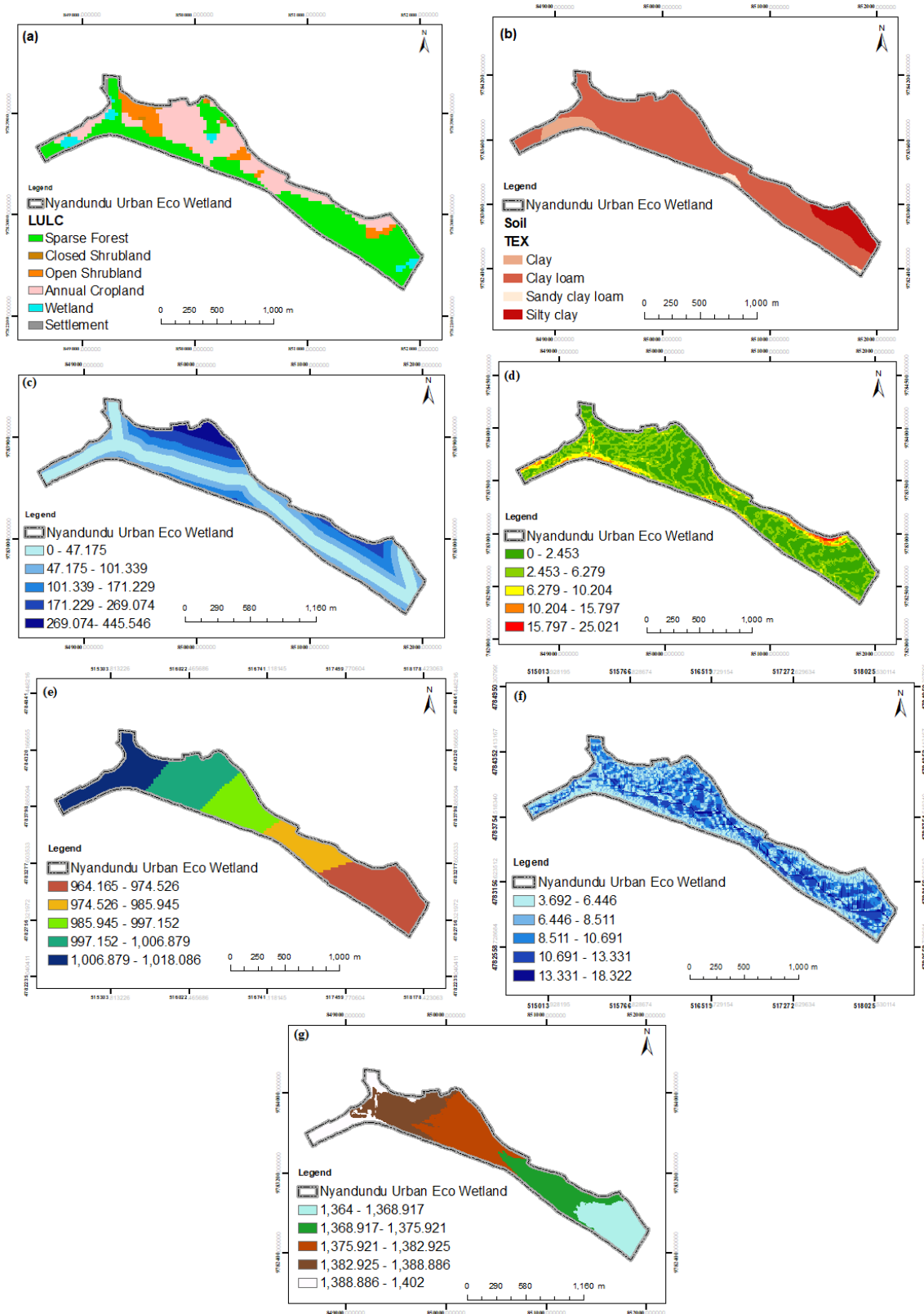
### Annex III: Difference Vegetation Index



### Annex IV: Sediment Transportation Index



### Annex V: Flood susceptibility analysis factors



a) Landuse LandCover (LULC), b) Soil texture, c) Precipitation d) Distance from River, e) Slope f) elevation and g) Topographic Wetness Index (TWI)

VI) Factors for Suitability analysis of Sponge city infrastructures

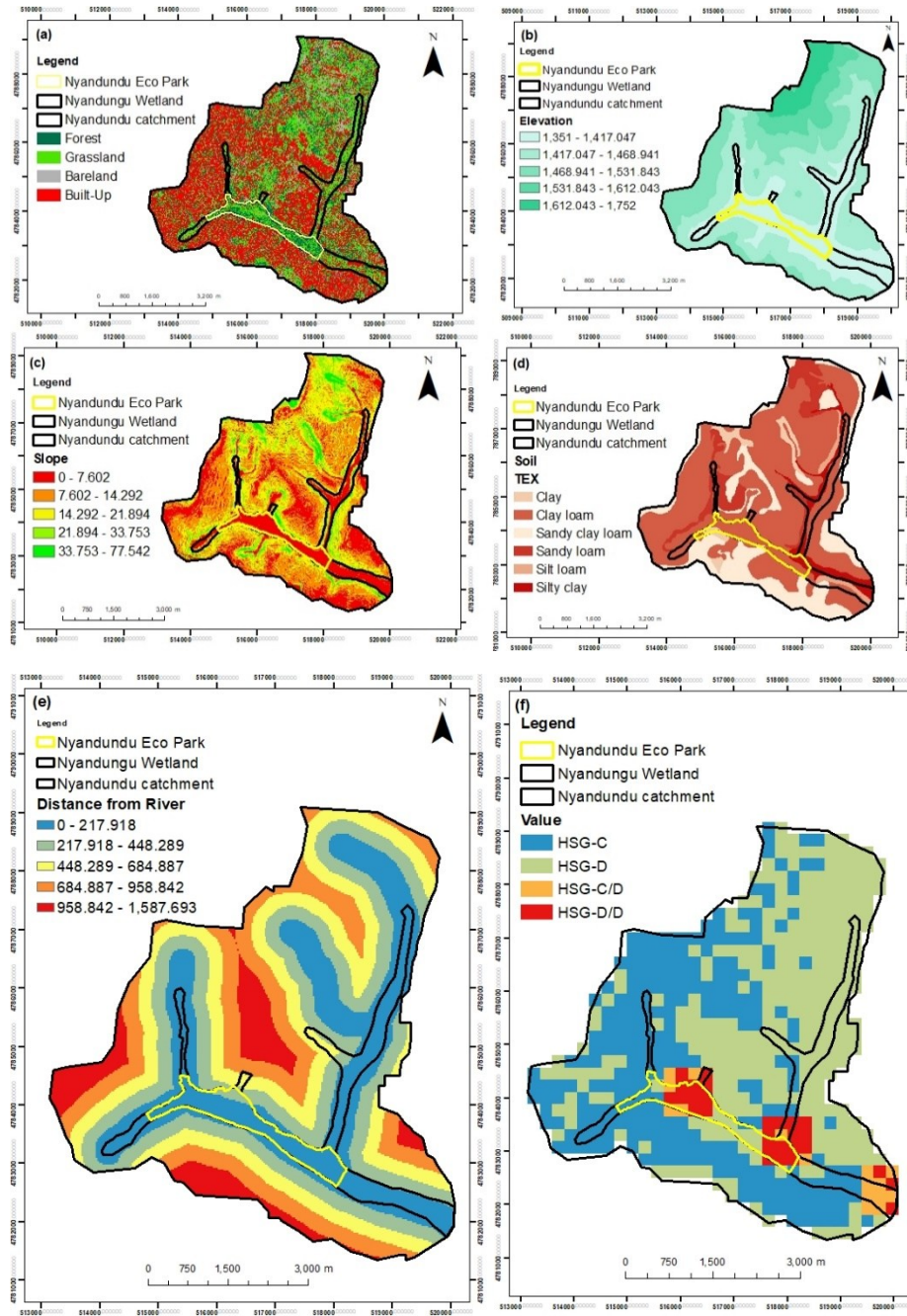
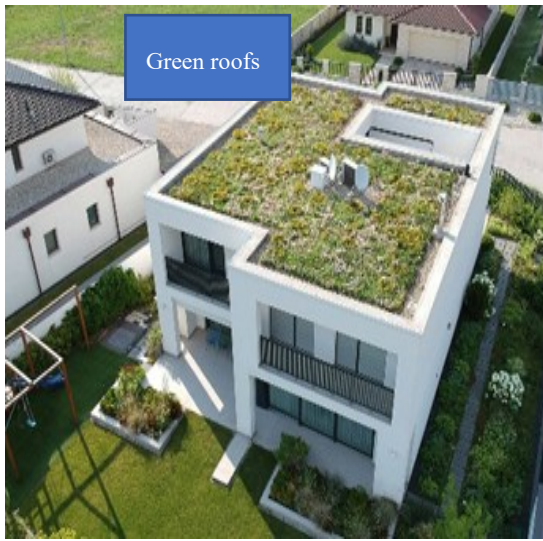


Figure 24 Factors used in analysis of Suitable Sponge city infrastructures

a) LULC, b) Elevation, c) slope, d) Soil texture, e) Distance to rivers, f) Soil Hydrological group

**Annex VII: Sponge city interventions pictures**



Green roofs



Bioswales



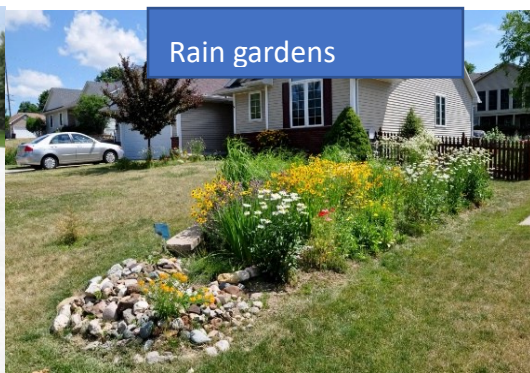
Sunken green areas



Infiltration ponds/basins



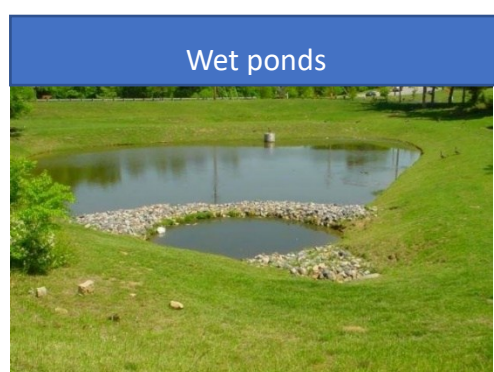
Grass swales



Rain gardens



stormwater wetland/ constructed wetlands



Wet ponds



Water storage modules



### Annex VIII: Details on Sponge city infrastructures

Interventions/Infrastructures	Description and function	outcomes	F(1)	(F 2)	F(3)
	Sponge city Infrastructure (NbS)				
Green roofs	A green roof refers to a building roof that is either partially or fully covered in vegetation and a growing medium. This greenery is planted on top of a waterproof membrane.	Green roofs have multiple functions for buildings, one of which is the absorption of rainwater.	✓		✓
Sunken green areas	A sunken green space refers to a type of public green area that lies below the level of the surrounding road surface. The plants found within this space predominantly consist of herbaceous vegetation.	Sunken green spaces are typically characterized by having a ground elevation lower than the surrounding area. As a result, runoff from the surrounding area naturally flows into these spaces due to gravity.	✓		✓
Infiltration ponds/basins	An infiltration basin is a type of shallow impoundment designed to allow stormwater to infiltrate into the soil.	This control effectively increases groundwater recharge, which in turn increases the baseflow to nearby streams.		✓	✓

Bio-retention facilities	Bioretention facilities, also known as rain gardens, are designed to store stormwater and allow it to drain within a 48-hour period.	Bioretention facilities, which are an integral part of the sponge city concept, help manage stormwater by capturing runoff, thus reducing the risk of flooding.	✓
Grass swales	Bioswales are linear landscape features that often consist of a drainage channel with gently sloping sides. They may be filled with engineered soil and/or contain a layer of coarse gravel material for water storage.	As stormwater passes through these channels, the vegetation present slows it down, allowing for sedimentation, soil filtration, and infiltration into the underlying soils. Various types of grassed swales include the grassed channel, dry swale, bioswale, and wet swale.	✓ ✓
Rain gardens	A rain garden is a low-lying area in the landscape that gathers rainwater from a roof, driveway, or street and allows it to be absorbed into the ground.	They reduce runoff	✓ ✓
Stormwater wetland/ constructed wetlands	Constructed stormwater wetlands temporarily store runoff in shallow pools.	When stormwater flows through a constructed wetland, it reduces its runoff.	✓

Wet ponds	Wet ponds are basins that are constructed with a permanent pool of water all year round, or at least during the wet season.	Wet ponds are designed to have a permanent pool of water, which allows them to effectively store stormwater runoff and release it in a controlled manner. They are also beneficial for flood control.	✓	✓ ✓
Retention basins	Retention basins are designed to hold a consistent level of water, which may vary based on the amount of precipitation and runoff they receive. They are low-lying areas meant for this purpose.	They are used to collect surface runoff	✓	
Detention basins	Detention basins are low lying areas that are designed to temporarily hold a set amount of water for a set amount of time.	They help to prevent localized flooding	✓	
Vegetated buffer zones	Vegetated buffers are strategically located areas with dense growth of shrubs, trees, high grasses, perennials, and other plants. They are designed to help slow down and capture stormwater runoff.	Vegetated buffers offer numerous benefits for managing stormwater. Specifically, these buffers efficiently absorb and filter stormwater.	✓	✓

Permeable pavements	Water-permeable pavements are designed to be porous, allowing for voids, open structures, or the use of partially pervious materials.	They allow water to pass through or around them into the soil.	✓	✓
Underground rainwater tanks	The underground tank is typically designed as a single piece and is commonly made from high-density polyethylene or GRP.	Underground tanks are secure and secure from vandals and cruel climate conditions.	✓	✓
Water storage modules	Water storage modules, such as tanks, bladders, cisterns, and reservoirs, are specifically designed to collect and store water in different environments, including residential, commercial, agricultural, and industrial settings.	They play a crucial role in guaranteeing a dependable water supply, promoting water conservation, and facilitating water management across various applications.	✓	

Table 9 Benefits of sponge city in urban flood risk reduction

Other Grey Solutions include Seepage wells, Seepage pipes, Seepage canals rainwater drainage facilities, rainwater purification facilities, green Area irrigation and artificial soil filtration. See annex III.... for their photos

Source: (S. K. Biswas et al., 2019; Bosma, 2019)

**F (1)** stands for function 1 which Retention and absorption of Stormwater during flooding, **F (2)** which Increase infiltration and groundwater recharge and **F (3)** which is Runoff Reduction and Delay.

### Annex IX: Field observation checklist

List	Observation Made
NUWEP Project interventions	Locations, design, status
Current Land Use Land Cover	The main Landuse Landcover (Blue-Green infrastructures)

### Annex X Recommendation letter for data collection



*Republic of Rwanda*  
*City of Kigali*



Ref. N<sup>o</sup> 9734...../07.01.16/24                      Kigali, on.....19. APR. 2024.....

**Mr. Fidele MWIZERWA**  
University of Rwanda  
TEL: 0785800243  
Email: mwizerwaf@gmail.com

SECTEUR NDERA  
POUR RECEPTION  
**22 APR 2024**  
Signature: .....  
A Traiter par: .....

Dear Sir,

**Re: Your request for permission to conduct research**

Reference is made to your letter dated on 15<sup>th</sup> April 2024 requesting for permission to conduct research in the Ndera Sector/ Gasabo and Nyarugunga Sector/ Kicukiro Districts/ City of Kigali on “*Evaluating the benefits of ecosystem based adaptation wetland restoration based on sponge City approach. A case of Nyandungu Wetland in Gasabo and Kicukiro Distric, Kigali City, Rwanda*”;

We would like to inform you that your request is hereby granted. However, before starting your research, you must first introduce you to the Gasabo and Kicukiro **District Administration**, and clarifying your research need.

Sincerely,




**Joseph NIYONGABO**  
Director General of Corporate Services

**Cc:**

- City Manager of the City of Kigali
- District Executive Administrator/ Gasabo
- District Executive Administrator/ Kicukiro

**KIGALI**

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COLLEGE OF SCIENCE AND TECHNOLOGY (CST)

SCHOOL OF ARCHITECTURE AND BUILT ENVIRONMENT (SABE)

Office of the Dean

## TO WHOM IT MAY CONCERN

Dear Sir,

Kigali, 18 January 2024

Dear Madam,

**Data Collection for MSc Dissertation by Mr. Mwizerwa Fidele**

Through this letter, we would like to confirm that **Mwizerwa Fidele** is a final year student in the MSc of Geo-Information Science for Environment and Sustainable Development (GI-ESD) under the School of Architecture and Built Environment (SABE), College of Science and Technology (CST), at the University of Rwanda (UR). He is currently working on the MSc dissertation, with the topic " *Evaluating the flood control Benefits of Nyandungu Wetland Restoration Approach Vis-à-Vis Sponge City Approach. The Case of Nyandungu Wetland Eco-Park, Kigali City, Rwanda* ", under the supervision of Dr. Ernest Uwayezu (+250 783 022 510).

From January up to April 2024, he will be collecting data which are relevant to that topic in Kimironko and Ndera Sectors of Gasabo district and Nyarugunga Sector of Kicukiro district, Kigali City. Data collection will include the household surveys and interviews with local leaders, and various government officials. In addition, he will need access to various spatial datasets and documents that are held by both public and private organizations. We would therefore like to request for your support so that he can get access to those data and documents. For any question related to his research, do not hesitate to contact his supervisor or the Dean of the School on the tel. or email below.

We do appreciate your support to that UR Student in his academic journey.

Sincerely yours.

**Dr. Ernest Uwayezu**  
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## Annex XI: Interview guide



### LETTER OF INFORMED CONSENT

Dear Respondent,

My name is *Fidele MWIZERWA*, a Final year student in Master programme in Geo-Information Science for Environment and Sustainable Development at the University of Rwanda, College of Science and Technology, School of Architecture and Built Environment. Currently, I am writing a dissertation which is part of the requirements to be awarded a MSc degree at the University of Rwanda and I am at the stage of data collection. A title of a research that I am currently conducting is **“Harnessing nature to Advance Sponge City in Rwanda: Empirical Analysis of the Impacts of Restoration of Nyandungu Urban Wetland on Flood Risk Reduction”**

The aim of this research is to evaluate the benefits of Nyandungu wetland restoration based on sponge city approach. In this line, a comparison between the achieved benefits of the used approach while restoring Nyandungu wetland will be compared with the benefits that would have been achieved if sponge city was used as the restoration approach. Based on the findings of this study, appreciation of the used approach will be given or recommendations to enhance restoration of Nyandungu wetland Eco-Park will be suggested.

In this regard, you have been selected as one of the respondents and the information you will give will be treated with most confidentiality and used purely for academic purposes. Kindly please spare some of your valuable time to answer these questions.

Thank you for your participation

Instructions:

- (1) There are 2 sections in this questionnaire. Please answer ALL the questions in ALL sections.
- (2) This will only take you approximately 5 – 15 minutes
- (3) The content of this questionnaire will be private and confidential.

**Your participation will greatly help to obtain the accurate results.**

**Section of questionnaire**

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**Instruction:** Please tick the most suitable option given. You are allowed to tick only ONE option for each question unless it is specific. For open-ended questions write all answers that you think to be useful in this study.

**A. Identification**

- 1. Respondent Name: .....
- 2. Institution: .....
- 3. Position: .....

**B. Structure questions**

- 4. How familiar are you with the Nyandungu wetland restoration project?
  - a) Very familiar
  - b) Somewhat familiar
  - c) Not very familiar
  - d) Haven't heard of it
  
- 5. Are you familiar with flooding disaster and its cause?
  - a) Yes
  - b) No
  
- 6. Among the factors listed below, what do you think to be among the cause of flooding that had been impact Nyandungu wetland?
  - a) Landuse LandCover (LULC),
  - b) Soil texture
  - c) Precipitation
  - d) Distance from River
  - e) Slope

- f) Elevation
- g) Topographic Wetness Index (TWI)

7. Can you rank them based on their contribution to this disaster? You can rank them from 1 to 9 where 1 indicates low level of influence and 9 High level of influence.

- a) Landuse LandCover (LULC),
- b) Soil texture
- c) Precipitation
- d) Distance from River
- e) Slope
- f) Elevation
- g) Topographic Wetness Index (TWI)

8. Are you familiar with Nature based Solutions for urban flood control?

- a) Yes
- b) No

9. Among the factors listed below, what do you think to can be crucial in flood risk reduction in Nyandungu catchment?

- a) Landuse LandCover (LULC),
- b) Elevation
- c) Slope
- d) Soil texture
- e) Slope
- f) Distance to river
- g) Soil Hydrological group

10. Can you rank them based on their contribution to flood risk reduction? You can rank them from 1 to 9 where 1 indicates low level of influence and 9 High level of influence.

- a) Landuse LandCover (LULC),

- b) Elevation
- c) Slope
- d) Soil texture
- e) Slope
- f) Distance to river
- g) Soil Hydrological group

11. If there is some other relevant information to share, please use the blank space below to describe them.

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Thank you for taking time to fill this.