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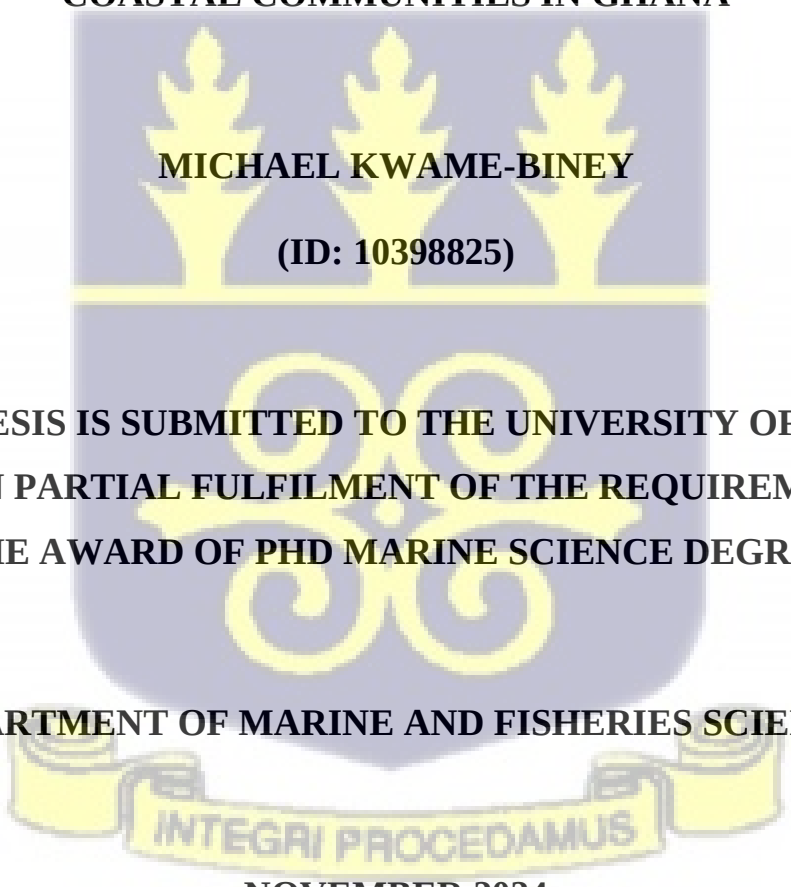
PREDICTING FUTURE FLOODING TRENDS UNDER DIFFERENT SEA LEVEL RISE AND PRECIPITATION SCENARIOS IN SOME COASTAL COMMUNITIES IN GHANA

MICHAEL KWAME-BINEY

(ID: 10398825)

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DECLARATION

This thesis is the result of original research undertaken by Mr. Michael Kwame-Biney in the Department of Marine and Fisheries Sciences (DMFS) of the University of Ghana. The research was carried out under the supervision of Professor Kwasi Appeaning Addo, Dr. Benjamin Osei Botwe, Dr. Peter Borgen Sorenson and Dr Philip-Neri Jayson-Quashigah. All references cited in the study have been duly acknowledged.

Signature:…… Date: **12/11/2024**

Michael Kwame-Biney

(Student ID: 10398825)

Signature:…… Date: **09/11/2024**

Professor Kwasi Appeaning Addo

(Department of Marine and Fisheries Sciences, University of Ghana)

Signature:…….. Date:**12/11/2024**

Dr. Benjamin Osei Botwe

(Department of Marine and Fisheries Sciences, University of Ghana)

Signature:…….. Date: **13/11/2024**

Dr. Peter Borgen Sorenson

(Department of Ecoscience, Aarhus University, Denmark)

Signature:……. Date: **12/11/2024**

Dr. Philip-Neri Jayson-Quashigah

(Institute for Environmental and Sanitation Studies, University of Ghana)

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ABSTRACT

Coastal areas in Ghana are critical to the nation's socio-economic fabric but face growing threats from erosion and flooding due to a mix of climatic and anthropogenic factors. Accurate and high-resolution scientific data are essential to manage these challenges sustainably. Previous studies have often relied on low-resolution imagery, compromising the precision required for effective decision-making and engineering responses. This study leverages a combination of high-resolution data from Unmanned Aerial Vehicles (UAVs), satellite imagery, and medium-resolution Digital Elevation Models (DEMs), along with hydrological modelling using the Malstroem (Bluespots) model, to explore the complex dynamics of coastal vulnerability across Ghana's central and eastern coasts.

Employing aerial surveys with a DJI Phantom 4 drone and high-resolution satellite imagery, this study quantified short- and mid-term shoreline changes from January 2021 to December 2023 and 1974 to 2023 respectively. In the Mumford community, modest erosion rates stand in stark contrast to a worrying trend where 53.33% of the coastline is fast eroding, exacerbated by human activities such as sand mining and infrastructural development, particularly at the new fish landing site. The Atiteti community faces even more severe challenges, with 93.33% of its coastline retreating due to natural and human factors. These observations underscore the urgent need for tailored coastal management strategies to address the specific conditions in each region.

Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) analyses and bathtub model projections based on Shared Socioeconomic Pathways (SSPs) reveal significant flood risks. Under the high-emission scenario SSP 5-8.5, the projections indicate that up to 47% of Atiteti will be submerged by 2100. This integration of models with actual subsidence

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measurements shows how geological and human-induced subsidence exacerbate vulnerability to sea level rise (SLR) and relative sea level rise (RSLR).

Furthermore, the Malstroem model simulations revealed critical vulnerabilities due to varying rainfall scenarios. In Mumford, flooding risks are exacerbated at lower rainfall levels (100 mm), showing an increase of 55,000 m^2 of flooded areas by 2040 due to subsidence, rising to over 60,000 m^2 at 150 mm of rainfall by 2060. Atiteti exhibits a continuous increase in flooded areas with no plateau even at 1 in 25-year flood simulations at high rainfall intensities (300 mm), suggesting a broader spread due to its flatter terrain and less effective drainage. Simulations using the Malstroem model uncovered critical vulnerabilities, particularly in Atiteti, where flattening terrain and ongoing subsidence significantly increased flood risks. This study provides a comprehensive assessment of current vulnerabilities and recommends the development of localized early warning systems or decision tools that can help alert communities in advance and aid planners in managing these coastal challenges more effectively. The findings highlight the pressing need for robust data-driven policies and adaptive strategies to bolster the resilience of these crucial areas against looming environmental threats.

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DEDICATION

This work is dedicated to the memory of my beloved mother, **Grace Akyeneba Baaba Fitz Williams**.

Mom, your love, guidance, and strength continue to inspire me every day. I love you always.



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LIST OF ABBREVIATIONS

AMBUR:	Analysing Moving Boundaries Using R
ArcGIS:	Aeronautical Reconnaissance Coverage Geographic Information System
ASTER:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CVA:	Coastal Vulnerability Assessment
CVI:	Coastal Vulnerability Index
CZM:	Coastal Zone Management
DEM:	Digital Elevation Model
DSAS:	Digital Shoreline Analysis System
EbA:	Ecosystem-based Adaptation
FOCC:	Florida Oceans and Coastal Council
GIS:	Geographical Information Systems
GSRL:	Global Sea Level Rise
HEC-RAS:	Hydraulic Engineering Centre's River Analysis System
HWL:	High Water Line
IAMs:	Integrated Assessment Models
ICZM:	Integrated Coastal Zone Management
IPCC:	Intergovernmental Panel on Climate Change
ISIS:	Integrated Simulation of Integrated Systems
KSDP:	Keta Sea defence project

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Landsat TM:	Landsat Thematic Mapper
Landsat ETM+:	Enhanced Thematic Mapper Plus
LISFLOOD-FP:	LISFLOOD Floodplain Model
LS:	Land Subsidence
MoFA:	Ministry of Food and Agriculture
NbS:	Nature-based Solutions
NGO:	Non-governmental Organization
NOAA:	National Oceanic and Atmospheric Administration
PS-InSAR:	Persistent Scatterer Interferometric Synthetic Aperture Radar
RSLR:	Relative Sea Level Rise
RTK-GPS:	Real-time Kinetic Global Positioning System
SLR:	Sea Level Rise
SWAT:	Soil and Water Assessment Tool
UAV:	Unmanned Aerial Vehicle
VCS:	Video Camera Systems
WLR	Weighted Linear Regression



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CHAPTER ONE

1.0 INTRODUCTION

1.1 Overview

Coastal zones around the world are highly vulnerable to the effects of climate change and sea level rise (Gallina *et al*., 2020; Shepard *et al*., 2012). Approximately 680 million people live in low-lying coastal zones (IPCC, 2019). The low-elevation coastal zone refers to land below 10 m elevation along the shores connected to water bodies (Keogh & Törnqvist, 2019; Lichter *et al*., 2011). In Bangladesh and China, the population in the low-elevation coastal zone doubled between 1990 and 2000, with the urban areas experiencing high growth (Magnan *et al*., 2022). The appeal of coastal zones lies in their rich and attractive resources, including subsistence resources, entry points for shipping and transportation, and venues for entertainment events (Leka *et al*., 2022). Over the past decades, coastal zones have undergone significant changes, a trend that is expected to continue due to global urbanization (Neumann *et al*., 2015). This has led to an increase in the number of people and assets exposed to hazards due to coastal development, land use changes, urbanization, and climatic hazards such as sea-level rise and coastal flooding. It is estimated that approximately 310 million people and 11 trillion dollars in global GDP are at risk from a 100-year flood event (Steven *et al*., 2020). This risk is set to further increase due to rising sea levels and other climatic factors, coupled with massive population growth (IPCC, 2019; Steven *et al*., 2020).

Current estimates predict mean sea levels rising by 1 m or higher by 2100, which will have severe impacts such as flooding and inundation on coastal environments and ecosystems (Brown *et al*., 2018; IPCC, 2007). To manage these climate-induced changes, there is a need to develop national strategies to predict and mitigate the devastating effects of flooding and

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inundation to protect coastal regions and populations in low-elevation coastal zones (Agrawala *et al*., 2003; Handayani *et al*., 2019; Lewsey *et al*., 2004; Onyshchenko, 2019).

While extensive research and innovative solutions have been developed for large coastal zones in developed countries such as the Netherlands, Denmark, and Japan (de Bruin *et al*., 2014; Deighton-Smith & Bell, 2017; Kaiser & Witzki, 2004; Suppasri *et al*., 2013), less developed countries, especially along the West African coast, such as Ghana, have relatively little research and sparse data in this area (Appeaning Addo *et al*., 2011; Tano *et al*., 2018). This presents a significant challenge for coastal engineers and managers in these regions, hindering efforts to protect the coast and understand coastal dynamics to suggest and adopt appropriate management strategies (Armah, 2005; Jayson-Quashigah *et al*., 2013).

It is crucial to periodically map coastal communities through continuous monitoring to understand the dynamic nature of coastal systems. This ongoing assessment will facilitate the development and adoption of suitable mitigation and adaptive solutions to counteract the impacts of coastal flooding. At the local level, key findings from regular monitoring can influence policy formulation, thereby improving governance structures in coastal regions (Appeaning Addo, 2015). This study employed Unmanned Aerial Vehicles (UAVs), Digital Elevation Models (DEMs), and flood models to predict future flooding trends in coastal communities. The approach involves a detailed examination of shoreline morphology as well as flood estimation and prediction from precipitation and oceanic factors (Sea Level Rise). The lessons from this research will contribute to the framework for disaster management, building on previous works conducted in other Ghanaian communities.

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1.2 Background

Ghana's coast, spanning approximately 550 km along the Gulf of Guinea, encompasses diverse ecosystems and valuable natural resources (Ly, 1980). Serving as a vital economic asset, the region boasts thriving fisheries, vibrant tourism attractions, and ports that support trade and maritime activities (Gordon & Ayivor, 2003; Jennifer *et al*., 2013; Mensah & Track, 2013). However, this coastline is vulnerable to various climatic and anthropogenic impacts (Addo & Adeyemi, 2013; Armah, 2005; Boateng *et al*., 2017). The reduction of coastal vegetation, a natural defence against erosion and flooding, combined with disruptive practices such as sand mining, has disturbed the sediment balance, and accelerated coastal degradation (Loucks, 2019). Moreover, coastal defense structures, while intended to protect, inadvertently disrupt sediment transport and trigger erosion in adjacent unprotected areas.

Historical analyses indicate that sections of the shoreline have been subjected to erosion and flooding since the mid-1880s, a trend significantly exacerbated by infrastructural developments that hindered sediment supply, as observed in the knock-on effects of projects such as the Keta Sea Defence (Appeaning Addo *et al*., 2018). Upstream activities, particularly dam construction and altered water management practices, have led to sediment starvation, intensifying erosion especially along the eastern coast. This erosion not only undermines natural defences against storm surges and tidal forces but also increases the coastline's vulnerability to flooding. Land subsidence, resulting from both natural processes and human activities, further amplifies this flood risk, underscoring the complex challenge of managing coastal vulnerability (Avornyo *et al*., 2024).

In Ghana, flooding in coastal areas typically manifests in three main forms: fluvial flooding resulting from river overflow, pluvial flooding caused by intense or prolonged rainfall leading to surface water accumulation, and coastal or tidal flooding driven by storm surges, sea-level

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rise, and wave overtopping. The interplay between these flood types often worsens impacts, particularly in low-lying coastal settlements such as Keta, Ada, and parts of Accra, where drainage systems are inadequate and natural buffers like mangroves have been degraded (Boateng, 2012). Anthropogenic pressures including unregulated urbanisation, poor land-use practices, and the reclamation of wetlands further compound these flood risks.

Historically, major flood events such as the 1968 Accra floods, the 1995 Keta coastal inundation, and more recent events in June 2015 and October 2020 have caused widespread destruction of homes, displacement of thousands of residents, and significant damage to public infrastructure. These events underscore the socio-economic vulnerabilities of coastal communities and highlight the urgent need for proactive flood prediction and management strategies.

Improving flood forecasting and early warning systems would greatly enhance coastal resilience. The ability to predict and map flood-prone zones using high-resolution models and long-term climate projections can inform evidence-based coastal management, guide infrastructure planning, and support the design of adaptive interventions such as nature-based defences and sustainable drainage systems. Ultimately, strengthening predictive capacity is critical to reducing flood impacts, safeguarding livelihoods, and promoting sustainable development along Ghana's vulnerable coastline.

This background highlights the complex interplay between climatic and anthropogenic factors driving the multifaceted nature of coastal vulnerability in Ghana. The interconnectedness of coastal erosion and flooding demonstrates a cyclical threat: erosion reduces barrier protection and increase the likelihood of flooding, which in turn can lead to further erosion. Understanding these dynamics is essential for accurately predicting future flooding trends and for developing effective mitigation and adaptation strategies.

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In response, this study seeks to enhance the resilience of Ghana's coastal zones by focusing on the most affected coastal communities and utilizing scientific methodologies to evaluate the implications of sea level rise and precipitation changes. This approach aims to provide innovative solutions that will bolster the resilience of these communities, thereby addressing a critical knowledge gap and setting the stage for future research. This study sought to answer the following questions:

1. What is the trend (short-term and mid-term) of shoreline evolution along the central and eastern coasts of Ghana?
2. What are the differences in the area of inundation under the projected sea-level rise and relative sea-level rise scenarios across various temporal scales?
3. What are the expected future flooding trends under different precipitation scenarios?

1.3 Aim and Objectives

This study aimed to evaluate the impacts of coastal erosion and flooding on Ghana's central and eastern coasts using high-resolution data and advanced hydrological modelling.

1.3.1 Objectives

1. To estimate short-term (3 years) and mid-term (30 years) erosion rates in some coastal communities along the central and eastern coast of Ghana using orthophotos from a DJI phantom IV drone and high-resolution satellite imagery.
2. To determine coastal flooding under projected Sea Level Rise and Relative Sea Level Rise Scenarios
3. To simulate coastal flooding under different precipitation scenarios using the malstroem model.

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1.4 Justification of Study

Coastal flooding and erosion along parts of the Central and Eastern coasts of Ghana have destroyed many infrastructures, ranging from small fishing villages (Appeaning Addo *et al*., 2018; Fitton *et al*., 2021; Jayson-Quashigah *et al*., 2019) to urban areas (Addo *et al*., 2011; Angnuureng *et al*., 2018; Appeaning Addo, 2014) causing some economic crisis through its effect on the tourism and socioeconomic life of the people who depend on them. Although parts of both the central and eastern coasts are considered hotspots of erosion and flooding (Wiafe *et al* 2013), a review of the literature shows limited comprehensive and reliable information that is key for decision-making in preparing frameworks for disaster management (Appeaning Addo *et al*., 2018; Armah, 2005). Previous research along the central and eastern coasts focused on the ecological, socio-economic and morphodynamics of the coastal zone which is a great step toward understanding the environment (Angnuureng *et al*., 2022; Appeaning Addo *et al*., 2018; Boateng *et al*., 2017; Jayson-Quashigah *et al*., 2019). However, an important piece of the puzzle that uses dynamic numerical flood models to help predict future flooding trends and serve as a decision support tool is still lacking and presents a great challenge to coastal engineers and Disaster Management Organizations.

Therefore, the first objective was to use UAVs and satellite images to estimate the rate of change along parts of the coast for short-term (3 years) and mid-term (30 years) analysis. The second objective was to use remote sensing and the INSAR approach to assess the incidence of flooding and the risk of inundation from Sea Level Rise and Relative Sea Level Rise scenarios along the study sites using SAR imagery and a 12m DSM world-DEM. The third objective was to adopt the Blue Spot model (malstroem) to help predict future flooding under different precipitation scenarios and go a step further to investigate flooding trends under different topographical changes. Such information will be important in developing an Early

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Warning System or decision support tools for flooding along the central and eastern coasts of Ghana. Figure1.1 shows the linkages among the research objectives.

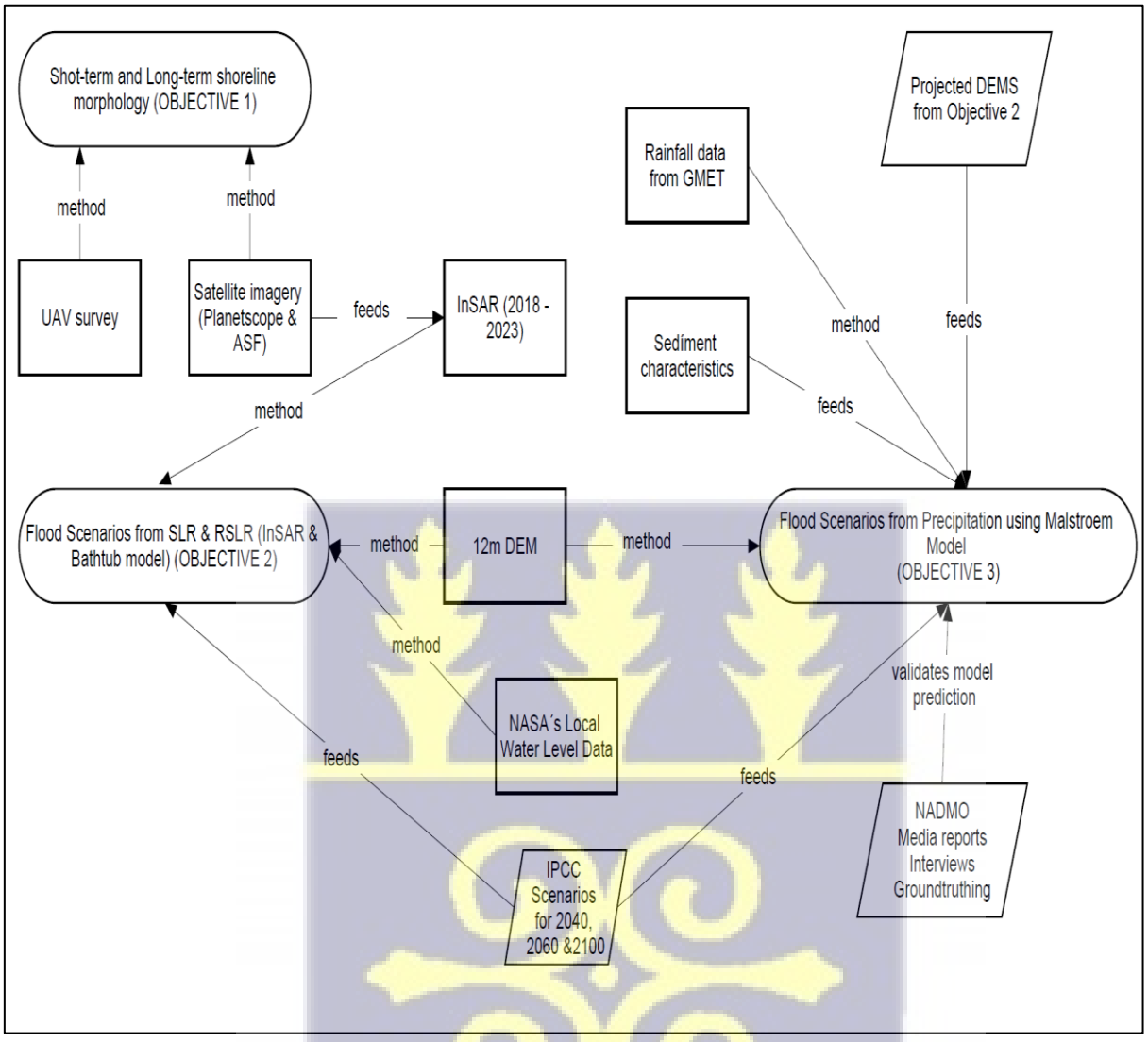


Figure1.1 Linkages between research objectives

1.5 Research Methodology

This research is based on the premise that parts of the central and eastern coasts in Ghana have been assessed using low-resolution data that provides less accuracy and many uncertainties in the results and representation of the coast (Jayson-Quashigah *et al*., 2013). Additionally, flood-

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related decision support tools that account for precipitation and SLR are not available to help coastal managers develop risk indices. To predict future flooding trends along coastal communities in Ghana, a robust approach using high-resolution data and dynamic models was adopted. They include;

I. The use of UAV surveys and high-resolution satellite imageries to assess shoreline dynamics and to estimate the rate of change along parts of Ghana's Central and Eastern Coasts for short-term (January 2021 - December 2023) and mid-term (1974-2023). This involved the generation of high-resolution orthophotos which were digitized to assess erosion rates. Uncertainties in these changes were quantified.

II. Second, an Interferometric Synthetic Aperture Radar (InSAR) approach was adopted together with high-resolution DEMs in a bathtub model to calculate the risk of inundation. Interferograms from the SAR images were used to deduce vertical land movement for 2040 (short-term), 2060 (mid-term) and 2100 (long-term) following IPCC definitions. A projected coastal inundation assessment was performed using projected topographical changes and sea-level rise scenarios.

III. Finally, future predictions for flooding scenarios from rainfall and changing topography were performed by combining the use of malstroem and the INSAR approach.

1.6 Thesis Structure

The thesis structure follows from the introductory section (Chapter 1) outlined above. Chapter 2 reviewed the literature on coastal zones, focusing on shoreline monitoring and modelling flooding scenarios using various methodologies. Chapter 3 investigated shoreline morphodynamics using UAV surveys to estimate the rates of change. Chapter 4 utilized high-resolution DEMs, sea-level rise scenarios, and the InSAR approach to project topographical

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changes and assess the risk of inundation in the study areas. In Chapter 5, the Blue Spot model was employed to predict future flooding scenarios based on precipitation patterns. Chapter 6 synthesized the key findings of the research, while Chapter 7 presented the main conclusions and recommendations for future studies.



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CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

In an era marked by the escalating impacts of climate change, coastal zones worldwide face unprecedented challenges. Rising sea levels, increased coastal flooding, and accelerated erosion rates threaten the ecological integrity and socio-economic fabric of coastal communities. Therefore, it is important for effective Coastal Zone Management (CZM) strategies to be more critical. These strategies are essential not only for mitigating the adverse effects of these changes but also for safeguarding the future of coastal ecosystems and the communities that depend on them. This literature review aims to delve into the existing body of research on CZM strategies, focusing on their efficacy, socio-economic and environmental implications, challenges and solutions across different coastal settings, and the role of modelling in the development of early warning systems. This will contribute significantly to the field of coastal zone management, aspiring not only to bridge the gaps in current knowledge but also to inspire future research that can lead to more resilient and sustainable coastal communities.

This review is grounded in a comprehensive analysis of recent studies, selected through a systematic search of databases such as Scopus and Web of Science, focusing on keywords related to Coastal Zone Management, climate change impacts, and modelling techniques. Priority was given to research published in the last decade, ensuring the relevance and inclusion of the latest findings in the field. This approach enables a critical examination of the breadth and depth of the current understanding and methodologies in coastal zone management.

This chapter is divided into eight sub-sections (sub-sections 2.2 – 2.9). Sub-section (2.2) broadly looks at coastal zones and their importance, classification and risks. Sub-sections 2.3

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focus on the coastal vulnerability. This section takes a deeper look into coastal vulnerability agents and different coastal vulnerability assessments. Sub-sections 2.4 and 2.5 look at the Malstroem and Bathtub models, respectively. These models were adopted in this study therefore, this section gives detailed information on the two models. Sub-section 2.6 looks at uncertainties related to coastal assessments. The issues of how to reduce errors and biases are discussed extensively in this sub-section. Sub-section 2.7 focuses on adaptive management strategies for coastal zones. It reviews a wide range of strategies used to manage coastal issues, such as erosion and flooding, and outlines their effectiveness. Sub-section 2.8 provides global case studies and lessons that should be considered in Ghana. Sub-section 2.9 looks at past research on issues relating to coastal zones, gaps, and uncertainties, and sets a tone for future research.

2.2 Coastal Zone Concepts

Coastal zones are defined as the interface or transition areas between the land and sea, including both coastal land areas and adjacent marine environments, extending seaward to the limit of significant coastal processes, typically including the intertidal zone and nearshore waters influenced by tides, waves, and coastal currents (Ayyam *et al*., 2019; Crossland *et al*., 2005). These regions are characterized by unique ecological processes and biodiversity. Coastal zones can be classified into various types based on their geographical features, ecological characteristics, and the processes that shape them (Finkl, 2004). Common classifications include estuaries (where rivers meet the sea and are brackish water zones important for the breeding of many marine species), deltas (formed from sediment deposits at river mouths, creating fertile lands but often vulnerable to flooding), mangroves (which are normally found in tropical regions with dense forests in tidal areas, acting as crucial buffers against storm surges), coral reefs (biodiverse underwater ecosystems providing habitat for thousands of

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marine species) and beaches (both sandy and rocky, which are dynamic environments heavily influenced by wave action, offering recreational spaces while facing significant erosion challenges). Each classification represents a unique coastal environment with specific ecological functions, management needs, and conservation challenges (Ayyam *et al*., 2019; IPCC, 2003).

Globally, approximately 40% of the world's population lives within coastal zones which have a vast majority of resources for the current and emerging sectors (United Nations, 2017). Most of the world's commercial, residential, transport and national defence infrastructure are situated along the coast. Coastal zones also provide habitats for numerous species of plants and animals (Seitz *et al*., 2014). They offer protection from storm surges and erosion, support fisheries and aquaculture, and contribute to the global economy via tourism and shipping. Moreover, coastal zones serve as buffers against climate change, with ecosystems such as mangroves and coral reefs playing key roles in carbon sequestration (Srikanth *et al*., 2016). However, they are also profoundly changing across human timescales as they are challenged by extreme climate events that are escalating in frequency and severity. In addition, anthropogenic factors such as over-exploitation, population growth, conversion of coastal habitats, and the influx of pollutants, all affect these coastal environments (Appeaning Addo, 2014). These factors threaten the coastal environment.

2.3 Coastal Vulnerability

Coastal vulnerability is a critical area of concern within the broader discourse on climate change and its impact on natural and human systems (Kelly and Adger, 2000). Coastal vulnerability is defined as the degree to which coastal regions are susceptible to or unable to cope with the adverse effects of climate change, including sea-level rise, extreme weather events, and coastal erosion (Ramieri *et al*., 2011). The Intergovernmental Panel on Climate

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Change (IPCC) emphasizes the compound nature of coastal vulnerability, integrating exposure, sensitivity, and adaptive capacity as its three critical dimensions. Understanding coastal vulnerability requires not only recognizing the drivers and impacts but also identifying the specific agents that exacerbate vulnerability (Thomas *et al*., 2019).

2.3.1 Coastal Vulnerability Agents

In coastal areas, vulnerability agents typically refer to factors or elements that contribute to the susceptibility of a coastline to various hazards, such as erosion and flooding. These agents can include physical, environmental, and socio-economic factors that interact to determine the vulnerability of a coastal zone (Cruz-Ramírez *et al*., 2024).

The physical agents of coastal vulnerability may include factors such as geomorphology (the shape and structure of the coastline), sediment supply, wave and current patterns, and shoreline characteristics. These physical agents influence the susceptibility of coastal areas to erosion and flooding (Cannon, 1994).

Environmental agents refer to natural processes and phenomena that can affect the vulnerability of a coast (Klein *et al*., 2003). This may include sea-level rise, storm surge events, wave action, and changes in climate patterns. These factors can significantly affect the stability and resilience of coastal areas.

Socio-economic agents involve human activities and societal factors that can increase or decrease the vulnerability of a coastline (Mavromatidi, Briche and Claeys, 2018). For instance, coastal development, population density, infrastructure, land use practices, and coastal management strategies can influence the susceptibility of a coastal zone to hazards. In the broader discourse on coastal vulnerability, two key environmental vulnerability agents are critically examined (Clark, 2000). These two agents are distinguished by their significant contributions to altering coastal dynamics and resilience. They are global agents (climate

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change and climatically induced sea-level rise) and local agents (human-induced subsidence and changes as a result of land use) (Anfuso *et al*., 2021).

2.3.1.1 Climate Change

Climate change refers to significant changes in global temperature and weather patterns over time. While climate variability has always existed, the term often specifically denotes the accelerated changes observed since the pre-industrial era due to human activities. The primary agents of anthropogenic climate change include the increased emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, largely from burning fossil fuels, deforestation, and industrial processes (Abbass *et al*., 2022). These emissions enhance the greenhouse effect, leading to changes in rainfall and temperature patterns, melting of ice cups, and expansion of water molecules, which results in sea-level rise, thereby affecting the coastal zone and human societies that depend on them (Gahlawat & Lakra, 2020).

Coastal zones around the world are affected in several ways by the inundation of low-lying areas, flooding as a result of the influx of tidal waves, coastal erosion, damage to property, salinization, and wetland loss (Chen *et al*., 2012; Genua-Olmedo *et al*., 2016). Developing countries are more vulnerable to the effects of climate change because of their geographic location, lack of early effective warning systems, and appropriate intervention measures, which make them globally the most vulnerable and foremost affected countries when it comes to the effects of sea-level rise as a result of increasing global temperatures. It has been projected by the National Oceanographic and Atmospheric Agency (NOAA) and Intergovernmental Panel on Climate Change (IPCC) that these threats will increase with increasing global mean temperature. This means that for every degree of temperature rise, its negative effect would be felt by those residing in low-lying coastal areas due to increased sea-level (Lawson, 2016; Wainer *et al*., 2017).

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2.3.1.2 Sea Level Rise

Sea-level rise (SLR) is a critical aspect of global climate change and is characterized by an increase in the average height of the world's oceans over time (Elneel *et al*., 2024). This phenomenon poses significant threats to coastal ecosystems, human settlements, and infrastructure around the globe. SLR is primarily measured using tide gauges and satellite altimetry, which offer precise readings of sea level changes across different regions (Cazenave and Moreira, 2022). There are two types of SLR. The first is the Eustatic Sea-Level Rise, which refers to a global increase in sea level caused by the addition of water to the world's oceans. Major contributors to eustatic SLR include the melting of glaciers and ice caps, and the thermal expansion of seawater as it warms. The eustatic SLR is uniform across the globe, although its local impacts can vary due to land movements and ocean currents (Rovere, Stocchi and Vacchi, 2016). Under Eustatic SLR, there is another subset which refers to steric changes at sea level. This refers to the expansion and contraction of seawater as it warms and cools, without any change in its mass. The thermal expansion of water contributes to sea level rise as ocean temperatures increase. Salinity variations can also play a role, as freshwater inputs from melting ice and precipitation can change the density of seawater, further influencing steric sea level changes. The second form of SLR is the Isostatic Sea Level Rise which involve changes in the level of the land relative to the sea. This can occur due to the loading and unloading of ice on continental shelves during glacial periods and the subsequent melting of these ice masses. Post-glacial rebound is a common form of isostatic adjustment, where land previously depressed by the weight of ice sheets rises, affecting local sea levels (Spada, 2017).

Understanding these types of sea level rise is crucial for accurately assessing coastal vulnerability, predicting future changes, and developing effective mitigation and adaptation measures (Webb *et al*., 2013).

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Sea level rise (SLR) is also influenced by a combination of natural processes and anthropogenic drivers, each of which contributes distinctively to its dynamics. Natural drivers, including tectonics and isostasy, significantly affect SLR over geological timescales. Tectonic actions, through rifting and subduction, alter ocean basin volumes, whereas isostatic adjustments affect the elevation of the ocean floor in response to shifts in mass distribution, such as melting ice sheets (Kopp *et al*, 2015). These processes are crucial for understanding global and regional variations in sea levels (Dolan and Walker, 2006). Additionally, climate change accelerates SLR through the thermal expansion of seawater and melting of glaciers, ice sheets, and permafrost, which not only increases ocean volumes but also introduces rapid changes in sea levels.

In the case of anthropogenic drivers, human activities profoundly affect local and global SLR. Urban development, sediment compaction from infrastructure projects, and drainage of coastal areas lead to land subsidence, amplifying SLR's effects. Sediment starvation, exacerbated by dam construction and river regulation, reduces sediment supply to deltas and coastal zones, and increases erosion risks. Moreover, beach sand mining, which is particularly prevalent in West African coastal countries, disturbs sediment budgets, causing further coastal erosion (Alves, 2022). These human-driven factors contribute to the relative SLR by altering land elevations and disrupting natural sediment processes, highlighting the need for integrated management strategies that consider both natural processes and human interventions to address the multifaceted challenges of SLR (Kirwan and Megonigal, 2013).

Approximately 541 million years ago, the location, age, and continuity of marine sedimentary rocks, were used with a high level of certainty than global sea level, which implies that global temperatures were higher than present-day levels (DiPietro, 2018). The sea level during the last interglacial warm period around 125,000 years ago, before the most recent ice age, was 6 to 9 m higher than at present (Dutton and Lambeck, 2012; Kopp *et al*., 2013). Within this period,

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global air temperatures were pegged at around 2 ^{o}C, which is higher than at present (Allison *et al*., 2014). During the last 3000 years, the eustatic sea-level rose steadily until rates began to increase during the mid-nineteenth century (Church and Gregory, 2001; Ericson *et al*., 2006). Hitherto the twentieth century, global sea level since the late 19th century rose by about 1.6 mm/yr (Church and White, 2011), whiles its rate did not surpass 0.6 mm/yr during the two previous millennia (Kemp *et al*., 2011; Le Cozannet *et al*., 2014). The IPCC (2013), estimates mean rate of global averaged sea level rise as 1.7 mm/yr between 1901 and 2010, 2.0 mm/yr between 1971 and 2010, and 3.2 mm/yr between 1993 and 2010. Sea level has been reported by DiPietro (2018) to be between 165 and 500 feet above the present-day level at some point with high-stand occurring between 50 and 55 million years ago.

Presently the use of satellite altimeter observations of sea level has been available since 1993, resulting in measurements of sea-level rise that are more spatially comprehensive and accurate than relying on tide-gauge reconstructions alone (Allison *et al*., 2014). Since its availability, satellite altimetry has indicated GSLR at 3.2 ± 0.4 mm/year, while tide-gauge reconstructions have pegged GSLR at 2.8 ± 0.8 mm/year (Milne *et al*., 2009; Church and White, 2011; Meyssignac and Cazenave, 2012; Allison *et al*., 2014). The current increasing trend in GSLR is predominantly due to global warming arising from the industrial revolution (IPCC, 2007, 2013), global temperatures that have led to significant eustatic SLR due to the thermal expansion of oceans and the transfer of glaciers and ice sheet mass into the ocean through melting and runoff, as well as iceberg calving (Allison *et al*., 2014). The trend of global warming has increased dramatically, at a rate of over 50% higher than the historic global mean value during the 20th century (Dvorak *et al*., 2018). The IPCC (2014) reports that there has been an alarming 300% increase in the rates of SLR during the last 20 years compared to the previous 20 years, at around 3.2 mm/y for the global mean sea-level rise.

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Available data support an anticipated increase in the rate of sea level rise with no evidence proving otherwise (Bloetscher *et al*., 2016; FOCC, 2010; Gregory, 2013) largely due to the continuous increase in the thermal expansion of the ocean, water volume in the sea due to glacial, ice sheet and permafrost melting, and reduction of liquid water storage capacity on land (IPCC, 2014). Since CO_2 emissions are the main driving force of global warming, several studies including those of the IPCC have developed a sequence of CO_2 emission-driven global warming scenarios ranging from stringent mitigation efforts to high CO_2 emission scenarios. Other model-based projections of global and regional SLR indicate higher rates of SLR with corresponding temperatures under various emission scenarios (Church *et al*., 2014; Katsman *et al*., 2011; Sriver *et al*., 2012; Brown *et al*., 2018; Pickering *et al*., 2017). In Africa, the Hulme *et al*. (2001) scenarios suggest future annual warming across Africa ranging from below 0.2 ◦C per decade to over 0.5 ◦C per decade with model-based predictions of future greenhouse gas-induced climate change estimating average temperatures between 2 ◦C and 6 ◦C warmer in 100 years' time (Hulme *et al*., 2005). This range far exceeds that of the IPCC and will result in rates of SLR in Africa. This means that any coastal tragedy caused by climatically induced SLR (tidal waves, storm surges, flooding, etc.) will cause loss of property and lives, including adverse economic effects.

2.3.1.3 Coastal Land Subsidence

Coastal Land Subsidence is the slow or abrupt foundering of the Earth's surface in coastal areas as a result of the underground motion of materials. Additionally, it alludes to the phenomena of the Earth's surface moving vertically downward and sinking land. This is caused by both natural and anthropogenic activities (Raspini *et al*., 2022).

Some natural processes such as earthquakes, isostasy, and dissolution are responsible for many subsidence occurrences. Various factors may contribute to land subsidence during an earthquake. Due to the offsets along fault lines, substantial sections of land are susceptible to

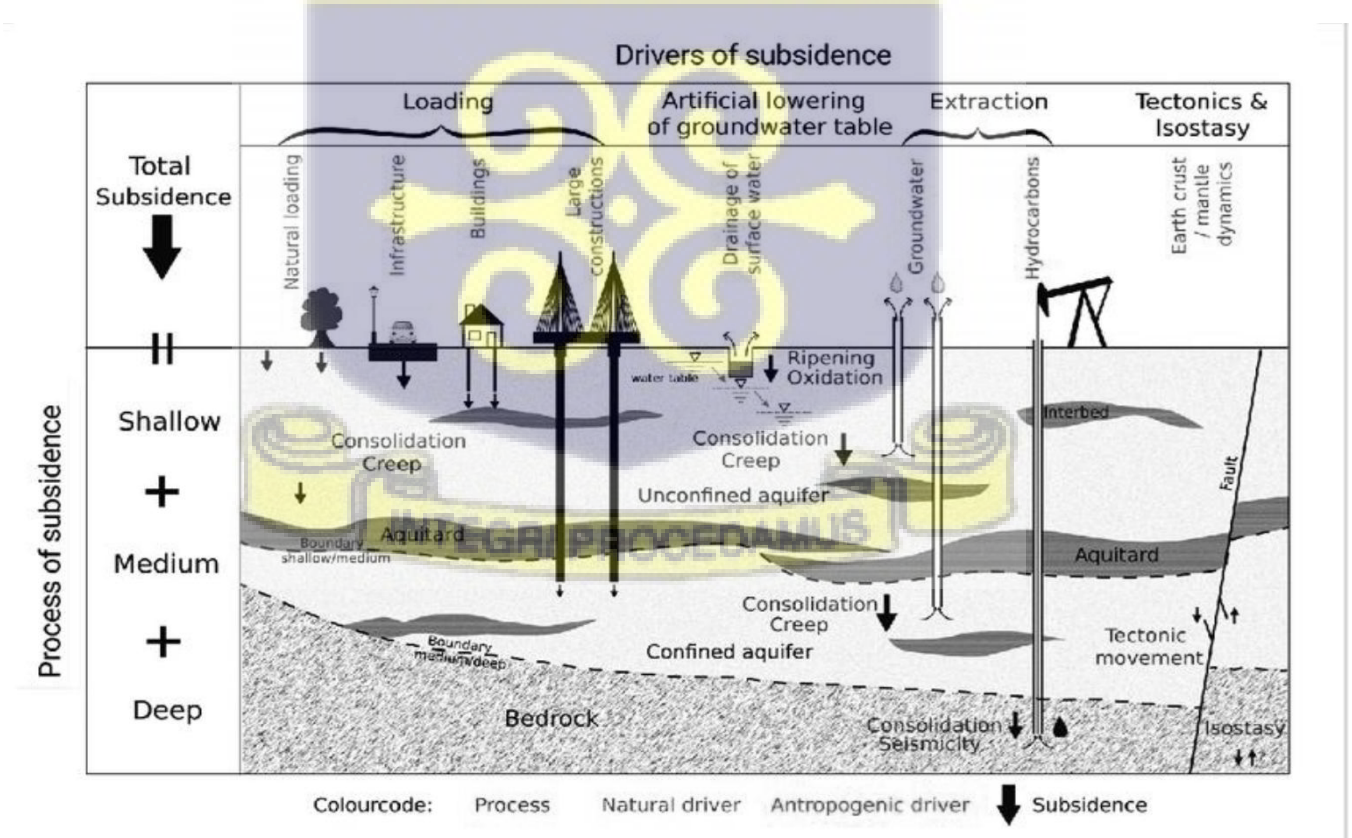
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abrupt subsidence during an earthquake. Another cause of land subsidence is the settling and compaction of loose sediments caused by seismic activity (Carreón-Freyre *et al*., 2021). For example, at shallower depths, groundwater flows that break down limestone to generate caves can also carve out caverns that enlarge until the roofs are unable to hold the strata above. In karst terrains, where the breakdown of limestone by fluid movement in the subsurface forms cavities, subsidence frequently leads to significant issues (Gutiérrez *et al*., 2014). Subsidence at the surface results from the overlaying rock and soil falling into the gap if the ceiling of a void collapses due to excessive weakness. Sinkholes that can be hundreds of metres deep can be created by this form of subsidence (Waltham, Bell and Culshaw, 2007). When weight is withdrawn from or added to the Earth's crust and upper mantle, a section rises or settles to maintain the balance between buoyancy forces that drive the lithosphere higher and gravity forces that drag it below. This process is referred to as isostasy (DiPietro, 2013). The Earth's crust sinks to make up for the mass that is added to it due to an activity such as deposition in order to maintain isostatic equilibrium (Allaby, 2013).

Current research indicates that subsidence is frequently caused by human activities. The rapid depletion of the water table caused by groundwater pumping and removal has severely affected the ecology in many places (Gambolati, Teatini and Ferronato, 2006). According to the United States Geological Survey, over 80% of documented subsidence in the US is caused by groundwater consumption (Gómez *et al*., 2021) . Recent research has found that approximately one-fifth of the world's population resides in regions in which subsidence caused by groundwater extraction poses a serious hazard. Ground failures occur in areas where the water table is severely lowered. These collapses result from the differential compression of incoherent sediments that occurs during underground water extraction, which causes earth cracks and contributes to coastal subsidence (Amin and Bankher, 1997). Petroleum extraction can also result in considerable subsidence (Monroe and Wicander, 1992). The earliest pressure

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at a natural gas site will progressively decrease over time if the natural gas is removed. The pressure supports the soil strata above the field. If the gas is removed, the compacted sediment caused by the overloaded pressure may cause land subsidence. Surface subsidence is a consequence of several subsurface mining techniques, particularly those that purposefully induce the mined space to collapse, such as pillar removal and ore deposit mining techniques that utilize caving. Except in cases of rapid pillar or near-surface tunnel collapse, mining-induced subsidence is foreseeable in degree, appearance, and scope (Herrera *et al.*, 2007). Subsidence caused by mining is almost always restricted to the region immediately above the mined area and a margin around the outside. The worst damage to the surrounding natural environment, structures, and infrastructure is typically caused by the affiliated surface constrictive and tensile strains, arch, tilts, and horizontal displacement rather than the vertical intensity of the subsidence itself, except for drainage. Mining-induced subsidence may be successfully managed provided all stakeholders work together.



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Figure 2.1 An overview of natural and anthropogenic drivers and processes of subsidence in a delta system (Woillez et al., 2021)

The impacts of subsidence ranges from a decrease in surface ascent, changes to canal gradients, a reduction in surface elevation, variations in chemical water-rock relations in subsided areas, changes to underground water quality parameters, changes to arth's surface morphology, coastal flooding, biodiversity loss, saline water intrusion, fresh water scarcity, changes to river watercourses, deteriorated quality of groundwater, increased riverine or coastal storm surges, distortion of surface water intrusion mechanisms, and a reduction in transportation ability all of which increase the likelihood of erosion (Wang, Zhang and Li, 2023).

Sinking coastal areas are affected by subsidence. The cumulative consequences of land subsidence and increased population pressure are the main causes of coastal zone vulnerability (Fuchs, 2010). Many of the largest and fastest-growing cities on the planet are situated near rivers and coasts, which makes them susceptible to natural catastrophes. The risk of loss in these locations increases as nations continue to invest resources, people, and facilities in these cities. Sinking areas face significant obstacles if they are to adequately prepare for today's changing environment (Re, 2014).

Another impact of ground subsidence is a reduction in underground water storage capacity of aquifers. The irrevocable compression of an aquifer system's is the primary source of subsidence. The ability of the aquifer system to hold water decreases because of this irrevocability. Once an aquifer's water level drops and becomes compressed, its pore space is permanently lost (Holzer and Galloway, 2007; Agarwal *et al.*, 2021).

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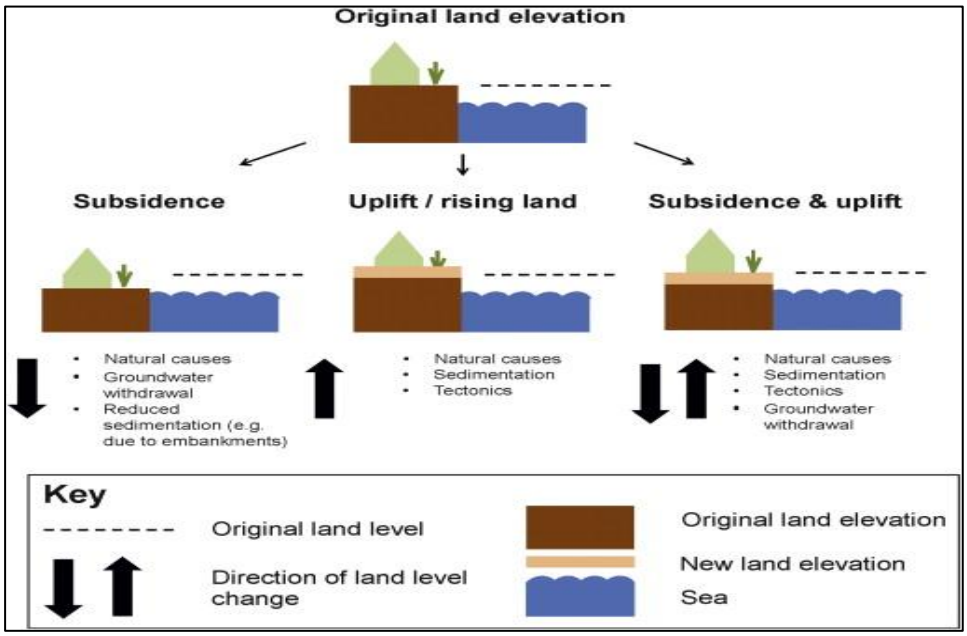


Figure 2.2 Possible illustrations of how land uplift and subsidence cause changes in land elevation over time (Brown and Nicholls, 2015).

2.3.1.4 Coastal vulnerability in the Ghanaian setting

The coastal zone of Ghana, extending over a 550km stretch, is not only the economic backbone of the nation, attributed to its strategic industrialization near vital ports and harbours but also a treasure trove of ecological and cultural riches. This area, characterized by diverse landscapes including beaches, cliffs, and lagoons, alongside its wildlife, cultural, and historical sites, holds immense potential for tourism development. The region has abundant natural resources such as salt, limestone, silica, and crude oil, which are vital for the country's economy (Giardino *et al*., 2018).

Communities across four key administrative regions - Greater Accra, Western, Central, and Volta - depend heavily on marine ecosystems for their livelihoods, particularly in fisheries. Notably, 80% of the nation's capture fish is from the marine environment, providing substantial employment through artisanal fishing in seas, lagoons, and estuaries (MoFA, 2016).

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Despite their economic and ecological significance, the coastal regions of Ghana face heightened vulnerability due to a mix of human activities, climate change, and sea-level rise, compounded by high population densities and urbanization rates. These pressures exacerbate environmental challenges, including erosion and flooding, further intensified by the sediment deficit from the Volta River following the construction of the Akosombo hydroelectric dam, particularly affecting areas such as the eastern coast of Keta (Anthony *et al*., 2016).

To address these challenges, hard engineering approaches such as groynes, sea walls, and revetments have been commonly deployed. However, these measures have shown limited effectiveness, often leading to increased coastal erosion downdrift, particularly towards the Ghana-Togo border (Angnuureng *et al*., 2013). The utilization of such structural protection methods underscores the need for critical reassessment of coastal management strategies, highlighting the necessity for holistic, climate-smart approaches informed by scientific and empirical evidence.

The state of Ghana's coastal and marine ecosystem health, as assessed by the Ocean Health Index (2015), revealed varying trends across key indicators from 2012 to 2015. These indicators, encompassing aspects such as artisanal fishing opportunities, coastal protection, biodiversity, and coastal livelihoods and economies, reflect the multifaceted impacts of both natural and anthropogenic pressures on coastal health. Notably, the trends in food provision and species decline underscore the urgent need for integrated strategies to mitigate vulnerability and enhance coastal resilience.

Recent research, such as the study by Brempong *et al*. (2023), provides a critical examination of coastal vulnerability in the Volta Delta, emphasizing the compounded effects of sea level rise (SLR) and land subsidence (LS). By leveraging satellite-based SAR-Interferometry for quantifying LS rates, this research highlights significant land movements, with displacement rates of up to 4 mm/year, attributed to factors including sediment compaction and aquifer

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exploitation. The projected implications of these findings for the future underscore the pressing need for adaptive management strategies, capable of addressing the intertwined challenges of environmental change and socioeconomic vulnerability along the coast of Ghana. The path forward requires a competent coastal vulnerability assessment combined with integrated coastal management practices that embrace scientific insights, local knowledge, and community participation to safeguard this vital region for future generations.

2.3.2 Coastal vulnerability assessment

Coastal vulnerability assessment (CVA) is an essential tool for understanding and managing the risks posed to coastal regions by natural and anthropogenic factors. These assessments are crucial for developing strategies to mitigate the effects of climate change, sea-level rise, extreme weather events, and human activities on coastal ecosystems and communities (Bukvic *et al*., 2020). CVA methodologies often integrate geographic, oceanographic, and socio-economic data to evaluate the resilience of coastal areas to potential hazards (Nicholls *et al*., 2008). Tools such as the Coastal Vulnerability Index (CVI) are commonly used to quantify vulnerability by combining variables such as shoreline erosion rates, sea-level change, and coastal geomorphology to produce a relative measure of risk (Loinenak, Hartoko and Muskananfola, 2015). Adopting multi-disciplinary approaches to understand and mitigate coastal vulnerability using various tools is an important task to achieve (Kesavan and Rajendran, 2023). There are seven types of coastal vulnerability assessments. This includes;

1. Physical Vulnerability Assessments

These assessments focus on the physical processes and natural hazards affecting coastal areas, such as erosion, sea-level rise and storms. Geographical and geological data are often utilized to model and predict physical impacts on coastlines (Kantamaneni *et al*., 2018).

2. Ecological Vulnerability Assessments

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Ecological CVAs evaluate the sensitivity, exposure, and adaptive capacity of coastal ecosystems such as mangroves, coral reefs, and seagrasses to environmental changes and human activities. These assessments aim to understand the impacts of pollution, habitat destruction, climate change, and invasive species on biodiversity and ecosystem services (Farhan and Lim, 2012; Myers *et al*., 2019).

3. Social Vulnerability Assessments

Social CVAs concentrate on the human dimensions of coastal vulnerability, examining how social, economic, and demographic factors influence communities' ability to anticipate, respond, and recover from coastal hazards. Factors such as population density, economic status, infrastructure, and emergency preparedness are analysed to assess community resilience (Ballesteros and Esteves, 2021).

4. Economic Vulnerability Assessments

These assessments evaluate the potential economic impacts of coastal hazards on local and regional economies. Economic CVAs consider the direct and indirect costs of damage to infrastructure, loss of property, impacts on tourism and fisheries, and broader implications for economic growth and sustainability (Lins-de-Barros, 2017).

5. Integrated Vulnerability Assessments

Integrated CVAs combine the physical, ecological, social, and economic perspectives to provide a comprehensive overview of coastal vulnerability. They employ multidisciplinary approaches to assess the complex interactions between natural systems and human societies, aiming to inform holistic management and policy decisions (Nicholls *et al*., 2008).

6. Climate Change Vulnerability Assessments

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Specifically focused on the impacts of climate change, these CVAs evaluate how rising sea levels, changing weather patterns, increased temperatures, and ocean acidification affect coastal zones. This type of assessment can also be termed indicator-based assessment. They are crucial for climate adaptation and mitigation planning (Bukvic *et al*., 2020).

7. Geographical Information Systems (GIS)-Based Assessments

GIS-based CVAs use spatial data and mapping technologies to visualize and analyse the geographic distribution of vulnerability factors. These assessments can overlay multiple layers of data, such as land use, topography, population distribution, and hazard projections, to identify areas of high vulnerability (Loinenak *et al*., 2015).

2.3.2.1 Evolution of Coastal Vulnerability Assessment from Traditional to Integrative Assessment

The evolution of coastal vulnerability assessment can be traced back to early efforts to understand and manage coastal hazards. Although the specifics may vary, the general trajectory of this evolution can be outlined as follows:

Early Approaches (Pre-20th century): Prior to the 20th century, coastal management primarily focused on short-term solutions to address specific hazards such as erosion and storm damage. However, these efforts are often reactive and localized and lack comprehensive assessment methods (Bevacqua, Yu and Zhang, 2018).

Emergence of Systematic Studies (20th Century): In the mid-20th century, there was a shift towards more systematic studies of coastal processes and hazards. This period saw the development of basic coastal geomorphology principles and the beginning of efforts to map coastal vulnerability using rudimentary techniques such as aerial photography and basic field surveys.

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Advancements in Technology and Data (late 20th century): The latter half of the 20th century witnessed significant advancements in technology, particularly in remote sensing, GIS, and computer modelling. These advancements have allowed for more detailed mapping of coastal features and better analysis of coastal dynamics, leading to more sophisticated vulnerability assessments (Smith and Jones, 2023).

Climate Change Awareness and Integration (late 20th century to Present): The late 20th and early 21st centuries brought increased awareness of climate change and its potential impacts on coastal areas. Coastal vulnerability assessments began by integrating climate change projections, considering factors such as sea-level rise, changing storm patterns, and temperature increases in assessing future risks.

Holistic and Multi-Hazard Approaches (21st century): In recent years, there has been a shift towards more holistic and multi-hazard approaches to coastal vulnerability assessment. Instead of focusing solely on individual hazards, assessments now consider the interconnected nature of the multiple threats facing coastal areas, leading to more comprehensive risk assessments and adaptation strategies (Bokhoree *et al*., 2023).

Community Engagement and Adaptive Management (21st century): Another notable trend in contemporary coastal vulnerability assessments is the increased emphasis on community engagement and adaptive management. Recognizing the importance of local knowledge and stakeholder involvement, assessments often incorporate participatory approaches to ensure that the assessment outcomes are relevant and actionable for local communities (Christie and White, 1997).

Current trends in coastal vulnerability assessment include the integration of advanced technologies, climate change considerations, holistic risk assessments, and stakeholder

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engagement, all of which aim to improve the resilience of coastal communities in the face of evolving coastal hazards (Linkov *et al*., 2006).

The incorporation of predictive modelling has become increasingly fundamental in the progression of coastal vulnerability assessment methodologies. These models play a critical role in simulating future scenarios and provide essential data for coastal management planning (Guerry *et al*., 2012; Iglesias *et al*, 2010). As such, they have become indispensable tools for coastal managers tasked with developing strategies to mitigate future risks and ensure sustainable management of coastal zones.

2.3.2.2 Using Models for Coastal Vulnerability Assessment

CVA models are computational or mathematical frameworks designed to simulate the interactions between coastal systems and the driving forces affecting them (Kumar *et al*., 2010). This is critical for several reasons. This includes:

- Predictive Capability: Models allow for the projection of future conditions based on various scenarios, including climate change, socio-economic developments, and land-use changes. This predictive capability is essential for planning and implementing adaptation strategies to mitigate adverse impacts (Ramieri *et al*., 2011).
- Understanding Complex Systems: Coastal zones are complex and dynamic systems that are influenced by a myriad of interrelated factors. Models help to understand these complexities by simulating the interactions between the physical, biological, and human components of coastal systems.
- Decision Support: Models serve as valuable decision-support tools by providing insights into the potential impacts of different management strategies and interventions (Christie and White, 1997). They help policymakers and stakeholders make informed choices regarding coastal management and conservation efforts.

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- Risk Assessment: Models play a crucial role in identifying areas at high risk of coastal hazards. They enable the assessment of the exposure, sensitivity, and adaptive capacity of coastal regions to various threats, aiding in the prioritization of risk reduction measures.

CVA models are in different forms and includes:

- Physical Models: These models simulate the physical processes affecting coastal zones, such as wave dynamics, sediment transport, erosion, and sea-level rise. Examples include hydrodynamic and shoreline change models.
- Ecological Models: Ecological models are used to assess the impacts of environmental changes and human activities on coastal ecosystems. They can model habitat suitability, species distribution, and the health of ecosystems such as coral reefs, mangroves, and salt marshes.
- Socio-Economic Models: These models evaluate the socio-economic aspects of coastal vulnerability, including the impacts on human communities, economic activities, and cultural values. They can simulate demographic changes, economic losses, and the effectiveness of adaptation measures (Lins-de-Barros, 2017).
- Integrated Assessment Models (IAMs): IAMs combine physical, ecological, and socio-economic elements to provide a holistic view of coastal vulnerability. These models are particularly valuable for integrated coastal zone management (ICZM), since they can assess the cumulative effects of multiple stressors on coastal systems (Nicholls *et al*., 2008).
- Geographic Information Systems (GIS)-Based Models: GIS-based models leverage spatial data to map and analyse the geographic distribution of vulnerability factors. They are effective in visualizing areas of high vulnerability and for planning purposes.

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The use of CVA models to accurately predict and assess flood risks is paramount for the development of effective mitigation and adaptation strategies for coastal communities. The advent of sophisticated flood models has greatly enhanced our capacity to simulate water dynamics under various environmental conditions, thereby improving our understanding of flood risks in coastal environments (Ramieri *et al*., 2011; Oloyede, Benson and Williams, 2021). These models serve as crucial tools in the planning and implementation of flood defence mechanisms, sustainable coastal development, and formulation of policy decisions aimed at reducing the impacts of flooding. Each model possesses unique features that make it suitable for specific types of analysis, ranging from precipitation flooding to coastal storm surges. This section explores several key models employed in flood risk assessment and, highlights their applications, advantages, and disadvantages. Some of these models include the following:

- HEC-RAS (Hydraulic Engineering Centre's River Analysis System)

Applications: It is predominantly used in the United States for coastal riverine flooding assessment and flood insurance mapping (Hu and Walton, 2008).

Advantages: Free access, capable of modelling complex flow regimes, and has a user-friendly interface.

Disadvantages: They are mainly one-dimensional, and may not capture the full complexity of flood dynamics in certain environments.

- LISFLOOD-FP (LISFLOOD Floodplain Model)

Applications: Implemented across Europe for flood hazard mapping, notably in the UK for detailed flood risk assessment (Bootsma, 2022).

Advantages: Efficient computational performance, suitable for large-scale inundation mapping.

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Disadvantages: Simplified hydrodynamics may not be ideal for detailed hydraulic analysis.

- MIKE 21

Applications: Globally utilized for coastal and marine modelling, including storm surge forecasting and flood risk analysis (Warren and Bach, 1992).

Advantages: Comprehensive modelling capabilities for a variety of coastal environments.

Disadvantages: Commercial software, potentially high costs, and significant computational resource requirements.

- Flood Modeller (Formerly ISIS)

Applications: It supports flood forecasting and management by the UK Environment Agency (Hamer and Mocke, 2002).

Advantages: It provides versatile modelling options, from 1D hydraulic calculations to complex 3D simulations.

Disadvantages: While offering a free version, more advanced features require paid licenses.

- Delft3D

Applications: It is employed globally for studying water flow, sediment transport, and morphology in coastal settings. It is notably used for sediment transport analysis in the Yangtze River, China, and for coastal erosion studies in the Netherlands.

Advantages: It is capable of simulating multi-dimensional hydrodynamic processes, is versatile for integrated environmental studies, and has an open-source community version (Ramieri *et al*., 2011).

Disadvantages: It has a complex software that requires a steep learning curve, computationally intensive for detailed models, and its full support and advanced features may necessitate a paid license.

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The selection of an appropriate flood model is crucial for effectively addressing the specific needs of a flood risk assessment project. Factors such as the geographical setting, scale of analysis, data availability, and specific objectives guide this choice. By leveraging the strengths of these models, coastal managers and researchers can enhance flood prediction accuracy, develop robust management strategies, and ultimately mitigate the adverse impacts of flooding on vulnerable communities (Tariq, Farooq and Van de Giesen, 2020).

Due to the complexities related to scarcity of data availability in coastal communities in Ghana, this study adopted the malstroem and bathtub models to estimate flooding at the study sites from different precipitation and SLR scenarios respectively. The Malstrom model, with its open-source accessibility and modest data requirements, is a particularly suitable tool for this endeavour. The advantages of this model align well with the research objectives, offering a pragmatic and effective approach to flood modelling in data-sparse regions.

2.4 Malstroem (Bluespots) Model

The Malstroem model offers a unique and accessible means for estimating flood areas based on precipitation data (Balstrøm and Crawford, 2018). It is categorized under physical models due to its ability to use changing climatic patterns (precipitation as a hydrological process) to critically predict flooding scenarios. Again, the model predicts flood events, which are physical occurrences that can directly impact the geomorphology and infrastructure of coastal areas (Pallathadka *et al.*, 2022). The output from the Blue Spot Model can inform physical vulnerability assessments by identifying areas at a high risk of flooding, thereby contributing to the development of mitigation and adaptation strategies. While primarily a physical model, the insights provided by the Blue Spot Model could also be integrated into broader, multidisciplinary assessments, such as Integrated Assessment Models (IAMs) or GIS-Based Models, to analyse the interplay between hydrological hazards and socio-economic or

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ecological factors in coastal zones (Kingsley, 2023). This integration can help formulate comprehensive plans for coastal management and disaster preparedness. Malstroem has several advantages. These include:

- Open-Source Accessibility; The open-source nature of the Malstrom model allows access to advanced flood modelling capabilities (Balstrøm and Crawford, 2018). This aspect is vital for research within regions such as Ghana, where financial constraints may limit the availability of commercial software. Open-source models facilitate a broader community of users to contribute to and benefit from, ongoing improvements and updates, ensuring that the tool remains relevant and adapted to users evolving needs.
- Reduced Data Requirements: Malstrom's ability to operate with less data is a critical advantage, especially in relation to Ghana's context, where comprehensive environmental datasets are often not readily available. This feature enables researchers to make meaningful predictions and analyses despite data limitations, thereby providing a significant leap forward in the ability to manage flood risks effectively.
- Flexibility and Adaptability: The flexible design of the Malstrom model allows easy adaptation to the specific hydrological and topographical conditions of Ghana. This adaptability ensures that the model can accurately simulate local flood dynamics, offering insights that are directly applicable to a region's unique environmental challenges (Pallathadka *et al*., 2022).
- Community Engagement and Capacity Building: The model's open-source framework fosters a collaborative environment that encourages community engagement and capacity building among local researchers, policymakers, and practitioners. This collaborative aspect is instrumental in developing locally tailored flood risk

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management strategies and promotes a sense of ownership and empowerment among stakeholders.

- Efficiency and Scalability: Malstrom's computational efficiency makes it well-suited for scaling up to larger geographic areas or down to detailed local studies. This scalability is particularly beneficial in a developing country context, where resources for extensive computational analysis may be limited. It allows for the assessment of flood risks across different scales, from localized flood events to broader, regional analyses (Balstrøm and Crawford, 2018).
- Support for Climate Change Adaptation: Finally, the Malstrom model is appropriately suited for integrating climate change projections (example precipitation), which is paramount for long-term planning and adaptation strategies in Ghana. By accommodating future climate scenarios, it provides a forward-looking perspective that is essential for developing resilient flood risk management and adaptation plans (Scientific, 2024).

Considering these compelling advantages, the Malstrom model stands out as an exceptionally fitting choice for flood modelling in Ghana. By leveraging the Malstrom model, this study not only navigates the challenges associated with data scarcity but also contributes to building local capacity for sustainable flood risk management in the face of climate change.

2.5 Bathtub Model

The bathtub model is widely used to simulate sea-level rise and its potential impact on coastal areas by assuming that areas lower than a certain elevation will be inundated if sea levels reach that height, much like water filling a bathtub. This model was implemented using ArcGIS and presented an innovative solution tailored to these challenges. The simplicity, accessibility, and adaptability of this method make it an invaluable asset against flood risks, especially in

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developing regions (Bootsma, 2022). When implemented in ArcGIS, the Bathtub Model leverages spatial data and mapping capabilities to visualize the geographic extent of sea-level rise impacts. It integrates elevation data, tide gauges, and other geographic information to delineate areas at risk of inundation, making it a powerful tool for spatial analysis and planning (Williams and Lück-Vogel, 2020). Some of the advantages of the bathtub model include the following:

- Simplicity and Accessibility: The bathtub model offers a straightforward and accessible method for estimating flood extents based on static water levels, without the need for complex hydrodynamic modelling. This simplicity is crucial in regions such as Ghana, where computational resources and specialized modelling expertise may be limited. ArcGIS provides a user-friendly platform for implementing the "bathtub" model, making sophisticated flood risk assessments feasible with more readily available topographical and hydrological data.
- Visualization and Mapping: Its implementation in ArcGIS provides clear visual representations of inundation areas, aiding in communication and planning efforts.
- Data Integration: It can incorporate various sources of spatial data, such as digital elevation models (DEMs), to improve the accuracy of inundation predictions. The use of ArcGIS for the "bathtub" model facilitates seamless integration with existing geographic information system (GIS) datasets, including land use, population density, and infrastructure maps. This integration enables a multi-dimensional analysis of flood impacts, informing more comprehensive flood risk management strategies that consider social, economic, and environmental factors.
- Scenario Analysis: The model allows for the examination of different sea-level rise scenarios, assisting policymakers in understanding potential future conditions and

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making informed decisions. The "bathtub" approach's compatibility with scenario analysis makes it a powerful tool for climate change adaptation planning. By simulating flood extents under various sea-level rise or precipitation scenarios, policymakers and planners can better anticipate future risks and develop adaptive strategies to safeguard vulnerable communities and critical infrastructure.

- Resource Efficiency: Compared with more complex hydrodynamic models, the Bathtub Model requires fewer computational resources, enabling quicker assessments. In Ghana, where detailed environmental and hydrological datasets are often lacking, this model allows for meaningful flood risk analysis using basic elevation data and predicted or observed water levels. This capacity significantly enhances our ability to understand and mitigate flood risk in underserved areas.
- Capacity Building and Stakeholder Engagement; Implementing the "bathtub" model within the widely accessible ArcGIS platform promotes capacity building among local researchers, planners, and decision-makers. The straightforward methodology of the approach enables stakeholders with varying levels of technical expertise to engage actively in the modelling process, fostering a collaborative approach to flood risk management and enhancing local resilience to flooding.

Despite its advantages, it is important to note that the Bathtub Model assumes static water levels and does not account for dynamic factors such as wave action, storm surges, or tidal variations, which can affect the accuracy of its predictions in certain contexts. Nevertheless, it remains a valuable tool for the initial assessments of sea-level rise impacts and for supporting coastal management and adaptation planning. By employing this method, this study not only addresses the challenge of limited hydrological data but also lays the groundwork for informed, inclusive, and proactive flood risk management strategies, bolstering Ghana's coastal community resilience in the face of evolving environmental threats.

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2.6 Uncertainties in Coastal Vulnerability Assessment Research

Uncertainty refers to the degree to which a value (such as the outcome of a measurement or model prediction) is unknown. In environmental and scientific research, uncertainty arises due to limitations in knowledge, data availability, methodological approaches, and inherent variability of natural systems (Stephens *et al*, 2017). It encompasses all aspects of the comprehension and interpretation of reality that are not fully known or completely predictable (Stephens, Bell and Lawrence, 2017). In coastal vulnerability assessments, it is important to recognize and quantify uncertainties. According to Stephens, Bell and Lawrence (2017), noting uncertainties is important for the following reasons:

- Improved Transparency: Acknowledging uncertainties enhances the transparency of research findings, making it easier for other researchers and stakeholders to understand the limits of knowledge and confidence in the results presented.
- Enhanced Decision Making: By providing a more nuanced understanding of risks and uncertainties, decision-makers can better evaluate options and strategies under conditions of uncertainty, leading to more robust and adaptable policies and practices.
- Continuous Learning: Identifying areas of uncertainty highlights gaps in current knowledge and understanding, guiding future research priorities and encouraging a continuous learning process.
- Risk Management: Understanding the range and sources of uncertainty helps in the development of risk management strategies that are more resilient to unexpected and unforeseen events.
- Scientific Integrity: Explicitly addressing uncertainties reinforces the credibility of scientific research, acknowledging the complexity of natural systems and the limitations of current methodologies.

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Due to the complexities of Coastal Vulnerability Assessment research, it is important to carefully consider the different types of uncertainties encountered in such studies. These types include:

- Epistemic (or Knowledge) Uncertainty: Stemming from a lack of knowledge about the system under study, this type of uncertainty can often be reduced through further research, data collection, and analysis (Swiler, Paez and Mayes, 2009).
- Aleatory (or Statistical) Uncertainty: Originating from the inherent variability or randomness in natural or human-made systems, aleatory uncertainty is irreducible and must be managed through probabilistic methods and risk analysis (Senge *et al*., 2014).
- Measurement Uncertainty: Associated with the limitations of measurement processes and instruments, reflecting the precision and accuracy of the data collected (Meyer, 2007).
- Parameter Uncertainty: Related to the uncertainty in the values of parameters used in models or analyses, due to variability in data or incomplete understanding of the system.
- Model Uncertainty: Arising from the simplifications and assumptions made during the modelling process, this includes uncertainties in the model structure, parameters, and input data

2.7 Adaptive Management Strategies in Response to Coastal Vulnerability: A Post-Assessment Perspective

In response to the vulnerabilities identified through assessments, coastal management strategies and adaptation practices are essential for safeguarding coastal zones against the adverse effects of climate change, sea-level rise, and natural disasters. These strategies encompass a blend of engineering, ecological, and policy-based solutions, tailored to address

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specific challenges faced by coastal communities and ecosystems. Some strategic frameworks for coastal management and adaptation include the following:

- Integrated Coastal Zone Management (ICZM): ICZM is a cornerstone strategy that promotes a holistic approach to sustainably manage coastal resources. It emphasizes the integration of environmental, economic, and social objectives, facilitating cooperation among various stakeholders (Nicholls *et al*., 2008).
- Ecosystem-based Adaptation (EbA): EbA leverages the conservation, restoration, and sustainable management of ecosystems to provide natural defences against coastal hazards, supporting both biodiversity and community resilience (Myers *et al*., 2019).
- Living Shorelines: This strategy incorporates natural elements, such as plants, sand, and rock to stabilize shorelines, protect against erosion and flooding, and enhance habitat areas for wildlife.

2.7.1 Adopted Strategies in Managing Coastal Erosion and Flooding in Ghana

Coastal erosion and flooding are significant issues along the Ghanaian coastline, with some areas losing up to 30 m annually. This erosion and flooding threaten coastal communities, key economic infrastructure, and valuable land (Boateng, Wiafe and Jayson-Quashigah, 2017). In response, Ghana has implemented several strategies to combat erosion and flooding to protect its coastlines. Some of these include:

- Sea Defence Projects: Ghana has undertaken sea defence projects along parts of its coastline (Jonah *et al*., 2016). These projects often involve the construction of groynes, sea walls, and revetments to reduce the wave energy and prevent further land loss.
- Mangrove Reforestation: Recognizing the importance of mangroves in stabilizing coastlines, reducing erosion, and supporting biodiversity, efforts have been made to restore mangrove forests in areas such as the Volta Estuary (Nunoo and Agyekumhene, 2022).

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- Improved Drainage Systems: Enhancing drainage systems in coastal cities to manage stormwater more effectively and reduce flood risks.
- Community-based Adaptation: Initiatives that involve local communities in planning and implementing flood resilience measures such as the construction of elevated safe havens.

Despite these efforts, Ghana's coastal management faces challenges including limited funding, the need for comprehensive planning and enforcement of regulations, and the impacts of climate change (Boateng *et al*., 2020). A more integrated approach that combines hard engineering solutions with ecosystem-based approaches and active community participation could offer a sustainable path. This would involve not only governmental agencies but also local communities, NGOs, and international partners working collaboratively. Enhanced monitoring and research into coastal dynamics, alongside public education on sustainable coastal practices, are vital for long-term success. As climate change continues to pose a significant threat to Ghana's coastlines, adaptive management strategies that can evolve under changing conditions are crucial (Kankam *et al*., 2013). Ghana's experience underscores the complexity of coastal management and the need for innovative and adaptable solutions that address both the current challenges and future uncertainties.

2.7.2 Consequences of Adopting Hard Engineering Structures in Managing Coastal Erosion and Flooding in Ghana.

Ghana's commitment to protecting coastal zones is evidenced by significant investments in hard engineering projects (Boye, 2015). These structures are engineered to withstand natural forces and provide immediate and durable solutions for coastal erosion and flooding. However, they are difficult to manage and can adversely affect coastal communities across the coastline. Examples of these projects include:

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- Ada Sea Defence Project: To protect the Ada Foah area from severe erosion, this project includes the construction of groynes, sea walls, and revetments that extend along the coast to reduce wave energy and prevent further erosion (Kusimi and Dika, 2012).
- Keta Sea Defence Project: One of the most significant engineering interventions, this project was implemented to protect the Keta municipality from Atlantic encroachment. It features groynes and sea walls that have substantially reduced erosion and safeguarded communities and agricultural land (Angnuureng *et al*., 2023; Boateng, 2009).
- Sakumono Sea Defence Project: This project protects Sakumono beach and surrounding areas by utilizing sea walls and groynes to prevent coastal erosion and protect properties (Angnuureng *et al*., 2023)
- Axim Sea Defence Project: This project protects Axim beach and surrounding areas by utilizing revetment to prevent coastal erosion and protect properties (Opoku, 2019).

These structures have some disadvantages, are prone to failures, and may require maintenance every 15 to 30 years.

Table 2.1 An outlines of the types of hard engineering structures, and their advantages, disadvantages and failures.

Structure	Advantages	Disadvantages	Type of Failure
Sea Walls	Protects against erosion, flooding, and storm surges. Shields coastal properties and infrastructure.	Expensive to construct and maintain. Can be visually intrusive. May increase erosion downdrift.	Undermining and collapse due to strong wave action. Overtopping in extreme weather conditions.

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Groynes	Enhances beach area by trapping sand, creating larger recreational spaces and natural barriers.	Can cause knock-on effects downdrift by interrupting sediment transport, leading to erosion. Maintenance can be costly.	Toe failure from scouring around the base. Outflanking when waves or currents bypass the structure. Settling or sinking on unstable substrates.
Revetments	Reduces wave energy impacting the shore. Offers a more natural appearance compared to sea walls.	May not provide complete protection in severe storms. Requires maintenance to manage scouring and erosion at their base.	Scouring in front of and underneath the structure leading to instability. Material displacement or damage by wave action.

2.7.3 Innovations; Nature Based Solutions (NbS)

Following the exploration of hard engineering structures and their specific roles in coastal protection, it is imperative to consider alternative and complementary strategies that align with the sustainable development and environmental conservation goals. This perspective leads us to the realm of nature-based solutions (NbS), which offer a harmonious blend of ecological preservation and socio-economic benefits, particularly vital for countries such as Ghana (Kooijman *et al.*, 2021). Some of the advantages of NbS include:

- Ecosystem and Biodiversity Enhancement: Ghana's diverse coastal ecosystems are critical for the survival of numerous species and for the provision of ecosystem services.

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NbS such as mangrove reforestation not only bolster biodiversity but also improve water quality and offer protection against storm surges (Xie, Bulkeley and Tozer, 2022).

- Climate Change Resilience: As Ghana faces the brunt of climate change impacts, including rising sea levels and increased storm intensity, NbS stand out as effective measures for adaptation (Chausson *et al.*, 2020). The natural barrier functions of restored ecosystems can mitigate the effects of coastal hazards and offer a buffer for communities against climate change.
- Cost-Effectiveness and Long-term Viability: In contrast to the often expensive and maintenance-intensive hard engineering approaches, NbS present a cost-effective alternative (Panduro *et al.*, 2021). These natural systems require less financial input over time and become more robust and effective as they mature, thereby creating sustainability in coastal management.

Integrating NbS not only addresses immediate protection needs but also ensures the long-term health and productivity of coastal ecosystems, thereby supporting economic development and community resilience. For Ghana, prioritizing NbS within its coastal management policies means committing to a sustainable and resilient future for its coastlines and communities. Collaborative efforts across governmental, non-governmental, and local community spheres are crucial for developing and implementing effective NbS (Chausson *et al.*, 2020). Moreover, public awareness and education on the benefits of NbS can cultivate a sense of stewardship and collective responsibility towards coastal conservation

2.8 Global Case Studies and Lessons Learnt

Globally, many advanced countries have developed strategies to facilitate coastal management and adaptation. Some countries were selected based on their successful adaptation techniques. These include:

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- The Netherlands (Dutch Mastery)

A Model of Engineering Excellence: The Netherlands exemplifies advanced engineering solutions for coastal management. The Delta Works project, featuring an intricate system of dams, locks, and storm surge barriers, protects against sea-level rise and flooding.

Another innovative approach is the Sand Motor, a massive sand nourishment project that naturally reinforces the coastline through tidal movements.

Lessons for Ghana: The Dutch model emphasizes the importance of comprehensive planning, stakeholder engagement, and integration of hard engineering with ecosystem-based approaches. Ghana could benefit from adopting a similar holistic perspective, particularly in combining robust infrastructure with natural defences such as mangrove restoration

- Bangladesh

Community-Based Adaptation: Facing frequent flooding, Bangladesh has implemented community-based adaptation strategies, including the construction of raised plinths for homes and community centres that serve as shelters during floods. The country's extensive mangrove reforestation efforts, particularly in Sundarbans, act as a natural barrier against storm surges and erosion.

Lessons for Ghana: Active involvement of local communities in planning and implementing adaptation strategies can enhance resilience. Adopting community-based approaches in Ghana can strengthen the local capacity to manage and respond to coastal hazards.

- United States

Living Shorelines: In various States, including Maryland and North Carolina, the concept of living shorelines is being employed to combat coastal erosion. These projects used natural materials to build barriers that absorb wave energy and provide habitats for marine life, demonstrating an effective blend of protection and ecological enhancement. Early warning systems have been adopted to warn citizens ahead of storm events (Chen and Lin, 2019).

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Lessons for Ghana: Investing in the development and application of predictive models could provide Ghana with valuable insights into future vulnerability and the effectiveness of various management strategies, enabling more informed decision-making.

- Vietnam

Mangrove Reforestation for Coastal Protection: Vietnam has successfully implemented large-scale mangrove reforestation projects that have proven effective in reducing coastal erosion and providing livelihood resources for local communities (Ngoc *et al*., 2020).

Lessons for Ghana: The Vietnamese experience underscores the value of mangrove ecosystems in coastal defence and economic development. Ghana can explore similar large-scale reforestation initiatives to enhance coastal resilience and support community livelihoods.

- Denmark

A Leader in Coastal Climate Adaptation: Denmark has implemented comprehensive coastal zone management strategies, focusing on climate adaptation and sustainable development. The country's approach includes using "Climate Change Adaptation Plans" to address sea-level rise and storm surges.

Lessons for Ghana: The Danish model highlights the importance of proactive planning and integration of climate change predictions into coastal management. Ghana could benefit from Denmark's emphasis on national frameworks that support local adaptation efforts, thus encouraging a similar forward-thinking approach in policy and planning.

- Japan

Advanced Technology in Disaster Risk Reduction: Japan's extensive experience with flooding has led to the development of some of the world's most advanced coastal defence mechanisms, including seawalls, floodgates, and tsunami evacuation buildings.

Lessons for Ghana: Japan's commitment to technological innovation and community-based disaster risk education offers important lessons for preparedness and resilience. Ghana could

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explore adopting advanced monitoring and early warning systems, coupled with community drills and education programs, to enhance coastal hazard preparedness.

- **China**

Large-Scale Coastal Reforestation and Wetland Restoration: China has undertaken significant efforts to restore and protect its coastal ecosystems, notably through the Mangrove Protection Project and Coastal Wetland Protection and Restoration Initiative.

Lessons for Ghana: China's experience underscores the effectiveness of large-scale ecosystem restoration for providing coastal protection and enhancing biodiversity. Ghana may consider similar extensive reforestation and wetland restoration projects to bolster natural defences and support ecological health.

The global landscape of coastal management presents a rich tapestry of strategies, successes, and lessons learned that can significantly inform and enhance Ghana's approach to its coastal challenges. Coastal managers in Ghana can enrich their coastal management strategies to make them more resilient, sustainable, and inclusive. By adopting a multifaceted approach that combines the best technology, community engagement, and integrated planning, Ghana can better protect its coastal zones, reduce vulnerability, and support the well-being of its coastal communities.

2.9 Past Coastal Zone Management Studies in Ghana, Research Gaps and Uncertainties

1. Remote sensing and predictive models to analyse shoreline changes along the central coast

The article, Detection, Measurement, and Prediction of Shoreline Recession in Accra, Ghana (Appeaning Addo *et al*., 2008) focuses on the application of various remote sensing techniques and predictive models to analyse shoreline changes in Accra, Ghana, over a historical period and to project future shoreline positions. Utilizing data from 1904, 1974, 1996, and 2002, this

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study employs linear regression analysis to calculate the historical rates of shoreline recession and employs a range of predictive models to forecast future shoreline dynamics under scenarios of accelerated sea-level rise.

Research Gaps:

- Extended Temporal and Spatial Analysis: While this study provides a comprehensive analysis up to 2002, ongoing and future research could benefit from extending this temporal frame to include more recent data, allowing for the examination of trends following the last data point and the effectiveness of any management interventions made since then.
- Integration with Coastal Management Practices: This study highlights the potential impacts of shoreline recession on coastal infrastructure and ecosystems but could be expanded to more explicitly examine the effectiveness of existing coastal management practices in Ghana, identifying areas where improvements or changes could be made.
- Socio-Economic Impacts: Further research could delve deeper into the socio-economic impacts of shoreline recession on local communities, including its effects on livelihoods, displacement, and economic activities. This would provide a more holistic understanding of the implications of coastal changes and inform integrated management strategies.
- Comparative Analysis with Other Regions: A comparative analysis of similar coastal environments in other parts of the world could offer insights into different management approaches and their outcomes, potentially identifying strategies that could be adapted and applied in the Accra region.

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Uncertainties:

- Climate Change Projections: This study acknowledges the uncertainty in the future rates of sea-level rise due to climate change. This uncertainty extends to the prediction of future shoreline positions, highlighting the need for adaptive management strategies that can be adjusted as new information becomes available.

- Human Intervention and Coastal Processes: Uncertainties regarding the cumulative impact of human activities (e.g., coastal development and sand mining) on shoreline dynamics underscore the need for integrated coastal zone management that considers both natural processes and human influences.

- Ecosystem Responses: The responses of coastal ecosystems to shoreline changes and human interventions remain uncertain. Further research could explore the resilience of coastal habitats and their roles in buffering erosion and flooding.

- Data Quality and Availability: The reliance on historical data sources of varying quality and detail introduces uncertainties into both the analysis of past trends and the projection of future changes. Improving the quality, resolution, and accessibility of coastal data would enhance the accuracy of shoreline change assessments.

By addressing these research gaps and uncertainties, future studies can contribute to the development of more effective, evidence-based coastal management strategies in Accra and similar contexts globally, thereby enhancing resilience to shoreline changes and sea-level rise.

2. RTK-GPS for shoreline morphodynamics

The article "Short-term shoreline evolution trend assessment: A case study in Glefe, Ghana" (Amoani *et al.*, 2012) focuses on the application of Real-time Kinematic Global Positioning System (RTK-GPS) technology and digitizing shorelines from orthophotos to detect, analyse,

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and quantify shoreline change in Glefe, a suburb of Accra, Ghana. Between 2005 and 2011, the study found an average shoreline change rate of 1.2 m/year ± 1.3 m/year, indicating significant erosion.

Research Gaps:

- Integration with Climate Models: The study calculated erosion rates but did not integrate these findings with climate models to forecast how changing climate conditions might further influence shoreline recession. This integration can provide a clearer picture of future risks and inform more effective adaptation strategies.
- Impact of Coastal Defences: While the study notes erosion, it does not deeply explore the effectiveness of existing coastal defences or propose specific interventions tailored to the observed trends. Research into the long-term sustainability of various coastal defence mechanisms in Glefe and similar environments would be valuable.
- Socio-economic Impacts: The study highlights the negative impacts of erosion on local industries and infrastructure but does not delve into detailed socio-economic analyses. Further research could quantify the economic costs of shoreline changes and assess the effectiveness of different management strategies for mitigating these impacts.
- Ecosystem Responses: There is a gap in the understanding of how coastal ecosystems, including mangroves and other vegetation, respond to and influence shoreline dynamics in Glefe. Studies on ecosystem health in relation to erosion and sedimentation processes could inform more integrated coastal zone management practices.

Uncertainties:

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- Future Erosion Trends: The study presents short-term erosion rates but acknowledges uncertainties regarding future shoreline dynamics, especially in the context of accelerated global climate change and its impact on sea levels and storm intensity.
- Effectiveness of Management Interventions: There is uncertainty regarding the most effective strategies for managing shoreline recession in Glefe, considering the complex interplay between natural dynamics and human interventions.
- Community Resilience and Adaptation: The capacity of the Glefe community to adapt to ongoing and future shoreline changes remains unclear. Research on community-based adaptation measures and their effectiveness in enhancing resilience can provide important insights.
- Data Limitations: The study relied on RTK-GPS and orthophoto data for a limited number of years. Uncertainties associated with extrapolating these results to predict long-term trends necessitate ongoing monitoring and data collection.

By addressing these research gaps and exploring the outlined uncertainties, future studies can provide a more comprehensive understanding of the shoreline evolution in Glefe and inform the development of more effective coastal management strategies to protect vulnerable communities and ecosystems.

3. Satellite imagery for shoreline change assessment

The article medium resolution satellite imagery as a tool for monitoring shoreline change: Case study of the Eastern coast of Ghana (Quashigah *et al*., 2013) explores the potential of medium resolution satellite imagery, specifically Landsat TM, Landsat ETM+, and ASTER, for monitoring shoreline changes over a 25-year period. This research is crucial for understanding the dynamics of coastal erosion and accretion in Ghana, particularly in the context of the Keta Sea Defence Project (KSDP) and its impact on the shoreline dynamics of the eastern coast.

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Research Gaps Identified:

- Temporal Granularity and Frequency: The study spanned 25 years with specific snapshots (1986, 1991, 2001, 2007, and 2011). While valuable, this leaves gaps in understanding annual or even more frequent shoreline changes that could offer insights into the immediate impacts of events or interventions.
- Comparative Analysis with High-Resolution Imagery: The study focused on medium-resolution imagery. A gap exists in comparing these findings with high-resolution satellite imagery or aerial photographs, which may reveal finer-scale coastal processes and changes not captured by medium resolution data.
- Impact of Anthropogenic Activities Beyond KSDP: While the Keta Sea Defence Project is analysed, a broader range of human activities along the coast (e.g., urbanization, industrial development, and small-scale local interventions) and their cumulative impact on shoreline dynamics could be further explored.
- Integration with Socio-Economic Data: The study primarily focused on physical changes to the shoreline. Integrating these findings with socio-economic data could highlight the impact of shoreline changes on local communities, including displacement, livelihood changes, and economic losses or gains.

Uncertainties Highlighted:

- Future Shoreline Dynamics Under Climate Change: The study acknowledges erosion and accretion trends but does not project these into future scenarios under different climate change models. Uncertainty in future sea-level rise and storm patterns makes it difficult to accurately predict long-term shoreline dynamics.

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- Efficacy of KSDP Over Long-Term: The study points out the "knock-on effects" of the KSDP but does not delve into long-term sustainability and the potential need for additional interventions. However, the effectiveness of such hard engineering projects in the context of ongoing climate change remains uncertain.

- Accuracy of Medium Resolution Imagery for Fine-Scale Coastal Processes: While the study successfully employed medium-resolution satellite imagery for shoreline monitoring, there is an inherent uncertainty in capturing detailed coastal processes such as small-scale erosion, sediment deposition patterns, and vegetation changes that influence shoreline stability.

- Generalization of Findings Across Different Coastal Contexts: The study focused on the eastern coast of Ghana, particularly around the Keta area. The generalizability of these findings to other coastal regions with different geomorphological and hydrological conditions remains uncertain.

This study contributes significantly to the understanding of shoreline dynamics in Ghana, offering a valuable foundation for future research aimed at filling the identified gaps and addressing uncertainties. Further studies incorporating higher temporal and spatial resolution data, broader anthropogenic factors, and integrated socio-economic impacts could provide a more comprehensive understanding of coastal zone management challenges and opportunities in Ghana and similar contexts globally.

4. Using Analysing Moving Boundaries Using R (AMBUR) for shoreline change analysis

Assessment of the Volta Delta Shoreline Change (Appeaning Addo, 2015) focused on evaluating erosion and accretion trends along the Volta Delta in Ghana. Utilizing satellite imagery data from 1986, 1991, 2001, 2004, and 2013, the shoreline was divided into four sections based on orientation and human interventions. This method enabled a detailed analysis

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of shoreline evolution by leveraging AMBUR software for statistical analysis. Over the 27-year period studied, the shoreline exhibited an average accretion rate of about 0.53 m/year, though rates varied significantly across different sections. This variance highlights the complex interplay between natural dynamics and human interventions, such as the Keta Sea Defence Project (KSDP), in shaping shoreline changes.

Research Gaps:

- Comprehensive Impact Assessment of Human Interventions: While the influence of KSDP on accretion and erosion is noted, there is a broader scope for assessing the cumulative impact of multiple human interventions across the entire delta, including urban development, industrial activities, and land use changes.
- Longitudinal Studies Post-2013: The study concludes in 2013. Ongoing longitudinal research post-2013 would offer insights into the sustained impacts of the KSDP and other interventions, as well as the evolution of natural processes influencing shoreline dynamics.
- Integrated Socio-Environmental Impact Studies: Research integrating environmental changes with socio-economic impacts on delta communities is limited. There is a need for holistic studies that consider how shoreline changes affect livelihoods, migration patterns, and socio-economic stability.
- Ecosystem Health and Biodiversity: The study largely focuses on physical shoreline changes without delving deeply into the implications for ecosystem health, biodiversity, and the functionality of associated coastal habitats.

Uncertainties:

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- Future Trajectories of Shoreline Change: Predicting future shoreline dynamics remains uncertain, particularly in the context of accelerating climate change impacts, sea-level rise, and potential shifts in sedimentation patterns.
- Efficacy of Existing and Future Coastal Management Strategies: There's uncertainty surrounding the long-term effectiveness of the KSDP and similar engineering projects, particularly considering the dynamic and interconnected nature of coastal ecosystems.
- Adaptation and Resilience of Coastal Communities: Uncertainties exist regarding the adaptive capacities of the communities within the Volta Delta. The resilience of these communities to ongoing and future shoreline changes, particularly in terms of adjusting livelihood strategies and infrastructure, remains unclear.

Addressing these gaps and uncertainties requires a multidisciplinary approach, encompassing geospatial analysis, environmental science, social sciences, and policy studies. Future research should aim to provide a more integrated understanding of the Volta Delta's shoreline dynamics, supporting the development of effective and sustainable coastal management strategies that safeguard both natural ecosystems and human communities.

5. Topographic maps and orthophoto to assess shorelines in the western region

The study, Spatio-temporal analyses of shoreline change in the Western Region of Ghana (Boye *et al.*, 2018) provides an in-depth examination of shoreline dynamics within Ghana's Western Region over both short-term (1974–2005) and long-term (1895–2005) periods. Utilizing topographic maps, orthophotos, and employing the High-Water Line (HWL) as an indicator for shoreline extraction, this research calculates shoreline change rates using Digital Shoreline Analysis System (DSAS) in ArcGIS. The results revealed a mean rate of change of -4.18 m/year across the study area, with significant variability between the Western Section (-5.4 m/year) and the Eastern Section (-2.36 m/year). The long-term analysis further underscores

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a general trend of recession, with an average change rate of −6.55 m/year, indicating pronounced erosion across timeframes and sections.

Research Gaps:

- In-depth Causal Analysis: While the study effectively quantified shoreline change, there is room for more detailed analyses regarding the specific drivers of these changes, including the relative impacts of natural processes and human activities.
- Ecosystem and Biodiversity Impacts: The study focused on physical changes to the shoreline but does not delve into how these changes affect coastal ecosystems and biodiversity. Future research should explore these relationships to inform conservation strategies.
- Socio-economic Consequences: Further studies could examine the socio-economic implications of shoreline changes in greater detail, evaluating the impact on local communities, industries, and infrastructure.
- Effectiveness of Mitigation and Adaptation Measures: The study suggests a need for mitigation efforts, but does not evaluate the effectiveness of existing or potential measures to combat shoreline recession.

Uncertainties:

- Future Shoreline Dynamics: The study showed some degree of shoreline recession but without uncertainties regarding future trends, especially under scenarios of accelerated climate change and sea-level rise.
- Resilience and Adaptation of Coastal Communities: The capacity of coastal communities to adapt to these changes remains uncertain, highlighting the need for research into resilient infrastructure and community-based adaptation strategies.

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- Comprehensive Coastal Management Approaches: Given the complex interplay of factors driving shoreline changes, uncertainties persist regarding the most effective integrated coastal management practices that can be implemented to address these issues sustainably.

By addressing these gaps and uncertainties, future research can provide a more comprehensive understanding of shoreline dynamics in the Western Region of Ghana and beyond, supporting the development of more effective, holistic coastal management strategies. This would entail a multidisciplinary approach, incorporating geospatial analysis, environmental science, social sciences, and policy studies, to ensure the sustainability of coastal zones and communities that depend on them.

6. UAV for coastal flood monitoring

Based on the article "Drone as a tool for coastal flood monitoring in the Volta Delta Ghana" by Appeaning Addo *et al*., 2018, the research presents a comprehensive study on the use of Unmanned Aerial Vehicles (UAVs) for monitoring coastal erosion and flooding in the Volta Delta, Ghana. The study specifically focuses on Fuvemeh, a flood-prone fishing community, demonstrating the impact of coastal processes on livelihoods and infrastructure between 2005 and 2017. The following outlines some identified research gaps and uncertainties based on the findings and discussions presented in the article.

Research Gaps:

- Temporal and Spatial Coverage of Drone Data: While the study showcased the application of drones for coastal monitoring over a specific period and area, there is a research gap in continuous, long-term monitoring and broader spatial coverage across the entire Volta Delta region. Continuous monitoring will provide a more

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comprehensive understanding of coastal dynamics and the effectiveness of adaptation strategies over time.

- Comparison with Other Remote Sensing Technologies: The article discusses the advantages of drone technology over traditional remote sensing and land-based methods but does not extensively compare the effectiveness, accuracy, and cost-benefit of drones against these other methods in the context of Ghana's coastal zones. Further comparative research could identify the most efficient methodologies for achieving different coastal management objectives.

- Socio-Economic Impact Assessment: The study briefly touches on the socio-economic impacts of coastal erosion and flooding, such as the destruction of livelihoods and displacement of communities. However, there is a need for in-depth socio-economic studies that quantify these impacts and evaluate the effectiveness of potential mitigation and adaptation strategies in improving community resilience.

- Integration of UAV Data with Climate Models: The research utilizes UAVs to monitor physical changes along the coast, but does not integrate these observations with climate models to predict future scenarios of coastal erosion and flooding under different climate change projections.

Uncertainties:

- Climate Change and Sea-Level Rise Projections: The study acknowledges the role of climate change in exacerbating coastal erosion and flooding but also highlights the uncertainty in future climate change and sea-level rise projections. This uncertainty challenges the ability to predict the extent and impact of coastal hazards accurately.

- Technological Limitations of UAVs: While drones offer numerous advantages for coastal monitoring, the article mentions operational challenges such as strong winds

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affecting flight stability and short flight times due to battery constraints. These technological limitations can affect the reliability and consistency of data collection.

- Community Adaptation and Resilience: The uncertainty surrounding the capacity and willingness of affected communities to adapt to changing coastal conditions and implement recommended adaptation strategies poses a significant challenge in reducing vulnerability and enhancing resilience.

Addressing these research gaps and uncertainties requires a multidisciplinary approach that incorporates advanced technologies, socio-economic research, and robust policy frameworks to develop sustainable coastal management and adaptation strategies in Ghana and similar contexts globally.

7. Shore-based Video Camera Systems for shoreline monitoring

The article (Application of Shore-Based Video and Unmanned Aerial Vehicles (Drones): Complementary Tools for Beach Studies) by Angnuureng et., 2020 presents an innovative approach to beach monitoring by combining shore-based video camera systems (VCS) with unmanned aerial vehicle (UAV) surveys. This combination offers a novel perspective on the quantification of beach topography and its evolution, particularly at Dzita beach in Ghana. The study spans a year of data collection, comparing high-frequency, 15-minute interval video data with monthly UAV observations to assess intertidal profile changes and validate the accuracy of video-derived topographic data against UAV surveys.

Research Gaps:

- Longitudinal and Seasonal Variation Analysis: The study covers a year, highlighting significant short-term erosion and accretion patterns. However, longer-term studies encompassing several years can provide insights into seasonal variations, long-term erosion trends, and the effectiveness of coastal management interventions over time.

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- Integration of Environmental and Anthropogenic Factors: While the study effectively captures physical changes, further research could integrate the impact of environmental factors (e.g., climate change and sea-level rise) and human activities (e.g., coastal development and sand mining) on shoreline dynamics.

- Socio-economic Impact Assessment: An analysis of the socio-economic impacts of shoreline changes on the local community, including the effect on livelihoods, property, and coastal infrastructure, would complement the technical findings of this study.

- Ecosystem Health Evaluation: Investigating the impact of shoreline changes on coastal ecosystems, biodiversity, and habitat health could provide a more comprehensive understanding of the ecological consequences of coastal dynamics.

Uncertainties:

- Future Shoreline Dynamics and Climate Change Impacts: The study acknowledges the dynamic nature of coastal environments but does not project future shoreline changes under different climate change scenarios, leaving uncertainties about long-term coastal resilience.

- Accuracy and Resolution of Measurement Techniques: While the study validates the accuracy of the VCS against UAV data, uncertainties remain regarding the optimal spatial and temporal resolutions required for various coastal management applications.

- Effectiveness of Coastal Management Strategies: The study provides valuable data for coastal management but does not explicitly evaluate the effectiveness of existing or potential coastal management strategies in mitigating erosion and enhancing resilience.

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- Adaptation Strategies for Coastal Communities: Uncertainties exist regarding the best practices for community adaptation to shoreline changes, including the development of sustainable livelihoods and construction of resilient coastal infrastructure.

Addressing these research gaps and exploring the outlined uncertainties could significantly enhance the understanding of coastal dynamics and inform more effective and sustainable coastal management and adaptation strategies in Ghana and similar contexts globally. This would require a multidisciplinary approach that incorporates advances in remote sensing technologies, ecological studies, socio-economic analyses, and participatory governance models.

8. Satellite, orthophotos and topographic maps for shoreline assessment

The article Assessment of the dynamics of the Volta River estuary shorelines in Ghana (Appeaning Addo *et al*., 2020) provides an in-depth analysis of shoreline changes along the Volta River estuary in Ghana using satellite imagery, orthophotos, and topographic maps over a period of 120 years. The study aims to assess the erosion and accretion trends along both the estuarine and marine coastlines of the Volta Delta, contributing to the understanding of coastal dynamics in the face of climate change impacts and anthropogenic activities. Some research gaps and uncertainties can be derived from this study:

Research Gaps:

- Long-term Impacts of Anthropogenic Activities: While the study focused on the effects of upstream water management, such as damming, there is a gap in detailed research on the cumulative long-term impacts of various anthropogenic activities including sand mining, urbanization, and changes in land use on estuarine shoreline dynamics.

- Ecological and Socio-economic Integration: The study primarily focused on physical changes to the shoreline. Further research integrating ecological impacts, such as

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changes in habitat quality and biodiversity, with socio-economic aspects such as the effect on fisheries and local livelihoods, would provide a more comprehensive understanding of the dynamics of the estuary.

- Effectiveness of Coastal Management Interventions: The article mentioned the construction of sea defence structures but lacked an in-depth evaluation of their effectiveness over time, including potential negative impacts such as downdrift erosion. Research on alternative or complementary soft engineering approaches and their long-term sustainability is valuable.

- Predictive Modelling and Future Scenarios: While historical changes are well-documented, there is a research gap in the predictive modelling of future shoreline dynamics under various climate change scenarios and potential adaptation strategies. This is crucial for effective long-term planning and disaster risk reduction.

Uncertainties:

- Future Climate Change Impacts: The study acknowledged the exacerbation of coastal erosion and flooding risks due to climate change but there remains uncertainty in predicting the extent and specific impacts of climate change on the dynamics of the Volta estuary.

- Adaptation and Resilience of Local Communities: Uncertainties exist regarding the capacity of local communities to adapt to changing shoreline dynamics, particularly in the absence of extensive monitoring and early warning systems.

- Long-Term Sediment Dynamics: Given the significant role of sediment supply reduction post-dam construction, there is uncertainty in how ongoing and future

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changes in sediment dynamics will affect shoreline stability and coastal erosion patterns.

- Policy and Governance Effectiveness: The evolving nature of policy and governance in coastal zone management introduces uncertainties into the implementation and effectiveness of strategies aimed at mitigating erosion and enhancing community resilience.

Addressing these research gaps and uncertainties requires multidisciplinary approaches that combine physical, ecological, and socio-economic studies, alongside the development of robust predictive models and effective governance frameworks. This will enhance our understanding of coastal dynamics, inform sustainable management practices, and improve the resilience of vulnerable communities along the Volta River estuary in Ghana.

9. UAVs for shoreline assessing morphodynamics

Based on the abstract of "Short-term seasonal changes of the Dzita beach of Ghana using geographic information system and photogrammetry (Brempong *et al.*, 2021) provides valuable insights into the dynamics of shoreline changes, sediment volume, and profile elevation at Dzita beach in Ghana, utilizing Unmanned Aerial Vehicles (UAVs) for data collection. The research covers observations from May 2018 to December 2019, revealing significant erosion and accretion patterns over different periods and suggesting the implementation of soft engineering approaches for shoreline protection. The following is an outline of the potential research gaps and uncertainties derived from the abstract:

Research Gaps:

- Comprehensive Analysis of Sediment Budget: The study focused on shoreline changes and profile elevation without an in-depth analysis of the sediment budget, including

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sources and sinks of sediment, which is crucial for understanding the complete sediment dynamics and planning effective beach nourishment projects.

- Long-term Shoreline Change Analysis: While the study provides valuable data on short-term seasonal changes, there is a gap in long-term analysis that could reveal decadal trends in shoreline dynamics, which are essential for comprehensive coastal zone management.

- Impact of Anthropogenic Activities: The study suggests preventing nearshore sand and gravel mining but does not delve into the quantification of the impact of these activities on shoreline changes. Further research should investigate the specific contributions of human activities to beach erosion and accretion.

- Integration with Nearshore Bathymetry: Although the need for further studies on nearshore bathymetry is mentioned, integrating the current findings with detailed bathymetric data could provide a more comprehensive understanding of the coastal processes influencing Dzita beach.

Uncertainties:

- Future Shoreline Dynamics under Climate Change: The study acknowledges the impact of global warming on sea-level rise and subsequent erosion but does not predict future shoreline dynamics under various climate change scenarios, leaving uncertainties about long-term coastal resilience.

- Effectiveness of Proposed Soft Engineering Measures: While beach nourishment is recommended, the study does not provide details on the design, implementation, and maintenance of such interventions, nor does it assess their long-term effectiveness in protecting the Dzita shoreline.

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- Seasonal Variability and Predictability: The observed cycle of erosion and accretion suggests a pattern of seasonal variability, however, the predictability of these patterns under changing climatic conditions remains uncertain.

- Compliance and Enforcement of Mining Restrictions: The recommendation to prevent nearshore sand and gravel mining raises questions about the feasibility of enforcement and compliance, given the economic incentives for such activities.

10. Future flooding of the Volta Delta as a result of SLR and Subsidence

The study, Future flooding of the Volta Delta caused by sea level rise and land subsidence by Brempong *et al*., 2023 addressed the growing impact of sea level rise (SLR) and land subsidence (LS) on the Volta Delta in Ghana, West Africa. The research utilized satellite-based SAR-Interferometry to quantify recent land subsidence rates and assesses the combined impact of SLR and LS on relative sea level rise (RSLR). This assessment is crucial for understanding the future vulnerability of the Volta Delta to flooding, salinization, and land loss, which could threaten the local populations, infrastructure, and economies.

Research Gaps:

- Local Ground-Based LS Investigations: The study mentions the need for local ground-based investigations to calibrate Persistent Scatter Interferometry (PS-InSAR) outcomes. This suggests a gap in direct, on-site measurements of land subsidence, which are critical for validating and enhancing the accuracy of remote sensing data.

- Comprehensive Assessment of LS Causes: While the study discusses various causes of LS, including natural sediment compaction, aquifer over-exploitation, and salt mining, there is a need for more detailed research into how these and other factors individually and collectively contribute to LS in the Volta Delta.

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- Socio-Economic and Ecological Impacts: The research identifies significant impacts of SLR and LS on the delta but calls for further investigation into the socio-economic and ecological consequences of these changes. This includes how flooding and salinization affect local livelihoods, agricultural productivity, and biodiversity.

- Effectiveness of Adaptation and Mitigation Strategies: There is a gap in the understanding and assessment of the effectiveness of current and potential adaptation and mitigation strategies to address the challenges posed by SLR and LS. This includes both structural measures (e.g., sea defences) and non-structural approaches (e.g., community resilience building).

Uncertainties:

- Future SLR and LS Rates: The study projects future SLR and LS impacts using IPCC scenarios, but there remains significant uncertainty regarding the exact rates of SLR and LS and their spatial distribution within the delta. This uncertainty complicates planning and implementation of effective coastal management strategies.

- Interactions Between SLR, LS, and Coastal Dynamics: The complex interplay between SLR, LS, and other coastal processes (e.g., sediment transport and erosion) is not fully understood, creating uncertainties regarding the future morphology and stability of the Volta Delta shoreline.

- Adaptation Capacity of Local Communities: The study highlights potential future challenges but does not extensively address the capacity of local communities and ecosystems to adapt to increasing flood risks and other impacts of SLR and LS.

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Addressing these research gaps and uncertainties is critical for developing a comprehensive understanding of the risks facing the Volta Delta, and for crafting effective strategies to protect vulnerable coastal zones and communities in Ghana and similar contexts globally.

11. Inundation assessment using InSAR

The study, the contribution of coastal land subsidence to potential sea-level rise impact in data-sparse settings: The case of Ghana's Volta delta (Avornyo *et al*., 2024) addresses the implications of land subsidence for sea-level rise impacts in the Volta Delta of Ghana.

Research Gaps:

- Local Ground-Based LS Investigations: The study identified the need for local ground-based investigations to calibrate Persistent Scatter Interferometry (PS-InSAR) outcomes, suggesting a gap in on-site measurements critical for enhancing remote sensing data accuracy.
- Comprehensive Assessment of LS Causes: While various causes of LS have been discussed, such as natural sediment compaction and aquifer over-exploitation, there is a need for more detailed research into their individual and collective contributions to LS in the Volta Delta.
- Socio-Economic and Ecological Impacts: The research identifies significant impacts of SLR and LS but calls for further investigation into their socio-economic and ecological consequences, particularly how flooding and salinization affect local livelihoods, agricultural productivity, and biodiversity.
- Effectiveness of Adaptation and Mitigation Strategies: There is a gap in understanding and assessing the effectiveness of current and potential adaptation and mitigation strategies, including both structural (e.g., sea defences) and non-structural (e.g., community resilience building) approaches.

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Uncertainties:

- Future SLR and LS Rates: Although future SLR and LS impacts are projected using IPCC scenarios, there's significant uncertainty regarding their exact rates and spatial distribution within the delta, complicating effective coastal management strategies.
- Interactions Between SLR, LS, and Coastal Dynamics: The complex interplay between SLR, LS, and other coastal processes such as sediment transport and erosion is not fully understood, creating uncertainties about the future morphology and stability of the Volta Delta shoreline.
- Adaptation Capacity of Local Communities: The study acknowledges potential future challenges but does not extensively address the capacity of local communities and ecosystems to adapt to increasing flood risks and other impacts of SLR and LS.

Addressing these research gaps and uncertainties is vital for developing a comprehensive understanding of the risks facing the Volta Delta and for devising effective strategies to protect vulnerable coastal zones and communities in Ghana and similar contexts globally.

The comprehensive exploration of coastal zone management practices, vulnerability assessments, modelling techniques, and strategic interventions, as evidenced by the extensive body of literature and detailed case studies examined, underscores the complexity and urgency of addressing coastal erosion, flooding, and land loss.

This literature review sets the stage for the subsequent chapters, which delve into the objectives and methodologies employed, present the findings of the original research, and discuss their implications within the broader context of coastal zone management. Building upon the foundational knowledge outlined in this review, this thesis aimed to provide valuable insights into the ongoing discourse on coastal resilience and management strategies.

INTEGRI PROCEDAMUS

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CHAPTER THREE

3.0 ESTIMATING SHORT-TERM AND MID-TERM SHORELINE EVOLUTION DYNAMICS

3.1 Introduction

The study of shoreline evolution dynamics play a crucial role in understanding the changes occurring along coastal areas and their impact on various ecosystems (Splinter & Coco, 2021). Shoreline migration, a dynamic interplay between natural forces and human activities, intricately shapes coastal landscapes. Beaches undergo constant changes occurring on both short- and long-term timescales (Loureiro & Ferreira, 2020).

Shoreline retreat, marked by gradual inland movement, results from a combination of factors. Erosion, intensified by wave action, storm surges, and rising sea levels. Utilizing advanced monitoring techniques such as satellite imagery and coastal modelling, scientists quantify retreat rates and predict future changes. Conversely, shoreline progression signifies the seaward advancement of coastal boundaries influenced by natural processes, including sedimentation, accretion, and deposition, which contribute to the expansion of coastal land (Weitzner, 2015). Mangroves, barrier islands, and sedimentary systems act as crucial elements that act as buffer against erosive forces. Striking the balance between these processes and human interventions is vital for sustainable coastal management.

Human activities, such as urbanization, infrastructure development, and sand mining, can significantly alter natural shoreline dynamics (Ankrah *et al*., 2023). Unplanned interventions may exacerbate retreat or disrupt progression, emphasizing the need for integrated coastal zone management (Tellier *et al*., 2009).

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In Ghana, the central and eastern coastal region, faces significant challenges in the form of coastal erosion and flooding, as highlighted in studies by Addo *et al*. (2018), Alves *et al*. (2020), Angnuureng *et al*. (2022) and Jonah *et al*. (2016). These challenges arise from increased pressures on coastal regions due to rapid population growth and climate change effects such as rising sea levels and more frequent storm events. Factors such as land subsidence, enhanced wave action, reduced sediment supply, and sand extraction also significantly contribute to these issues. Among these factors, rising sea levels and wave dynamics have been identified as the main drivers of modern shoreline change (Bird, 2008). As sea levels rise, it is expected that shorelines (especially sandy ones) will recede to maintain an equilibrium beach profile (Sanford and Gao, 2018). Additionally, wave heights are expected to increase in the face of a changing climate and sea level rise (Sterl and Caires, 2005; Woolf, 2002). To mitigate these effects, numerous hard engineering defense structures have been implemented along the central and eastern coasts. However, this inadvertently led to increased erosion in other areas, particularly on the downdrift side.

To formulate effective coping strategies for the coast, it is imperative for vulnerability studies to comprehensively analyse the extent of erosion and flooding in the region before proposing alternative methods. Unfortunately, due to the scarcity of high-resolution data, high processing powered computers and effective monitoring of this aspect are lacking across the central and eastern coasts.

The objective of this chapter is to investigate shoreline morphodynamics at the study sites, utilizing Linear Regression Rate calculations derived from digitized orthomosiac obtained through a short-term drone survey and the use of historical satellite images to estimate the erosion rate along the study sites.

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3.2 Study Sites

This study focuses on two distinct sites along the coasts of Ghana, identified as Site A (Mumford) and Site B (Atiteti), located in the central and eastern regions respectively. Both sites are positioned below the 5-meter contour line extending from the coast, offering a valuable perspective on coastal dynamics.

Site A: Mumford, situated in the Gomoa West District of the Central Region of Ghana, is characterized by sandy beaches that face low to moderate wave action. The coordinates for Mumford are approximately 05°15'653" N and 000°45'373" W. The coastline features a mix of geomorphological structures including sandy bars and spits that form natural barriers around coastal lagoons. The local geology comprises Precambrian to Mesozoic igneous, sedimentary, and metamorphic rocks, alongside unconsolidated Quaternary sediments exposed to wave action predominantly from the south-southwest. Historical data suggest erosion rates ranging from -0.5 to -3.4 meters per year (Boateng, 2012).

Site B: In this study, the neighbouring coastal villages of Fuvemeh, Agorkedzi and Atiteti are collectively analysed under the designation 'Atiteti' due to their shared geographical and environmental characteristics. These small, closely situated communities are predominantly inhabited by the same ethnic groups, emphasizing uniformity in demographic and socio-economic conditions across the area. This grouping facilitates a unified approach to address the significant challenges of erosion and tidal flooding that these communities face. Atiteti is located in the Anlo District of the Volta Region with coordinates of 5°46'18.61"N and 0°43'36.24"E. Boateng (2012) highlighted ongoing erosion activities, with the beach exhibiting dynamics typical of a highly erosive environment. Historically, areas around Atiteti have been noted as erosion hotspots, with some of the highest recorded rates reaching up to -40 meters per year. Chronic erosion has led to significant property and livelihood losses, prompting major

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sea defense projects in this area such as the Dzita-Atorkor, Keta and Ada Sea defense. Although these interventions have stabilized parts of the shoreline, erosion remains a pressing concern, particularly downdrift of protected areas (Angnuureng *et al*., 2013; Appeaning Addo, 2015; Jayson-Quashigah *et al*., 2013).

Both sites, extend approximately 4 km alongshore and 300 m cross-shore and serve as exemplary models for studying coastal erosion. The cross-shore analysis was confined to the landward edge of the beach to maintain a focus on the immediate impact zone.

The selection of Mumford and Atiteti for this study was strategically based on the observed long-term erosion trends and their respective coastal dynamics, as documented in various shoreline analyses.

3.2.1 Justification for Site Selection

The selection of Mumford and Atiteti for a comprehensive shoreline change and flooding analysis is strategic and well-founded based on several key criteria. These criteria encompass geographical, socio-economic, and environmental factors that underscore the significance of conducting studies in these areas.

Mumford: A Low-Lying, Understudied Coastal Area

1. *Geographical Vulnerability:*
    - Elevation and Topography: Mumford is characterized by its low-lying terrain, making it inherently susceptible to the impacts of sea-level rise and coastal erosion. This geographical vulnerability necessitates focused study to understand and mitigate the potential risks.
2. *Lack of Existing Research:*

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- Research Gap: There is notable scarcity of scientific studies and data on shoreline dynamics and flooding in Mumford. By selecting this site, the study aims to fill a critical knowledge gap and provide new insights and data that can inform local and national coastal management strategies.

3. *Community Impact*:
   - Socio-Economic Considerations: The local community's dependence on coastal resources for livelihoods, such as fishing and tourism, underscores the importance of understanding shoreline changes. Protecting these resources from erosion and flooding is crucial to the socio-economic stability of the area.
   - Landing site Project: In 2018, the government selected Mumford as 1 of 10 fishing communities to be awarded a new landing site project which was about $24 million. Post landing site construction, there appears to be a knock off effect downdrift. Therefore, it will be interesting to examine the effects of the new landing site.

Atiteti: A Flooding and Subsiding Delta

1. *Flood Risk and Subsidence*:
   - Deltaic Environment: Atiteti is situated within a deltaic region that is prone to both natural flooding and subsidence. The unique combination of these factors makes it an ideal site for studying the combined effects of shoreline change and flood risk.
   - Hydrological Dynamics: Atiteti is located between the Volta River and the sea. This makes it dynamic. Therefore, understanding the hydrological dynamics of Atiteti, including flooding and subsidence trends is essential for predicting future changes and implementing effective mitigation measures.

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2. *Previous Flooding Events*:
    - Historical Flood Data: Atiteti has a history of flooding events, making it a critical area for investigating the patterns, causes, and impacts of flooding. This historical context provides a valuable foundation for assessing the current vulnerabilities and future risks.
3. *Ecological and Environmental Significance:*
    - Biodiversity and Habitats: The deltaic region around Atiteti is rich in biodiversity, with numerous habitats sensitive to changes in water levels and sedimentation. Studying this area will help ´to understand the ecological impacts of shoreline changes and flooding.

Comparative Analysis:

By selecting Mumford and Atiteti, this study can perform a comparative analysis between a low-lying coastal area and a subsiding delta. This contrast will enrich our understanding of how different coastal environments respond to similar climatic and oceanographic forces.

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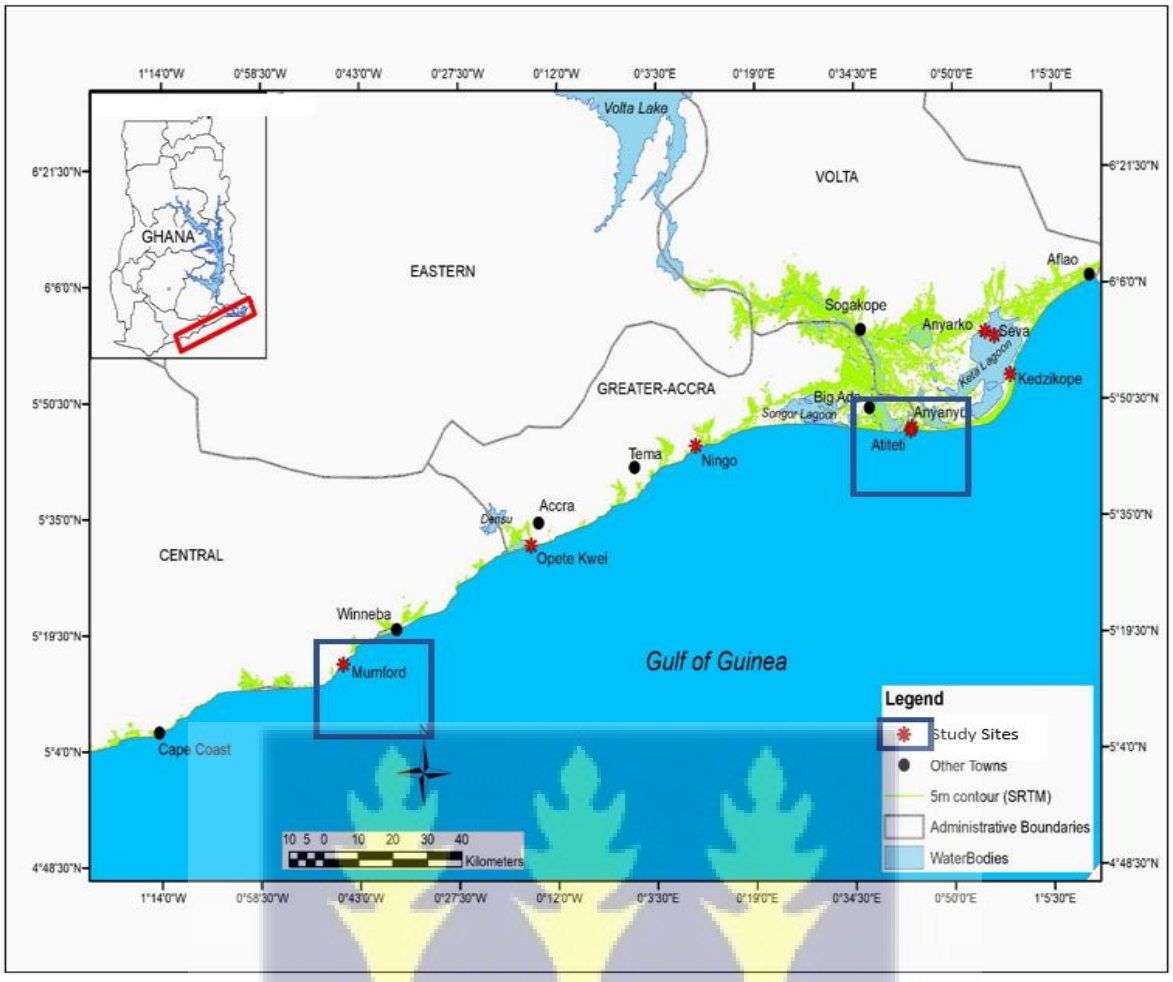


Figure 3.1: A map showing the two study sites along the central and eastern coast of Ghana.

3.3 Methods

3.3.1 Data collection and pre-processing

The research methodology for this study incorporated an extensive series of drone surveys, along with an analysis of historical satellite imagery sourced from the Digital Globe Foundation and Planetscope.

Between January 2021 and December 2023, a total of 36 drone surveys were conducted at each study site, using a DJI Phantom 4 Professional drone equipped with a 4K camera. This high-

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resolution imaging capability is crucial for capturing the detailed coastal features and erosion patterns over a specified period.

Ground Control Points (GCPs); The initial phase of the drone monitoring campaign included the critical setup of Ground Control Points (GCPs), which were coordinated to align with the Ghana Metre grid, following methodologies akin to those employed by the Ghana Survey Department (Ofori-Boadu, 2006). Each site was equipped with eight robust GCPs constructed from iron rods and PVC pipes, which were filled with concrete, buried at ground level, and clearly marked for visibility and durability (Figure3.2). This setup surpasses the minimum requirements for effective photogrammetry, which necessitates at least four to five symmetrically distributed points for accurate geo-referencing (Mířijovský and Langhammer, 2015; Wolf *et al*., 2000). By employing eight GCPs at each site, this study ensured a highly reliable framework for the subsequent spatial analysis of drone imagery.

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Figure 3.2: An image showing the establishment of the Ground Control Points (GCPs)

Employing a static Differential GPS (D-GPS) approach, with reference to well-established national coordinated control points, each pillar underwent observation sessions lasting an average of 30 min. The primary objective was to minimize the Root Mean Square Error (RMSE) of the base minimum. Subsequently, the data underwent post-processing using the established algorithms within Topcon post-processing software. The resulting RMSE values demonstrated accuracies of less than 0.04 meters for both vertical and horizontal dimensions.

The flight paths were pre-planned using a drone deployment platform (Adjidjonu & Burgett, 2017). The height was set at 80 m above ground level to allow for wider coverage (approximately 140 m swath width) of the beach while maintaining a considerably high ground sampling distance of 5 cm (0.05 m). A frontal overlap of 80% and a side overlap of 70% were defined to improve stereoscopy and 3D reconstruction. The flight times were designed to

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coincide with low tides as much as possible using available tide forecast (Tide-Forecast, Site A and Site B https://www.tidetime.org/africa/ghana) and to cover periods of low and high wave heights. Table 3. 1 shows the details of the surveys conducted at the various sites. Depending on the wind conditions, each flight lasted between 25 min and 40 min. GCP markers (printed on A0 flexible white materials) were placed on the permanent GCPs before every flight to allow easy identification during image processing.

Table 3.1: A table showing flight survey dates for the study sites

Site	Site Description	Flight Dates	Total Flight
A	Mumford, steadily eroding beach	January 2021 – December 2023	36
B	Atiteti, a very dynamic beach with high rates of erosion	January 2021 – December 2023	36

3.3.2 Data Processing (Geospatial Analysis of Coastal Terrain Using Agisoft Metashape and Drone Imagery)

On an average, approximately 500 images were captured during each flight. The images were manually filtered to exclude instances of blurriness or overexposure, as well as images featuring the drone's landing gear due to strong wind conditions. This reduced the error in the final point cloud. A three-dimensional scene reconstruction was executed through the application of the Structure from Motion (SfM) technique and Multi-View Stereo (MVS) algorithms (Smith *et al*., 2015; Snavely, 2011) implemented in the Agisoft Metashape software (Agisoft, 2018).

The selection of Agisoft Metashape as the primary software for drone image processing was based on the findings of Sona *et al*. (2014), who noted that the algorithms used by Agisoft

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products provided more reliable outcomes than other tested software solutions. This software suite facilitates a comprehensive processing workflow that includes the following steps:

1. Image Alignment: This initial step involves detecting and matching key features across multiple images to establish a coherent structural framework within the dataset (Mancini *et al*., 2013).
2. Dense Stereo Reconstruction: Following alignment, the software performs pixel-based dense stereo reconstruction using the aligned images in conjunction with the established Ground Control Points (GCPs). This process generates a detailed point cloud that captures intricate topographical features of the coastal landscape.
3. Orthophoto and DEM Construction: The aligned and reconstructed data were then used to create high-resolution, georeferenced orthomosiac—2D visual representations of the terrain. Concurrently, Digital Elevation Models (DEMs) are generated that depict elevation variations. The creation of DEMs involves a critical filtering stage where non-ground elements such as buildings and fishing boats are identified and excluded to minimize exaggerations in topographic height representations.

This methodical approach ensures that the resulting orthophotos and DEMs provide a comprehensive and accurate depiction of the coastal environment, which is essential for analysing erosion patterns and assessing coastal dynamics.

3.3.3 Shoreline extraction

Diverse proxies have been employed to determine shoreline position. This includes features such as the vegetation line, low water mark, and high-water mark. (Fletcher *et al*., 2012; Romine *et al*., 2016). The high-water mark (HWM), commonly used for shoreline assessment, is recognized by visually identifying the noticeable change in tone caused by the highest point reached during the previous high tide. This mark can be easily identified on orthophotos and

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satellite imagery and has been used in studies related to Ghana and the Volta Delta (Angnuureng *et al*., 2013; Appeaning Addo *et al*., 2008; Appeaning Addo, 2015; Boateng, 2012; Jayson-Quashigah *et al*., 2013) and was, therefore, adopted for this study. The high-resolution images obtained in this study clearly show the HWM. The HMW line was digitized in an ArcGIS environment by the same person and at a consistent scale from each drone imagery. A total of 36 shoreline positions were extracted from each site

3.3.4 Shoreline Change Analysis

The extracted shorelines were combined in a GIS environment (ArcGIS 10.7.1) to create one shapefile. This shapefile was assigned attributes such as date and accuracy. The Single Transect (ST) method is necessary to compute the rates of shoreline change. The estimation of historical changes was performed in comparison with a manually delineated offshore baseline position. To adequately capture the changes along the beach, perpendicular transects were cast at 10m intervals along the shore (Fletcher *et al*., 2012). Various statistical methods have been developed to estimate the rate of change in shorelines such as endpoint rate (EPR), linear regression rate (LRR), weighted linear regression (WLR) and jack-knifing (JK) (Dolan *et al*., 1991; Genz *et al*., 2007). Linear regression has been extensively used (Appeaning Addo *et al*., 2008; Hapke *et al*., 2006; Kuleli, 2010). Calculating the 'best fit' line using the least-squares method is how the shoreline data points for each transect are analysed. This approach is statistically robust and allows the utilization of other statistical methods to determine the quality of the fitted line and estimate the variance of the data. Therefore, the LRR method was selected to calculate the rates of change in this study. The rate of change analysis was performed using Digital Shoreline Analysis Software (DSAS v5). The tool can be customized to perform various tasks and analyses such as linear regression forecasting. It can calculate the raw changes in the End Point Rate, Linear Regression Rate and Weighted Linear Regression Rate for each transect.

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3.3.5 Error Estimation from Shoreline Change

This study identified and quantified four primary sources of error that impact the accuracy of shoreline positioning. These sources include the ground sampling distance (Ep), geo-referencing error (Eg) (derived from the average RMSE of geo-referencing), digitizing error (Ed) (estimated at 1.5 times the pixel size), and tidal error (Et) (based on the tidal range for the area) (Ford, 2013; Li *et al*., 2001). The overall positional error (Er) of each shoreline was calculated using the following formula:

$$E_r\sqrt{E_p^2 + E_g^2 + E_d^2 + E_t^2} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In the analysis, the following errors were recorded: a ground sampling error of 0.07 m, a geo-referencing error of 0.1 m, a digitizing error of 0.15 m, and a tidal measurement error of 1 m across all images. Consequently, the total estimated error for each shoreline position was calculated to be 1.02 m. To calculate the annualized error for each site, Equation 3.4 was employed, taking into consideration the uncertainty in the rate of change along each transect (Fletcher *et al*., 2012; Hapke *et al*., 2006; Moore, 2000). The annualized rates were found to be 1.5 m/yr for Mumford and 1.25 m/yr for Fuvemeh, respectively.

$$E_x = \frac{\sqrt{E_a^2 + E_b^2 + \cdots E_z^2}}{\mathrm{T}} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where E_a, E_b……. Ez, are the individual shoreline positional error and T is the time that has elapsed (Appeaning Addo *et al*., 2008; Jayson-Quashigah *et al*., 2013)

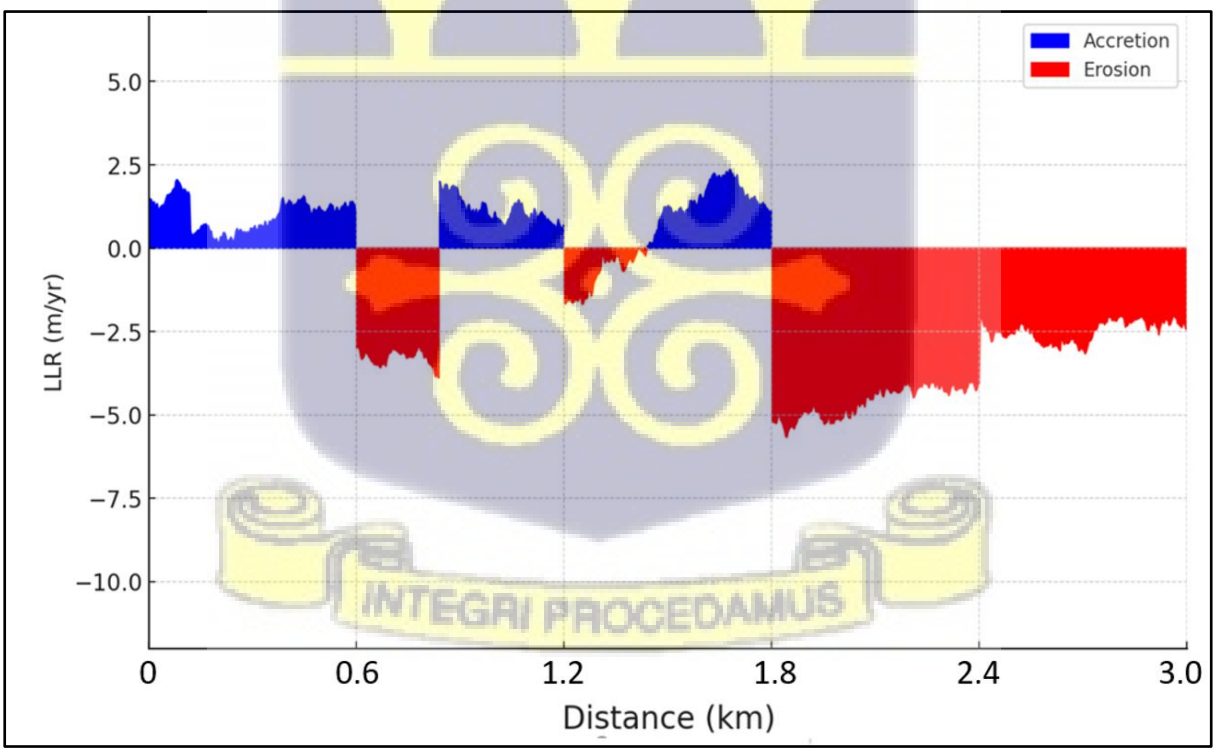
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3.4 Results

3.4.1 Morphological changes at Mumford (Site A)

The beach at Mumford, spanning approximately 133,641 m², is narrower than at Atiteti. Shoreline change analysis from January 2021 to December 2023, conducted using the DSAS method and drone surveys, revealed erosion rates ranging from -0.1 m/yr to -5.5 m/yr and accretion rates from 0.1 m/yr to 2.4 m/yr. The mean erosion rate was -2.3 ± 1.23 m/yr, while the accretion rate averaged 1.2 ± 1.23 m/yr. The highest rates of erosion were observed on the downdrift side of the landing site and near the sand mining area on the western side of the coast. These patterns indicate that specific human activities, such as the construction of the landing site (which involved the use of boulders to alter the coast and sand mining), significantly influence shoreline dynamics at Mumford.



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Figure 3.3 Shoreline Linear Regression Rate (LRR) of change at Mumford from January 2021 to December 2023.

Further analysis shows that approximately 46.67% of the coast which translates into approximately 62,370 m^2 across shore, is accreting and approximately 53.33% which is approximately 71,271 m^2 is eroding.

Table 3.2: Summary of mean shoreline erosion rates for Mumford (from 1974 to 2023)

PERIOD	MEAN EROSION RATE (M/YR)
1974 - 2002	-1.6
2005 - 2010	-1.9
2016 - 2018	-2.0
2021 - 2023	-2.3

3.4.2 Morphological changes at Atiteti (Site B)

Lateral shoreline change analysis at Atiteti, conducted from monthly drone surveys, reveals short-term erosion rates (covering the period from January 2021 to December 2023) ranging from -2.5 m/yr to -44 m/yr, with a mean of -25 ± 1.25 m/yr. This significant erosion has led to the destruction of over 40 houses and critical public facilities, including toilets. The beach at Atiteti, covering an area of approximately 66,043 m^2, remains relatively wide across the shore compared with Mumford. A mid-term analysis (from 1974 to 2023) showed a consistent erosion rate of -13 m/yr, indicating ongoing challenges in coastal management.

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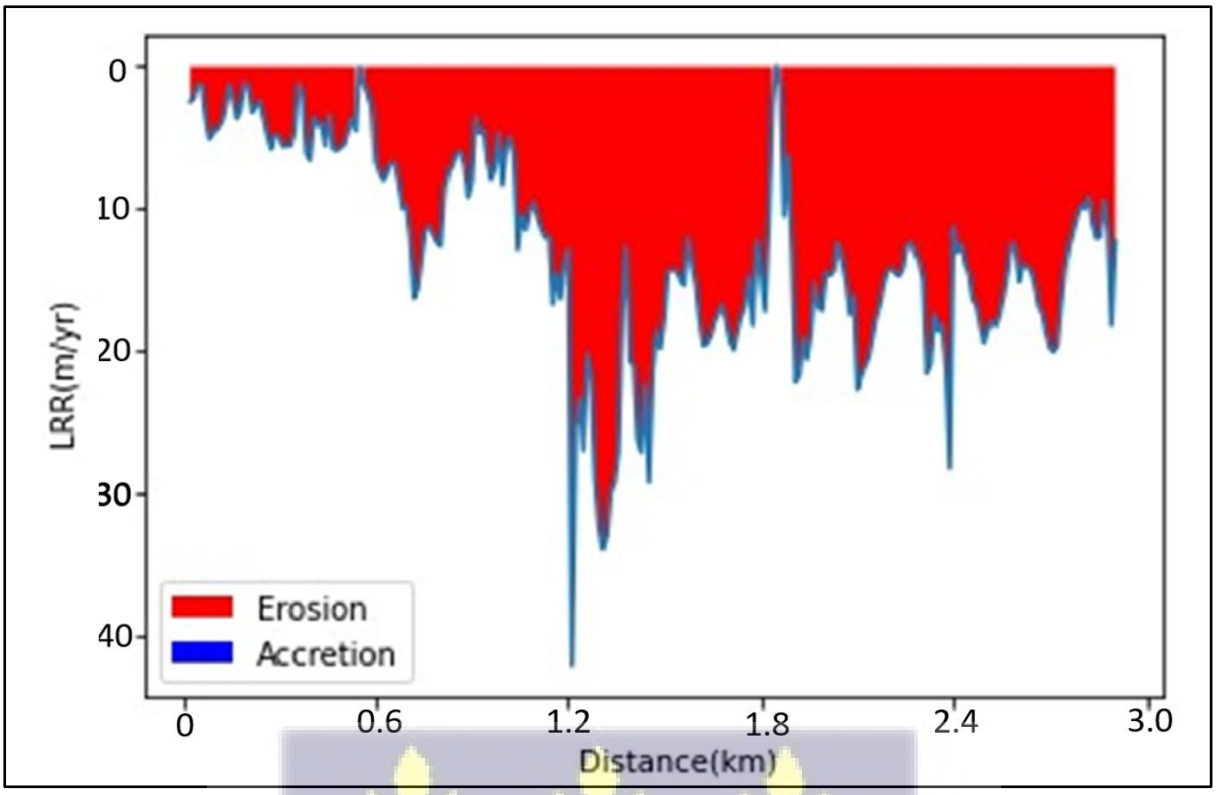


Figure 3.4 Shoreline Linear Regression Rate (LRR) of change at Atiteti from January 2021 to December 2023.

Subsequent calculations show that approximately 93.33% (≈ 61,638 m^2) of the coastline experiences erosion and approximately 6.67% (≈ 4,405 m^2) experiences accretion.

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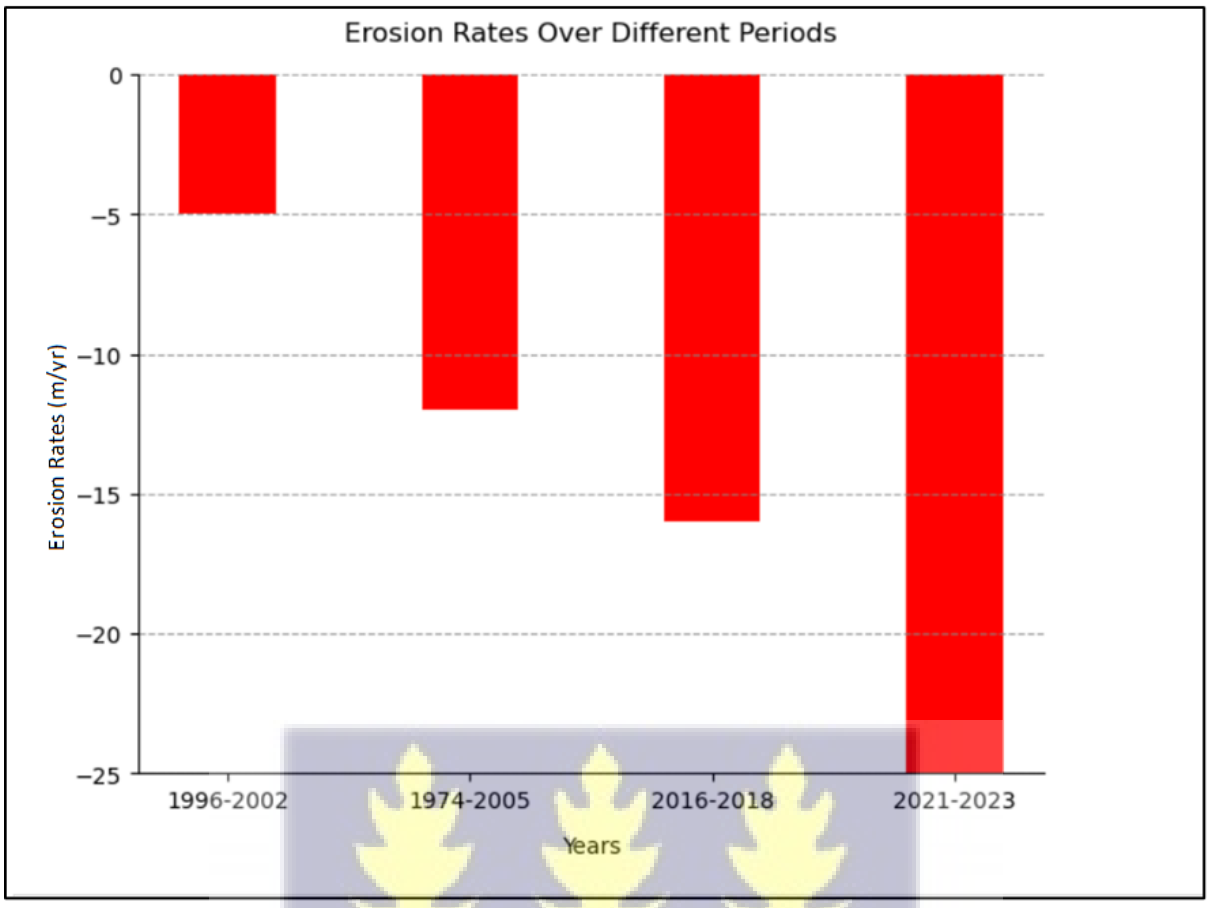


Figure 3.5 Shoreline erosion rates from 1974 to 2023 for the Atiteti beach.

Table 3.3: Summary of mean shoreline erosion rates for Atiteti (from 1974 to 2023)

PERIOD	***MEAN EROSION RATE (M/YR)***
1996 – 2002	-10
1974 - 2005	-15
2016 -2018	-20
2021 - 2023	-23

3.5 Discussion

The results of the shoreline morphological analysis from January 2021 to December 2023 revealed significant differences in coastal dynamics between the two study sites, Mumford (Site A) and Atiteti (Site B), which warrants a nuanced understanding of the drivers of coastal

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erosion and accretion in these areas. This section discusses the observed erosion and accretion patterns, their spatial variability, and how these patterns align with long-term trends and human-induced factors, as well as their broader implications for coastal management.

3.5.1 Morphological Changes at Mumford (Site A)

The beach at Mumford exhibited relatively modest, yet consistent, morphological changes over the study period. The observed erosion rates, ranging from -0.1m/yr to -5.5m/yr, with a mean erosion rate of -2.3 ± 1.23m/yr, reflect the ongoing natural and anthropogenic pressures on this coastline. Approximately 53.33% of the total area across the shore, equivalent to 71,271 m², is eroding, while 46.67% (62,370 m²) is experiencing accretion, with accretion rates ranging from 0.1m/yr to 2.4m/yr and a mean of 1.2 ± 1.23m/yr.

The highest erosion rates were recorded on the downdrift side of the landing site and in areas subjected to sand mining. These findings suggest that human activities, particularly sand mining and construction of coastal infrastructure, contribute significantly to the observed shoreline instability. The construction of landing sites and other hard structures along the coast may alter longshore sediment transport, resulting in sediment deposition (accretion) on the updrift side, and exacerbating erosion on the downdrift side. This phenomenon aligns with studies on coastal systems where coastal armouring and infrastructural developments disrupt natural sediment flow (Pilkey *et al*., 2020).

Although accretion was observed in a significant portion of the shoreline, the variability in erosion rates highlights the vulnerability of coastal areas, especially in areas where human activities are concentrated. This dual process of erosion and accretion necessitates a balanced coastal management strategy that addresses both sediment supply and the regulation of human

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activities such as sand mining, which has been identified as a key contributor to shoreline retreat in the region.

3.5.2 Morphological Changes at Atiteti (Site B)

The shoreline at Atiteti is experiencing more severe and alarming erosion compared to Mumford, with erosion rates ranging from -2.5m/yr to -44m/yr and a mean rate of -25 ± 1.25m/yr. Notably, 93.33% of the coastline, representing 61,638 m² of the total beach area, is eroded, while only 6.67% (4,405 m²) is accreted. The Atiteti beach, which is relatively wider than Mumford, is undergoing rapid and destructive changes, leading to the loss of properties, public infrastructure, and essential community spaces.

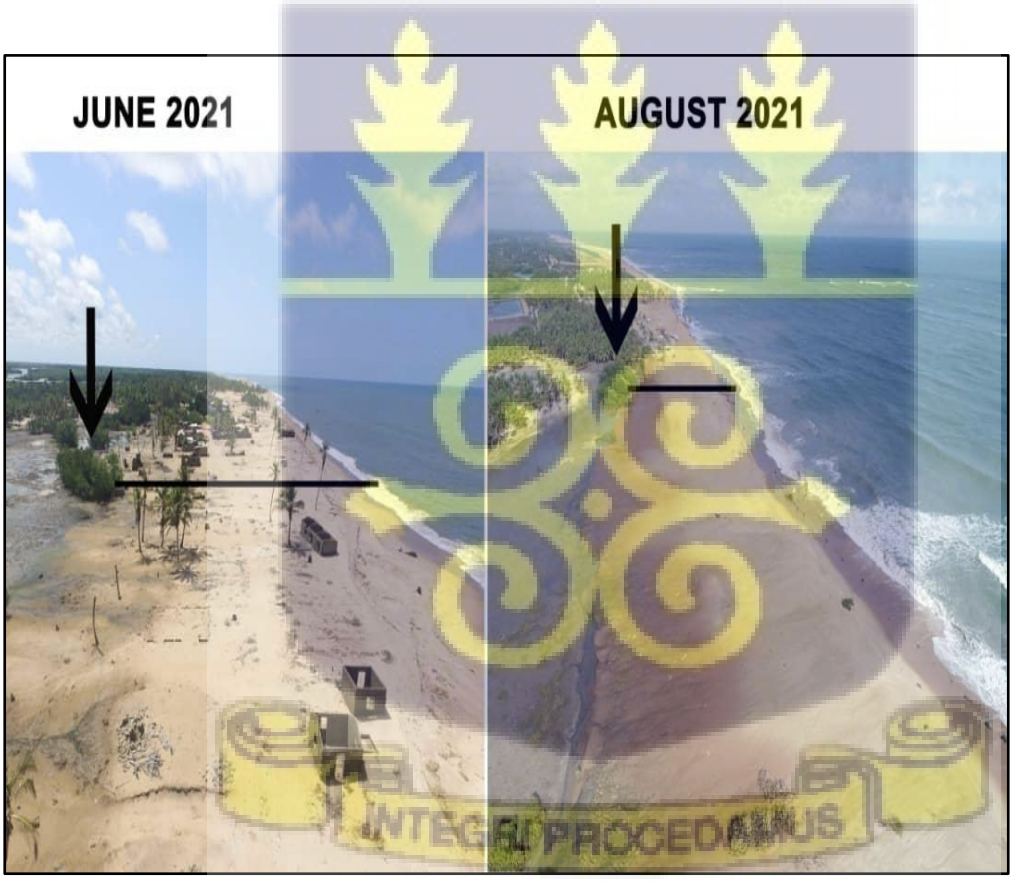


Figure 3.6 shows a drone image before and after a storm event at Atiteti in 2021 with the mangrove and destroyed buildings serving as reference points

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The extreme erosion rates at Atiteti could be attributed to both natural and anthropogenic factors. The long-term trend, as illustrated in Figure3.5, which tracks shoreline changes from 1996 to 2023, shows a persistent trend of significant shoreline retreat over decades. Historical analysis revealed that this site has been subject to sustained erosion for many years, exacerbated by rising sea levels and increased storm intensity associated with climate change. The lack of sufficient natural buffers, such as mangroves or dunes, further exposes the coastline to wave action and tidal forces, resulting in accelerated erosion.

Comparing the results from 2021–2023 with the long-term trend in Figure3.5, it is evident that the rates of erosion at Atiteti have worsened in recent years. This could be linked to both natural climatic variations and the growing influence of human activities such as unregulated coastal development and inappropriate sand mining practices. The recent sharp increase in erosion rates highlights the urgent need for intervention to halt the progression of shoreline retreat.

3.5.3 Long-Term Trends and the Role of Human Intervention

The long-term analysis presented in Figure3.5 and Table 3.2 traces the evolution of the shorelines in the two study areas from 1996 to 2023, providing a valuable context for interpreting the recent findings. The data show that coastal erosion has occurred at Atiteti for several decades. However, the rate of erosion has intensified over the last two decades, and extreme erosion has become a defining feature of the coastline. An analysis of historical data from 1996 to 2023 revealed that Mumford experienced comparatively lower erosion rates than Atiteti. However, a gradual increase in erosion was observed over the 27-year period.

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Figure 3.7 An image showing the different position of standpipe in Atiteti from 2015 to 2023

This trend of intensification is consistent with broader global patterns of coastal erosion, where rising sea levels, coupled with increasing frequency and intensity of storms, are driving coastal retreat in many regions. However, human activity plays a disproportionate role in accelerating this process. At both sites, the localized acceleration of erosion can be linked to human interventions, such as the construction of infrastructure, sand mining, and land reclamation. These activities disrupt natural sediment dynamics, leading to sediment deficits in certain areas and excess accumulation in others.

The erosion at Atiteti, which affects 93.33% of the coastline, suggests that the natural resilience of the coastal system was overwhelmed by both natural and anthropogenic stressors. Without intervention, the current trajectory indicates that the coastline will continue to recede, potentially resulting in the complete loss of critical land areas and displacement of coastal communities.

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3.5.4 Implications for Coastal Management

The findings of this study underscore the need for an integrated coastal zone management (ICZM) approach that addresses both the environmental and socio-economic dimensions of coastal erosion. At Mumford, where accretion occurs alongside erosion, management efforts should focus on mitigating human impacts, such as regulating sand mining and introducing buffer zones alongside the exploration of artificial dunes that have been proven to work in other parts of the world. This could involve the implementation of policies that balance economic activities with environmental protection, such as the development of sustainable sand mining guidelines and establishment of buffer zones to protect eroding shorelines.

At Atiteti, the situation is more critical, with the need for immediate intervention to protect the coastline and livelihoods of the communities living there. The development of hard coastal defense, such as seawalls, groynes, and revetments, could be considered short-term solutions to halt further erosion. However, in the long term, softer approaches, such as beach nourishment and restoration of natural barriers such as mangroves, should be prioritized to enhance the resilience of the coastline.

3.6 Conclusion

The study employed aerial survey using DJI Phantom 4 and Digital Shoreline Analysis Software to calculate the Linear Regression Rate from January 2021 to December 2023. The analysis revealed significant disparities in coastal erosion and accretion patterns between Mumford and Atiteti, emphasizing the complex interplay between natural processes and human interventions in shaping these coastal environments.

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At Mumford, the observed erosion rates, although modest, indicated a trend of shoreline instability. The findings demonstrate that approximately 53.33% of the total shoreline is eroded, with human activities such as sand mining and coastal infrastructure development playing a significant role in exacerbating these processes. While some areas experience accretion, the variability in erosion rates highlights the vulnerability of the coastline, necessitating a balanced coastal management strategy that addresses both the sediment supply and the regulation of human activities.

In contrast, Atiteti faces a more severe situation, with alarmingly high erosion rates affecting 93.33% of its coastline. The analysis indicated that both natural and anthropogenic factors have contributed to the rapid deterioration of this area. Historical trends show a persistent retreat of the shoreline, which has intensified in recent years due to climate change, rising sea levels, and inadequate natural buffers. These findings underscore the urgent need for immediate intervention to protect coastlines and the livelihoods of communities dependent on these resources. This thesis did not consider extreme wind erosion problems, not because this is not important but because it will be out of limit for a PhD to handle all aspects.

Long-term trends highlight a broader pattern of coastal erosion driven by increasing storm intensity and rising sea levels, with human activities further accelerating this process. At both sites, this study emphasizes the critical role of integrated coastal zone management (ICZM) approaches that consider both environmental and socio-economic dimensions.

Therefore, effective coastal management strategies must be implemented to mitigate erosion and protect vulnerable communities. This includes the regulation of sand mining, establishment of buffer zones, and exploration of both hard and soft coastal defense solutions. By adopting a holistic and adaptive management approach, it is possible to enhance the resilience of coastal systems and safeguard the livelihoods of communities facing ongoing environmental change.

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CHAPTER FOUR

4.0 ESTIMATING FLOODING UNDER PROJECTED SEA LEVEL RISE AND RELATIVE SEA LEVEL RISE SCENARIOS

4.1 Introduction

The global phenomenon of sea level rise, exacerbated by climate change, poses a significant threat to coastal communities worldwide (Meli *et al*., 2023). This threat is compounded by land subsidence, which can accelerate the rate at which these areas are susceptible to flooding, erosion, and saltwater intrusion (Chen & Tfwala, 2018). In Ghana, coastal belts, particularly in the central and eastern regions, are characterized by vibrant communities that depend heavily on fishing, tourism, and port operations (Danquah *et al*., 2021; Eshun *et al*., 2019). However, these communities face increasing risks due to the dual forces of rising sea levels and subsidence (Avornyo *et al*., 2024)

Subsidence in coastal areas can be induced by both natural processes and human activities. Naturally, subsidence occurs over extended periods due to geological changes but is significantly accelerated by human factors such as groundwater extraction for agriculture and domestic use, as well as by the weight of urban infrastructure. These activities lead to a faster and more dramatic change in land elevation, which is particularly problematic in low-lying areas where even small changes in land elevation can lead to significant increases in flood risk (Avornyo *et al*., 2023). In Ghana's coastal regions, rapid urbanization and the lack of sustainable land and water resource management contribute significantly to subsidence, further increasing the vulnerability of these areas to climate change impacts.

This study focuses on the coastal communities of Mumford and Atiteti, where the interplay between sea level rise and subsidence present unique challenges. These areas, which are critical

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to the socio-economic structure of Ghana's coastal region, experience considerable ecological and economic shifts due to these environmental stresses (Angnuureng *et al*., 2022). Erosion rates are alarmingly high, and the combination of erosion and subsidence threatens vital infrastructure and livelihoods of local populations. Furthermore, the degradation of mangrove forests and other coastal wetlands, exacerbated by altered hydrology and increased saltwater intrusion, compromises their ability to act as natural buffers against coastal hazards (Gordon & Ayivor, 2003).

This research employs a multidisciplinary approach, integrating advanced geospatial technologies, such as Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite System (GNSS) surveys, with a robust modelling approach to map and analyse the impacts of subsidence and sea-level rise in Mumford and Atiteti. By doing so, it aims to provide a detailed understanding of how these factors collectively influence flood risk and to propose adaptive management strategies that can mitigate these impacts. The findings are expected to not only contribute to the scientific understanding of subsidence and sea level interactions but also inform practical interventions that can enhance the resilience of these vulnerable coastal communities.

4.2 Methodology

4.2.1 Data Acquisition (Using Synthetic Aperture Radar Images for Subsidence)

SAR images were downloaded from the Sentinel 1 Alaska Satellite Facility webpage (https://www.asf.alaska.edu). The SAR signals utilized were a 250*180 km Wide Swath, which uses the TOPSAR method for acquiring the image (Lu *et al*., 2007; Hewson *et al*., 2018). A single flight was observed at each study location. Figure 4.1 shows the flight path. Within

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Interferometric Wide Swath, there were three more swaths that individually included nine bursts.

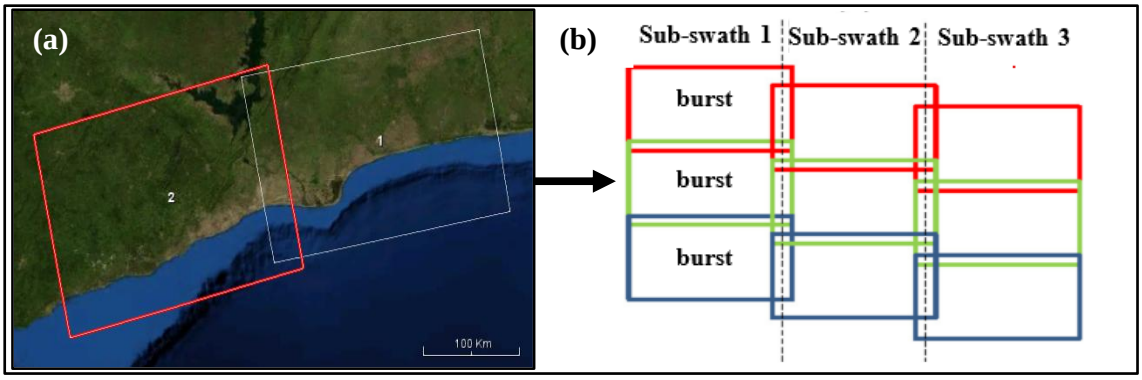


Figure. 4.1: Shows interferometric swath tiles (a) and sub-swath with burst structure overlap (b).

Each study area was divided into three sub-swaths for analysis. During a span of 6 years, 135 SAR scenes were collected for individual sub-swaths. The scenes were obtained using C-band with a 5.6-centimetre wavelength. Vertical co-polarization and ascending geometry were also used in the process of obtaining the scenes (Hewson *et al*., 2018). The downloaded images span January 2018 to December 2023.

4.2.1.1 Using ESA SNAP to Calculate the Persistent Scatter Interferograms with the STAMPS Approach

The InSAR method used in this study was the PSI method based on the PS algorithm developed by Ferretti (Ferretti *et al*., 2001). The process follows the steps outlined in Figure 4.2. Sentinel software (SNAP, V8) was utilized for PSI analysis along with the Stanford Method for Persistent Scatterers (StaMPS) open-source toolbox (StaMPS, 2021). The processed data results were calculated based on the Interferometric Phase (ϕ) including various elements and

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signified elevation (Höser, 2018). The difference in images ϕ^{disp} calculated by subtracting the phase contributions from the Interferometric Phase (ϕ) (Crosetto *et al*., 2016).

$$\phi = \phi^{flat} + \phi^{topo} + \phi^{disp} + \phi^{atm} + \phi^{orbit} + \phi^{noise} \ldots . (3)$$

Where: ϕ^{flat} = flat earth; ϕ^{topo} = the topography; ϕ^{disp} = displacement amongst two scenes; ϕ^{atm} = atmospheric signal; ϕ^{orbit} = changes in platform's orbit; ϕ^{noise} = noise component.

In Differential InSAR (DInSAR), the main focus is on the displacement of images ($\phi^{disp)}$). Detecting tiny differences in magnitude is possible by isolating this component and minimizing the extra phase components (Xu *et al*., 2022). The difference in the array between the two orbits is influenced by the satellite path and the landscape it covers. This includes; ϕ^{orbit}, ϕ^{flat} and ϕ^{topo} (Osmanoğlu *et al*., 2016). The attributes of the phases were adjusted using the SNAP tool. The TOPSAR Split tool was used to choose bursts in specific areas of interest. The "Apply Orbit File" feature updates state vectors in orbit for products with precise satellite information (speed and location) thus ϕ^{orbit} (Figure 4.1).

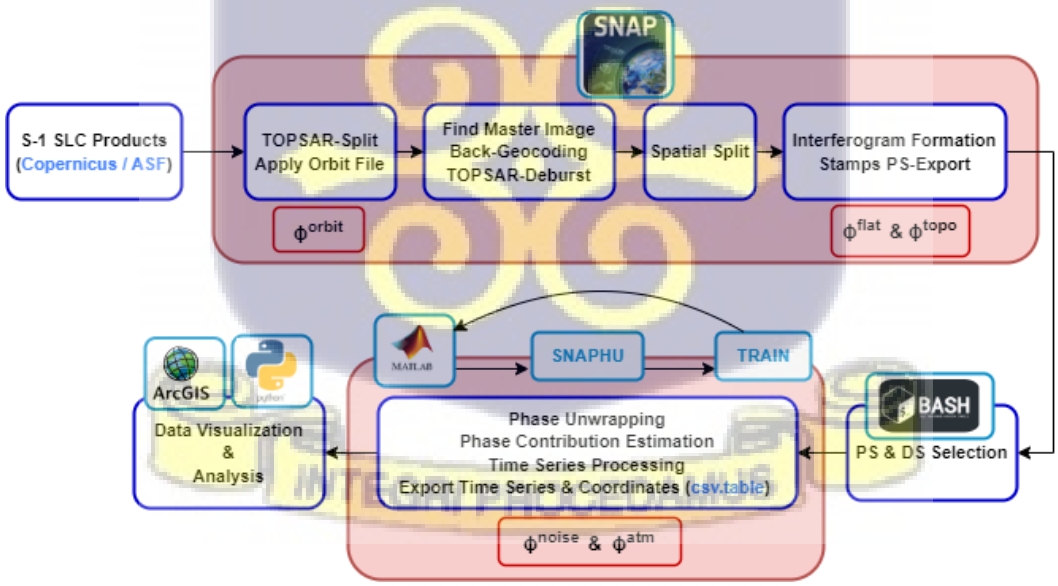


Figure. 4.2: Workflow for PS-InSAR (Avornyo *et al*., 2024).

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The flat earth signal (ϕ^{flat}) caused by Earth's curvature was eliminated using a flattening method of the interferogram (Lu *et al.*, 2007), and the topography component ϕ^{topo} was eliminated with the 12m DSM DEM from L3HARRIS. The two components were automatically cleared during the "Interferogram Formation" process in SNAP (Figure 4.3), translating into Equation 2.

$$\phi = \phi^{disp} + \phi^{atm} + \phi^{noise} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The filtering of the noise component (ϕ^{noise}) was performed using a toolbox in MATLAB (ϕ^{noise}) by following a seven-step process outlined by Goldstein & Werner (1998). The final step in MATLAB involves using the Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) by Bekaert *et al*. (2015) to eliminate the atmospheric component (ϕ^{atm}) caused by ionospheric and tropospheric effects. This resulted in the derivation of the optimal equation (3), where the interferometric component is equivalent to the displacement observed in the scenes.

$$\phi = \phi^{disp} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The ultimate outcome, in terms of pixel velocities, was represented through the visualization of the average ground deformation using ArcGIS. Additionally, the deformation time series for individual pixelated components, situated in designated zones of significance, was visualized using Python scripts.

4.2.1.2 Integration and Calibration of Ground-based GNSS Data with Remotely-Sensed InSAR Observations for Geodetic Monitoring

The incorporation of ground-based GNSS data along with remotely sensed InSAR observations is necessitated by the inherent constraints of InSAR technology, as highlighted in studies by

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Abidin *et al*. (2015) and Fiaschi *et al*. (2018). GNSS investigations, which leverage a constellation of satellites, yield highly accurate positional data. Given the diminished sensitivity InSAR to erosional and depositional changes due to pixel coherence loss and the restricted capability of GNSS in detecting sub-structural or platform-based movements, a synergistic application of both methodologies is advocated (Higgins, 2016).

Accordingly, GNSS surveys were deployed as a geodetic calibration tool for InSAR-derived findings, following the precedent set by researchers such as Fiaschi *et al*. (2018), Da Lio *et al*. (2018) and Amato *et al*. (2020). by Wiafe *et al*. (2013) created seven GCPs in 2009. A follow-up survey was conducted in April 2020. This method employs precise point positioning in a static setup. This triangulation approach utilized two Leica GPS with a source from the EGM2008 geoid model. A stationary Leica GS10 GNSS receiver served as the base station for the height measurements at all seven GCPs. The survey results were validated against Unremitting GNSS values from the Ghana Geological Survey Department. Each survey spanned approximately 4.5 h. Deformation velocities (mm/yr) were calculated from the temporal changes in the surveys and normalized by absolute year changes (Amato *et al*., 2020). Comparisons involved aligning the mean velocities from InSAR in a 100-metre radius of individual GCP against GNSS-obtained velocities (Braun *et al*., 2020). The bias was ascertained by averaging the absolute discrepancies from the GNSS and InSAR velocity measurements, thereby calibrating the rates derived from the InSAR (Tomás *et al*., 2014).

4.2.1.3 Analysing Vulnerability to Sea-Level Rise and Subsidence: Methodological Approach and Risk Assessment

5 Given the limited spatial coverage of the deformation rates from InSAR, Inverse Distance Weighted (IDW) method was adopted to generate an unceasing representation of the terrain for subsequent analysis. The IDW technique is frequently used to infer unknown quantities

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within a region by assigning significance to proximate measured values based on their distances (Masoomi *et al*., 2011). Due to the non-uniformity of land movement and linearity of deformation rates, InSAR-sourced measurements were projected forward from 2020 towards the designated future periods. A notable constraint of this approach is its static nature in mapping SLR impacts, overlooking dynamic environmental processes such as flooding or inundation events. The methodology, as depicted in the workflow diagram (Fig. 5) follows Aucelli *et al*. (2017) and involves the integration of extrapolated InSAR deformation rates with selected DEMs for each forecasted period using the ArcGIS's Plus tool to create projected DEMs. These projected DEMs, along with the baseline DEMs, were then added to Sea-Level forecast data to derive the rSLR, incorporating local Vertical Ground Deformation (VGD) measurements from this research and SLR scenarios.

6 To minimize underestimation of potential risk areas, a conservative analytical stance was adopted, considering all territories below the Local Mean Sea Level as vulnerable in either DEM model across all assessed timeframes for both SLR and rSLR scenarios. The probabilistic forecasts, demarcated by the 17th and 83rd percentile thresholds, served as bounds for this analysis. The disparity in at-risk areas under different SLR and rSLR projections was estimated to evaluate the extent of the effect of subsidence on imminent vulnerability to rSLR impacts.

4.2.2 Assessing Regional Sea Level Rise Projections and Their Implications for Vulnerability to Climate Change using Regional SLR Projections

Regional Sea Level Rise (SLR) forecasts were derived using NASA's IPCC Regional Sea Level Projection Tool, which incorporates findings from the Intergovernmental Panel on Climate Change (IPCC, AR6), specifically from Working Group I (Garner *et al*., 2021). The projection intervals defined by the IPCC—short-term (2021 to 2040), intermediate (2041 to 2060), and long-term (2081 to 2100)—was adopted as basis for forecasting timelines. Selection was made

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for two Shared Socioeconomic Pathways (SSP) scenarios. These included 2-4.5 and 5-8.5, which represent, moderate and very high emission of greenhouse gas scenarios, respectively, both regarded with medium confidence. The analysis considered projections with probabilities representing the likelihood range, denoted by a probability of 67% (spanning the 17th to 83rd percentiles) of Sea Level Rise under these two SSPs. To isolate the impact of local Vertical Ground Deformation (VGD) identified in this research on the risk analysis of exposure, SLR forecasts for each SSP setting were calculated excluding the VGD component as specified by the IPCC.

Table 4.1: Regional SLR forecasts without the VLM component.

Scenario	Percentiles	2021-2040	2041-2060	2080-2100
SSP2-4.5	17	0.13 m	0.238 m	0.464 m
	83	0.213 m	0.392 m	0.838 m
SSP5-8.5	17	0.148 m	0.286 m	0.673 m
	83	0.233 m	0.449 m	1.118 m

4.2.2.1 Limitations of Regional SLR Projections

Regional sea level rise (SLR) projections are essential for understanding the impacts of climate change, particularly in vulnerable coastal regions. However, deriving accurate projections involves addressing various limitations and uncertainties inherent in the methods used. This section highlights key limitations and uncertainties associated with the use of regional SLR projections, focusing on the assumptions, uncertainties, and challenges involved.

4.2.2.2 Model Assumptions and Simplifications:

The methodology relies on the NASA IPCC Regional Sea Level Projection Tool and IPCC's Sixth Assessment Report, which incorporate assumptions and simplifications to represent

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complex climate processes. These assumptions may introduce uncertainties into the projections, particularly concerning the representation of feedback mechanisms and non-linear interactions within the climate system.

4.2.2.3 Uncertainty in Future Emissions Scenarios:

The method considers different emissions scenarios (SSP 2-4.5 and SSP 5-8.5) to account for a range of potential future greenhouse gas emissions. However, uncertainty remains regarding which scenario will unfold, depending on socio-economic and policy factors. This uncertainty in emissions scenarios can affect the reliability of SLR projections and the associated risks.

4.2.2.4 Model Sensitivity and Parameterization:

The accuracy of SLR projections may be sensitive to the choice of model parameters and parameterization schemes used in the projection tool. Variations in these parameters could lead to differences in the projected SLR outcomes, introducing uncertainty into the results and affecting their reliability for decision-making purposes.

4.2.2.4 Inherent Limitations of Regional Projection Tools:

Although regional projection tools provide valuable insights, they may have limitations in capturing local-scale variability and extreme events. This could affect the reliability of the SLR projections, particularly in regions with complex coastal dynamics or geological characteristics that are not adequately represented in the models.

4.2.2.5 Subsidence Uncertainty:

This method excludes the subsidence component from the SLR projections to isolate its impact on the risk analysis. However, uncertainties in estimating subsidence, could introduce additional uncertainty into the projected SLR outcomes, affecting their accuracy and reliability.

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4.2.2.6 Interpretation of Probabilistic Projections:

This method incorporates probabilistic SLR projections that represent the likely range of the outcomes. However, interpreting probabilistic projections presents challenges, including effectively communicating uncertainty to stakeholders and decision-makers for informed decision-making.

4.2.2.7 Data Limitations and Spatial Resolution:

Limitations in the availability or quality of input data, such as elevation data or sea level observations, can affect the accuracy of SLR projections, particularly at regional or local scales. Spatial resolution limitations may also impact the representation of coastal features and dynamics in projections, introducing uncertainties into the results.

4.2.3 Estimation of Potential Inundation Impact (Integration of DEMs for Assessing Inundation Vulnerability)

The bathtub model, a rudimentary yet effective approach, was employed to assess the prospective impacts of relative Sea Level Rise (rSLR) across various temporal scales within the two study sites. This geospatial methodology primarily integrates water levels with Digital Elevation Models (DEMs), making its accuracy directly contingent upon DEM quality and utilized to delineate zones susceptible to danger (Van de Sande *et al.*, 2012). Given the unavailability of a precise locally corrected elevation dataset and the scarcity of sufficient control points, this study incorporated a 12m Digital Surface Model (DSM) DEM from L3HARRIS (https://www.l3harris.com). The elevation dataset was calibrated to the local Mean Sea Level by employing corrections from the mean dynamic topography data from Mulet *et al.* (2021) and adhering to the datum conversion methodology outlined by (Seeger *et al.*, 2023).

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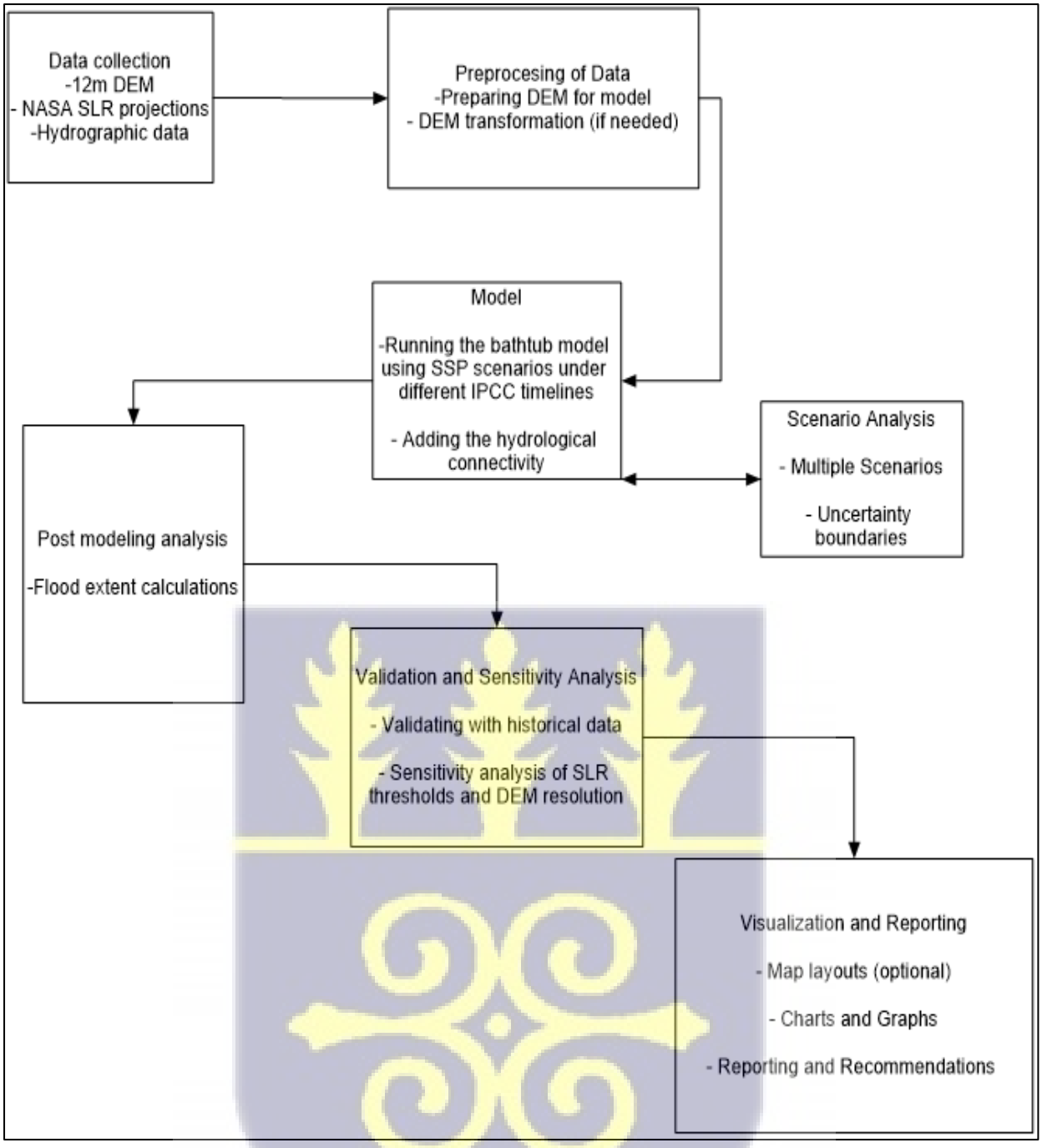


Figure. 4.3: Workflow for bathtub model

4.2.4 Bathtub Model Assumption

Although the bathtub model provided a useful first-order estimation of potential future flooding under projected sea-level rise (SLR), it remains a simplified representation of coastal inundation. Even with the inclusion of land subsidence and NASA-projected water levels for

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SSP2-4.5 and SSP5-8.5 across the 2040, 2060, and 2100 timelines, the model assumes a static water surface and uniform flood level, without accounting for dynamic hydrodynamic processes such as tides, waves, and storm surges.

The model produces static inundation snapshots, representing possible exposure zones rather than the temporal evolution of flooding. It also simplifies hydrological connectivity, drainage, and surface roughness, and does not consider future morphological changes such as erosion or sediment accretion. Furthermore, it assumes a "no-adaptation" condition, excluding potential human interventions or coastal defences that may alter future exposure.

Despite these limitations, the enhanced bathtub model remains a valuable tool for spatially assessing potential flood-prone areas under different sea-level rise scenarios, providing critical insight into areas of future coastal vulnerability and exposure.

4.3 Results

4.3.1 PSInSAR derived Deformation Velocities

4.3.1.1 Mumford (Site A)

The number of persistent scatters (PS) from the PSInSAR methodology recorded for Mumford was 80,000 with a PS density of 62.13 PS/km^2 excluding the water covered surfaces. Along the Sentinel 1 line of sight (LOS) the PS deformation velocities ranged from uplifting rates of 4.11 mm/yr to subsiding rates of -5.24 mm/yr. The highest mean subsiding velocity for Mumford was -4.52 mm/yr. The subsiding PSs (72.32%) were mostly found along the coast with a few points close to the central part of the town. From the absolute deviation of velocities

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calculated, a notable peak at the 0.2 deviation was observed with uniform distribution from 0.1 to 0.8.

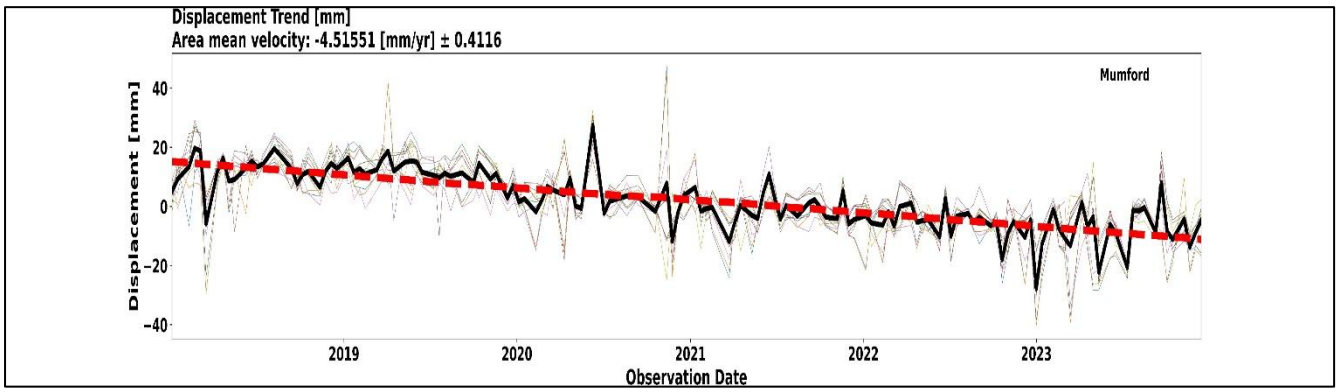


Figure 4.4: A graph showing the displacement trend in Mumford

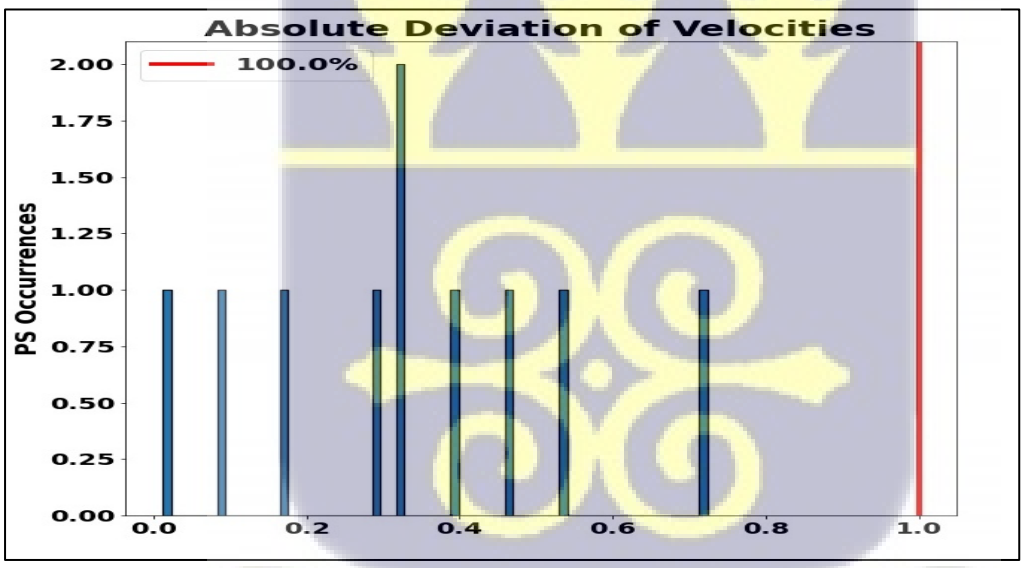


Figure 4.5: A graph showing the absolute deviation of velocities for Mumford.

4.3.1.2 Atiteti (Site B)

The number of persistent scatters (PS) from the PSInSAR methodology was 50,000 with an area PS density of 60.37 PS/km^2 excluding water-covered surfaces. Along the Sentinel 1 line of sight (LOS) the PS deformation velocities ranged from uplifting rates of 6.90 mm/yr to

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subsiding rates of -5.95 mm/yr. The highest mean subsiding velocity for Atiteti was -4.55 mm/yr. Subsiding PSs (64.78%) were found mostly along the coast. Based on the absolute deviation of the calculated velocities, several peaks around 0.3 and 0.6 intervals were observed

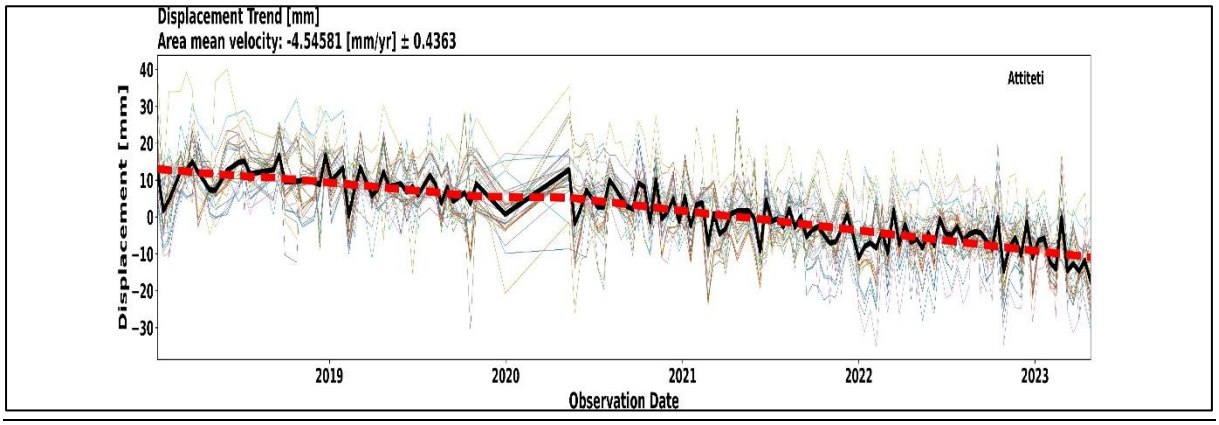


Figure 4.6: A graph showing the displacement trend in Atiteti

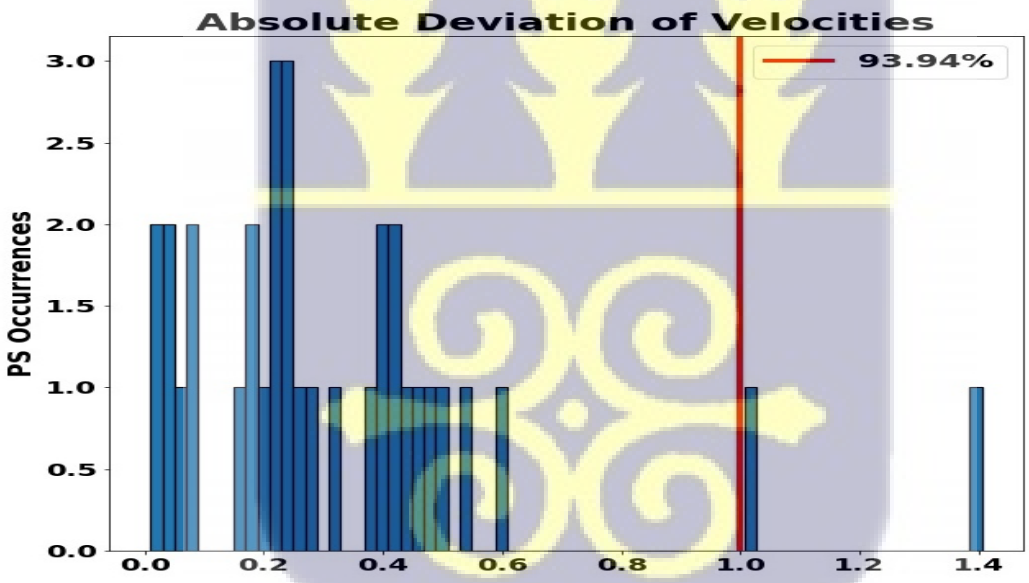


Figure 4.7: A graph showing the absolute deviation of velocities for Atiteti.

Table 4.2: Summary of PSInSAR derived Deformation Velocities

Site	*Highest Uplifting Rate (mm/yr)*	*Highest Subsiding Rate (mm/yr)*	*Highest Mean Subsiding Rate (mm/yr)*
A	4.11	-5.24	-4.52

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B	6.90	-5.95	-4.55

4.3.2 GNSS- calibrated deformation velocities

To coordinate and validate the deformation velocities from the SAR images, known GNSS stations were used. InSAR-derived velocities within 100- and 200-meter radii around each Ground Control Point (with known xyz), were averaged and compared with the GCP deformation rates. The GNSS-derived velocities at all GCP locations indicated subsiding deformation. The closest GCP to Mumford was between the Mumford township and Apam, which recorded a subsidence rate of -4.11 mm/yr. The most reliable GCP to Atiteti was in Woe -2.82 mm/yr. The total error margin which is the absolute difference between the GCP deformation rate and InSAR velocities for each buffer dataset for Mumford and Atiteti was ±0.44 and ±1.82 mm/yr respectively.

4.3.3 Flooding Trends from Sea Level Rise and Relative Sea Level Rise

The Bathtub model was used to predict areas that would be flooded due to SLR and rSLR as a result of local subsidence. Following the IPCC timelines, predictions were made for short-term (2040), mid-term (2060) and long-term (2100) for Shared Socioeconomic Pathways 2-4.5 (intermediate) and 5-8.5 (very high).

4.3.3.1 Mumford (Site A)

Under SSP scenario 2-4.5, projections indicate that approximately 2 to 4 percent of Mumford's area will be below the local mean sea level (LMSL) by 2040, according to the 17th and 83rd percentile estimates, respectively, when sea level rise (SLR) alone is considered. When local subsidence is accounted for, these figures are anticipated to rise, with 5 to 9 percent of the area expected to be below the LMSL by 2040.

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By 2060, the extent of areas submerged below the LMSL is projected to increase further, with SLR alone resulting in 8-14 % of the land being submerged, and 15-20 % when relative SLR (rSLR), inclusive of subsidence, is considered. The projections for 2100 are even more stark, with 16-24 % of the area anticipated to be below the LMSL under SLR alone, and 24-33 % when rSLR is factored in

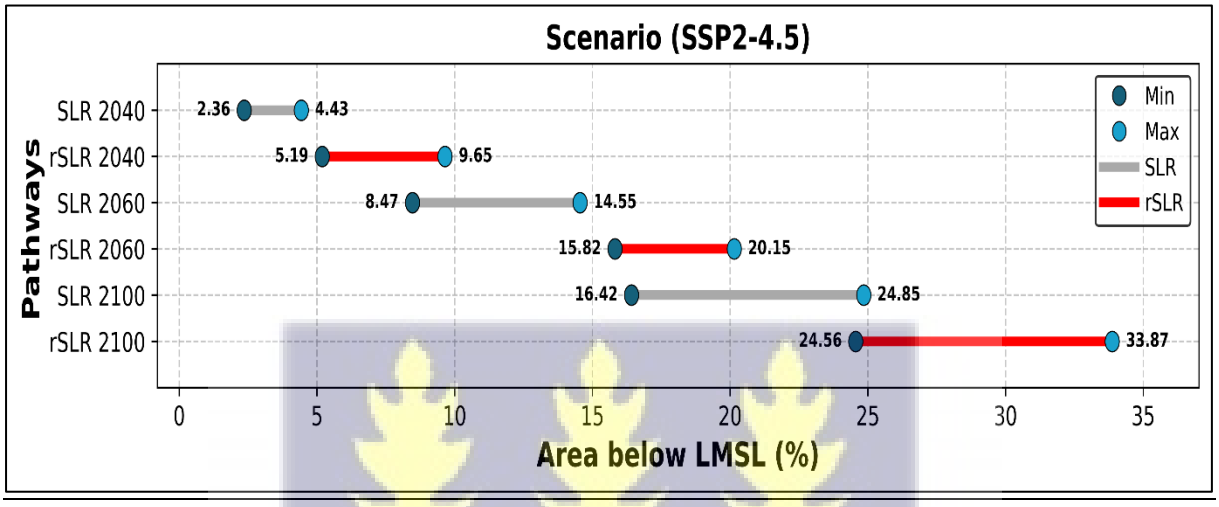


Figure 4.8: A graph showing areas below LMSL from SLR and rSLR for SSP 2-4.5 scenario

Under SSP scenario 5-8.5, which anticipates a very high radiative forcing, initial short-term projections (2020-2040) indicate that between 2% and 4% of Mumford's area will be below the local mean sea level (LMSL). This range is expected to expand to 5-11 % with the inclusion of subsidence impacts.

By the mid-term horizon of 2060, the projections suggest a more pronounced submergence. Specifically, sea level rise (SLR) alone is projected to submerge 13-15 % of the land below the LMSL, with this figure rising to 17-26 % when accounting for relative SLR (rSLR), which includes the effects of local subsidence.

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For the long-term outlook of 2100, the scenario becomes increasingly severe. Areas anticipated to fall below the LMSL are projected to be between 22 and 34 % under SLR alone, escalating to 29-40 % when rSLR is considered

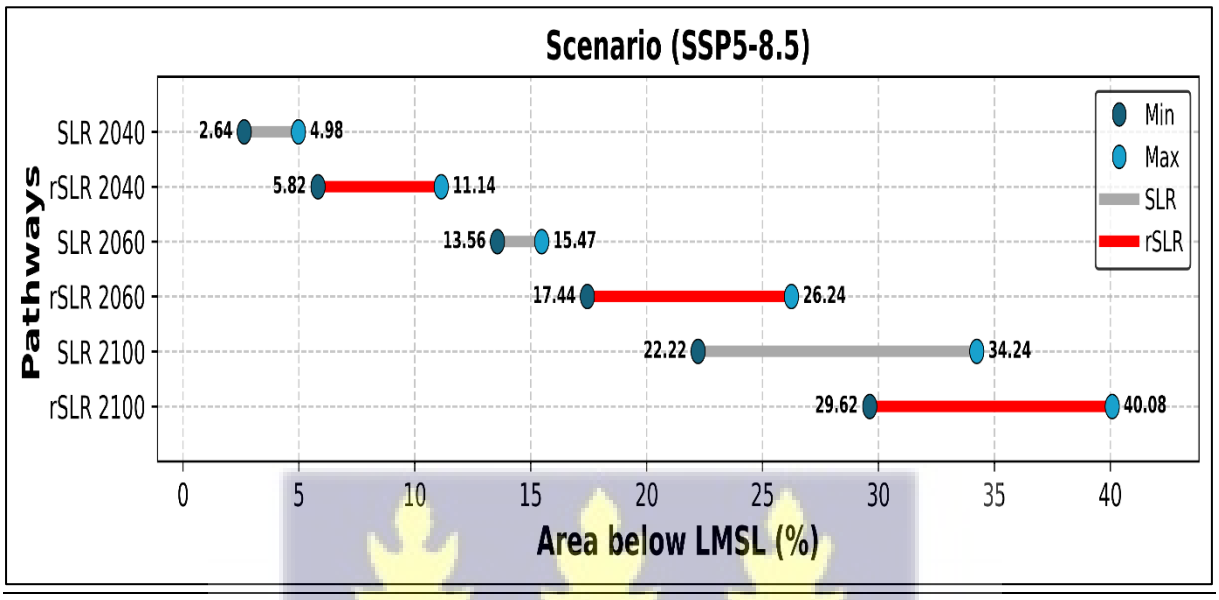


Figure 4.9: A graph showing areas below LMSL from SLR and rSLR for SSP 5-8.5 scenario

4.3.3.2 Atiteti (Site B)

Under SSP scenario 2-4.5, the projections indicate that approximately 13-15 % of Atiteti area will be below the local mean sea level (LMSL) by 2040, according to the 17th and 83rd percentile estimates, respectively, when sea level rise (SLR) alone is considered. When local subsidence is accounted for, these figures are anticipated to rise, with 17-29 % of the area expected to be below the LMSL by 2040.

By 2060, the extent of areas submerged below the LMSL is projected to increase further, with SLR alone resulting in 16-21 % of the land being submerged, and 24-27 % when relative SLR (rSLR), inclusive of subsidence, is considered. The projections for 2100 are even more stark, with 23-38 % of the area anticipated to be below the LMSL under SLR alone, and 32-47 % when rSLR is factored in.

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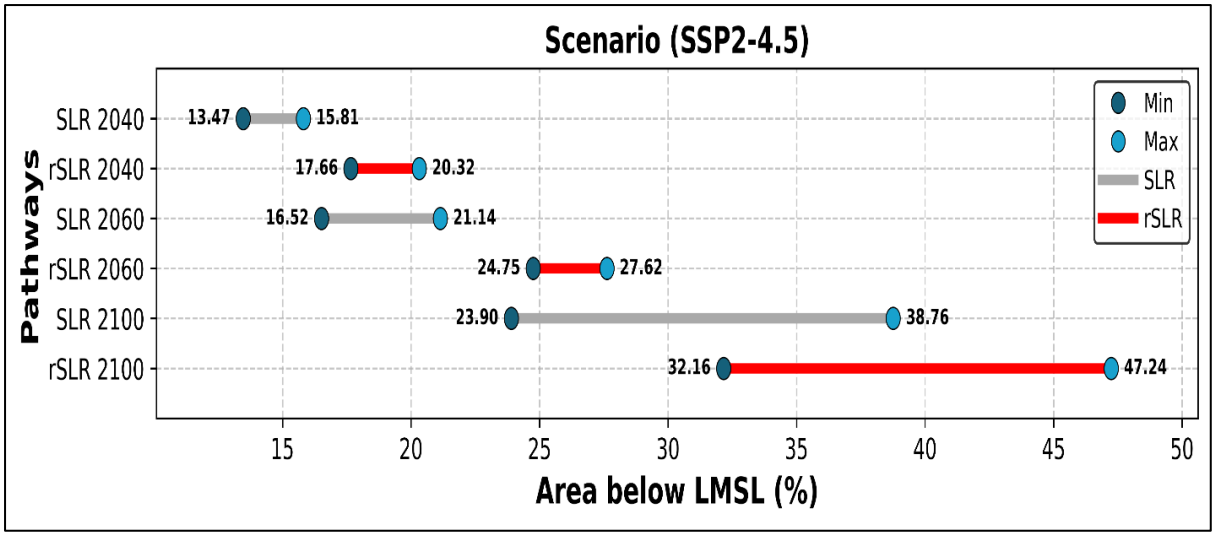


Figure 4.10: A graph showing areas in Atiteti below LMSL from SLR and rSLR for SSP 2-4.5 scenario

According to projections derived from SSP scenario 5-8.5, for the period 2020-2040, it is anticipated that 13-16 % of Atiteti will be submerged below the local mean sea level (LMSL). Including the impacts of subsidence, these estimates were revised upwards, suggesting that 18-21 %of the area could be submerged.

As we approach the mid-term period around 2060, the extent of the inundation is expected to widen significantly. Isolated effects of sea level rise (SLR) are likely to result in 16-23 % of Mumford falling below the LMSL. When combined with relative SLR (rSLR), which incorporates the additional influence of subsidence, the affected area is projected to increase from 23 to 29 %.

2100 long-term projections underscore an escalating threat with the anticipated submerged area ranging from 31-58 % under the influence of SLR alone. When adjustments for rSLR are applied, the projections adjust to a range of 41-64 % of the area falling below the LMSL

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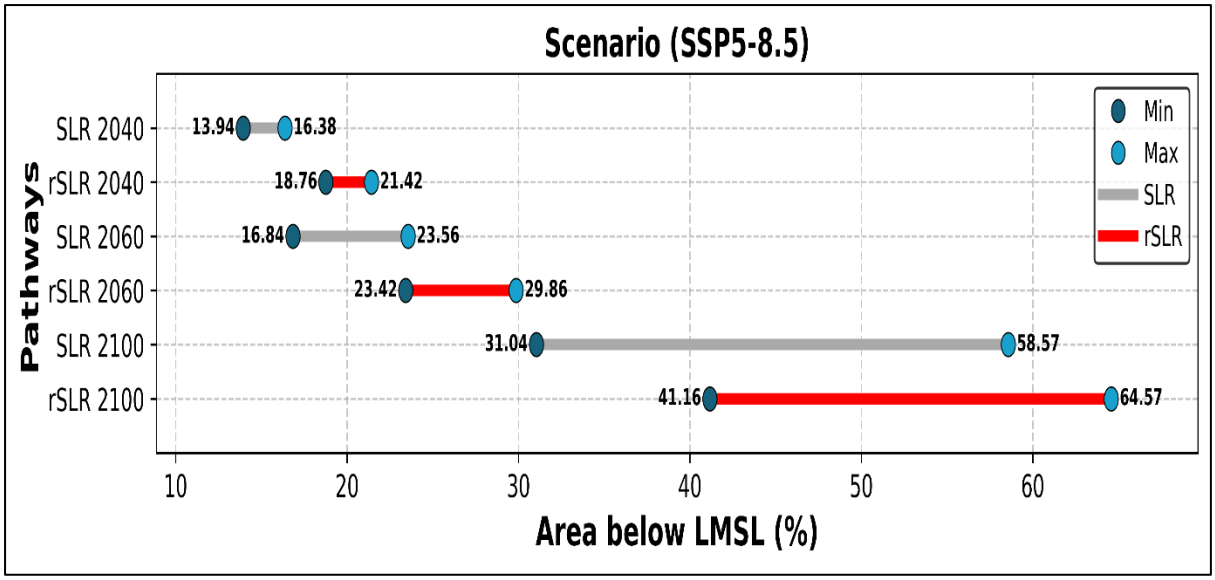


Figure 4.11: A graph showing areas in Atiteti below LMSL from SLR and rSLR for SSP 5-8.5 scenario

4.4 Discussion

4.4.1 Deformation Patterns and Subsidence in Mumford and Atiteti

The PSInSAR results from Mumford and Atiteti demonstrated significant subsidence across these coastal sites. This subsidence is predominantly observed along the coast, aligning with broader regional patterns within the Volta Delta, where subsidence rates exceed 8 mm/yr in some areas (Avornyo *et al.*, 2024). These results underscore the dual role of natural processes, such as the compaction of mudflats, and human interventions, including extensive dyke-bordering salt pans, which disrupt natural sediment replenishment mechanisms.

4.4.1.1 Hydrological and Geomorphological Influences

Construction of the Akosombo Hydroelectric Dam in 1965 markedly altered the hydrological and morphological dynamics of the delta. Boateng *et al*. (2012) and Amenuvor *et al*. (2020) revealed that the dam has significantly reduced allochthonous sediment influx, exacerbating

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subsidence by failing to compensate for losses in elevation. This situation is compounded by the geological features of the region, particularly the impermeable basement rocks noted by Finlayson *et al*. (2000), which restrict groundwater recharge and promote inelastic subsidence. In contrast, Mumford, being a peri-urban area, experiences subsidence primarily due to intensive building and land development activities along with groundwater extraction from local wells, highlighting different drivers of land subsidence between the two locations.

4.4.1.2 Anthropogenic Factors and Groundwater Abstraction

In communities such as Anloga, Anyanui and Atiteti extensive groundwater extraction for agriculture and domestic use has been a longstanding practice, contributing to subsidence. Overexploitation of groundwater resources, has not only led to saltwater intrusion as reported by Helstrup *et al*. (2007) and Yidana *et al*. (2010) but also to the compaction of aquifer systems. This anthropogenic subsidence is highlighted by Galloway and Burbey (2011) and Gambolati and Teatini (2015) as a critical factor in regional land subsidence patterns.



Figure 4.12: An image showing groundwater extraction in a farm in Atiteti.

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4.4.1.3 Spatial Variability and Subsidence Mechanisms

The varied subsidence and uplifting rates within the delta highlight the complex interplay between the geotechnical, hydrological, and anthropogenic factors. While some areas exhibit stability or minor uplift, likely influenced by low population density and less intensive land use, other areas, particularly those with heavy anthropogenic alteration, show marked subsidence. This spatial variability necessitates a nuanced understanding of subsidence mechanisms to develop effective mitigation strategies.

4.4.2 Impact of Sea Level Rise and Relative Sea Level Rise in Mumford and Atiteti

The results from the bathtub model projections highlight a significant increase in flooding risks in Mumford and Atiteti due to both SLR and rSLR, which includes the compounding effects of local subsidence. These projections align with broader findings reported for the Volta Delta, emphasizing an increasing trend in flood risk and severity over the upcoming decades.

4.4.2.1 Subsidence Exacerbation of Flooding

Consistent with the findings of Abidin *et al*. (2015) and Chaussard *et al*. (2013), our study confirmed that subsidence significantly exacerbates the frequency and magnitude of flooding incidents. In Mumford, the projected increase in areas below the LMSL from 2040 to 2100 underscores the critical role of subsidence in enhancing flood risk. Similarly, Atiteti showed a dramatic increase in flood coverage, with up to 47% of the area expected to be submerged by 2100 under the combined effects of SLR and rSLR.

4.4.2.2 Socio-Economic and Environmental Consequences

Increased flooding has dire implications for socio-economic stability and environmental sustainability in these regions. As observed by Appeaning Addo *et al*. (2018), flood-prone areas face significant infrastructural damage, which can disrupt economic livelihoods and displace

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communities. The continued exploration and exploitation of resources, such as oil and gas in nearby regions, may further strain these vulnerable ecosystems and communities, as suggested by Imirhe (2019).



Figure 4.13: Images showing the impacts of coastal flooding in Atiteti, with eroded coastline, damaged infrastructure and floodwaters encroaching on buildings.

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4.4.2.3 Comparative Analysis of SSP Scenarios

The differences between scenarios SSP 2-4.5 and SSP 5-8.5 illustrate a concerning trend where more severe impacts are anticipated under higher emission scenarios. This trend is evident in both Mumford and Atiteti, where the percentage of flooded area escalates more steeply under SSP 5-8.5. This aligns with the delta studies, where the increased flood extent over time reflects the progressive nature of climate impacts under unmitigated emission trajectories.

4.4.2.4 Long-term Projections and Mitigation Strategies

Based on these projections, long-term planning and mitigation strategies are crucial. Adaptation measures, including the construction of soft engineering sea defences (managing with nature) and elevation of infrastructure, can be considered to mitigate the most severe impacts of flooding. Engaging in robust climate action to curb emissions could also significantly alter these trajectories, as demonstrated by the differences in the impact projections of the SSP scenarios.

4.5 Conclusion

This chapter utilized PSInSAR technology to provide a detailed understanding of the subsidence and uplift patterns in Mumford and Atiteti, highlighting the significant subsidence along these coastal areas within the context of broader regional trends influenced by natural processes and human activities. The bathtub model projections, considering different Shared Socioeconomic Pathways (SSPs) and IPCC timelines, indicate that Mumford and Atiteti face increasing risks of flooding due to sea level rise (SLR) and relative sea level rise (rSLR). These risks are exacerbated under scenarios with higher radiative forcing (SSP 5-8.5), emphasizing the urgent need to address both the current and future challenges.

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Significant subsidence rates observed in these regions are driven by geological conditions, extensive groundwater extraction, and infrastructural impacts, such as the construction of the Akosombo Hydroelectric Dam, which has altered sediment dynamics and water flow for communities in the volta delta such as Atiteti. These factors not only increase vulnerability to SLR and rSLR but also pose direct threats to the socio-economic stability and environmental sustainability of the communities. In contrast, Mumford, being a peri-urban area, experiences subsidence primarily due to intensive building and land development activities, along with groundwater extraction from local wells, highlighting different drivers of land subsidence between the two locations.

This study highlights the necessity for an integrated approach to coastal management in Mumford and Atiteti, advocating for robust monitoring and adaptive mitigation strategies that incorporate findings from SLR and rSLR projections. Adaptation measures such as constructing soft engineering sea defense and elevating infrastructure should be prioritized alongside policies aimed at reducing groundwater abstraction and managing sediment flows to mitigate future risks.

Policy interventions must also be aligned with SLR and rSLR projections under various SSP scenarios to prepare for different degrees of impact. This involves planning for worst-case scenarios under SSP 5-8.5, which predicts more severe and rapid increases in flooded areas. Engaging local communities in these planning processes ensures that the adaptation strategies are both effective and sustainable.

By synthesizing these findings, this thesis not only documents the current state of coastal subsidence in Mumford and Atiteti but also sets a course for future research and policy-making that will help mitigate the impacts of sea level rise and ensure the long-term resilience of these coastal communities.

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CHAPTER FIVE

5.0 ESTIMATING COASTAL FLOODING UNDER DIFFERENT PRECIPITATION SCENARIOS USING MALSTROEM MODEL

5.1 Introduction

The escalating frequency and intensity of rainfall, driven by climate change, present significant challenges to coastal regions worldwide, particularly regarding flooding and associated hazards. In the coastal communities of Mumford in the Gomoa District and Atiteti in the Volta Region of Ghana, the effects of heavy rainfall are compounded by geographic vulnerabilities and socio-economic practices, intensifying the risks of flooding and its consequent impacts on infrastructure, ecosystems, and livelihoods.

Recognizing the critical need to address these challenges, this chapter employs the Malstrøm model to identify potential flood-prone areas (bluespots) under various rainfall scenarios (Balstrøm & Crawford, 2018). By integrating this model with detailed DEM projections, this study aimed to assess the combined impact of rainfall and subsidence on Mumford and Atiteti, focusing on the resultant flooding patterns, number of people affected, and broader community impacts. This analysis was designed to provide a comprehensive overview of vulnerability to flooding, serving as a decision support tool for urban planning and doubling as an early warning system.

The objectives of this research were twofold: to offer precise predictive insights into flood risks under different rainfall scenarios, and to quantify the human and infrastructural vulnerabilities to these risks. By mapping bluespots that are particularly vulnerable to flooding, this study both contributes to the body of knowledge on flood prediction and offers practical insights that can inform local disaster risk management strategies. Furthermore, the findings are intended to

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guide the development of adaptive management strategies that enhance resilience and support the sustainability of coastal communities in the face of increasing climatic threats.

Through the application of advanced geospatial technologies and robust hydrological modelling, this chapter provides a detailed understanding of how precipitation and subsidence collectively influence the flood risk. The results are expected to inform practical interventions that enhance the resilience of Mumford and Atiteti, equipping local authorities and stakeholders with the tools necessary for effective planning and rapid responses to emerging flood events.

5.2 Methodology

5.2.1 Data Collection and Preparation

5.2.1.1 Topographical Data

A Digital Elevation Model (DEM) data with a spatial resolution of 12 meters was obtained from L3HARRIS (https://www.l3harris.com) for the two study communities. The DEM was in the UTM zone 30N format. The DEM was pre-processed to remove any errors or artifacts that might affect the identification of low-lying areas.

5.2.1.2 Rainfall Data

Historical daily rainfall data for 1970-2021 were obtained from the Ghana Meteorological Agency. The mean monthly rainfall data were analysed and trend projections were plotted based on the dataset. This rainfall analysis was integrated into the model to assess the rainfall-induced flooding risks.

5.2.1.3 Soil Data

The wetting factors for various soil types in the study areas were obtained in collaboration with the Soil Science Department of the University of Ghana. Each soil type has different

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characteristics. Organic soil absorbs and retains most of the water due to its high organic content, whereas clay soil absorbs water more slowly but retains it for longer periods. Sandy soils absorb water quickly but retain much of it. For this study, the following soil types were identified, and their corresponding wetting factors were factored into the Bluespot model:

- **Sandy Soils**: Characterized by high permeability and rapid drainage. These soils were assigned a lower wetting factor due to their ability to quickly absorb and drain water. A wetting factor of 6 mm was used in this study.
- **Clay and Silt Soils**: With smaller particles and low permeability, these soils exhibit slower water absorption and greater surface runoff. A low wetting factor was applied to account for the difficulty of absorption. A wetting factor of 3mm was used.
- **Organic Soils**: High organic content enables significant water absorption, justifying the use of an intermediate wetting factor of 4 mm in this study.

5.2.1.4 Subsidence Data

The DEM for 2040 and 2060 were integrated into the Malstroem model from the subsidence chapter in Objective 4 to enable an assessment of how land subsidence exacerbates flooding from precipitation. By integrating subsidence-adjusted DEMs into the Malstroem model, this methodology captures the compounded effects of both large-scale subsidence and local rainfall, offering a more accurate prediction of blue spot formation and expansion in response to future subsidence trends.

5.2.2 Malstroem model (Bluespot Model) Implementation

The installation and execution of the Malstroem model were carried out in Python version 3.12, facilitated through the Anaconda Prompt, which allowed for the streamlined installation of all necessary dependencies. This procedure ensures a reproducible and efficient setup for running the model. Chosen for its open-access nature, less processing power requirement and its

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effectiveness in identifying floodable zones, the Malstroem model aligns with the study's objectives of facilitating easy replication and continuity in flood monitoring efforts (Balstrøm & Crawford, 2018). The key assumptions of the model, including the impermeability of the terrain (which was corrected by introducing the wetting factor) and the simplification of water flow dynamics, were critically considered for their implications on the outcomes of the study's.

$$Bspot = \text{Identify (Waccum, Fpath)} \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$Sspill = \sum (Bspot, overflow\ paths) \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where Waccum is water accumulation, Fpath is flow path, Bspot is Bluespot and Sspill is the Spillover calculations.

The execution of Malstroem through the Anaconda Prompt and subsequent visualization of the generated bluespots and flow direction data in ArcGIS 10.7.1 provided an integrated approach for identifying potential flood accumulation zones (Skovbo Petersen, 2020).



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Figure 5.1: Local Bluespot map showing critically located buildings (dark grey) (Balstrøm & Crawford, 2018)

5.2.3 Analysis and Interpretation

5.2.3.1 Segmentation of DEMS based on the Soil Characteristics

Before simulating the flooding scenarios, the DEM for each study area was segmented based on soil characteristics. This segmentation allowed for more accurate modelling of flood risk by considering the different soil types present in each study location, which played a key role in the wetting factor component of the model.

5.2.3.2 Simulation of Flooded Areas

Using the segmented DEMs, the flooded areas for each study area were calculated using precipitation scenarios ranging from 1 to 300 mm. The 300 mm rainfall scenario was selected as the extreme case, reflecting the historical maximum daily rainfall records for the two study communities. After running the malstroem model for each scenario, 6 output files were obtained (accum.tif, bluespot.tif, flowdir, filled.tif, final depth.tif and final bluespot.tif). For this study, the focus was on the final bluespot.tif, which represents the total flooded areas, and the final depth.tif, which helps to show the depth of flooding.

5.2.3.3 Exporting Output files to ArcGIS and Flooded Area Calculations

The final bluespot.tif and final depth.tif files were exported to ArcGIS for further analysis. Using ArcGIS 10.7.1 tools such as raster-to-polygon conversion, flooded areas were calculated based on each rainfall scenario. The raster-to-polygon tool was used to convert the flood extent data into polygons, and the resulting polygons were quantified to determine the total flooded area in square meters for each rainfall scenario, ranging from 1 to 300 mm of precipitation. This step provides an overview of how different levels of rainfall affect the total flooded area

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in each community. Based on the soil type, wetting factors were deducted from each rainfall scenario. For instance, in sandy areas, the wetting factor is 6 mm**,** meaning that rainfall amounts from 0 to 6 mm would percolate into the soil, with flooding beginning at 7 mm of rainfall. Consequently, in the simulation, 7 mm of rainfall was assigned as 1 mm, and this adjustment was continued for higher precipitation scenarios up to 300 mm**.**

5.2.3.4 Estimation of Affected Population

The methodology for estimating the number of people affected by flooding followed these steps:

1. Population Density: Population data from the Ghana Statistical Service were used to calculate the population density (the product of the total population by the total area in square meters) of each community. The number of affected people was then calculated by multiplying the population density by the flooded area in square meters, based on the different precipitation scenarios.
2. Household Data**:** Orthomosiac images from drone flights were analysed to estimate the number of houses in each town. From the census data, the average number of people per household was determined, allowing us to extrapolate the number of people likely to be affected in each flooded zone.
3. By combining these data sources, the total population affected by flooding under the different precipitation scenarios was estimated.

5.2.3.5 Hazard Score Calculation

To assess flood hazard, the hazard score was calculated using normalized rainfall data from the past 51 years**.**

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1. Rainfall Bins (Normalization)**:** The rainfall data were segmented into bins representing different rainfall ranges. The probability density for each bin was calculated based on the historical data.
2. Flooded Areas**:** The flooded areas in square meters from the Malstroem model**,** adjusted for wetting factors, were used to represent the effect of flooding for each precipitation scenario.
3. Hazard Score Calculation**:** The probability density for each rainfall bin was multiplied by the corresponding flooded area. A histogram was plotted to visualize the hazard scores across different rainfall ranges.

$$Hazard = (Probability\ density * Effect(flooded\ area\ from\ malstroem)) \ldots\ldots (8)$$

5.2.3.6 Risk Index Calculation

The risk index was calculated by summing the hazard scores from the histograms. This index provides an overall measure of flood risk for each community. The risk index was used to classify communities into low, medium, or high-risk categories.

$$Risk\ index \sum Hazard \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

5.2.4 Validation and Sensitivity Analysis

To ensure the accuracy and reliability of the Bluespot model for identifying flood-prone areas, a comprehensive validation process was undertaken. This involved both qualitative and quantitative approaches utilizing local data sources, media reports, and field observations. Given the limitations of official spatial flood data, multiple strategies were employed to cross-check the model's predictions with real-world flood occurrences. The following steps outline

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the methods used for validation, followed by sensitivity analysis to test the robustness of the model under varying conditions.

5.2.4.1 Validation Steps:

1. Consultation with NADMO**:** The first validation step involved consulting the National Disaster Management Organization (NADMO**)** offices in Anloga and Apam municipalities. While NADMO had records of the number of people affected by flooding, they lacked data on the specific areas or square meters of flooded land, which limited the comparison of spatial flood coverage.
2. Media Reports**:** The second step was to analyze media reports of flooding in the study communities. These reports provide qualitative insights into the timing, severity, and affected areas during major flood events.
3. Community Interviews**:** In the third step, interviews were conducted with town residents to gather information on the number of people affected by flooding events. This information was cross-referenced with rainfall data from the Ghana Meteorological Agency (GMet**)** to establish a correlation between the intensity of rainfall and the extent of flood impact.
4. Field Observations**:** The final step involved conducting field visits after recent flood events. The coordinates of the affected buildings were recorded, and the watermarks on the walls were measured to capture the maximum floodwater 5.2.4.2 Sensitivity Analysis:

5.2.4.2 Sensitivity Analysis:

Sensitivity analysis was performed by varying the threshold values used for Bluespot detection. This involved adjusting parameters such as the minimum depth and area of depressions classified as bluespots. The goal was to test how changes in these input parameters

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influenced the model outputs, ensuring robustness in the identification of flood-prone areas under different conditions.

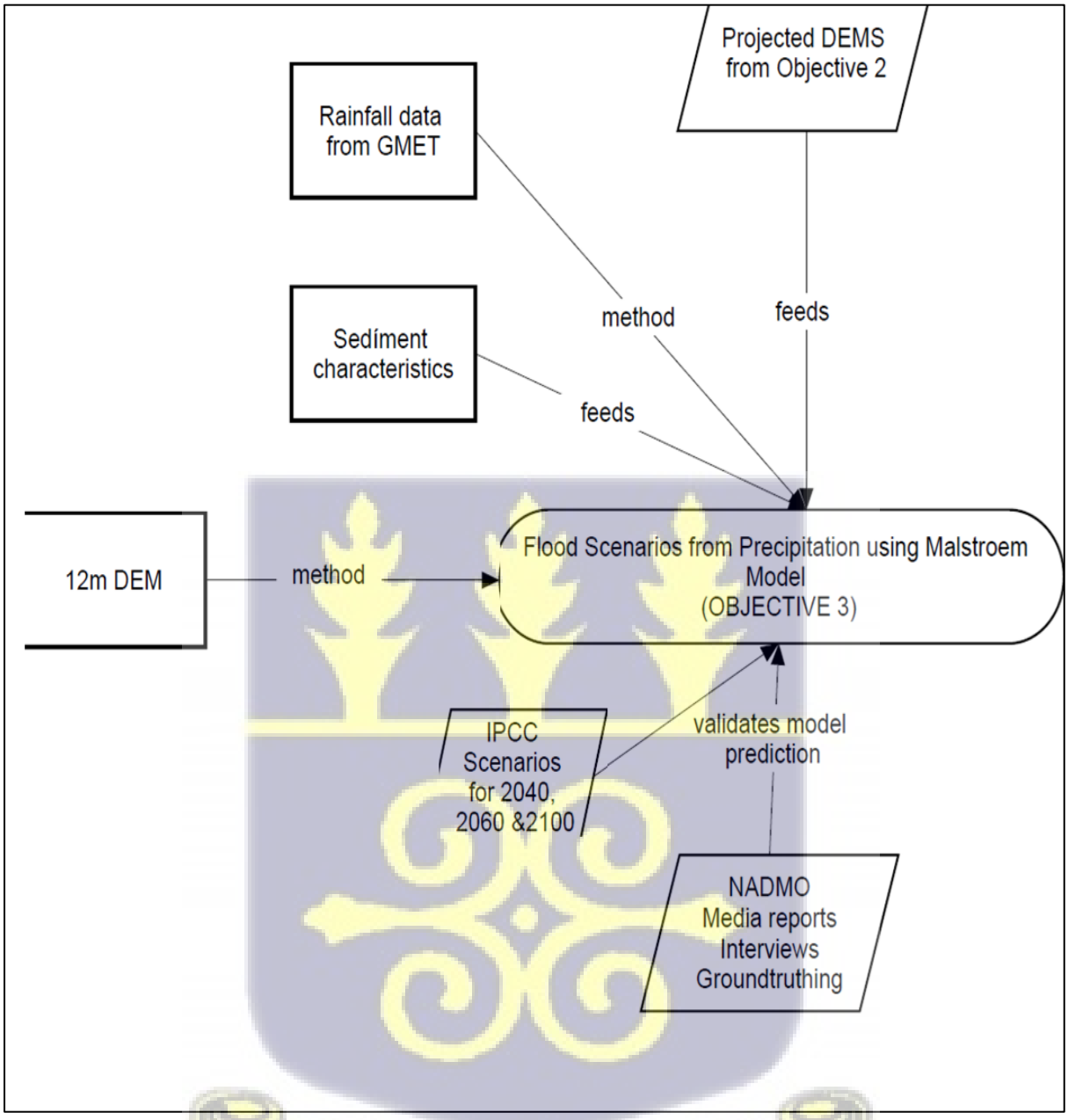


Figure 5.2: Workflow for the Malstroem model

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Model Assumptions and Limitations

Model Assumptions

The Malstrøm Bluespot model operates based on several simplifying assumptions regarding terrain and hydrological behaviour:

1. Impermeable Terrain Assumption: The model assumes that the ground surface is entirely impermeable, meaning all rainfall contributes to surface water accumulation. However, in this study, this limitation was addressed through the introduction of a wetting factor, which represents the amount of rainfall that infiltrates different soil types before surface flooding begins. The wetting factor varied according to soil characteristics such as sandy, clay/silt, and organic soils thus providing a more realistic estimation of initial infiltration losses
2. Absence of Temporal Dynamics: Malstrøm does not account for the passage of time; it assumes that water accumulation occurs instantaneously, without simulating the rate or duration of runoff, infiltration, or drainage.
3. Flow Direction Simplification: Water movement is determined using the D8 flow direction algorithm, where each cell drains into only one of its eight neighbouring cells the one with the steepest downslope gradient. This simplification may not accurately capture complex flow paths or lateral water spreading in flat terrain.
4. Sequential Filling of Depressions: Partially filled bluespots are assumed to fill sequentially in cell Z-order, from the lowest to the highest elevation within each depression. This approach neglects hydrodynamic interactions between adjacent depressions or overflow dynamics during intense rainfall.

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Model Limitations

Despite its effectiveness in identifying surface depressions and simulating potential rainfall-induced flooding, the Bluespot model even with the inclusion of wetting factors retains certain limitations:

1. No Hydrodynamic Processes: The model does not simulate flow velocity, turbulence, or lateral water exchange between adjacent depressions. It represents only the potential extent and depth of water accumulation, not the dynamics of flow or drainage.
2. Static Representation of Flooding: Because the model lacks a time component, it cannot describe how flooding develops, recedes, or interacts with rainfall duration and intensity. The results represent static snapshots of potential ponding under given rainfall scenarios.
3. Simplified Infiltration Representation: Although the wetting factor introduces infiltration effects, it is applied as a constant deduction for each soil type. This means that spatial and temporal variations in infiltration due to antecedent moisture, land cover, or rainfall intensity are not explicitly modelled.
4. Dependence on DEM Accuracy: The model's reliability is highly dependent on the quality and resolution of the DEM. Vertical inaccuracies or artefacts in the DEM may result in false depressions or misrepresentation of flow paths, especially in flat or vegetated terrain.
5. No Consideration of Drainage Infrastructure: Built drainage systems, culverts, or stormwater channels are not accounted for. Thus, in urban areas, the model may overestimate potential flooding where artificial drainage exists.

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6. Neglect of Surface Roughness and Land Use Effects: The model does not consider surface resistance or roughness (e.g., vegetation, roads, or urban structures) that influence overland flow behaviour and water retention capacity.

5.3 Results

5.3.1 Rainfall trend

5.3.1.1 Mumford (Site A)

The analysis of monthly rainfall values for Mumford from 1970 to 2021 revealed significant variability in both the average monthly rainfall and extreme daily events (figure 5.3). The highest recorded daily rainfall reached 214.7 mm, occurring in June 2005, which marks a 1 in 50-year value a clear outlier compared to other observed values. Despite this peak, the general trend of maximum daily rainfall events over the years fluctuated without any consistent upward or downward movement. The monthly averages remained relatively low, typically under 50 mm, with periodic spikes in extreme rainfall events, particularly during the early 1990s and the mid-2000s.

Linear trend analysis of the total annual rainfall over the study period indicated a gradual decline (figure 5.4). The recorded annual rainfall varied considerably, ranging between 400 mm and 1,400 mm. The overall trend points to a decrease in total yearly rainfall, with a recorded slope of -5.21 mm/year. Based on this linear trend, the projected rainfall for the next decade indicates a further decline, suggesting that by 2030, the annual rainfall in Mumford is expected to decrease by approximately 5% from the mean values of the last decade (2010–2020).

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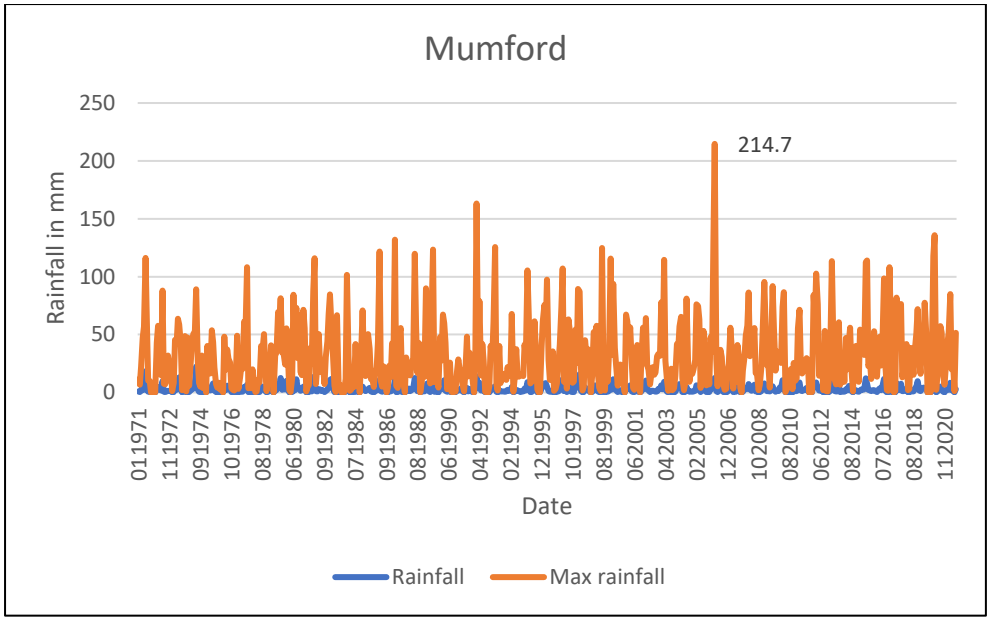


Figure 5.3 A graph showing the average monthly and maximum daily rainfall for Mumford

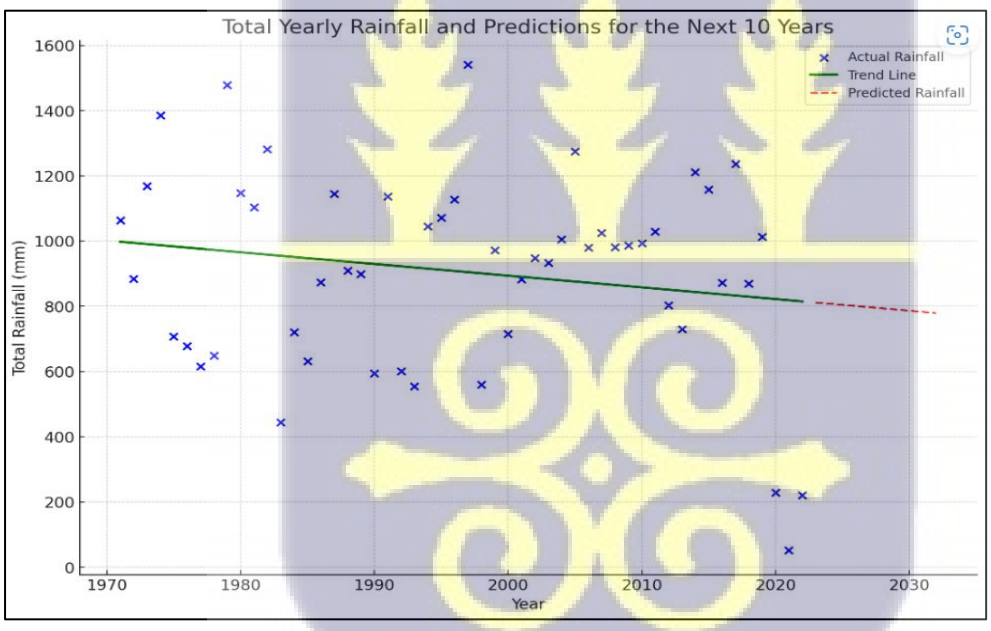


Figure 5.4 A graph showing rainfall trend from 1971 to 2020

5.3.1.2 Atiteti (Site B)

The analysis of monthly rainfall values for Atiteti from 1971 to 2017 revealed notable variability in both the average monthly rainfall and extreme daily events (figure 5.5). The highest recorded daily rainfall reached 205.7 mm, occurring in June 2002, which is a clear

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outlier compared to other values in the dataset. Despite this significant peak, the general trend of the maximum daily rainfall events over the years fluctuated without a consistent upward or downward pattern. Monthly averages typically remained below 50 mm, with occasional spikes in extreme rainfall events, especially in the early 1990s and the 2000s.

The linear trend analysis of the total annual rainfall over the study period showed a clear declining trend (figure 5.6). Recorded annual rainfall ranged from 400 mm to 1,200 mm, and the trend line suggests a decrease in yearly rainfall at a rate of -11.36 mm per year. This decline indicates that by 2030, the total annual rainfall in Atiteti could be reduced by approximately 15% from the mean values of the last decade (2010–2020).

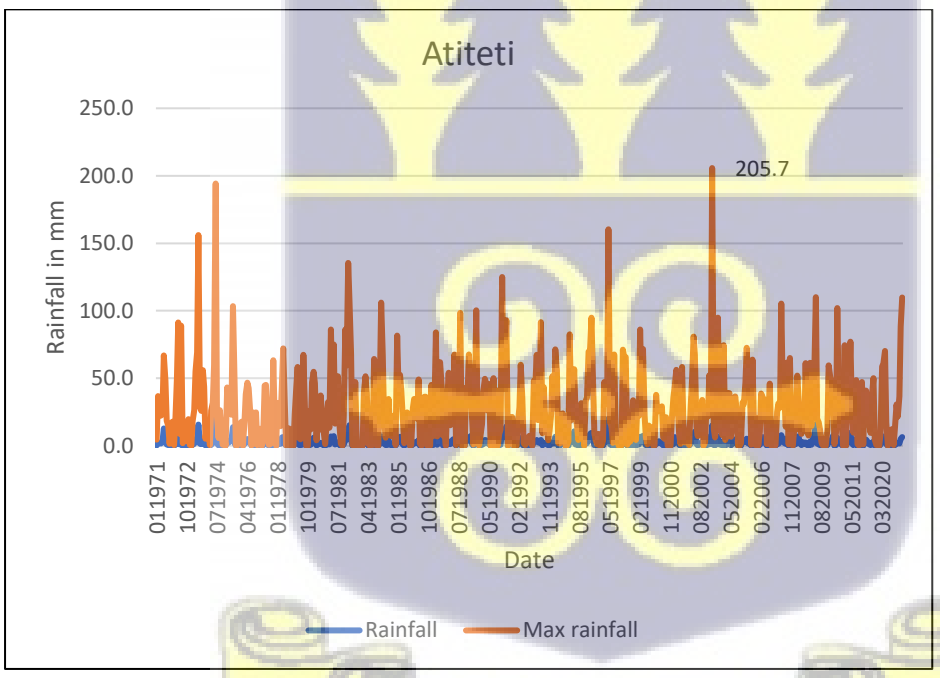


Figure 5.5 A graph showing the average monthly and maximum daily rainfall for Atiteti

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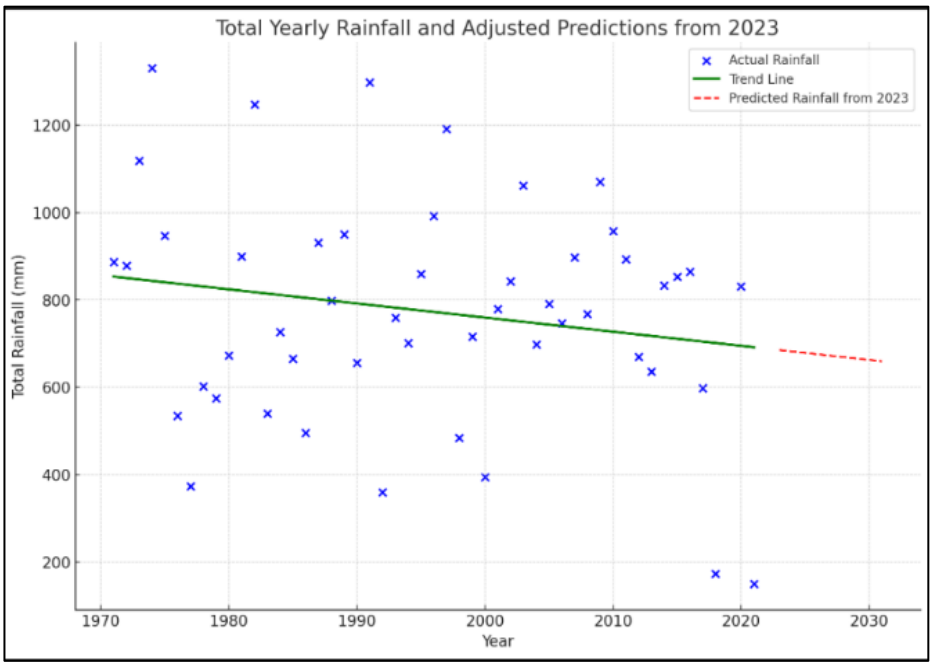


Figure 5.6 A graph showing rainfall trend from 1971 to 2020 for Atiteti

5.3.2 Flooding Scenarios from Precipitation Using the Malstroem model

5.3.2.1 Mumford (Site A)

The Malstroem model was applied to simulate potentially flooded areas in Mumford under varying rainfall scenarios ranging from 0 to 300 mm. The results are presented in square meters (sqm) of flooded area. The highest recorded daily rainfall for Mumford, 214.7 mm (June 2005), was included in the analysis to serve as a key historical reference for assessing flood risks.

Current DEM (Baseline)

As shown in Figure 5.7, the flooded area increased sharply with increasing rainfall intensity up to approximately 150 mm, after which the flood expansion curve began to plateau. At 150 mm of rainfall, approximately 50,000 m^2 of land is projected to be inundated. Beyond this threshold, additional rainfall did not significantly increase the extent of flooding, suggesting that the area's topography and drainage capacity reached a saturation point around this level of

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precipitation. The model projected that the highest recorded daily rainfall of 214.7 mm would lead to a near-maximal flooded area of approximately 50,000 m^2, with minimal additional flooding beyond this level. This indicates that even extreme historical rainfall events would saturate the landscape, causing widespread flooding under current topographical conditions.

2040 DEM with Subsidence

When incorporating subsidence into the 2040 DEM (figure 5.8), the flooded areas expanded more quickly compared to the current DEM. The flooded area reached 55,000 m^2 by 100 mm of rainfall and levelled off afterward, indicating that the landscape was more vulnerable to lower rainfall intensities due to subsidence. This suggests that by 2040, subsidence will cause flooding to occur earlier in rainfall events, with larger areas affected compared to the current conditions. The highest recorded daily rainfall of 214.7 mm would still result in a e maximum flooded area of approximately 55,000 m^2, showing that while the total area affected by flooding increases, the saturation threshold remains similar to the present day.

2060 DEM with Subsidence

In the 2060 DEM, the subsidence effects became even more pronounced (figure 5.9). The flooded area reached over 60,000 m^2 with 150 mm of rainfall and remained relatively stable beyond this point. The rapid expansion of flooded areas at lower rainfall levels shows that the landscape is becoming increasingly prone to flooding. Even moderate rainfall events of approximately 100 mm could result in significant flooding by 2060, with the highest recorded rainfall of 214.7 mm, flooding approximately 60,000 m^2. This represents a substantial increase in flood-prone areas compared to both the current and 2040 projections.

Hazard Score Calculation Based on Measured Precipitation Data

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As depicted in figure 5.10, the hazard score was highest for lower rainfall values and decreased sharply as rainfall intensity increased. Rainfall events between 0 and 30 mm contributed the most significantly to the hazard score, peaking at approximately 1800. This indicates that the probability of flooding is highest for low-to-moderate rainfall events, reflecting the frequency and likelihood of these events occurring within the historical rainfall dataset for Mumford.

Beyond 30 mm of rainfall, the hazard score declined steeply, and by 150 mm, it stabilized at very low values. This reflects the fact that while extreme rainfall events (e.g., above 100 mm) can cause severe flooding, they are relatively rare and thus contribute less to the overall hazard score than more frequent, lower-intensity rainfall events.

This hazard score analysis provides a quantitative measure of flood risk in Mumford, showing that the area is particularly vulnerable to more frequent lower rainfall events. As a result, even though extreme rainfall events like the 214.7 mm recorded in 2005 pose a significant risk, the overall hazard is more strongly influenced by less extreme but more frequent rainfall events

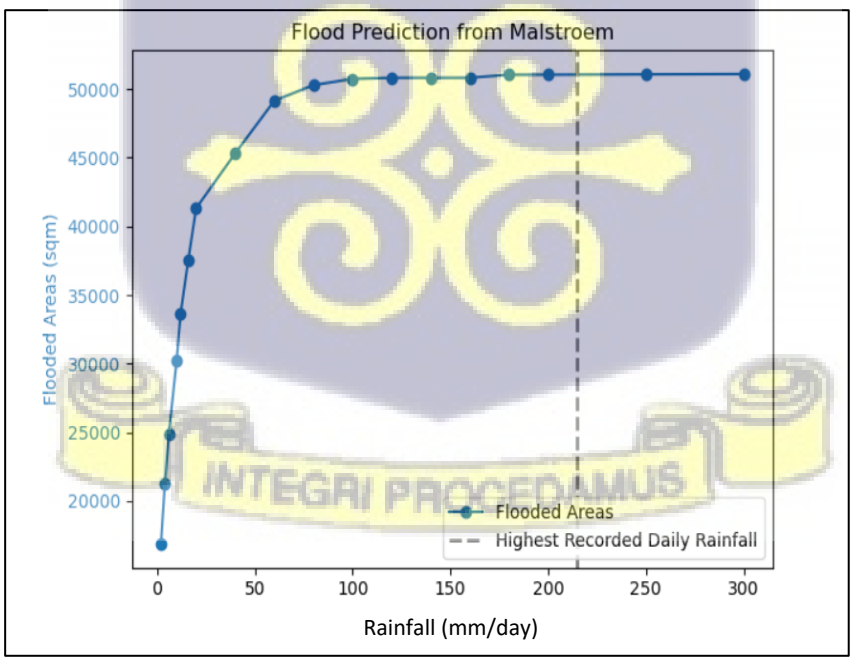


Figure 5.7 A graph showing predicted flooded areas in Mumford based on different rainfall scenarios

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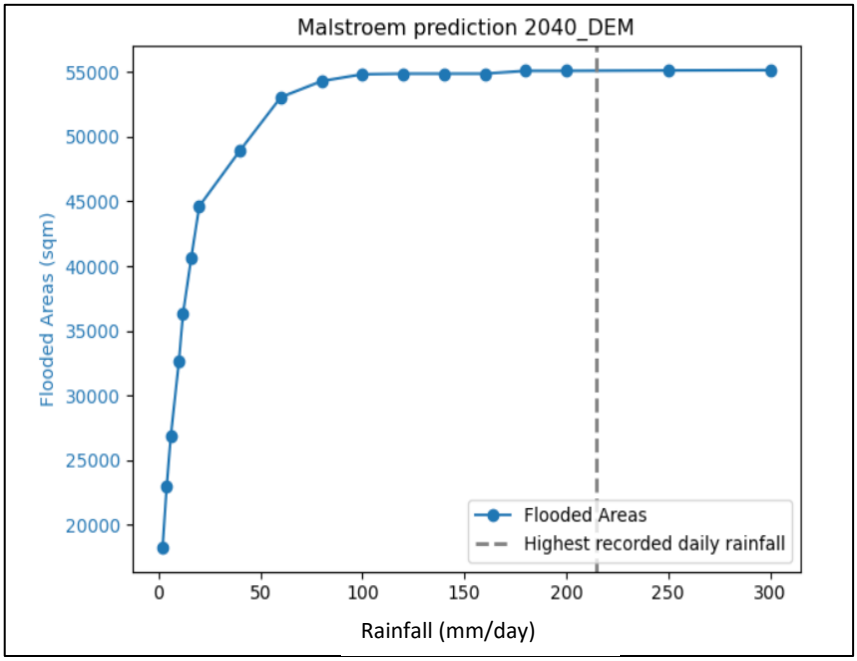
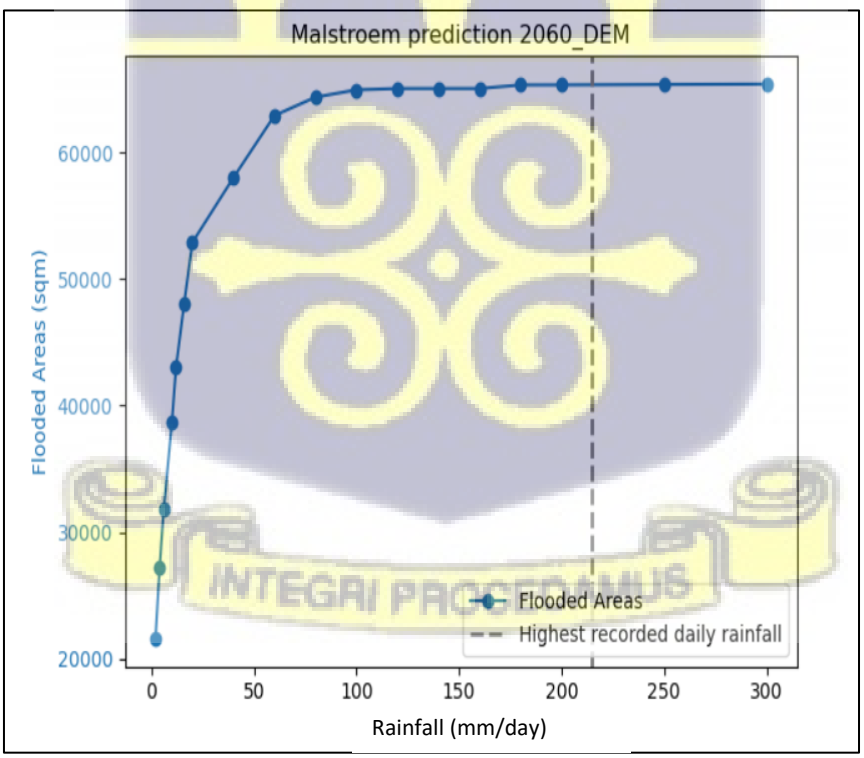


Figure 5.8 A graph showing model results of flooded areas in Mumford based on rainfall scenarios and future DEM (2040) as a result of Subsidence



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Figure 5.9 A graph showing model results of flooded areas in Mumford based on rainfall scenarios and future DEM (2060) as a result of Subsidence

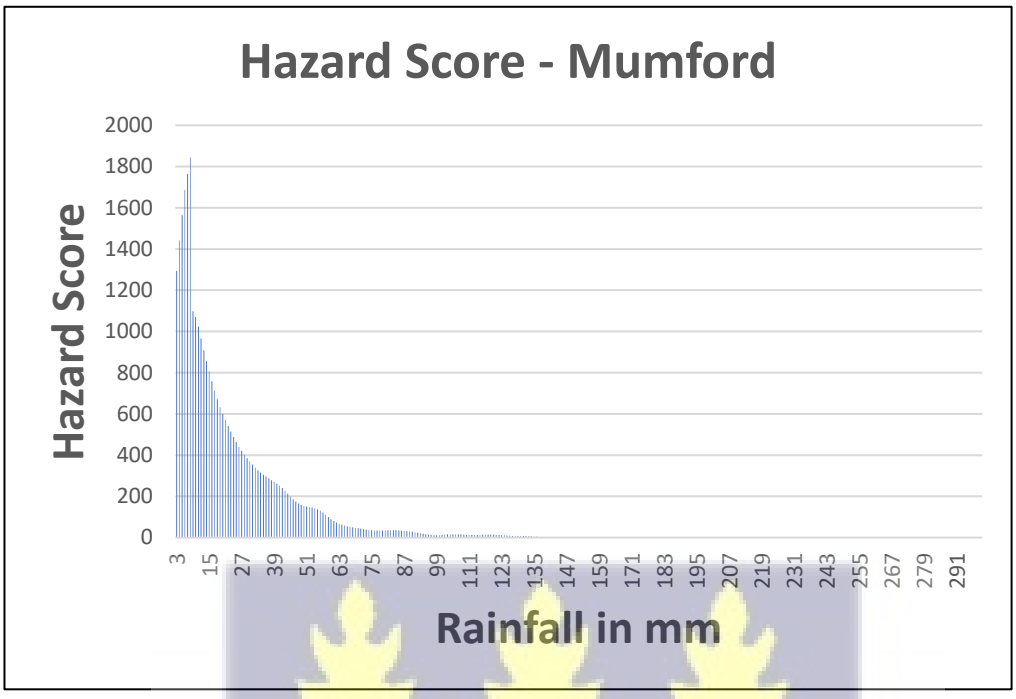


Figure 5.10 A graph showing Hazard Scores for Mumford

5.3.2.2 Atiteti (Site B)

The Bluespot model was applied to simulate potential flooded areas in Atiteti under varying rainfall scenarios ranging from 0 mm to 300 mm. The highest recorded daily rainfall of 205 mm serves as a historical reference point.

Current DEM (Baseline)

In the baseline scenario (Figure 5.11), the flooded areas increased progressively with rainfall intensity, with no indication of a plateau across the simulated rainfall levels. At 150 mm of rainfall, approximately 25,000 m^2 of land is projected to be flooded. With 215 mm of rainfall

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(the historical maximum), the flooded area expands to approximately 30,000 m^2. The flooding continues to increase steadily, reaching approximately 32,000 m^2 by 300 mm of rainfall.

2040 DEM with Subsidence

For the 2040 DEM scenario (Figure 5.12), incorporating subsidence led to a faster expansion of flooded areas compared to the baseline. At 100 mm of rainfall, approximately 22,000 m^2 of land is predicted to be flooded, increasing to approximately 30,000 sqm by 150 mm. By 215 mm, the flooded area reaches nearly 33,000 m^2, and flooding continues to rise to over 35,000 m^2 by 300 mm.

2060 DEM with Subsidence

Flooding becomes more extensive in the 2060 DEM scenario (Figure 5.13). At 150 mm of rainfall, more than 35,000 m^2 was inundated. The area affected by flooding reached approximately 40,000 m^2 at 215 mm and continued to increase steadily, reaching over 42,000 m^2 by 300 mm of rainfall.

Impacts of Rainfall on Population in Atiteti

Figure 5.15 shows the relationship between rainfall (mm) and the number of people affected in Atiteti. The graph demonstrates a clear upward trend, with the number of people affected increasing as the rainfall intensified. At lower rainfall levels (0 --50 mm), approximately 50-100 people are affected. As the precipitation reached 100 mm, the number of people affected increased significantly, exceeding 150. Beyond 150 mm of rainfall, the graph continues its upward slope, showing a steady increase, with more than 225 people affected under the highest rainfall scenario of 300 mm.

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Notably, the graph includes a vertical line representing the highest recorded daily rainfall, which occurred at approximately 200 mm. Beyond this threshold, the graph suggests that additional rainfall further exacerbates the impact on the population, highlighting the vulnerability of the community to extreme rainfall events. The steady increase throughout the range suggests that rainfall-driven flooding in the area tends to affect more people as precipitation intensifies, even without plateauing at higher values, indicating that the system remains sensitive to increases in rainfall of up to 300 mm.

Hazard Score Calculation Based on Measured Precipitation Data

The hazard score for Atiteti, shown in Figure 5.14, indicates how frequently specific rainfall scenarios occur in the region. The results showed a steep decline in the hazard score as the rainfall amount increased. For lower rainfall levels (below 50 mm), the hazard score is the highest, peaking around 2500, indicating that such rainfall events are frequent in the area. As rainfall intensified beyond 50 mm, the hazard score decreased progressively, with rainfall events greater than 100 mm occurring less frequently. When rainfall reaches 200 mm, the hazard score approaches zero, suggesting that extreme rainfall events are rare in Atiteti. This pattern highlights the dominance of low-to-moderate rainfall events in shaping the flood risk profile of the area.

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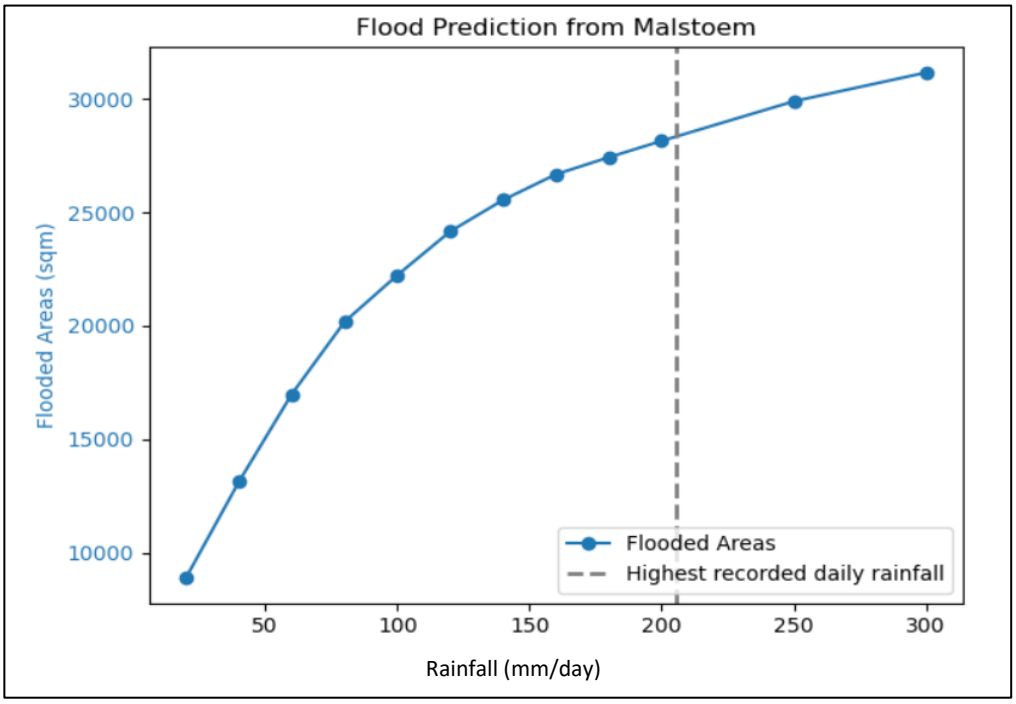
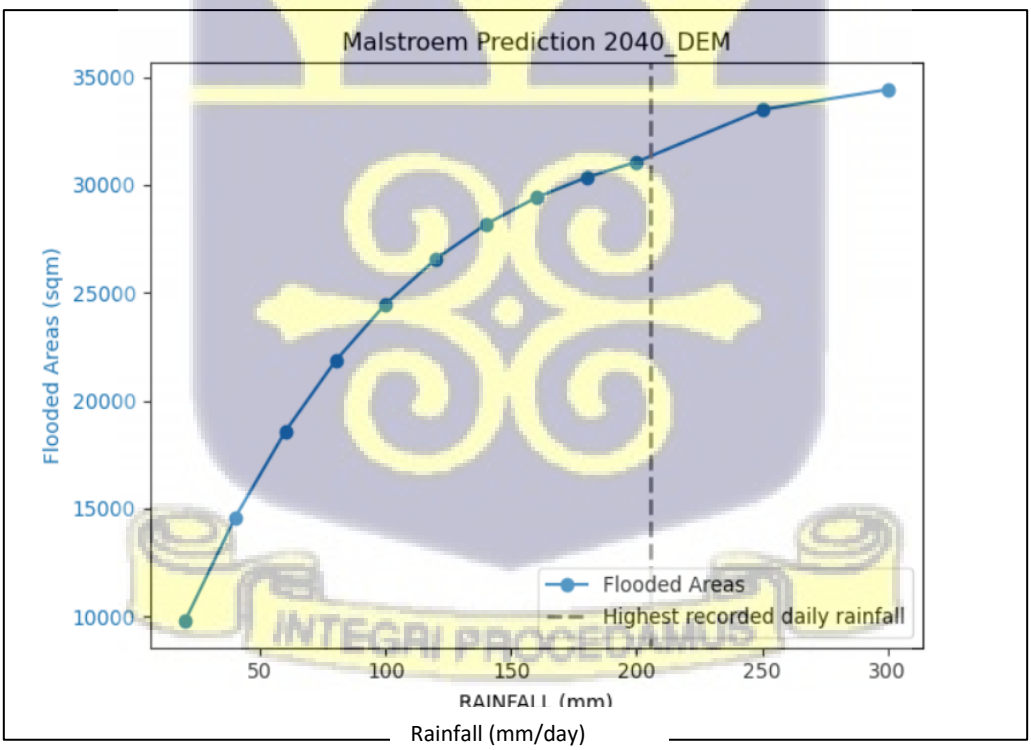


Figure 5.11 A graph showing predicted flooded areas in Atiteti based on different rainfall scenarios



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Figure 5.12 A graph showing model results of flooded areas in Atiteti based on different rainfall scenarios and future DEM (2040) as a result of Subsidence.

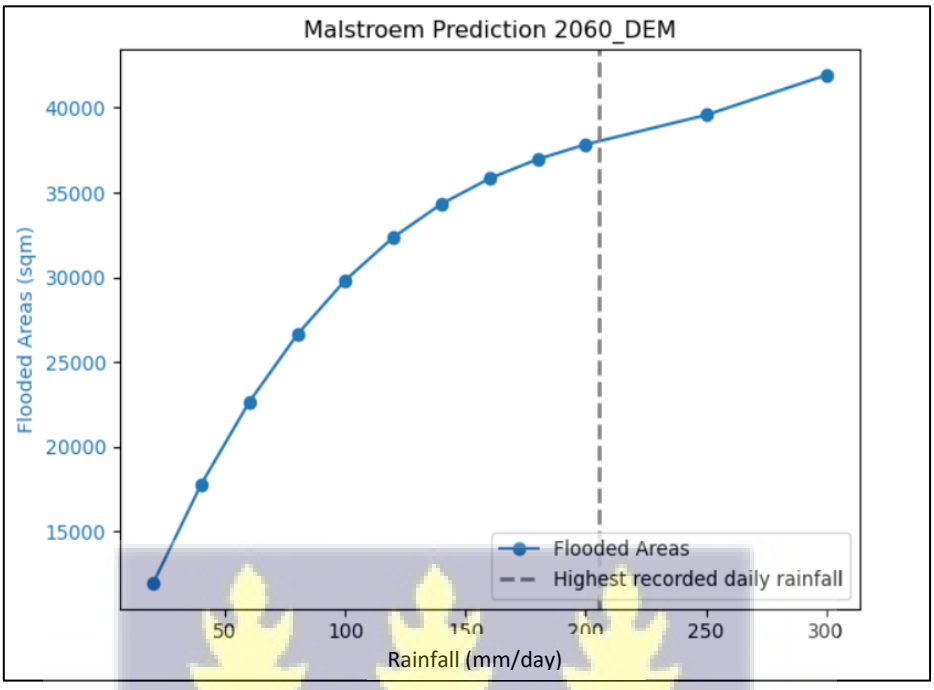


Figure 5.13 A graph showing model results of flooded areas in Atiteti based on different rainfall scenarios and future DEM (2060) as a result of Subsidence

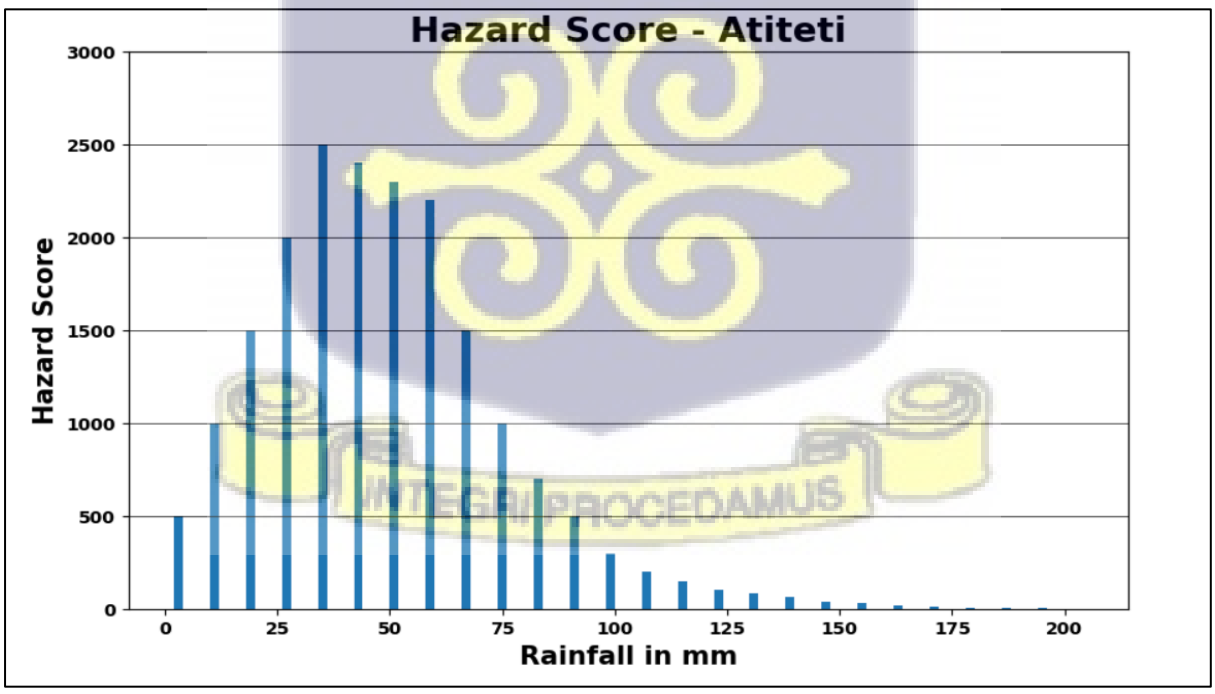


Figure 5.14 A graph showing Hazard Scores for Atiteti

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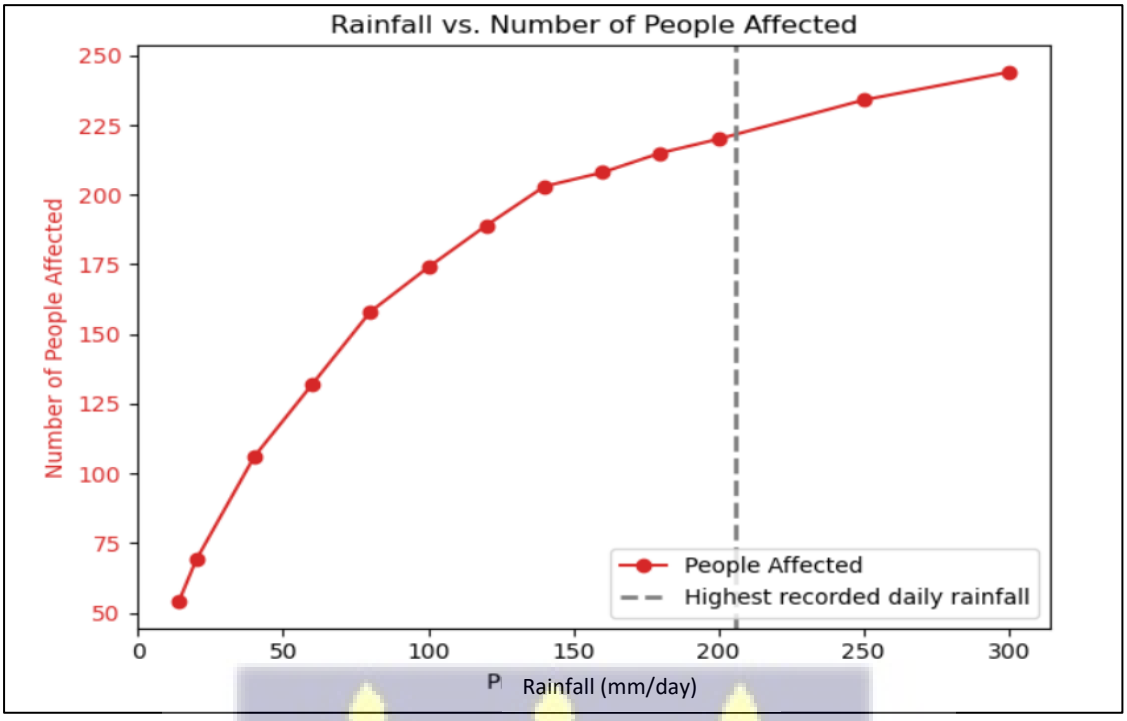


Figure 5.15 A graph showing the number of people who will be affected based on the modelled flooding scenarios

5.3.3 Risk from Hazard Score Calculations

The table below summarizes the hazard and risk scores for two key sites in the study area, Mumford and Atiteti. The hazard score indicates how frequently certain rainfall events occur in these locations, while the risk score quantifies the potential impact of these events in terms of flood severity and the population affected. Risk indications were categorized based on these scores.

Table 5.1 Hazard score and Risk calculations for Mumford and Atiteti

Site	Precipitation (mm)	Hazard Score	Risk	Risk Indication
Mumford	12	1844	104,109	Medium Risk
Atiteti	35	2495	175,406	High Risk

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Atiteti showed a high hazard score of 2495 for a rainfall event of 35 mm, indicating that this level of precipitation is common. The risk score for Atiteti was 175,406, reflecting the high vulnerability of the community to even low levels of rainfall due to significant exposure to flooding. Therefore, Atiteti is categorized as a high-risk area.

Mumford, with a hazard score of 1844 at 12 mm of rainfall, showed medium risk, with a risk score of 104,109. Although the frequency of rainfall events at Mumford is somewhat lower than that at Atiteti, the risk remains considerable, although it is less severe in comparison.

This analysis underscores the varying levels of risk across the study sites, highlighting that Atiteti is particularly vulnerable to flooding even with minimal rainfall.

5.4 Discussion

5.4.1 Rainfall Trends

The results of the rainfall trend analysis for both Mumford and Atiteti provided key insights into the historical variability and projected future trends in rainfall patterns for these coastal regions in Ghana. The discussion of these findings will focus on interpreting the variability in rainfall extremes and trends in the context of broader climate dynamics, the implications for coastal flooding, and how these trends compare with other studies in similar coastal environments.

Declining Rainfall Trends

Both Mumford and Atiteti exhibit a declining trend in total annual rainfall over the study period, with Mumford showing a decline of -5.21 mm per year and Atiteti experiencing a more rapid decline of -11.36 mm per year. These findings are consistent with global patterns

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observed in several tropical and subtropical regions, where decreases in annual precipitation have been linked to the effects of climate change, particularly the shifting of climate zones and weakening of the West African Monsoon (Nicholson, 2013). The decline in rainfall at these sites suggests a potential reduction in freshwater availability exacerbates water scarcity issues in the region, especially during the dry season when rainfall is minimal.

Moreover, the decline in rainfall observed in Atiteti is more pronounced than that in Mumford, with a projected reduction of 15% in total rainfall by 2030, compared to a 5% reduction for Mumford. This discrepancy could be attributed to the localized impacts of climate variability, as well as differences in geographical features between the two sites, with Atiteti's more exposed coastal position potentially contributing to higher sensitivity to changing weather patterns (Owusu *et al.*, 2021). Additionally, the decline in rainfall could have significant implications for the frequency and intensity of flood events in both areas because reduced annual rainfall does not necessarily correlate with a decrease in extreme rainfall events, which are the primary drivers of flooding.

Variability in Extreme Rainfall Events

The analysis of extreme daily rainfall events in both Mumford and Atiteti revealed significant variability, with notable outliers observed in 2005 and 2002, respectively. These events highlight the sporadic nature of extreme rainfall in these coastal areas, where intense rainfall can occur suddenly with limited predictability. This variability aligns with findings from other studies in tropical regions, where climate change has been linked to more frequent and intense extreme weather events, even in the context of declining total rainfall (Donat *et al.*, 2016). The presence of such outliers suggests that despite the overall downward trend in annual rainfall, the risk of extreme events remains high and may even increase in frequency due to the intensification of the hydrological cycle under climate change (IPCC, 2021).

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The occurrence of these extreme events has profound implications for the flood risk in coastal communities. In Mumford, the highest recorded daily rainfall of 214.7 mm in June 2005 likely contributed to significant flooding, given the area's relatively low elevation and poor drainage infrastructure. Similarly, in Atiteti, the 205.7 mm event in 2002 likely exacerbated coastal flooding, particularly given the area's vulnerability to tidal flooding and sea level rise (Mensah *et al*., 2021). These events underscore the importance of considering both long-term rainfall trends and short-term risk of extreme events when assessing flood vulnerability in coastal regions.

Implications for Coastal Flooding

The projected decline in rainfall, coupled with the continued occurrence of extreme events, presents a complex challenge for flood risk management in Mumford and Atiteti. Although reduced annual rainfall may lead to fewer flooding events overall, the potential for extreme rainfall to trigger severe floods remains high. This dual trend of declining annual rainfall and increasing extreme events has been observed in other coastal regions, where rising sea levels further compound the flood risk by reducing the drainage capacity of coastal areas (Vitousek *et al*., 2017). In Atiteti, where subsidence has already been identified as a contributing factor to increased flood vulnerability, the combination of reduced rainfall and extreme events can exacerbate the impacts of both fluvial and coastal flooding (Owusu *et al*., 2021).

Furthermore, declining rainfall trends may have significant implications for the resilience of coastal ecosystems and the livelihoods of these communities. Reduced rainfall could affect agricultural productivity and freshwater availability, whereas extreme events may cause significant damage to infrastructure, homes, and coastal ecosystems such as mangroves. These issues highlight the need for integrated flood risk management strategies that address both long-term trends in rainfall and the immediate risks posed by extreme events.

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Comparison to other Coastal Regions

The declining rainfall trends observed in Mumford and Atiteti are in line with broader findings from other coastal regions in West Africa, where a combination of climate variability and anthropogenic factors led to similar patterns of reduced rainfall and increased flood risk (Sylla *et al*., 2016). Studies in Senegal, Nigeria, and Sierra Leone have documented comparable trends, with coastal areas experiencing both reduced annual rainfall and more frequent extreme events, which are often attributed to the influence of Atlantic Ocean dynamics and changing atmospheric circulation patterns (Niang *et al*., 2014). Thus, the findings from this study contribute to the growing body of evidence highlighting the vulnerability of the West African coastal regions to the dual threats of reduced rainfall and increased flooding under climate change.

5.4.2 Projected Flooding Trends from Malstroem

The results of the Malstroem model simulations for Mumford and Atiteti reveal significant insights into the potential for flooding under varying rainfall scenarios, highlighting the role of both topography and subsidence in shaping flood vulnerability. This section discusses the implications of these findings for flood risk management, compares the susceptibility of the two site to flooding, and explores projected future risks driven by subsidence and climate change.

Mumford: Impact of Subsidence and Rainfall on Flooding

The Malstroem model results for Mumford showed a pronounced increase in flood-prone areas as rainfall intensified, with the flooded area plateauing at approximately 150 mm of rainfall under current conditions. This saturation point indicates that the area's natural topography and drainage system become overwhelmed beyond this rainfall threshold, which likely corresponds

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to the limits of the soil's absorption capacity and drainage infrastructure. Despite this plateau, the results suggest that extreme events, such as the historical 214.7 mm rainfall, still pose a significant risk, leading to near-maximal flooding with approximately 50,000 sqm of land inundated. This finding is consistent with studies in other coastal regions, where extreme events tend to saturate drainage systems, leading to widespread but localized flooding (Fowler & Wilby, 2010).

The projected 2040 and 2060 DEMs, which are subsidence factors, reveal a concerning trend. By 2040, the flooded area will increase to 55,000 m^2 at lower rainfall levels (100 mm), indicating that subsidence will exacerbate flooding, even at moderate rainfall intensities. This trend becomes more pronounced in the 2060 DEM, where the flooded area exceeds over 60,000 m^2 by 150 mm of rainfall. These results highlight that, with ongoing subsidence, Mumford will become increasingly vulnerable to flooding, even under less extreme rainfall conditions. This finding is supported by research showing that subsidence in coastal areas can significantly worsen flood risks by lowering the elevation of land relative to sea level and reducing drainage capacity (Syvitski *et al*., 2009).

The hazard score analysis further emphasizes Mumford's vulnerability to frequent, low to moderate rainfall events. The highest hazard scores were associated with rainfall between 0 and 30 mm, reflecting the frequency of such events in the historical rainfall dataset. Although extreme events like the 214.7 mm rainfall in 2005 are rare, their impact is still profound because of the already saturated landscape. The dual challenge of frequent moderate floods and occasional extreme events underlines the need for both short-term flood prevention strategies and long-term adaptation to mitigate subsidence-related risks (Nicholls & Cazenave, 2010).

Atiteti: A Rising Tide of Risk

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The results for Atiteti showed a different pattern compared with Mumford, with no clear plateau in the flooded area even when rainfall increased to 300 mm. This continuous expansion of flooded areas suggests that Atiteti's topography allows for greater floodwater spread across the landscape, particularly as the rainfall intensifies. At 150 mm of rainfall, approximately 25,000 m^2 of land is inundated under baseline conditions, and by 215 mm, the flooded area reaches approximately 30,000 m^2. The lack of a plateau may indicate that the terrain is flatter, allowing water to spread more freely, or that the drainage system is less effective in handling large volumes of runoff (Lara-Lara *et al*., 2020).

With subsidence incorporated into the 2040 and 2060 DEMs, Atiteti's flood risk becomes even more pronounced. By 2040, the flooded area will expand to nearly 33,000 m^2 at 215 mm of rainfall, and by 2060, it will reach approximately 40,000 m^2. This expansion is coupled with an increasing number of people affected by flooding, as the population impact graph shows a sharp rise beyond 100 mm of rainfall. This trend suggests that even moderate rainfall events, which are projected to become more frequent under future climate scenarios, could result in substantial flooding and displacement of residents of Atiteti. Studies in similar coastal communities have shown that the combination of rising sea levels, subsidence, and more intense rainfall events can lead to increased flood exposure and heightened population vulnerability's (Hinkel *et al*., 2014).

The hazard score analysis for Atiteti further underscores the community's vulnerability to frequent low-to-moderate rainfall events, with the highest hazard scores associated with rainfall below 50 mm. This indicates that flood risk in Atiteti is largely shaped by frequent but lower-intensity rainfall events despite the potential for catastrophic flooding during extreme events. The progressive increase in flooded areas and population impacts as rainfall intensifies highlights the ongoing sensitivity of Atiteti to current and future climate risks, necessitating

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robust flood mitigation measures that address the dual threats of subsidence and increasing rainfall intensity.

Comparison of Flood Vulnerability (Mumford and Atiteti)

The comparison between Mumford and Atiteti revealed key differences in their flood vulnerability profiles. While Mumford exhibits a clear plateau in flooded areas beyond 150 mm of rainfall, indicating a saturation point, Atiteti continues to experience an increase in flooded areas even at higher rainfall levels. This difference may be attributed to the varying topographical and hydrological characteristics of the two sites, with Mumford possibly having better drainage systems or natural barriers that limit flood expansion, whereas the flatter terrain of Atiteti allows water to spread more widely.

Subsidence further exacerbates these vulnerabilities, with both Mumford and Atiteti projected to experience more extensive flooding in the future. This happens when vertical land motion affects landscape elevation and drainage patterns, leading to increased local flooding (blue spots). As subsidence lowers the landscape, drainage capacity decreases, causing rainwater to pool in localized depressions. This large-scale flattening reduces the drainage gradient, making water more likely to accumulate, thereby enlarging blue spots. Subsidence also alters regional topography, redirecting runoff to local low points and intensifying flooding. Over time, the effects of subsidence become more pronounced, and by modelling future DEMs, we can predict how these changes will expand blue spot areas through increased water retention.

However, the rate of flood expansion is more pronounced in Atiteti, where subsidence leads to substantial increases in both flooded areas and population impact. This indicates that Atiteti may face greater challenges in managing future flood risks, particularly as population density increases and subsidence accelerates (Syvitski *et al*., 2009).

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Figure 5.16: An image showing flooding in some parts of Mumford after a rainfall event.



Figure 5.17 An image showing a flooded house in Atiteti after a rainfall event.

Implications for Coastal Management and Adaptation

The findings from the Malstroem model simulations highlight the urgent need for adaptive management strategies to mitigate the impact of both current and future flooding risks in Mumford and Atiteti. At both sites, subsidence is projected to significantly worsen flood risks, underscoring the importance of addressing land subsidence through improved land-use

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planning, enhanced drainage infrastructure, and, where feasible, the implementation of green infrastructure solutions such as wetland restoration to enhance natural flood mitigation (Temmerman *et al*., 2013).

Moreover, the hazard score analyses for both sites emphasize the importance of focusing not only on extreme rainfall events but also on more frequent, lower-intensity events that contribute significantly to flood risk. This suggests that flood management efforts should prioritize building resilience to moderate rainfall events, which are expected to become more frequent under climate change scenarios, while also preparing for occasional extreme event that can overwhelm existing flood defences.

Finally, community-based flood early warning systems and emergency response plans should be strengthened to account for the increasing population at risk at both sites. The projected increase in population impacts, particularly in Atiteti, suggests that future adaptation strategies must integrate social vulnerability assessments to ensure that most at-risk populations are protected from adverse effects of climate-induced flooding.

5.4.3 Risk from Hazard Score Calculation

The risk of flooding in Mumford and Atiteti was evaluated using hazard score calculations based on historical precipitation data. The hazard score provides a measure of how frequently specific rainfall scenarios occur, whereas the risk score quantifies the potential impact of these events on flood severity and the population affected. This section discusses the combined hazard and risk scores for these two key sites in the study area, highlighting the implications for flood management and comparing the findings with the existing literature.

Mumford Hazard Score and Risk

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The hazard score for Mumford indicates that lower-intensity rainfall events, particularly those below 30 mm, occur most frequently, with scores peaking at approximately 1800. These more frequent, lower-intensity events contributed significantly to recurrent flooding in the area. Similar findings were reported in studies by Noyola *et al*. (2021), who noted that urban areas are often more vulnerable to frequent, lower-intensity rainfall events due to inadequate drainage systems.

While larger rainfall events (above 100 mm) are less frequent, they pose a considerable flood risk, particularly during extreme rainfall events such as the 214.7 mm recorded in June 2005. Research by Akintunde *et al*. (2023) highlights the importance of considering extreme events in flood risk assessments, as their infrequency can lead to underestimation of the overall risk.

The risk score for Mumford complements the hazard score by quantifying potential impacts. The combination of frequent low-intensity events and rare but impactful extreme events positions Mumford at a moderate to high risk of recurrent flooding, requiring ongoing flood management efforts. These findings align with those of Diez *et al*. (2019), who emphasized that communities must develop adaptive strategies to manage flood risks associated with both frequent and extreme rainfall events.

Atiteti Hazard Score and Risk

In Atiteti, the hazard score for rainfall below 50 mm is notably high, peaking at approximately 2500, indicating that such rainfall events are frequent in the area. The steep decline in hazard scores beyond 100 mm reflects the rarity of extreme events, consistent with observations made by Oduro *et al*. (2022), who showed that less frequent, high-intensity rainfall can lead to severe flooding due to the lack of preparedness and infrastructure.

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The risk score for Atiteti underscores the population's vulnerability to frequent lower-intensity rainfall events and extreme rainfall events. With rainfall intensities of 150 mm a day in about once in two decades, the model predicts approximately 35,000 sqm will be flooded, affecting over 150 people. This relationship between rainfall and population impact aligns with the findings of Racz *et al*. (2021), who observed that increasing rainfall directly correlates with the number of individuals affected in vulnerable communities.

The steady increase in flooded areas and about 250 people affected by increasing rainfall intensity, even up to 300 mm, suggests that Atiteti is highly sensitive to rainfall-induced flooding. This sensitivity is exacerbated by subsidence, as noted by Van Kooten *et al*. (2020), emphasizing the need for integrated flood risk management strategies that address both environmental and socio-economic factors.

The results indicate that both sites are at substantial risk of flooding, but the nature of these risks differs. Mumford experiences moderate to high risks, primarily due to a combination of frequent low-intensity events and occasional extreme events. Conversely, Atiteti faces high risk, driven by frequent moderate rainfall events and an amplified impact from extreme events due to its sensitivity to subsidence.

These findings resonate with the broader literature on flood risk, which emphasizes the importance of addressing both frequent low-intensity rainfall and rare high-intensity events in flood management strategies (e.g., Jha *et al*., 2019). The risk scores suggest that targeted interventions, particularly around improving drainage infrastructure and preparing for population impacts, are critical for reducing flood risk in both locations.

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5.5 Conclusion

This study highlights the critical interplay between rainfall trends, extreme weather events, and subsidence in shaping flood risk profiles for coastal communities in Ghana, specifically in Mumford and Atiteti. The analysis of historical rainfall data reveals a concerning decline in total annual rainfall at both sites, with Atiteti experiencing a more pronounced reduction than Mumford. These trends align with broader climatic patterns observed in tropical regions, where changing weather dynamics have led to decreased precipitation and an increased frequency of extreme rainfall events (Nicholson, 2013; Donat *et al*., 2016).

These findings underscore the need for comprehensive flood risk management strategies that address not only declining rainfall but also the inherent variability and unpredictability of extreme rainfall events. The results from the Malstroem model simulations revealed significant vulnerabilities in both Mumford and Atiteti, exacerbated by subsidence. In Mumford, flooding risk is influenced by frequent low-intensity rainfall and occasional extreme events, whereas Atiteti demonstrates a more continuous increase in flood-prone areas with rainfall intensity, highlighting the site's heightened sensitivity to flooding due to its flatter terrain and ongoing land subsidence.

Furthermore, the hazard and risk score analyses indicated that both communities were at substantial risk, albeit for different reasons. The high hazard scores for frequent lower-intensity rainfall in Atiteti emphasize the need for targeted interventions to enhance drainage capacity and prepare for increased flooding impacts as climate change progresses (Racz *et al*., 2021). The projected increase in the population affected by flooding, particularly in Atiteti, calls for adaptive management strategies that integrate socio-economic factors and community resilience measures (Syvitski *et al*., 2009).

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CHAPTER SIX

6.0 SYNTHESIS OF OBJECTIVES

6.1 Introduction

This study aimed to determine the role of sea-level rise, subsidence, and precipitation on the incidence of coastal erosion and flooding in coastal communities. This overarching aim was achieved through three (3) distinct research objectives: The first research objective involved the use of UAV surveys and high-resolution satellite imagery to assess shoreline dynamics and estimate the rate of change along parts of Ghana's central and eastern coasts for short-term (January 2021- December 2023) and mid-term (1990-2023). This involved the generation of high-resolution orthophotos that were digitized to assess erosion rates. Uncertainties in these changes were quantified. The second objective involved the use of an Interferometric Synthetic Aperture Radar (InSAR) approach together with high-resolution DEMs in a bathtub model to calculate the risk of inundation. Interferograms from the SAR images were used to deduce vertical land movement for 2040 (short-term), 2060 (mid-term) and 2100 (long-term) following IPCC definitions. A projected coastal inundation assessment was performed using projected topographical changes and Sea Level Rise scenarios. Finally, the third objective looked at future predictions for flooding scenarios based on rainfall and changing topography. This was carried out by combining the Malstroem and INSAR approaches.

The research objectives were set out to answer three research questions: What is the trend of shoreline evolution along the central and eastern coast of Ghana? What are the differences in the area of inundation under the projected sea-level rise and relative sea-level rise scenarios across various temporal scales? What are the expected future flooding trends under the different precipitation scenarios? A summary of the answers to these questions by way of research findings is presented in this Chapter.

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6.1.1 Summary of Synthesized Research Findings

The analysis of shoreline dynamics revealed a stark contrast in erosion rates between Mumford and Atiteti. At Mumford, the mean erosion rate of -2.3 ± 1.23 m/yr, with erosion ranging from -0.1 m/yr to -5.5 m/yr, underscores the relatively moderate yet steady erosion that threatens over half of the shoreline (53.33%, equivalent to 71,271 m²). In contrast, Atiteti exhibits much more severe erosion, with a mean erosion rate of -25 ± 1.25 m/yr and rates reaching up to -44 m/yr. An alarming 93.33% of Atiteti's coastline (61,638 m²) was eroding, whereas only 6.67% was accreting. These extreme erosion rates, particularly in Atiteti, highlight the need for urgent coastal management interventions to prevent further land loss and protect the community infrastructure from ongoing destruction.

The high variability in erosion rates between the two sites points to the different drivers of coastal change, with human activities such as sand mining and infrastructure development playing a significant role. For instance, sand mining severely affects sediment transport dynamics, exacerbating erosion on the downdrift side of landing sites. These findings align with broader global trends that link human activities to coastal degradation, emphasizing the need for integrated management practices that regulate such activities.

Subsidence emerged as a critical factor exacerbating flooding risks in both study areas. The PSInSAR results revealed significant subsidence rates in Mumford and Atiteti, with some areas in the Volta Delta subsiding at rates exceeding 8 mm/yr. At Mumford, subsidence is primarily driven by intensive urban development and groundwater extraction, while at Atiteti, subsidence is compounded by natural processes and infrastructural changes, particularly the reduction in sediment supply following the construction of the Akosombo Dam.

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The Bathtub model projections, combined with subsidence and SLR data, show that flooding risks will increase substantially by 2100. In Atiteti, up to 47% of the area could be submerged under higher emission scenarios (SSP 5-8.5), while Mumford faces similar risks with significant land areas predicted to be below mean sea level by 2040. These findings highlight the urgent need for coastal management strategies that account for both SLR and relative sea level rise (rSLR) due to subsidence. The projected increase in the extent and severity of floods underlines the importance of integrating subsidence monitoring into flood risk assessments to develop more effective mitigation strategies.

The rainfall trend analysis highlights a concerning decline in total annual rainfall at both sites, with Mumford experiencing a decline of -5.21 mm per year and Atiteti seeing a more rapid decline of -11.36 mm per year. This reduction in rainfall is compounded by the increased frequency of extreme rainfall events, which remain the key drivers of flooding. Notable extreme events include the 214.7 mm recorded in Mumford in 2005 and the 205.7 mm event in Atiteti in 2002, both of which contributed to severe flooding in these coastal communities.

The Malstroem model simulations revealed significant vulnerability to flooding, particularly when combined with subsidence. In Mumford, the model shows that the flooded area plateaus at approximately 150 mm of rainfall, with approximately 50,000 m^2 of land inundated during extreme events like the 214.7 mm rainfall in 2005. The subsidence projections for 2040 and 2060 show even more rapid flood expansion, with flooded areas reaching 55,000 m^2 at 100 mm of rainfall by 2040 and over 60,000 m^2 by 2060.

At Atiteti, the situation was even more critical, with no clear plateau in flooded areas, even at higher rainfall levels. At 215 mm of rainfall, the flooded area reaches 30,000 m^2, and by 2060, the model predicts flooding of over 40,000 m^2. The hazard score analysis emphasized that

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frequent low-intensity rainfall events pose the highest flood risk in Atiteti, which is exacerbated by subsidence. This reinforces the need for robust flood mitigation measures, including improved drainage infrastructure and better preparedness for extreme events.

Hazard and risk score calculations provide quantitative insight into the flood risks faced by Mumford and Atiteti. In Mumford, lower-intensity rainfall events (< 30 mm) were the most frequent, with hazard scores peaking at approximately 1,800. Although extreme rainfall events are less common, their impact remains significant, as demonstrated by the flooding of 50,000 m^2 during the 214.7 mm event in 2005. This combination of frequent low-intensity events and occasional extreme events positions Mumford at a moderate to high flood risk.

Atiteti's hazard scores peaked at approximately 2,500 for rainfall below 50 mm, reflecting the community's vulnerability to frequent moderate rainfall events. With rainfall intensities of 150 mm, the model predicts that approximately 35,000 m^2 will be flooded, affecting over 150 people. The consistent increase in flooded areas and population impacts with increasing rainfall intensity, combined with the effects of subsidence, suggest that Atiteti faces a particularly high flood risk in the future.

INTEGRI PROCEDAMUS

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CHAPTER SEVEN

7.0 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This study aimed to comprehensively assess the effects of sea level rise (SLR), subsidence, and precipitation on coastal erosion and flooding in the coastal communities of Mumford and Atiteti, Ghana. By employing advanced methodologies, including UAV surveys, high-resolution satellite imagery, PSInSAR technology, and modelling techniques, this study addresses three distinct research objectives. The following sections summarize the key findings and implications for coastal management.

The first objective was to evaluate the shoreline dynamics and erosion rates in Mumford and Atiteti. The analysis revealed significant differences in the erosion patterns between the two sites. At Mumford, the shoreline exhibited moderate erosion, whereas Atiteti faced more severe and alarming rates of coastal retreat. These findings underscore the significant role of human activities, such as sand mining and coastal infrastructure development, in exacerbating coastal erosion.

These results emphasize the urgent need for coordinated actions to protect vulnerable coastlines. Integrated coastal management strategies should be developed to balance economic development with environmental sustainability by incorporating both short- and long-term approaches to mitigate erosion impacts while promoting sustainable practices.

The second objective assessed the subsidence patterns and their contribution to the flood risk in the study areas. The findings identified significant subsidence in both Mumford and Atiteti, influenced by natural processes and human activities such as groundwater extraction and land

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development. The study highlighted that these patterns of subsidence play a critical role in increasing flooding risks associated with sea level rise.

These insights underline the importance of addressing subsidence as a factor that exacerbates flooding risks. Effective policies must be implemented to regulate groundwater extraction and promote sustainable land-use practices to mitigate these risks. Integrating subsidence monitoring into coastal management frameworks is essential for the development of adaptive strategies that respond to ongoing changes.

The third objective was to analyze historical rainfall trends and their implications for flooding. The study revealed a decline in total annual rainfall at both sites. These trends contribute to a heightened risk of flooding, particularly as extreme rainfall events continue to pose a threat to both communities.

The analysis demonstrated that flooding areas in Mumford could significantly increase during extreme rainfall events, whereas Atiteti could see considerable expansions in flood-prone areas. The findings from hazard and risk score analyses further illustrated that both communities are at substantial risk of flooding, with Atiteti particularly vulnerable to frequent low-intensity rainfall and subsidence.

7.2 Recommendations

Based on the findings and conclusions drawn from this study, the following recommendations have been outlined to help reduce the impact of erosion and flooding on coastal communities.

- Establish a robust monitoring regime: Implementation of continuous monitoring of coastal dynamics using UAV technology and remote sensing to collect high-resolution

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data. This will facilitate real-time assessments of erosion and accretion patterns, enabling timely responses to changes in the coastal environment.

- Integrated Coastal Zone Management (ICZM): Develop a collaborative ICZM approach that integrates various stakeholders and disciplines. This should involve government agencies, local communities, and research institutions working together to create holistic, sustainable coastal management strategies.
- Explore the Sand Motor Concept: Investigate the potential of the sand motor concept by utilizing sediment deposition to enhance coastal resilience across other vulnerable coastal regions in Ghana. Pilot projects can help evaluate their effectiveness and adaptability.
- Reinstate and enforce sand mining laws: Strengthen the enforcement of existing regulations concerning sand mining activities. This includes regular inspections and penalties for non-compliance to prevent the degradation of coastal systems and ensure sustainable sediment management.
- Implement buffer zones: Establish buffer zones along coastal areas to protect sensitive ecosystems and mitigate the impact of human activities on erosion and flooding. These zones can serve as natural barriers to enhance coastal resilience.
- Construct artificial dunes: Evaluate the feasibility of creating artificial dunes to serve as protective barriers against storm surges and erosion. This approach can be coupled with thew use of native vegetation to enhance stability and biodiversity.
- Long-term monitoring of sea-level rise: Set up tidal monitoring stations to provide accurate and long-term data on sea-level rise. These data are crucial for understanding local SLR trends and informing adaptive management strategies.
- Promote renewable energy sources: Avoid petroleum extraction and transition to more renewable and environmentally-friendly energy sources to minimize the ecological

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footprint of coastal communities. This includes harnessing solar, wind, and tidal energy.

- Reduce catchment area modifications: Mitigate catchment area modifications and upstream river obstructions that contribute to altered sediment dynamics. This could involve restoring natural river flows and enhancing watershed management practices.
- Utilize advanced InSAR measurements: Employ advanced InSAR technology for precise measurements of land subsidence and deformation. Regular updates to these data can provide insights into ongoing subsidence trends and inform risk assessments.
- Incorporate early warning systems: Integrate early warning systems and decision-support tools into urban planning processes. This will enhance community preparedness for flooding events and allow for timely evacuation and resource allocation.
- Develop flood monitoring stations: Establish dedicated flood monitoring stations equipped with real-time data collection tools. This will enable a better forecasting of flood events and enhance community resilience.
- Continuous model calibration and validation: Regularly calibrate and validate the predictive models used in coastal management to ensure that they reflect current conditions and accurately predict future scenarios. This will enhance the reliability of the planning efforts.
- Create localized robust models: Develop localized models that account for the unique geographical and socio-economic factors affecting coastal communities. Tailoring models in specific contexts can improve the effectiveness of management strategies.
- Increase the number of Ground Control Points (GCPs): To improve the accuracy of spatial analyses, it is recommended to increase the number of GCPs distributed across the study area. Utilizing Real-Time Kinematic (RTK) surveying equipment will

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enhance the coordinate precision and minimize positional errors, providing a more robust foundation for subsequent analyses.

- Utilize higher resolution Digital Elevation Models (DEMs): Instead of relying on the 12m L3Harris DEM, consider procuring a higher resolution DEM or generating site-specific DEMs using UAV technology prior to modelling. This approach will enhance the fidelity of topographic data and improve the accuracy of inundation and flood modelling.
- Employ multiple modelling approaches: While an open-source model was utilized, future studies should incorporate two or three different modelling platforms to simulate various scenarios. Comparing the results across models will help to identify the most accurate and reliable methods for predicting coastal flooding and erosion.
- Upgrade processing hardware for ESA SNAP analysis: The subsidence analysis conducted using ESA SNAP on an Nvidia GTX 1080 Ti processor with 64GB RAM experienced limitations in processing speed. Future research should consider upgrading to more powerful processors with greater RAM capacities to facilitate faster data processing and analysis.
- Integrate tide gauge data for sea-level reconstruction: While NASA's water level data were used in this study, future work should prioritize the use of local tide gauge measurements for sea level reconstruction. This approach provides more accurate and localized water level data, thereby enhancing the reliability of flood risk assessments.
- Implement advanced remote sensing techniques: Future studies could benefit from incorporating advanced remote sensing techniques, such as LiDAR, to obtain high-resolution topographical and bathymetric data. These data can improve the understanding of coastal morphology and enhance modelling accuracy.

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- Enhance data integration techniques: Future work should explore more sophisticated data integration techniques, such as machine learning algorithms, to synthesize various datasets



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9.0 APPENDIX

APPENDIX A: CONCEPT FOR EROSION AND FLOODING

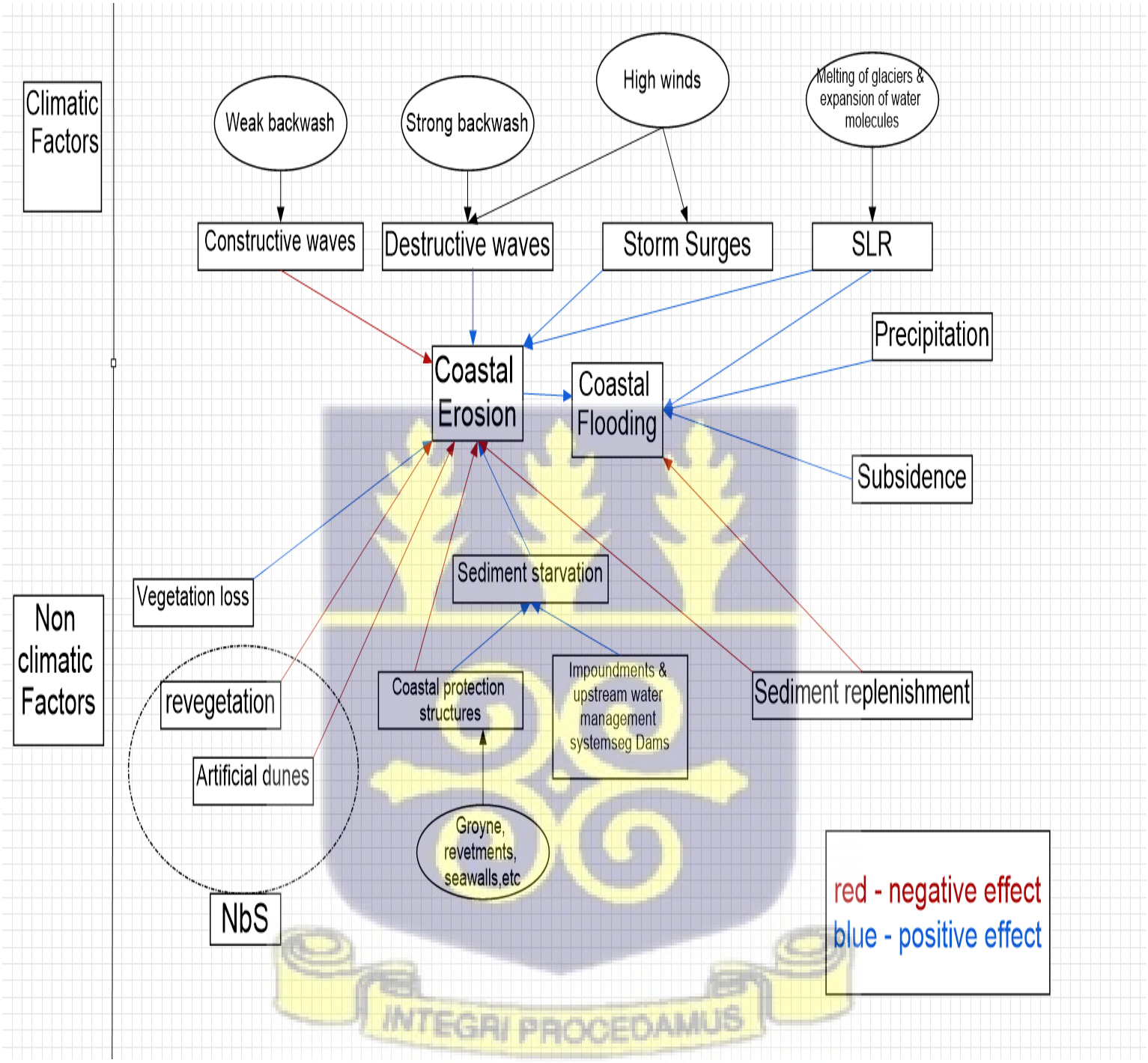


Figure 9.1: An illustration of the different factors that affects flooding and erosion.

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APPENDIX B: SHORELINE EVOLUTION DYNAMICS

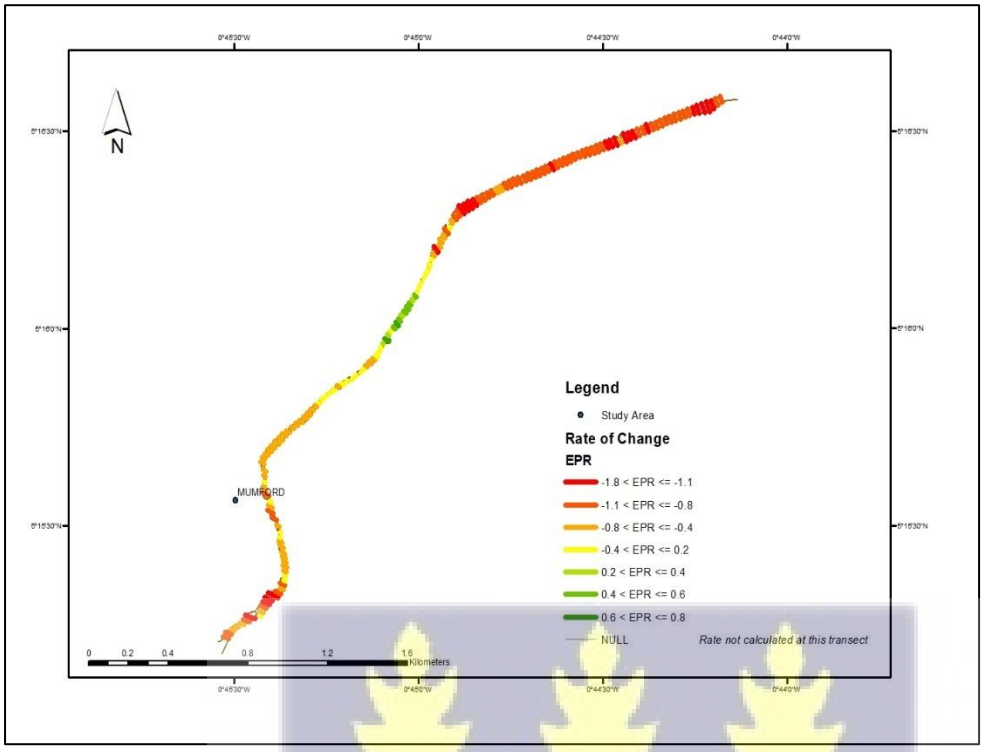


Figure 9.2: End Point Rate (EPR) for Mumford

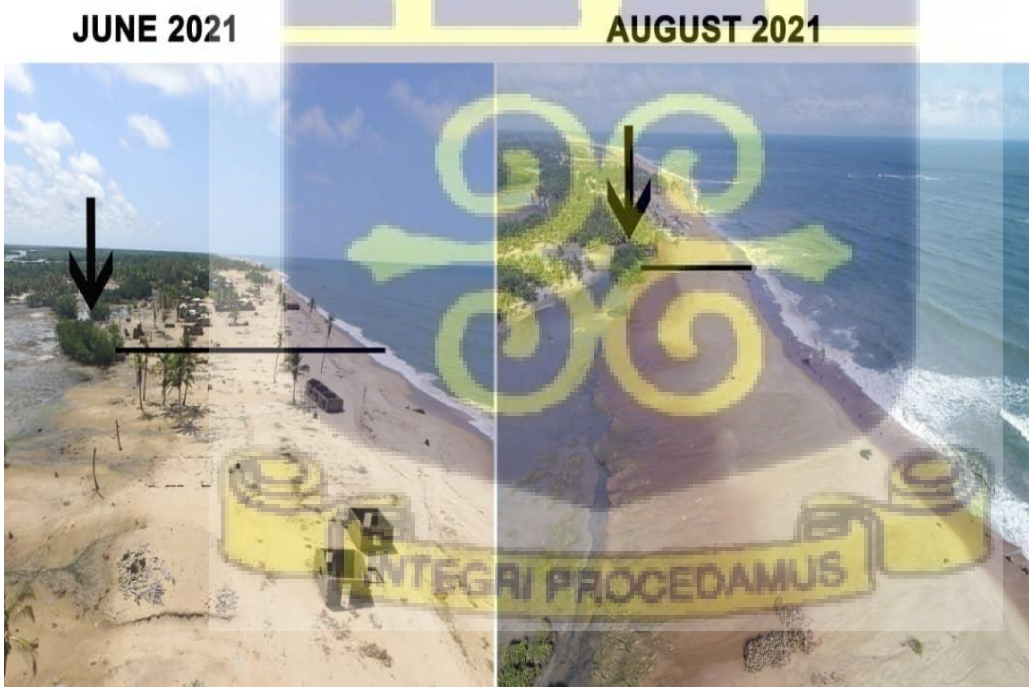


Figure 9.3: An image showing drastic changes in Atiteti after a storm event

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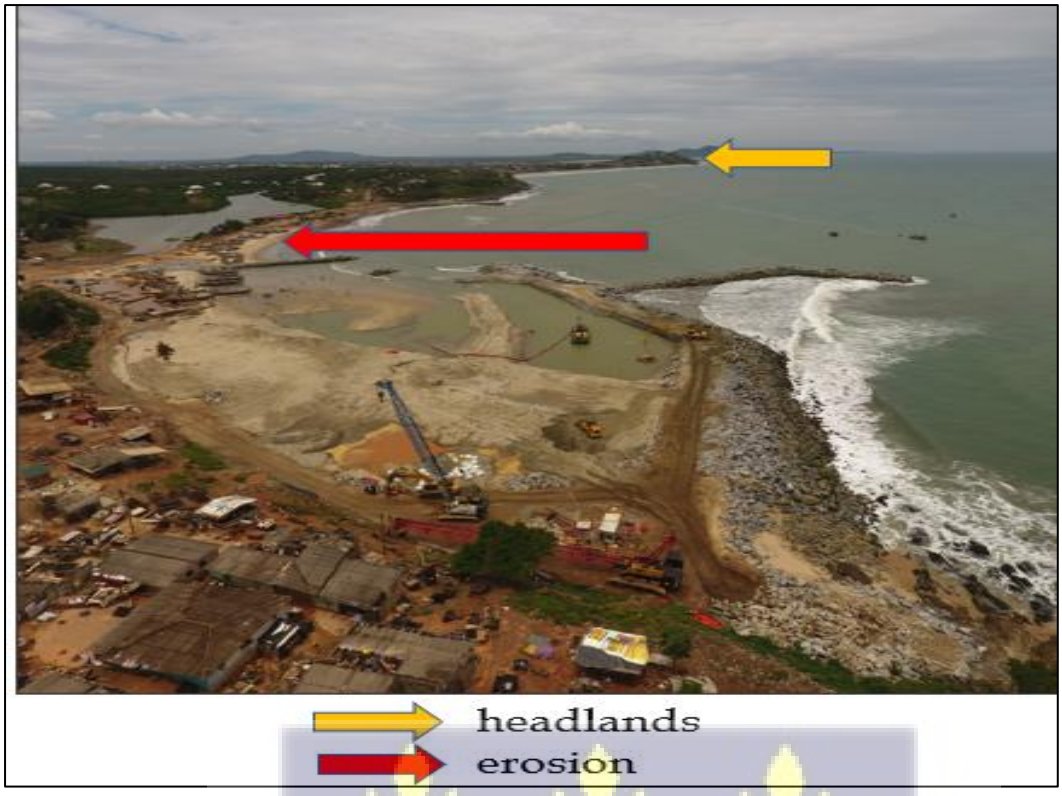


Figure 9.4: An image showing the Landing site construction in Mumford

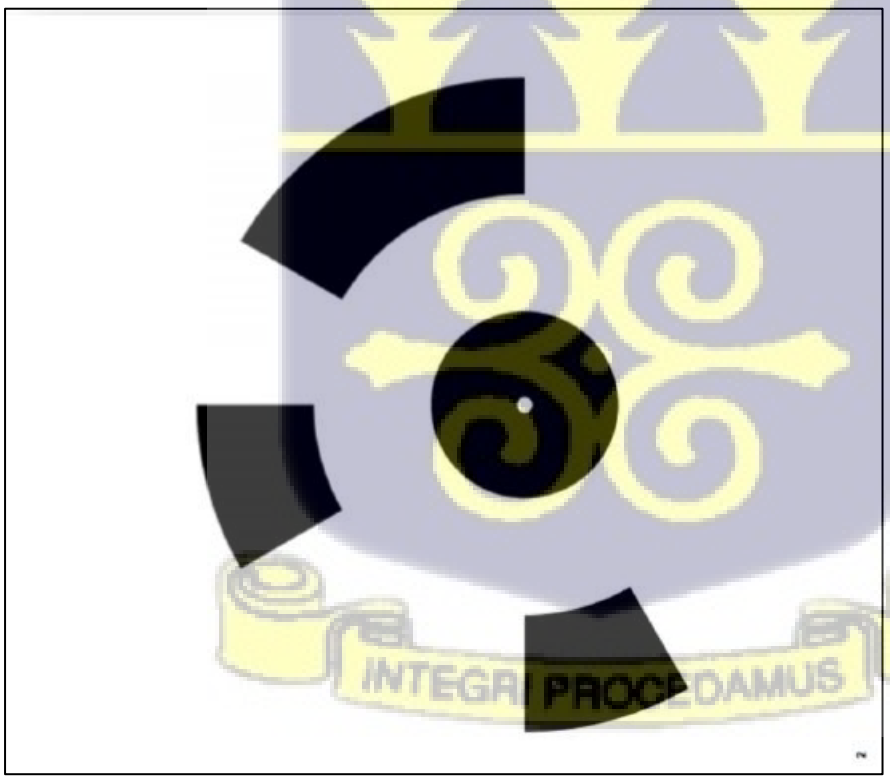


Figure 9.5: GCP marker for drone flights

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APPENDIX C: SUBSIDENCE, SEA LEVEL RISE AND RELATIVE SEA LEVEL RISE

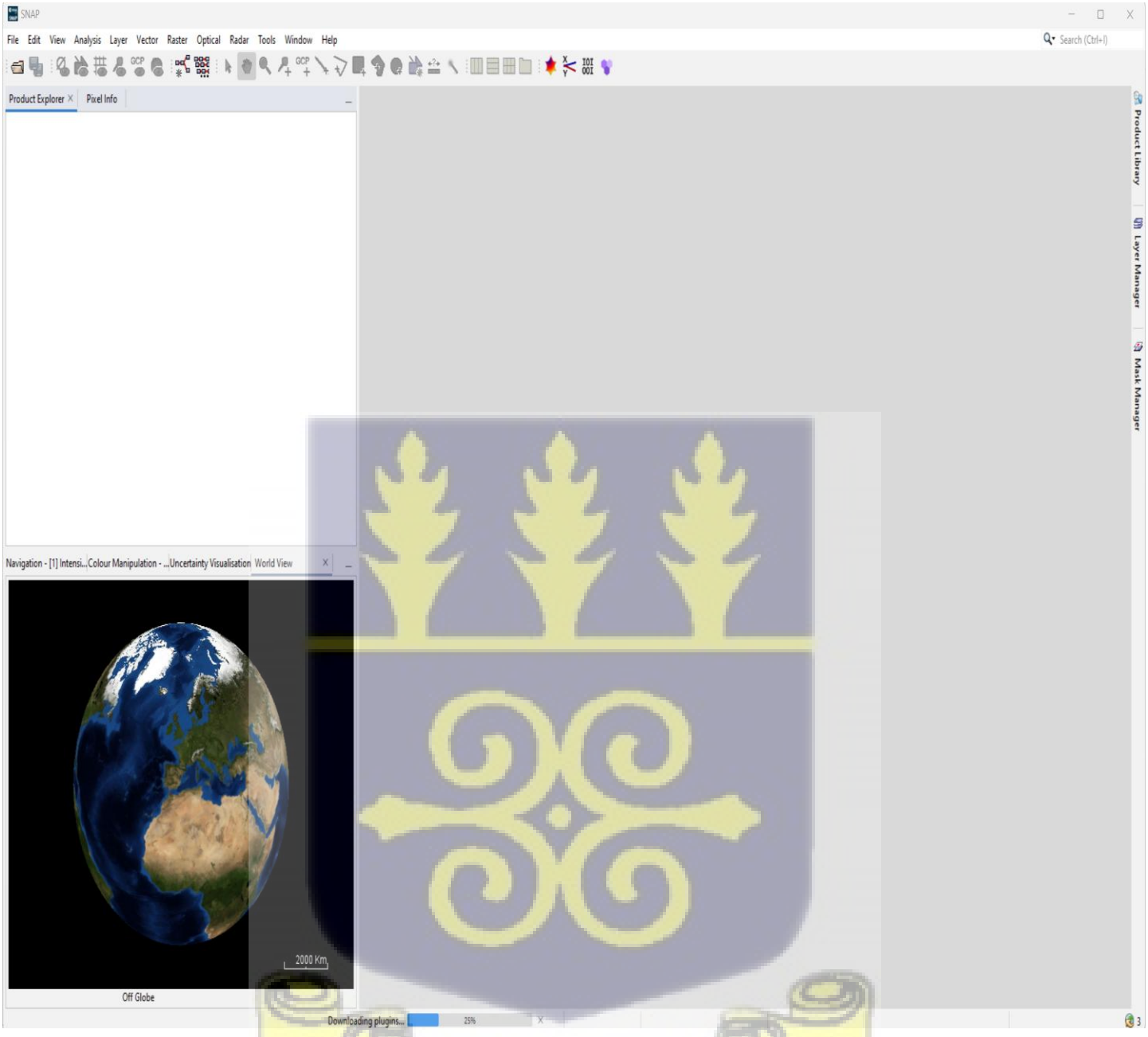


Figure 9.6: An interface of the ESA SNAP software.

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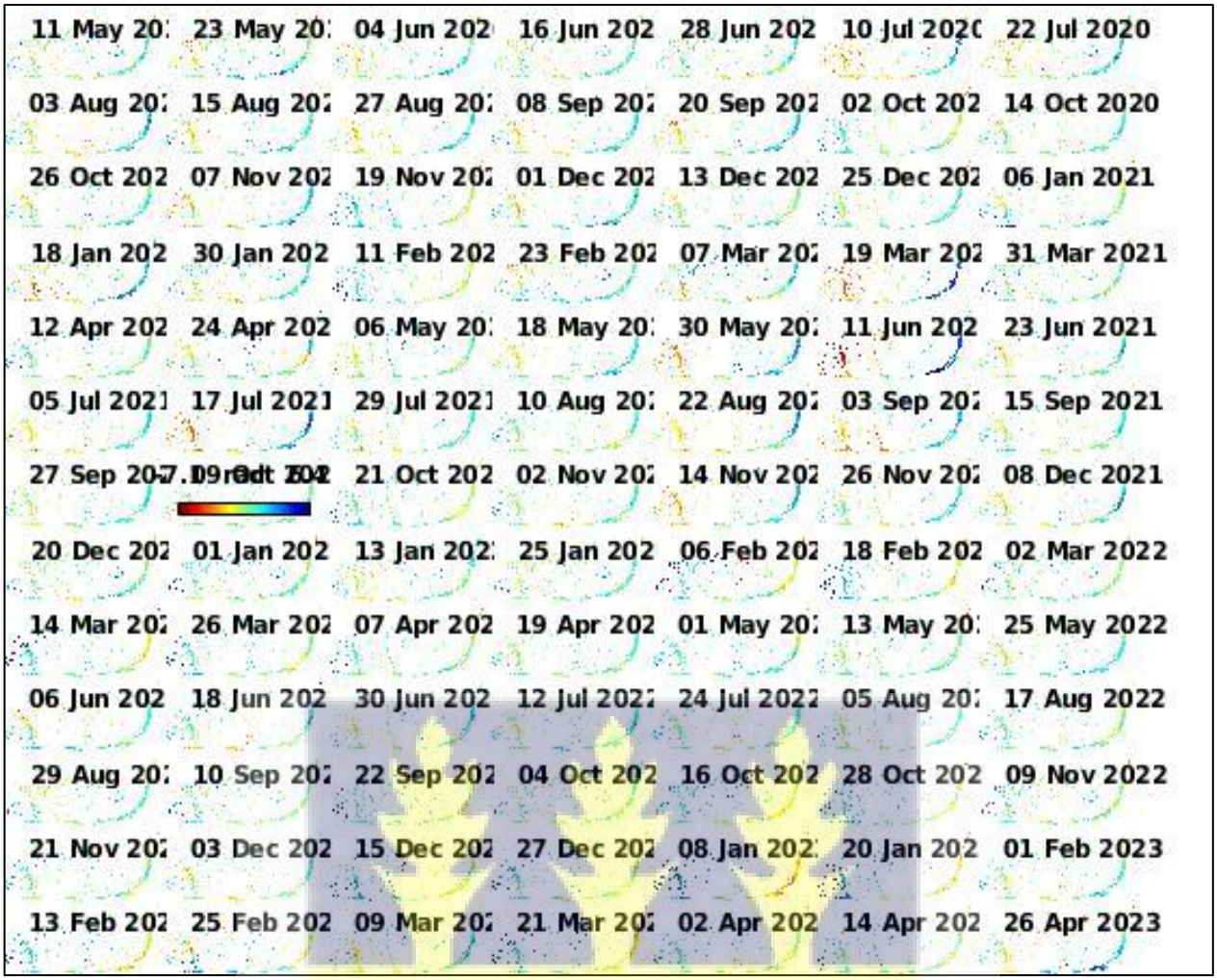
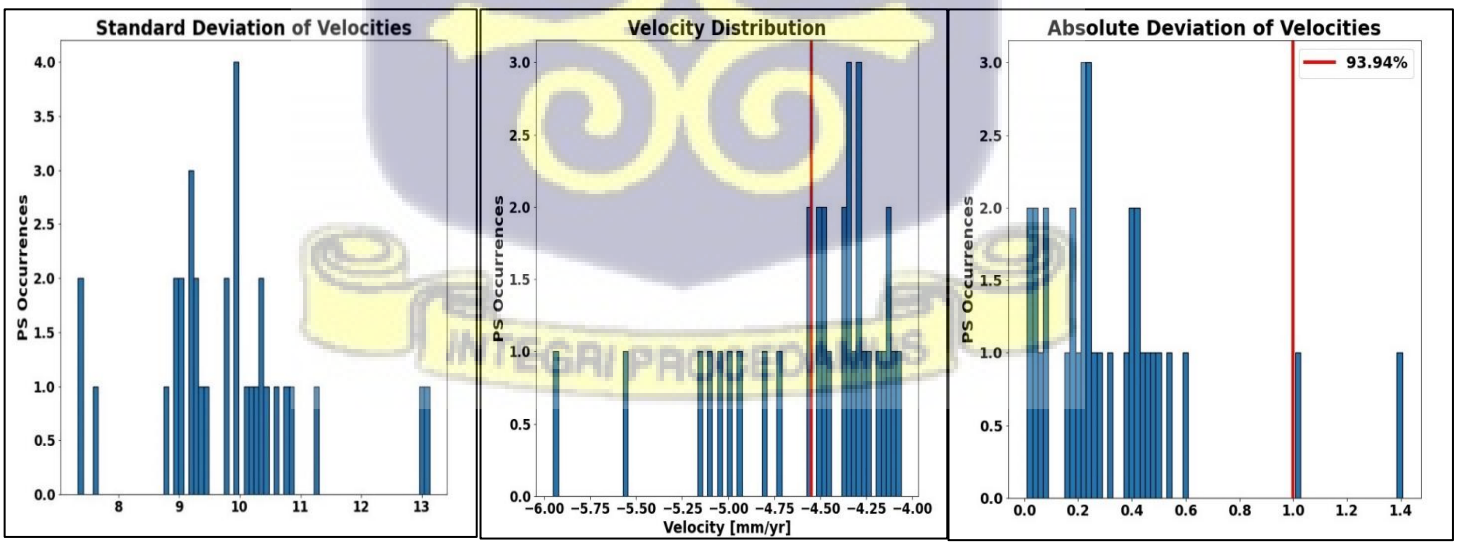


Figure 9.7: An image showing some generated interferograms during the subsidence analysis



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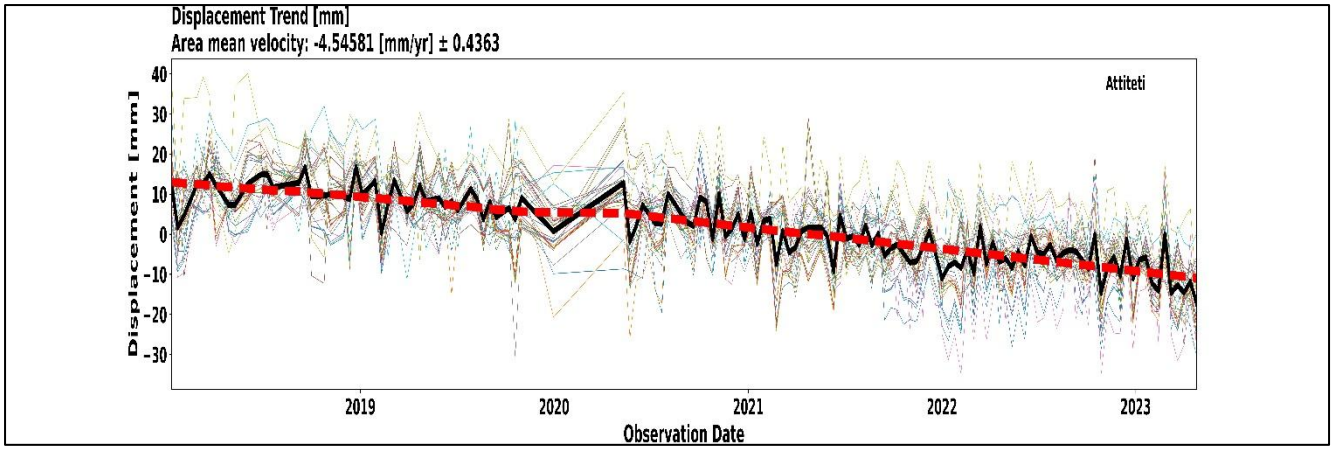
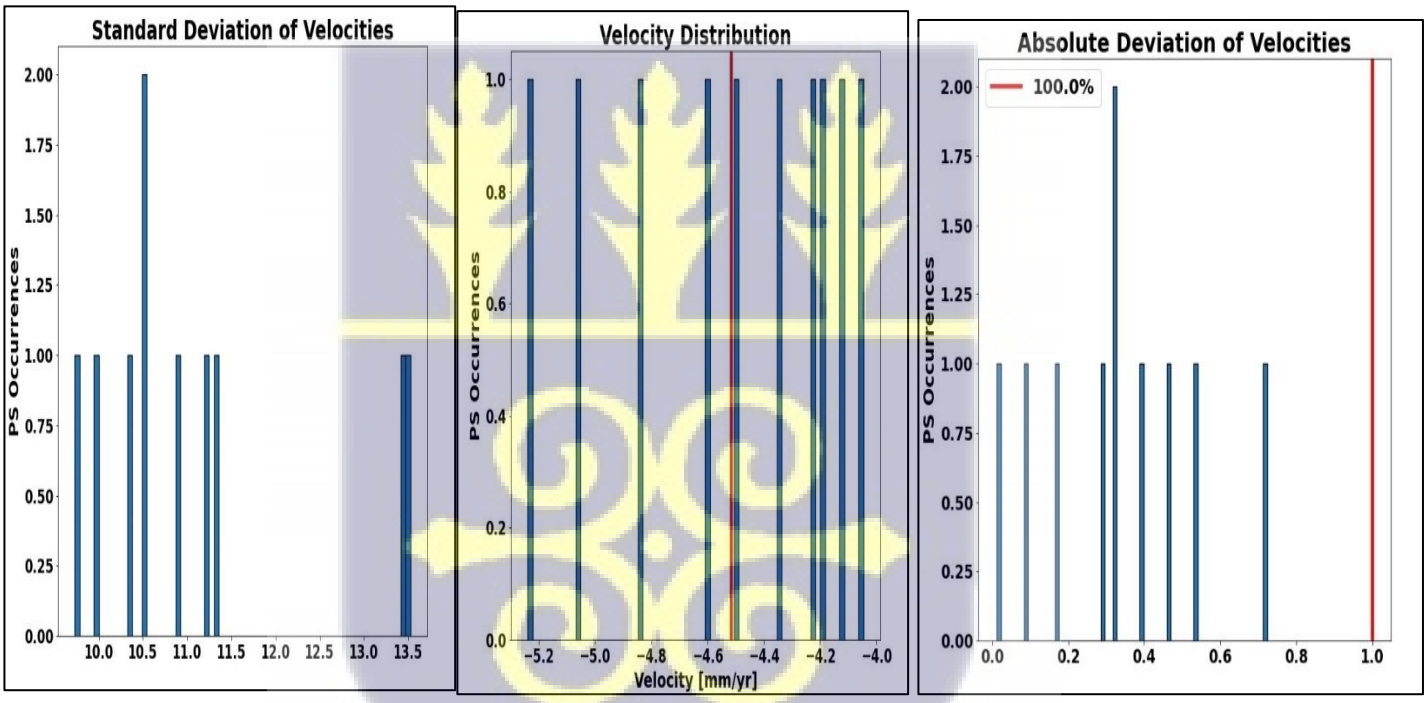
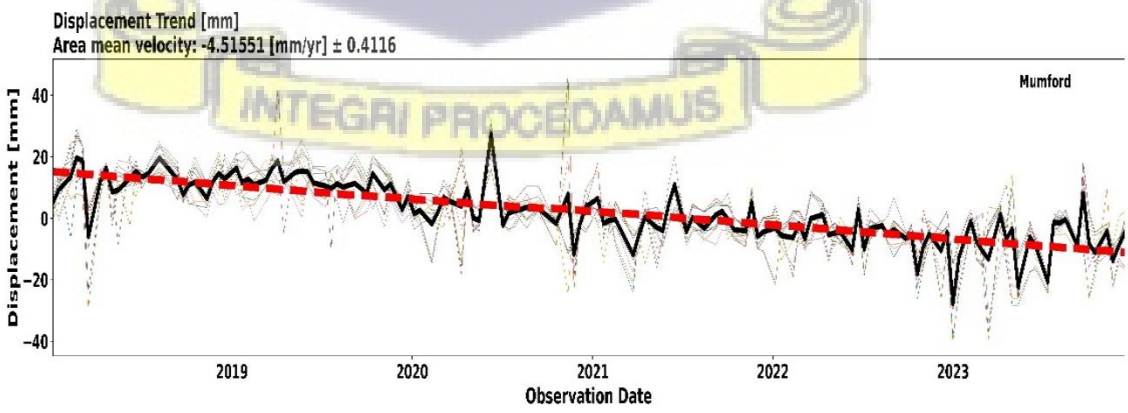


Figure 9.8: A graph showing the standard and absolute deviations, velocity and trend displacement for Atiteti.





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Figure 9.9: A graph showing the standard and absolute deviations, velocity and trend displacement for Mumford.

Table 9.1: Absolute difference between SLR and RSLR for SSP 2-4.5 for Mumford

Year	Projection Type	17th Percentile (%)	83rd Percentile (%)	Difference at 17th (%)	Difference at 83rd (%)
2040	SLR vs. rSLR	2.36 vs 5.19	4.43 vs 9.65	2.83	5.22
2060	SLR vs. rSLR	8.47 vs 15.82	14.55 vs 20.15	7.35	5.60
2100	SLR vs. rSLR	16.42 vs 24.56	24.85 vs 33.87	8.14	9.02

Table 9.2: Absolute difference between SLR and RSLR for SSP 5-8.5 for Mumford

Year	Projection Type	17th Percentile (%)	83rd Percentile (%)	Difference at 17th (%)	Difference at 83rd (%)
2040	SLR vs. rSLR	2.64 vs 5.82	4.98 vs 11.14	3.18	6.16
2060	SLR vs. rSLR	13.56 vs 17.44	15.47 vs 26.24	3.88	10.77
2100	SLR vs. rSLR	22.22 vs 29.62	34.24 vs 40.08	7.4	5.84

Table 9.3: Absolute difference between SLR and RSLR for SSP 2-4.5 for Atiteti

Year	Projection Type	17th Percentile (%)	83rd Percentile (%)	Difference at 17th (%)	Difference at 83rd (%)
2040	SLR vs. rSLR	13.47 vs 17.66	15.81 vs 20.32	4.19	4.51
2060	SLR vs. rSLR	16.52 vs 24.75	21.14 vs 27.62	8.23	6.48
2100	SLR vs. rSLR	23.90 vs 32.16	38.76 vs 47.24	8.26	8.48

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Figure9.4: Absolute difference between SLR and RSLR for SSP 5-8.5 for Atiteti

Year	Projection Type	17th Percentile (%)	83rd Percentile (%)	Difference at 17th (%)	Difference at 83rd (%)
2040	SLR vs. rSLR	13.94 vs 18.76	16.38 vs 21.42	4.82	5.04
2060	SLR vs. rSLR	16.84 vs 23.42	23.56 vs 29.86	6.58	6.3
2100	SLR vs. rSLR	31.04 vs 41.16	58.57 vs 64.57	10.12	6

APPENDIX D: TEMPERATURE, RAINFALL TREND AND BLUESPOT

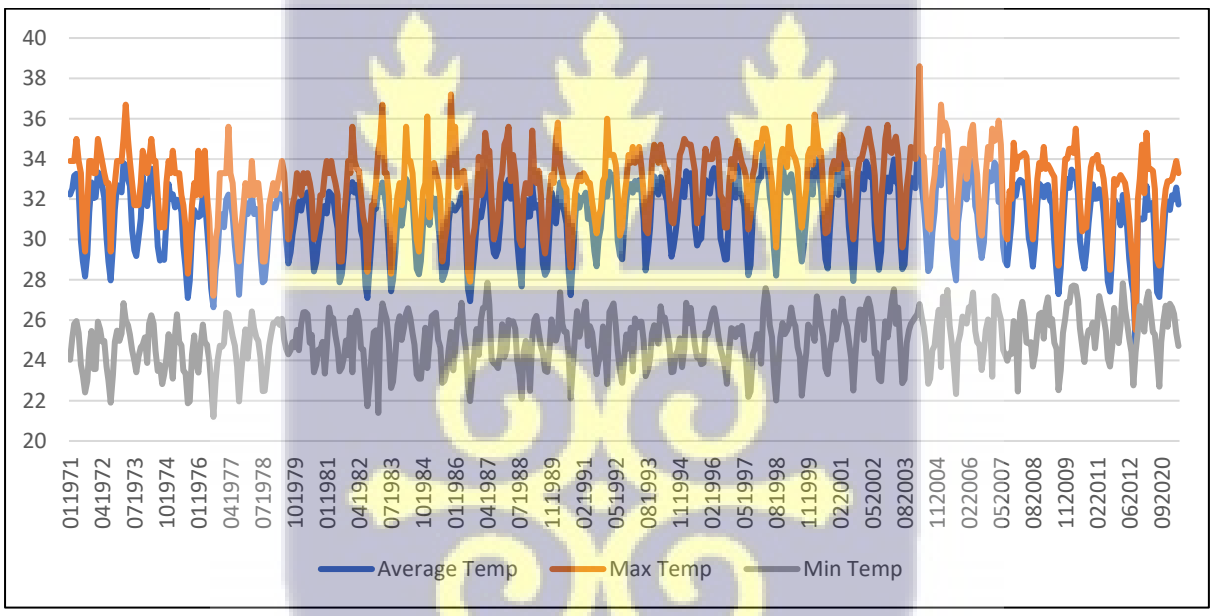


Figure 9.10: A graph showing the relationship between the average, min and max temperatures for Atiteti

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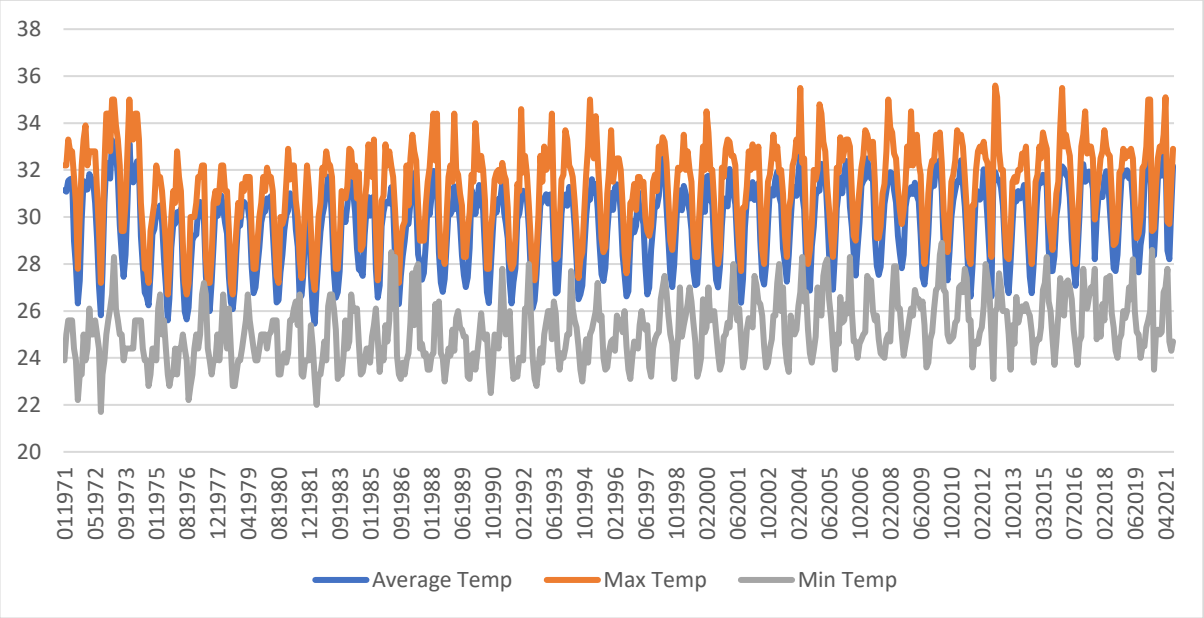


Figure 9.11: A graph showing the relationship between the average, min and max temperatures for Mumford

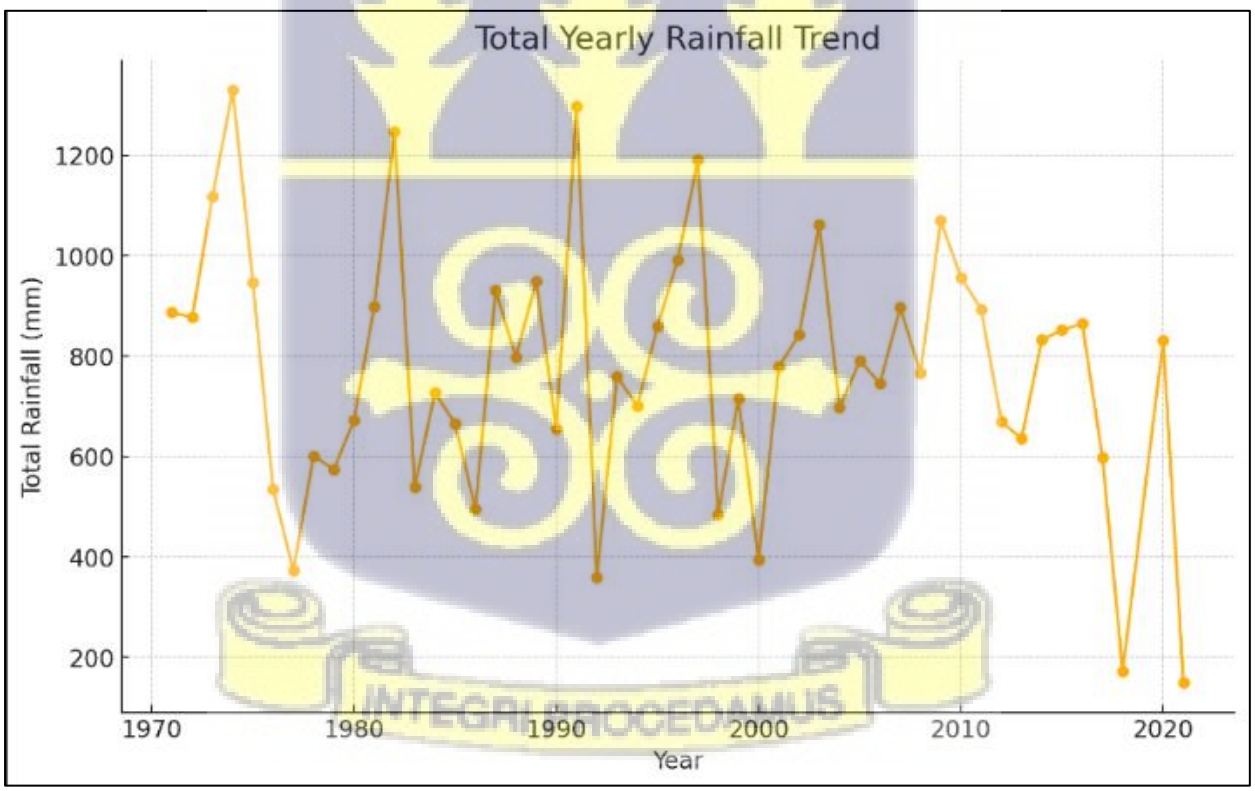


Figure 9.12: Yearly rainfall trend for Atiteti.

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Figure 9.13: Bluespot visualization with hillshade for Atiteti a

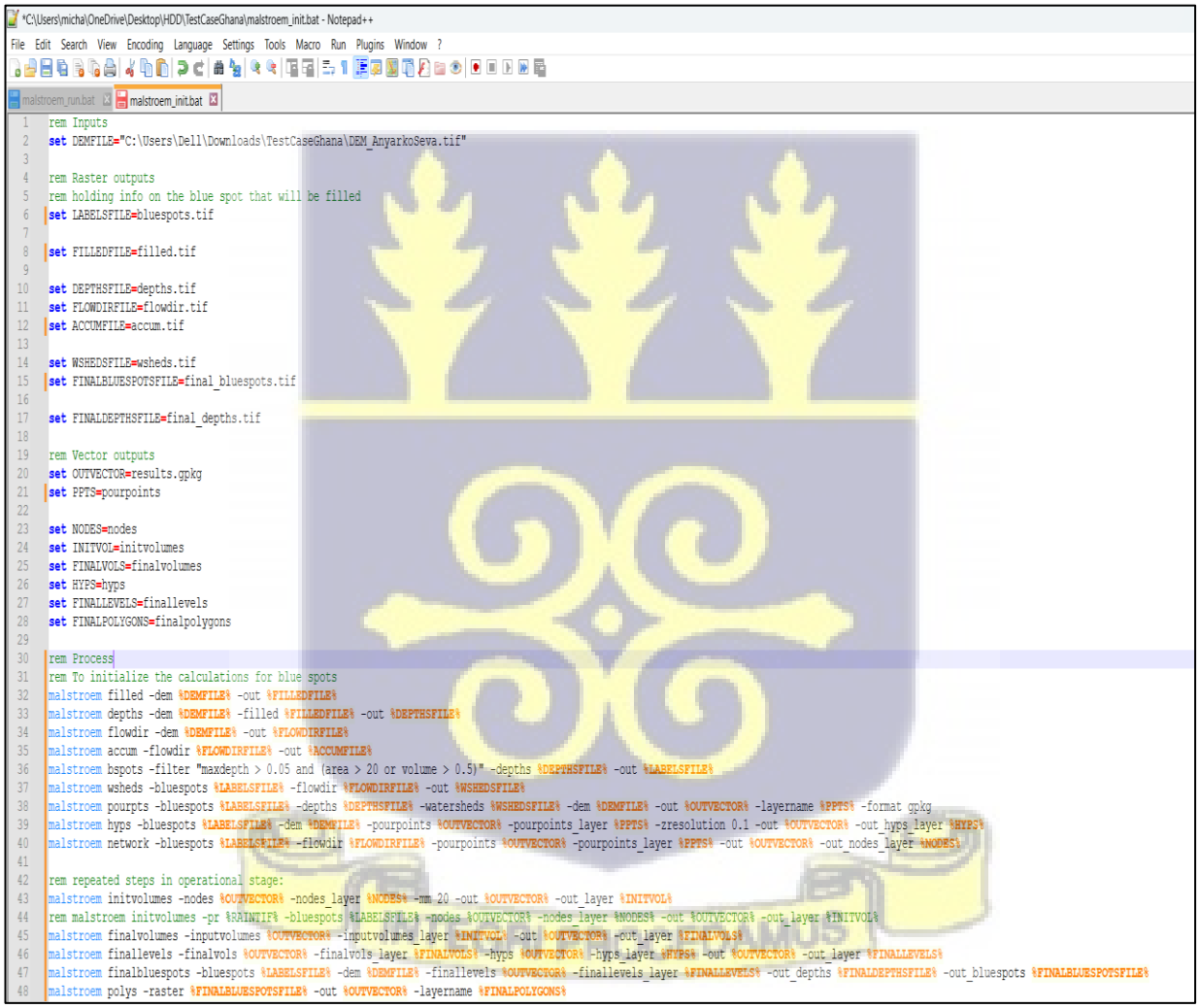


Figure 9.14: Bluespot visualization for Atiteti

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Figure 9.15: Sample DEM from L3HARRIS for Atiteti



```
rem Inputs
set DEMFILE="C:\Users\Dell\Downloads\TestCaseGhana\DEM_AnyarkoSeva.tif"

rem Raster outputs
rem holding info on the blue spot that will be filled
set LABELSFILE=bluespots.tif

set FILLEDFILE=filled.tif

set DEPTHSFILE=depths.tif
set FLOWDIRFILE=flowdir.tif
set ACCUMFILE=accum.tif

set WSHEDSFILE=wsheds.tif
set FINALBLUESPOTSFILE=final_bluespots.tif

set FINALDEPTHSFILE=final_depths.tif

rem Vector outputs
set OUTVECTOR=results.gpkg
set PPTS=pourpoints

set NODES=nodes
set INITVOL=initvolumes
set FINALVOLS=finalvolumes
set HYPS=hyps
set FINALLEVELS=finallevels
set FINALPOLYGONS=finalpolygons

rem Process
rem To initialize the calculations for blue spots
malstroem filled -dem %DEMFILE% -out %FILLEDFILE%
malstroem depths -dem %DEMFILE% -filled %FILLEDFILE% -out %DEPTHSFILE%
malstroem flowdir -dem %DEMFILE% -out %FLOWDIRFILE%
malstroem accum -flowdir %FLOWDIRFILE% -out %ACCUMFILE%
malstroem bspots -filter "maxdepth > 0.05 and (area > 20 or volume > 0.5)" -depths %DEPTHSFILE% -out %LABELSFILE%
malstroem wsheds -bluespots %LABELSFILE% -flowdir %FLOWDIRFILE% -out %WSHEDSFILE%
malstroem pourpts -bluespots %LABELSFILE% -depths %DEPTHSFILE% -watersheds %WSHEDSFILE% -dem %DEMFILE% -out %OUTVECTOR% -layername %PPTS% -format gpkg
malstroem hyps -bluespots %LABELSFILE% -dem %DEMFILE% -pourpoints %OUTVECTOR% -pourpoints_layer %PPTS% -zresolution 0.1 -out %OUTVECTOR% -out_hyps_layer %HYPS%
malstroem network -bluespots %LABELSFILE% -flowdir %FLOWDIRFILE% -pourpoints %OUTVECTOR% -pourpoints_layer %PPTS% -out %OUTVECTOR% -out_nodes_layer %NODES%

rem repeated steps in operational stage:
malstroem initvolumes -nodes %OUTVECTOR% -nodes_layer %NODES% -mm 20 -out %OUTVECTOR% -out_layer %INITVOL%
rem malstroem initvolumes -pr %RAINTIF% -bluespots %LABELSFILE% -nodes %OUTVECTOR% -nodes_layer %NODES% -out %OUTVECTOR% -out_layer %INITVOL%
malstroem finalvolumes -inputvolumes %OUTVECTOR% -inputvolumes_layer %INITVOL% -out %OUTVECTOR% -out_layer %FINALVOLS%
malstroem finallevels -finalvols %OUTVECTOR% -finalvols_layer %FINALVOLS% -hyps %OUTVECTOR% -hyps_layer %HYPS% -out %OUTVECTOR% -out_layer %FINALLEVELS%
malstroem finalbluespots -bluespots %LABELSFILE% -dem %DEMFILE% -finallevels %OUTVECTOR% -finallevels_layer %FINALLEVELS% -out_depths %FINALDEPTHSFILE% -out_bluespots %FINALBLUESPOTSFILE%
malstroem polys -raster %FINALBLUESPOTSFILE% -out %OUTVECTOR% -layername %FINALPOLYGONS%
```

Figure 9.16: A truncated source code for the malstroem model.

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APPENDIX D: UNCERTAINTIES

Table 9.5: A table showing the objectives and the type of uncertainties associated with them

OBJECTIVE	METHOD	UNCERTAINTY
	Extracting shoreline positions from orthomosaics	- Weather condition leading to distorted images - People interfering LOS - Sensor calibration errors & Signal loss - Satellite geometry (E) - Reference station stability (E) - Post processing error (E)
	Calculating subsidence using the InSAR approach Estimating flooding from SLR/RSLR scenarios using SSPS (2-4.5 & 5-8.5)	- VGD not parallel to the LOS - Temporal decorrelation - InSAR phase unwrapping error **Assumptions
	Estimating flooding from rainfall & different topography scenarios	- Model structure, selection & assumptions (No tide gauge & NSB) - DEM error (No DATA) (E) - Uncertainties in estimating the number of peop who will be at risk (net migration) (E) - Adaptation Structures - Weather stations being farther apart from the study sites (E)

Controls

Malstroem (varying model parameter to check the response), LRRs with error margin, flood validation from NADMO, GMET, Media and Groundtruthing

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APPENDIX E: FIELD PICTURES



Figure 9.17: An image showing parts of Fuvemeh-Atiteti



Figure 9.18: Flooding in Atiteti

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Figure 9.19: An image showing the source of drinking water from a pipe (Ghana water) in the sea (Fuvemeh)



Figure 9.20: Erosion in the Atiteti Community

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Figure 9.21: Displaced GCPs in the field

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Figure 9.22: An aerial image of the Mumford Community