# ASSESSING THE IMPACT OF FUTURE RAINFALL AND URBAN GROWTH ON FLOOD HAZARD IN KUMASI, GHANA: IDENTIFYING POTENTIAL FLOOD MITIGATION MEASURES.

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JULY 2024

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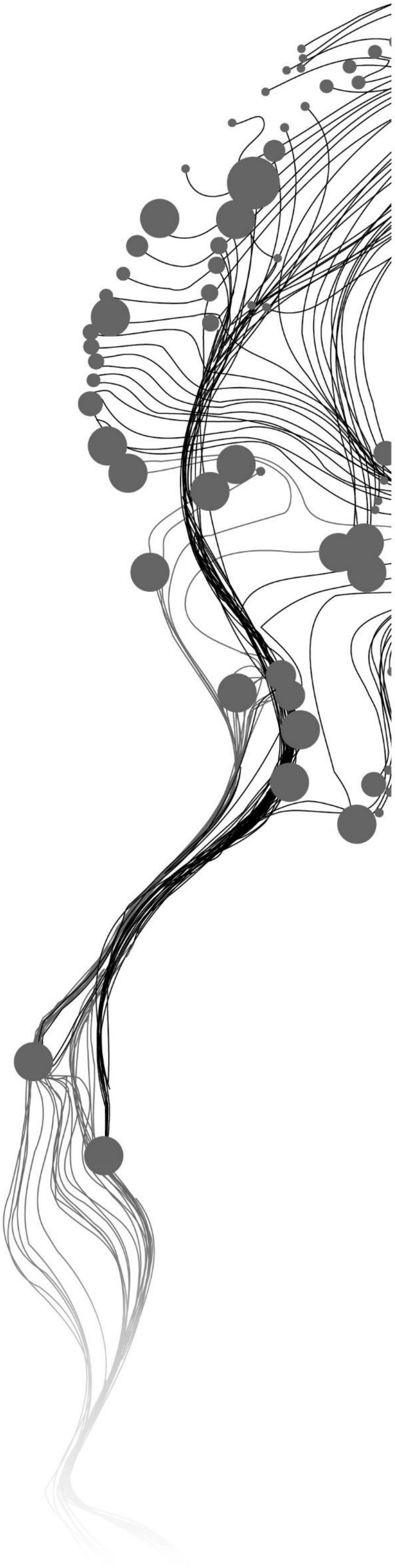

# ASSESSING THE IMPACT OF FUTURE RAINFALL AND URBAN GROWTH ON FLOOD HAZARD IN KUMASI, GHANA: IDENTIFYING POTENTIAL FLOOD MITIGATION MEASURES.

JOEL AWIRE KETU
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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Urban planning and management.

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# ABSTRACT

This study aims to assess the impact of projected future rainfall patterns and urban growth on flood hazards in Kumasi, Ghana, and propose effective flood mitigation measures. It integrates historical flood data, land cover analysis, and advanced flood modeling to understand the dynamics and implications of urban flooding in this rapidly developing region. The research is structured around four main objectives: identifying the contributing factors to urban flooding, analyzing changes in land cover over the past decade, assessing future flood scenarios, and proposing viable flood mitigation strategies.

The study begins with an analysis of flood incidences in Kumasi from 2013 to 2023, revealing significant fluctuations in flood cases and affected populations, underscoring the growing vulnerability of the city to flood hazards. **The contributing factors were identified through key informant interviews. The research highlights that rapid urbanization, inadequate drainage systems, poor waste management, deforestation, improper urban planning and increasing rainfall intensity due to climate change are primary contributors to urban flooding in Kumasi.**

Using satellite imagery for land cover analysis from 2013 and 2023, the study documents significant transformations in Kumasi's land cover, notably the expansion of built-up areas by 21.35 square kilometers and the substantial reduction of dense vegetation by 22.05 square kilometers. **This urban growth trend is projected to continue, with predictions for 2033 indicating further increases in built-up areas and decreases in natural land covers, exacerbating flood risks.**

To model future flood scenarios, the study employs the fastflood tool, incorporating projected rainfall data and land cover changes. Four scenarios are developed: baseline, future rainfall impact, urban growth impact, and combined future impact. The results indicate that future rainfall and urban growth will significantly increase flood depths and extents, with combined impacts posing the greatest hazard. Calibration of the flood model with historical data ensures the accuracy of these projections.

The study proposes several flood mitigation measures following **a feasibility analysis**, which includes public education, regular desilting of drainages, reforestation, and effective waste management. These measures were assessed based on economic, environmental, and social criteria to determine their viability. Recommendations for future research emphasize the importance of stakeholder engagement and the use of higher resolution data for improved flood modelling.

**Keywords:** Urban flooding, flood mitigation, climate change, land cover change, urban Growth, flood hazards, fastflood model, flood modelling, flood scenarios.

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| **Abbreviations** | **Full meaning** |
|---|---|
| KMA: | Kumasi Metropolitan Assembly |
| NADMO: | National Disaster Management Organisation |
| USGS: | United States Geological Survey |
| DEM: | Digital Elevation Model |
| ANN: | Artificial Neural Network |
| CA: | Cellular Automata |
| LULC: | Land Use and Land Cover |
| OSM: | OpenStreetMap |
| CBD: | Central Business District |
| BRRI: | Building and Road Research Institute |
| SSP: | Shared Socioeconomic Pathways |
| GFDRR: | Global Facility for Disaster Reduction and Recovery |
| IPCC: | Intergovernmental Panel on Climate Change |
| UN HABITAT: | United Nations Human Settlements Programme |
| TVA: | Tennessee Valley Authority |
| UNDRR: | United Nations Office for Disaster Risk Reduction |
| CCKP: | Climate Change Knowledge Portal |
| NASA: | National Aeronautics and Space Administration |
| RCP: | Representative Concentration Pathways |
| SSP5-8.5: | Shared Socioeconomic Pathway 5-8.5 |
| MOLUSCE: | Modules for Land Use Change Evaluation |
| GCP: | Ground Control Points |
| UNISDR: | United Nations International Strategy for Disaster Reduction |
| GAR: | Global Assessment Report |
| WWF: | Worldwide Fund |
| UNEP: | United Nations Environment Programme |
| IUCN: | International Union for Conservation of Nature |
| EPA: | Environmental Protection Agency |
| EEA: | European Environment Agency |
| UNESCO: | United Nations Educational, Scientific and Cultural Organization |
| FAO: | Food and Agriculture Organization |

# 1. INTRODUCTION

## 1.1. Background of the study

Flooding stands as a critical global challenge, significantly impacting lives, economies, and ecosystems. It is one of the most prevalent natural disasters, affecting over 20 million people worldwide annually (World Bank, 2020). This situation is exacerbated by climate change, leading to more intense and unpredictable rainfall patterns, sea-level rise, and increased riverine and coastal flooding (IPCC, 2021a). Urban areas, particularly those characterized by dense populations and inadequate infrastructure, are particularly vulnerable. The economic impacts are profound, with the Global Facility for Disaster Reduction and Recovery estimating billions of dollars in losses each year due to flooding (GFDRR, 2022).

In Africa, the flooding situation is dire due to rapid urbanization, poor urban planning, and lack of effective flood management measures. Cities across the continent, from Lagos to Cairo, have experienced devastating floods (UN HABITAT, 2011). The African Climate Policy Center (2011), highlights the impact of climate change, likely increasing the intensity and frequency of extreme weather events such as floods, placing additional strain on already strained urban systems.

Ghana has seen its share of catastrophic floods over recent decades. The Ghana Meteorological Agency (2018) has noted an increase in extreme weather events, including heavy rainfall leading to flooding in many parts of the country. These floods have caused loss of life, displacement of communities, property destruction, and outbreaks of waterborne diseases. In Ghana, the combination of natural factors (such as topography and climatic conditions) and human factors (including rapid urbanization, deforestation, poor drainage systems, low law enforcement and ineffective flood mitigation and management measures etc.) have exacerbated the flooding problem (Karley, 2009).

According to the Ghana National Climate Adaptation Strategy, in 2007, flooding affected more than 300,000 people in the country, necessitating over $25 million for emergency response and incurring more than $30 million worth of direct damages. Such devastation highlights a critical vulnerability, many developing countries, and cities, are not adequately prepared for such disasters.

Kumasi, Ghana’s second-largest city, epitomizes the urban flooding challenge within the Ghanaian context. The city has experienced rapid growth, leading to urban sprawl and destruction of natural vegetation for urban development which further exacerbate the flooding situation due to inability of the city to cope with excess water. This is coupled with ineffective flood management and mitigation strategies such as zoning and proper land use planning, ecosystem restoration, flood forecasting and early warning systems and inadequate flood infrastructure (Amoako, 2017; Amoako & Boamah, 2014)

Kumasi’s history with flooding includes several notable events, such as the floods of 1995, 2001, 2015, and 2019. These events have underscored the city’s vulnerability and highlighted the need for effective flood mitigation and management measures (IFRC, 2020). Comparative research from cities like Jakarta, Miami, and Rotterdam shows a range of effective measures and infrastructures against urban flooding, including advanced drainage systems, green infrastructure, and community-based adaptation measures (Bouwer et al., 2022). However, while this has been proven to be effective, applying these strategies in Kumasi requires a local understanding of existing flood mitigations and management measures and the projected future flood that might occur in the city of Kumasi.

## 1.2. Problem statement

Globally, numerous studies have been conducted to understand urban flooding, focusing on both the occurrences and impacts (Kabisch et al., 2016). These studies provide valuable understandings into the nature of urban floods, their frequency, and the various ways they affect cities and their inhabitants. However, in the context of developing countries, research that specifically examines how future rainfall projections could influence urban flooding is relatively less, so also in the context of Ghana. This is compounded when considering the simultaneous effects of urban growth on flooding patterns.

In many developing cities like Kumasi (Ghana), flood mitigation measures are predominantly cantered around short-term solutions (Asare et al., 2023a). These often include strategies such as the occasional desilting and the construction of small-scale drains along major and inner-city roads. While such measures are crucial for flood management, their effectiveness may be limited in the face of urban expansion and densification, which can significantly alter hydrological responses and exacerbate flood hazards. The predominant approach to flooding has been reactive, with measures typically implemented post-event rather than through proactive planning and preparedness aimed at reducing or preventing incidence of current let alone future flooding (Amoako, 2017; Karley, 2009).

As Kumasi evolves, its urban landscape undergoes significant changes from land-use alterations to the intensification of built-up areas that are likely to influence flood risk just as much as, if not more than, changing rainfall patterns due to climate change. Thus, a significant question that arises is how effectively can the city of Kumasi address the flood hazards that may arise not only from future rainfall scenarios but also from the complex interplay of urban growth?

To address this, the research will delve into the factors currently contributing to flooding in Kumasi, examining both historical and contemporary influences. The goal is to develop a comprehensive understanding of urban flooding, which will serve as a basis for evaluating future flood hazard considering Kumasi's urban evolution and climate change projections (particularly rainfall patterns) and finally identify potential measures that are feasible to be implemented to reduce possible future floods and impact.

## 1.3. Research objectives and questions.

### 1.3.1. Main research objective

The main objective of the study to assess how projected future rainfall patterns and urban growth will influence flood hazards in Kumasi and to propose possible flood mitigation measures to reduce the impact of future floods.

### 1.3.2. Specific objectives and questions

**Objective 1: To identify the contributing factors of urban flooding in Kumasi.**

1. How have the frequency of flood events in Kumasi changed over the past decade?
2. What have been the major primary contributing factors?
3. What are the current flood mitigation measures put in place in Kumasi?

**Objective 2: To Analyse urban growth and Land cover change in Kumasi.**

1. How has land cover in Kumasi changed over the last decades from 2013 to 2023?

2. What is the relationship between landcover change and urban flood in Kumas?

**Objective 3: To assess future flood scenarios in Kumasi considering future rainfall and urban growth.**

1. What is the likely urban growth scenario?
2. What are the future rainfall projections?
3. How will projected changes in rainfall patterns and urban growth likely affect urban floods in Kumasi?

**Objective 4: To identify potential flood mitigation measures for the future floods.**

1. What are the potential flood mitigation measures that can be proposed to mitigate floods in Kumasi?
2. How feasible are these measures in the context of Kumasi?

## 1.4. Thesis structure

The study is organized into six chapters, each serving a specific function within the research. Chapter one lays the foundation with an introduction that outlines the background of the study, articulates the research problem, and sets forth the objectives and questions that guide the investigation. Chapter two delves into a comprehensive literature review, discussing critical concepts relevant to the study including climate change, urban growth, urban flooding, spatial planning, and flood mitigation strategies. Chapter three provides a detailed description of the study area, the research design, and the methodologies employed for data collection and analysis. Chapter four presents the data that has been analysed and addresses the research questions posed earlier in the study. Following this, chapter 5 discusses, the findings and results derived from the study.

The concluding segment of the research is found in chapter 6, where the study wraps up with its conclusions and offers recommendations for future research. This final chapter synthesizes the insights gained throughout the study and suggests directions for further investigation to build upon the findings established.

# 2. LITERATURE REVIEW

This part of the thesis delves into the essential concepts surrounding the effects of anticipated shifts in rainfall patterns and urban growth on urban flood hazard. It offers an in-depth analysis of the ways in which urban expansion aggravates flooding issues. Additionally, this section examines how urban planning and flood risk management intersect, with a specific focus on the practices and policies pertinent to Ghana.

## 2.1. Urban Flood

Urban Flood refers to the inundation of water in populated areas, primarily caused by heavy rainfall that the urban drainage systems cannot accommodate (Rijke et al., 2012).

According to Smith and Jones (2021), urban flooding occurs when water flows into an urban region faster than it can be absorbed or managed by existing drainage systems, leading to inundation of areas that are not typically submerged. Characterized by its multifaceted nature, urban flooding results from a confluence of factors like geography, urbanization, land use patterns, and climate change impacts (Shao et al., 2020) In urban centres, the interplay of these elements often leads to exacerbated flood risks. Heavy rainfall, coupled with inadequate drainage infrastructure and rampant urban development, significantly contributes to the frequency and intensity of flood events (Trenberth, 2009). The situation is further compounded by climate change, which is expected to increase the intensity of extreme weather events, including heavy rainfall (Hallegatte et al., 2013).

Urban floods have far-reaching consequences. Economically, they can cause substantial damage to infrastructure and property, leading to significant financial losses. The social costs are equally profound, with floods often resulting in displacement, health crises, and long-term impacts on well-being (Hallegatte et al., 2013). Furthermore, urban flooding tends to disproportionately affect vulnerable communities, particularly those in informal settlements or low-income areas that are frequently situated in flood-prone zones. These communities often lack the resources and infrastructure to effectively respond to and recover from flood events, exacerbating existing social inequities (UNDRR, 2015).

The different types of urban flooding can have various causes and impacts, and understanding these distinctions is crucial for effective flood management and mitigation. Based on the recent studies, urban flooding can be broadly categorized into coastal flooding, fluvial flooding, pluvial flooding, and groundwater flooding (Raadgever et al., 2018; Vojinović, 2015).

*1. Coastal Flooding*

Coastal flooding occurs when sea water inundates land areas along the coast (Vojinović, 2015). This type of flooding is typically caused by storm surges associated with tropical cyclones and other severe storm events. Coastal cities and delta areas are particularly vulnerable due to their low elevation and proximity to the sea. A characteristic feature of coastal flooding is the fluctuation of water levels with the tide, which can exacerbate the extent and impact of flooding. The rising sea level due to climate change is increasing the vulnerability of coastal areas, potentially leading to more frequent and severe coastal flooding events (Osumanu, 2023).

*2. Fluvial Flooding*

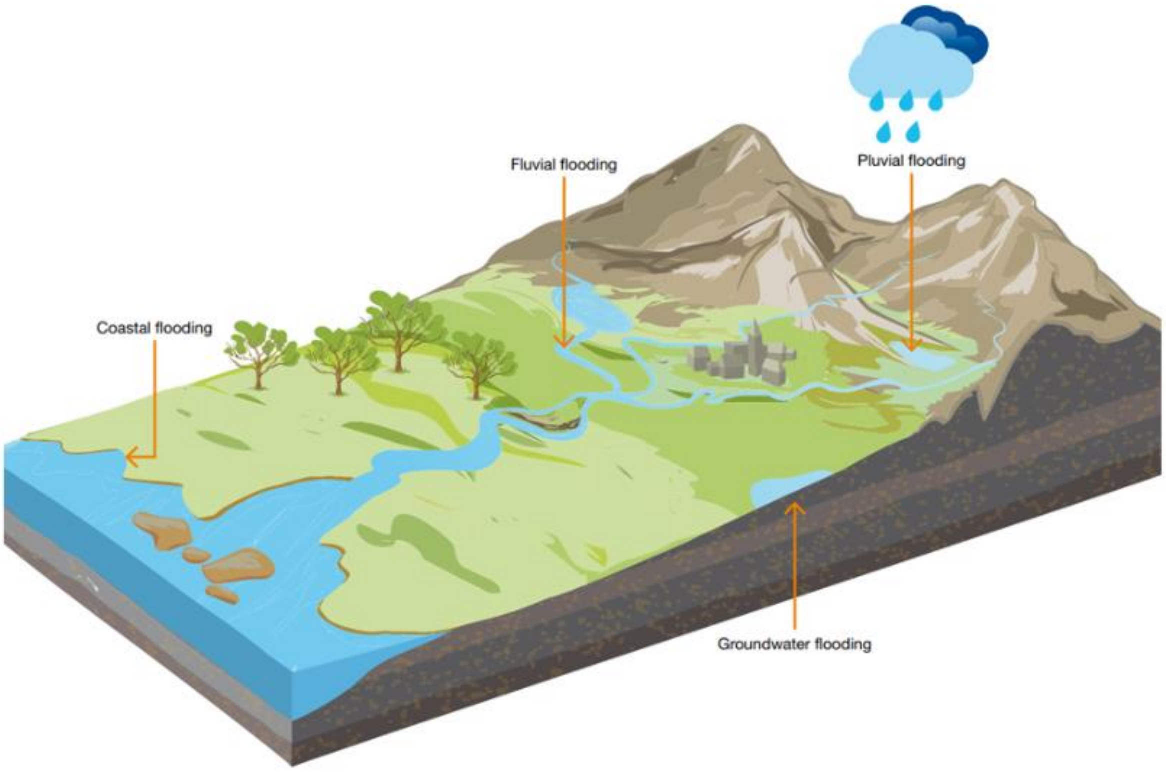
Fluvial flooding, also referred to as riverine flooding, happens when rivers overflow their banks as a result of heavy rainfall or snowmelt in the upstream catchment area (Osumanu, 2023). This type of flooding is influenced by the capacity of river channels and the presence of flood defences such as levees and dams. The complexity of managing fluvial flooding lies in the need to consider the entire river system, including upstream and downstream areas. Effective management requires integrated approaches that account for the hydrological connectivity and land use changes within the watershed (Zevenbergen et al., 2018)

*3. Pluvial Flooding*

Pluvial flooding occurs as a result of intense, short-duration rainfall that overwhelms the local drainage systems. (Chen et al., 2010).This type of flooding is common in urban areas where impervious surfaces like roads and buildings prevent water infiltration, leading to rapid surface runoff. Pluvial floods can happen anywhere, often with little warning, and are not necessarily connected to river or coastal systems. The increasing occurrence of extreme weather events as a result of climate change is expected to exacerbate the occurrence of pluvial flooding (IPCC, 2021b). Managing pluvial floods involves improving urban drainage infrastructure, creating, and enhancing green spaces to absorb rainfall, and implementing early warning systems.

*4. Groundwater Flooding*

Groundwater flooding occurs when the water table rises above the ground surface, typically following prolonged periods of heavy rainfall (Vojinović, 2015). This type of flooding can happen in both urban and rural areas, particularly where the ground is saturated, and can persist for weeks or even months. Groundwater flooding is often less predictable than other types of flooding and can cause significant damage to buildings and infrastructure due to prolonged inundation (Koh et al., 2020).



Source: Lembley (2017)

Figure 1: Types of urban flooding.

## 2.2. Climate change

Climate change, according to Intergovernmental Panel on Climate Change (IPCC) is a substantial and enduring shift in global temperatures and weather patterns, primarily driven by human activities such as fossil fuel consumption and deforestation (Romero-Lankao et al., 2018) This phenomenon poses significant challenges for urban areas, particularly by increasing the risks of urban flooding.

A key impact of climate change on urban settings is the modification of rainfall patterns and intensities. According to climate models, there is an expected increase in the frequency and severity of extreme weather events, including intense rainfalls that significantly contribute to urban flooding (Awotwi et al., 2021) These changes involve not only more severe rainfall events but also alterations in their timing and distribution, which can strain the existing urban infrastructure.

Furthermore, the combination of climate change with rapid urbanization intensifies flood risks. Urban expansion typically results in the creation of more impervious surfaces such as concrete, which diminishes the ground's natural ability to absorb water, thereby increasing surface runoff (IPCC, 2021b). When this scenario is combined with the heavier rainfall brought about by climate change, urban drainage systems can become overwhelmed, leading to heightened flood hazards.

Focussing on climate change in Ghana, a significant body of research has focused on the trends and variability of rainfall in Ghana. Studies by Amekudzi et al., (2015)) demonstrate a marked variability in rainfall patterns across different ecological zones in Ghana. These studies highlight a reduction in mean annual rainfall and an increase in the frequency of extreme weather events. Particularly, the northern regions of Ghana have experienced more pronounced decreases in rainfall, impacting agriculture and water resources significantly.

Research linking global warming to rainfall patterns in Ghana has shown that rising temperatures are influencing rainfall distribution and intensity (Damte et al., 2023). A study by Ayanlade and Drake (2016) utilized satellite data to analyse temperature trends and their correlation with rainfall over a 20-year period. Their findings suggest that as temperatures have risen, there has been a shift in the onset and interruption of the rainy seasons, with prolonged dry spells interspersed with heavy rainfall events. This irregular pattern has been linked to the warming of the Atlantic Ocean, which affects atmospheric conditions over West Africa where Ghana is located.

Furthermore, future rainfall projections, derived from various climate models and scenarios, play a crucial role in understanding the impacts of climate change across the globe. Models such as Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), project significant changes in rainfall patterns due to increased atmospheric temperatures which allow the air to hold more moisture. As outlined by the Intergovernmental Panel on Climate Change (IPCC), these changes will not be uniformly distributed, with some regions experiencing increases in rainfall while others face more severe droughts (IPCC, 2021b).

In the context of Ghana, the situation reflects the broader regional trends. Research indicates that Ghana will experience a shift in rainfall patterns, with an increase in variability which includes both more intense rainy seasons and extended dry periods (Dankwa et al., 2021).

## 2.3. Urban growth and land use

Urban growth and land use are interconnected aspects that are pivotal for understanding the dynamics within rapidly expanding urban areas. The UN-Habitat describes urban growth as the expansion of a city or metropolitan area in terms of both population and geographic spread. This growth typically entails the development of land for residential, commercial, industrial, and public purposes, transforming rural or undeveloped land into urban settings (UN-Habitat, 2020).

As urban areas expand, they frequently convert natural lands and green spaces into built-up regions, significantly altering the natural hydrological cycle. Yeboah & Asibey, (2019)note that this transformation leads to an increase in impervious surfaces such as roads and buildings, which replace absorbent soils and reduce the ground's ability to absorb rainfall. These changes in land use patterns are crucial for understanding urban flooding risks, as the increase in impervious surfaces typically results in heightened surface runoff, which contributes directly to the risk and severity of urban floods (Amoako & Boamah, 2014).

Further exploring the concept, Zhao et al., (2023) discuss land use as the management and utilization of land, especially for human activities such as agriculture, and residential, industrial, and commercial developments. In urban settings, land use decisions greatly influence the hydrological cycle by affecting water absorption, storage, and diversion. Changes in land use, particularly those that increase impervious surfaces, exacerbate urban flooding risks by enhancing runoff and reducing natural infiltration. Within the framework of this study, land use is identified as a critical factor influencing urban flood risk. Effective land use management, which includes the preservation of natural waterways and the integration of floodplains into urban planning, is vital for mitigating flood hazards and enhancing the resilience of urban environments against flooding, underscoring the importance of thoughtful and strategic planning in flood-prone areas.

## 2.4. Urban growth modelling

Urban growth modelling and prediction have become crucial tools for urban planning and management, particularly in rapidly urbanizing regions. The application of various techniques and algorithms in this field has led to significant advancements in understanding and forecasting urban expansion patterns (Li et al., 2020). Key methodologies include the integration of remote sensing and GIS, as well as the use of machine learning and hybrid models.

Remote sensing and GIS technologies allow for the analysis of spatial and temporal changes in land use and land cover. For instance, in a study on East Kalimantan, Indonesia, land cover changes were mapped for the years 2008, 2013, and 2018, and predictions were made for 2023 using Landsat images and the MOLUSCE plugin in QGIS (Arimjaya & Dimyati, 2022). This study employed a pixel-based digital classification with a maximum likelihood algorithm and utilized artificial neural networks (ANN) and cellular automata (CA) for predictions.

Machine learning algorithms, particularly ANN and CA, have proven effective in urban growth prediction by handling the complexity of urban dynamics through learning from historical data and simulating future scenarios (Rani et al., 2023).

## 2.5. Flood mitigation measures.

According to the UNDRR (2015), flood mitigation Strategies are actions implemented to reduce flood risk and impact. They include nature-based solutions like green spaces that can absorb floodwaters, spatial planning that dictates land use to minimize flood risk, law enforcement that ensures compliance with flood safety regulations, community engagement that prepares and educates citizens, and resettlement from high-risk areas These strategies are necessary to manage and mitigate the impact of urban flooding and are designed to improve urban resilience against future flood events (UNDRR, 2015).

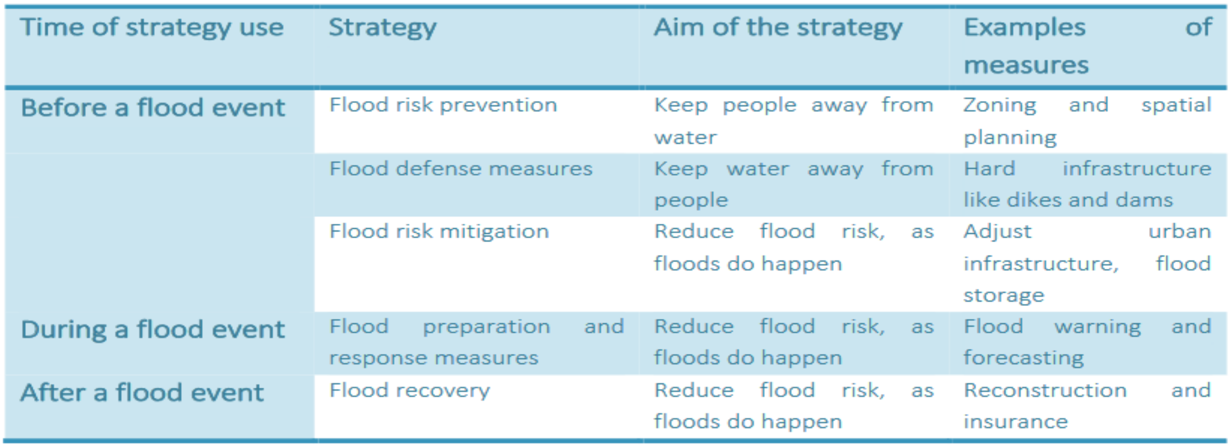
Flood management strategies encompass a variety of approaches designed to minimize the adverse impacts of flooding on human health, property, and the environment. These strategies can be broadly classified into structural and non-structural measures.

Structural measures aim to control floodwaters and include engineering solutions such as dams, levees, and floodwalls. These measures are designed to prevent floodwaters from reaching vulnerable areas (Hegger et al., 2016).

Non-structural measures focus on reducing the vulnerability of communities and enhancing their resilience to floods (Hegger et al., 2016). These measures include zoning laws, land use planning, and the implementation of early warning systems. For instance, the use of land use regulations and flood plain management in Limburg, Netherlands, has been crucial in addressing the impact of floods (Wiering et al., 2017).

Raadgever et al., (2018), also classified flood management strategies into five main types. These were prevention, defence/protection, mitigation, preparation, and recovery.

Table 1 : Types of flood management strategies.



| Time of strategy use | Strategy | Aim of the strategy | Examples of measures |
|---|---|---|---|
| Before a flood event | Flood risk prevention | Keep people away from water | Zoning and spatial planning |
| | Flood defense measures | Keep water away from people | Hard infrastructure like dikes and dams |
| | Flood risk mitigation | Reduce flood risk, as floods do happen | Adjust urban infrastructure, flood storage |
| During a flood event | Flood preparation and response measures | Reduce flood risk, as floods do happen | Flood warning and forecasting |
| After a flood event | Flood recovery | Reduce flood risk, as floods do happen | Reconstruction and insurance |

Source: Hegger et al. (2016)

Flood prevention strategies aim to reduce the exposure of people and property to flood hazards (Raadgever et al., 2018). These include measures such as zoning ordinances that restrict development in flood-prone areas and the creation of open spaces to absorb floodwaters. The Tennessee Valley Authority (TVA) categorizes flood measures into corrective and preventive measures, where preventive measures include floodplain regulations and development policies.

Flood defence or protection involves engineering works designed to prevent floodwaters from impacting communities (Matczak et al., 2022) This includes the construction of levees, floodwalls, and reservoirs. For example, in urban areas like Valkenburg in the Netherlands, increasing the capacity of water buffers significantly helps in managing flood peaks and reducing water levels during extreme events(Hegger et al., 2016) .

Flood mitigation focuses on reducing the impact of floods through measures such as flood-proofing buildings and creating retention areas (Raadgever et al., 2018) The study on the Geul watershed in the Netherland demonstrated that afforestation and the use of water buffers can improve water levels and velocity, thereby reducing flood risks (Hegger et al., 2016) Additionally, the integration of green infrastructure, such as green roofs and rain gardens, helps in managing urban runoff and reducing peak flows during small and frequent storms.

Flood preparation includes developing early warning systems, disaster management plans, and public awareness campaigns to enhance community readiness (Raadgever et al., 2018)

Post-flood recovery strategies focus on rebuilding and restoring normalcy after a flood event (Hegger et al., 2016). This includes reconstruction plans, insurance schemes, and financial compensation for affected individuals. Effective recovery plans are essential for minimizing long-term impacts and facilitating a swift return to normal life (Hegger et al., 2016).

In this study the focus of flood management will be on flood mitigation thus measures implemented to reduce flood risk.

## 2.6. Conceptual framework

The conceptual framework presented is a model for understanding and addressing urban flooding, a pressing issue intensified by climate change, urban growth, and land use.

The relationships indicate that while climate change, urban growth and land use significantly influence flood risk, proactive mitigation and planning can effectively increase a city's capacity to manage and mitigate such risks.

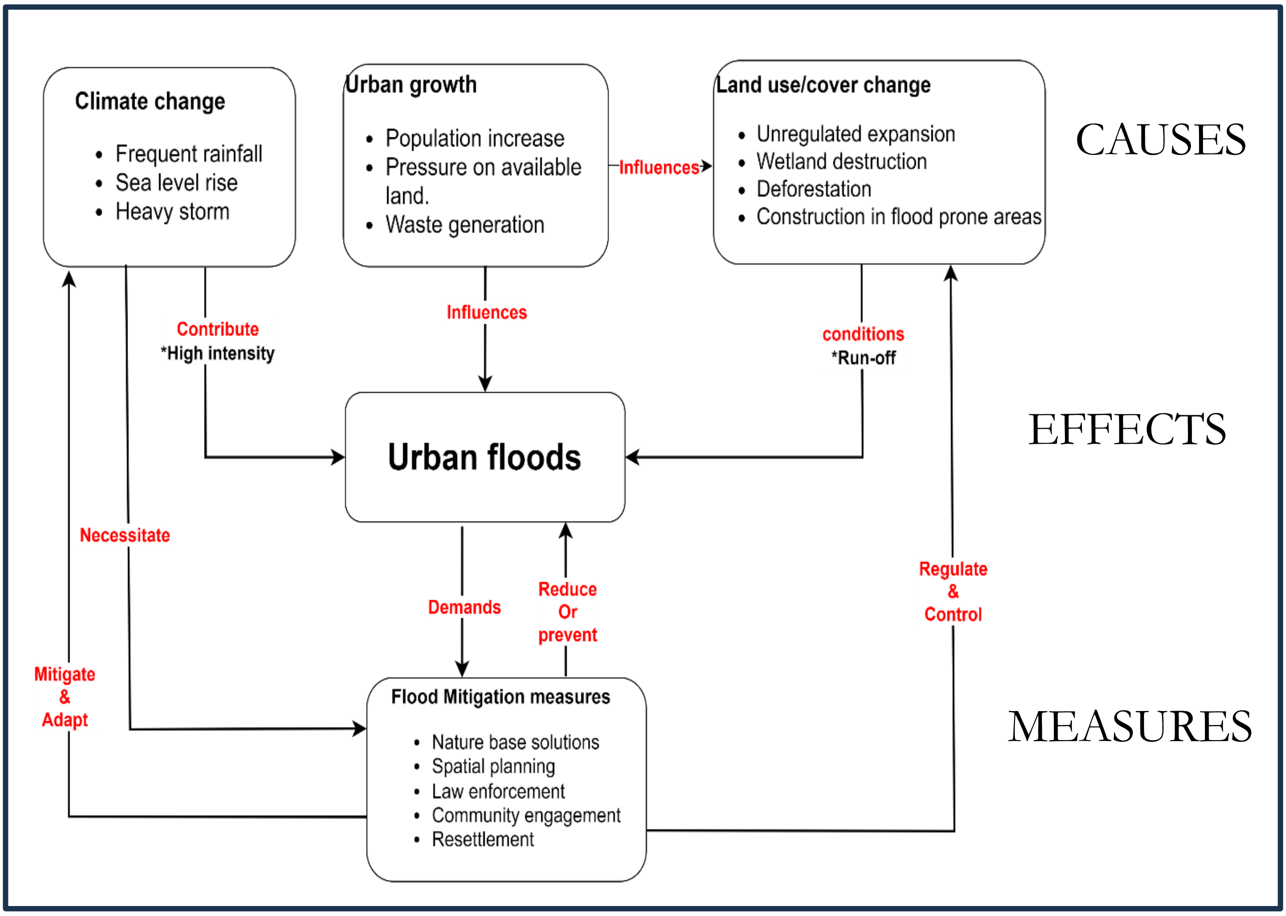


Figure 2: Conceptual framework.

# 3. RESEARCH DESIGN AND METHODS

The aim of the research is to analyse the effect of future rainfall and urban growth on flood hazard in Kumasi. This section, provides a brief overview of the study area's background, outlines how the research objectives and questions were addressed, and details the data used in the analysis.

### 3.1.1. Study Area

Kumasi, the capital of the Ashanti Region and Ghana's second-largest city, is strategically located at approximately 6.6666° N, 1.6163° W, marking it as a central transportation and commerce hub. Its tropical wet and dry climate features a long rainy season from June to October. The average annual rainfall of Kumasi is about 1,400 mm with temperatures ranging between 19 to 30°C. This climate, alongside fertile soils prone to waterlogging, shapes Kumasi's land use, which combines residential, commercial, and significant agricultural activities.

Kumasi's hydrology, with key rivers like Subin, Offin and Owabi, faces challenges due to strained drainage systems during heavy rains, often leading to flooding. These issues are intensified by rapid urbanization and the conversion of natural areas into urban landscapes, affecting the city's natural water bodies (Ahadzie et al., 2016). The population, exceeding two million as per the 2020 census, and total land areas of over 254 square kilometres, put further pressure on the environment and amplify flood risks (Amekudzi et al., 2015). This interplay of factors, including geographic position, climate, soil, vegetation, hydrology, demographic growth, and urban development, heightens Kumasi's vulnerability to flood hazards, challenging urban planning and environmental sustainability (Amoako & Boamah, 2014; Owusu, 2018)

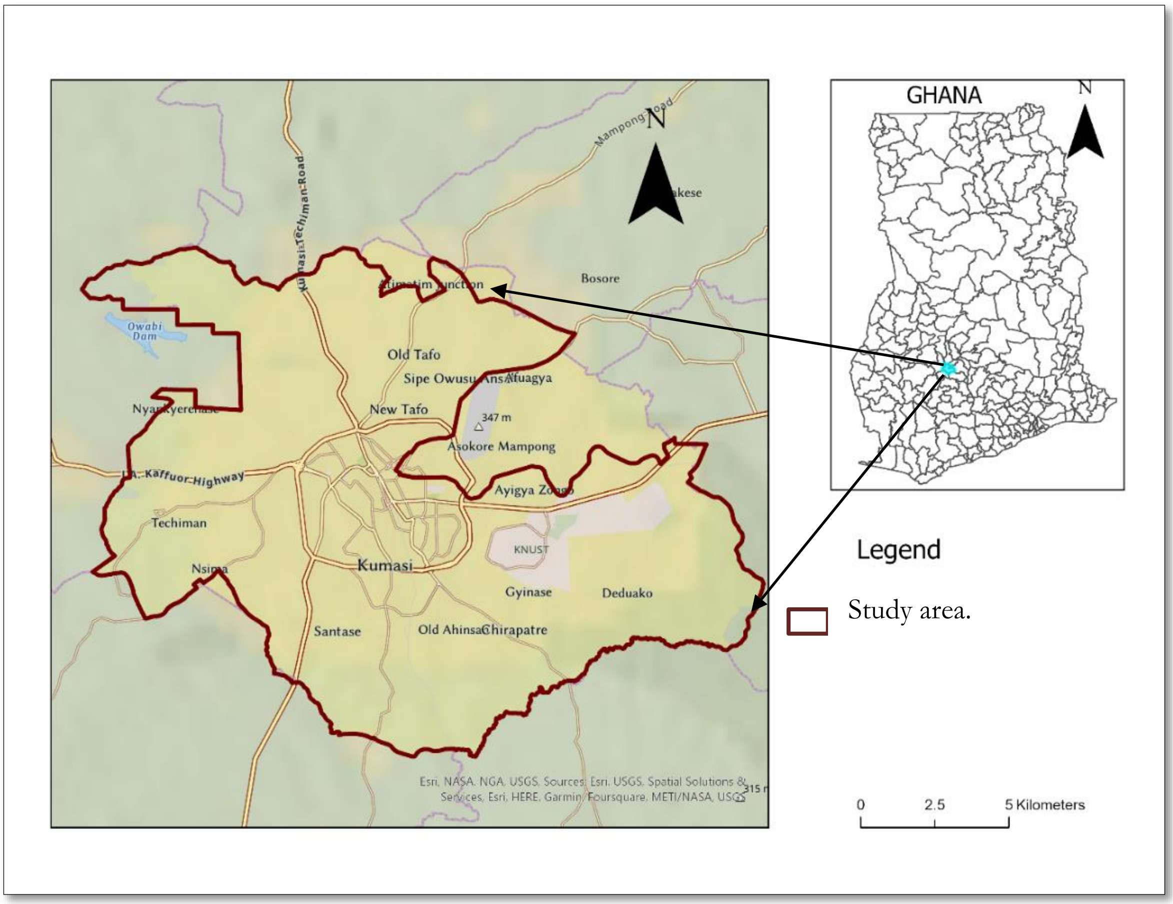


Figure 3: Study area.

### 3.2. Research design and approach.

This study adopted a case study approach, selected for its effectiveness in deeply examining real-life issues within a specific jurisdiction. The focus was on future rainfall, urban expansion, and urban flooding in Kumasi. A mixed-method approach combining both quantitative and qualitative techniques was utilized to investigate various aspects of the case, thereby enriching the research through triangulation. Heale et al. (2013) suggest that triangulation enhances the reliability of research findings by using multiple methods to gather and analyse data.

The study included a comprehensive mix of spatial, statistical, interview and document review to generate detailed insights. McBride et al. (2019) emphasizes the benefits of mixed methods, explaining that they deepen understanding by revealing the underlying reasons behind quantitative results. This integrative approach allowed for a more nuanced exploration of the complex dynamics at play in urban growth and flood.

### 3.3. Data sources and collection

The study incorporated both primary and secondary data to fulfil its research aims. Primary data were gathered from the viewpoints of flood management stakeholders and spatial planning institutions regarding the primary contributing factors of flooding in Kumasi and the implemented mitigation strategies. This data was collected via semi-structured interviews, conducted in person. Further explanation on primary and secondary data are provided in the corresponding section.

### 3.3.1. Primary data collection

#### 3.3.1.1. Sampling technique of key informants and interviews

To gather in-depth insights for the first and last objectives of the research, semi-structured interviews were employed, focusing on the views of professionals from spatial planning and flood mitigation institutions regarding the primary causes of flooding and the mitigation measures in place in the study area. The choice of semi-structured interviews, as explained by (M. M. Rahman, 2019), facilitates the extraction of targeted and relevant responses, providing valuable information about the major flood causes and the implemented mitigation strategies. These interviews allowed for detailed discussions on the participants', general knowledge of urban floods, the contributing factors, the measures being implemented to manage these issues and suggestions for future mitigations.

The selection of participants for these interviews was guided by a purposive sampling technique, aiming to include professionals involved in urban flood management and spatial planning. The key informants were drawn from specific relevant institutions including the Physical Planning Department of Kumasi Metropolitan Assembly, the Development Planning Department of Kumasi Metropolitan Assembly, Kwadaso Municipal Planning Department, Oforikrom Municipal Planning Department, National Disaster Management Organisation (NADMO), and the Ghana Hydrological Agency. These institutions were selected because of their involvement in flood management activities in the study area. This selection process ensured that the respondents had pertinent expertise and could provide substantial information relevant to the study.

In preparation for the interviews, formal letters were sent to the respective institutions to obtain permission and arrange suitable dates for the interviews. Consent was acquired from the participant before the interview. Six face-to-face interviews were conducted out of the ten initially planned because the other four institutions did not respond to the letters and permission was not also granted after several contacts. The researcher used pen and paper to write down the necessary points from all the interviews and supplemented them with audio recordings, however, permission to audio record was granted for only two of these six interviews, in some cases, official documents such as previous storm drainage plans were given to the researcher to support the interview responses. The details of these interviews and the list of institutions visited are summarized in the corresponding table 2.

Table 2: Institutions of key informant

| **Informant code** | **Institutions** | **Number of interviewees** | **Date of interview** |
|---|---|---|---|
| 1 | Physical planning department (KMA) | 1 | 12/02/2024 |
| 2 | Development planning department (KMA) | 1 | 04/03/2024 |
| 3 | National disaster management organisation (NADMO). | 1 | 15/02/2024 |
| 4 | Physical planning department (Kwadaso municipal) | 1 | 18/02/2024 |
| 5 | Physical planning department (Oforikrom municipal) | 1 | 19/02/2024 |
| 6 | Ghana hydrological agency | 1 | 15/03/2024 |

### 3.3.2. Secondary data

Secondary data sources included satellite (Landsat) images from 2013, 2018 and 2023, historical flood event records from 2013 to 2023, future rainfall projections from 2020 to 2039, locations of rivers and water bodies, a Digital Elevation Model (DEM) and flood management literatures. These secondary data were acquired from various government bodies, research institutions, and online platforms. Data obtained from Open Street Map (OSM) were non-authoritative and that no quality assessment have been done. A detailed summary of the data utilized, along with their sources, is provided in Table 1 below. The use and application of these data are elaborated in the analysis section of the research.

Table 3: Data sources

| **Data type** | **Sources** | **Spatial resolution** | **Year** | **Data format** |
|---|---|---|---|---|
| Administrative boundary | OSM | - | - | Vector |
| Projected rainfall data | Climate change Knowledge portal (CCKP) | - | 2020-2040 | Text and Numbers |
| Dital elevation model (DEM) | NASA | 30m | 2023 | Raster |
| Historical flood data | NADMO | City level | 2013-2023 | Text/Numbers |
| Satellite imagery (Landsat) | NASA USGS | 30m | 2013, 20018 and 2023 | Raster |
| Slope | NASA | 30m | 2023 | Reaster |
| Population Density | Worldpop | 100m | 2020 | Raster |
| Location of rivers/water bodies | OSM | - | - | Vector |
| Road networks | OSM | - | - | Vector |
| Location of transport stations | OSM | - | - | Vector |
| Location of CBD | OSM | - | - | Vector |
| Literature on urban growth, flood, and mitigation | Scopus, Web of science, Google scholar, Science direct etc. | - | 2010 and above | Text |

## 3.4. Data Analysis and software tool

### 3.4.1. Objective 1: To identify the contributing factors to urban flooding in Kumasi.

**Flood incidences.**

To examine flood incidences in Kumasi over the past decade, data from 2013 to 2023 was gathered from the NADMO. This dataset includes areas of incidences of flood, the frequency of flood events, and the number of people affected. The geographic details of these flood incidences and prone communities were mapped using ArcGIS Pro to visualize spatial patterns from 2013 to 2023. Additionally, Microsoft Excel was employed to organize the data regarding flood frequencies and affected populations. This data was then visualized using bar charts to highlight trends and patterns in the occurrence of floods in Kumasi.

**Primary contributing factors to flood.**

To identify the primary factors contributing to the occurrences of flooding in Kumasi over the past decade, data was collected from selected institutions and departments through interviews. To ensure no important details were missed, documentation was completed on the same day as each interview through Microsoft word. Further analysis was performed by applying weighted approach to rank the factors according to its importance. The weighted approach was adopted from (Roszkowska, 2013).

### 3.4.2. Objective 2: To analyse urban growth and land cover change in Kumasi.

#### 3.4.2.1. Land cover change.

The land cover change analysis utilized Landsat 8 OLI images from the years 2013 and 2023, obtained from the United States Geological Survey (USGS) online portal https://earthexplorer.usgs.gov/. Both images were taken in the month of December marking the dry season in Ghana. This was to make sure the image has fewer cloud cover to avoid differences in land cover reflectance.

Table 4: Details of satellite images

| Image | Year | Resolution (m) | Cloud cover % | Source |
|---|---|---|---|---|
| LANDSAT 8 OLI | 2013 | 30 | 0 | USGS |
| LANDSAT 8 OLI | 2018 | 30 | 5 | USGS |
| LANDSAT 8 OLI | 2023 | 30 | 0 | USGS |

#### 3.4.2.2. Image processing

Image processing commenced by stacking the various band images extracted from the downloaded Landsat images. This stacking process facilitated the composition of different bands into a unified multispectral image, enhancing the interpretability of the data. Subsequently, a sub-setting procedure was undertaken to define and isolate the specific study area for subsequent analysis because the original Landsat images encompassed a broader extent beyond the study area.

Following sub-setting, the image underwent projection into the Universal Transverse Mercator (UTM) zone 30N coordinate system to ensure geometric accuracy and compatibility with further spatial analyses.

#### 3.4.2.3. Image classification

For the supervised classification, specifically employing the random tree/forest algorithm, image pixels were categorized into distinct classes based on their spectral properties. To achieve this, 50 training samples were systematically collected for each identified land cover class by delineating polygons around relevant features. These polygons were strategically positioned to encompass diverse sections of the study area and capture the spectral variability inherent within each land cover type.

The acquisition of training samples was supported by Google Earth in conjunction with the researcher's knowledge with the study area. The execution of the supervised image classification was carried out using ArcGIS pro software, ensuring accurate and efficient analysis of the imagery data.

The image for the land cover classification was classified into six main classes namely, built up, water, grassland, bare land dense vegetation and crop field. These classes were selected based on their relevance to the study area and their impact on urban flooding dynamics.

Table 5: Land cover classes and description

| Land cover class | Description |
|---|---|
| Built up | Buildings, transportation facilities (roads, pavements), industrial and commercial structures |
| Bare land | Exposed soil areas and exposed rocks. |
| Dense Vegetation | Dense bush areas, forest reserve, evergreen, and deciduous forest land areas. |
| Grass land | Shrubs, lawns, parks, pastures. |
| Water | Rivers, ponds, lakes, and reservoirs. |
| Crop land | Agriculture lands for crop planting. |

#### 3.4.2.4. Accuracy assessment

An accuracy assessment of the land cover classification was conducted using Ground Control Points (GCPs), which were randomly generated for the years 2013 and 2023, a total of 250 GCPs were generated respectively. These GCPs served as reference data, providing a basis to verify the precision of the classified maps.

#### 3.4.2.5. Land cover area change analysis.

The changes in the classified land cover classes from 2013 to 2023 were determined and analysed using the area change parameter in the MOLUSCE plugin in QGIS 2.18.24. The analysis involved calculating the initial area covered by each land cover type in 2013 and comparing it with the area in 2023. The plugin automatically computes the increase or decrease in area for each type, providing a quantitative measure of change over the ten-year period. The results are presented in a table that details the changes in each land cover type. This same method was applied to analyse the changes between 2023 and the projected land cover for 2033.

### 3.4.3. Objective 3: To assess future flood scenarios in Kumasi considering future urban growth.

#### 3.4.3.1. Land use land cover change prediction for urban growth.

The Cellular automata (CA) model within QGIS 2.18.24 software facilitated the prediction of future land cover for the year 2033, drawing from historical land cover maps dated 2013 and 2018. This analysis employed the MOLUSCE plugin in QGIS 2.18.24, specifically designed for evaluating and simulating land use changes. The model has been used by several researchers such as Khan & Sudheer, (2022), Muhammad et al., (2022), Nugroho et al., (2018). Spatial variables serving as an input were used together with 2013 and 2018 land cover maps, the variables were elevation, slope, distances from roads, distance from rivers/water body, distance from CBD, distance from transport station and population density were prepared. The rationale for these variables area explained in the corresponding section. All spatial variables were processed in raster format with a pixel resolution of 30 m x 30 m. All distance rasters were calculated using Euclidean distance tool in ArcGIS pro. Slope was extracted from digital elevation model (DEM) using ArcGIS pro.

Table 6: Spatial factors/variables for land cover prediction

| **Categories** | **Independent Variables** |
|---|---|
| Topographical elements | Elevation |
| | Slope |
| Proximity determinant | Distance water/river |
| | Distance to roads |
| | Distance to Central Business District (CBD) |
| | Distance to transport stations |
| Socio-economic indicators | Population density |

#### 3.4.3.2. Rationale for the selection of driving factors for predicting future land cover.

- *Digital Elevation Model*

Elevation directly impacts drainage, flood risk, and the cost of land development. In regions like Kumasi, where varying elevations can influence water flow and susceptibility to flooding, elevation data becomes crucial for planning (Okolie et al., 2023) Higher ground is generally preferred for urban development due to lower flood risk and cost of construction, influencing urban sprawl patterns and infrastructure planning.

- *Slope*

The slope of the land affects construction techniques, costs, and the type of infrastructure that can be built. Flat lands are typically more conducive to large-scale construction and are thus more likely to be developed first. Steeper slopes may require more extensive engineering solutions, affecting their attractiveness for immediate development but may be considered as the city expands (Tariq et al., 2020)

- *Distance to Water/River*

Water bodies are vital for urban areas, providing resources, recreation, and aesthetic value. However, their proximity increases flood risks, necessitating careful planning to balance development benefits with potential hazards. The history of human settlements demonstrates a preference for locations near water for both practical and economic reasons, despite the risks (Bouziotas et al., 2014)

- *Distance to Roads*

Accessibility is a key determinant of land value and development potential. Proximity to existing road networks signifies easier access to markets, services, and other parts of the city, driving both residential and commercial development. This variable captures the centrality and connectivity essential for urban growth (G. Li et al., 2018)

- *Distance to Central Business District (CBD)*

The CBD, typically being a focal point of commercial and financial activities, exerts a strong gravitational pull-on urban development. Land closer to the CBD is in higher demand due to the proximity to jobs, services, and entertainment, shaping the urban growth pattern towards and around these areas (G. Li et al., 2018)

- *Distance to Transport Stations*

Transport stations are catalysts for development, creating nodes of activity and accessibility. The development of residential, commercial, and mixed-use areas around these nodes can significantly shape the urban landscape, promoting densification and efficient land use (Yeboah & Asibey, 2019)

- *Population density*

Population dynamics are fundamental to understanding urban growth. Increases in population drive demand for housing, services, and infrastructure, directly influencing urban expansion and land use changes. Areas experiencing rapid population growth are likely to see accelerated development to accommodate this growth, impacting land use patterns and necessitating expanded urban services and infrastructure (G. Li et al., 2018)

#### 3.4.3.3. **Validation of the predicted land cover with Kappa Statistics**

To ensure the reliability of the projected future and land cover map, the model first calculated the transition potentials between 2013 and 2018. This process was instrumental in forecasting the land cover conditions expected in 2023. The accuracy of this forecasted 2023 land cover map was tested by comparing it to the actual observed map of 2023. The kappa index, a statistical measure that quantifies the agreement between two categorizations of the same variables (Ensrud, 2021), was employed to validate this comparison.

Once confirmed that the model predictions for 2023 were accurate the methodology was applied to project future changes, extending the predictions to the year 2033. This step involved simulating changes in land use and cover over the next decade, using the validated model.

#### 3.4.3.4. **Fastflood model and flood scenario simulation**

To determine the influence of future urban growth and rainfall on flooding in the study area, the fastflood model developed by van den Bout et al., (2021) was employed. It is a super-fast simulation tool known for its speed and accuracy (van den Bout et al., 2023). Developed initially in 2021 and continuously improved over the years, fastflood now offers a web-based platform that significantly outperforms traditional models. It achieves over 97% accuracy and is 1500 times faster than conventional methods (van den Bout et al., 2023) making it an ideal choice for this study.

Fastflood utilizes several unique algorithms and supports a variety of parameters tailored to different flooding scenarios. The tool can be used to download data from global datasets. Users also have the option to input or load prepared or external data directly into the tool.

The model offers comprehensive tools for flood simulation and mitigation design. It facilitates rainfall analysis, flood analysis, calibration, and validation, allowing users to produce and evaluate various flood and mitigation scenarios effectively. This capability makes fastflood particularly suitable for assessing the impacts of urban growth and climatic changes on flood hazard.

In this study, key inputs such as elevation data, land cover, infiltration rates and rainfall data were incorporated to simulate future flood scenarios. The model's ability to handle these diverse inputs and its rapid computation power helps to efficiently analyse potential flood depths and identify areas at risk under different future conditions.

#### 3.4.3.5. Fastflood Model inputs.

To simulate the flood the following parameters were utilised.

***Elevation data***

To accurately represent the terrain's surface in our flood simulation, Digital Elevation Models (DEMs) was utilized. These models are crucial as they provide detailed topographic information, which significantly impacts water flow and accumulation during rainfall events (Okolie et al., 2023). For this simulation, DEMs with a 30-meter resolution used. This resolution was selected to ensure consistency with other datasets used in the study, allowing for a more precise and coherent analysis of the terrain and its influence on flooding patterns.

***Land cover.***

To represent various surface types such as urban areas, vegetation, bare land, cropland, grassland, and water bodies, integration of land cover data was included in the flood simulation model. This data is essential for determining the roughness, water penetration rates and runoff characteristics of different surfaces. To be able to assess the impact of urban growth on flooding in the study area, current (2023) and simulated future land cover map for 2033 were used, which included six distinct classes: Built-up areas, Water, Bare land, Dense vegetation, Cropland, and Grassland.

Each land cover class was assigned a Manning coefficient value, a parameter for accurately modelling water flow across different surfaces. These values were derived from ESA (https://climate.esa.int/en/projects/land-cover/).

Table 7: Land cover Manning value coefficient

| LAND COVER CLASS | MANNING VALUES |
|---|---|
| Built up | 0.015 |
| Water | 0.02 |
| Bare land | 0.03 |
| Grass land | 0.04 |
| Dense vegetation | 0.12 |
| Crop land | 0.035 |

Source: ESA

***Infiltration Rates***

Infiltration data, which indicates how quickly water is absorbed into the ground, was essential for simulating realistic flood scenarios. Different soil types and land covers have varying infiltration capacities, affecting how much water contributes to surface runoff. To add infiltration to the simulation, the fastflood provide an avenue to download an infiltration data from SOILGRIDS.

***Rainfall***

To assess the potential flood hazard in the study area, rainfall intensity and duration data were critical inputs for the flood simulation. This data helps model how much rain falls over a specific period and its impact on runoff and potential flooding. The rainfall data was sourced from the Climate Change

Knowledge Portal (CCKP) for the World Bank, including projections for 2020-2039 and historical rainfall for 1995-2014 used as reference period.

The data was provided as averages for the largest one-day precipitation. To determine the rainfall intensity, the average duration of rainfall for the month with the highest rainfall (September) was used. This value was divided by the average rainfall amount to calculate the rainfall intensity. The formula used is:

$$\text{Rainfall Intensity (mm/hour)} = \frac{Average\ rainfall\ (mm)}{Average\ duration\ (hours)}$$

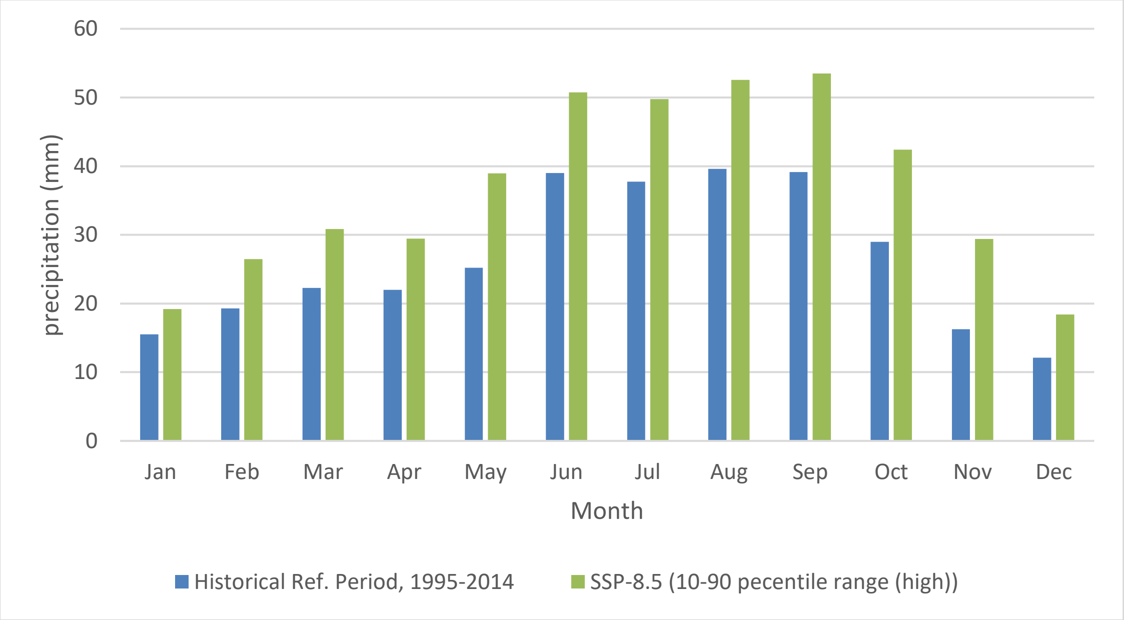


Figure 4:Average largest one-day precipitation. Sourced: Climate change knowledge portal (CCKP)

#### 3.4.3.6. Calibration and Validation

The fastflood-model calibration focused on finding the optimal combination of settings to achieve the best approximation of the observed and modelled flood. Three calibration parameters were used: flood depth, Manning multiplier, and infiltration multiplier.

A selection of eight historic flood depth was used, with observed depths ranging from 0.4 to 2.4 meters. The Table 8 below shows the observed flood depth points collected from Building and Road Research Institute (BRRI), Geo-informatic and planning division.

Table 8: Observed flood depth used for calibration.

| Date | Flood depth | Longitude | Latitude |
|---|---|---|---|
| 11/05/2018 | 2.4 | 6.647673 | -1.598807 |
| 11/05/2018 | 1.1 | 6.713501 | -1.600517 |
| 11/05/2018 | 0.7 | 6.649319 | -1.621259 |
| 11/05/2018 | 1.5 | 6.622027 | -1.603143 |
| 17/09/2021 | 1.7 | 6.699686 | -1.624374 |
| 17/09/2021 | 0.9 | 6.649414 | -1.599859 |
| 17/09/2021 | 0.5 | 6.709081 | -1.617893 |
| 17/09/2021 | 0.4 | 6.697333 | -1.621592 |

*Source: Building and Road Research Institute (BRRI)-Kumasi.*

After inputting the historical flood depths into the model, auto-calibration was employed to determine the best fit for the Manning and infiltration multipliers. The calibration was performed on the baseline scenario employing current land cover and observed rainfall intensity. After getting the best fit for the model, other inputs for future scenarios (projected rainfall and projected land cover depicting future urban growth) were input to simulate the future flood scenarios based on the calibrated baseline scenario. To further enhance the calibration quality, a flood depth threshold was set at 0.03m, as used by Moftakhari et al. (2018) indicating that any depth below this threshold is not considered a flood, while any depth value above is considered a flood.

#### 3.4.3.7. Flood scenario model development.

Flood scenarios were developed to assess the potential flood hazard in the study area using both rainfall and land cover data. Current and projected future land cover data were incorporated to evaluate their impact on flood depth and extent. To enhance comparability and better analysis, four scenarios were created.

***Scenario 1: Baseline (current land cover with observed rainfall)***

This scenario uses observed rainfall data and current land cover data (objective two) to represent observed current flood conditions. It provides a benchmark for comparison with future scenarios, allowing for an assessment of how changes in land cover and rainfall patterns might impact future flood.

***Scenario 2: Future rainfall impact (current land cover with projected future rainfall)***

The scenario assumes that the projected future rainfall, based on the SSP5-8.5 climate change scenario, will be realized. This includes an increase in the intensity of extreme rainfall events. It is assumed that the current land cover data will remain unchanged during the analysis period. This scenario helps to understand the impact of future rainfall without changes in land cover or urban growth. It isolates the effect of projected future rainfall patterns while keeping land cover constant.

***Scenario 3: Urban growth impact (future land cover with observed rainfall)***

This scenario assumes a change in land cover reflecting projected changes in urban growth.

It uses observed rainfall to represent current rainfall conditions. This scenario helps to understand the impact of future land cover changes on flood using observed rainfall. It isolates the effect of urban growth and land cover changes while keeping the rainfall constant, providing insight into how changes in land use and urbanization affect flood dynamics.

***Scenario 4: Combined future impact (future land cover with projected future rainfall)***

This scenario assumes future land cover changes reflecting projected urban growth and projected future rainfall. Here it is assumed that these two future projections will be realized.

This scenario helps to understand the combined impact of future rainfall and land cover changes on flood hazards. It provides a comprehensive view of potential future flood hazards by considering both climate change impacts on rainfall and urbanization effects on land cover, enabling effective planning and mitigation strategies for future conditions.

Table 9:Summary of flood scenario

| Scenario Number | Scenario | Rainfall per hour (mm/h) | Landcover | Hours for simulation | Scenario description |
|---|---|---|---|---|---|
| 1 | Baseline | 13.04 (Observed) | 2023 (Current) | 6 | Current land cover with observed Rainfall |
| 2 | Future Rainfall impact | 17.83 (Future) | 2023 (Current) | 6 | Current land cover with Projected Future Rainfall |
| 3 | Urban growth impact | 13.04 (Observed) | 2033 (future) | 6 | Future land cover with observed Rainfall |
| 4 | Combine future impact | 17.83 (Future) | 2033 (future) | 6 | Future land cover with Projected Future Rainfall |

### 3.4.4. Objective 4: To identify potential flood mitigation measures for future floods in Kumasi.

The interviews from the key informant as already stated in sub-section 3.4.1 on suggested mitigation measures for future floods in Kumasi were analysed. After the analysis, further feasibility analysis was performed through literature by focusing on economic cost, environmental benefit, and social acceptability of each measure. This was important to identify the feasible measures that can be implemented in Kumasi which are economically viable, environmental beneficial and socially acceptable.

Table 10: Summary of research methodology

| Questions | Data | Analysis method | Tools | Expected output |
|---|---|---|---|---|
| **1. To identify the drivers of urban flooding in Kumasi** | | | | |
| How have the frequency of flood events in Kumasi changed over the past decade? | Key informant interview data. | Qualitative text analysis,<br>Quantitative analysis. | Microsoft word,<br>Excel. | Historical flood events. |
| What were their primary contributing factors? | Key informant interview data. | Qualitative text analysis<br>Weighting frequency. | Microsoft word. | List of contributing factors of flood in Kumasi. |
| What are the current flood mitigation measures in Kumasi? | Key informant interview data. | Qualitative text analysis. | Microsoft word. | Current flood mitigation measures. |

| | | | | |
|---|---|---|---|---|
| **2. To analyse urban growth and land cover change in Kumasi.** | | | | |
| How has land cover in Kumasi changed over the last decades? | Satellite imagery. | Land cover change analysis. | ArcGIS pro. | Land cover maps. |
| **3. To assess future flood scenarios in Kumasi considering future urban growth.** | | | | |
| What is the likely urban growth scenario? | land cover data,<br>Spatial variable (Elevation, slope, road, CBD, population, water bodies transport stations). | Urban growth modelling. | ArcGIS pro, QGIS (Molusce plugin). | Predicted land cover map (Urban growth). |
| How will projected changes in rainfall patterns and urban growth likely affect urban floods in Kumasi? | Current and projected rainfall data.<br>Current and projected land cover. | Flood modelling. | Fastfood. | Current flood map,<br>future flood map. |
| **4. To identify potential flood mitigation measures for future floods in Kumasi.** | | | | |
| What are the potential flood mitigation measures that can be proposed to mitigate floods in Kumasi? | Key informant interview data. | Qualitative text analysis. | Microsoft word. | List of identified potential mitigation measures. |
| How feasible are these measures in the context of Kumasi? | List of identified potential mitigation measures. | Feasibility analysis through literature. | Microsoft word. | Recommended potential measures. |

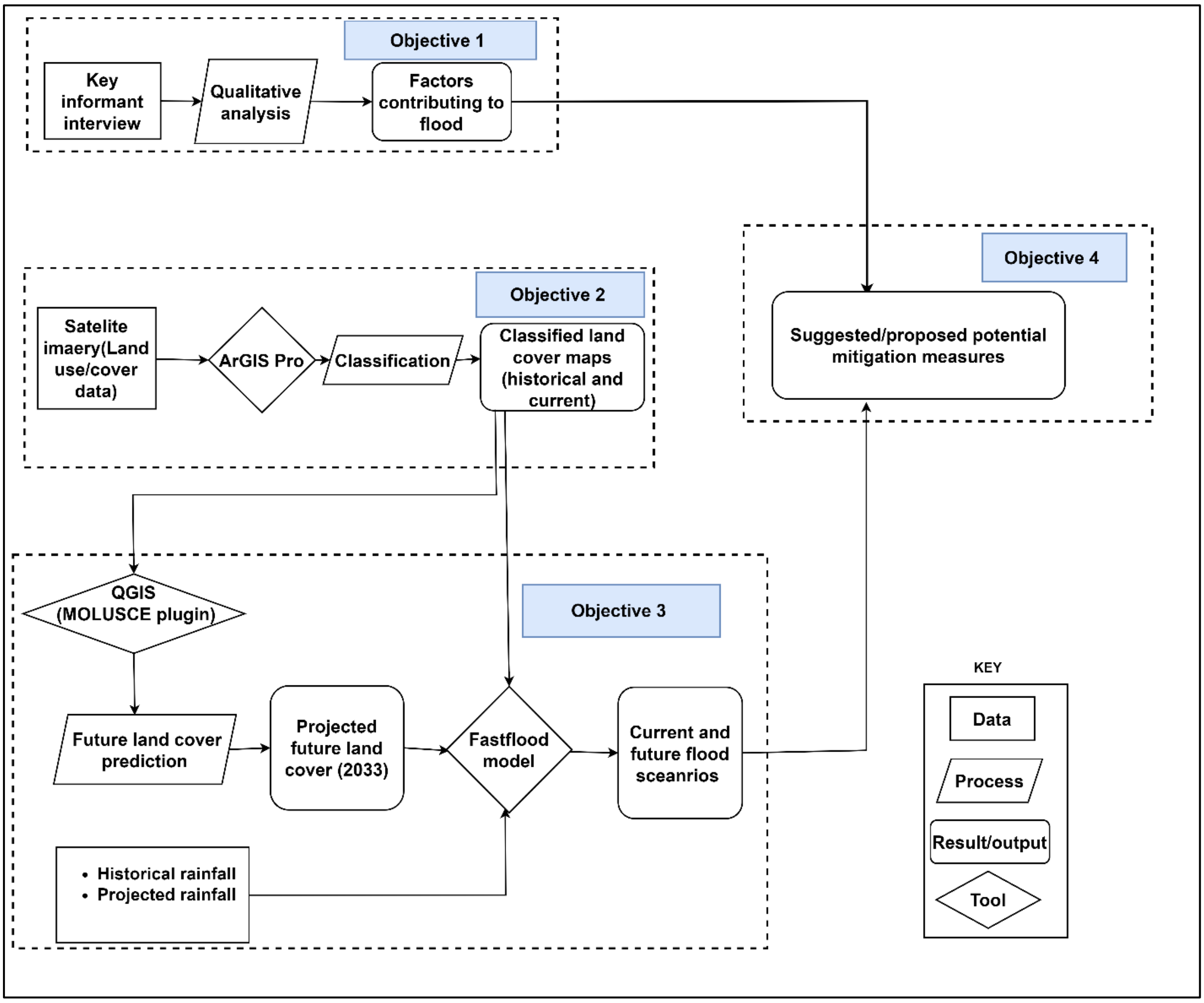


Figure 5: Summary methodological framework.

# 4. RESULTS

This section discusses the findings and outcomes derived from the methodologies applied in relation to the primary objectives of the study. Detailed explanations are provided for the results obtained concerning flood incidences, contributing factors, land cover changes, urban growth, and flood mitigation measures. The findings are systematically organized to align with the specific research objectives and questions outlined in the study, ensuring a clear and structured presentation of the results.

## 4.1. Objective 1: To identify the contributing factors of urban flooding in Kumasi.

Before identifying the contributing factors to flooding, an analysis of flood incidences and cases was conducted. This preliminary step was essential to establish a foundation for exploring the underlying factors contributing to these flood events.

### 4.1.1. Flood incidences in Kumasi over the past decade.

The analysed data on flood events from 2013 to 2023 in Kumasi indicates significant fluctuations in both the number of recorded flood cases and the population affected. In 2013, there were 12 flood cases affecting 391 individuals. The number of cases dropped to 4 in 2014 but impacted a larger population of 614. In 2015, the number increased to 10, affecting 1757 people. A notable rise occurred in 2016, with 17 cases impacting 2990 individuals, and peaking in 2017 with 38 cases affecting 3236 people. In 2018, flood cases dramatically rose to 53, though the affected population was lower at 672. In 2019, there were 33 cases affecting 809 people, followed by a sharp decrease in 2020 to 6 cases impacting 113 individuals. The trend reversed in 2021 with 29 cases affecting 2377 people, and slightly increased in 2022 to 34 cases with 3141 individuals affected. By 2023, the number of flood cases rose to 37, impacting a record high of 3958 people.

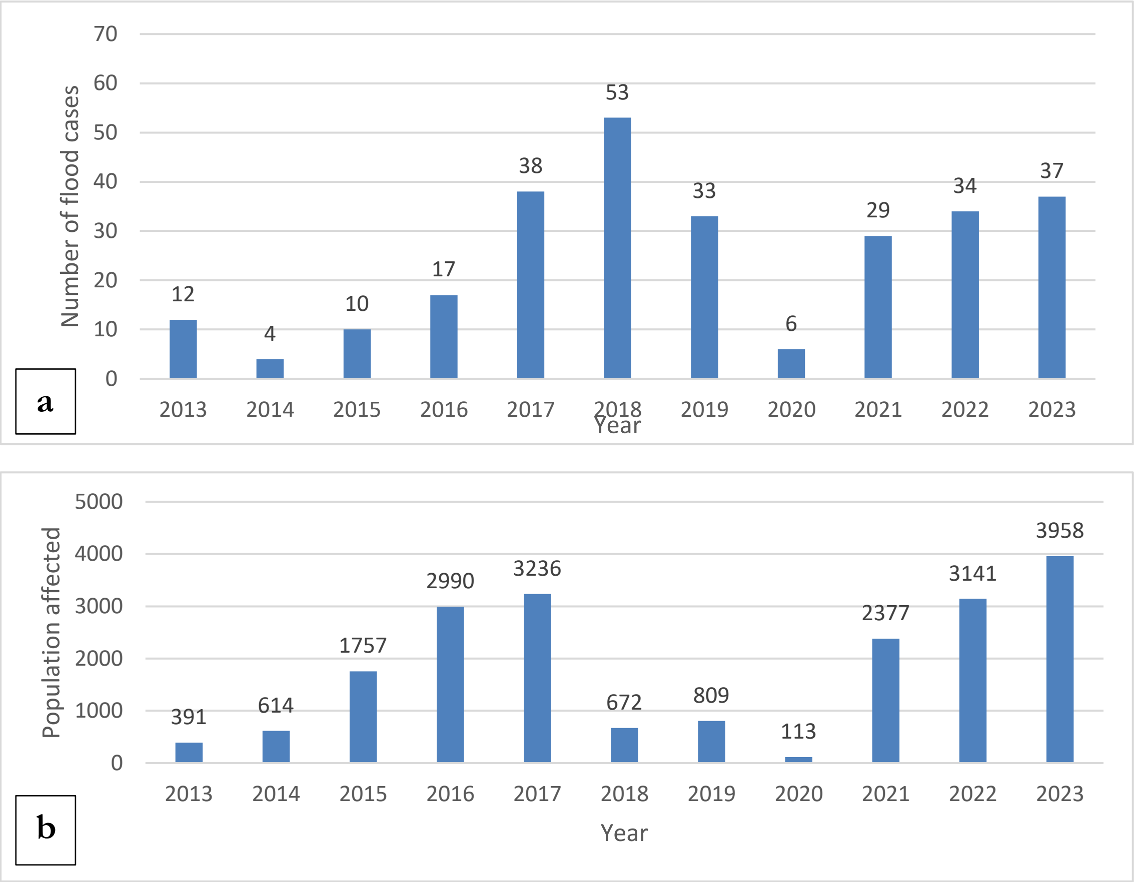


Figure 6: The trend of flood cases (a) and population affected (b) in Kumasi from 2013 to 2023.

The analysis of flood incidence in Kumasi between 2013 and 2023 reveals a significant evolution in flood risk within the city (Shown in figure 7) below. In 2013, flood incidence areas were relatively less, affecting specific locations at the central and the southern part such as Atonsu, Aputuogya, Ahinsan, Subin and Kaase. In total, seven areas were affected and experienced flood in 2013. In 2023, however, there was a noticeable increase in both the number and spread of flood-incidence areas, increasing to twelve suburbs. New suburbs, including Kwadaso, Dechemso, Adiebeba, Edwenase, and areas extending towards Subin Ampabame and Asuoyeboa. The analysis shows that, areas that used to experience flooding in 2013 still experience flooding in 2023. This increase illustrates that the risk of flooding is no longer confined to isolated areas but has become a gradual widespread concern in Kumasi.

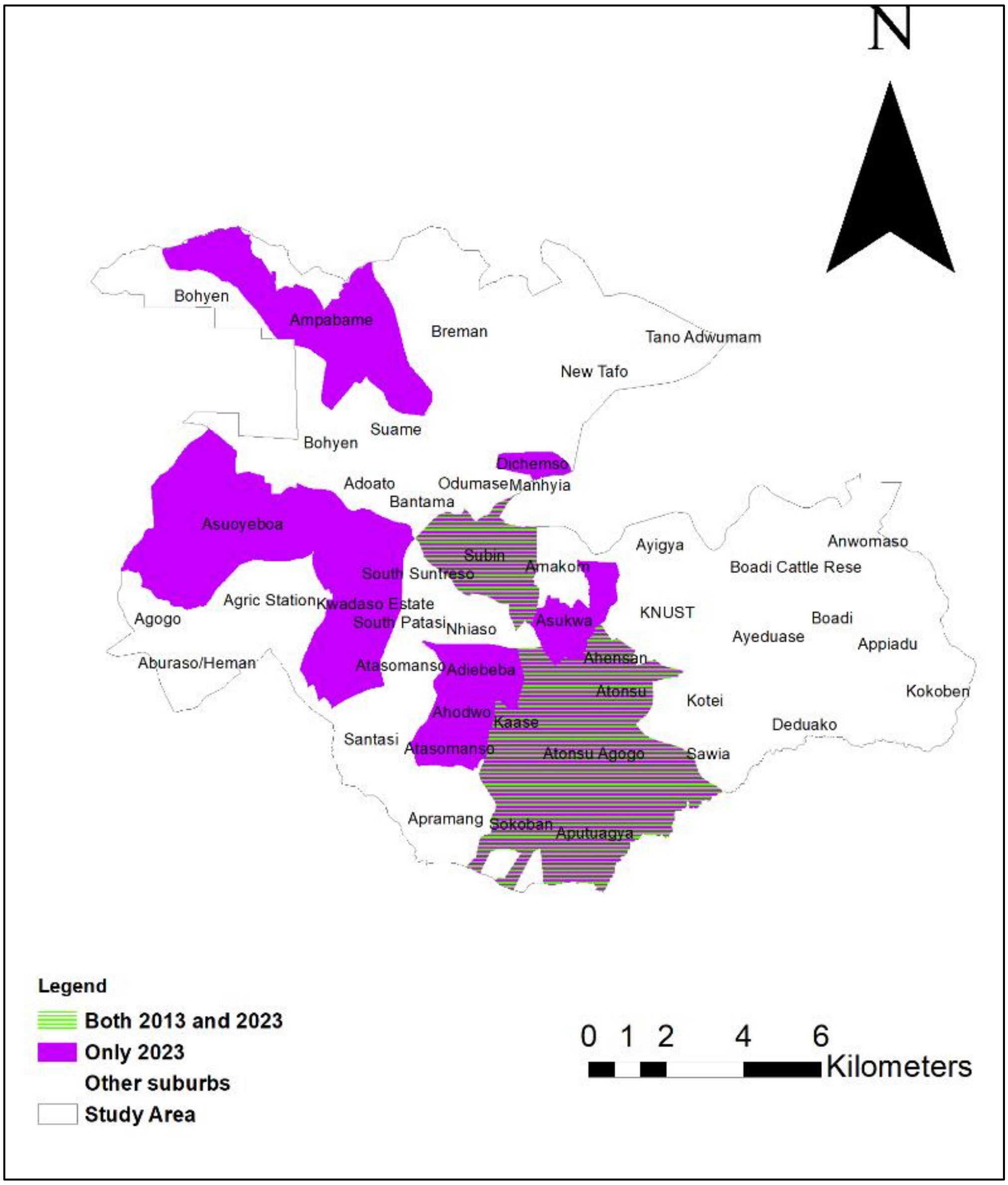


Figure 7: Historical flood incidence areas for 2013 and 2023.

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#### 4.1.2. Contributing factors to the increasing urban flood in Kumasi.

From the analysis of flood contributing factors as shown in

Table 11 and Table 12, each factor's total weight across all departments and institutions was calculated to determine its overall significance. The final ranking of these factors was established by summing the weights, providing a clear hierarchy of flood causation according to the collective assessment of the departments and institutions. This weighted approach ensures that factors consistently ranked as more influential receive appropriate emphasis in the analysis.

Table 11: Identified contributing factors of flood in Kumasi.

| **Institution/Departments** | **Primary contributing factors of flood (Institution ranking)** | **Assigned weight** |
|---|---|---|
| **KMA physical planning department** | 1. Poor drainage systems | 5 |
| | 2. Rapid urbanisation | 4 |
| | 3. Deforestation | 3 |
| | 4. Climate change | 2 |
| | 5. Inadequate waste management. | 1 |
| **KMA Development planning department** | 1. Poor drainage systems | 5 |
| | 2. Inadequate waste management (Dumping of waste in drains and on the street). | 4 |
| | 3. Climate change (Excessive rainfall). | 3 |
| | 4. Deforestation (Cutting down of trees and clearing of vegetations). | 2 |
| | 5. Rapid urbanisation (Population growth) | 1 |
| **National disaster management Organisation (NADMO)** | 1. Climate change | 5 |
| | 2. Poor and inadequate drainage systems and facilities | 4 |
| | 3. Rapid urbanisation causing poor urban planning | 3 |
| | 4. Poor environmental attitude (Deforestation) | 2 |
| | 5. Inadequate waste management. | 1 |
| **Ghana hydrological agency** | 1. Climate change | 5 |
| | 2 Poor drainage systems | 4 |
| | 3. Inadequate waste management | 3 |
| | 4.Improper urban planning and careless physical development. | 2 |
| | 5. Deforestation | 1 |

| | | |
|---|---|---|
| **Physical planning department (Kwadaso municipal)** | 1. Climate change | 5 |
| | 2 Poor drainage systems | 4 |
| | 3. Inadequate waste management | 3 |
| | 4. Improper urban planning | 2 |
| | 5. Deforestation | 1 |
| **Primary causes of flood by Physical planning department (Oforikrom municipal)** | 1. Poor drainage systems | 5 |
| | 2. Rapid urbanisation | 4 |
| | 3. Deforestation | 3 |
| | 4. Climate change | 2 |
| | 5. Inadequate waste management. | 1 |

Table 12: Ranked flood contributing factors after aggregated weight.

| **Contributing factors** | **Aggregated weight** | **Rank** |
|---|---|---|
| Poor and inadequate drainage systems | 27 | 1st |
| Climate change (Excessive/intensity rainfall) | 22 | 2nd |
| Inadequate waste management | 13 | 3rd |
| Deforestation | 12 | 4th |
| Rapid urbanisation | 10 | 5th |
| Improper urban planning. | 2 | 6th |

In Table 12 above, the results from the aggregated weights provide a clear picture: poor and inadequate drainage systems, including broken drains, uncovered drains, undersized drains, and a lack of drainage infrastructure in certain areas, emerge as the most critical factor. Participants in interviews indicated that many neighbourhoods that experience consistent flooding often suffer from inadequate or non-existent drainage infrastructure (key informant 1, 2 and 3). A visit to some of these flooded neighbourhoods showed poorly managed and maintained drains (Figure 8), in some cases, uncovered drains were filled with waste and weeds. This highlights the prevalent issue of flooding as a result of inadequate and poor drainage infrastructure unable to cope with water flow during heavy rainfall events in Kumasi.

Figure 8: Small scale street drain unconstructed (image a) and covered with weeds (image b)

Source: Field work by the author.

Closely following is the factor of climate change, particularly changes in rainfall patterns and intensity resulting in excessive rainfall. This factor ranks second and is notably recognized by NADMO and the Ghana Hydrological Agency as a pressing issue. Experts from these organizations emphasized the increasing unpredictability and intensity of rainfall due to climate change, noting that existing infrastructure is not equipped to handle such volumes of water. An expert from NADMO (Key informant 3) stated: "*We are seeing more intense rainfall events than before, and our infrastructure is not designed to handle such volumes of water, leading to frequent flooding.*"

Inadequate waste management is identified as the third most significant factor. It points to issues with waste disposal practices that obstruct drainage systems and exacerbate water accumulation during floods. Several informants pointed out that inadequate waste management exacerbates flooding. Informant 2 stated: *"People often throw trash into the drains, especially plastic bags, because of the lack of proper waste disposal systems, which clogs the drains and causes flooding even with moderate rain."* The key informant 2 added that the central business districts of Kumasi, areas like Adum, Asafo, Kejetia, Central market, Alabar, as well as areas like Moeshie Zongo and Asawase, suffer from waste accumulation on the streets. To him, this waste is often dragged into drains, causing blockages, and increasing the incidence of flooding. The interview revealed that many residents have turned drainages into garbage dumping sites, leading to sediment and refuse accumulation, which completely blocks drains during rainfall.

Deforestation associated with urban expansion has caused the city to lose much of its vegetation which could have helped in water absorption and infiltration. Key informant 3 and 4 emphasized that the loss of vegetation has resulted in impervious surfaces, significantly contributing to the flood cases in Kumasi.

Rapid urbanization is the fifth-ranked factor, indicating that the rapid expansion of the city into previously undeveloped areas is a notable concern, though not perceived as critically as other factors by all departments. However, it has a significant impact on flood occurrence in Kumasi. Key informant 1 and 4 related rapid urbanization to the increasing population and expansion of built-up areas, causing the city to become more impervious.

Improper urban planning was acknowledged as one factor contributing to urban flooding in Kumasi. According to the key informants, constructions in floodplains has resulted to an increase in flood prone areas resulting to an overwhelming increase in flood cases.

#### 4.1.3. Current flood management/mitigation measure being implemented in Kumasi.

In identifying the current flood management and mitigation measure in Kumasi, NADMO provided insights into the ongoing measures being undertaken to prevent flooding in the city. Below is a detailed overview of these initiatives, reflecting the areas affected, the specific measures implemented, and the institutions involved in these efforts.

Table 13: Current flood mitigation measures being implemented in Kumasi.

| **Current flood mitigation measures** | **Areas or Location** | **Institutions/Departments involved** |
|---|---|---|
| Desilting of existing clogged drainages | Adum, Asafo, Oforikrom, Atonso. | NADMO |
| Construction of new drainages along inner city roads and streets | Sokoban, Atasemanso | Ghana hydrological agency and KMA, NADMO |
| River channel modification and expansion | Atonsu, Ahodwo-Adiebeba | Ministry of Works and housing, Ghana hydrological agency and NADMO |
| Evacuation of people in flood prone areas | Part of Atasemanso, part of Atonsu-Ahinsan. Asawasi | NADMO |
| Community sensitization on flooding | All flood prone zones | NADMO |

***Desilting of existing clogged drainages***

Drainage desilting was found to be a foundational flood mitigation strategy implemented regularly across the city due to its cost-effectiveness and minimal capital requirements. This procedure typically carried out two times a year thus, before and during the rainy season. This is to clear drainage systems of sediments and waste, to ensure smooth water flow during heavy rains. Area identified to have such measure were Adum, Asafo, Oforikrom, and Atonso.

Figure 9: Drainage being desilted at Subin (Asafo)

*Source: (Author's field work)*

***Construction of new drainages along inner city roads and streets***

In addition to desilting, construction of new drainage systems was also mentioned as part of the current measures, particularly in areas undergoing road construction or upgrade. For instance, about fifteen (15) kilometers of street drainage is being constructed in Sokoban, while Atasemanso is seeing the construction of approximately eleven (11) inner drainages. The idea is to channel excess water away from neighbourhoods.

Figure 10: Construction of new drainages at Atasomanso.

*Source: (Author's field work)*

### *River channel modification and expansion*

Another significant measure being implemented in Kumasi involves the modification and expansion of river channels. This includes concreting river walls and diversifying channels to accommodate increased water flow during rainy seasons. Notable areas benefiting from these measures include Atonsu, where concrete river walls are being built, and Ahodwo-Adiebeba, where bridge and channel diversion projects are in progress.

Figure 11: Channel modification at Atonsu and Adiebeba.

*Source: (Author's field work)*

### *Evacuation of people in flood prone areas*

Recognizing the risks posed by construction in flood plains, NADMO revealed that, they have taken proactive steps to evacuate people from high-risk areas, such as parts of Ahinsan, Atonsu, and the lower parts of Asawase. These areas are frequently affected by floods due to their proximity to river channels and wetlands, making them particularly vulnerable. This is to reduce flood occurrence and its impact.

Figure 12: Areas of evacuation.

*Source: (Author's field work)*

***Community sensitization on flooding***

To complement physical mitigation measures, emphasizes on the importance of community awareness and cooperation was acknowledged. Through regular educational and sensitization programs, the organization aims to equip residents of flood-prone zones with the knowledge and tools necessary to effectively prepare for and respond to flooding incidents. These programs focus on instilling an understanding of the risks and the critical actions to take before, during, and after a flood, ultimately fostering a community-oriented approach to disaster preparedness.

## 4.2. Objective 2: To Analyse urban growth and Land cover change in Kumasi for the past decade 2013-2023.

### 4.2.1. Accuracy assessment of land cover analysis.

The classification results for the land cover data from 2013 and 2023 showed overall accuracy of 76.8% and 83.2% and overall kappa statistics of 0.66 and 0.75, respectively. These accuracy rates show the reliability of the tools and methods employed in the classification process, indicating a solid performance in accurately capturing the changes in land cover over the period.

Table 14: 2013 land cover accuracy assessment

| **Class name** | **Reference points** | **classified total** | **Number correct** | **Producer Accuracy** | **User accuracy** | **Kappa stat** |
|---|---|---|---|---|---|---|
| Built up | 101 | 116 | 91 | 90.10% | 78.45% | 0.190 |
| Water | 5 | 4 | 3 | 60.00% | 75.00% | 0.000 |
| Bare land | 11 | 9 | 5 | 45.45% | 55.56% | 0.002 |
| Dense Vegetation | 75 | 74 | 61 | 81.33% | 82.43% | 0.090 |
| Crop field | 17 | 10 | 7 | 41.18% | 70.00% | 0.003 |
| Grassland | 39 | 31 | 25 | 64.10% | 80.65% | 0.022 |
| Total | 250 | 250 | 192 | | | |
| **Overall Accuracy = 76.8%**<br>**Overall Kappa statistics = 0.66** | | | | | | |

Table 15: 2023 land cover accuracy assessment

| **Class name** | **Reference points** | **classified total** | **Number correct** | **Producer Accuracy** | **User accuracy** | **Kappa stat** |
|---|---|---|---|---|---|---|
| Built up | 101 | 117 | 95 | 94.06% | 82.05% | 0.19 |
| Water | 5 | 5 | 3 | 80.00% | 80.00% | 0.0004 |
| Bare land | 11 | 10 | 7 | 63.64% | 70.00% | 0.0017 |
| Dense Vegetation | 75 | 73 | 65 | 85.33% | 87.67% | 0.09 |
| Crop field | 19 | 16 | 13 | 63.16% | 77.00% | 0.005 |
| Grassland | 39 | 29 | 25 | 64.10% | 86.21% | 0.0200 |
| Total | 250 | 250 | 208 | | | |
| **Overall Accuracy = 83.2%**<br>**Overall kappa statistic = 0.75** | | | | | | |

### 4.2.2. Land cover coverage percentage and changes for 2013 and 2023.

The land cover change in Kumasi over the past decade shows significant transformations driven by urbanization and related socio-economic factors. Figures 13, 14, 15, and 16 illustrate these changes across six land cover classes: Built-up, Water, Bare land, Dense vegetation, Crop field, and Grassland. The most striking change is the expansion of built-up areas, which increased from 70.10% in 2013 to 80.06% in 2023, representing a substantial area increase of 21.35 sq. km. Conversely, dense vegetation experienced a significant decline, dropping from 26.15% coverage in 2013 to 15.86% in 2023, corresponding to a reduction of 22.05 sq. km. Water bodies also saw a notable decrease, from 0.23% coverage in 2013 to 0.03% in 2023, indicating an area reduction of 0.43 sq. km. Bare land increased from 0.32% coverage in 2013 to 1.02% in 2023, corresponding to an area increase of 1.49 sq. km.

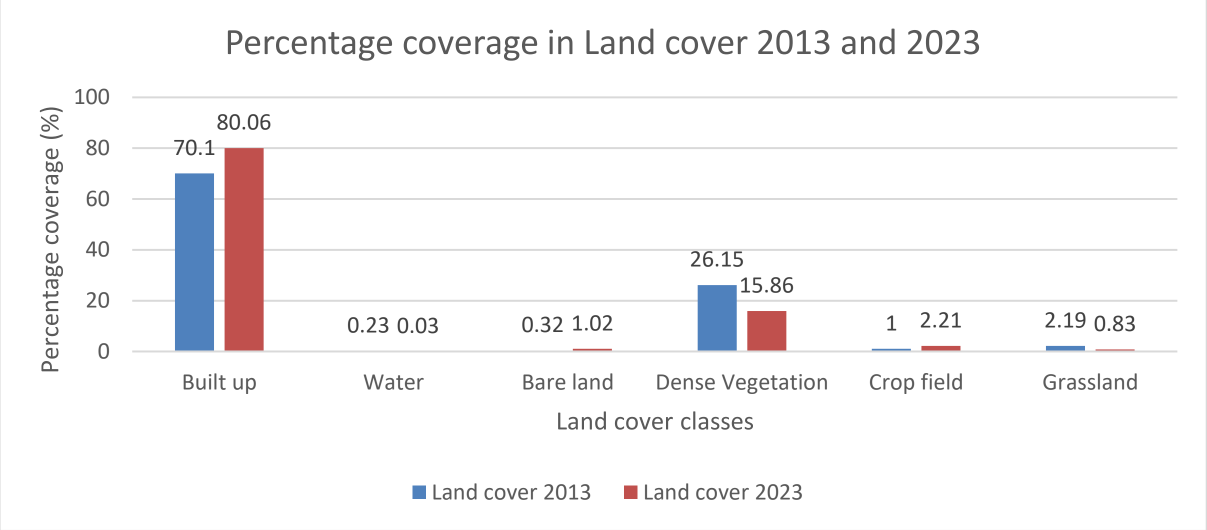


Figure 13: Land cover coverage percentage for 2013 and 2023.

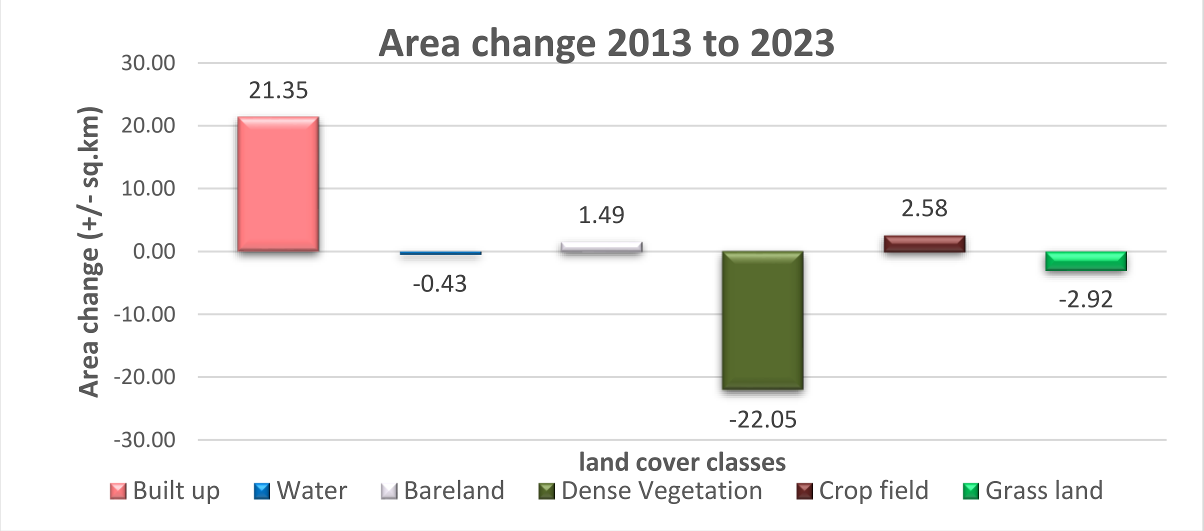


Figure 14 : Area change between 2013 and 2023.

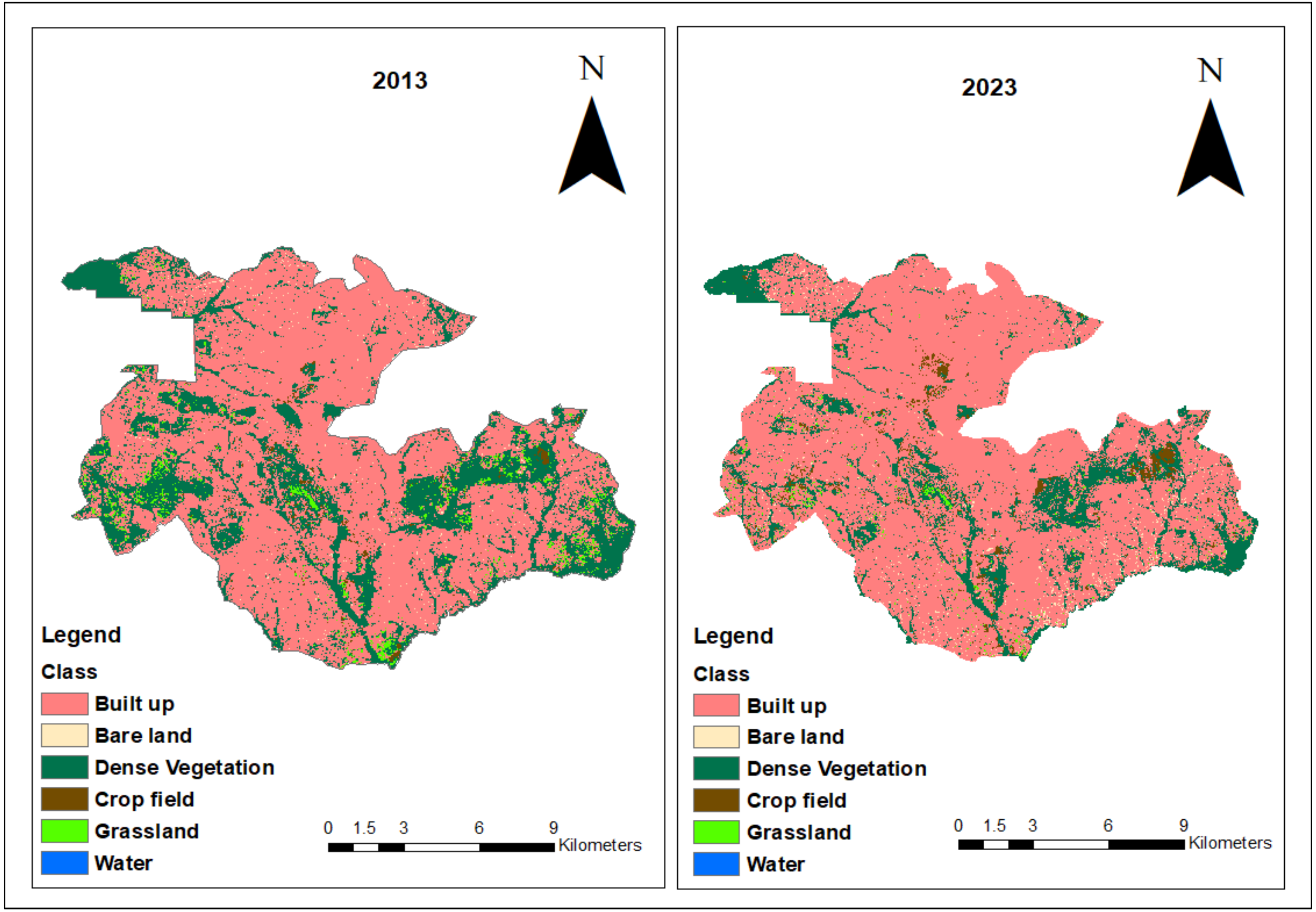


Figure 15: Land cover map for 2013 and 2023

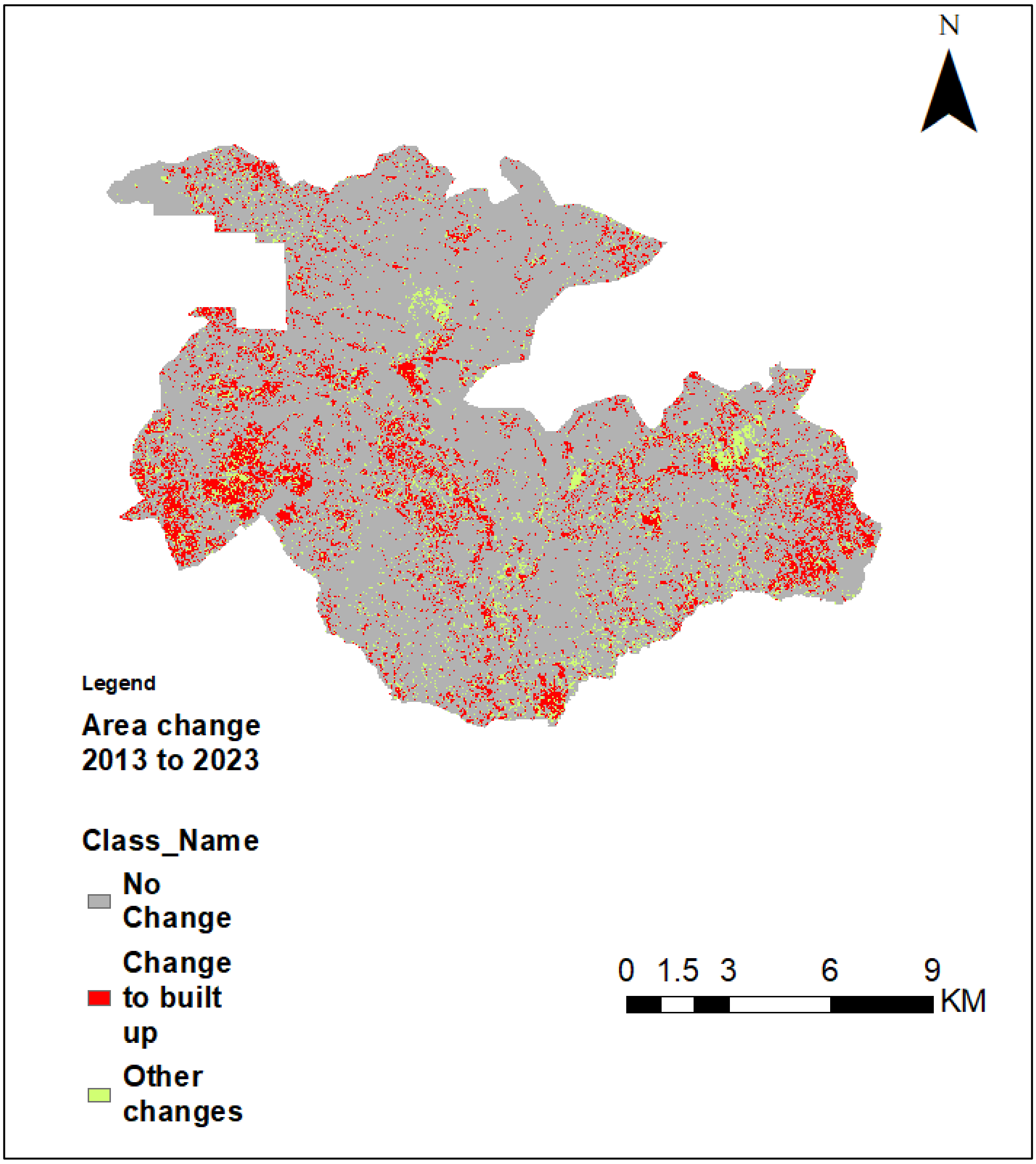


Figure 16: Area changes from 2013 to 2023.

### 4.3. Objective 3: To assess future flood scenarios in Kumasi considering future urban growth.

The result for objective three is divided into two parts. The first part involves predicting urban growth for the year 2033, covering a 10-year span. The second part involves flood scenario modelling using the fastflood model tool. The following results address objective three.

#### 4.3.1. Urban growth based on land cover prediction.

The growth predictioon involved a number of steps, the steps have been described in chapter three under the methodology together with urban growth variables used. Below provide the results of the steps in the growth prediction using land cover data.

#### 4.3.1.1. Transition matrix.

The transition matrix analyses changes in land cover over time by detailing the proportion of pixels moving between categories. Rows represent the initial year's categories, and columns represent the final year's categories. Diagonal entries indicate class stability, showing the proportion of unchanged pixels, while off-diagonal entries indicate transitions between classes. High diagonal values signify stable categories. Transition matrices are essential for assessing temporal changes across regions (Nugroho et al., 2018).

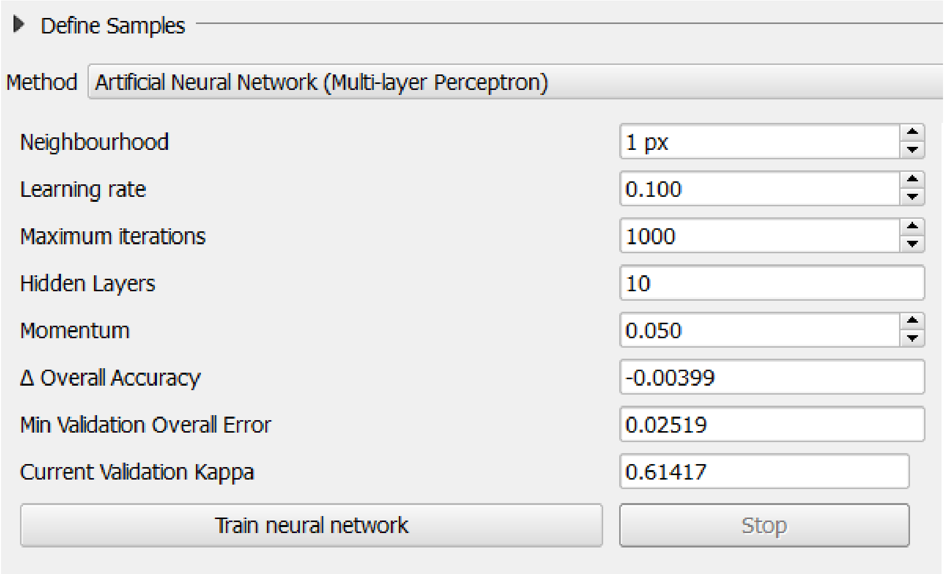
To illustrate projected land cover changes within the study area, the transition potential matrix for 2013-2018 was created using the MOLUSCE plugin. Built-up land demonstrated high stability (0.909401) with minimal transitions. Water showed moderate stability (0.048309), transitioning significantly to dense vegetation (0.320451) and crop fields (0.344605). Bare land had low stability (0.066038) but transitioned mainly to built-up land (0.913208). Dense vegetation was highly stable (0.724547), crop fields had moderate stability (0.088006) with transitions to built-up land (0.502785) and dense vegetation (0.386929), and grassland showed moderate stability (0.131547) with significant transitions to dense vegetation (0.455772) and built-up land (0.389911). The 2018 land cover map is available in the appendix 5.

Table 16 : Transition matrix result for 2013-2018.

| **YEARS** | **2018** | | | | | | |
|---|---|---|---|---|---|---|---|
| **2013** | **Land cover classes** | Built up | Water | Bare land | Dense vegetation | Crop field | Grass Land |
| | Built up | 0.9094 | 0.0012 | 0.0072 | 0.0704 | 0.0046 | 0.0071 |
| | Water | 0.2818 | 0.0483 | 0.0000 | 0.3205 | 0.3446 | 0.0048 |
| | Bare land | 0.9132 | 0.0019 | 0.0660 | 0.0113 | 0.0028 | 0.0047 |
| | Dense vegetation | 0.2395 | 0.0011 | 0.0032 | 0.7245 | 0.0141 | 0.0176 |
| | Crop field | 0.5028 | 0.0004 | 0.0085 | 0.3869 | 0.0880 | 0.0134 |
| | Grass land | 0.3899 | 0.0009 | 0.0130 | 0.4558 | 0.0089 | 0.1315 |

#### 4.3.1.2. Artificial Neural Network (ANN) based land cover change transition potential modelling.

Using MOLUSCE, transition potential modelling was performed with an artificial neural network (ANN), guided by the multilayer perceptron method. The parameters included a neighbourhood of 1 pixel, a learning rate of 0.10, a maximum of 1000 iterations, a hidden layer with 10 neurons, a momentum of 0.050, a fixed overall accuracy of -0.00399, a minimum error for validation of 0.02519, and a validation kappa of 0.61417. The model utilized 5000 randomly distributed samples to offer spatial representation for the ANN. With a fixed learning rate of 0.10, the neural network effectively learned and simulated land use and land cover (LULC) changes for 2023. Figure 15 and 16 below shows the results for the artificial neural network (ANN) Based for land cover Change transition potential modelling.



Method: Artificial Neural Network (Multi-layer Perceptron)

Neighbourhood: 1 px
Learning rate: 0.100
Maximum iterations: 1000
Hidden Layers: 10
Momentum: 0.050
Δ Overall Accuracy: -0.00399
Min Validation Overall Error: 0.02519
Current Validation Kappa: 0.61417

Figure 17: Results for the artificial neural network (ANN) learning curve.

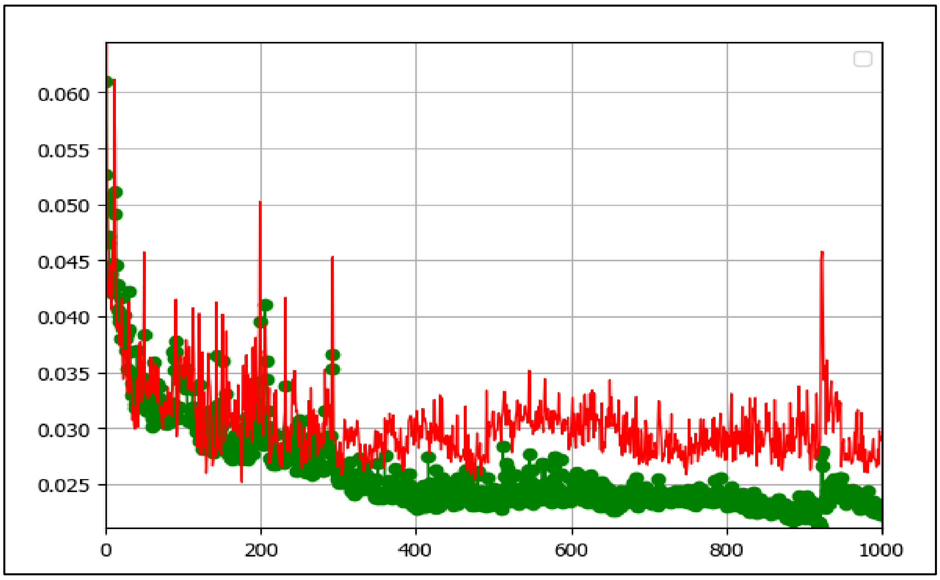


Figure 18: Artificial neural learning curve result for land cover prediction.

#### 4.3.1.3. The land cover model prediction and validation.

Before using the model to predict future land cover for 2033, a prediction for 2023 was made using the land cover data from 2013 and 2018. The predicted land cover for 2023 was then compared to the actual land cover of 2023 to validate the model's accuracy. The validation results, shown in Table 17, reveal that the model achieved a correctness of 90% and an overall kappa of 0.82, indicating 82% agreement. All Kappa coefficients were above the acceptable threshold, confirming that the model's accuracy is adequate for predicting future land cover for 2033.

Table 17: Land cover prediction model validation result for kappa statistics.

| Metric | Value |
|---|---|
| Percentage of Correctness (%) | 90.03497 |
| Kappa (overall) | 0.8257 |
| Kappa (histo) | 0.90404 |

| | |
|---|---|
| Kappa (loc) | 0.91334 |

#### 4.3.1.4. Area change between 2023 and predicted 2033 land cover

The current (2023) and projected (2033) land cover analysis shows a significant increase of 21.13 square kilometers in built-up areas, rising from 169.02 square kilometers in 2023 to 190.15 square kilometers in 2033. There is a minor decrease in water coverage by 0.003 square kilometers, from 0.08 to 0.04 square kilometers. Bare land decreases slightly by 0.06 square kilometers, from 2.82 to 2.76 square kilometers. Dense vegetation is projected to see a substantial reduction of 17.24 square kilometers, decreasing from 35.17 square kilometers in 2023 to 17.93 square kilometers in 2033. Crop fields will decrease by 1.76 square kilometers, from 5.16 to 3.41 square kilometers. Grasslands will reduce by 1.34 square kilometers, from 2.05 to 0.71 square kilometers. The analysis shows a trend towards increased urbanization with significant expansion in built-up areas, while natural land covers such as dense vegetation, crop fields, and grasslands are projected to diminish.

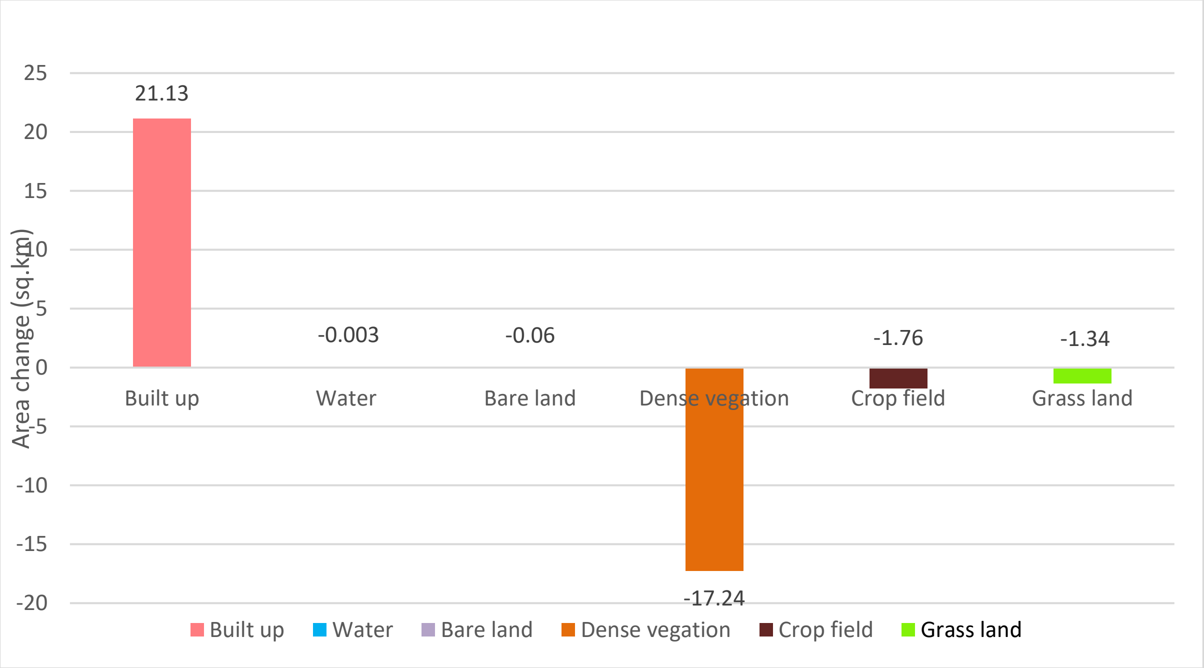


Figure 19: Area change statistics between 2023 and 2033 land cover.

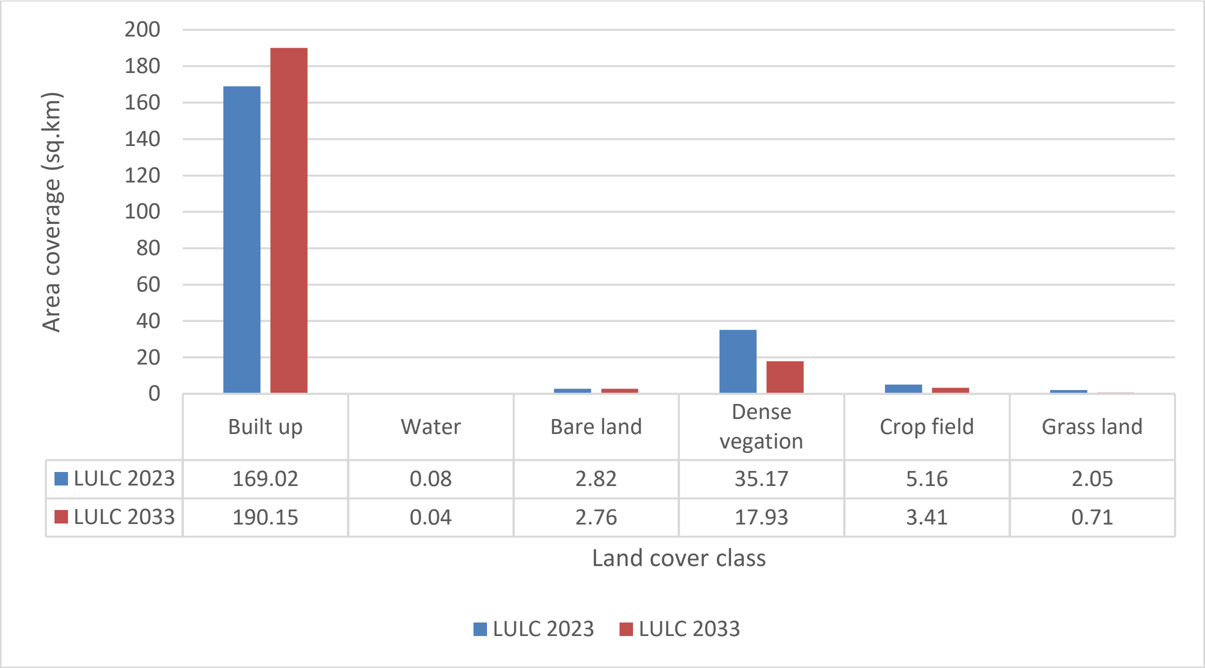


Figure 20: Land cover Area coverage between 2023 and 2033.

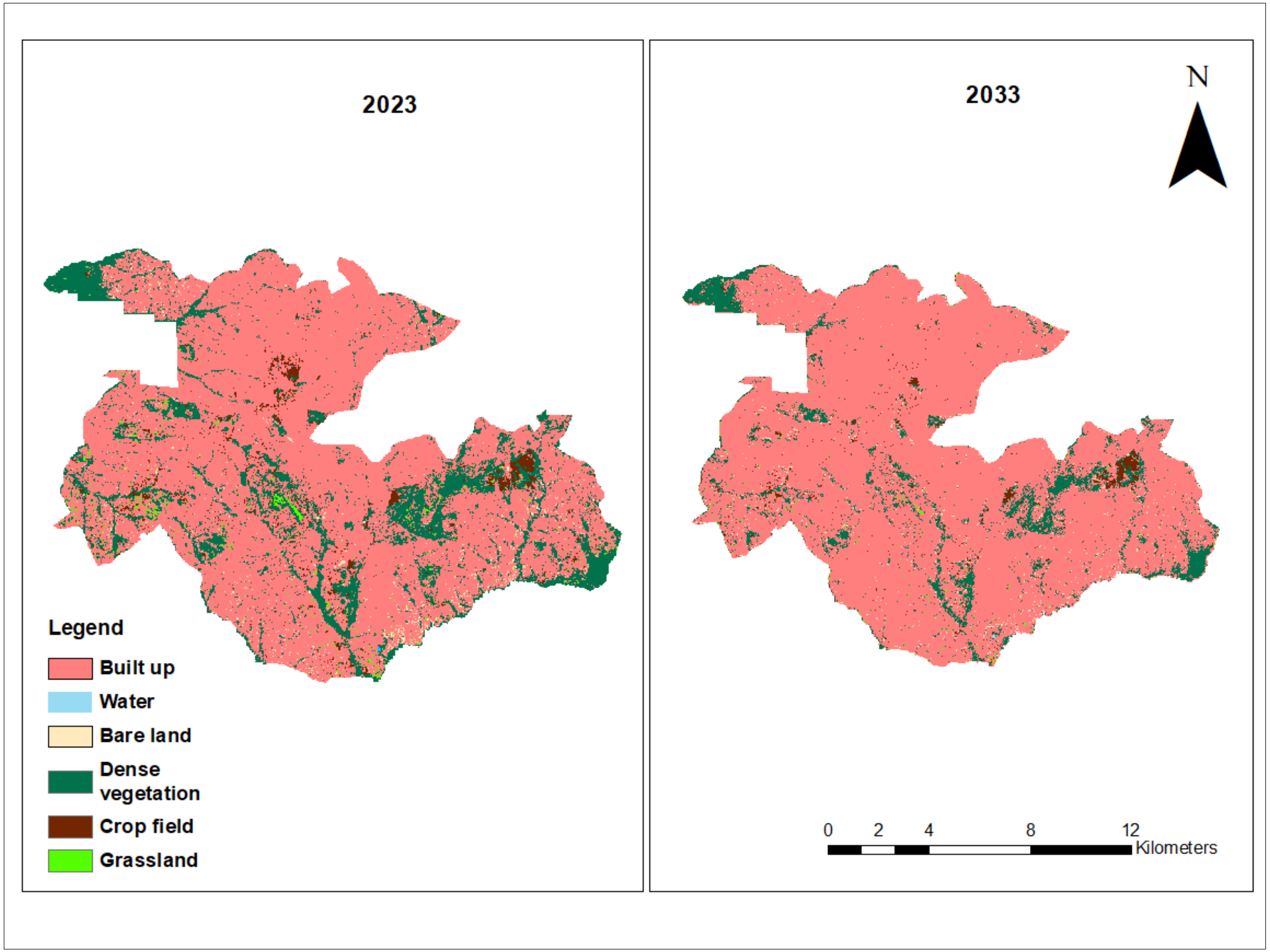


Figure 21: Current (2023) and predicted future land cover (2033)

#### 4.3.2. Flood hazard scenario simulation.

##### 4.3.2.1. Rainfall analysis

The study analysed the average largest one-day precipitation for both historical and projected future precipitation. The results shows that the highest historical average one-day precipitation occurs in September, with 39.12 mm. Future projections under the SSP-8.5 scenario also indicate that September will have the highest average one-day precipitation. The analysis considered the 10-90 percentile range, representing the variability in precipitation. The extreme high scenario which is SSP-8.5 (10-90 percentile range (high)) projects an average of 53.5 mm in September, indicating the potential for significant rainfall and flooding. These historical and projected peaks were used for further rainfall and flood analysis due to their critical significance.

##### 4.3.2.2. Rainfall intensity

Rainfall intensity is crucial for simulating flood scenarios especially in fastflood model. It was calculated by dividing the average largest one-day precipitation by the average observed one-day rainfall duration in peak wet periods (3 hour). The results showed the highest historical rainfall intensity of 13.04 mm/h and a projected future intensity of 17.83 mm/h. Both peaks were recorded in September, confirming it as the wettest month in the study area.

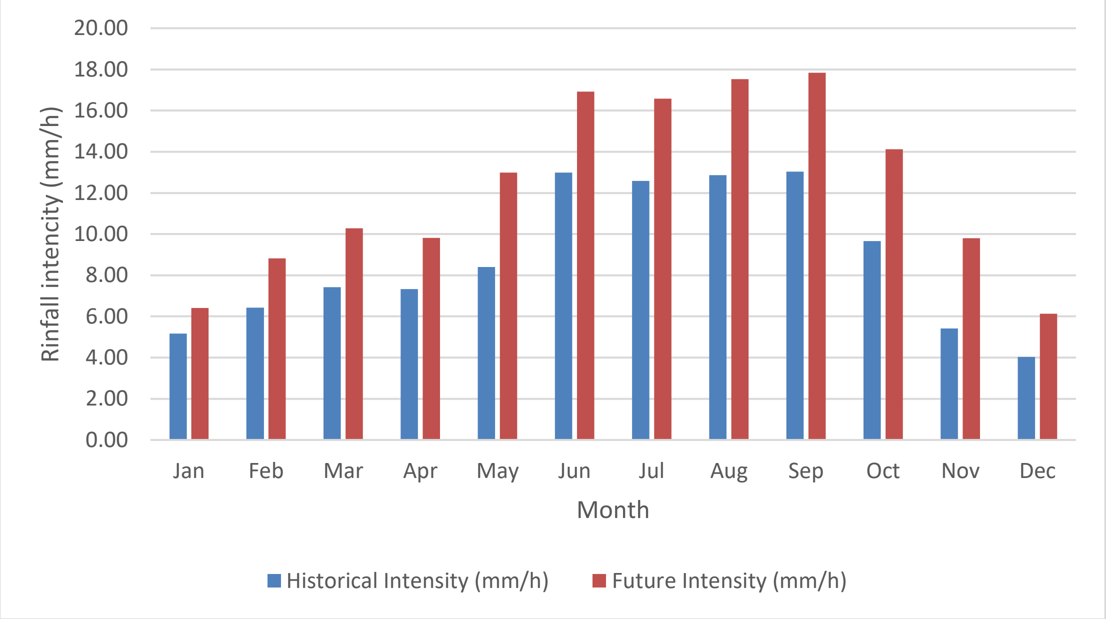


Figure 22: Rainfall intensity.

##### 4.3.2.3. Calibration and validation of the flood model.

Before modelling for flood scenarios, the fastflood model needed calibration using observed rainfall and flood data. Eight observed flood depths were used to calibrate the model with a historical rainfall intensity of 13.04 mm/h over 6 hours, representing the baseline scenario. The calibration process yielded optimal simulation multipliers of 0.5 for both land cover manning's coefficient and infiltration.

Using these multipliers, the model was run to ensure the best fit and mitigate the risk of overfitting. The calibrated flood depths closely matched the observed flood depths, producing a flood height error of 19%.

From the Figure 23 below, the non-calibrated model showed the highest flood depth of 2.70m. After calibration, the highest flood depth reduced to 2.43m, closely matching the highest observed flood depth of 2.4m. This calibration resulted in a reduction of approximately 0.3m from the highest depth in the non-calibrated model. The Figure 23 below illustrates the comparison between calibrated and non-calibrated modelled flood depths.

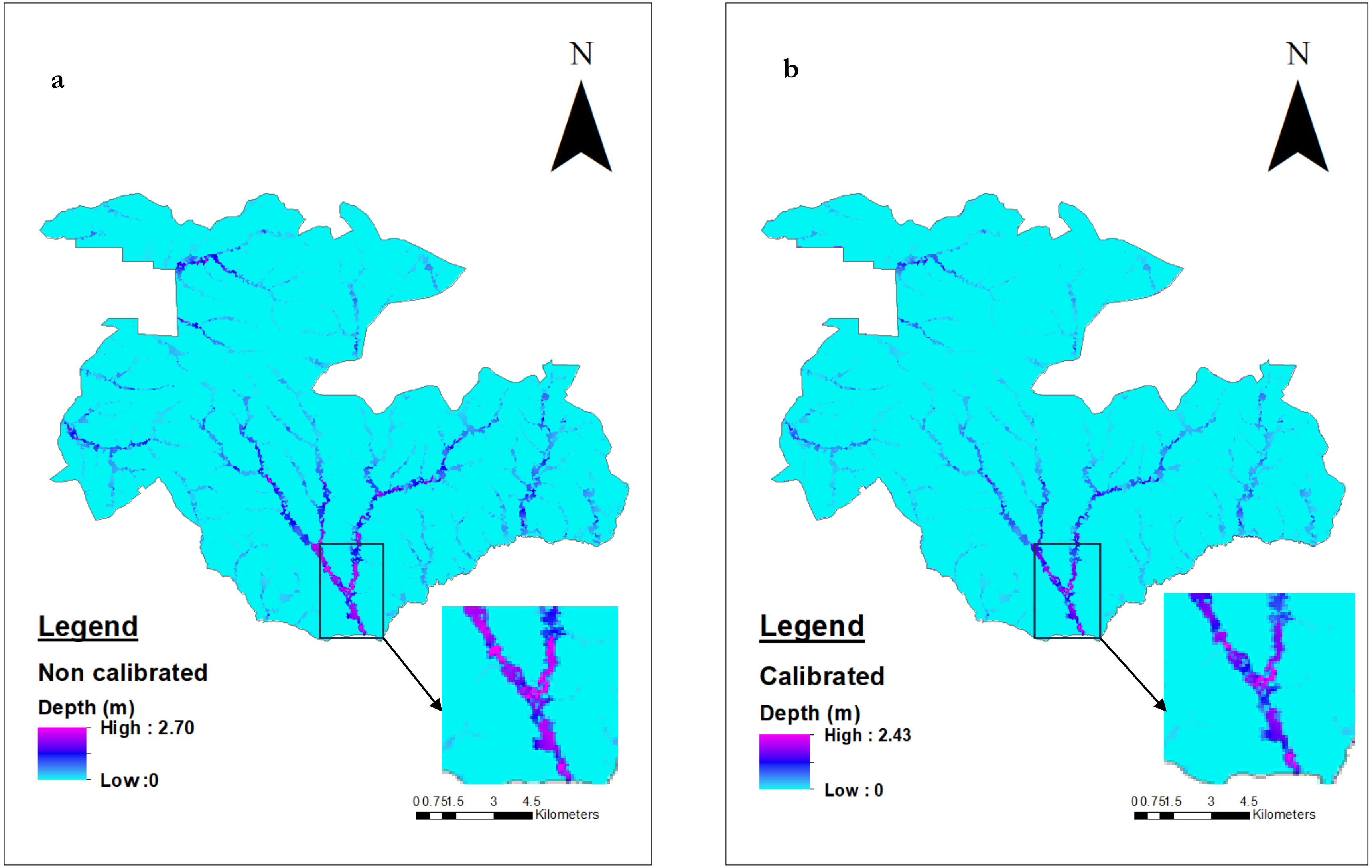


Figure 23: Non-calibrated (a) and calibrated flood (b) model for observed flood at 78.24mm rainfall event.

#### 4.3.2.4. Observed and calibrated depth result

The Table 18 below illustrates the flood depth after using the observed depth to calibrate the model. The same points were measured post-calibration, and the results were compared to each corresponding point between the observed and calibrated data.

Table 18: Observed and calibrated depth

| Observed Flood depth | Calibrated flood depth | Longitude | latitude |
|---|---|---|---|
| 2.4 | 2.4 | 6.647673 | -1.598807 |
| 1.1 | 1.05 | 6.713501 | -1.600517 |
| 0.7 | 0.6 | 6.649319 | -1.621259 |
| 1.5 | 1.40 | 6.622027 | -1.603143 |
| 1.7 | 1.7 | 6.699686 | -1.624374 |
| 0.9 | 0.8 | 6.649414 | -1.599859 |
| 0.5 | 0.5 | 6.709081 | -1.617893 |
| 0.4 | 0.3 | 6.697333 | -1.621592 |

#### 4.3.2.5. Future flood scenarios modelling.

In this section, the model results of the different future flood scenarios are presented and analysed. The impact of rainfall events and urban growth are compared by examining the flood extent, depth, and distribution. For these analyses, only flood depths with a minimum of 0.03 meters were taken into account, as lower depths of standing water are not considered problematic inundation or flooding. Therefore, all flood maps and plots visualized only show flooding with depths of at least 0.03 meters.

There are two rainfall intensities used in the scenario development. The 13.04 mm/h stand for the observed or historical rainfall intensity and 17.83 mm/h represents the future projected rainfall intensity. Two land cover maps were used, 2023 land cover map represents the current and the 2033 represents the future. All scenarios were simulated using a rainfall duration of 6hours. This duration is based on the Ghana Meteorological Agency records (severe floods in Kumasi mostly occur with a rainfall duration of five to six hours).

#### 4.3.2.6. Maximum Flood depth of each scenario.

The results of the flood scenarios in Figure 24 show some variations in the flood depth. The Baseline Scenario representing the current land cover and observed rainfall had a maximum flood depth of 2.4 meters. This scenario sets the benchmark for comparing to the future scenarios.

In Scenario 2 (Rainfall Impact Scenario), the land cover remained constant, the same as in the baseline scenario, here, the rainfall was adjusted using the projected future rainfall. The idea was to test how future rainfall would affect flooding, assuming no change in land cover. The results showed an increase in flood depth by 0.2 meters compared to the baseline scenario, reaching 2.6 meters. This demonstrates that increased rainfall intensity has the tendency to increase flood depth even without changes in land cover. This scenario emphasizes the significant impact that climate change can have on urban flooding, independent of land cover changes. As noted by the IPCC (2021), climate change is projected to increase the rate and intensity of extreme weather events, including heavy rainfall. The findings from Scenario 2 align with these projections. However, it shows that, even in the absence of further urban expansion, the projected increase in rainfall alone can exacerbate flooding issues.

In Scenario 3 (Urban Growth Impact Scenario), the focus was on projected future land cover representing future urban growth, keeping the historical rainfall constant as the baseline scenario. The flood depth increased significantly to 5.1 meters. This substantial rise from 2.4 meters to 5.1 meters can be attributed to the increase in impervious surfaces due to urban growth, which reduces infiltration and increases surface runoff and water stagnation, leading to deeper floods depths. This scenario illustrates that urbanization leads to more severe flooding, particularly increasing flood depth.

The Scenario 4 (Combined Future Impact Scenario) combines both future land cover and projected future rainfall. This scenario shows the most severe flooding, with a maximum flood depth of 5.8 meters. The flood map indicates extensive flooding with deeper water in most areas. This scenario highlights the compounded effects of increased rainfall and urbanization, which together lead to more extensive and deeper flooding.

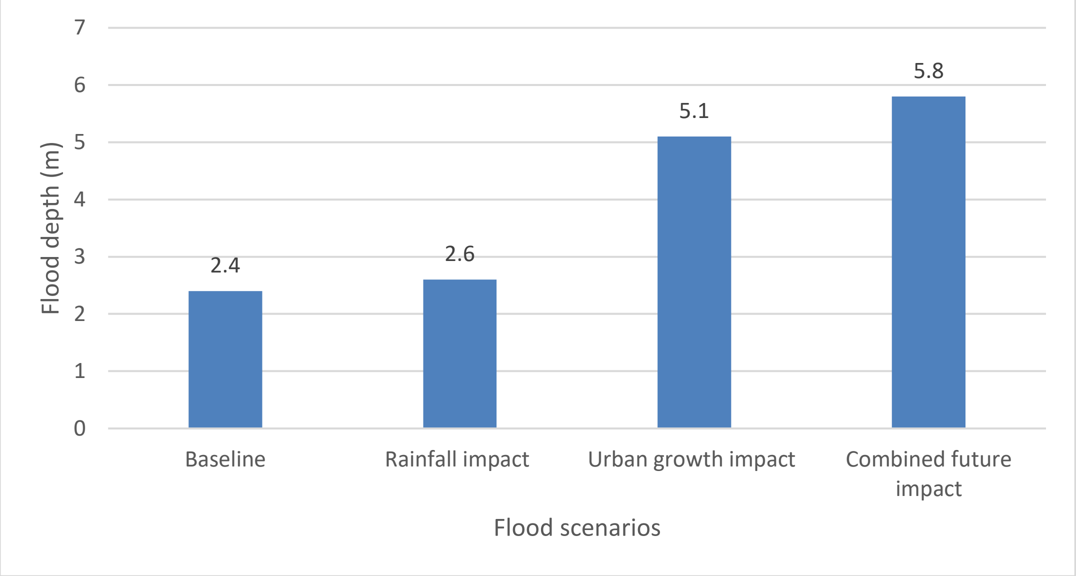


Figure 24: Maximum flood depth for baseline and future scenarios.

### 4.3.2.7. Maximum Flood extent of each scenario.

The results of the flood extent, shown in Figure 25, depicts the area covered by each flood scenario. The Baseline Scenario, reflecting the existing conditions with observed rainfall and land cover, shows a total flood area of 25.27 sq.km. In the Rainfall Impact Scenario, shows a total flood area of 27.02 sq.km, indicating that higher rainfall intensities significantly expand the area affected by flooding. Interestingly, the Urban Growth Impact Scenario, which assumes future land cover with observed rainfall, shows a slight decrease in the flood area to 25.08 sq.km. This suggests that urban growth can lead to more localized, intense flooding, concentrating floodwaters in newly developed areas and resulting in deeper but less widespread flooding (Shao et al., 2020). The Combined Future Impact Scenario, which combines future rainfall and land cover, presents the most severe impact with a flood area of 27.12 sq.km. This scenario highlights the compounded effects of urbanization and increased rainfall, exacerbating both the extent and depth of flooding illustrating how changes in both rainfall patterns and land cover can significantly alter flood dynamics.

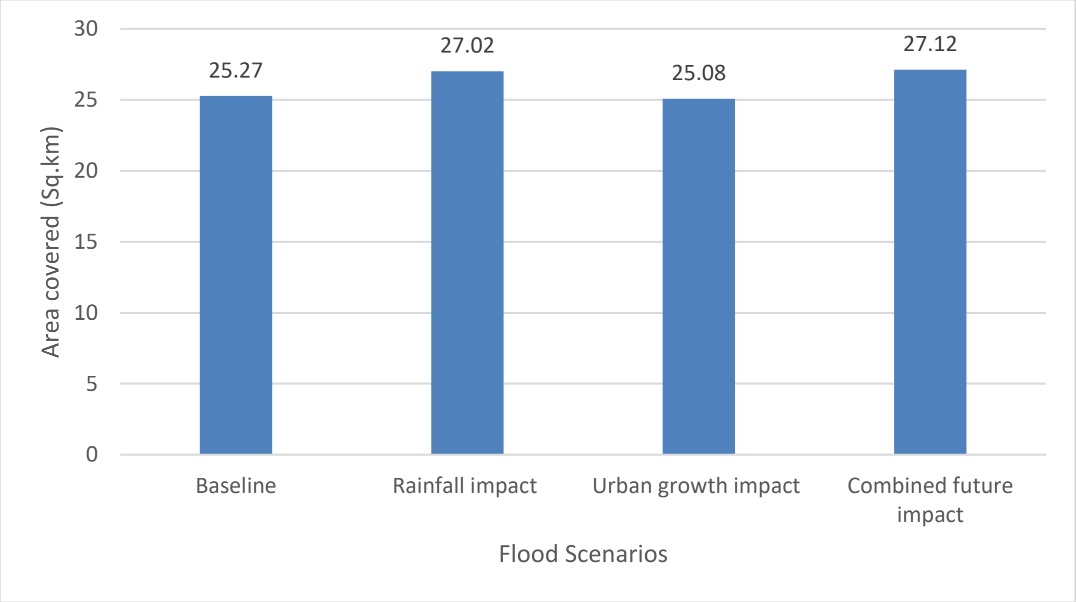


Figure 25: Maximum flood extent for baseline and future scenarios.

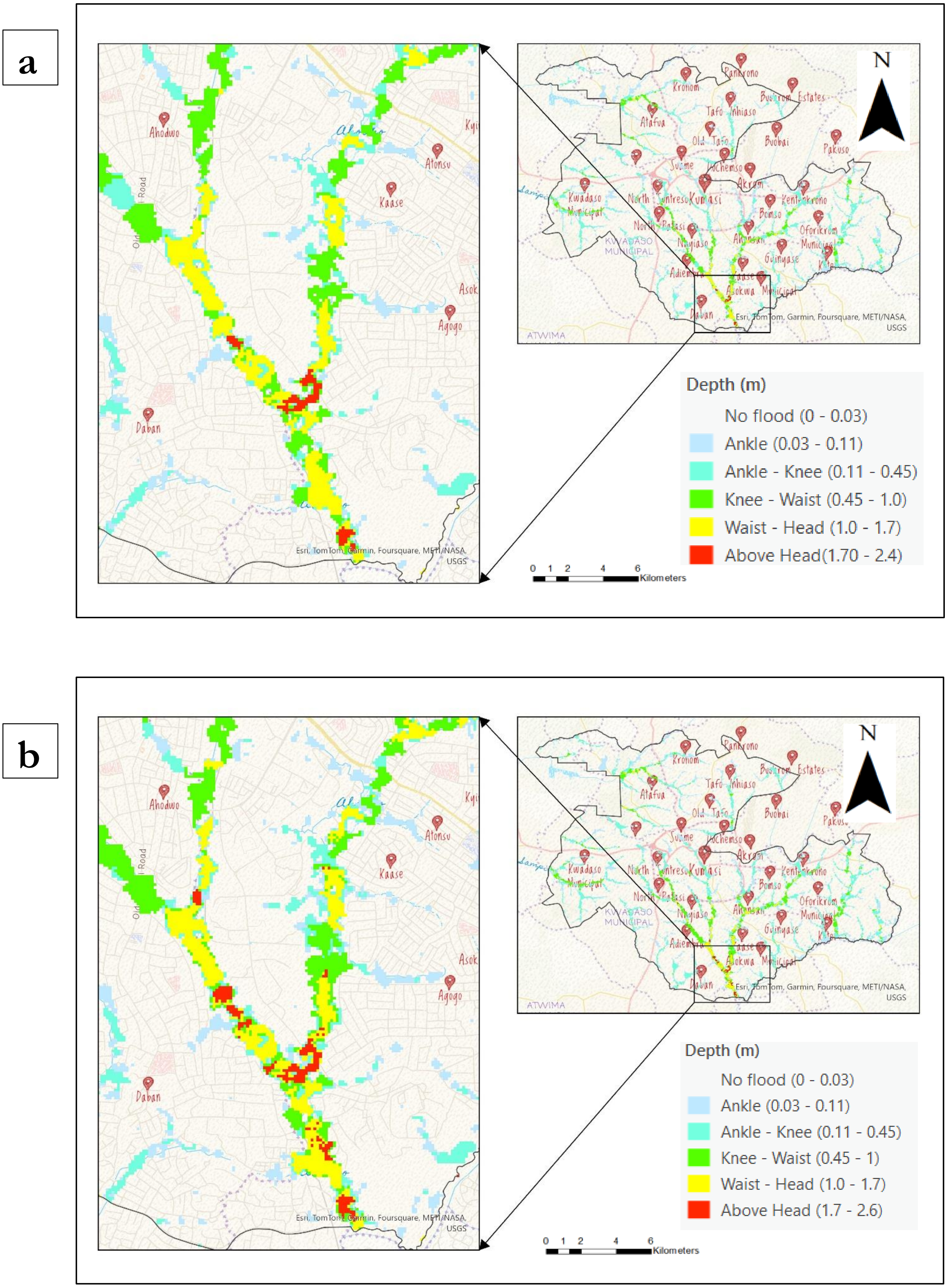


Figure 26: Flood hazard map of baseline scenario (a) and rainfall impact scenario (b)

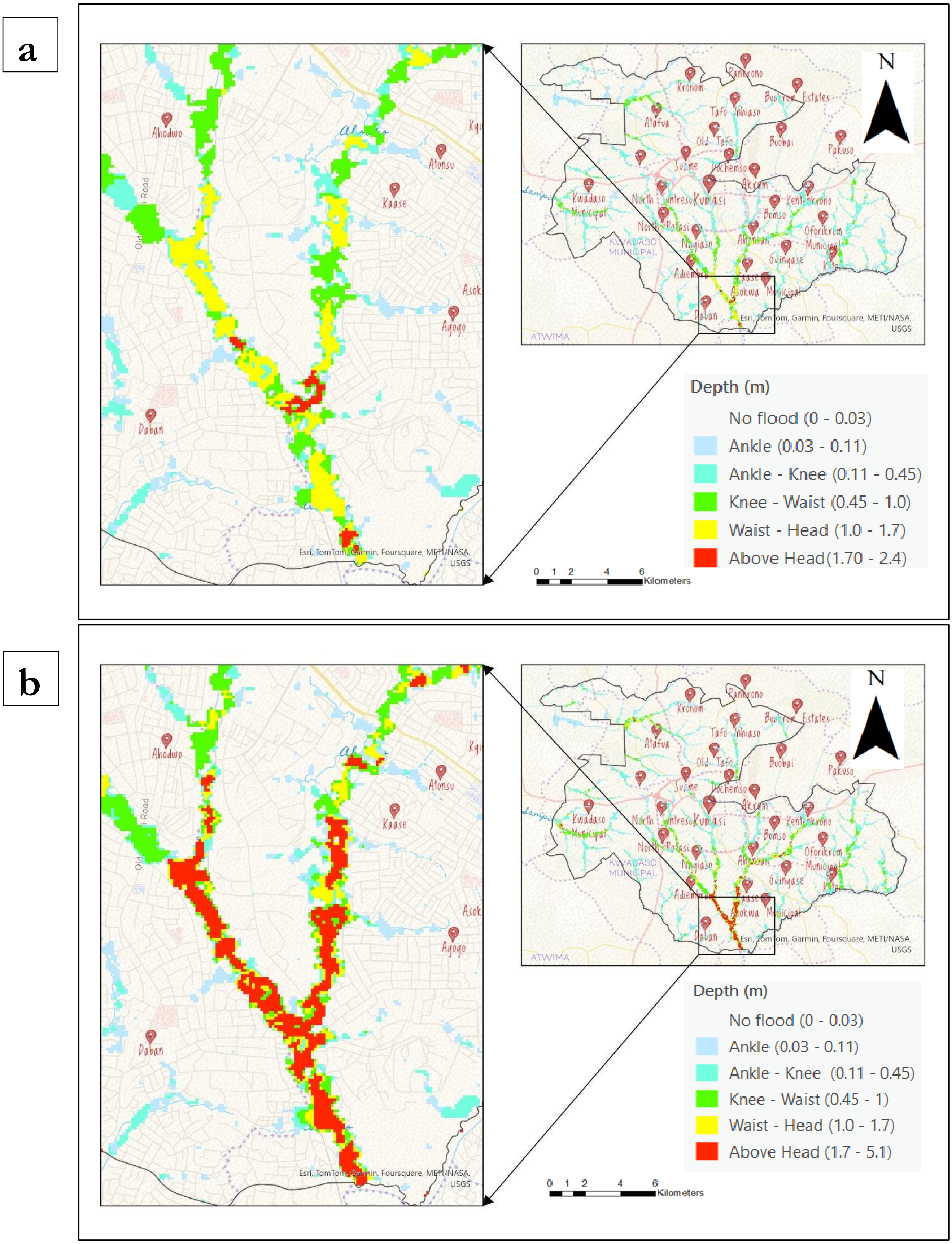


Figure 27: Flood hazard map of baseline scenario (a) and urban growth impact scenario (b)

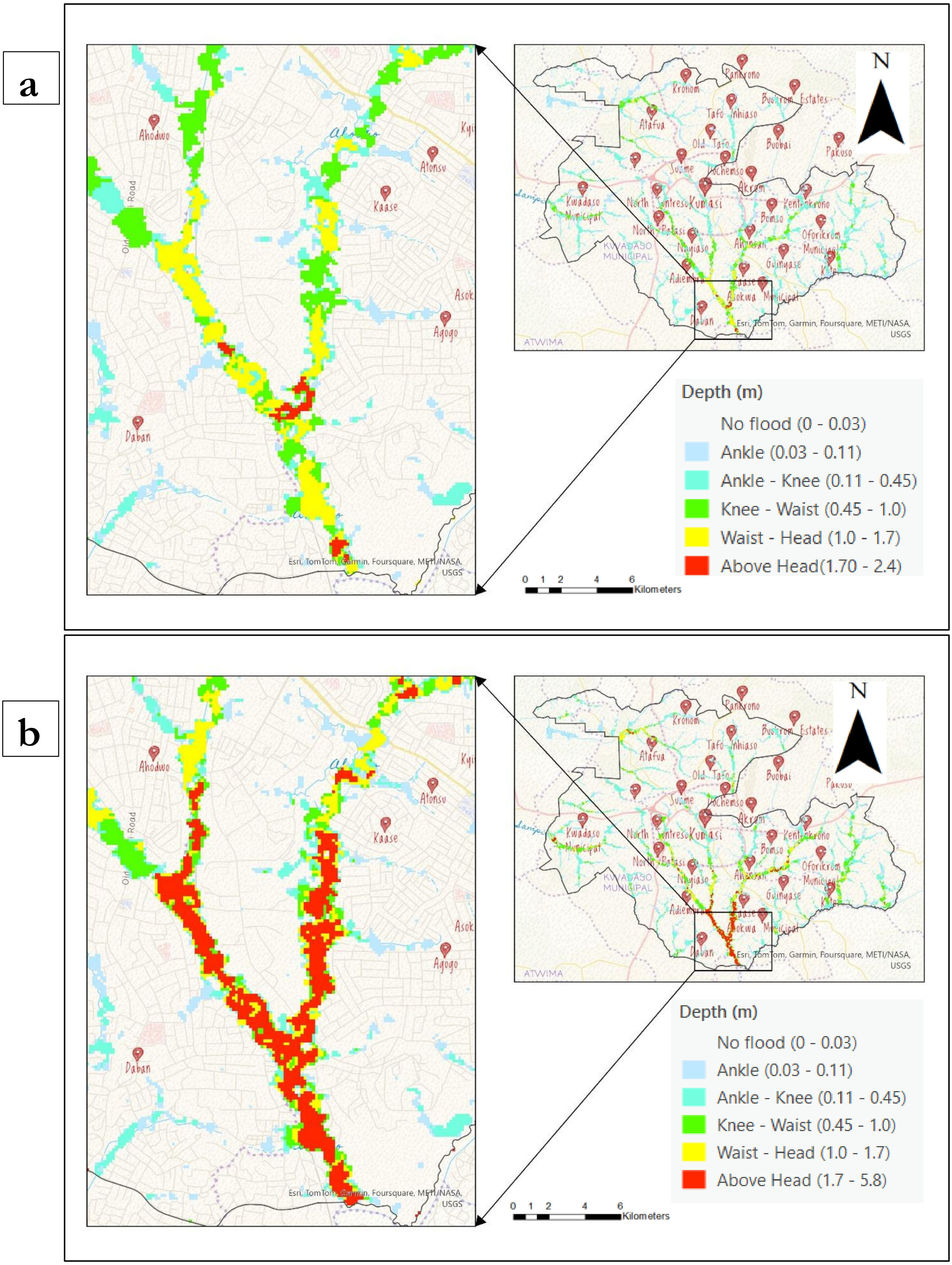


Figure 28: Flood hazard map of baseline scenario (b) and combined future impact scenario (b)

### 4.3.3. Relationship between predicted future flood hazard and current flood incidence areas in Kumasi.

Figure 29 illustrates the relationship between the current flood incidence areas in 2023 and the predicted future flood hazard in Kumasi. It shows a significant overlap between the current flood incidence areas and the predicted future flood hazard zones, indicating that many areas that experienced flooding in 2023 are projected to remain at high risk in the future. The depth of future flooding corresponds closely with the current flood incidence areas, with areas that experienced flooding in 2023 projected to face severe flooding in the future, with depths ranging from ankle (0.03 - 0.11 meters) to above head (1.7 - 5.8 meters). The spatial distribution of future flood hazards also extends to other suburbs and regions within the study area. Specific high-risk zones such as Sokoban, Atonsu, and Kaase, which are highlighted in the current flood incidence map, are also shown to be at high risk in the future flood hazard projection. This demonstrates a clear relationship between current flood incidence areas and predicted future flood hazards.

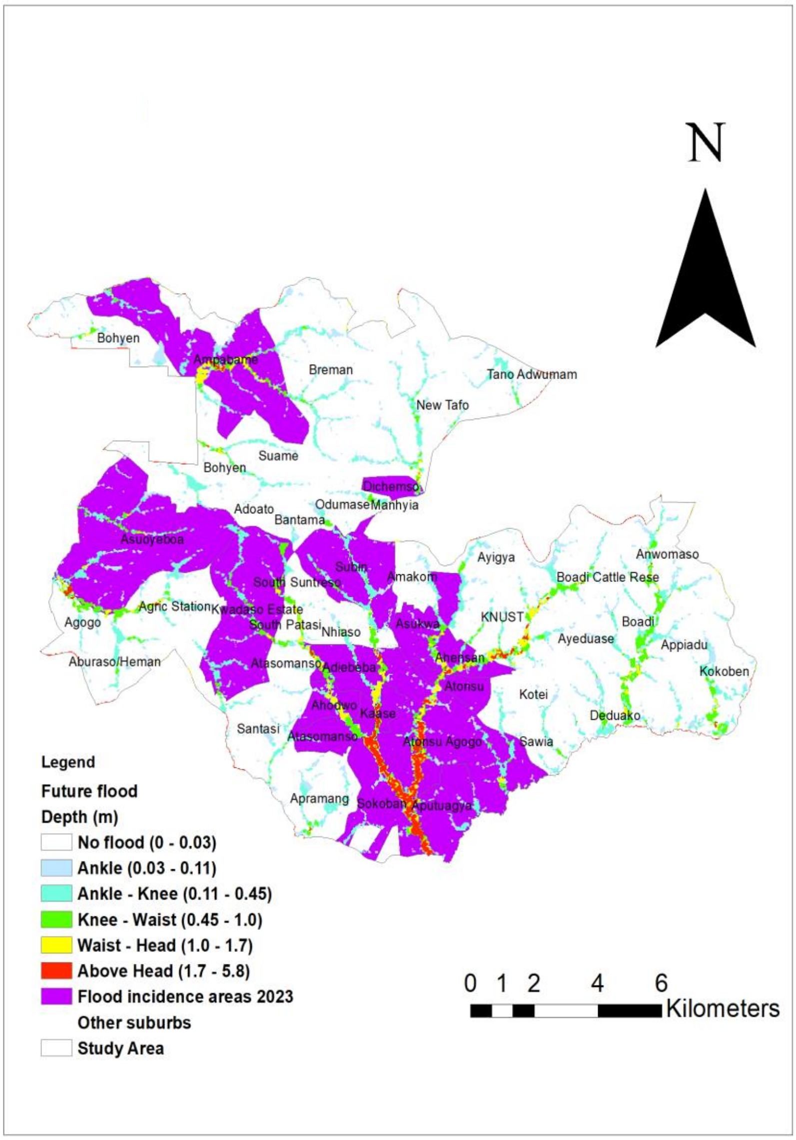


Figure 29: Current flood incidence (2023) areas and future flood scenario.

## 4.4. Objective 4: To identify potential flood mitigation measures for the future floods

### 4.4.1. Potential flood mitigation measures proposed by key informant.

To address urban flooding in Kumasi, key informants from selected institutions and departments were contacted, these were NADMO, the Ghana Hydrological Agency, Physical Planning Department of the Kumasi Metropolitan Assembly, Development planning department (KMA), Physical planning department (Kwadaso municipal) and Physical planning department (Oforikrom municipal). The analysis identified nine potential mitigation measures: public education, reforestation, wetland restoration, upgrading and expanding drainage infrastructure, regular desilting, advanced early warning systems, constructing physical barriers, proper waste management, and integrating green infrastructure into housing projects.

The Table 19 presents the overview of the findings from the proposed measures suggested by the key informants to reduce urban flooding in Kumasi.

Table 19 : Proposed flood mitigation measures suggested by key informants.

| **Suggested measures for future flood.** | **Quote from the informant** |
|---|---|
| • Public education | *"I think most people are ignorant about the consequences of their actions in terms of waste disposal and putting up buildings. The public must be educated to prevent unnecessary disposal and construction"- key informant 3.* |
| • Reforestation | *"Tree planting was proven right from the government agenda of planting 1million trees in Kumasi. Though a number of floods occurred from 2018 to 2020 but the impact was very low during that period. A focus on reforestation will go a long way to help us mitigate flood in the future."- key informant 5* |
| • Wet land restoration | *"The increase population in Kumasi has led about 3/4 of wetlands being encroached which has increased the number of flood prone areas in the city. When these areas are restored, there will be a significant reduction in flood cases in the city." Key informant 2* |
| • Upgrading and expansion of drainage infrastructure to improve storm water management. | *"We have been working on drainage expansions because it is one of the major flood causers in the city. With good investments we hope to double our work, and this will go a long way reduce flood incidences in the future."- key informant 1* |
| • Regular desilting of drainages | *"If all areas in Kumasi agree to embark on weekly desilting of drains, there will be less flooding and even no flood at all"- key informant 4* |
| • Developing an advanced early warning system to alert communities about impending floods. | *"Though the GMet and NADMO provides warnings to communities about upcoming floods, but it does not really work. I think an advanced way of early warnings like digitalised prompts of heavy rain/flood to individual mobile phones will help reduce flood and its overall impact in the future."- Key informant 6.* |
| • Constructing physical barriers such as flood walls to protect vulnerable areas from rising water levels. | *"Some areas cannot be evacuated or demolished due to its significance and cost involved so such areas will require protection like flood barriers to reduce floods."- Key informant 2* |
| • Proper waste management practices | *"If am correct, the major problem of flood is directly related to waste disposal. It causes blockages. If we are able to control and* |

| | |
|---|---|
| | *manage our waste, we can reduce and prevent future flood occurrences"- Key informant 3* |
| • Integrating Green infrastructure into housing projects | *"Green infrastructure such as green roof might be very difficult to implement due to the nature of housing ownership in Ghana, but it is one way I would like to use to prevent future flood in Kumasi as a physical planner."- Key informant 5.* |

As presented in Table 20, the potential measures to reduce urban flooding suggested by the key informants in Kumasi include both structural and non-structural approaches, incorporating a mix of green and grey infrastructure. One intriguing insight derived from the interviews is that most people in Kumasi are unaware of green infrastructure as a means to reduce urban flooding. According to the key informants, many people construct their homes without considering the incorporation of vegetated zones, either on the compound or on the roof. There is little attention given to rain gardens, grass compounds, and green roofs. Though green roofs are mentioned as expensive, other less costly approaches are not well known to the public, and even if known, they are not valued. This highlights the importance of public education in addressing the issue of flooding in Kumasi.

It was also revealed that people in Kumasi prefer physical structural measures, especially grey infrastructure, for flood mitigation, compared to non-physical structural measures. This preference is due to low public awareness of the potential of certain measures in reducing flood risk.

Regular desilting of drainages has long been practiced and is the most common measure in Kumasi. However, it is only effective when done on a continuous basis. The key informant revealed that regularly removing sediment from drains could solve most of the flood issues in certain places in Kumasi.

Other measures, such as constructing physical barriers like flood walls to protect vulnerable areas from rising water levels, developing an advanced early warning system to alert communities about impending floods, and upgrading and expanding drainage infrastructure to improve stormwater management, could only be implemented with government or external support. All these measures are important, but their implementation depends on multiple factors.

### 4.4.2. Assessment of suggested flood mitigation measures based on economic, environmental, and social conditions.

Implementing the suggested flood mitigation measures will be crucial for enhancing urban infrastructure and supporting existing efforts to reduce urban flooding in Kumasi. However, several critical factors must be taken into account, as they can either impede or enhance the smooth implementation of these measures. In this study three major factors were considered due to their important impacts on project implementation. These factors were also chosen because they are most widely used indicators for validating the feasibility or sustainability of many flood projects. This includes economic conditions, environmental conditions, and social conditions. To assess these factors, the measures were subjected to a feasibility assessment based on literature review. The result presented in the table below is based on what the cited paper or report has indicated concerning the measure. The results are presented in Table 20.

Table 20: Overview of the feasibility of the suggested measures

| Suggested Measures for Future Flood | Economical cost | Environmental benefit | Social acceptability |
|---|---|---|---|
| **Public Education** | Moderate costs for continuous community engagement and awareness programs (UNEVOC, 2014). | Generally positive impact: better waste management and construction practices (EEA, 2015).<br>No environmental impact during execution (Aghimien et al., 2019). | High acceptability. People feel involved and tend to appreciate the effort (World Bank, 2016). |
| **Reforestation** | Moderate initial investment in planting and maintenance (FAO, 2012). | Generally positive impact: Enhances biodiversity and ecosystem restoration (IPCC, 2014).<br>Execution do not pose threat to the environment (Carrick et al., 2019). | Generally, has high acceptability due to aesthetic benefit (IUCN, 2016). |
| **Wetland Restoration** | High costs associated with restoration and legal protection (Moreno & Bank, 2015).<br>Cost associated with evacuation of occupiers (Hakeem et al., 2022). | Positive impact by adding to increase vegetation (Schindler et al., 2016).<br><br>Has no threat to the environments (Carrick et al., 2019). | High acceptability in the case of persistent flooding and provision of compensation in case of evacuation (Moreno & Bank, 2015). |
| **Upgrading and Expansion of Drainage Infrastructure** | High financial investment required (World Bank, 2013). | Negative: Potential environmental impact during construction. (EPA, 2016).<br>Alters natural drainage channels. | High community acceptability (UN-Habitat, 2015).<br>Can be impeded if the expansion affect resident (Rosmadi et al., 2023). |
| **Regular Desilting of Drainages** | Moderate costs (Cosgrove & Loucks, 2015).<br>Could be done with very less financial investment (Aghimien et al., 2019). | Generally positive: Improves environmental quality by preventing blockages and flooding (EPA, 2014).<br><br>Less significant threat to the environment (Epa & Change Division, 2014). | Has high acceptability. People feel involved and tend to appreciate the effort which increases the acceptability of the initiative (World Bank, 2016). |
| **Developing an Advanced Early Warning System** | High initial investment in technology; cost-effective in the long run (GAR, 2011). | Generally positive impact – No harm to the environment. (GAR, 2011). | Generally, has high acceptability. Citizens embrace new safety technology and feel safe under disaster. (UNISDR, 2014). |

| | | | |
|---|---|---|---|
| **Constructing Physical Barriers** | High initial costs (Cosgrove & Loucks, 2015). | Negative: Potential impact on natural water flow and ecosystems and landscape (WWF, 2015).<br>Could be worse if construction fails (O'Donnell & Thorne, 2020). | Generally, has high acceptability. strong community support. (UNISDR, 2014). |
| **Proper Waste Management Practices** | Moderate costs for establishing and maintaining waste management systems (World Bank, 2018). | Generally positive: Reduces pollution and blockages, improving environmental health (UNEP, 2016). | Generally, has high acceptability (World bank, 2016). |
| **Integrating Green Infrastructure into Housing Projects** | High initial costs; long-term savings on energy and water management (Massey et al., 2014). | Positive: Benefits urban ecology and microclimate (IPCC, 2014). | Generally, has high acceptability (IUCN, 2016). Comes with aesthetic features. |

As presented in Table 20, some of the measures suggested by the key informants as it was subjected to literature review could have a less implementation challenges in Kumasi. After the review based on economic, environmental, and social conditions from literature, four measures were found to be moderate in terms of cost associated with implementation, positive environmental impact, and high level of social acceptability. These measures were public education, reforestation, regular desilting of drainages, and proper waste management.

Other measures, such as wetlands restoration, advanced early warning systems, and green infrastructure, have generally a high cost associated with implementation and maintenance but offer positive environmental impacts and high social acceptability. On the other hand, measures such as constructing physical barriers like flood walls and upgrading and expanding drainage infrastructure have high costs and high social acceptability but present negative environmental impacts during construction and also could involve displacement of occupiers depending on the location of the project.

It is important to note that, this assessment was based previous papers and reports, and their scalability might also influence their claims and results. With that being said, the result in the table (Table 20) above do not explicitly determine the actual feasibility of the measure in the context of Kumasi, but they provide a fair idea about their implementation and suggest that some measures may be easier to implement than others.

# 5. DISCUSSION

## 5.1. Objective 1: To identify the contributing factors of urban flooding in Kumasi

The analysis of contributing factors to urban flooding in Kumasi revealed a multifaceted issue primarily driven by poor drainage systems, rapid urbanization, deforestation, climate change, inadequate waste management, and improper urban planning. These factors were consistently identified across selected institutions and departments, including the Kumasi Metropolitan Assembly Physical Planning Department, the Development Planning Department, the National Disaster Management Organization, the Ghana Hydrological Agency, and the Municipal Planning Departments in Kwadaso and Oforikrom.

Some of these identified factors align with findings from other studies in similar urban environments. For instance, studies in Accra, Ghana, have also highlighted rapid urbanization and inadequate drainage systems as primary drivers of urban flooding (Amoako & Boamah, 2014; Asumadu Sarkodie et al., 2015). Similarly, research in Lagos, Nigeria, identified poor waste management and deforestation as significant contributors to flooding issues in rapidly growing urban areas (Echendu, 2023).

In Kumasi, the situation with poor and inadequate drainage systems contributing to floods is compounded by improper waste disposal, which clogs and blocks the already overburdened and insufficient drainage systems, exacerbating the flooding situation. It was insightful for key informants to point out inadequate waste management as a major contributing factor. While these factors do not cause floods independently, they significantly contribute to the occurrence of flooding events. For instance, poor drainage infrastructure alone cannot cause flooding unless there is heavy rainfall, often driven by climate change, that overwhelms the drainage capacity.

A unique aspect of the contributing factors to flooding in Kumasi is improper urban planning, which is particularly complex. While it might be easy to attribute this to haphazard development, the situation in Kumasi is complicated by the local land tenure system. In Kumasi, lands are vested in the hands of local traditional authorities as customary lands, which poses a significant challenge for urban planners attempting to implement effective and coherent urban development plans. This land tenure system often leads to unplanned and unauthorized construction, undermining efforts to manage urban growth and mitigate flood risks effectively.

In Ghana, housing development is predominantly undertaken by individuals rather than large-scale developers, leading to irregular and uncoordinated urban expansion. This individualistic approach to building homes often results in the construction of structures in flood-prone areas without proper planning and infrastructure support, further contributing to the city's vulnerability to flooding. The increase in slums around floodplains and drainages which often lacks proper infrastructure and are most vulnerable to flooding are all as a result of the above factor of improper planning.

## 5.2. Objective 2: To Analyse urban growth and land cover change in Kumasi for 2013 and 2023

The land cover change in Kumasi over the past decade shows transformations driven by urbanization and related socio-economic factors. The findings revealed notable changes across six land cover classes: Built-up, Water, Bare land, Dense vegetation, Crop field, and Grassland. The most striking change is the expansion of built-up areas, which increased from 70.10% in 2013 to 80.06% in 2023, representing a substantial area increase of 21.35 sq. km. This rapid urban growth highlights Kumasi's role as a major commercial and transportation hub in Ghana, attracting a continuous influx of people seeking economic opportunities (Yeboah & Asibey, 2019). The development of residential, commercial, and industrial infrastructure has driven this expansion, reflecting the city's dynamic economic environment. Such growth is essential for economic development; however, it poses challenges to sustainable urban planning and environmental management (Frimpong, 2021).

The loss of vegetation and water and an increase in bare land is indicative of deforestation and land clearing for urban development. The reduction in green spaces highlights the environmental costs of rapid urbanization correlating with population increase, including loss of biodiversity, increased urban heat island effects, diminished ecological balance, and increase in impervious surfaces. This trend is consistent with findings by Oduro et al. (2015), who noted similar patterns of vegetation loss in other rapidly growing urban areas in Accra, Ghana. Comparable studies in other parts of the world, such as Jakarta, Indonesia, have shown that urban expansion often comes at the expense of natural vegetation, leading to significant environmental challenges (Seto et al., 2011). In São Paulo, Brazil, rapid urbanization has resulted in extensive deforestation and loss of green spaces, which has exacerbated urban heat island effects and biodiversity loss (Moschetto et al., 2021). Similarly, in Nairobi, Kenya, urban expansion has led to significant changes in land cover, with built-up areas increasing and natural vegetation decreasing, posing challenges for sustainable urban development and increasing flooding (Mundia & Aniya, 2005).

## 5.3. Objective 3: To assess future flood scenarios in Kumasi considering future rainfall and urban growth.

### 5.3.1. Possible future urban growth scenario for 2033

The findings from the land cover projections for Kumasi indicate significant future urban growth, characterized by a massive increase in built-up zones. The analysis forecasts a reduction in vegetation by 17.24 sq. km and an increase in built-up areas by 21.13 sq. km by 2033. This confirms the UN urbanisation estimate indicating that, more than two-third of the world will live in urban areas by 2050. Most of the areas projected to become built-up in Kumasi are currently vegetated. Per visual assessment, the projection shows both inward and outward growth, suggesting that future urban growth will occur both inland and the periphery.

This pattern corresponds to the literature on urban expansion, which indicates that urban sprawl often spreads from the city center outward, encroaching on natural landscapes and agricultural land (Angel et al., 2011; Seto et al., 2011). Similar trends have been observed globally. For instance, in Shanghai, China, urban expansion has led to significant loss of agricultural land and green spaces, resulting in environmental and socio-economic challenges (Shi et al., 2016). If these projections continue beyond 2033, it is possible that land cover classes in Kumasi such as water bodies, bare land, agricultural land, and dense vegetation might be significantly reduced or entirely lost (see Figure 19). This indicates a potentially drastic transformation of the natural environment, leading to increased urbanization.

Though the expansion of built-up areas for Kumasi was expected during the analysis, however, the rate and magnitude of change was alarming considering a ten-year span. This growth is specific to Kumasi and might be different from other areas or regions due to differences in geographical characteristic. Comparing the 2023 and projected 2033 land cover maps in Figure 21, reveals that Kumasi is rapidly becoming saturated with built-up areas. If this growth trend continues, there will be little to no available land for essential purposes such as green spaces, agriculture, and forestry. According to worldpop, Ghana's population will increase significantly up to 45 million by 2040 in which Kumasi will have a share of this projected increase. This population growth will likely result in significant changes in land cover, with an increase in built-up areas and a decrease in vegetation and other land use classes. This projected scenario in Kumasi differs from cities such as Jurong in Singapore where despite population increases, they were able to maintain their vegetation cover through effective urban planning and green space management policies (Tan et al., 2013).

### 5.3.2. Future flood scenarios in Kumasi considering future urban growth.

The impact of land cover patterns on flooding in Kumasi is evident from the analysis of different flood scenarios. These scenarios incorporated four distinct inputs: current rainfall, current land cover, future rainfall, and future land cover.

Using projected future land cover, where 90% of the land is built up compared to the current land cover with 80.06% built up in the flood analysis, the results showed more than double the increase in flood depth for future flood scenario. This increase is primarily due to the rise in impervious surfaces, which prevent rainwater from being absorbed into the soil, leading to increased runoff. This runoff is often channelled into downstream drainages or lower-elevated areas, increasing flood levels in downstream. In the flood analysis, it was revealed that downstream areas observed very high flood levels of above 5 meters. The correlation between the increase in built-up surfaces in the projected land cover and the flood depth indicates that the higher percentage of hard surfaces significantly influenced the increased flood depth (see Figure 24). Comparing this to other studies such as Amoako, (2017) and Damte et al. (2023), the situation is different as their studies attributed the increase in flood depth to rainfall.

Comparing the baseline scenario (current land cover and rainfall) to the future scenario (projected urban growth and rainfall), the variation in flood levels was significant, showing a difference of about 3 meters. This difference is understandable, as the Intergovernmental Panel on Climate Change (IPCC) and other climate change models, such as SSPS-8.5, predict intense future rainfall, which will amplify flood situations. It is clear that high rainfall intensity, coupled with rapid urban growth and inadequate flood infrastructure, as revealed in Kumasi, will inherently result in severe flooding. This aligns with findings from other cities globally, where rapid urbanization and inadequate drainage infrastructure exacerbate flooding risks (World Bank, 2020).

## 5.4. Objective 4: To identify potential flood mitigation measures for Kumasi.

The final research objective was to identify potential flood mitigation measures for Kumasi that have the possibility to reduce urban flooding and are potentially practical to implement. As discussed in Chapter 3, these measures were gathered from key informants directly involved in flood management activities in Kumasi. In total, nine measures were suggested: public education, reforestation, wetland restoration, upgrading and expanding drainage infrastructure, regular desilting, advanced early warning systems, constructing physical barriers, proper waste management, and integrating green infrastructure into housing projects. These measures were in line with the contributing factors to urban flooding in Kumasi in the quest to solve current and future floods.

The measures proposed were all considered applicable in the context of Kumasi. However, further analysis, which involved a feasibility assessment through a literature review focusing on economic conditions, environmental conditions, and social conditions as indicators, revealed that four specific measures were particularly feasible with higher chances of successful implementation with minimal challenges. These measures were public education, reforestation, regular desilting, and proper waste management. Their feasibility is attributed to being economically less costly, environmentally sound, and high level of social acceptability compared to the other measures.

According to the African Partnership for Flood Management, countries with limited financial resources should focus on measures that require fewer financial investments. This is particularly relevant for Kumasi, where economic constraints limit the feasibility of high-cost interventions such as road infrastructure, educational infrastructure etc. Public education, reforestation, and drainage desilting are ideal measures for Kumasi because they have moderate economic costs compared to other flood management strategies. Given the city's budgetary limitations and the need to prioritize cost-effective solutions, these measures offer a practical approach to mitigating urban flooding while considering the local economic context.

Regular desilting of drainages was highlighted as a measure that could be implemented with minimal capital investment. This practice can be organized by mobilizing community members, thus involving residents and community people in the flood mitigation strategy. Many communities and volunteers in Ghana already engage in drainage desilting independently (Mangai, 2017), which can be advantageous for authorities in Kumasi by organizing weekly exercises. This approach is cost-effective, environmentally sound, and socially acceptable since it is already a common practice in many Ghanaian communities.

Proper waste management, as emphasized by the World Bank, (2016), requires an attitudinal change and policy enforcement rather than huge financial backing. Effective waste control can generate revenue for both the people and the government and is one of the most economical ways to control floods compared to physical structural measures. UNEP, (2016) highlighted the environmental benefits of waste management, noting that it reduces pollution and drainage blockage (see Table 20), thereby improving environmental health. This, combined with its social acceptability as indicated by World Bank, confirms the potential of waste management as a measure to reduce flooding in Kumasi with least implementation challenges. In the same vein, reforestation, according to the FAO, (2012), IPCC (2014), and IUCN, (2017) is moderately costly, enhances biodiversity, and is socially acceptable due to the aesthetic and serene environment it provides. It can be an effective method for mitigating urban flooding in Kumasi without major implementation obstacles. This analysis is consistent with findings in other parts of the world where reforestation and proper waste management have been crucial in flood mitigation strategies in urban areas such as Jakarta in Indonesia, improving local environmental conditions and reducing flood risks (Ward et al., 2013). Similarly, in Nairobi, Kenya, public education, and community involvement in drainage maintenance have been effective in mitigating flood risks (Mutisya & Yarime, 2011).

While other measures were found to be crucial and important, their feasibility in terms of economic, environmental, and social aspects might poses a challenge to their implementation in Kumasi. This means that while these measures could be recommended, their implementation might be difficult or challenging without necessary support. Effective flood mitigation measures according to Rosmadi et al. (2023), must be economically viable, environmentally sound, and socially acceptable. This means, meeting these criteria is essential for smooth implementation and significant benefits.

Measures requiring high capital investment, such as upgrading and expanding drainage infrastructure and constructing physical barriers, often necessitate external support (UNEP, 2016) especially in the context of Ghana. Without external support, these projects might face significant implementation challenges and could remain incomplete or poorly executed. This justifies the reason for measure such as public education, regular desilting, reforestation, and waste management being a recommendable measure that can be implemented with immediate effect in Kumasi based on the results from the cited literatures in Table 20.

# 6. CONCLUSION AND RECOMMENDATION

## 6.1. Conclusion

This section of the research summarizes and wrap up the key methods and findings from the objectives that were outlined. The main objective of the research is to assess how future urban growth and projected rainfall will affect Kumasi and to propose potential flood mitigation measure that will help in reducing the impact of the current and future floods. The conclusion is organized according to the specific objectives of the research.

### 6.1.1. Objective 1: To identify the contributing factors to urban flooding in Kumasi.

To address this objective, interviews were conducted with key stakeholders in flood management bodies in Kumasi. The findings revealed poor and inadequate drainage systems emerging as the most significant contributor to the increased flood risk, with many neighbourhoods suffering from inadequate or non-existent drainage infrastructure. Climate change, characterized by an increase in extreme weather events and heavy rainfall, was identified as the second most critical factor. Other contributing factors include inadequate waste management, leading to clogged drainage systems; deforestation, which reduces the land's natural water absorption capacity; and rapid urbanization, which has led to the expansion of built-up areas into flood-prone zones.

### 6.1.2. Objective 2: To Analyse urban growth and Land cover changes in Kumasi.

To understand the impact of urban growth on land cover changes, ArcGIS Pro software was used, employing the random forest/tree method to analyse the changes in urban expansion over the last decade from 2013 to 2023. The findings show a significant transformation in the urban landscape. Between 2013 and 2023, built-up areas increased substantially by 21.35 square kilometers, while vegetated areas decreased by 22.05 square kilometers. This rapid urban growth is driven by population increases and economic development, leading to the conversion of natural lands into residential and commercial zones.

The correlation between land cover change and urban flooding is evident. The expansion of impervious surfaces has reduced the land's natural absorption capacity, increasing surface runoff and exacerbating flood risks. This was seen from the recorded increase in flood incidence areas between 2013 and 2023. Thus, it can be concluded that changes in land cover directly contribute to the rising number of flood-prone/incidence areas in Kumasi.

### 6.1.3. Objective 3: To assess future flood scenarios in Kumasi considering future rainfall and urban growth.

The assessment of future flood scenarios in Kumasi, considering both projected rainfall and urban growth, highlighted the significant impact these factors will have on flood hazards. Using predictive modelling tools (Molusce and fastflood), the study projected land cover changes for 2033 and simulated flood scenarios under different conditions: current conditions (baseline), future rainfall impact, urban growth impact, and combined future impact.

The findings indicate a in the urban growth projection, showed a substantial increase in built-up areas by 2033, with a corresponding reduction in vegetated areas. This urban expansion is expected to contribute significantly to increased surface runoff and reduced natural water absorption, exacerbating flood risks.

Specifically, built-up areas are projected to increase by an additional 21.13 square kilometers, while vegetated areas are expected to decrease by another 17.24 square kilometers.

Flood scenario modelling revealed that the combined future impact scenario, which accounts for both projected urban growth and projected rainfall intensity due to climate change, would result in the most severe flooding. This scenario showed a significant increase in flood-extent and flood depth, highlighting the compounded effects of urbanization and climate change on flood hazards.

#### 6.1.4. Objective 4: To identify and propose potential flood mitigation measures for future floods in Kumasi.

In relation to the suggested measures by the key informants on potential flood mitigation measure, the analysis reveals four potential feasible measures for mitigating flood in Kumasi, focusing on solutions that are economically viable, environmentally beneficial, and socially acceptable. The three mentioned factors above were used as an indicator for assessing the feasibility of the measures. The findings show some key recommendations to the context of Kumasi including public education, reforestation, regular desilting of drainage systems, and improved waste management. These measures were considered feasible due to their relatively low cost, positive environmental impact, and high level of social acceptability.

Conversely, measures such as wetlands restoration, advanced early warning systems, and the implementation of green infrastructure, while beneficial, may present considerable challenges. These measures entail high implementation and maintenance costs. Additionally, constructing physical barriers and upgrading drainage infrastructure, although necessary, require substantial capital investment and may pose environmental challenges during the construction phase.

### 6.2. Limitations associated with the method and model applied

The study employed a number of methods and models to assess and evaluate the impact of urban growth and rainfall on urban flooding and to identify and propose appropriate flood mitigation measures to reduce future floods. Despite the successful usage and application of these methods and models, some limitation existed.

**Land cover prediction with cellular automata in MOLUSCE plugin.**

The Cellular Automata model in the MOLUSCE plugin relied heavily on spatial variables for predictions. Seven spatial variables were used: elevation, slope, population, distance to roads, water bodies, transport stations, and the central business district (CBD). While these variables were sufficient to make good predictions, the model's accuracy could have been improved by including additional spatial and non-spatial variables such as land use policies, and socio-economic factors such as access to education, health facility and factors of income etc. The inclusion of these factors could have yielded an improve result in the land cover predictions due to their influence on determining human settlement.

**Flood simulation with fastflood model.**

Although the flood simulation included external areas outside the study boundary, using an even larger area could have influenced the flood results due to the inclusion of external drainages, which also carry some volume of water into the study area. The data for the dimensions of the drainage channels in the study area were not available, and the study relied on the default channel information in the fastflood model for the simulation. The actual on-ground channel dimensions and volumes could have improved the model's accuracy. Additionally, the use of a 30m resolution dataset might have reduced the accuracy and precision of the flood output since a higher resolution dataset provides higher accurate and precise result. The observed flood depth points used for calibration were not evenly spread across the city, being mostly concentrated in the central and southern parts of the study area. An evenly distributed set of flood depth points could have resulted in different calibration outcomes. Furthermore, obtaining data on observed flood extents to support the calibration of the model could have influenced the calibration results.

**Assessing the feasibility of flood mitigation measures with economic, environmental, and social conditions from literature.**

Ideally, feasibility assessments must be conducted together with stakeholders in the study area, however, due to a change of method, this study had to rely on literature and reports to assess the feasibility of the suggested measures. Without consultations with field participants, the study might miss specific local insights and contextual factors that could influence the feasibility and effectiveness of the proposed measures. Local stakeholders might provide crucial information on cultural practices, community preferences, and historical data that literature alone cannot capture. Relying solely on a literature review may lead to assumptions that do not align with the on-ground reality. For instance, the perceived economic costs, social acceptability, and environmental impacts derived from literature might differ when applied to the actual context in reality. Furthermore, the choice of literature and sources could introduce bias, as certain perspectives or data points might be overrepresented or underrepresented.

## 6.3. Recommendations for future research

Future research should consider addressing the limitations identified in this study to enhance the accuracy and reliability of results.

For land cover prediction using the Cellular Automata model in the MOLUSCE plugin, it is recommended to incorporate additional spatial and non-spatial variables such as land use policies, socio-economic factors including access to education, health facilities, and income levels. These factors significantly influence residential patterns and could provide a more comprehensive prediction model.

In terms of flood simulation with the Fastflood model, expanding the study area to include a larger region with external drainages could improve the accuracy of flood predictions by accounting for all water flow dynamics affecting the study area. Additionally, obtaining and incorporating data on the actual dimensions and volumes of drainage channels within the study area would refine the simulation results. Utilizing higher resolution datasets than the 30m resolution used in this study is also recommended to achieve more precise flood outputs. It is also crucial to gather a more evenly distributed set of observed flood depth points across the entire city, rather than concentrating in specific areas, to ensure a more representative calibration of the model. Incorporating observed flood extents data would further enhance model calibration and validation.

Furthermore, future feasibility assessments of flood mitigation measures should prioritize direct engagement with local stakeholders in the study area. Conducting consultations with field participants can provide valuable local insights and contextual factors that are crucial for accurately evaluating the feasibility and effectiveness of proposed measures. These stakeholders can offer essential information on cultural practices, community preferences, and historical data that cannot be captured through literature alone. Incorporating local knowledge will help ensure that the perceived economic costs, social acceptability, and environmental impacts align with the on-ground reality, thereby enhancing the relevance and applicability of the measures. Additionally, a more balanced and comprehensive literature review process should be adopted, including a diverse range of sources to mitigate potential biases.

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# APENDICES

## Appendix 1: Interview invitation letter

Joel Awire Ketu

Boulevard 1945 – 4

7511 AE Enschede

The Netherlands.

07/02/2024

Dear Sir/Madam,

**PERMISSION TO CONDUCT MSc. RESEARCH INTERVIEW**

My name is Joel Awire Ketu, a second-year master's student at the University of Twente, Faculty of ITC, The Netherlands. I am currently undertaking a significant research project titled "Assessing the Effect of Future Rainfall and Urban Growth on Flood Hazard in Kumasi." The purpose of this research is to understand the dynamics of flood hazards in the rapidly evolving urban context of Kumasi, focusing on future rainfall, urban growth, and mitigation measures.

In that regard, I would like to have an interview with a planner and/or disaster management officer with your institution to discuss the primary causes of flood in Kumasi and the current mitigation measures being practiced and implemented.

I will therefore want to use this opportunity to seek permission to have an interview with any of the above-mentioned officials at their own convenient time between 19th February and 4thth March 2024. The discussion would take approximately 30-45 minutes.

If you require any further information or have any questions regarding the research, please do not hesitate to contact me.

This Interview responses will be used solely for academic purpose.

Thank you and I hope to hear from you soon.

Yours Sincerely,
Joel Awire Ketu
Email: j.a.ketu@student.utwente.nl
Mobile: +233 5459037/+31 642085998

## Appendix 2: Informed consent form

### Informed consent for key informant interviews

### Consent Form for [ASSESSING THE EEFECT OF FUTURE RAINFALL AND URBAN GROWTH ON FLOOD HAZARDS IN KUMASI, GHANA]

*You will be given a copy of this informed consent form.*

This research aims to assess the increasing issue of urban flooding in Kumasi, Ghana, focusing on the effects of urban growth and climate change. The research seeks to understand how rapid urbanization and changing rainfall patterns contribute to flood risks. Our study will analyse land use changes, project future flood scenarios, and propose effective mitigation strategies. By interviewing key stakeholders, this aims to gather insights into local experiences, challenges, and potential solutions. Your participation and insights as a stakeholder are invaluable in shaping a comprehensive understanding of the challenges and opportunities in managing urban flood risks.

The conduction of this research on future flood assessment and mitigation will add up to the existing knowledge on urban flood management in Ghana. This research will also provide knowledge to authorities on possible future flood hazard necessitating proactive measures.

In that regard, this form is to seek your consent of participation in an interview asking for your views relating to major drivers of urban flooding in Kumasi and the current flood mitigation measures that are being practiced preventing urban flood. The interview is therefore scheduled to last for about 30 to 45 minutes.

Thank you.

***Please tick the appropriate boxes*** ***Yes No***

**Taking part in the study**

I have read and understood the study information, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

Yes ☐ No ☐

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

Yes ☐ No ☐

I understand that taking part in the study involves [taking notes of interview responses]

Yes ☐ No ☐

I understand that taking part in the study also involves [recording (if possible - activating the recording of the online platform which will later be transcribed as text) of interview responses]

Yes ☐ No ☐

**Use of the information in the study**

I understand that information I provide will be used for [Purely for academic purpose in the form of report presentation to the Faculty ITC, University of Twente]

Yes ☐ No

I understand that personal information collected about me that can identify me, such as [name or position held in organization/ institution], will not be shared beyond the study team.

Yes ☐ No ☐

I agree that my information can be quoted in research outputs.

Yes ☐ No ☐

**Future use and reuse of the information by others**

I give permission for the [interview transcripts] that I provide to be archived in [Faculty ITC, University of Twente file repository] so it can be used for future research and learning.

Yes ☐ No ☐

I give the researchers permission to keep my contact information and to contact me for future research projects.

Yes ☐ No ☐

**Signatures**

……………………………….. ……………………… ………………..

Name of participant [printed] Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

………………………….. …………………………… …………………

Researcher name Signature Date

**Study contact details for further information: [Joel Ketu, j.a.Ketu@student.utwente.nl]**

**Contact Information for Questions about Your Rights as a Research Participant**

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-itc@utwente.nl

## Appendix 3: Interview guide

## TOPIC: ASSESSING THE EFFECT OF FUTURE RAINFALL AND URBAN GROWTH ON FLOOD HAZARD IN KUMASI, GHANA.

### Interview guide.

### Introduction

Good morning/ afternoon/ evening Sir/ Madam. Please, my name is Joel Awire Ketu, a second-year master's student at the University of Twente, Faculty ITC, The Netherlands. I am currently working on a research topic "Assessing the effect of future rainfall and urban growth on flood hazards in Kumasi, Ghana". As part of conducting this research, I would like to know the primary drivers of urban flooding in Kumasi and the existing mitigation measures that are being practiced or implemented to mitigate the occurrence of flood in the metropolitan area. The interview will consist of a series of questions related to your experiences and observations about flooding in Kumasi. I encourage you to speak freely and share as much as you can. There will also be room for you to add any additional comments or information that you feel is relevant, which might not be directly prompted by my questions.

Finally, I want to assure you that all the information you provide today will be kept confidential. Your responses will be used solely for the purpose of this research.

### Initial Questions:

1. Can you describe your experience or familiarity with the city of Kumasi?
2. Have you personally witnessed or been affected by flooding in the city? If yes, can you share your experiences?

### Historical flood events and primary causes

1. Let's talk about the history of flooding in Kumasi. From your perspective, what have been some of the most significant flood events in the city?
2. Per your experiences, what have been the primary drivers behind these flood events?
3. Can you rank or rate these drivers from 1(very low contribution) to 5 (Very high contribution)?
4. Can you mention which areas in Kumasi experiences flood the most based on past and current records? (Assisted with map).
5. How would you describe the changes in flooding patterns over the years in Kumasi?
6. How do you think urban development has impacted the frequency and severity of floods in Kumasi?
7. Aside urban development, do you see other causes or factors that impact the frequency and severity of flood?
8. In relation to the current urban development, how do you envisage the future of urban flood in Kumasi?

### Mitigation measures

9. Can you tell me some of the flood mitigation measures that are in place or have been implemented in Kumasi?
10. Are these measures structural (like dams, levees, drainage systems) or non-structural (like zoning, land use planning, information campaigns etc)?
11. Have there been any recent (In the past 10years) initiatives or projects aimed at flood mitigation?
12. Are there any success stories or examples where these measures have worked well?
13. What challenges have been faced in implementing these flood mitigation measures?
14. How were you able to overcome these challenges?
15. In your opinion, what additional measures or innovative solutions could be implemented to better manage flooding in Kumasi in the future?

**Additions**

16. Are there any aspects or issues related to urban flooding in Kumasi that we haven't covered but you feel are important?
17. Do you have any final thoughts or messages you'd like to share about this topic?

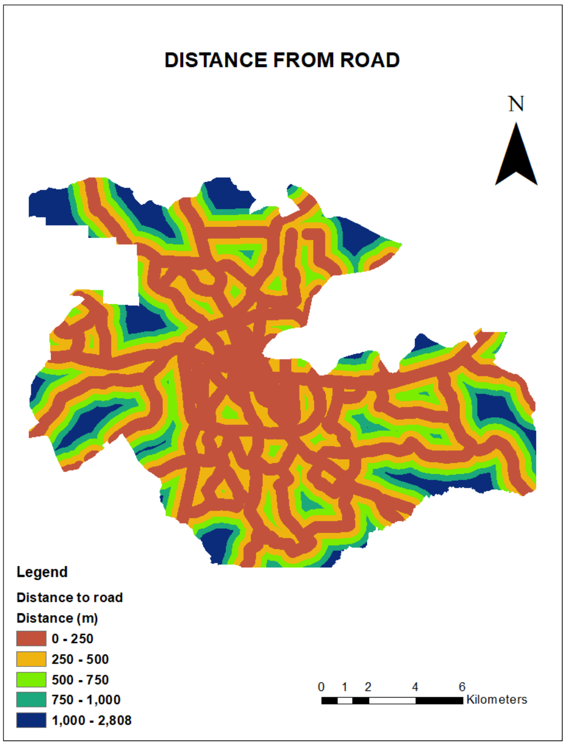
**Participant information**

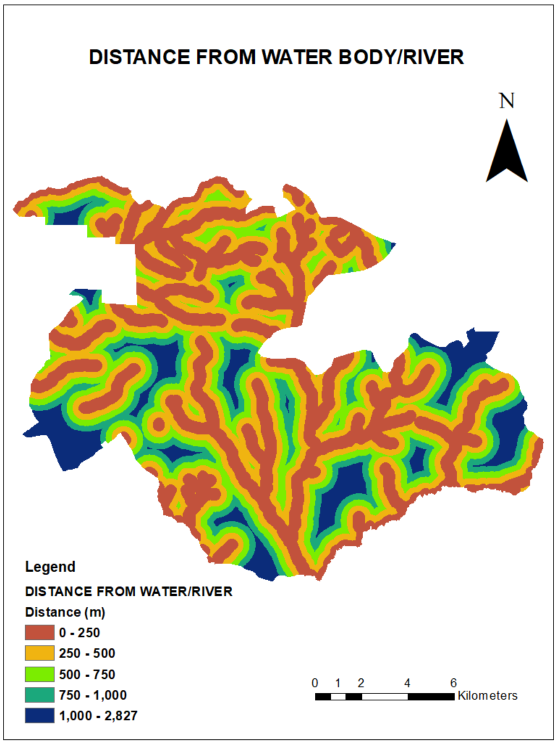
1. What is your professional background?

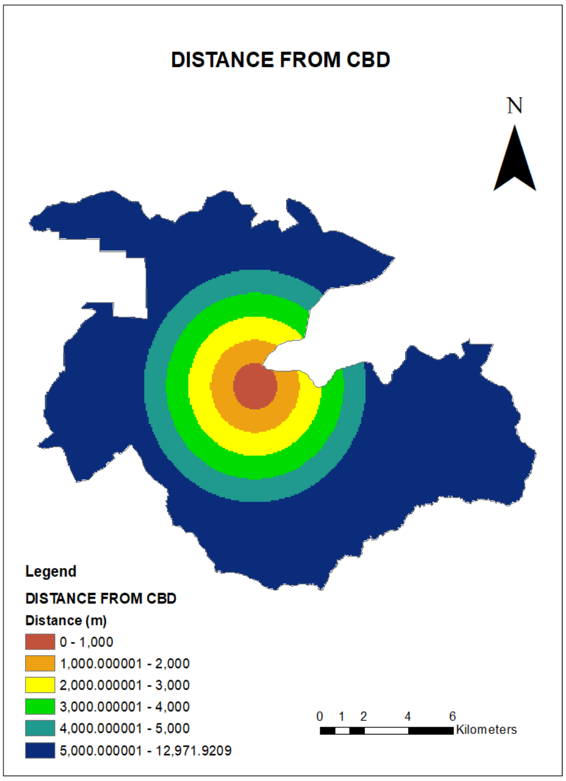
2. How many years have you been on this work?

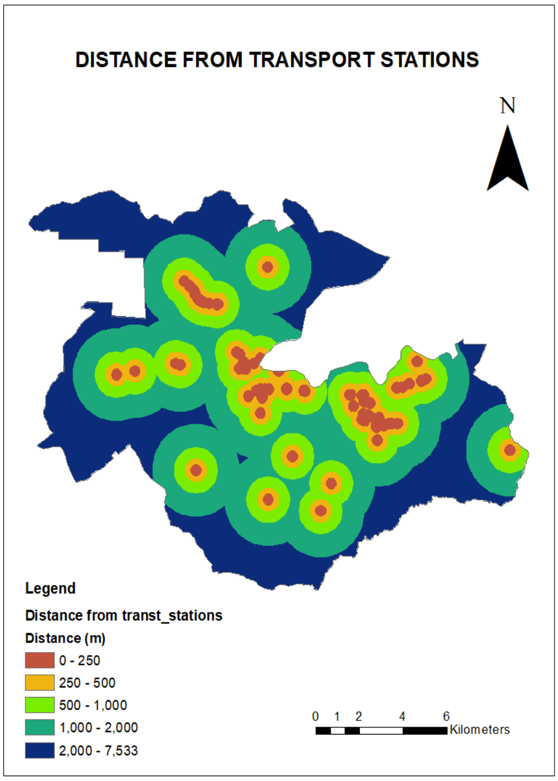
3. How old are you if I may ask?

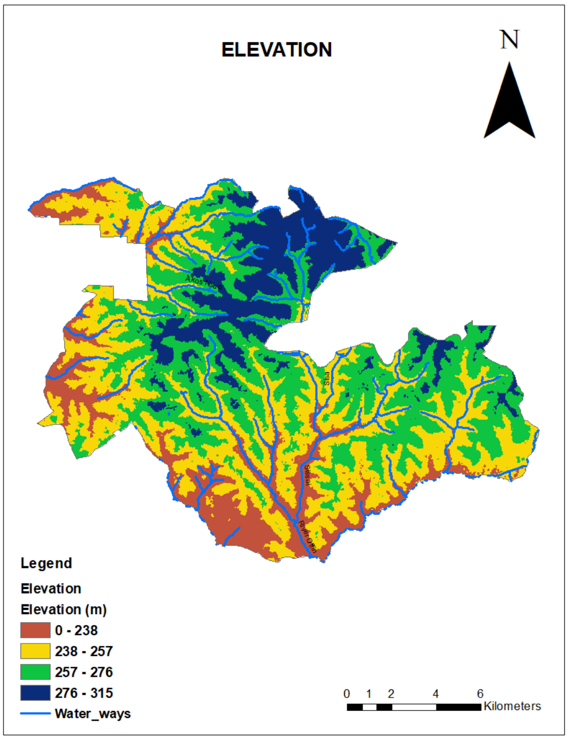
## Appendix 4: Spatial variables used for urban growth prediction

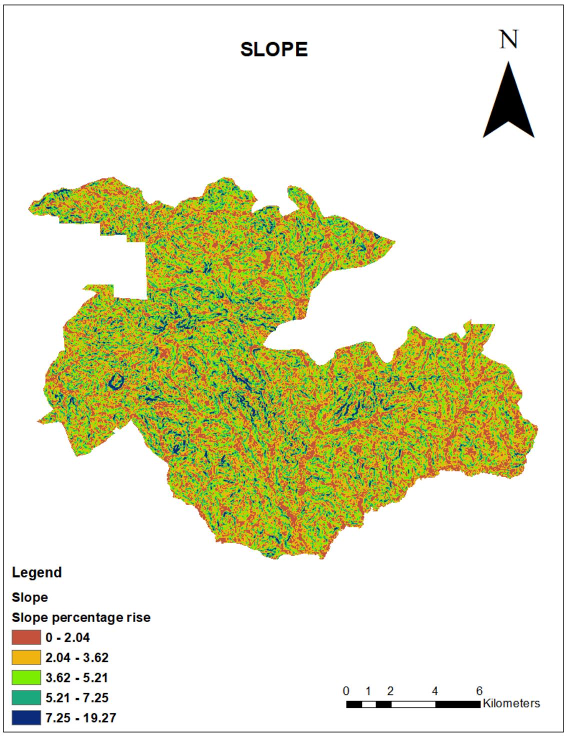


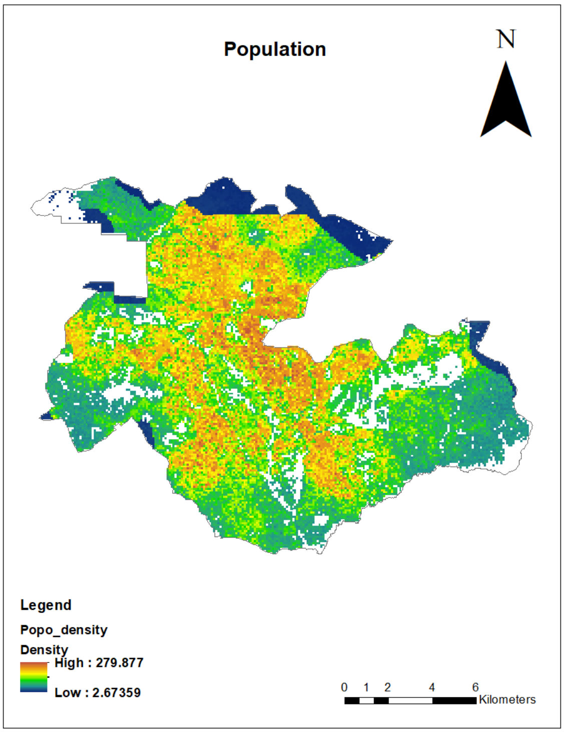




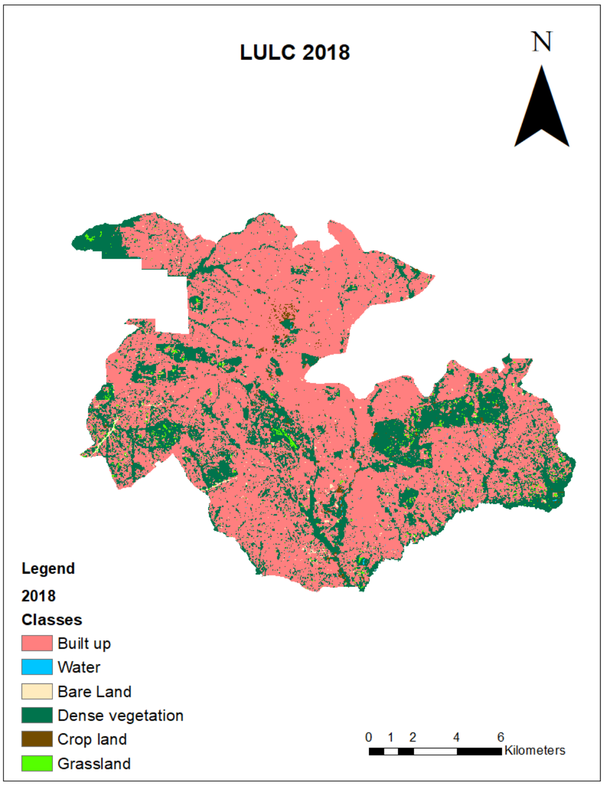



ELEVATION
N
Legend
Elevation
Elevation (m)
🟥 0 - 238
🟨 238 - 257
🟩 257 - 276
🟦 276 - 315
Water_ways
0 1 2 4 6
Kilometers


SLOPE
N
Legend
Slope
Slope percentage rise
🟥 0 - 2.04
🟧 2.04 - 3.62
🟩 3.62 - 5.21
🟩 5.21 - 7.25
🟦 7.25 - 19.27
0 1 2 4 6
Kilometers


Population
N
Legend
Popo_density
Density
High : 279.877
Low : 2.67359
0 1 2 4 6
Kilometers

### Appendix 5: Land cover map 2018



### Appendix 6: Rainfall intensity

| Month | Historical Intensity (mm/h) | Future Intensity (mm/h) |
|---|---|---|
| Jan | 5.17 | 6.41 |
| Feb | 6.43 | 8.82 |
| Mar | 7.42 | 10.29 |
| Apr | 7.33 | 9.81 |
| May | 8.41 | 12.98 |
| Jun | 12.99 | 16.92 |
| Jul | 12.58 | 16.58 |
| Aug | 12.87 | 17.53 |
| Sep | 13.04 | 17.83 |
| Oct | 9.66 | 14.13 |
| Nov | 5.42 | 9.80 |
| Dec | 4.03 | 6.13 |