UNIVERSITY OF CAPE COAST

ASSESSING MORPHOLOGICAL CHANGES AT THE OF MOUTH VOLTA RIVER

BUABENG RICHARD NELSON

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BY

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This thesis is submitted to the University of Cape Coast, Faculty of Social Sciences, College of Humanities and Legal Studies, Department of Geography and Regional Planning in partially meeting the prerequisites for the Master of Philosophy (Geography)

AUGUST, 2024

DECLARATION

Candidate's Declaration

I declare that this thesis is an entirely original research of mine and has not been submitted for credit toward any other degree, either at this university or any other.

Candidate's Signature ……………………………. Date …………………….

Name: Buabeng Richard Nelson

Supervisors' Declaration

I certify that the thesis was prepared and presented under supervision in compliance with the University of Cape Coast's thesis supervision criteria.

Principal Supervisor's Signature ……………………… Date …………

Name: Prof. Benjamin Kofi Nyarko

ABSTRACT

The Volta River's mouth, found near the eastern coast of Ghana is an ecosystem with a unique morphology of sand spits and islands. These morphological features of the eastern location near River Volta facilitate easier access to fisheries, fishing, tourism, raw materials, and transportation which significantly enhanced the economics of coastal areas, leading to increased population growth and infrastructural development. The morphological features such as sand spits and islands formed at the river mouth have been very dynamic in the last few decades. These morphological changes and the related coastal hazards surrounding the mouth of river Volta have been linked to both human activity and natural processes. These coastal hazards have expedited the loss of important wetland ecosystems, erosion, and flooding. These have made the eastern coast the most vulnerable coastal zone in Ghana.
It is also possible to better manage the Volta River system by knowing the dominant causes of those changes and how coastal and delta processes interact. Several studies conducted on the eastern coast have different objectives and approaches rather than assessing the morphological changes at the mouth of the River Volta. To accomplish this goal, data spans from publicly available historical satellites (Landsat 5, 7, 8, 9, and Sentinel 2) Coastsat toolkit software was used to assess the morphological changes at the mouth of the river Volta. In this study,

The findings indicated that the eastern coast of Ghana is highly eroding than accreting which has resulted from changes in sand spits and sand of the Volta River. In addition, it was discovered that the dominant causes among the driving forces of the changes in the case of the Volta River are linked to river discharge and wave current.
There is an urgent need for recommendations to stakeholders for sustainability and mitigation strategies including environmental planners, coastal engineers, government representatives, and planners of coastal hazards, who provide the necessary policies and measures to counteract the impacts of coastal hazards in the coastal community.

KEYWORDS

Coastal Flooding

Coastal vulnerability

Coastsat toolkit

Delta

Evolution

Remote sensing

River system

Sea level Rise (SLR)

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DEDICATION

This work is dedicated to Miss Fiona Opoku Mensah and my mother, Madam Mary Ackom.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASD	Ada sea Defense
Coastsat	Coastal satellite
DGPS	Differential Global Positioning System
DSAS	DigitalShorelineanalysissystem
ENVI	Environment for Visualizing Images
EOSDIS	Earth Observing System Data and InformationSystem GIS:
EPR	End Point Rate
GIS	Geographic Information System
KSD	Keta Sea Defence Project
MATLAP	Matrix Laboratory
NSM	Net Shoreline Movement
RSLR	Relative Sea Level Rise
SCE	Shoreline Change Envelope
SLR:	Sea Level Rise
SWH:	Significant Wave Height
USGS:	United States Geological Survey

CHAPTER ONE

INTRODUCTION

Background of the study

Right from the genesis of the human species, the river system has become one of the most essential natural phenomena to man and his environment (Kolbert, Wilson & Lovejoy, 2017). The river system consists of many parts such as tributes, confluence, sources, and mouth (estuary) Silva & Mendes,2009. Among all these parts it is the mouth that is of much interest to many stakeholders including human communities who live around the mouth, environmental managers, coastal Planners, Hydrologists, and researchers (Barletta, 2017).

River mouths serve as transition zones where freshwater from rivers meets saltwater from oceans, leading to unique ecological environments that support diverse habitats (Gopal, 2020). These areas are influenced by a variety of factors, including sediment transport, tidal dynamics and many more leading to the formation of certain vital morphological features such as Sand spits, sand bars, deltas, and islands (Das, Ghosh, Islam & Roy, 2020).

These morphological features located near water facilitate easier access to, raw materials, transportation, tourism, and fishing which has greatly improved the economics of coastal communities, resulting in greater population growth and infrastructure development. It also supports vital estuary ecosystems, and a diverse array of marine life (Dankwa, Owiredu, Amevenku, & Amedorme, 2017). A fertile land for agricultural activities cannot be exempted from the benefits derived from rivers' mouths as far as the river system is concerned.

The most crucial ecological habitats in the world possess distinct morphological characteristics, as they support biodiversity and contribute to socioeconomic development.

According to Szabo, et al. (2007), around 40% of the world's population resides in coastal or delta island regions. Additionally, studies calculated that roughly 7% of the world's labor is concentrated in a river's mouth. Approximately 27% of Africans, according to Wiafe and Kwakwa, 2013 reside beside rivers or their river banks. 31% of all people and human infrastructure in West Africa are located in the coastal zone.

River mouths with distinctive morphological features are important not just too many stakeholders because of the advantages they offer, but also for the speed at which these features are changing (Spinney, 2019). This can be linked to both anthropogenic activities like sand mining, building dams, and marine defense, which cause sedimentation and erosion, and natural processes like waves, tides, river discharge, and sea level rise. These morphological changes at the mouth of rivers have led to coastal erosion and floods, which makes low-elevation deltas more vulnerable (John, Brew & Cottle, 2017).

In most coastal zones, the circumstances lead to an increase in poverty, population displacement, and forced migration, all of which have an impact on the local economy (Smith, Nicholls, Tebboth & Kent, 2023). There will be more risk in developing nations with vulnerable coastal cities and populations, where there are insufficient resources and data to address these coastal concerns (Duijndam, 2022). Therefore, a vital study is needed to assess morphological changes near the mouth of a river and identify the underlying causes.

Statement of the problem

The Volta River is one of Ghana and Africa's most paramount river systems, with its sources in Burkina Faso and draining into the Gulf of Guinea (Appeaning et al. 2020). Features such as sand spits and islands formed at the mouth of the Volta River are in a highly dynamic coastal environment, these features have experienced significant morphological changes in recent decades. (Aagaard, 2021). These changes are triggered by different processes shaping the morphology in the area: river flow, waves, tides, and anthropogenic changes that have taken place over the last years (coastal protection, damming, cutting down of mangroves and others) (Appeaning et al. 2020).

These morphological changes and the related coastal hazards surrounding the mouth of river Volta have expedited the loss of important wetland ecosystems, erosion, and flooding. In addition, the removal of coconut trees, a reduction in fresh water and fish supply downstream, and also the introduction of water hyacinths affect aquatic life in the Volta River (Ibrahim, 2019). These coastal hazards have made the eastern coast the most vulnerable coastal zone in Ghana because it experiences flooding not less than twice every year (Boateng et al..,2020). Better management of this coastal zone may be possible with a thorough understanding of the main causes of these changes and the relationships between morphological characteristics and coastal processes (Masselink, Hughes, & Knight, 2014).

Existing studies many researchers worldwide have researched River Volta, some of the studies: Barry,2015, conducted a study on the River Volta by looking at the comprehensive assessment of water management in agriculture. In addition, (Gift, et al..,2016) also researched River Volta by evaluating the impacts of dredging and salinity water intrusion on the livelihood in the Volta estuary. Another piece of evidence can be inferred from a study by Owusu et al.., 2008 in their study, much attention was given to the Volta Delta and its challenge in an African setting

Despite these studies, attention to the changes, the dominant cause(s) of the changes at and mapping out the area (coastal communities) surrounding the mouth of the Volta River, and their vulnerability regarding coastal hazards has rarely been looked at. Thus, literature on the morphological changes and their effects at the mouth of the Volta River is scarce. This knowledge gap hinders the development of fruitful strategies and policies for mitigating the adverse effects of these changes and optimizing the management of this critical ecosystem. Therefore, there is a pressing need to conduct a vital study to assess morphological changes at the mouth of the Volta River.

Objectives of study

The general objective of this study is to assess the morphological changes at the mouth of the Volta River.

The specific objectives seek to;

1. quantify the changes that have occurred at the mouth of the river Volta over 30 years.
2. examine the dominant cause(s) of the changes at the mouth of the river Volta over 30 years.
3. map out some areas (coastal communities) surrounding the mouth of the Volta River regarding their vulnerability level

Research questions

The research questions that guided the study are:

1. What type of changes have occurred at the mouth of the river Volta over 30 years?
2. What is/are the dominant cause(s) of the morphological changes that have occurred at the mouth of the river Volta over 30 years?
3. Which communities or areas are more vulnerable at the mouth of River Volta in terms of coastal hazards?

Significance of the Study

This study assesses the morphological changes at the mouth of the river Volta. The following paragraphs depict why the study needed to be conducted

Thus, the objective of the study is to offer sufficient evaluation data that can aid in choosing the most effective approach.

This study could also contribute to our understanding of the natural processes that shape river mouths over time. Analyzing remote sensing data from different periods, changes in shape, size, and location of the Volta River Mouth can be tracked. This will help us to detect the underlying physical processes that bring about the changes. This information can be used to develop more effective strategies for managing the impacts of these changes.

Its ability to guide governmental decisions about the management of the Volta River Mouth and the neighboring communities is another noteworthy aspect of this study. Change patterns can be found by analyzing remote sensing data over time. After that, with this information, policies and management techniques that are better able to lessen the effects of these changes on the local community and the environment can be developed.

Also, this research may advance our knowledge of the evolutionary effects of human activity at the mouth of the Volta River, as well as strategies for limiting these intrusions that endanger the coastal system.

Organization of the study

This study has been organized into six different chapters.

Chapter One presents the background to the study, statement of the research problem, research objectives, research questions and significance of the study, and the scope of the study. Chapter two discusses the pertinent literature that is connected to the research.

The topic discussed is assessing the morphological changes at the mouth of Volta. Breaking down to the morphological changes, the dominant driving force(s) behind the causes of the morphological changes and some coastal communities at the mouth of river Volta and their vulnerability in terms of coastal hazards additionally and the theoretical underpinning this study were taken into consideration. Both natural and anthropogenic factors causing the changes in the mouth of the river Volta were reviewed. The study area was made to stand alone as one chapter consisting the chapter three, the four chapters of the study make up the methodology used in the study. Study design, data sources, data processing and analysis, and ethical considerations are presented. The study's results and comments are presented in the five chapters, and the study's summary, key findings, conclusions, and recommendations, as well as possible areas for further research, are presented in the sixth chapter.

Scope of the study

The study considered the issue of morphological changes at the Mouth of the Volta River and its effects on the surrounding communities as a pressing study. Communities along the eastern coastline of Ghana especially the eastern part of River Volta and its vicinities are really under the threat of coastal hazards which include coastal floods, storm surges, and erosion (Appeaning,2016). The findings will assist in the development of strategies to mitigate the impacts of these coastal hazards and protect the vulnerable areas along the Volta River Delta. It also provides valuable insights for coastal zone management, environmental planning, and decision-making processes which will help the communities along the eastern and the western coastline of the Volta River from facing the threat of coastal hazards

CHAPTER TWO

LITERATURE REVIEW

Introduction

Despite the extensive research conducted to date, much remains unknown about the morphological changes (evolution) near the mouth of the Volta River, including the dominant factors behind these changes, and their related effects. This study section reviews the essential body of literature on the morphology at the mouths of the Volta River. It also entails the ideas, perspectives, theories, and concepts that influenced this research

River System

In the past, the Freshwater distribution, availability, and the resources they hold in river systems have been largely credited with the evolution of numerous communities (Roszkowski, & Singer, 2022,). According to (Yitian & Gu, 2003), a river system is an intricate web of connected channels, tributaries, and other waterways that affect the overall water flow in a drainage basin. To the preceding definitions, Murray & Paola, 1994 additionally add that a river system is seen as a dynamic, interconnected network of watercourses that transfer sediment and water from higher to lower elevations while draining a specific area. Based on evidence from these sources, it can be said that the river Volta is part of a complex network of interconnected watercourses that constitute a watershed or drainage basin and work together to accomplish a common goal (Lagasse et al.., 2012).

Some essential components of a river system

According to Varrani, Nones & Gupana, 2019, a river system comprises numerous essential components, such as River catchment and Estuary.

These components of a river system allow the river to carry out its primary duties, which include eroding, carrying, and depositing sediment to maintain the landscape's equilibrium (Bizzi & Lerner, 2015).

River catchment

The term "catchment" is often used interchangeably with "drainage basin" or "watershed (Downs, Gregory & Brookes, 1991). A catchment is a region of land that, when it rains, gathers water; it is frequently surrounded by hills. Water travels throughout a terrain, entering streams and finally penetrating the earth to supply rivers Subramanya (2008).

During periods of little rainfall, a portion of this water remains subterranean and keeps feeding the river gradually. Every square inch of the planet's surface is a catchment. The size of catchments can vary widely, from tiny urban sub-catchments to massive catchments that span multiple states or countries (Le Roux, & Sumner,2013)

The boundaries of a river catchment are defined by the topography of the land and are often delineated using geographical features such as ridge lines or watershed divides (Naiman, Decamps & McClain, 2010). These boundaries determine the area from which rainfall and runoff are collected and channeled toward a common outlet.

River catchments play a crucial role in hydrology, as they influence the quantity and quality of water in a river system (Dunn & Youngson, 2007). The catchment area acts as a natural filter, as the land surface and vegetation help to intercept, store, and filter water before it reaches the main water body. The characteristics of the catchment, including its size, shape, slope, and land use, influence the flow patterns, water quality, and overall health of the river system (Hou, Liao, & Peng, 2016)

Estuary

The word "estuary" comes from the Latin word aestuarium, meaning tidal inlet of the sea. For Rezaye & Rao (2018) estuaries are places where the land meets the sea; they are sometimes referred to as bays, harbors, inlets, or sounds. These dynamic ecosystems support distinct plant and animal species that have adapted to brackish water a briny mixture of seawater and freshwater that drains from the land. When compared to similar-sized woods and agricultural regions, estuaries are among the most productive habitats on Earth, producing more organic matter annually (Kennish, 2022; Day, Hall, & Kemp, 2017). Additionally, they protect communities from flooding, offer a variety of habitats for animals and aquatic life, lessen pollution in waterways, and boost local economies. Estuaries are characterized by fluctuating salinity levels due to the mixing of freshwater and seawater. The amount of freshwater input and tidal influence (Kennish, 2012; Day, Hall, & Kemp, 2015).

Estuaries play a significant role in determining the salinity gradient within an estuary. This dynamic environment gives rise to diverse habitats and supports a wide variety of animal and plant species that have been uniquely modified to live in estuary conditions.

They act as nurseries and breeding grounds for many marine species, including fish, shellfish, and migratory birds. The nutrient-rich sediments carried by rivers and deposited in estuaries provide a fertile habitat for various organisms. Estuaries also play a crucial role in filtering pollutants, trapping sediments, and buffering against coastal erosion.

Importance of river system

The world is home to several major river systems that play vital roles in the continent's geography, ecology, and human activities (Hofstede, 2006). The following depicts some important aspects of a river system.

Throughout prehistoric times, people lived beside riverbanks because they could find fish to eat and water for bathing, cooking, and drinking (Matheny, 1976). It was discovered later that crops can be grown in the rich soil near rivers. According to Macklin and Lewin (2015), the world's earliest big civilizations emerged in the lush floodplains of the Tigris and Euphrates in the Middle East, the Huang (Yellow) in China, the Nile in Egypt, and the Indus in southern Asia. Rivers later on offered pathways for exploration, trade, and settlement (Rector, 2016).

River systems remain important today, river systems maintain the provision of power for houses and businesses, drinking water and irrigation for farms, and transportation networks. (Richter et al ...2013).

River systems are an essential component of the natural environment, and they play a crucial role in the lives of human beings (Chowdhary, 2020). The importance of the river system to coastal communities is essential and most of these apply to the Volta River.

Rivers serve as primary sources of freshwater for human consumption, agriculture, and industrial use (Leong & Mustafa, 2007). They provide a continuous flow of water that supports irrigation systems, enabling agricultural productivity and food production. Rivers also serve as reservoirs for drinking water supplies, especially in areas where groundwater resources are limited in supply (Newig, Challises, Cotta, Lenschow & Schilling-Vacaflor, 2020). Biodiversity and Ecosystems cannot be exempted from the key importance of rivers.

Rivers and their associated ecosystems support a high level of biodiversity (Moonen, & Bàrberi, 2008, Hauer, Stanford & Hawkins, 1990). Rivers are harnessed for the production of hydroelectric power. Dams and reservoirs built on rivers allow the controlled release of water, which is channeled through turbines to generate electricity. Hydroelectric power is a renewable and relatively clean energy source, reducing reliance on fossil fuels and contributing to sustainable development (Modal, Solomon, Tew, Gerhman & Lehner, 2014). These benefits can be seen from River Volta Anthony et al., 2016).

Studies from Erfurt-Cooper, 2009 again depicted that Rivers offer recreational opportunities and attract tourists. They provide settings for various activities such as boating, fishing, swimming, and river cruises. Which further reaved that the benefits from tourist attractions finally contribute to local economies.

Evidence from the stated several sources depicts that a river system is vital, thus it is important to manage and protect river systems sustainably to preserve their ecological integrity, ensure water availability, and optimize the benefits they provide to human societies and the environment ((Grizzetti et al …,2019).

Process at the mouth of the river

The mouth of a river is where it flows into a larger body of water, such as a lake, sea, or ocean. The interaction of a river with the surrounding body of water creates unique geological and biological processes around the river's mouth (Coleman & Wright, 1975). The two main processes that occur near the river mouth are the tidal effect on river discharge and sedimentation processes, which are impacted by wave activities (Hume, 2007). The Volta River does not exclude these processes.

Sediment transportation

Suresh and Mishra (2001) define sediment transport as the movement of solid particles due to either gravity pulling on the sediment or the fluid the sediment is entrained in moving. Rivers carry large amounts of silt, clay, and sand from their upstream sources to their mouths. Once friction is removed, materials can be transported via rivers because river channel walls are not completely smooth.

Because of the increased friction caused by the roughness of the channel, the water flows more slowly than it would otherwise. Swirling vortices arise in a small number of channels where the water flow is smooth due to certain barriers on the river bottom. Rivers usually have turbulent water flows (Reineck & Singh, 2012).

This indicates that while the main flow of water goes along the channel, there are unpredictable secondary flows that occur within the channel as erratic swirls and eddies. Heavy things are lifted off the riverbed and carried downstream by the river with the assistance of this turbulence. When a river's velocity profile or a curve showing how flow velocity varies with depth (depth distance below the surface or height above the river bed), is plotted, multiple primary types of velocity profiles, each corresponding to a particular flow regime, can be constructed. In naturally occurring rivers, laminar flow is rare, but it can occur when a river's channel is straight and smooth and the maximum flow velocity is modest, according to Reinbeck and Singh (2012). This can happen particularly in a river's lower course. The water in this instance flows smoothly in sheets parallel to the riverbed. The velocity of water is higher at the surface than near the riverbed, where flow is impeded by bed friction. The second kind of flow regime is called turbulent flow, and it is found in rivers and intricately twisting channels with sequences of riffles and pools, particularly when the water is moving quickly. The most prevalent kind of flow regime is this one. Rivers churn in erratic, chaotic eddies instead of flowing in serene sheets (Reineck & Singh).

Costa, 2016 explained that the main agents by which sedimentary materials are moved which influence evolution at the mouth of rivers include gravity, river and stream flow, ice, wind, and estuary and ocean currents.

Features formed at the mouth of some rivers as a result of the processes that take place at the mouth

At the mouth, the river slows down and loses the energy necessary to move all of the silt, sand, and clay Allen (1965). This process brings about morphological features which include bay, sand spits and sand bar, delta and others.

A bay

A bay is a body of water partially enclosed by land. It is typically smaller than a gulf but larger than a cove. Bays are formed through various geological processes, such as erosion, subsidence, or the flooding of river valleys. They can be found along coastlines, where the land curves inward, creating a sheltered area that is open to the sea on one side (Shipman, 2008). The depth of a bay can vary depending on factors such as tides, currents, and geological features. Bays are often important features of coastal geography and have various uses and significance. Bays provide natural harbors and sheltered anchorages for boats and ships (Kaufman, 1983).

Sand spits

Sand spits are narrow, elongated landforms that form at rivers' mouths where sediment is deposited due to changes in water flow patterns and wave action. In a similar vein, sand spit is a landform that forms as a result of sediment deposition along a coastline or at the mouth of a river (Jana & Paul, 2019). As the coastline experiences wave action that approaches the shore at an angle, sediment is carried along the shoreline. As the waves approach a point where the coastline changes direction or where a river meets the ocean, the wave energy diminishes, and sediment begins to accumulate over time, this accumulation of sediment leads to the formation of sand spit sand spit plays a crucial role in protecting the coastlines by absorbing wave energy and reducing erosion.

These Coastal features provide cheaper and more effective shoreline protection than sea walls. They also reduce erosion and promote accretion (Kunte, Alagarsamy, & Hursthouse, 2013).

Delta

A delta is a landform created when a river meets an ocean, lake, or another bigger body of water. Its formation took place over thousands of years, depending on various elements such as the amount of silt in the river, the power of the waves and tides, the geology and geography of the area, and variations in sea level. As the river slows down, silt deposition occurs, causing land to gradually accumulate close to the river mouth (Nicholls & Tol, 2006). This accumulation of silt creates unique pathways and landforms, which frequently move as a result of altering dynamics. The delta's evolution is further influenced by erosion, subsidence, and human activity, making it an intricate and dynamic structure that is essential to coastal ecosystems and landscapes. When silt, clay, and sand are carried downstream by a river and towards the ocean, delta formation begins. The river's velocity decreases as it approaches the water body, allowing the sediment to settle and build up a process known as deposition. The Mississippi River Delta in the US state of Louisiana and the Nile River Delta in Egypt are two examples of deltas (Gifford, 2005). According to Acheampong (2016), the River Volta is a cuspate delta, which is connected to bay shingles and sand spit.

Formation of Deltas

When a river empties into a body of water, typically the ocean or a lake, a delta is created as a landform. Most of the world's current deltas formed between 8000 and 6500 years ago, during the lower Holocene epoch, when the rate of sea-level rise slowed down and allowed for the deposition of river sediment loads along various coasts (Ericson et al., 2006).

The notable reduction in sea-level rise seems to be the main driver, even though other elements like tectonic displacement, temperature, and basin topography also played a role in their development (Anzidei et al., 2014).

Deltas are complex and dynamic systems shaped by interconnected processes and extensively studied in contemporary and prehistoric sequences. However, their shape and stratigraphy are highly variable due to tectonics, eustasy, basin geology, and climate. Deltas form at the interface between land and sea, where large rivers deposit sediment loads, creating broad coastal plains. Rivers lose velocity and carrying capacity as they get closer to their mouths, which causes silt to build up and the creation of a deltaic lobe. Several elements, such as the type of material present, river flow velocity, and coastal conditions determine a delta's volume, form, and size. Although outside sediments from currents or wave shifts can be found in modern deltas, maintaining sediment is essential to the deltas' resistance to shifting climates and increasing sea levels (FitzGerald et al., 2008).

Usually, the heavier and coarser sediments, such as gravel and sand, settle closer to the river's mouth first. As sediment builds up over time, some distributaries or channels eventually form and expand out into the body of water. A delta is eventually formed when sand builds up around these increasingly complex pathways. The land's slope, the river's volume and sediment load, the strength of the tides and waves, and other variables all affect how the delta is shaped. Deltas can be cuspate, bird's foot, or fan-shaped, among other forms. Deltas are dynamic ecosystems that change constantly due to physical processes including subsidence, deposition, and erosion. Deltaic plains are formed and preserved in large part by the nutrients and sediment that rivers carry (Bianchi & Allison, 2009). A deeper comprehension of the crucial processes and facies seen in deltaic environments has resulted from extensive research on both modern and ancient delta sequences.

Classification of Deltas

Deltas, formed at river mouths, have diverse traits and can be categorized by different methods. Delta regions frequently feature some of the densest populations on Earth and are wealthy, dynamic settings with a variety of economic activity. According to estimates from Ericson et al. (2006), deltas are home to 500 million people, or around 1% of the earth's surface is home to 7% of the world's people. Multiple drivers shape modern deltas. These include increased subsidence as a result of extracting petroleum and groundwater from aquifer materials located within deltas, which exacerbates naturally occurring subsidence (Ericson et al., 2006; Nicholls et al. 2017), and altered sedimentation of the coastal zone due to a variety of human activities, including farming, mining, urbanization, deforestation, construction of dams on major rivers, and milliman, broadus, and gable (1989; Walling and Fang, 2003; Woodroffe et al., 2006).

Delta classifications are determined by the following standards. Depending on the shape, depending on dominating processes, depending on sedimentary processes, and depending on geological settings.

Deltas can be categorized based on the primary processes that shape their formation:

a. River-Dominated Deltas: These deltas are shaped by the dominant influence of rivers, characterized by a high influx of sediment and the deposition of coarse-grained materials. Examples of river-dominated deltas include the Nile Delta and the Mississippi Delta.

b. Wave-Dominated Deltas: In these deltas, the shaping forces of waves and tidal actions play a significant role. They tend to possess smoother coastlines and fine-grained sedimentary deposits. The Ganges Delta and the Rhine-Meuse Delta exemplify wave-dominated deltas.

c. Tide-Dominated Deltas: These deltas are extensively impacted by tidal currents and typically form in regions with substantial tidal ranges. The Amazon Delta and the Brahmaputra Delta serve as illustrations of tide-dominated deltas.

II. Deltas can be classified based on their shape

a. Arcuate Deltas: These deltas exhibit a curved or semicircular shape and are typically found in regions with moderate wave and tidal energy. Examples of arcuate deltas include the Nile Delta and the Indus Delta.

b. Bird's Foot Deltas: These deltas feature multiple distributaries that extend into the sea, resembling the shape of a bird's foot. The Mississippi River Delta and the Ebro Delta are examples of bird's foot deltas.

c. Cuspate Deltas: These deltas have a triangular or pointed shape and are often formed in areas with strong wave and tidal energy. An example of a cuspate delta is the Tiber Delta in Italy.

III. Based on Sediment Discharge:

a. High Sediment Discharge Deltas: These deltas are formed in regions with significant sediment supply from the river, resulting in rapid accumulation and extensive land growth. The Mekong Delta and the Yellow River Delta are examples of high sediment discharge deltas.

b. Low Sediment Discharge Deltas: These deltas are formed in areas with lower sediment supply, leading to slower land accumulation and less extensive growth.

Examples of deltas with low sediment discharge are the Nile and Niger deltas.

IV. Deltas can be classified based on their geological age and developmental stage:

a. Active Deltas: These deltas are currently undergoing deposition and substantial land growth due to ongoing sedimentary processes. Examples of active deltas include the Amazon Delta and the Ganges-Brahmaputra Delta.

b. Abandoned Deltas: These deltas were previously active but have stopped growing due to alterations in river courses or fluctuations in sea levels. The historical distributaries of The Mississippi River Delta are one illustration of an abandoned delta. It's important to note that some deltas can exhibit characteristics of multiple classifications, making them complex and dynamic landforms. The classification of a delta may also evolve due to geological, environmental, or anthropogenic influences.

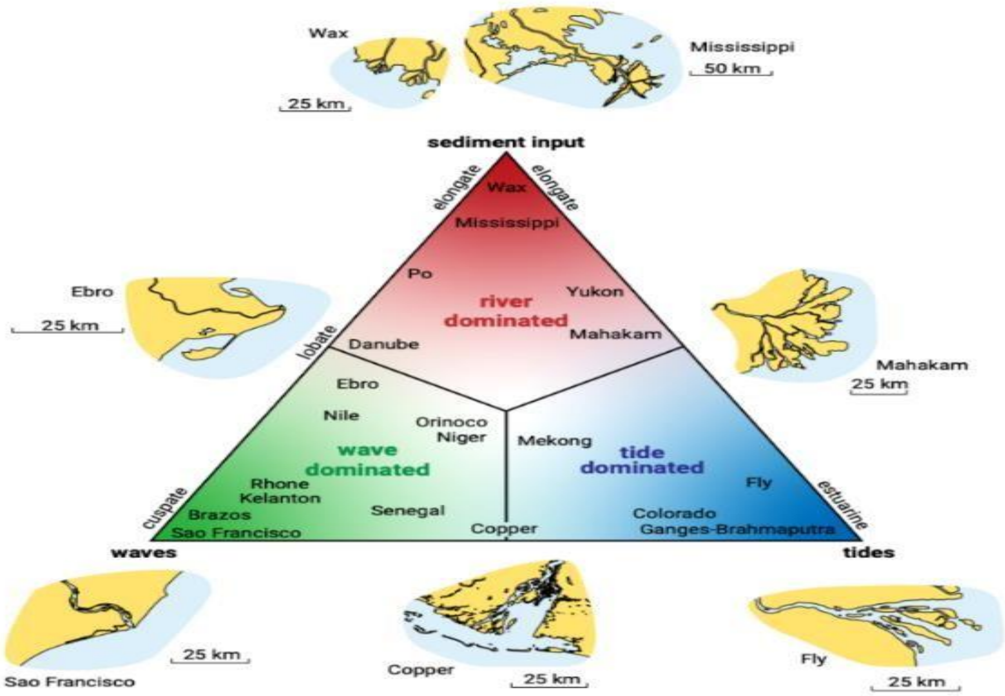


Figure 1.0*: *Types of Deltas based on their formations

Source: Brown and Nicholls, 2015

Importance / Benefits derived from Deltas

Deltas are essential ecosystems that offer various advantages to both the environment and human societies. Some importance and benefits that can be derived from deltas entail:

Agriculture purposes

The fertile soil of deltas supports agricultural activities, which enable the production of crops such as rice, cotton, and wheat. The Mississippi Delta in the United States, for instance, is a major agricultural area that produces a significant amount of the country's rice, soybeans, and cotton.

Deltas provide wildlife habitat

Deltas provide diverse habitats, such as wetlands, mudflats, and shallow-water areas, which are essential for various species of plants and animals. These ecosystems support a range of fish, crustaceans, and bird species, providing commercial and recreational fishing and birdwatching opportunities.

In addition; Deltas provide significant economic benefits to human societies, including fisheries, aquaculture, transportation, and tourism. The seafood industry is a significant source of income for many coastal communities, with deltas being essential breeding grounds for numerous fish and shellfish species.

Deltas act as a natural barrier against flooding and storm surges, protecting coastal areas. Mangrove forests and other vegetation found in deltas absorb and dissipate the energy of waves and storm surges, reducing their impact on the coast. Regarding Climate Change Mitigation: By storing carbon in the soil and vegetation, deltas contribute to the reduction of climate change. They take up and hold carbon dioxide from the atmosphere in their role as carbon sinks

All in all, deltas are vital ecosystems giving multiple advantages to human society and the environment. They sustain agriculture, give wildlife habitat, protect coastal areas from floods and storm surges, moderate climate change, and support diverse economic activities.

Major Challenges Factors Affecting Deltas

Numerous challenges that deltas face can affect their stability and longevity. Among these challenges are rising sea levels, which cause land erosion and submersion, which in turn cause habitat loss, population displacement, and a reduction in economic activity (see Figure 2.0). Delta regions may become more susceptible to floods and submergence as a result of both naturally occurring and man-made land subsidence. Furthermore, human actions that alter the natural flow of sediment to the delta, such as building dams, reservoirs, and other structures, can result in erosion and land loss. Natural catastrophes including hurricanes, tsunamis, tropical storms, and floods can also affect deltas.

Pollution, habitat degradation, and changes in land use are all results of human activity including mining, industrialization, urbanization, and agriculture. The effects of climate change worsen already-existing problems for deltas, adding to their challenges.

Handling these complex issues calls for an all-encompassing strategy that considers the complex interplay of environmental, social, economic, and physical aspects. For deltas to be managed effectively, different stakeholders must work together and execute flexible, integrated strategies. It is essential to have a thorough awareness of these issues and to take proactive steps to ensure the resilience and sustainable development of deltas. It will be possible to overcome these challenges and protect deltas for future generations if this is done.

Anthropogenic and Natural factors affecting deltas Anthropogenic and Natural factors affecting deltas

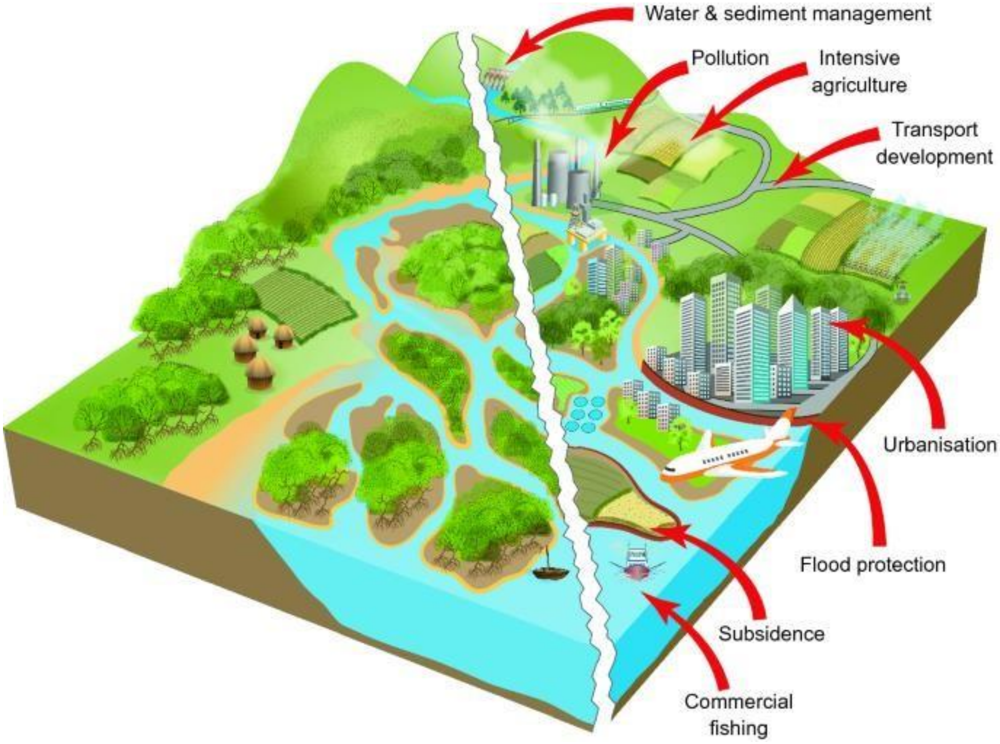


Figure 2*: Volta River Delta*
Source: Brown & Nicholls (2015)

The lower Volta River basin includes the Keta basin, which is home to the comparatively vast coastal lowland known as the Volta Delta.

Natural process

Major factors influence the changes of features (morphological changes) form at the mouth of rivers which result in changes and associated coastal dangers in the Volta Delta, including sea level rise, the effect of strong swell waves, tides, and river discharge.

Waves

Since 1936, waves have dominated the Volta River Delta, and in 1964, the rapid fall in sediment load made the delta even more wave-dominated. The river delta is significantly altered and moved toward a new equilibrium by the rather strong wave forcing. Waves play a critical role in shaping and preserving coastlines and deltas by redistributing sediment. Loose sediments along the coast are particularly vulnerable to substantial erosion and structural changes when exposed to extreme wave events (Hansom et al., 2015). Oceanic wind waves are characterized as gravitational waves in the open sea. The inclination of the coastline and the nearshore bathymetry are factors in how the waves of the ocean shape the delta front.

The Volta River mouth estuary is dominated by waves. Sandspit and beach evolution are influenced by the strong wave energies observed at the river mouth. Unhindered waves of moderate to strong energy, with an average height of around 1.4 meters (m) and a duration of roughly 11 seconds (s), approach the coast from the southwest in a southerly direction (Almar et al. 2015; Angnuureng et al. 2016). The energy dissipated when the waves break generates longshore currents that transport sediment alongshore from west to east, which causes one of the highest rates of annual unidirectional longshore sediment drift in the world (1–1.5× 106 m3/ yr) (Nairn et al. 2017). Strong wave events have caused dunes and beaches to deteriorate, as well as flooding and significant harm to coastal towns. These waves frequently result in localized or widespread flooding, which has a significant impact on the southern eastern coast's socioeconomic standing (Hansom et al., 2015). In particular, sandy shorelines are susceptible to modifications in wave patterns that alter the sediment transport down the shoreline, resulting in wave-induced floods (Ribas et al., 2023; Vousdoukas et al., 2022).

Tide

Tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Earth. (Alcántara-Carrió, Dinkel, Portz, & Mahiques, 2018). The combination of large alongshore drift and tidal in- and outflow causes the formation of the spit, which is then shaped by wave action and tidal currents.

They are also influenced by other factors such as the alignment of the Sun and Moon, the phase and amplitude of the tide, and the Earth's orbit around the Sun.

Tides play a significant role in influencing the evolution of the mouth of a river. This is how tides affect the evolution at the river mouth (Yang, Ding, & Chen 2001). Tidal currents associated with tides' rise and fall can influence sediment transport and distribution at the river mouth (Wright, 1977). During flood tides (rising tides), the increased water level can cause stronger currents, which enhance sediment transport towards the river mouth. Conversely, during ebb tides (falling tides), the water level decreases, resulting in reduced currents that may allow sediments to settle and accumulate near the river mouth (Friedrichs & Perry, 2001).

Tides at the mouth of the Volta River are roughly one meter in tidal range, and they are semi-diurnal. The mild currents created by these tides have little impact on the morphology of the shoreline. The semi-diurnal tides typically occur at 1.28 m for neap tides, and 0.64 m for spring tides. This region has a tidal range of 1 m, making it a micro-tidal area. and the sun, as well as the Earth's rotation. At the eastern side of the volta, higher than normal high tides were observed, and these tides are becoming increasingly impactful due to continued sea level rise. Higher high tides, sometimes lead to flooding in coastal communities.

The lunar and solar gravitational force, as well as their distances from Earth, influence the behavior of the tides in December. Neap tides produce moderate tides with greater low tides and lower high tides twice a lunar month. These tides can also affect the stability of the riverbanks and the distribution of sediments, which can alter the appearance of the river mouth.

River discharge

The length of the mouth channel of a river can be closely related to the cumulative sediment discharge of the river (Han, Wang, Zhou, & Meixner, (2018). The annual river discharge and sediment load of the Volta River have significantly decreased since the construction of the Akosombo Dam in 1964. This reduction in discharge and sediment load has had a profound impact on the morphological features at the mouth of the river. According to Anthony et al. (2016), before the Akosombo Dam was built in 1964, the shoreline of the Volta River Delta had undergone significant changes since the construction of the dam. The shoreline retreated intensely in the 1960s and has since attained a quasi-equilibrium at the latter stage of the post-Akosombo Dam period (1975–2018) (Boateng et al..2022)

This location has a 1 m tidal range, which is a micro-tidal since in 1964 the Volta River's discharge fluctuated from 1000 m3/s during the dry season.

to over 6000 m3/s during the wet season. Runoff was higher and more variable (87.5 mm/yr) before the construction of the Akosombo dam than it was after the dam (73.5 mm/yr) (Oguntunde et al. 2006).

The estuary's system dynamics have altered in terms of flow and sedimentation as water flow is now regulated. Before the construction of the dam, the annual sediment movement was around 7.5 million cubic feet per second (Appeaning et al., 2018). There have been no flow discharge maxima since the Akosombo dam was built, and the amount of sediment transported has decreased to a small portion of its previous level (Bollen et al. 2011). The delta's evolution has been impacted by this sharp decline in the amount of sediment that is supplied to the system, which has also been made. Although it was suggested that erosion had been present since the 1860s, especially in Keta, it was first documented in the Volta Delta in 1929 (Nairn et al. 2014).

Anthropogenic intervention

Sand mining, coastal protections, dredging, damming, urbanization, and the loss of coastal mangroves are some of the main anthropogenic drivers of morphological changes and the related coastal hazards in the southern-eastern Volta delta. The physical features at the mouth of the river Volta have been impacted by these human activities, but damming (Akosombo and Kpong dams), sea defense, and mining will receive a lot of attention**.**

Damming

Anthony (2015) claims that up until the 1960s, there was just one sand drift in the Volta River. Two dams that were built along the Volta River's path in the 1960s and 1980s have reduced the amount of sediment that the river receives as it flows toward the ocean. Wiafe et al. (2013) indicated that the Akosombo dam was constructed 100 kilometers upstream of the Volta River, between 1961 and 1965 and produced the largest artificial lake in the world, measuring 148 km3. A second dam, the Kpong dam, was built on the Volta

River between 1977 and 1982, about 20 kilometers downstream of the Akosombo project. Before the Akosombo dam was built, Halcrow (1954) conducted a pre-construction study and predicted that the dam would lessen sediment deposition. leading to erosion and other coastal hazards. Freedman (1955) accurately anticipated that erosion would continue on the southern eastern coast, particularly in the eastern towns surrounding the mouth of the Volta River. Erosion in Keta increased to 8–10 m/y after the completion of the Akosombo dam (Ly 1980).

According to past research, the Volta River Delta experienced severe local erosion at an earlier post-dam period due to a notable decrease in sediment load. Furthermore, the dynamic balance of sediments in the surrounding coastal area was seriously upset by the construction of ports in Cotonou, Benin (1964) and Lomé, Togo (1965–1968). There are places where local erosion rates are higher than 10 m/y (Ozer et al. 2017).

Let's look at how other factors, such as sand mining, affect morphological changes and related problems.

Sand mining

The Volta River's morphology has been significantly impacted by sand mining at its mouth (Amenuvor, Gao, Li, D., & Shao, 2020). Local communities in the Volta River are impacted by sand mining in many ways (Angnuureng et al., 2021). Sand mining has altered the riparian land cover in the Dallung-Kukou watershed of the Volta basin; this has worsened erosion by adversely affecting the sediment budget along the delta coast (Brempong et al., 2021). The Volta River's estuary and marine shorelines have seen morphological changes as a result of these activities, including patterns in erosion and accretion. Uncontrolled sand mining by people of Mepe, Battor, Torgorme, and other regions from the Volta River has resulted in damage to the Mepe-Sege Road and the Mepe-Dove Junction Road. Moreover, there is a constant leakage of water into the roads from the piled sand. Sand mining has made Ghana's coastal erosion problem worse. This is particularly true in the eastern portion of the country's coastline, which is impacted by the Volta Delta system (Appeaning et al., 2021).

Coastal protection

Coastal protection measures are counted among the activities that bring about morphological evolution at the mouth of the Volta River. It directly or indirectly influences the sediment transport and deposition patterns. Coastal protection measures, such as the construction of groins or breakwaters, can alter the natural sediment transport processes along the coastline. This can lead to sediment accumulation in certain areas, including the mouth of the river.

In 1923, a deliberate technical intervention was made to break up oncoming waves and promote sedimentation to stop erosion and its associated effects. Although this protection strategy appeared to be effective at first, erosion returned in 1926 after the sea demolished the groins (Van der Linden et al. 2013; Akyeampong, 2001). Coastal erosion naturally occurred between 1870 and 1880, according to the results of the first engineering study conducted on this coastal area in 1929 (Coode 1929).

A new steel wall constructed in 1955–1956 using sheet piling was an attempt at intervention, but it collapsed. A new steel wall constructed from sheet pilings was constructed in 1955–1956 in an attempt to intervene, but it also collapsed in the 1960s. To further safeguard the east shore, revetments were reinforced. This also failed, according to reports, because the rocks in the revetments tumbled into the sand (Alves et al. 2020).

sed in the 1960s. Another effort was to reinforce revetments to protect the east shore. Reports state that because the rocks in the revetments slid into the sand, this also failed (Alves et al. 2020).

Due to these difficulties, the Keta Sea Defence Project (KSDP) and the Ada Sea Defence Project (ASDP) were constructed. Addo et al. (2011) rebuilt the shoreline positions from satellite pictures collected in 1986, 1991, 2001, 2007, and 2011 to measure the coastline dynamics after the KSDP was formed. They conclude that there was greater erosion in the east of the project than in the west and that there was accretion in the western portion of the KSDP (Appeaning Addo et al. 2011). The rate of erosion was around 3.1 m/y when the project was completed. Similarly, as shown by Angnuureng et al. (2013), erosion east of the groins accelerated substantially from around 3.2 m/y (pre-construction period) to approximately 17 m/y (post-construction). Between 2012 and 2014, the "Atorkor-Dzita-Anyanui Sea Defence Project" (ASDP) was built. as an additional piece of infrastructure meant to impede coastal erosion.

Figure 3.0: Location of the Volta River mouth in Ghana

Source: Google Earth

A river mouth sandspit's response to alterations caused by jetty constructions or other natural events is known as the "impact of the ASDP on Sandspit Evolution." Studies by Tanaka, Lee, and Hiep et al. have shown that substantial changes in the region around a river mouth can cause discernible changes in the morphology of the river mouth. Sediment deposition and a decrease in wave configuration were two of the documented observations at the river mouth. The impact of the jetty and groin system on the morphology of the Volta River mouth was assessed to highlight its distinct response to the ASDP. The project was acknowledged as a depiction of the river mouth shorelines following development is depicted in Figure 3. Upon examination, the western side of the river mouth's shorelines showed expected beach improvement. On the other hand, the accreting groin system caused substantial erosion caused by an imbalance in the sediment balance at the river mouth on the eastern side.

In the post-ASDP era (2013–2020), it is seen that the updraft and downdrift sandspits enter the estuary. This is a typical scenario where unanticipated or inadvertent modifications to the coastal environment occur as a result of engineering efforts. To determine the rates of sandspit incursion into the estuary, these positions were used. These calculations show that the updraft sandspit invades the estuary at a pace of 60 m/year and the downdrift sandspit invades at a rate of 80 m/year. With the completion of the ASDP (2013–2020), the shorelines along the Volta River mouth are getting shorter.

The sandspits that are updraft and downdrift throughout the ASDP timeframe (2013–2020) encroach into the estuary. This is a common situation where engineering work alters the coastal environment in ways that are unexpected or unintentional. The sandspit intrusion rates into the estuary were assessed using these coordinates. According to our analysis, the rate at which the updraft sandspit invades the estuary is while the downdrift sandspit moves more slowly, 60 meters per year

The dominant driving force(s) behind the causes of the morphological changes

To determine the dominant causes of the change at the mouth of the river Volta. This section of this study seeks to determine the dominant causes of the morphological changes at the mouth of River Volta in terms of sand bars and sand spits. There have been numerous severe incidents of coastal erosion and its effects over many decades related effects on the southern coast of Ghana and its vicinities and this can be inferred from the objective one. The question here is what are the predominant causes of this evolution (morphological changes) at the mouth of River Volta? Knowing this is vital because understanding the causes would greatly aid decision-makers and other interested parties in their efforts to adopt and lessen the incidence of this issue both now and in the future.

Multiple studies conducted on the mouth of Volta River have linked morphological changes and the related coastal hazards surrounding the mouth of river Volta to both natural processes and anthropogenic activities (Appeaning et al..,2021). Several decades ago, only a few studies: Ly (1980), Boateng et al. (2012), and Mawusi Amenuvor et al..2020 looked at the relationship between the physical parameters and morphological changes at the mouth of river Volta to determine the dominant causes of this changes and it related coastal hazard. Therefore, this objective seeks to satisfy the gap. In other to enhance a comprehensive understanding of the major or the predominant causes of these coastal morphological changes, in objective three, some statistics were conducted on some of the physical features thought to be the main causes of the morphological changes and the problems associated with them.

Physical Vulnerability Assessment Index

In the past, mapping out the vulnerable communities in the southeastern coastline of Ghana has been very challenging. Researchers can now identify, map out and monitor areas susceptible to hot spots of coastal hazards such as erosion and floods through the Coastal Vulnerability Assessment Index. The eastern coastal areas are more vulnerable to coastal hazards due to geomorphological issues: climate change-induced sea level rise, and increasing human activities. The Coastal Vulnerability Assessment Index (CVI) usually deals with physical and socio-economic parameters as indicators, but this study only concentrates on physical parameters. A physical vulnerability assessment index is an indicator that combines the intrinsic vulnerability (IV) of buildings and flash flood intensity (FFI) to assess the physical vulnerability of buildings to flash floods.

The variability in the CVI to erosion and flooding along the mouth of the river Volta is influenced by different (geo)physical variables including sea level rise, wave climate, coastal slope, geomorphology, and shoreline change.

Simple linear regression

All the driving factors discussed in the various sections bring about morphological changes and are related to coastal hazards at the mouth of river Volta, specifically the eastern part. However, the question is which of these factors is (are) the dominant cause of the changes. This analogy can be best appreciated if a Simple linear regression is performed. Simple linear regression can be used to determine the relationship between the physical parameters and the morphological changes near the river mouth. It can be used to determine the relationship between physical parameters and morphological changes at the mouth of the Volta River.

analyzing how various independent variables—such as wave action, tide, sediment load, and river discharge affect the dependent variable, the shoreline change rate, stakeholders can better understand the morphological changes occurring in the environment. Researchers can identify the main causes of morphological change near the river mouth by examining the relationships between these variables. By using this information, strategies for managing and reducing morphological changes may be developed, as well as a deeper understanding of the primary causes of these changes can be obtained.

Coasts at toolkits

CoastSat is an open-source Python toolbox created especially for mapping coastlines with satellite images (Smith et al., 2020). This tool facilitates the extraction and analysis of coastline data, allowing for the monitoring of coastal dynamics over time. With an emphasis on sandy beaches around the world, it enables users to extract time-series data on shoreline positions from more than 39 years of publicly available satellite pictures. Utilizing information from satellite missions like Landsat and Sentinel-1, the toolkit interfaces with Google Earth Engine to expedite the retrieval and analysis of satellite imagery (Vos, Splinter, Harley, Simmons, & Turner, 2019). Coast Sat uses a powerful shoreline detection technique that combines sub-pixel resolution border segmentation with supervised picture classification to map shoreline positions with an accuracy of about 10 meters. This feature offers a realistic and easy-to-use tool for monitoring and investigating coasts, which is especially helpful for scientists, engineers, and coastal managers. The program is publicly accessible on GitHub and comes with thorough documentation and guided examples to help users with implementation (Harley, Vos, K., & Splinter, 2022)

The world's longest-running shoreline monitoring program is comprised of a growing library of thirty-five years' worth of satellite images that are freely accessible through Google Earth Engine (GEE).

This brief message explains and provides examples of an open-source Python toolbox that allows the user to extract time-series shoreline location data from 30þ years (and counting) of publicly accessible satellite photography at any coastline in the world. The program is open-source, cost-free, and simple to use (Palmsten & Brodie, 2022). Crucially, modern coastal management depends on the capacity to monitor and measure shoreline changes over the previous three decades, and Coast Sat offers a useful resource for a variety of prospective users.

Theoretical framework

A theoretical framework serves as a foundational analysis of existing theories, guiding formulating and presenting arguments. It helps structure the research by offering a lens through which the subject matter is examined and understood in research (Chan & Ngai, 2011). A theoretical framework can be applied in this study. This helps us understand the processes and factors that influence the changes occurring at the mouth of a river over the period. To understand or appreciate this phenomenon (morphological changes at the mouth of the River Volta) Sediment Transport Theory, Fluvial Interaction Theory, and Deltaic Evolution Models were used

The Fluvial Marine Interaction

The Fluvial Marine Interaction Theory was significantly developed by Dalrymple and Choi in 2007. Their work focused on the dynamics of the fluvial-to-marine transition zone (FMTZ) and how the interaction between riverine and marine processes influences sediment deposition and deltaic morphology (Dalrymple & Choi, 2007). This theory has been instrumental in understanding the complexities of sedimentary environments where rivers meet the sea.

According to Smith and Jones (2018), the theory emphasizes the interaction between riverine (fluvial) and marine processes, especially in the transition zone where rivers meet the sea. This framework is essential for comprehending sediment dynamics, delta morphology, and environmental changes in coastal regions.

The mouth of the River Volta undergoes considerable sediment transport due to the combined effects of river discharge and marine wave action. As highlighted by Brown et al. (2020), the theory aids in understanding the interaction between these forces, which is vital for predicting sediment deposition patterns and erosion rates at the river mouth.

Interactions between fluvial jets and longshore currents result in distinct morphological features such as mouth bars and delta formations. These features are shaped by the balance between riverine flow and marine influences, which vary with changes in discharge levels and wave conditions (Smith & Brown, 2019). This is especially relevant for the River Volta, where such dynamics play a crucial role in determining the delta's shape and stability.

Tidal influences at the River Volta's mouth play a crucial role in shaping flow dynamics and sediment distribution. The Fluvial Marine Interaction Theory offers valuable insights into how tidal forces modify the morphology of mouth bars and affect sediment transport pathways, ultimately reshaping the delta's architecture over time (Johnson & Lee, 2021).

Deltaic Evolution Models

The Deltaic Evolution Models were notably propounded by Galloway in 1975. He developed a ternary theory that associates characteristic delta morphology with specific combinations of wave, tidal, and fluvial factors. This model helps in understanding how different environmental forces shape deltaic systems and their evolution over time

These models describe how deltas evolve based on various forcing mechanisms such as riverine sediment supply, wave action, and tidal influences. The Galloway triangular diagram is often used to classify deltas based on their dominant processes (Galloway, 1975). The Volta Delta exhibits characteristics of both riverine sedimentation and wave influence, indicating a complex interplay that shapes its morphology over time (Anthony & Blivi, 1999). Knowing these models makes it easier to forecast how delta structure will alter in the future as environmental circumstances change.

These theories collectively provide a comprehensive framework for assessing morphological changes at the mouth of the River Volta, highlighting the intricate relationships between hydrological dynamics (Smith & Jones, 2010), sediment transport processes (Taylor, 2015), technological monitoring capabilities (Nguyen et al., 2018), and deltaic evolution patterns (Lee & Zhang, 2017).

Sediment Transport Theory

The Sediment Transport Theory was significantly developed by R.A. Bagnold, who published his foundational work on the subject in 1956. His research laid the groundwork for understanding sediment dynamics in rivers and other water bodies, focusing on how sediment is entrained and transported by flowing water.

This theory focuses on how sediments are moved by water flow and waves, which is crucial for understanding morphological changes at river mouths (Anderson, 2012). The interaction between river flow and coastal wave action significantly influences sediment deposition and erosion patterns (Johnson & Brown, 2015). In the case of the River Volta, sediment transport dynamics are affected by both river discharge and wave energy, which dictate how sediments accumulate or erode along the delta (Taylor et al., 2018)

CHAPTER THREE

STUDY AREA

Introduction

This section discusses the study area and some of the important communities by describing their location and size, as well as physical features such as climate, vegetation relief drainage minerals, and geology.

The study sites

Based on geomorphology, Ghana's coastal zone is divided into the western, central, and eastern coastal zones (Boateng, 2012).

The Eastern Coastal Zone of Ghana, particularly the area around the mouth of the Volta River, is utilized as a study area for assessing morphological changes based on evidence of notable erosion and floods, making the area a vulnerable coastal zone in Ghana. On average, the eastern estuary's shoreline is eroding at a pace of roughly 1.94 meters per year. (Charuka, Angnuureng, & Agblorti, 2023).

The research area, the Eastern Coastal Zone of Ghana, is approximately 149 kilometers long, stretching from Prampram to the Ghana-Togo border at Aflao, according to Codjoe, (2020). The Volta River Delta is the eastern coast of Ghana, extending from 5°25' to 6°20' N and 0°4' to 1°10' E along the Volta River coastal plain.

Out of the river's overall size of around 4562 km2 in Ghana, the Volta River Delta is made up of an active section that is about 2430 km2 at the river mouth. The Volta delta, according to Appeaning Addo et al. (2018), is the 5 m contour inside the Accra-Ho-Keta Plains. This area is known for its sandy beaches and, midway between, is the site of the Volta River's deltaic estuary.

The Keta Lagoon, the Volta Estuary, and the Songor Lagoon enclose a sizeable amount of the East Coast's landmass.

The Volta River mouth is a portion of the downdrift deflected Volta Delta System and is situated along Ghana's southeast coast.).

The Volta River was named by Portuguese gold traders in Ghana, and it means "twist" or "turn" in Portuguese (Nkrumah, Arrigoni, & Napolitano (1963). Volta River supports large populations of over 100000 people with particular concentrations in the southern coastline of Ghana (Roest. (2018).

The delta of the Volta River spans over 400,000 km2 (Steele-Dunne, et al. 2010). Six riparian states share the river basin, which is a transnational watershed. According to Oguntunde et al. (2006), the watershed is 40% in Ghana, 42% in Burkina Faso, 6% in Togo, 5% in Mali, 4% in Benin, and 3% in Côte d'Ivoire. The Oti River, Black Volta, and White Volta are the Volta River's three principal tributaries. According to Gassard & Ducrocq (2014), It is one of the Gulf of Guinea's main sources of silt supply. The river drains a watershed that is primarily composed of sandstone and encompasses a wide range of lithologic terranes, totaling roughly 390,000 km2 (Anthony 2015). At Ada, the Volta River has one outlet canal that leads to the sea and is connected to a sizable spit. According to Anthony et al. (2016), the site of the river's mouth naturally changed, leading to the formation of a sizable spit

Over many decades, the eastern coast's dominant feature, the Volta Delta, has changed the sediment regime and hydrodynamics.

Quaternary in nature, the Volta Delta's geology is mainly composed of clay, silt, and alluvial sand (Jason Quashigah et al., 2013). A narrow shelf that ranges in width from 15 to 33 kilometers encircles the delta shore. The shoreline face descends to a depth of 15 meters, which is thought to be the limit of significant wave-induced sediment movement on this shore., and is generally uniform and moderately steep (Rossi 1989; Anthony 2015). Situated along Ghana's eastern coast, the delta areas span an estimated 4562 km2 and have been divided into nine administrative

The delta's drift-aligned beaches are predominantly sandy (Anthony et al., 2019) and encircle two significant lagoons, the Songor Lagoon and the Keta Lagoon on the eastern and western portions of the Volta estuary, respectively. The delta is dominated by waves (Roest et al., 2018). The Volta Delta is one of Ghana's most prominent geomorphic and coastal characteristics. The present-day delta was created by the Volta River carrying enormous loads of material, particularly coarse-grained sand, to the sea and depositing it close to the river mouth (Nairn et al. 1999).

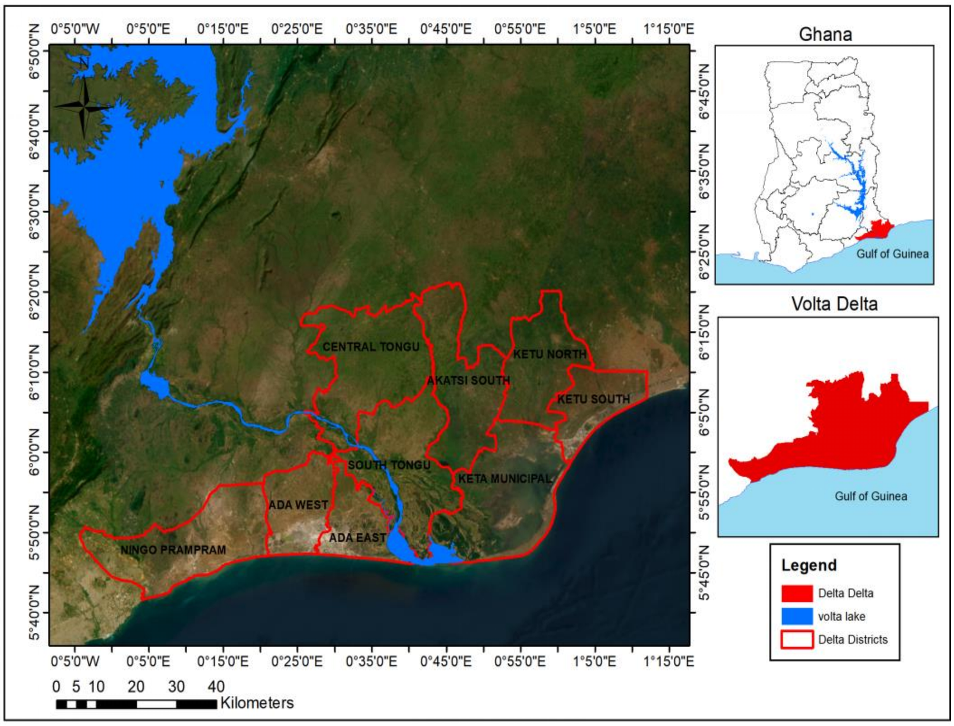


Figure 4.0 **depicts Coastal Districts on the eastern coast of Ghana which are affected by the effects of the morphological changes**
Sources: Department of Geography and Regional Planning, UCC,2024

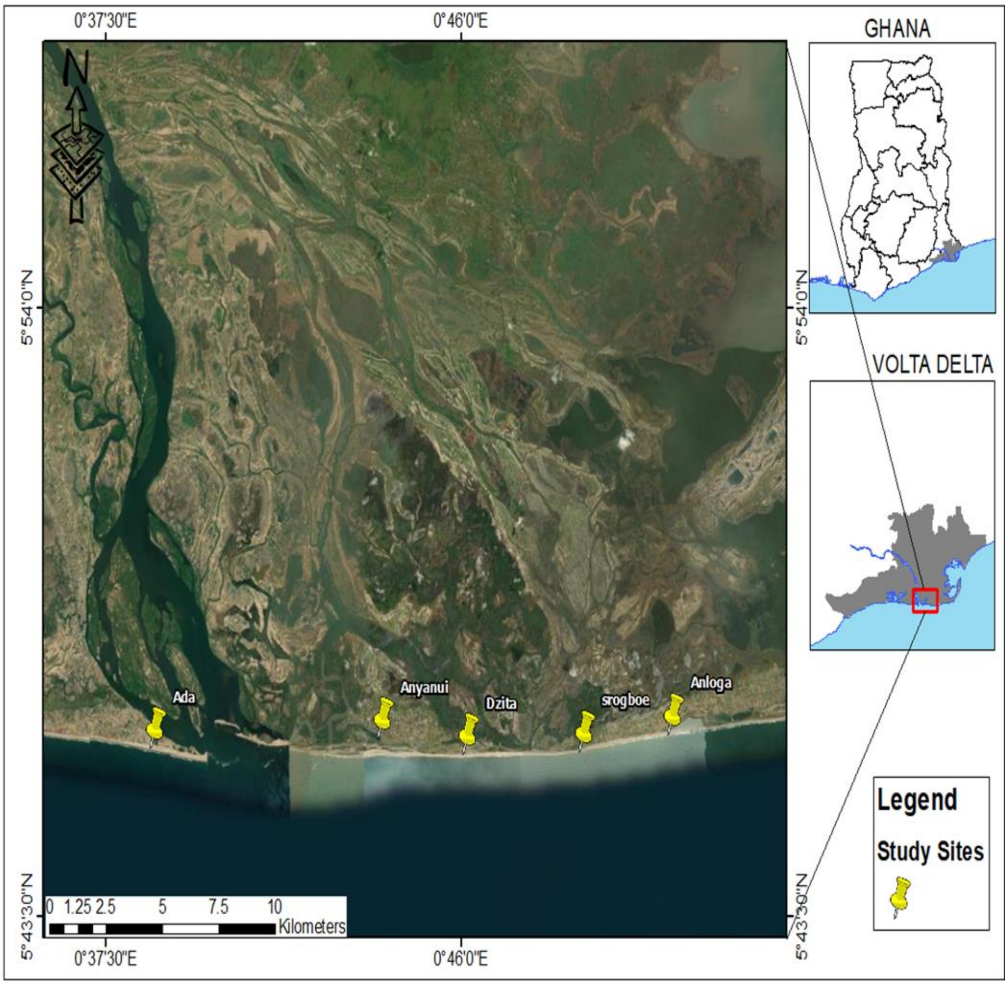


Figure *5* shows the communities selected for the study.

Sources: Department of Geography and Regional Planning, UCC,2024

Climate

The year-round high temperatures vary from 23°C to 28°C (Babson et al.., 2020). It is typically possible to reach a high of about 33°C during the sweltering summer months. The main season, which runs from March to September, generally sees a lot of rain. On average, 750 millimeters of rainfall. But the ground gets quite dry during the harmattan season when there is no rainfall at all. Because of the Volta River, the sea, and other nearby bodies of water, the humidity is approximately 60% higher than average. The range of daily evaporation rates is 5.4 to 6.8 millimeters (Andersen & Golitzen (Eds, 2005). *The Niger river basin: A vision for sustainable management*.

World Bank Publications. With an average temperature of 30°C, February is often the warmest month. August has the lowest average temperature of 26.1°C, making it the coolest month overall. Ada Foah's highest recorded temperature is 38.9°C, which was attained in April. According to Wegulo and Martinson (1998), the lowest temperature ever recorded in Ada was 17.8°C in September.

Relief and Drainage

Generally soft and rolling, the relief is a low plain rising no more than 60 meters (200 feet) above sea level (Ghosh, 2015). The Todjeh boulders, which rise to a height of approximately 240 meters (800 feet) above sea level, are one of the most notable relief features. Over the sea, these boulders are haphazardly arranged. Ada East District's overall drainage pattern can be characterized as dendritic, with the Volta River serving as the source of several of the district's streams.

The mouth of the Volta River empties into the Gulf of Guinea, forming an intricate network of waterways. At the river's mouth, the Volta River empties into the Atlantic Ocean after flowing primarily south through Ghana's Volta Region (Mul et al ..., 2015).

The drainage basin of the Volta River is around 407,000 km square kilometers, including portions of Ghana, Togo, Burkina Faso, and Ivory Coast. The river is fed by numerous tributaries, including the Black Volta, White Volta, and Oti rivers. At the river's mouth, the Volta River forms a large deltaic region that is characterized by a network of channels, creeks, and lagoons (Nicholls et al 2018). These waterways are influenced by tidal currents and fluctuating water levels, which can cause changes in the river's course and the formation of new channels.

In terms of relief, the Volta River mouth is characterized by a low-lying delta region that is composed of sedimentary deposits, including sand, silt, and clay (Thom & Roy, 1985). The delta is a dynamic region that is constantly changing due to the deposition of sediment by the river and the action of ocean currents and tides. The geology of the area surrounding the Volta River mouth is primarily composed of sedimentary rocks, including sandstone, shale, and limestone. These rocks were formed during the Paleozoic and Mesozoic eras, and have been subjected to a long history of erosion and weathering (Bridges, 1990). In addition to its geological features, the Volta River mouth is also an important ecological zone, providing habitat for a variety of plant and animal species.

Oceanography

Ghana's eastern shore is prone to gyral circulations in the ocean. These are the large-scale ocean flows (ocean basin flows) brought about by the bathymetry of ocean basins, the prevailing winds, and the Coriolis effect (Roest, 2018). The seas off the coast of Ghana are known as the Gulf of Guinea because they are home to numerous major ocean currents. The main one is the Guinea Current, which rises to the top of the water column and moves eastward. Local peaks of 2-3 knots (1.0-1.5 m/s) are the fastest throughout the year (Wiafe et al., 2018; Houghton, 1976).

The Guinea current flows eastward at an average speed of 0.7–0.9 knots (0.3–0.5 m/s), although strong easterly winds have the power to reverse this flow (Ingham, 1970).

A counter-current is present at depths greater than 40 meters, traveling westward at a slower speed. 40 to 60 meters below the ocean's surface are the range of pocnocline depths (Wiafe et al., 2013; Houghton, 1976; Ingham, 1970).

Although these currents' magnitudes decrease approach the coast and are unable to move substantial volumes of silt, they can aid in wave-driven transport.

The average temperature of surface waters is from 26 to 29 degrees Celsius. The surface temperature may drop by up to 20◦C during intense upwelling occurrences (Ingham, 1970).

The Ghanaian coast is a micro-tidal shoreline, where the spring tidal range is greatest at 1.8 m and averages 1.0 m. Ghana's tidal range gradually expands from 0.6–1.2 m in the west to 1.0–1.9 m in the east.

Nonetheless, one important factor influencing the flow of the Volta Estuary is the tide. At least as far upstream as Sogakope (30 km), where the tidal range is around 0.5 m and flow reversal persist, the tidal influence is apparent (Bolle et al. (2015) claim that up to 5 km upstream in the estuary, the tidal range rarely decreases.

At Sogakope, there is a phase lag of around two hours and a reduction in the tidal range to 0.4–0.6 m. The friction created by the river's tidal wave propagation is the cause of this lag. The shape of the river mouth has a significant impact on the river's tidal flow. The phase lag of the tide and the tidal amplitude in the river and estuary decrease with increasing flow resistance. Smaller tides in the estuary will result from a big spit blocking it, whereas the current "open" condition allows for significantly larger (less dampened) tides and currents (Haigh, 2020)

Sediment supply and catchment

One of the primary sources of sediment supply for the Gulf of Guinea is the Volta River (Goussard and Ducrocq, 2014). The river empties into a watershed that is mostly in the semiarid Sahel region of West Africa, covering an area of around 390,000 km2. Sandstone makes up the majority of the watershed's composition (Almar et al..,2015). There are many different types of lithological terranes in the catchment. Before the Akosombo Dam's completion in 1964, Throughout the dry season, the river's discharge varied between 1000 m3 /s and above 6000 m3 /s (Anthony, Almar, and Aagaard ,2015). There were two further dams built: one at Kpong in 1982 and another at Bui in 2013. According to Oguntunde et al. (2006), runoff was more variable and higher (87.5 mm/y) before dam construction than it was during the post-dam era (73.5 mm/y). Since water flow is now regulated, the region's natural flooding patterns have also altered, and the flood plains now depend on irrigation and a smaller amount of water (Corcoran, Ravilious & Skuja, 2007). According to Ofori. (2019), there was consistent flooding before to the construction of the dam, which allowed for the deposit of silt and allowed for the continuation of farming and fishing operations that were dependent on the river's and its subsidiary streams' flood regime. Roughly 7.5 million m3 of sediment were transferred annually before the dam was completed (Bollen, Mao & Pepe, 2011). This region of West Africa depicts the Volta Delta, the three hydroelectric dams in Ghana that are affecting the delta's structure and sediment supply, and the six nations that share the Volta Basin's water supplies.

Sediment transport has decreased to only a portion of the area since the dam's completion, and there have been no peaks in river discharge (Source: modified from Rodgers et al. 2021.

This sudden cutoff in the sediment supply to the delta system has caused significant coastal recession and affected the delta's evolution (Allersma & Tilmans, 1993;). Bollen et al. (2011) estimate that the shoreline in Totope–Ada is receding at a pace of about 6 m/y, while Ly (1980) calculated that the shoreline in Keta was eroding at a rate of 4 to 8 m/y.

According to Kumapley (1989), erosion has been destroying a kilometer-wide strip of coastal land since the 1880s.

Vegetation

Most of the vegetation at Ghana's Volta River mouth comprises brackish marshes and mangrove forests. The vegetation is a form of coastal savannah that is distinguished by short savannah grass and small trees and shrubs scattered throughout (Kizito & Balana, 2016). Ecosystem services in the Volta Basin. In *The Volta River Basin* (pp. 201-218). Routledge. The enormous lengths of coconut trees along the shore and the patches of coconut groves give the area a traditional appearance. In the salty, moist soil close to Songhor Lagoon and the tributaries of the Volta River, there are also a few mangrove tree strands, such as the Angor mangrove (Carrere, 2009).

Mangrove forests are a specialized type of forest that grows in coastal saline or brackish water. They are important ecosystems that provide a habitat for a diverse range of plant and animal species, including fish, birds, and reptiles.

The mangroves also protect the coastline from erosion and storm surges. Around Ghana's Volta River mouth, brackish marshes can be found in addition to mangrove forests. Freshwater mixed with saltwater creates a unique habitat in these marshes that supports specialist plants. Brackish marsh vegetation can include sedges, grasses, and other kinds of wetland plants (Mishra, 2009).

The mangrove forests and brackish swamps around the mouth of the Volta River in Ghana are critical habitats for several species of birds, fish, and other aquatic animals (DeGraff-Johnson, 2010). These habitats provide breeding grounds for fish and other marine life and serve as feeding grounds for migratory birds. Mangrove forests, in particular, are also important in carbon sequestration and climate change mitigation. They store large amounts of carbon, which helps reduce the amount of greenhouse gases in the atmosphere (Tibu, 2017).

Minerals and Geology

The Volta delta is a lobe-shaped delta that protrudes seaward and covers 5000 km2 on Ghana's eastern coast (Anthony et al., 2016). The Volta Delta in Ghana has mineral resources such as jasper, which is used mostly for jewelry, and whose deposits can be found in Kwamikrom in the Biakoye District and Bodada. The Ada Foah has a substantial salt deposit and significant economic potential. For a significant portion of the populace, especially in places where the resource is found, salt mining has historically and currently provided the highest level of employment (Kirabira, Kasedde & Ssemukuuttu, 2013). The district has long been a source of income for the area, which still depends on it for internally generated money. Tertiary and modern deposits underlie the majority of the district. The deltaic regions of the

Volta River and the vicinity of the recent unconsolidated sand, clay, and gravel are found in Songor Lagoon, which is close to Pute. The rock type of the basement is unclear; however, it is believed to be Dahomeyan, similar to the rock that is cropping out to the north of the basin (Coelho et al.., 2017).

The middle and upper Pendjari Supergroup and Obosum Group sandstones, mudstones, and siltstones typically have low mineralization but contain some fluoride, while the deeper Bambouaka Supergroup rocks have generally high concentrations of sulfate, iron, and manganese and, in some places, high salinity and fluoride. The sedimentary basins in the Volta Basin are significant aquifers in eastern Ghana. Precambrian to Paleozoic sandstones make up the Voltaian system, which is found in central Ghana, including the Volta Delta (Logah2023).

Biodiversity

The mouth of the Volta River is an important ecological region that supports a diverse range of species. The Volta River mouth is known for its rich fish diversity (Do Carmo,2008). Numerous species of fish inhabit these waters, including tilapia, catfish, Nile perch, African carp, and various species of cichlids. The river mouth serves as an important spawning ground and nursery for many of these fish. The river mouth and its surrounding wetlands attract a wide variety of bird species. It serves as a vital feeding and resting site for migratory birds, including waders, herons, egrets, and terns (Bergkamp, McCartney, Dugan, McNeely, & Acreman, 2000). The area is also home to resident bird species such as kingfishers, African jacanas, and African fish eagles. Mangroves act as breeding and nursery grounds for fish and serve as a protective buffer against coastal erosion. The area also supports a diverse array of invertebrate species, including crabs, mollusks, and various aquatic insects Bergkamp, McCartney, Dugan, McNeely, & Acreman, 2000).

CHAPTER FOUR

METHODOLOGY

Introduction

Research methods are the plans, procedures, or methods for gathering and examining data or supporting materials to find new knowledge or develop a deeper comprehension of a subject (Fellows & Liu 2021). The procedures used to carry out the study are described in this chapter. It describes the methods used to assess the morphological changes near the mouth of the River Volta as well as the philosophical underpinnings of the technique for this study. This chapter explains the rationale for the research design, the data collection process, and the research tool selected for data analysis. Additionally, it emphasized the kinds of data that were gathered and the reasons behind their value for the analysis and accomplishment of the study's objectives.

Research Philosophy

In this study, the positivist research philosophy is applied to the context of assessing the morphological changes at the mouth of the Volta River and its effects on the coastline. It is a school of thought that applies empirical evidence and scientific methods in gathering data on shoreline changes, sediment deposition, river flow rates, and other relevant factors to understand the historical evolution at the mouth of the Volta River and its effects on the coastline (Bridges, 1990). Positivism philosophy emphasizes the use of quantitative analysis to derive meaningful conclusions (Park, Konge, & Artino Jr, 2020). This could involve in analyzing historical satellite images, data on river discharge from the Volta River, and other quantitative measurements to understand the morphological changes at the mouth of the Volta River and its impact on the coastline. It helps promote replicability and objectivity in doing quantitative analysis.

Research approach

A research approach is an organized, methodical approach to investigating a certain issue or topic. Obtaining and analyzing information, it entails choosing the right methodologies, data collection strategies, and analytic processes (Tracy, 2024). A quantitative research technique is required for this project because it examines the evolution of the River Volta's River mouths. To manage and conserve these dynamic ecosystems, the quantitative research technique employed numerical indicators to analyze changes in morphology, sediment dynamics, and landscape patterns throughout time. (Obida, Blackburn., Whyatt & Semple, 2021).

Research design

The design used in this investigation was descriptive. Because the study aims to assess the morphological changes at the Volta River mouth and determine the primary physical parameter causing the alterations as well as the associated coastal dangers, it is descriptive research. When a researcher wishes to learn more about a certain phenomenon, such as morphological change, they conduct a descriptive study (Osanloo & Grant, 2016). According to Jaakkola (2020), the utilisation of descriptive design facilitates the collection of precise data on phenomena and aids in the comprehension and depiction of those phenomena. To be able to characterize the morphology, sediment dynamics, and landscape patterns that have changed throughout time there is a need for a descriptive research design

Data and sources

This study used satellite Imagery and Hydrological Data, Oceanography& data,

Landsat Satellite Data: Historical satellite imagery from Landsat (5, 7, 8& 9) provides data from 1984 to 2020. These images are crucial for analyzing long-term morphological changes at the river mouth, including sediment transport and shoreline dynamics. The Landsat images have a spatial resolution of 30m, which can be down-sampled to 15m for enhanced accuracy (Borgogno-Mondino, 2018)

Sentinel-2 Data: This satellite provides high-resolution imagery (20m, down-sampled to 10m) and is useful for monitoring changes in land cover and coastal morphology over time. Sentinel-2 data complements Landsat imagery, filling in gaps and providing more detailed observations (Vos, 2019).

Google Earth Imagery: Supplementary images from Google Earth were utilized to enhance visualization of how the volta mouth has evolved. Google Earth offers high-resolution images (2m/pixel) that can provide insight into recent changes at the river mouth.

River Discharge and Sediment Load Data:

Data on river discharge and sediment loads before and after the construction of the Akosombo Dam is vital for understanding how dam regulation has affected sediment supply and morphological evolution at the river mouth. These data were sourced from River discharge and sediment loads (Water Resources Institute)

Oceanography data

To assess the morphological changes at the mouth of the Volta River, oceanography data is needed to provide valuable insights into the physical processes to shape the river delta and coastline. wave data from European Re-Analysis (ERA-5) was downloaded at a sub-region of latitude points of 5.7 south, 5.6 from the north, and longitude points of 0.7 from the east and 0.6 at the point of the west. Tide data was downloaded from WXTide v32 and was used to help us understand the physical processes driving morphological changes at the mouth of River Volta.

Data collection procedures (Pre-data acquisition and Data processing**)**

Before the extraction of the data, a desktop study and reconnaissance survey were first conducted.

A desktop study

Desk Study is a critical initial step in the site investigation process, primarily aimed at assessing potential risks associated with a development site. This study involves the collection and analysis of existing documentary data to establish a comprehensive understanding of the site's history, geology, and hydrogeology (Maciejewska, Kuzak, Sobieraj & Metelski, 2022). Desktop research can be used to evaluate the morphological change at the Volta River mouth by examining a variety of data sources and modeling the changes with specialist software (Srivastava,2014). Desktop review was done to: apply statistical methods to analyze the data and identify trends and patterns in the morphological changes.

Compare the current morphological conditions with historical data to identify changes and understand the factors contributing to these changes.

A reconnaissance survey

A reconnaissance survey is a preliminary examination of a region to identify potential historic resources, assess the feasibility of a project, or gather initial data for a larger study. It involves a comprehensive review of existing information, including maps, aerial photographs, and historical records, to identify key issues and potential sites for further investigation (Kvamme, 2006). A thorough reconnaissance survey enabled this study to lay the groundwork for a comprehensive assessment of the morphological changes at the Volta River mouth, ultimately leading to more effective management and adaptation strategies (Huning, 2024).

Data Acquisition (satellite images)

Two separate sources of satellite imagery were used in the study: Sentinel and Landsat toolkits from Coast Sat, and solely Landsat satellite images. Landsat satellite photos from 1992, 2002, 2012, and 2022 were used in the study, including TM, ETM+, and OLI_TIRS. These images were chosen to assure transparency by having a cloud cover limit of less than 10%. They were downloaded from the USGS website. Table 1 displays the single Landsat picture that covers the research area, 193 and 56. The Landsat photos have perfect geodetic accuracy and were taken at Level L1T.

. The study delineated shorelines in several periods using multispectral Level-1 data from Landsat 7 (ETM +) and Landsat-8 (OLI). The study of coastal habitats and shoreline alterations is aided by the use of publicly available Landsat data Because successive datasets are available quickly, multispectral remote sensing offers extensive area coverage with repeated monitoring of the area. With its synoptic and repeated coverage, remote sensing is crucial for cost-effectively providing basic estimates of coastal change for coastal and deltaic research (Parthasarathy & Deka, 2021).

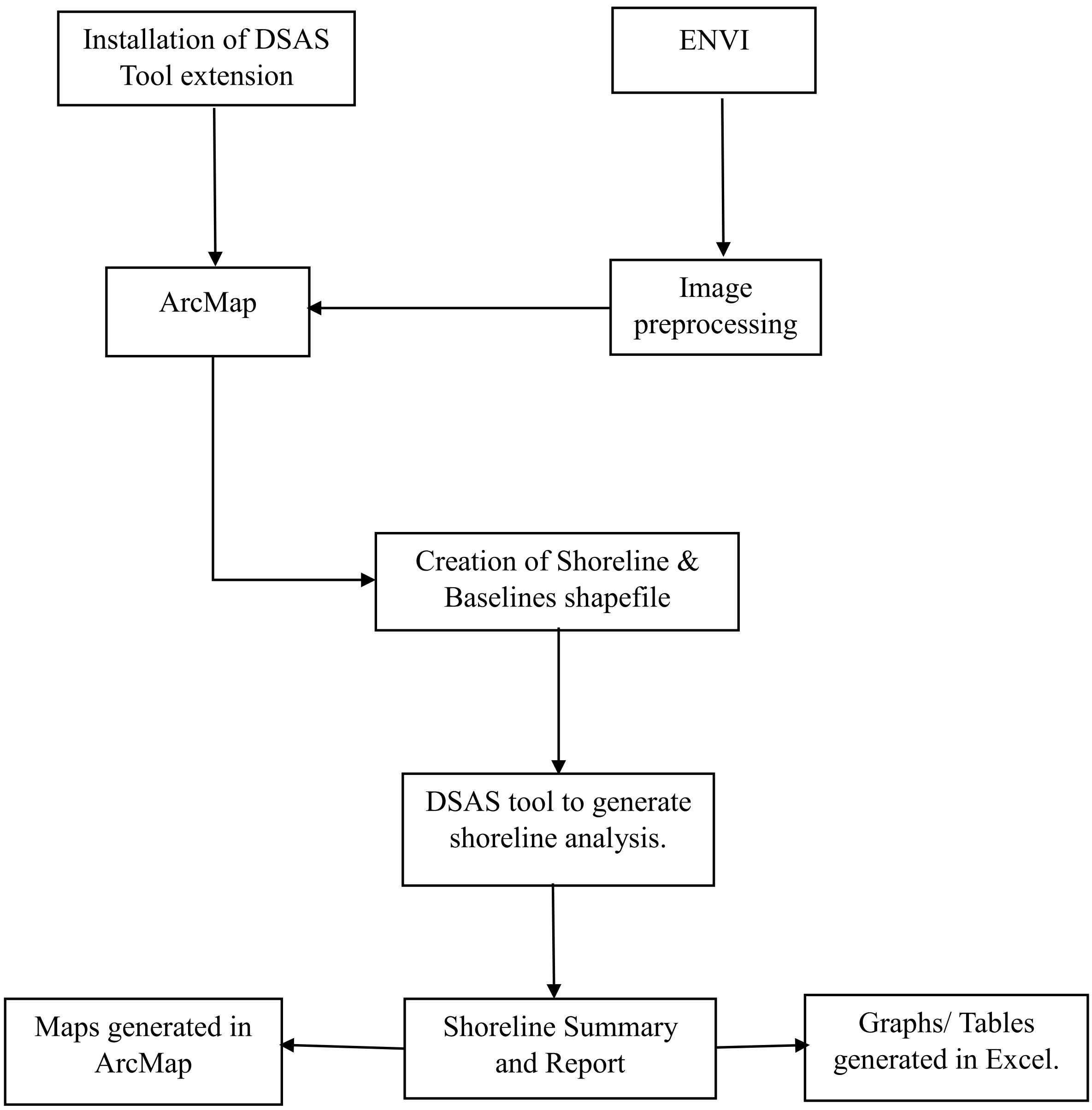


Figure 6: **Chart flow of DSAS installation**

Table 1. Characteristics of Landsat data (satellite imageries) used for the study.

Satellite images Used	Date of Acquisition	Resolution/Pixel Size (meters)	Land cloud cover (%)	Number of Bands
Landsat 5 TM	04/06/1992	30	0	7
Landsat 7 ETM	09/05/2002	30	0.86	8
Landsat 8 OLI_TIRS	10/08/2012	30	0.49	11
Landsat 8 OLI_TIRS	25/12/2022	30	0.72	11

Source: USGS Landsat Satellite Data (2023)

Using Landsat data, the mid-infrared (band 5) and green (band 2) band ratios were used to identify the water-land boundary. This technique lessened the subjectivity in defining the shoreline. Using optical remote sensing data, several methods have been developed to recover coastlines (Alesheikh, Ghorbanali & Nouri,2007). The ENVI software's band ratio model was used to apply the band ratio in this study, producing a ratio image with values between 0 and 3. To create a binary image, the image was then segmented and split into pieces, with values above 1 indicating land and below 1 denoting water. The line separating land from water was easy to discern using this strategy. Another research (Guariglia, Mateut, 2006). has effectively employed the separation ratio of 1. After that, the water class's raster to vector conversion was completed, and shape files were exported for ArcMap overlay.

To extract the target shorelines for use as a guide during the digitization process, the vector shorelines were superimposed over the color composites.

To calculate rates of change, the Digital Shoreline Analysis System (DSAS) Version 5.1 extension was installed in ArcMap. Excel was used to create the various charts and graphs, and ArcMap version 10.8 was used to make the maps.

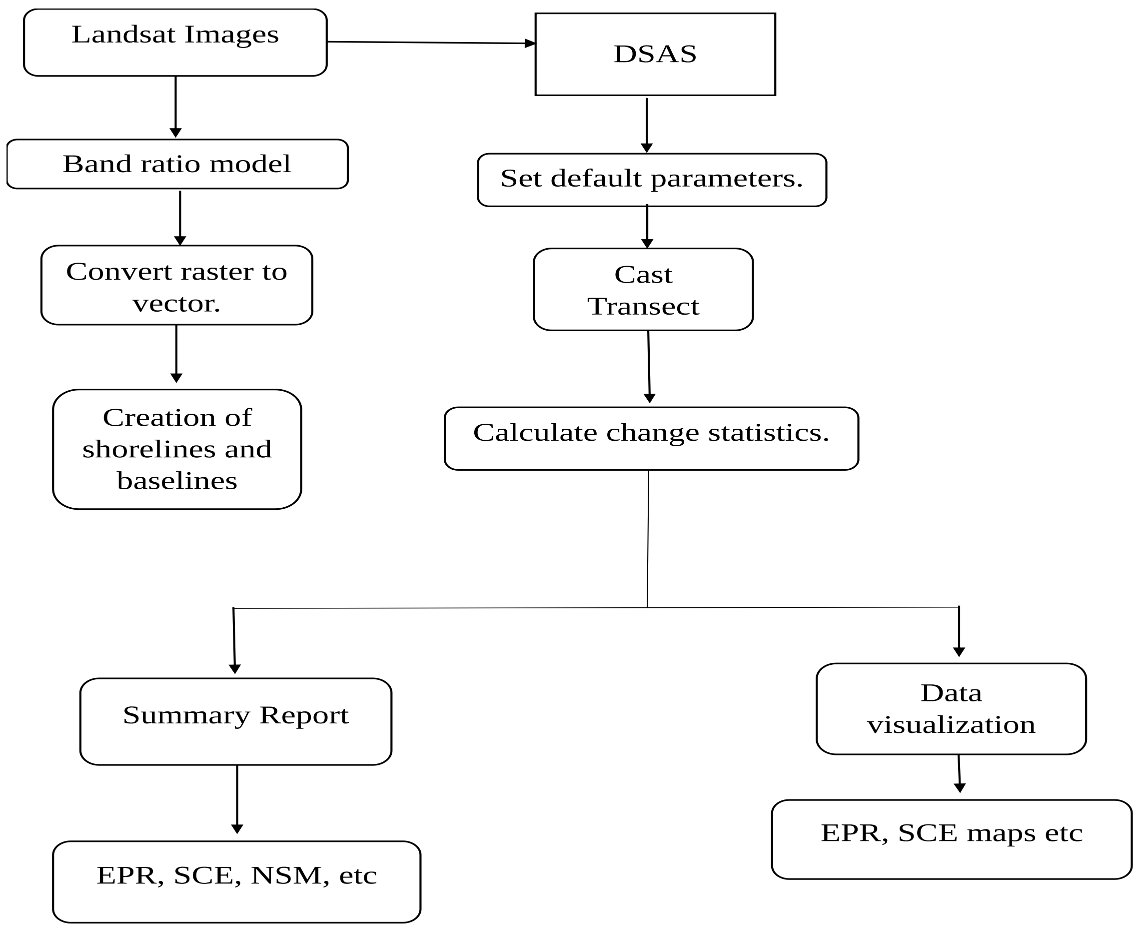


Figure 7:0 Flowchart for DSAS

Shoreline changes analysis

With the use of many statistical methods and the DSAS extension in ArcGIS, the analysis of shoreline change was carried out. Among the methods provided by DSAS for assessing shoreline changes are the Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression (LRR) (Tanga, et al., 2021).

Shoreline distance information for certain transects is provided by SCE and NSM.

However, it is important to note that these methods do not inherently provide insight into the rate of shoreline change. Whereas NSM shows the overall distance between the oldest and most recent shorelines, SCE determines the maximum distance between all shorelines without taking the shoreline's year into account.

On the other hand, EPR and LRR supply the coastline change rate for each transect. EPR is used to compute the amount of shoreline shift split by the time interval between the shorelines in 1992 and 2022.

Conversely, LRR calculates the rate by fitting every coastline point along a given transect with a least squares regression line. It is important to remember that while LRR is a strong statistical method that makes use of all the shoreline data that is available, it is vulnerable to the impact of outliers (Dolan et al, 1991). As a result, the EPR method was used for this study's analysis of the coastline change rate. Positive values in NSM and EPR indicate accretion and negative ones indicate erosion. Additionally, 516 transects that were positioned perpendicular to the baseline, extended 100 meters seaward and were separated by 50 meters were used in the study.

These transects served as the basis for the statistical calculations, spanning every shoreline starting from the baseline. The length and rate of shoreline change along each transect were determined by carefully examining each intersection point of the Volta delta front shoreline. This Data wasn't not enough for the study to be able to assess the real morphological changes at the mouth of River Volta so there was the need to employ the Coast SAT toolkit.

Shoreline Extraction from Satellite Data (coast sat toolkit)

The sub-pixel resolution border segmentation allows CoastSat to detect the shoreline with high precision, beyond the native resolution of the satellite imagery. The supervised image classification then helps identify the actual shoreline, rather than just detecting edges. This dual approach enables CoastSat to provide coastal monitoring data with an accuracy of approximately 10 meters (Vos & Harley,2019). CoastSat uses a powerful shoreline detection technique that combines sub-pixel resolution border segmentation with supervised picture classification to map shoreline positions with an accuracy of about 10 meters.

Nassar et al. (2019) state that extracting and detecting shoreline change rates at different intervals is crucial for beach monitoring. In order to adequately illustrate the changes in shoreline position at the study sites, the shorelines used in this study were taken throughout a 30-year period, starting in January 1992 and ending in January 2022.

CoastSat is an open-source Python toolbox designed specifically for using satellite imagery to map coastlines. It enables users to extract time-series data of shoreline positions from more than 39 years of publicly available satellite photos, with a focus on sandy beaches worldwide. The toolkit uses Google Earth Engine for efficient extraction and processing of satellite imagery, including data from the Sentinel-2 and Landsat missions.

According to Vos et al. (2019a), the shoreline that is taken into consideration in this toolkit is the instantaneous interface between water and sand captured at the instant of image acquisition.

The steps in Coastsat that were utilized in this investigation to extract shorelines from the areas chosen near the mouth of the River Volta are shown in Figure 3.9. It is intended for Coastsat to function with a broad variety of satellite imagery from various sources. To achieve a greater temporal resolution, this study took into account satellite photos from Sentinel-2A (S2) as well as Landsat (L:5,7,8, & 9). (Barsi et al., 2018).

To sufficiently quantify the positional changes of the shoreline at the study sites, some communities around the mouth of River Volta were selected. Towns selected for the study are Ada Foah, Anyanui, Dzita, Srogboe, and Anloga which consist of 6 polygons. Table 2.0 shows the inputs that were used to retrieve the satellite images at the mouth of the river Volta.

Table 2: depicts the various communities and their coordinates selected for the shoreline extractions

Communities	Longitude	Latitude
Ada Foah 1. .	0.618668	5.777491
	0.653406	5.774314
	0.653354	5.769243
	0.61851	5.772484
	0.618668	5.777491
Ada Foah2	0.653249	5.774158
	0.697815	5.773635
	0.697815	5.76919
	0.653249	5.769295
	0.653249	5.774158
Anyanui	0.697657	5.77353
	0.739963	5.773269
	0.740068	5.768824
	0.697815	5.769452
	0.697657	5.77353
Dzita	0.739858	5.773007
	0.787682	5.77306
	0.787682	5.769347
	0.73991	5.76919
	0.739858	5.773007
Srogboe	0.78763	5.772798
	0.871821	5.780746
	0.871611	5.776354
	0.787525	5.768824
	0.78763	5.772798
Anloga	0.647047	5.777452
	0.706013	5.77787
	0.705908	5.77306
	0.646942	5.773687
	0.647047	5.777452

Satellite missions used to extract the satellite images at the various communities (table 2) are L5, L7, L8, L9 &S2. The data range for the satellite images is from 1992 -2022 but in 1998- 2022 accurate images were obtained. Image extracted images from 1992 were bad(blurred). The Spatial Reference System is the Ghana Metre Grid

Shoreline change time series along cross-shore transects

The images were extracted and then pre-processed using methods such as downscaling, cloud masking, and image sharpening (Vos et al. 2019). The various shorelines were scanned and used as a reference line in the CoastSat toolbox to extract the additional shorelines. The remaining shorelines were automatically collected by the CoastSat toolkit after the images were recognized using a neural network classifier (Civco 2020) and divided into four different classes: "shoreline," "water," "sand," and "white water."

To more accurately identify the sand/water border, a sub-pixel resolution border segmentation was added to the image classification used in the detection of these classes. CoastSat (Vos et al. 2019a, b) has a horizontal accuracy of around 10 m. The reasons for this are the tidal inundation, the selection of the shoreline proxy, and the errors in the shoreline positions and scale extraction. There is no need for geometric adjustments because the data vendor has already orthorectified the satellite photos. (I) Preprocessed satellite pictures; (II) image categorization; and (III) satellite image border segmentation at sub-pixel resolution are the techniques that CoastSat uses for shoreline detection (Vos et al. 2019).

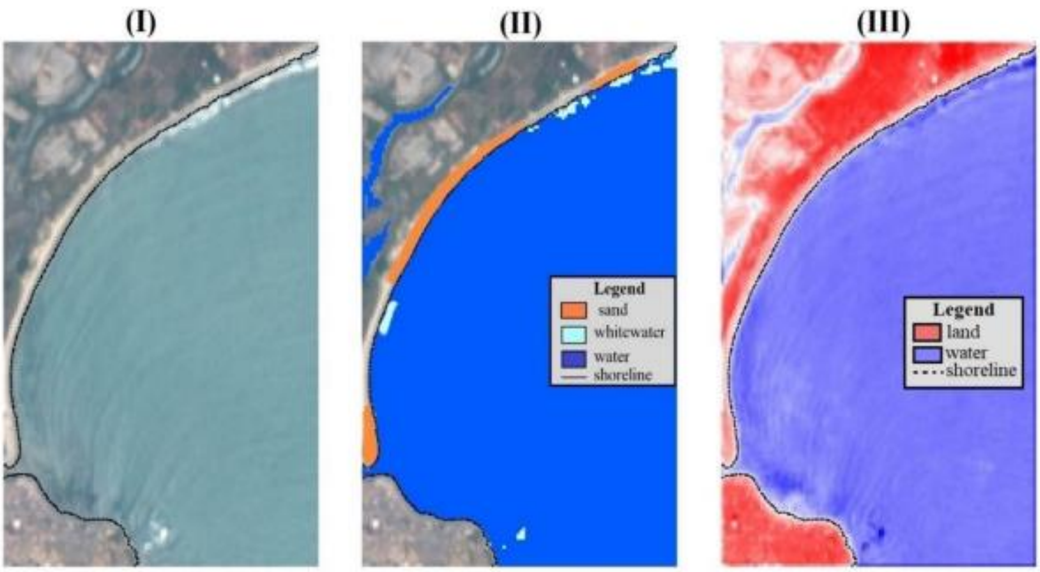


Figure 8: Image classification

Source; Coastsat toolkit, 2024

Table 3. Satellite dataset retrieved by using Coastsat toolkit GEE

Satellite	Number of datasets	Bands	Spatial resolution	Temporal resolution	Time coverage
L5	17	R, G, B, NIR, SWIR1	30m×30m	16days	1992-2013
L7	1636	R, G, B, NIR, SWIR1 + Panchromatic	30m×30m 15m×15m	16days	1999-2022
L8	1350	R, G, B, NIR, SWIR1+ panchromatic	30m×30m 15m×15m	16days	2013-2022
L9	302	R, G, B, NIR, SWIR1+ panchromatic	30m×30m 15m×15m	16days	2021-202
S2	1775	R, G, B, NIR+SWIRI	20m×20m 10m×10m	5days	2015-2022

The study used maximum cloud cover of 50% in Sentinel (S2) and Landsat (L5, L7, L8, and L9) satellite images to reduce the influence of clouds and other spectral variables. disturbance.

Approximately 5080 imageries were produced by all satellites between January 1992 and December 2022. An overview of all the datasets, their bands, resolutions, and time coverages is provided in Table 3. L5 and L9 recorded few images due to their time of invention

Following that, the images underwent pre-processing techniques such cloud masking, picture sharpening, and downscaling (Vos et al. 2019a, b). To extract the additional shorelines, a coastline was first digitalized using the CoastSat toolset and utilized as a reference line. After the photos were classified into four different classes "shoreline," "water," "sand," and "white water" using a neural network classifier (Civco 1993), the toolkit automatically retrieved the remaining shorelines (Fig.8.0). Sub-pixel resolution border segmentation was used to enhance the recognition of the sand/water border.

added to the image classification process during the detection of these classes. No geometric adjustments are required because the data vendor has already orthorectified the satellite images.

The various shoreline transects

This section explains the methodology used to obtain the shoreline change time series along shore-normal transects.

Shoreline transects at the mouth of the Volta River can be obtained using. Transects are straight lines drawn perpendicular to the shoreline at predetermined intervals. These lines allow for systematic measurements of shoreline position changes over time.

Coastsat, a tool that leverages satellite imagery to analyze coastal changes. Coastsat helped define the specific transects across the shoreline of the various communities selected for the study. Coastsat includes functions that automate the extraction of shoreline positions along the defined transects. This process involves identifying the waterline in the satellite images, which represents the shoreline at different time points (Vos, 2019).

Figure 9 .0. illustrates how the transects were obtained from the selected coastal communities using the Coastsat toolkit. In the CoastSat toolkit, a transect refers to a specific line or path defined across the shoreline, used for analyzing coastal changes. These shore-normal transects allow users to create time-series data of shoreline positions by intersecting the extracted 2D shorelines with these defined lines. This functionality is crucial for monitoring how shorelines change over time, as it enables the examination of variations in shoreline positions at specific locations along the coast (Fitzpatrick, 2024)

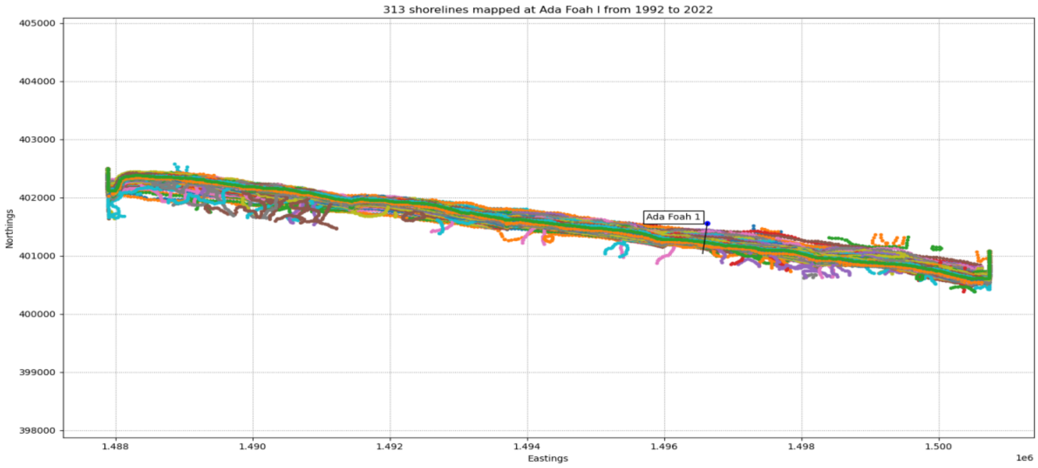


Figure 9:Transects of the shorelines at Ada Foah

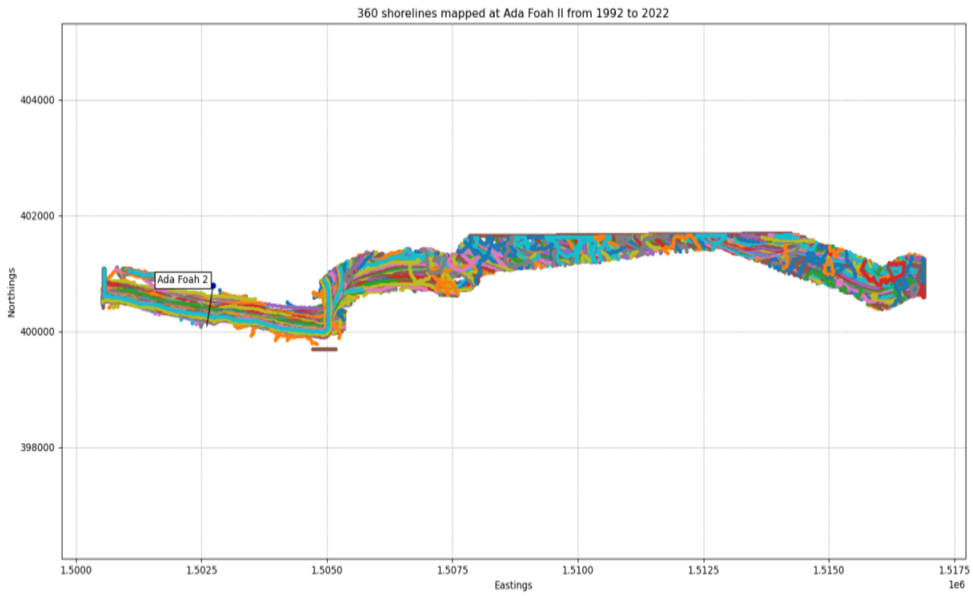


Figure *9b*: Transects of the shorelines at Ada Foah 2

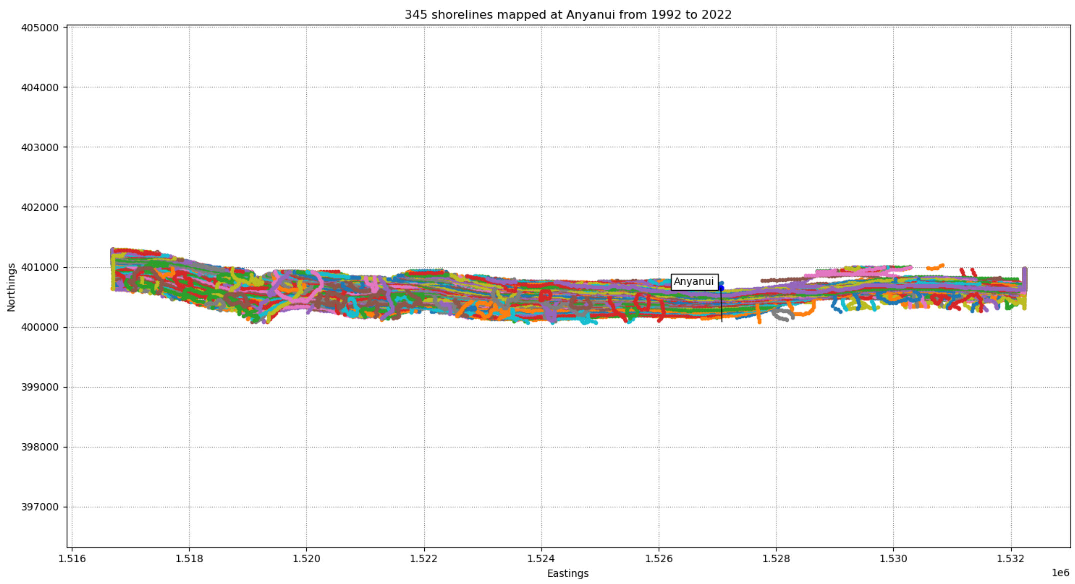


Figure *9c:* Transects of the shorelines at Anyanui

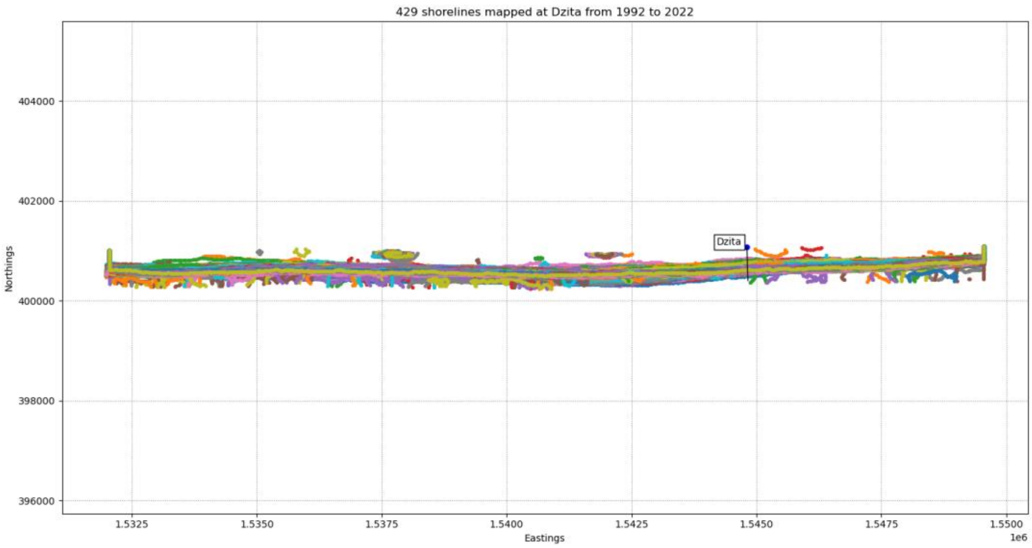


Figure 9d :Transects of the shorelines at Dzita

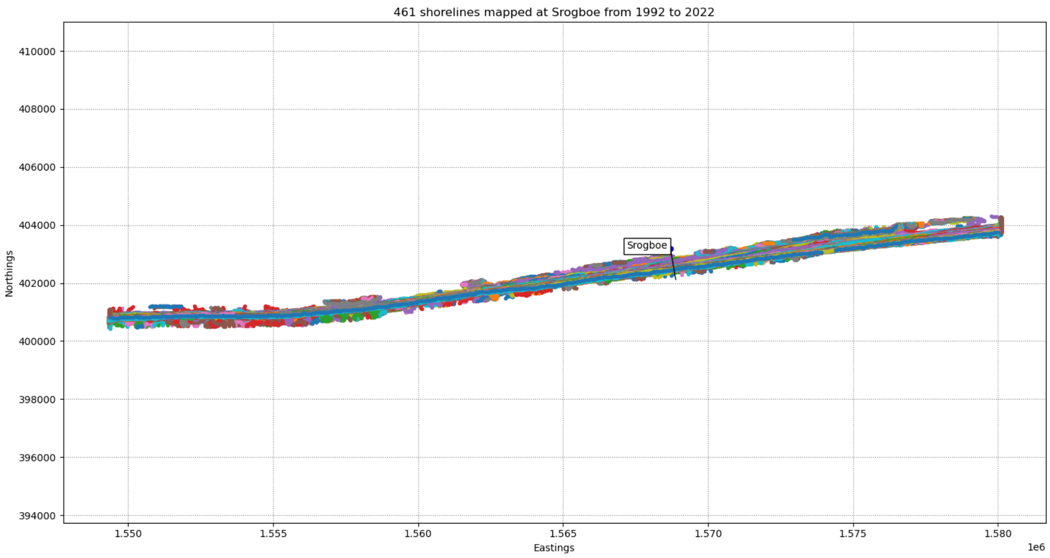


Figure 9e: Transects of the shorelines at Srogboe

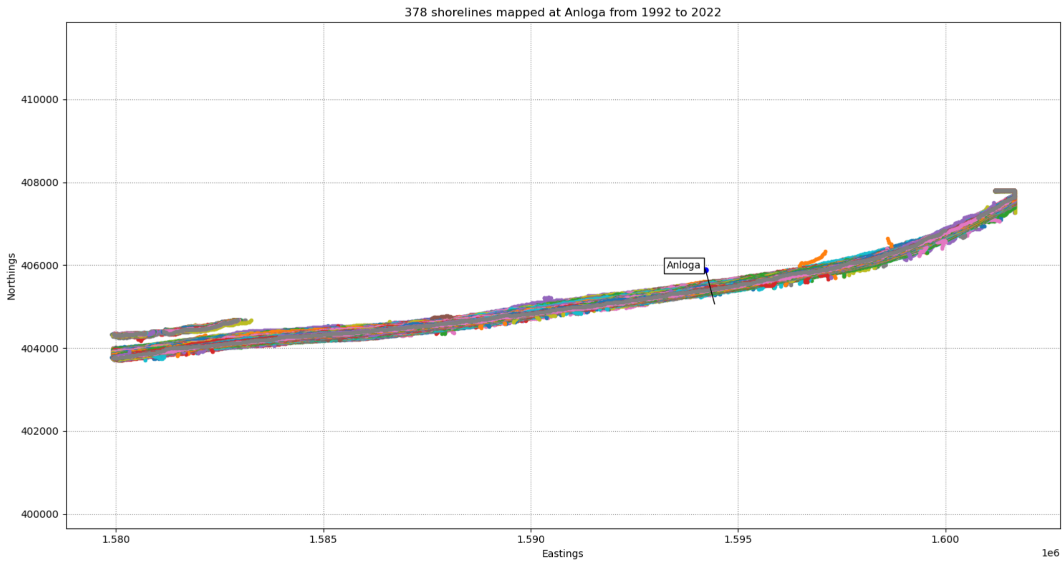


Figure 9f:Transects of the shorelines at Anloga

Tidal Correction

Tidal correction is a crucial process in the CoastSat toolkit for accurately analyzing shoreline changes (Doherty, Harley, Vos & Splinter, 2022). Since satellite images are captured at various stages, tidal fluctuations can create misleading impressions of shoreline movement. Without correction, these apparent changes could be mistaken for actual shifts in shoreline position, leading to inaccurate assessments of coastal dynamics. Tidal correction removes the effects of changing water levels on shoreline data, ensuring that the observed changes are due to actual geological processes rather than temporary tidal variations. This is essential for understanding long-term trends in coastal erosion or accretion (Vos, 2019)

Tide plays a significant role in shaping and influencing the morphological changes at the mouth of the river.

To perform tidal correction at the mouth of the Volta River using Coastsat after image extraction, 30-year tide data was extracted from WXTide v32 software from 1992 - 2022, at 5-minute intervals. WXTide32 is a free Windows program allowing users to predict worldwide tides and currents (Flater et al ..., 2010)

Since the satellite images were captured at different points throughout the tide, the apparent tidal fluctuations in the shoreline were removed by applying a tidal correction. Tidally correcting the shoreline change time series requires these details. A. CSV file was used to format the water/tide level time series. Due to CoastSat shorelines always being in UTC, the dates were in UTC. Each shoreline was translated to a reference elevation using a linear tidal adjustment that assessed water levels and the characteristic beach face slope. This allowed for an estimation of the beach-face slope at various tide stages for each transect.

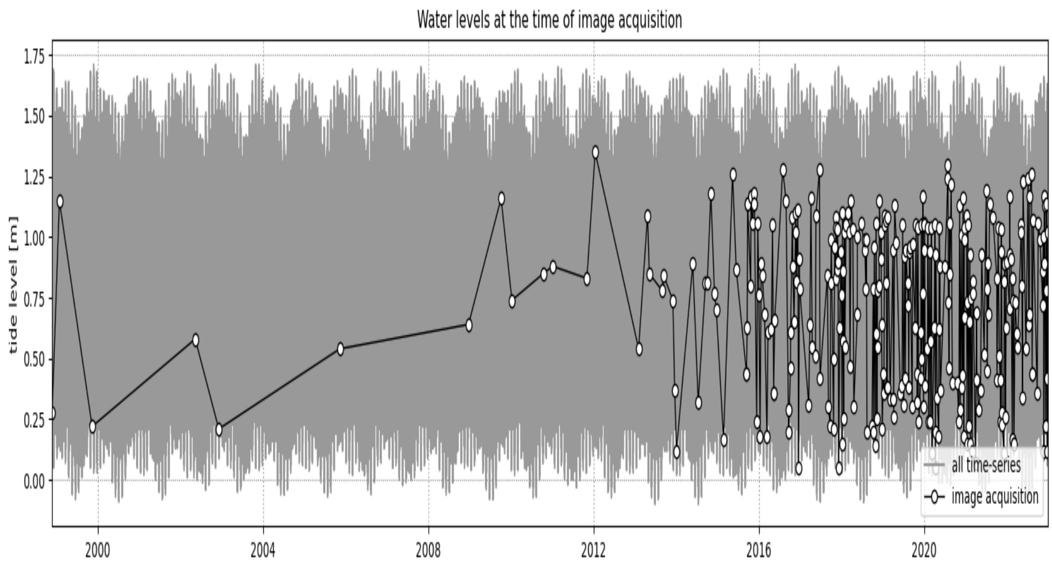


Figure *10:* Tidal Correction

Post-processing

A despiking technique was used to remove outliers from the tidally-corrected time series, and SDS transects were designed to dismiss anomalies. The purpose of this function was to remove conspicuous outliers from the time series by eliminating locations that, in the context of a shoreline change, are physically illogical.

Raw shorelines vs tidally corrected shorelines position

CoastSat applies tidal corrections to the raw shoreline positions by adjusting them based on the tidal heights recorded. This involves raising or lowering the shoreline position according to the tidal level at the time of image capture, ensuring that the shoreline accurately reflects the land-water boundary at mean sea level (MSL) rather than at high or low tide. Based on the general understanding of remote sensing and shoreline analysis, raw shorelines typically refer to the uncorrected shoreline positions extracted directly from satellite images (Vos et al., 2020) These shorelines are not adjusted for factors such as tidal variations and may be subject to biases introduced by water level changes. Tidally corrected shorelines, on the other hand, are adjusted for these variations, providing a more accurate representation of the true shoreline position. The following graphs depict how raw shorelines versus tidally corrected shoreline positions were obtained at various communities (Vos et al., 2020).

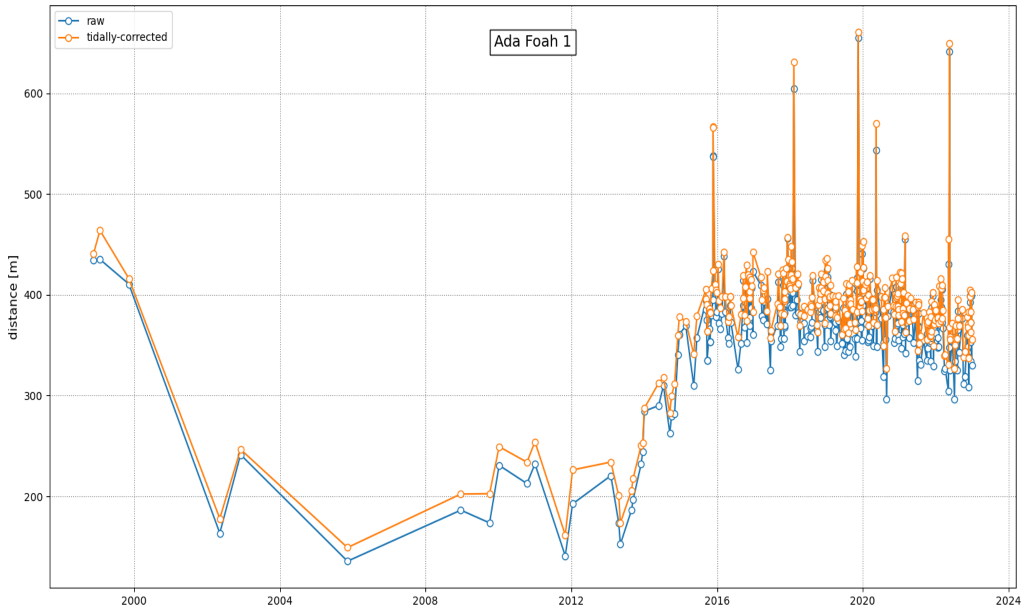


Figure 10a: Raw shorelines vs tidally corrected shorelines position at Ada Foah.

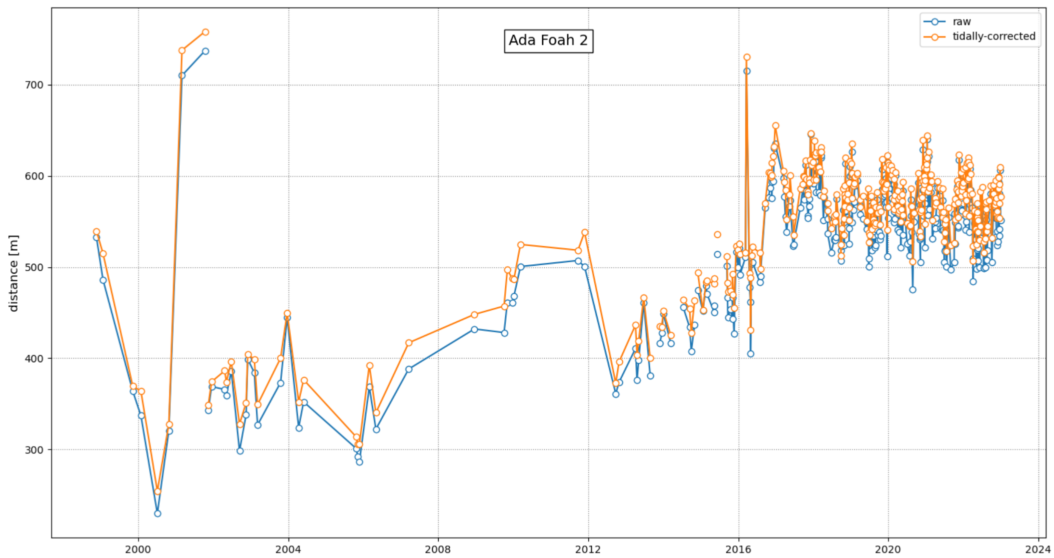


Figure 10b*: Raw* shorelines vs tidally corrected shorelines position at Ada Foah.2

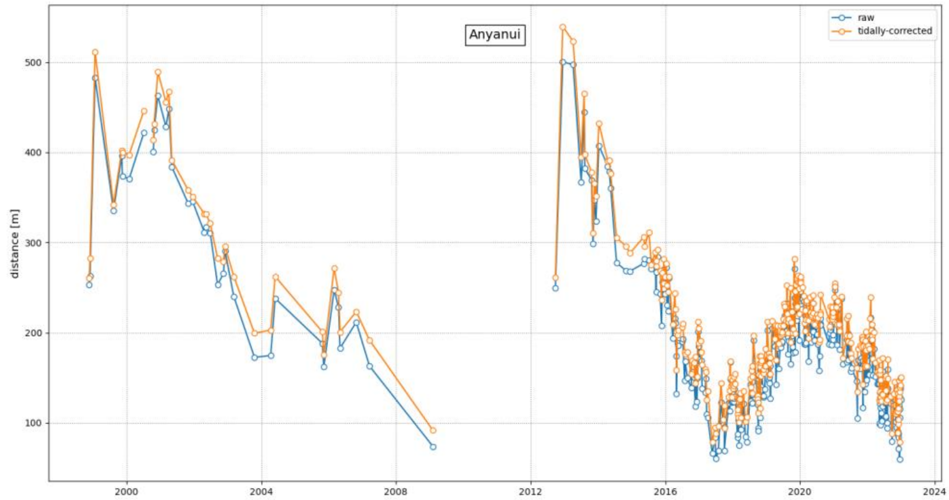


Figure 10c*: Raw* shorelines vs tidally corrected shorelines position at Anyanui

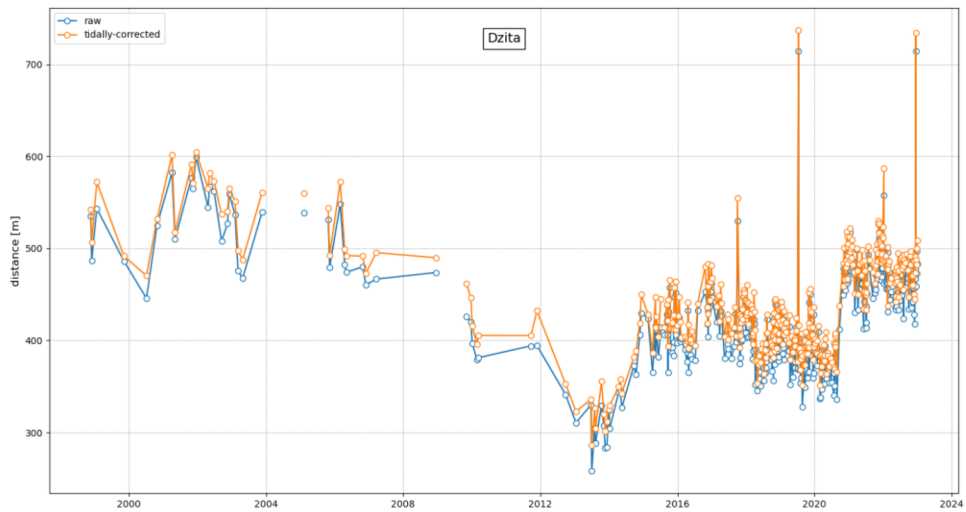


Figure 10d: Raw shorelines vs tidally corrected shorelines position at Dzita

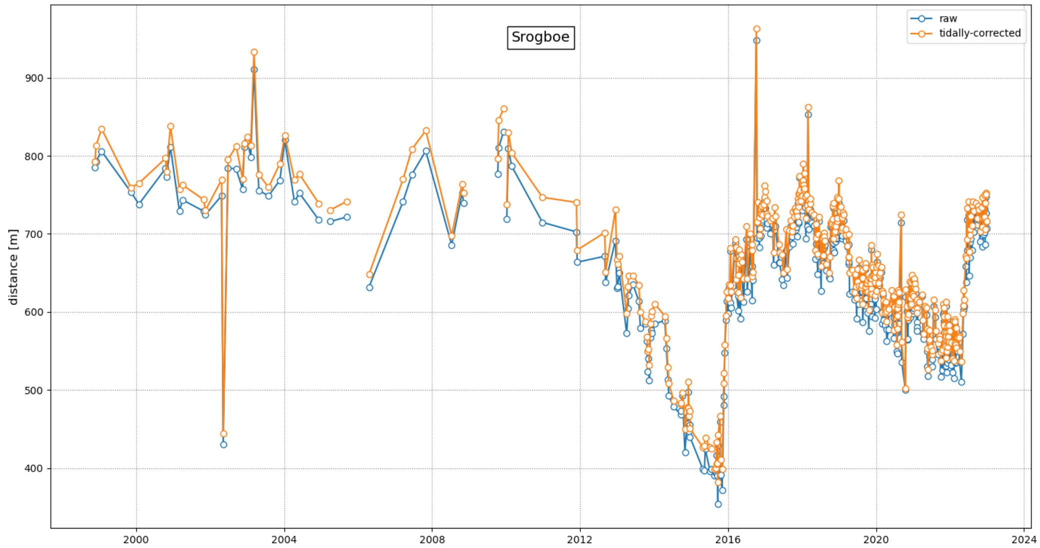


Figure 10e. Raw shorelines vs tidally corrected shorelines position at Srogboe.

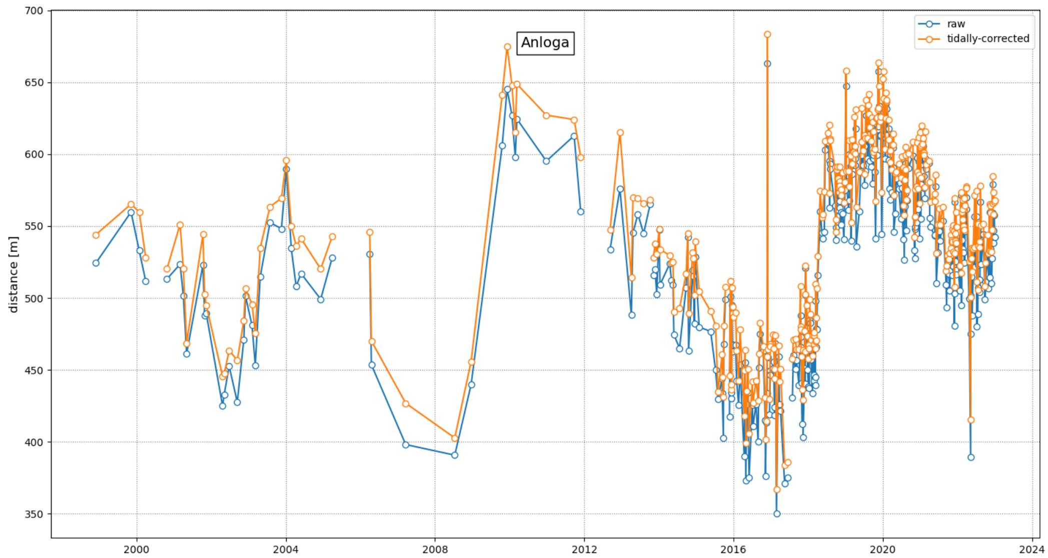


Figure 10f: Raw shorelines vs tidally corrected shorelines position at Anloga.

Raw shoreline position

CoastSat is a powerful tool to obtain raw shoreline positions at the mouth. The detected shoreline is digitized in a Coastsat toolkit, creating vector data that represents the shoreline's position during image capture. This raw shoreline data reflects the shoreline as it appears in the satellite images without any corrections for tidal influences(Curoy, Ward, Barlow, Moses & Nakhapakorn, 2022). The following graphs depict the raw shoreline position obtained by coastsat.

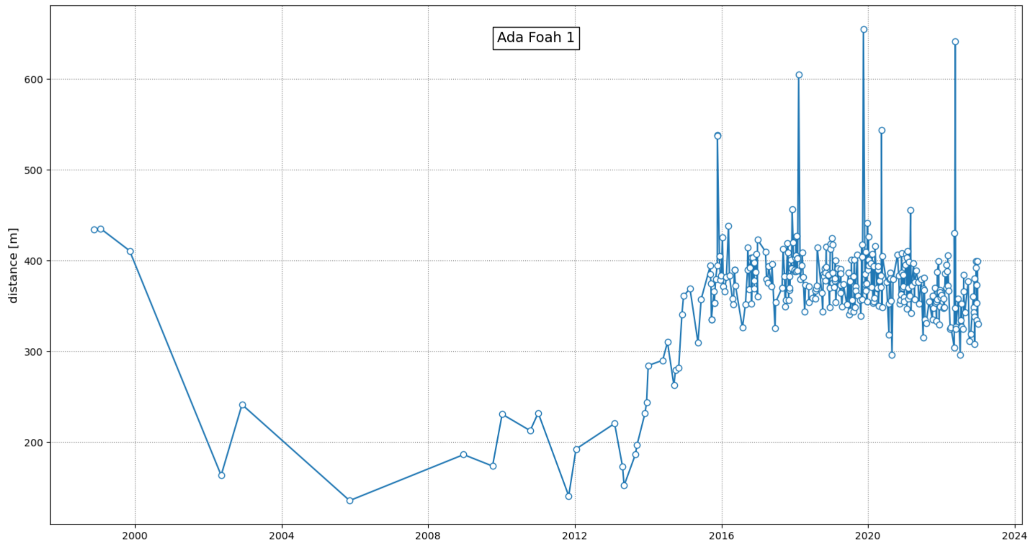


Figure 11a **the raw shoreline position obtained by coastsat at Ada Foah**

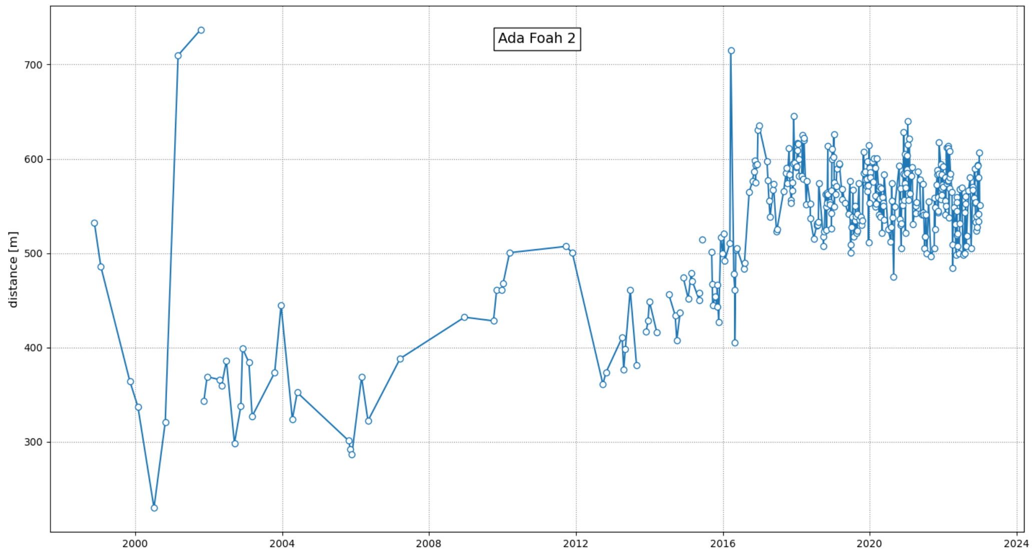


Figure 11b: the raw shoreline position obtained by coastsat Ada Foah 2

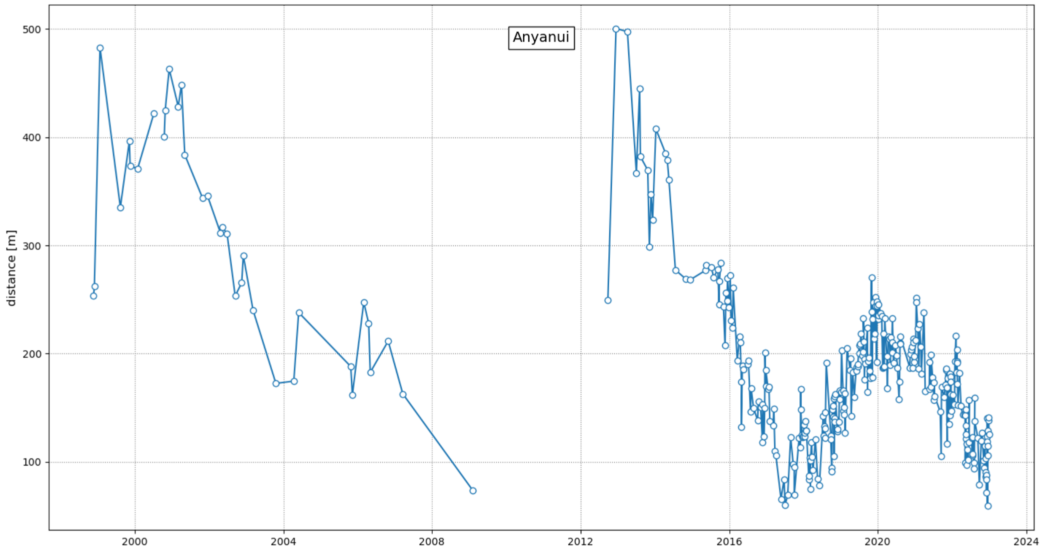


Figure 11c: The raw shoreline position obtained by coastsat at Anyanui

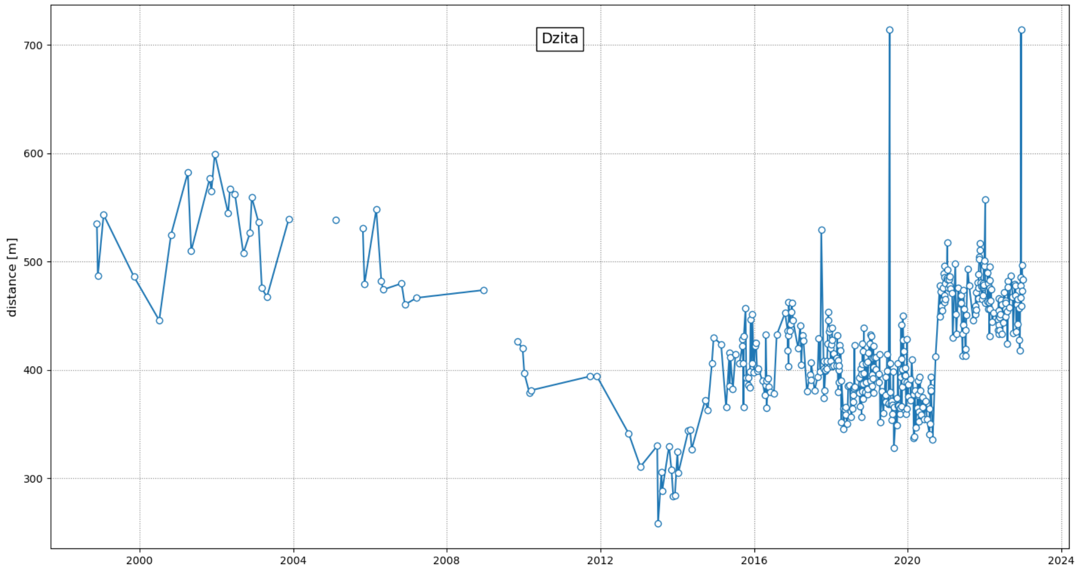


Figure 11d: the raw shoreline position obtained by coastsat at Dzita

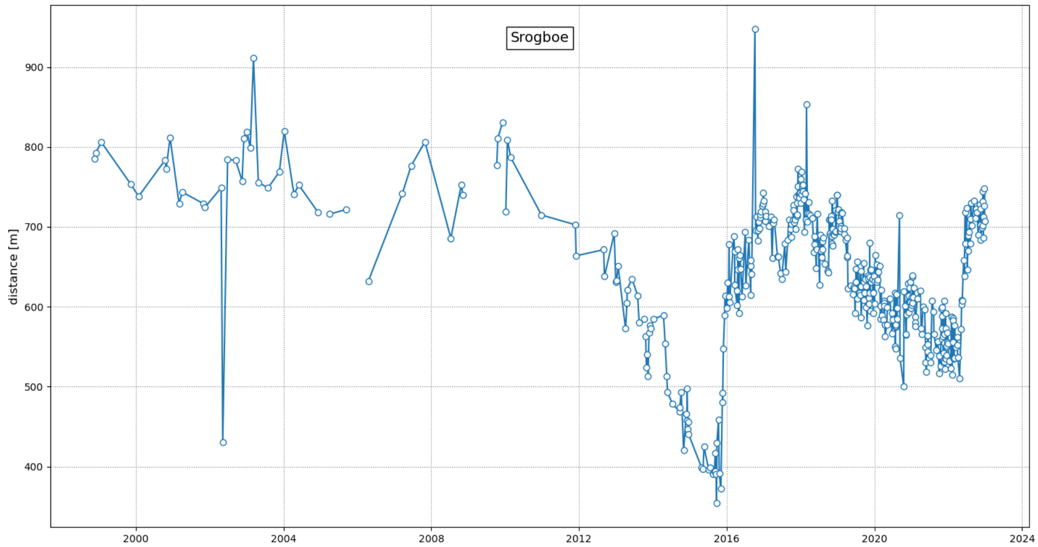


Figure 11d*: the raw shoreline position obtained by coastsat at srogboe*

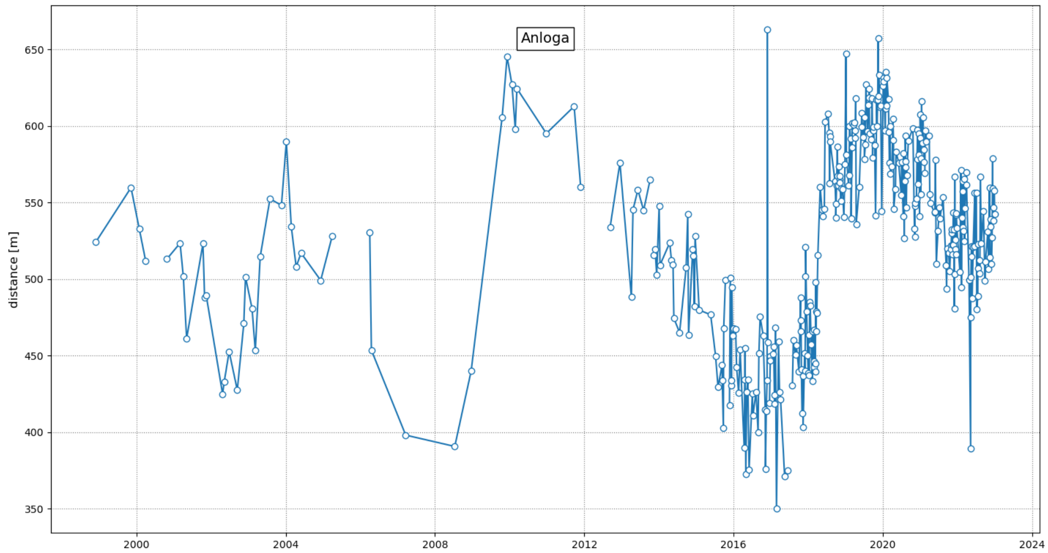


Figure 11f: The raw shoreline position obtained by coastssat

In summary, CoastSat is a suite of free and open-source software tools for mapping coastlines worldwide using publicly accessible satellite images., CoastSat allows users to access time-series data of shoreline positions at every sandy coastline worldwide. When there are no available in-situ field measurements, this capacity is especially helpful. Sentinel-2 from Landsat 5, 7, 8, and 9 was used to download and process the aforementioned data. The following chapter presents the findings from the Coastsat toolkit.

CHAPTER FIVE

RESULTS AND DISCUSSION

Introduction

This chapter presents the results and the discussions of the data analysis and links them with the literature. It covers some essential areas such as the morphological changes that have occurred at the mouth of the river Volta over 30 years, the dominant cause(s) of the morphological changes at the mouth of the river Volta over 30 years, and some coastal communities surrounding the mouth of river Volta and their vulnerability in terms of coastal hazards. Tables and graphs were essentially used to display the results. Interpretations and a discussion of the results were provided to draw attention to the problems being studied.

Objective one

Objective one of this study sought to identify the type of morphological changes that have occurred at the mouth of River Volta. The objective was achieved based on the various data analyzed from satellite images from publicly available satellites (Landsat 5, 7,8,9, and S2). The analysis was made in two parts, results from only Landsat imagery and both Landsat and Sentinel (Coastsat toolkit). The following illustrations show the pace of change at the Volta River's mouth during the past 30 years.

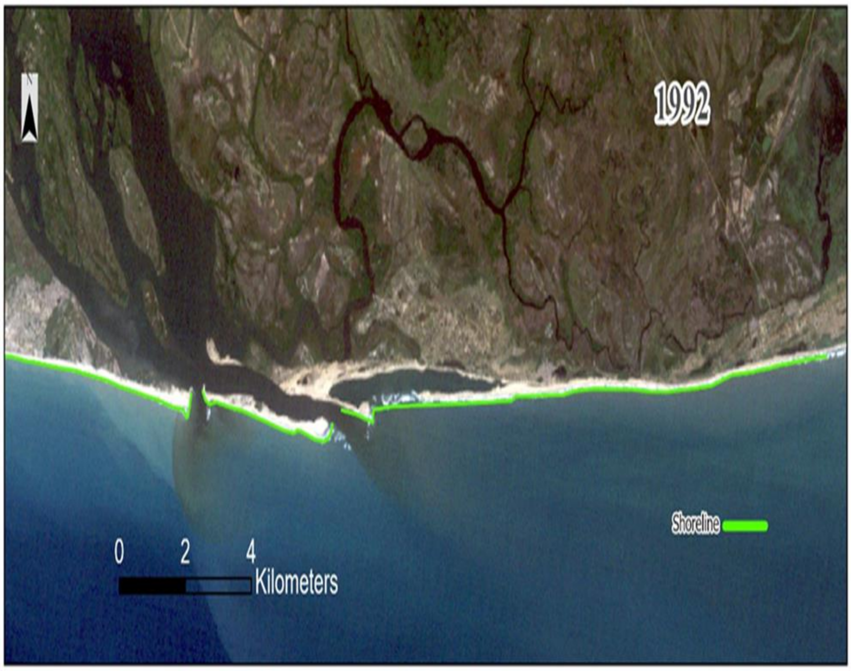


Figure 12a: The 1992 morphological changes near the mouth of the Volta River

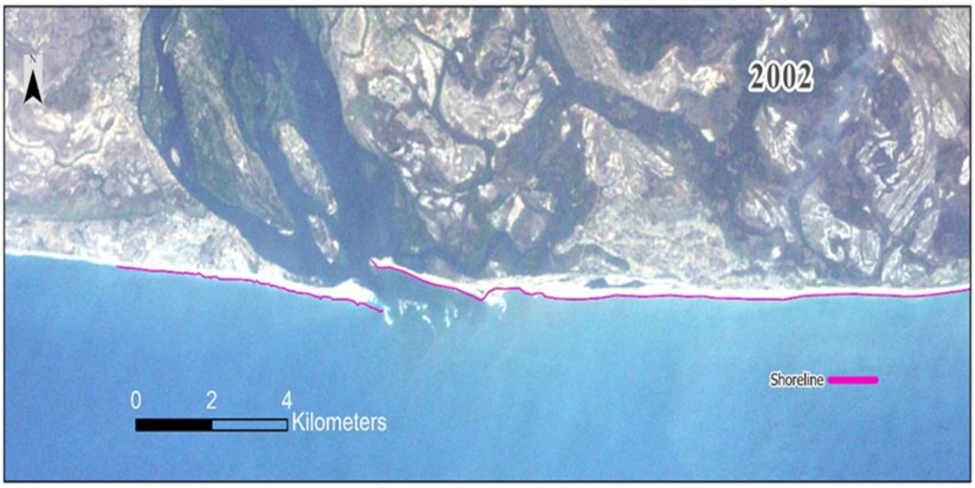


Figure 12b: Changes in the Volta River's morphology in 2002

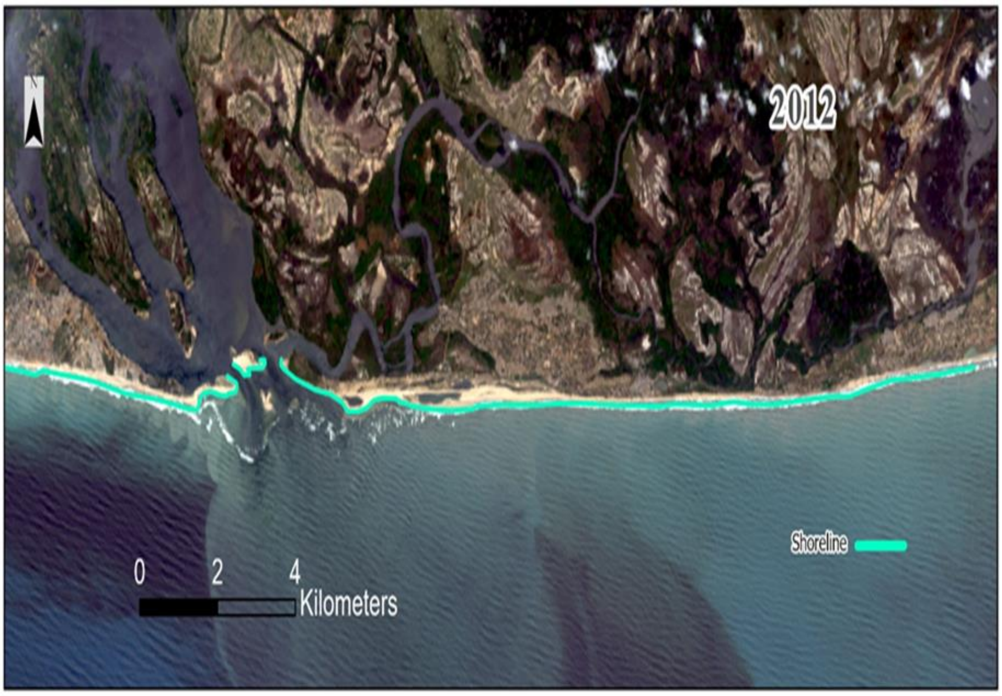


Figure 12c: The morphological changes at the mouth of the volta at 2012

Figure 12d: The morphological changes at the Volta River mouth at 2022

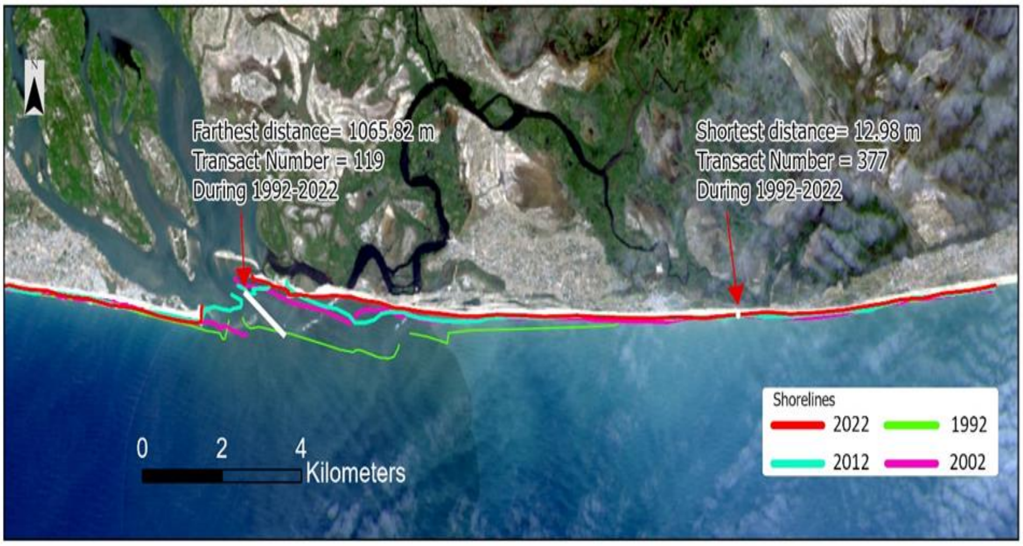


Figure 12e depicts maximum and minimum transect

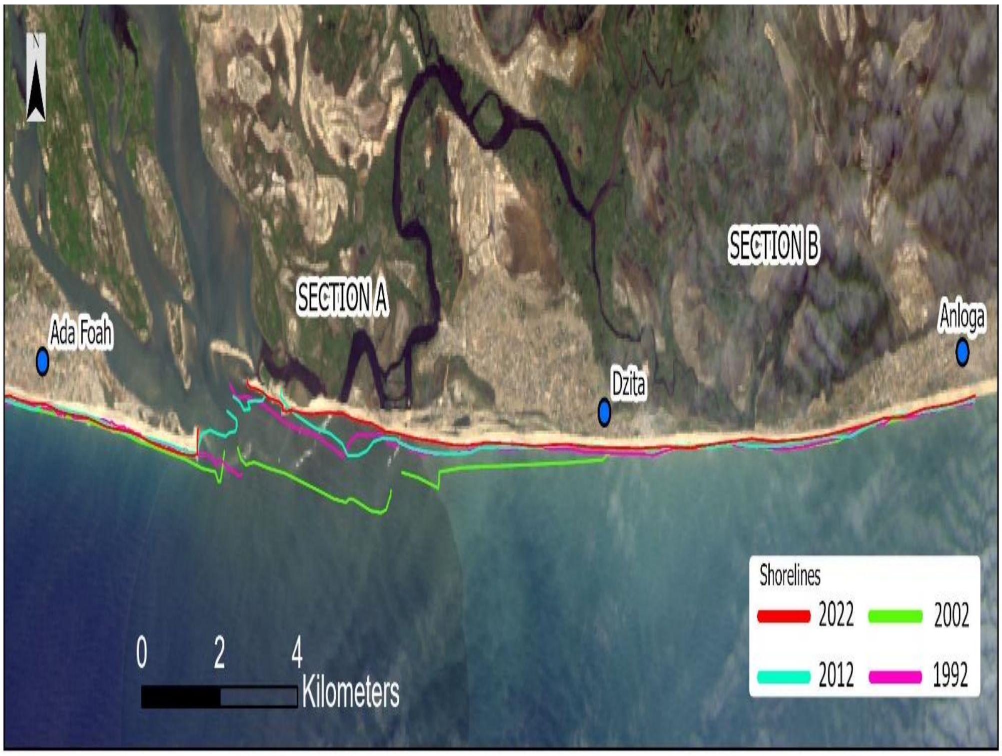


Figure 12f: Shoreline of 1992, 2002, 2012 and 2022.

The distance of shoreline change

This study utilized two key metrics, the Shoreline Change Envelope (SCE) and Net Shoreline Movement (NSM), to measure the distance of shoreline change over a three-decade span from 1992 to 2022. Additionally, the rate of shoreline change was calculated using the End Point Rate (EPR). The result of SCE (see Figure 14e and 14f, Table 4.) reveals that the largest changes to the shoreline between 1992 and 2022 were 1065.82 meters, which might be the result of erosion or accretion. It is important to stress that, although SCE results are invariably positive values, the resulting coastline alterations are not only indicative of accretion. They cover all aspects of coastal dynamics, including erosion and accretion. At transect number 119, the shoreline alteration in the research region is the furthest away.

. Nonetheless, there is an average of 243.5 meters between the coastline shifts that are the furthest and closest to the beach from 1992.

This revelation provides crucial insight into the dynamic nature of the shoreline within the research area.

Table 4 SCE Averages

Total Number of Transects.	516
Average Distance	243.5 meters
Maximum Distance	1065.82 meters
Maximum Distance Transects ID.	119
Minimum Distance	12.98 meters
Minimum Distance Transects ID.	377

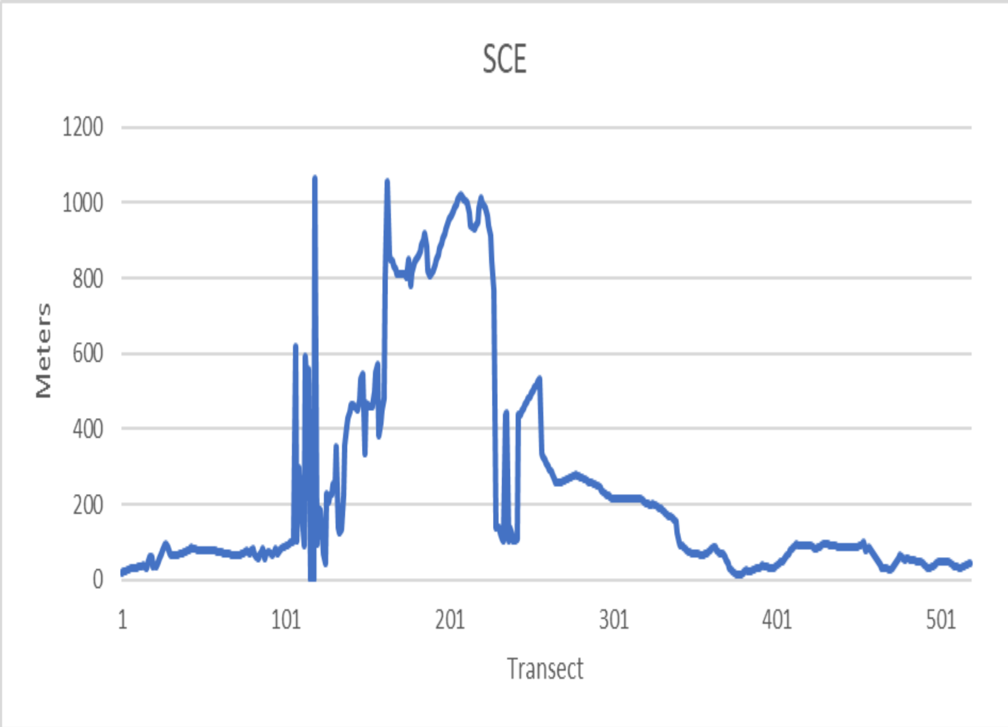


Figure 13a: The result of SCE in 1992 -2022.

The distance between the 1992 and 2022 shorelines, as measured using NSM, is presented in (19c). The data shows that the farthest accretion and erosion recorded during 1992–2022 amounted to 190.69 meters and -1018.98 meters, respectively. Notably, the average distance of shoreline change emerged as -229.88 meters. Unlike the Shoreline Change Envelope (SCE), NSM paints a nuanced picture by yielding positive and negative values corresponding to accretion and erosion, respectively. The result of NSM shows a negative value for the average distance of shoreline change, which represents the likeliness of erosion instead of accretion as the trend of shoreline change in Volta River delta shoreline. The negative average distance of shoreline change is indicative of this emerging pattern, emphasizing the importance of monitoring and understanding coastal dynamics in this unique and dynamic environment.

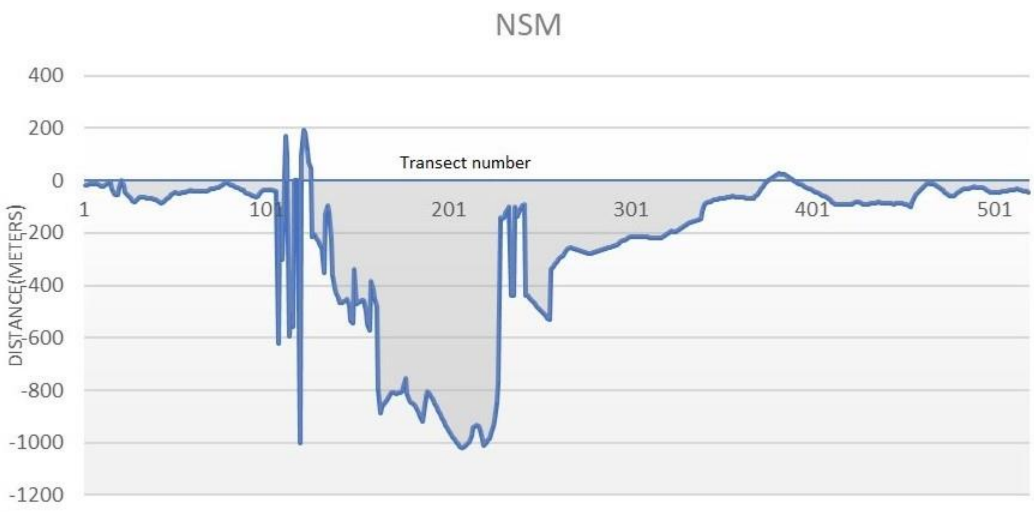
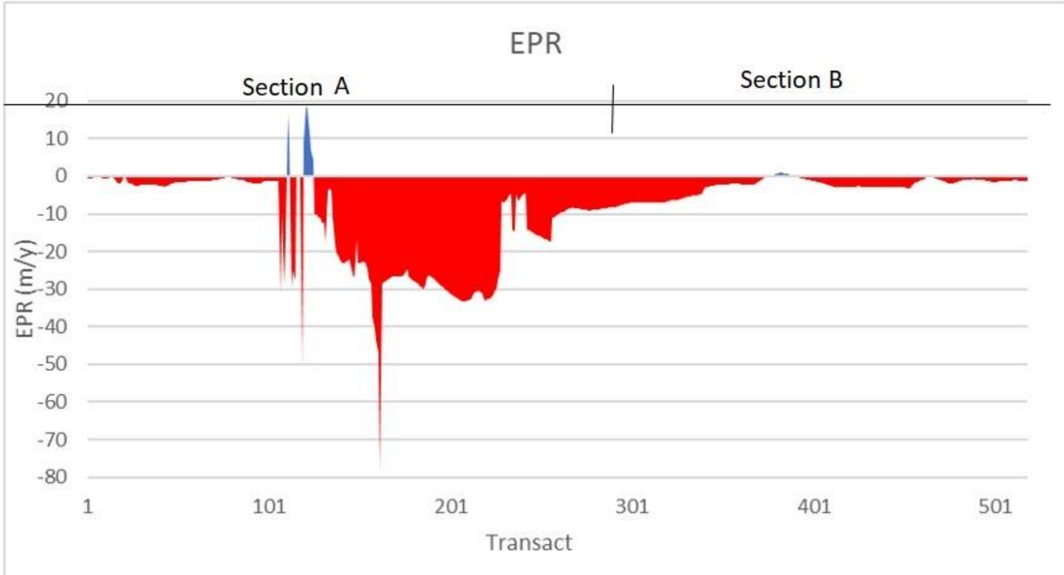


Figure 13b: The result of NSM in 1992 -2022.

The rate of shoreline change

Meters per year, or m/yr, are used to express the rate of coastline change. This metric was calculated by dividing the coastline displacement, expressed in meters, by the interval between the satellite image acquisitions that were used in the study. The combined different date shoreline positions within the research region demonstrated the notable and continuous lateral shifts that are taking place. In total, 516 transects were generated. It was discovered that 24 transects were either accreting or stable over the course of the 30-year study period, while 492 transects were eroding. In terms of coastline placements, the earliest and latest dates were 1992 and 2022, respectively. The End Point Rate technique, which calculates erosion rates of change for the oldest and youngest shoreline locations, indicates distinct trends of coastal accretion and erosion. The lively and continuous changes that have been occurring along the shore are highlighted by the average yearly rate of erosion, which was -8.32 meters. Conversely, the mean accretion rate of +4.22 m/yr indicates the places where the shoreline has increased. The NSM finding that erosion is a tendency of shoreline alteration in the study region that is more likely from 1992 to 2022 is consistent with the overall mean change rate for the 30 years under examination, which was -2.35 m/yr. Together, these results provide a comprehensive understanding of the dynamic, constantly-evolving coastal processes along the Volta delta front.



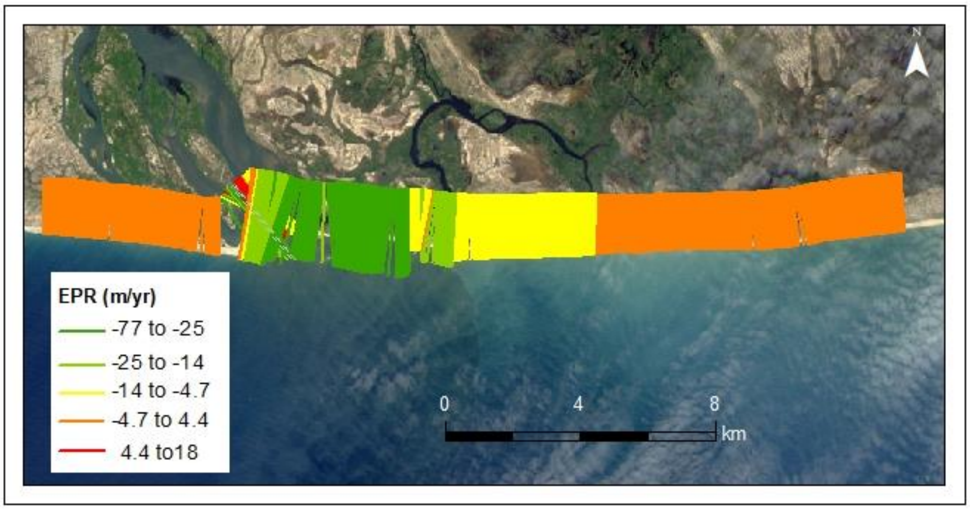


Figure 13c: The morphological changes at the Volta River mouth.The result of EPR

There are different degrees of change occurring along the front littoral of the Volta delta. There are two possible causes for this: natural and man-made. EPR is a valuable metric that helps us comprehend the dynamics of our coastal environment. EPR values can take both negative and positive forms, which have distinct implications for our study area. The negative values signify shoreline erosion (Manno, Basile & Ciraolo, 2022).

On average, our shoreline has retreated by 77 meters over the 30 years. Erosion can be attributed to elements like rising sea levels, higher storm activity, sediment loss, or coastal development. This rate of erosion highlights a significant concern for the stability of the coastal area. Positive EPR values indicate shoreline accretion. In our case, our shoreline has advanced by an average of 18 meters over the 30 years. Accretion can be associated with factors like sediment deposition or alterations in sediment supply (Simpson, 2010) While this may appear favorable for the expansion of coastal areas, it is essential to examine the broader context, as accretion can impact ecosystems and infrastructure.

Coastsat toolkit results

This section explains the monthly and seasonal average of shoreline changes at the mouth of River Volta and it is done based on the different polygons.

Monthly, and seasonal averages and linear trends of shorelines obtained from the various communities along the eastern coast of Ghana.

It is best to estimate the long-term trends on the seasonally-averaged shoreline time series, as the trend estimated on the raw time series may be biased towards the end of the record since the shoreline time series are not uniformly sampled and there is more density of data points towards the end of the record (more satellites in orbit).

Note

If there are more points below the trendline in the CoastSat toolkit, it implies that the shoreline positions are generally experiencing erosion or a net loss of land over time. When data points fall below the trendline, it suggests that the shoreline is retreating, indicating erosion in those areas. This can be a critical concern for coastal management as it may threaten infrastructure, ecosystems, and local communities (Warrick, 2023) on the contrary, if there are more points above the trendline in the CoastSat toolkit, it indicates that the shoreline positions are generally experiencing accretion or a net gain of land over time. A higher number of points above the trendline suggests that the shoreline is advancing seaward, indicating sediment deposition and land gain. This could be due to natural processes such as sediment transport, or human interventions like beach nourishment (Masiero, 2024)

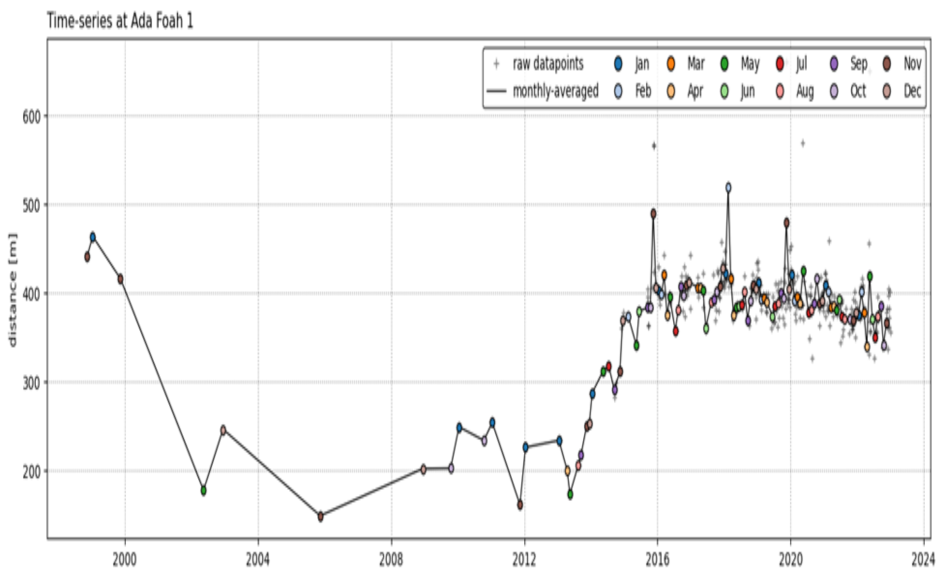


Figure 14a: Monthly averages and linear trend of shorelines obtained at Ada Foah site 1.

Figure 14b: Seasonal averages and linear trend of shorelines obtained at Ada Foah site 1. The observation that more points of seasonal averages and linear trends of shorelines obtained at the Ada Foah site are above the trendline suggests a positive trend of shoreline accretion in that area. Recent studies have highlighted that the Ada Foah shoreline has historically experienced erosion, with a mean change of approximately -280.49 meters since 1926 (Ali, 2016).

However, the new findings of seasonal averages and trends above the trendline suggest a potential reversal towards accretion.

The analysis indicates that while some areas may still be receding, the overall trend could be moving towards a net gain in shoreline area due to sediment deposition processes.

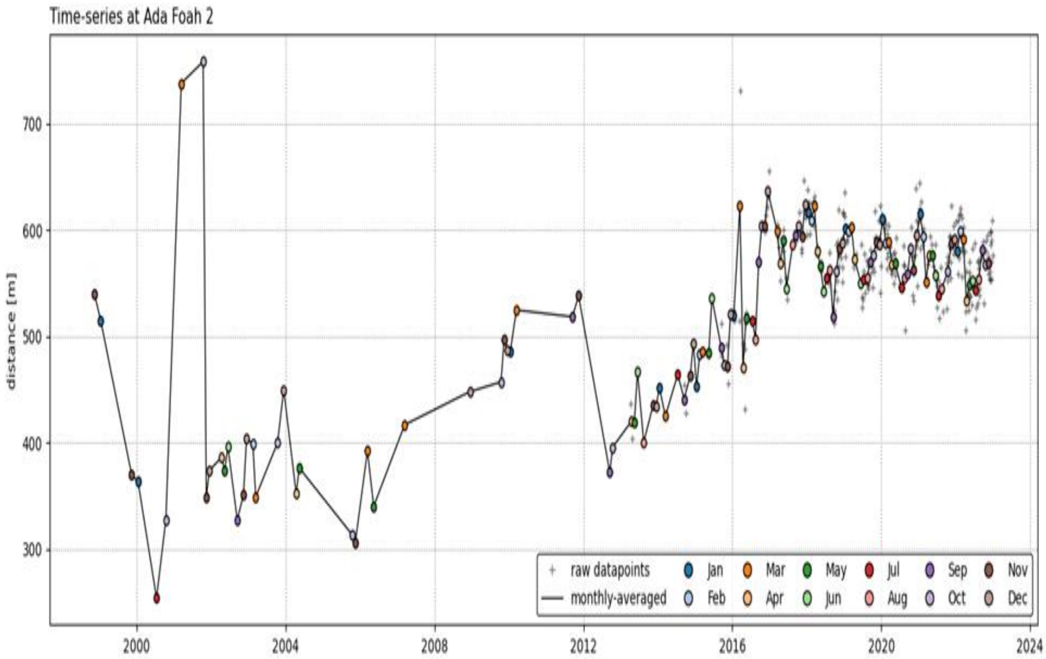


Figure 14c: Monthly averages and linear trend of shorelines obtained at Ada Foah Site 2.

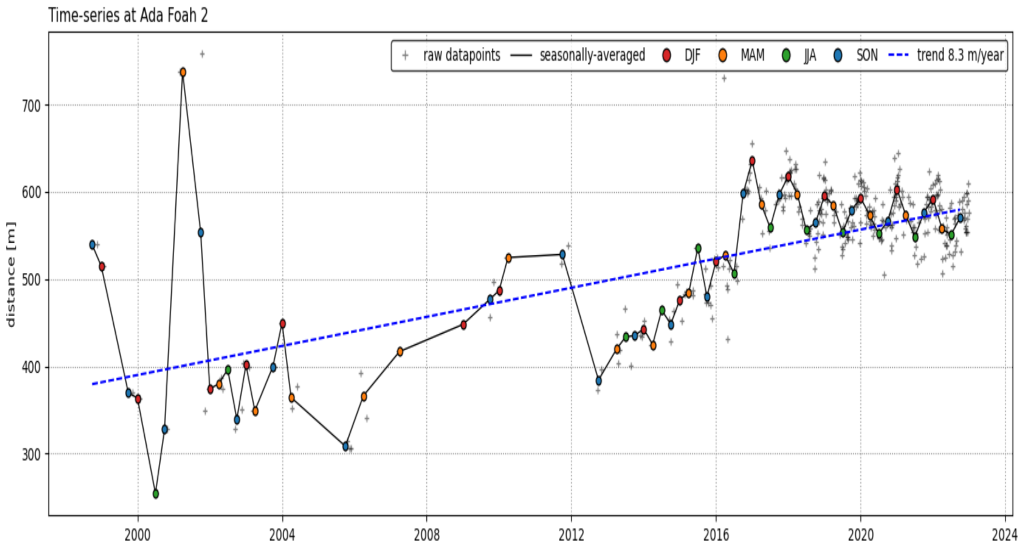


Figure 14d: Seasonal averages and linear trend of shorelines obtained at Ada Foah site 2

The observation that more points of seasonal averages and linear trends of shorelines at the Ada Foah site 2 are above the trendline, suggesting a trend of shoreline accretion, has several implications. The presence of more data points above the trendline indicates shoreline advancement, which may result from natural sediment deposition processes or effective coastal management practices. Protective measures, such as breakwaters or geotextile tubes, could contribute to this trend by reducing erosion and encouraging sediment accumulation (Rajasree, Deo & Nair, 2016). If accretion is linked to human interventions, it highlights the success of implemented coastal protection schemes. For example, studies in Eastern Ghana have shown that after implementing protective measures, erosion trends reversed into accretion at rates such as +1.0 m/year in some areas (Kefi, Bakouche & El Asmi, 2024).

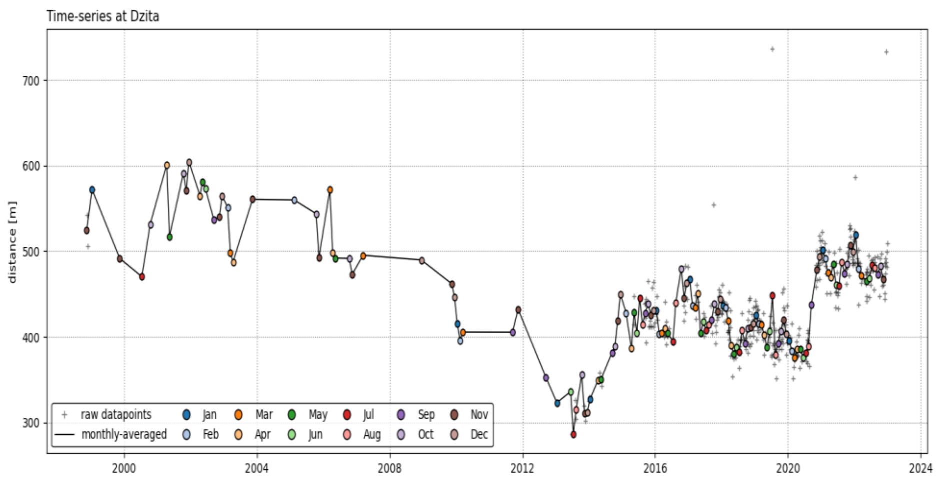


Figure 14e: Seasonal averages and linear trend of shorelines obtained at Dzita

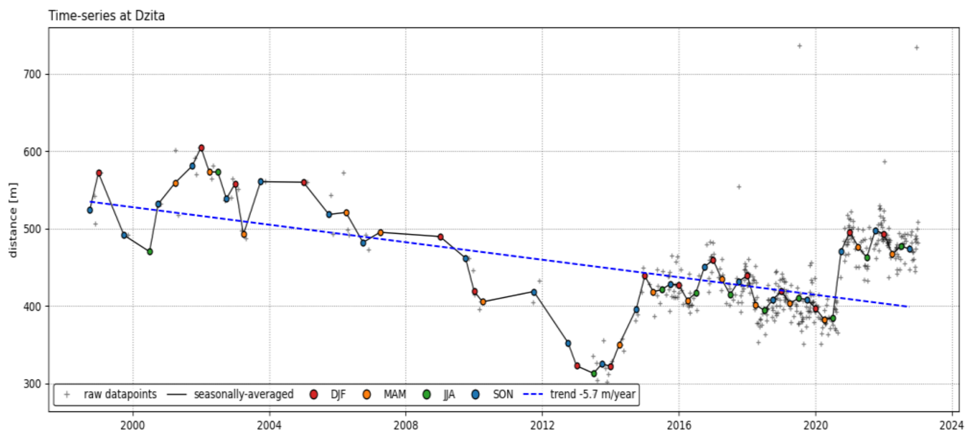


Figure 14f: Seasonal averages and linear trend of shorelines obtained at Dzita

The observation that more points of seasonal averages and linear trends of shorelines at Dzita are below the trendline indicates a concerning trend of shoreline erosion (Sigren, Figlus, & Armitage, 2014). The prevalence of data points below the trendline suggests that the shoreline is retreating, making the area more susceptible to coastal hazards such as flooding and storm surges. This trend can exacerbate the impacts of climate change, particularly as rising sea levels contribute to more severe erosion events

Erosion can lead to the loss of valuable coastal ecosystems, including mangroves and wetlands, which play critical roles in protecting shorelines and supporting biodiversity. The degradation of these natural barriers can further increase vulnerability to both natural and anthropogenic pressures

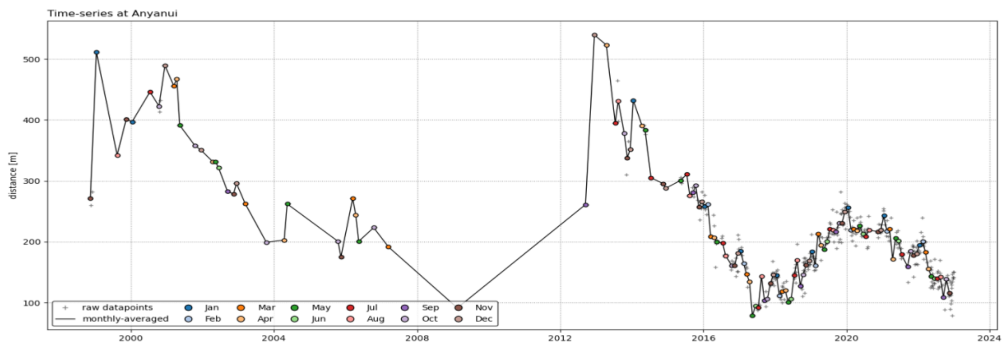


Figure 14g: Monthly averages and linear trend of shorelines obtained at Anyanui

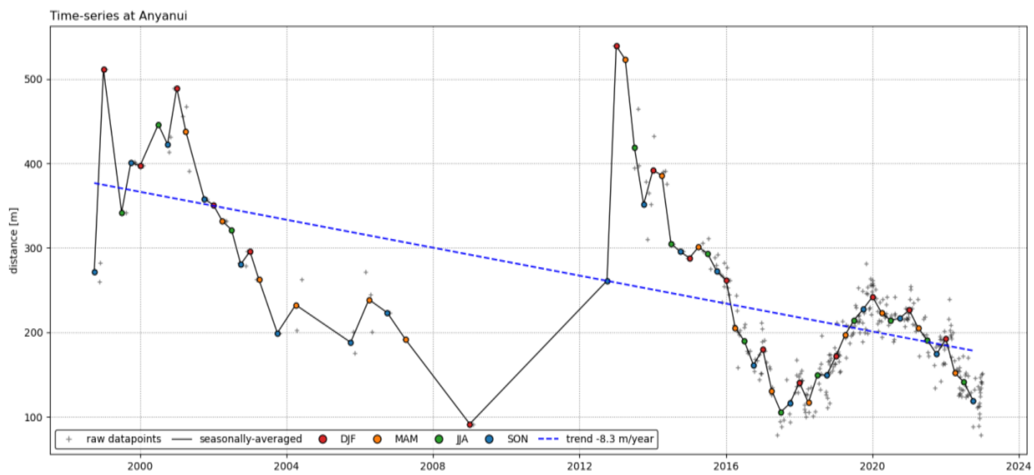


Figure 14i: Seasonal averages and linear trend of shorelines obtained at Anyanui

The presence of more data points below the trendline of seasonal averages and linear trends for shorelines at Anyanui indicates many important implications regarding coastal dynamics and environmental conditions (Thorne, 2019)

More points below the trendline may suggest that the shoreline is experiencing less erosion than expected. This could indicate a period of stabilization, where natural processes or human interventions are effectively reducing the rate of shoreline retreat.

The data could reflect a situation where sediment deposition is occurring at a rate that exceeds erosion. This might be due to favourable conditions that promote accretion, such as changes in sediment supply or reduced wave energy, leading to a net gain in land along the coast.

The trend may also be influenced by successful coastal management strategies implemented in the region. Initiatives such as mangrove restoration, beach nourishment projects, or the construction of protective structures could contribute to a decrease in shoreline erosion, resulting in more points falling below the expected trendline.

Figure 14j: Monthly averages and linear trend of shorelines obtained at Srogboe

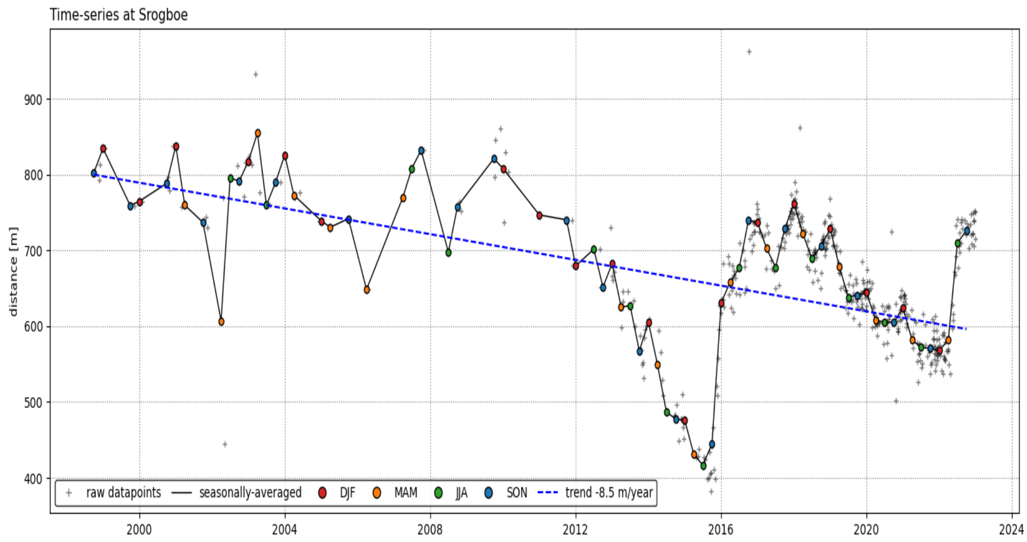


Figure 14k: seasonal averages and linear trend of shorelines obtained at Srogboe

The presence of more data points below the trendline of seasonal averages and linear trends for shorelines at Srogboe has a lot of implications regarding coastal dynamics and environmental conditions.

More points below the trendline may indicate that sea levels are rising at a slower rate than anticipated. This could suggest periods of stabilization or even slight declines in sea level, which might be influenced by various climatic factors or local geological processes.

The data could reflect a situation where coastal areas are experiencing more accretion than erosion. If the shoreline is building up due to sediment deposition, this could lead to increased land area and potentially improved habitats for local wildlife. It may also provide more buffer against storm surges and flooding events (Bilkovic, Mitchell, Mason & Duhring, 2016).

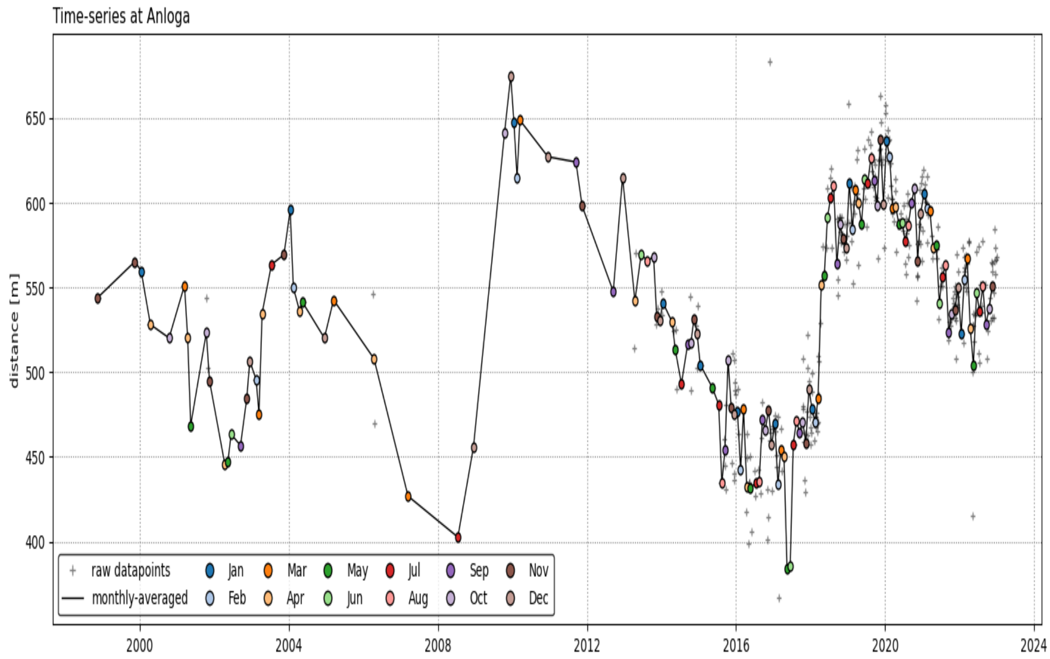


Figure 14l: Monthly averages and linear trend of shorelines obtained at Anloga

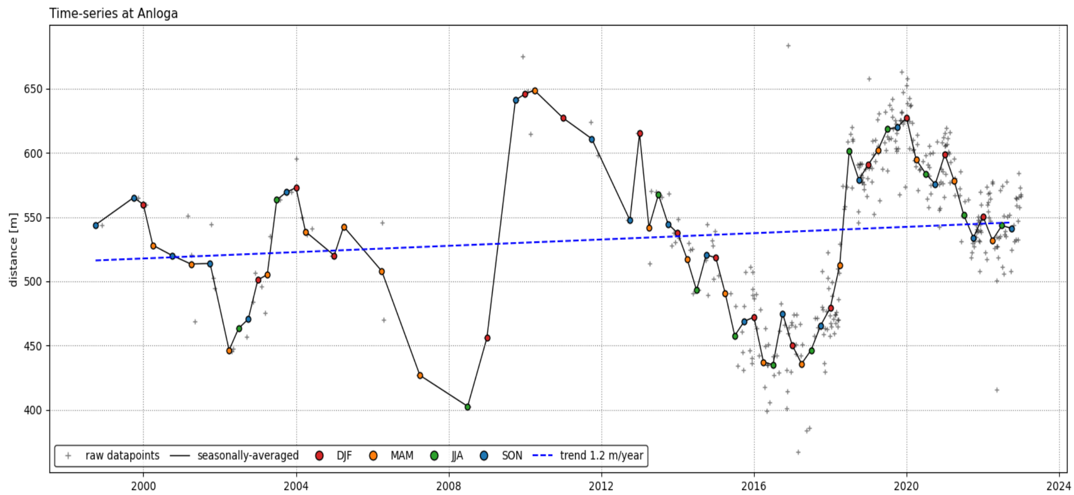


Figure 14m: Seasonal averages and linear trend of shorelines obtained at Anloga

The observation that more points of seasonal averages and linear trends of shorelines at the Anloga site are above the trendline suggests a positive trend of shoreline accretion in that area.

The presence of more data points above the trendline indicates that the shoreline is advancing, which may be due to natural processes such as sediment deposition or effective coastal management practices. This trend suggests a healthier coastal ecosystem, potentially leading to improved biodiversity and habitat availability. An accreting shoreline can provide greater protection against coastal hazards such as storm surges and flooding. The accumulation of sediment can help buffer against extreme weather events, reducing the vulnerability for coastal communities (Walker, 2017).

Table 5. summarized seasonal average shoreline results obtained from Coastsat toolkits

Selected communities	Shoreline changes m/y
Ada Foah1	5.5
Ada Foah 2	8.3
Anyanui	-8.3
Dzita	-5.7
Srogboe	-8.5
Anloga	1.2

Sources coastsat toolkit, 2024

The CoastSat toolkit was employed in this study to quantify the changes at the mouth of river Volta. Six polygons that define the coast into boxes with 1000 m length and 500 m width were generated for the CoastSat analysis. The accessible Landsat and sentinel images from 1992 to 2022 were found for every box that was made, and they were then downloaded from the GEE. The six polygons came with the shoreline of the following results. At Ada Foah, two polygons were taken namely Volta 1&2 with 5.5m/year and 8.5m/year, Anyanui which is site 3(volta 3) had a shoreline seasonal average rate of -8.5m/year, Dzita which is the four sites represent volta 4 emerged resulted into the seasonal average shoreline of -5.7m/year, Srogboe which is the site 5 or volta 5 had an average shoreline rate of -8.5m/year. The last site, Anloga or Volta 6, resulted in an average seasonal shoreline rate of 1.2m/year.

Among the six sites, three sites resulted in positive signs (+) these are Ada Foah 1&2 and Anloga. Anyanui, Srogboe, and Dzita also resulted in negative (-). The positive signs depict accretion and the negative sign means erosion. It implies that Ada Foah and Anloga are experiencing accretion rather than erosion. Then Anyanui, Srogboe, and Dzita communities are also encountering more erosion. In terms of erosion Anyanui and, Srogboe are eroding at -8.5m/year than Dzita which is eroding at -5.7m/year. With regards to the site accreting, site 2 which is volta two is accreting more than site 1(Ada Foah) and site 6(Anloga).

Regarding the search results, the elevation of Ada Foah is 4 meters or 13 feet above sea level while the elevation of Anyanui in the Eastern Volta region of Ghana is approximately 7 meters (23 feet) above sea level yet Anyanui has -8.3m/year whiles Ada Foah has 8.5m\year which implies that Anyanui is encountering more floods than Ada Foah due to high rate of erosion. These two towns can be seen. More erosion is occurring in the estuarine shoreline and marine side of the eastern coastline than in the western coastline. This study supports the findings by Boateng (2012), Appeaning Addo (2015), and Ly (1980) that the eastern volta is deteriorating more quickly than the western volta. While Ada Foah is found in the western Volta, Anyanui is found in the eastern Volta and it is counted among the towns suffering under the threat of constant flooding and erosion in Keta districts.

Summary of Objective One

The study has illustrated the process of erosion and accretion on Ghana's maritime shorelines and the estuary of the Volta River. As can be observed from the several graphs and accompanying images, both on the seaside and the estuary shoreline, the eastern coastline is deteriorating more swiftly than the western coastline and shoreline. This can be confirmed by studies by Boateng 2012, 2022 and Appeaning et al..,2018

The results of Boateng (2012), Appeaning Addo (2015), and Ly (2010) stated that the Volta Delta is deteriorating. Over 30 years, the average erosion rate along the coastal shoreline is approximately 0.79 ± 0.24 m/yr While the average accretion rate is around 1.24 ± 0.24 m/yr. Boateng (2019), This is seen in Table 5

Table 6. Shoreline change results

Location	Rate of erosion $^{m}/_{yr}$	Rate of accretion $^{m}/_{yr}$
Along the whole shore	-07.9	2.4
Eastern coastline	-.2.19	1.37
Western coastline	-0.62	0.33
Eastern estuarine shoreline	-1.94	-
Western estuarine shoreline	-0.54	0.14
Uncertainty (error)		0.24

Sources: Boateng et al..2020.

The average rate of erosion in the eastern portion of the maritime shoreline is 2.19 ± 0.24 m/yr, whereas the average rate of accretion is 1.37 ± 0.24 m/yr. Moving forward to Addo et al...,2020, on the western side of the maritime shoreline, the average rate of erosion is around 0.62 ± 0.242 m/yr, while the average rate of accretion is approximately 0.33 ± 0.24 m/yr. In the eastern estuary side, on the other hand, the average erosion rate is 1.94 ± 0.24 m/yr whereas the average accretion rate is 0.16 ± 0.24 m/year. On average, the shoreline of the western estuary experiences erosion at a rate of 0.54 ± 0.24 m/yr and accretion at an average of 0.14 ± 0.24 m/yr. Some of the hot sites for coastal erosion are Ada on the western coastline and Dzita, Srogboe Anyanui, and Anloga on the eastern coastline, according to Jayson-Quashigah et al. (2018). The local inhabitants and ecosystem may be adversely affected by the varying degrees of erosion that these locations are experiencing**.**

Objective 2

This section seeks to determine the dominant cause(s) of the changes and it related challenges at the mouth of the river Volta over 30 years.

Over several decades, there have been numerous severe instances of beach erosion and its related effects in the Eastern coast of Ghana and its vicinities and this has been attributed to both natural and anthropogenic activities such as infrastructural development, dredging, damming of rivers, and hard coastal defense systems (Ndour et al. 2017; Angnuureng et al., 2019; Alves et al. 2020).

The question here is what are the reasons or the factors behind this evolution (morphological changes) specifically sand spits and sand bars at the mouth of River Volta? This analogy can be best appreciated if a Simple linear regression analysis is performed.

Simple linear regression analysis is a statistical method used to model the relationship between two continuous variables: one independent variable (predictor) and one dependent variable (response). The goal is to find a linear equation that best predicts the dependent variable based on the independent variable (Corn, Feldman, & Wexler, 2020). Simple linear regression measures the strength and direction of the linear relationship between two numeric variables. The equation takes the form: $y = a + bx$ It lies between -1 and 1, When r calculated is close to 1, there is a stronger direction relationship between a dependent variable and the independent variable (Hazra & Gogtay, 2016). Simple linear regression can be used to determine the physical parameters and the morphological changes near the river mouth (Rivillas-Ospina, 2017)

Analyzing the relationship between variables such as waves, tides, sediment loads, and river discharge as against shoreline will enable us to identify the dominant factors responsible for morphological change at the river mouth. The following graphs show the relationships between the dependent variable and the independent variables

Relationship between sediment loads and shoreline changes

One useful statistical method for examining the connection between shoreline changes and sediment loads is simple linear regression (Kuang, 2014). This helps to measure and analyze how changes in sediment supply affect coastal dynamics like accretion and erosion using this technology. Figure 18a shows that the coefficient of R2 is 0.0046 m/s. The rate of shoreline change in response to changes in the sediment load level is shown by the slope coefficient of -(0.0321m/y). When the sediment load level variation is zero, the intercept of 6.5045. 90(m/y) indicates that the shoreline will change by 6.5045. 90(m/y) at point zero (0).

With a coefficient of determination (R2) of 0.0046, the variation in sediment loads can only account for 0.46% of the variation in shoreline alterations. This shows that the two variables have a relatively weak association, indicating that shoreline changes may be more significantly influenced by other factors not included in the model.

The rate of change in shoreline position for a unit change in sediment load level is represented by the slope coefficient, which is -0.0321 m/y. The inverse connection indicated by the negative sign means that the coastline changes by -0.0321 m/y for every unit increase in the sediment load level. The expected coastline change at zero sediment load level is shown by the intercept, which is 6.5045.90 m/y. This estimate indicates that a coastline shift of 6.5045.90 m/y would occur even if there was no fluctuation in sediment load.

The low R^2 value suggests that the model has limited ability to accurately predict shoreline changes based solely on sediment load variations. Other factors, such as wave climate, tidal patterns, and human interventions, may play a more significant role in shaping the shoreline.

The intercept suggests that even without variations in sediment load, there is an ongoing shoreline change of 6.5045.90 m/y. This change may be attributed to other factors not included in the model or may represent the natural variability of the shoreline system.

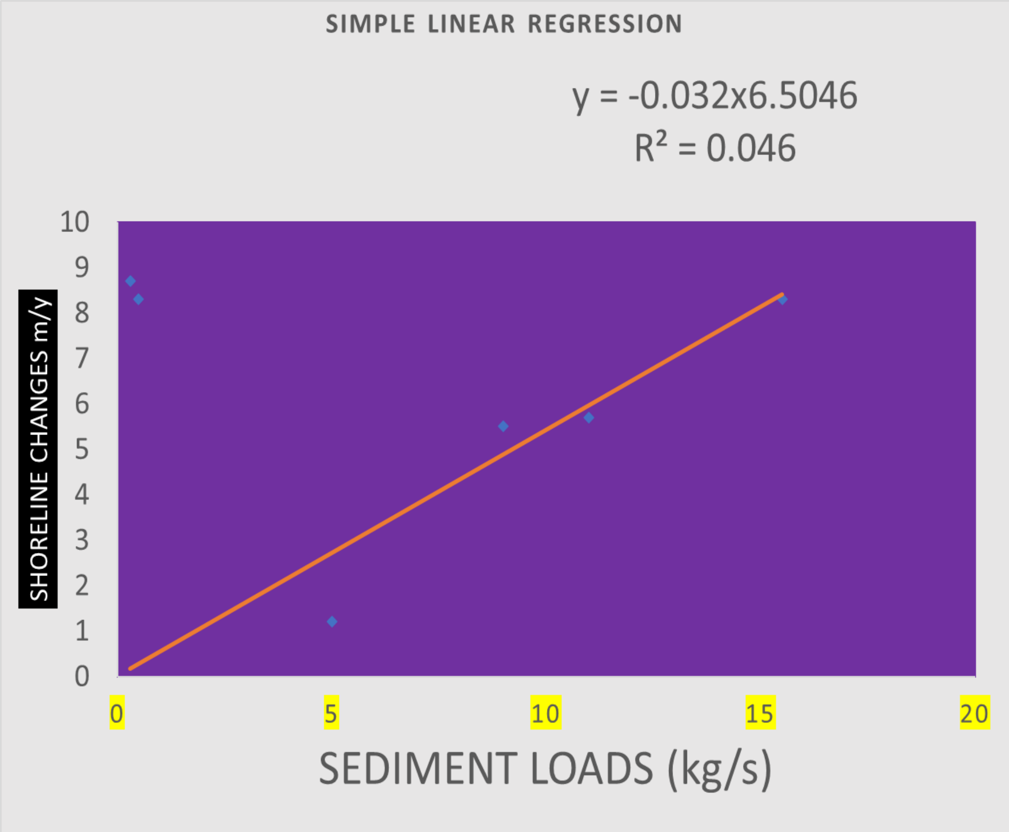


Figure 15a. Relationship between sediment loads and shoreline changes

The Relationship between shoreline changes and tide (Figure 15 a)

The correlation between shoreline changes and tides is a complex relationship that depends on various factors (Shi, & Conrad, 2009). Tides can influence shoreline position through processes like wave runup and water level variations. However, the strength of this correlation can be affected by other factors such as sediment supply, wave climate, and coastal morphology. The coefficient of R^2 is 0. 0037. The slope coefficient of – 17.03m/y shows the shoreline change rate when there is a change in tide level. The intercept of 16. 90m/y depicts that at point zero (0) there will be a shoreline change of 16.90m/y when the tide level variation is zero

The R^2 value of 0.0037 indicates that only 0.37% of the variation in shoreline changes can be explained by changes in tide levels. This very low R^2 suggests a weak predictive power of the model, meaning that the relationship between tide levels and shoreline changes is minimal. Other factors, such as wave action, sediment supply, and human activities, likely play a more significant role in influencing shoreline dynamics.

The slope coefficient of -17.03 m/y signifies that for every unit increase in tide level, the shoreline is expected to change (move landward) by 17.03 meters per year. The negative value indicates an inverse relationship, implying that higher tide levels are associated with greater shoreline erosion. This information could be critical for coastal management, as it highlights the potential impact of rising tide levels on coastal erosion and habitat loss.

The intercept of 16.90 m/y indicates that an annual shoreline shift of 16.90 m is still anticipated when there is no change in tide levels, or at tide level zero. This figure shows that substantial shoreline alterations are being caused by other forces even in the absence of tidal impacts. This could be the result of man-made factors like coastal development or natural ones like sediment movement.

The need for a more thorough model with more variables is suggested by the low R2, which shows that shoreline changes cannot be adequately explained by tidal levels alone.

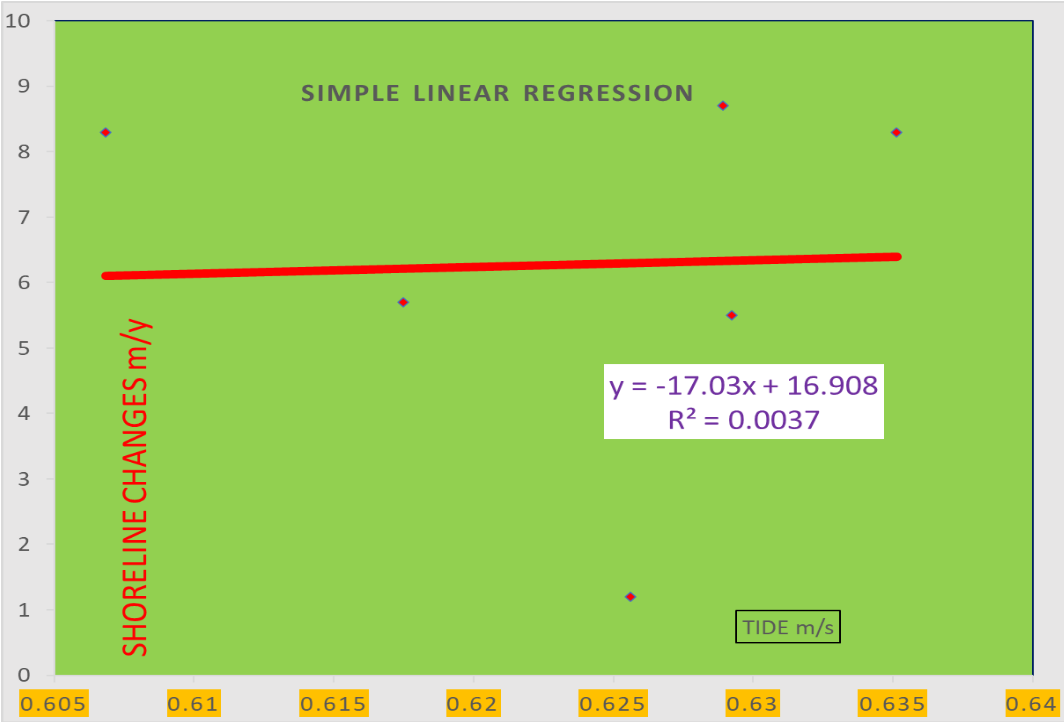


Figure 15 b. The correlation between shoreline changes and tide

The correlation between shoreline changes and wave

Because wave activity affects coastal dynamics through sediment transport and hydrodynamic consequences, there is a considerable link between shoreline alterations and wave action (Madeira, 2022). R2 has a value of 0.903. The coastline change rate in response to a change in wave activity level is shown by the slope coefficient of –51.4581m/y.

When the tidal level variation is zero, the intercept of 72. 312 m/y indicates that the coastline will change by 72.312 m/y at point zero (0).

The R^2 value of **0.945** indicates a very strong correlation between wave action levels and shoreline changes. Specifically, this means that approximately 94.5% of the variation in shoreline changes can be explained by variations in wave action. This high R^2 suggests that wave action is a significant factor influencing shoreline dynamics, making it a critical variable for understanding coastal erosion and accretion processes.

The shoreline is predicted to shift 51.4581 meters landward annually for every unit increase in wave activity level, according to the slope coefficient of -51.4581 m/y. The inverse association shown by the negative sign means that higher coastline erosion is correlated with stronger wave action. The intercept of 72.312 m/y indicates that an anticipated shoreline change of 72.312 m/y would still occur (theoretically) when wave action levels were at zero. This number suggests that substantial shoreline changes are caused by other sources other than wave action.

The strong R2 value suggests that wave action plays a major role in shoreline change prediction. This implies that shoreline dynamics may be accurately predicted by models that take wave activity levels into account. The coefficients show a strong correlation between shoreline modifications and wave action, which has important ramifications for planning and coastal management. According to the findings, significant coastline erosion is caused by increasing wave activity. Research by Brown and Nicholls in 2015 supports the idea that wave motion dominates the Volta River.

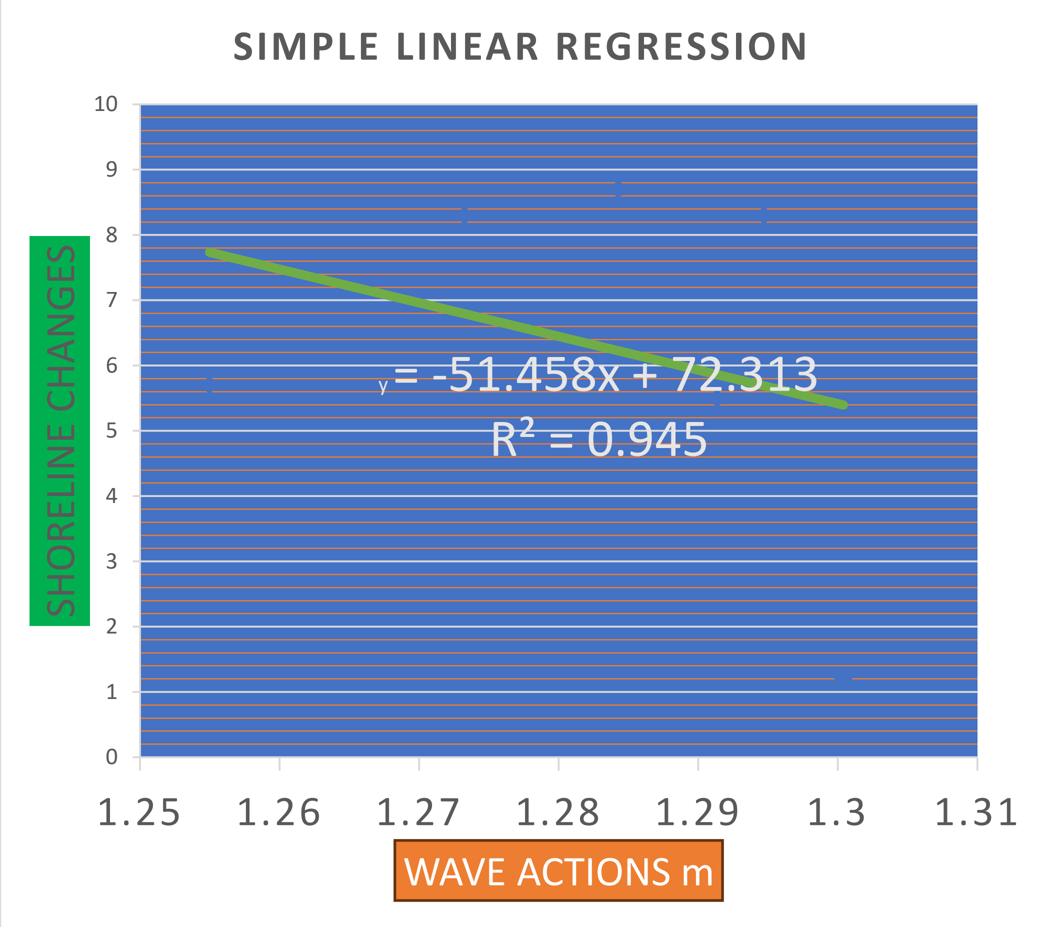


Figure 15 c. The correlation between shoreline changes and wave action

The correlation between shoreline changes and river discharge

Shoreline changes and river discharge are significantly correlated because sediment transfer and hydrodynamic impacts are two ways that river discharge affects coastal dynamics. Deshpande, Thatte, and Gogtay (2017). R2 has a coefficient of 0.943. The coastline change rate in response to a change in river discharge level is shown by the slope coefficient of –6.46m/y. When the river flow level variation is zero, the intercept of 6.54 m/y indicates that the coastline will vary by 6.54 m/y at point zero (0).

There is a substantial association between coastline alterations and river discharge levels, as indicated by the R2 value of 0.943. This indicates that fluctuations in river discharge account for around 94.3% of the variation in shoreline alterations. A high R2 value indicates that river discharge has a major role in shoreline dynamics, which makes it essential to comprehend the processes of accretion and erosion in coastal regions.

The coastline is predicted to shift (move landward) by 6.46 meters annually for every unit increase in river discharge level, according to the slope coefficient of -6.46 m/y. Because of the inverse link indicated by the negative sign, coastline erosion is positively correlated with river discharge levels.

The intercept of 6.54 m/y indicates that a predicted coastline change of 6.54 m/y would occur even in the absence of river flow fluctuation (i.e., at a discharge level of zero). This number suggests that shoreline changes are caused by a variety of reasons other than river flow. Wave action, sediment supply, tidal influences, and human impacts are a few examples of these variables.

River discharge is a major element in shoreline change prediction, as indicated by the high R2 value. Shoreline dynamics may be accurately predicted by models that take river flow levels into account, which is crucial for efficient coastal management.

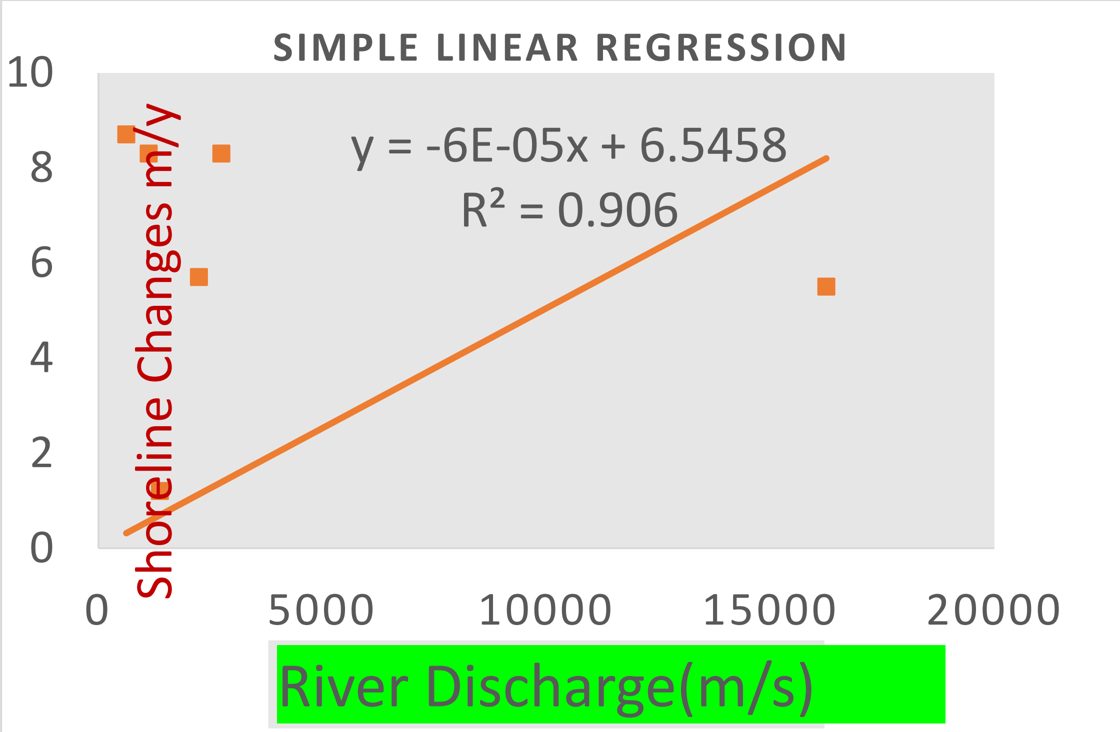


Figure 15 d. The correlation between shoreline changes and river discharge

Table 7. summarized and depicts the r calculated from the four physical parameters and the relationship between shoreline changes.

Physical parameters	**Results (r^2)**
Tide	0.0037
Sediment load	0.0046
River discharge	0.903
Wave actions	0.943

The respected values derived from simple linear regression in this investigation were sediment loads (0.0046), river discharge (0.943), wave actions (0.943), and tide effects (0.0037). With this, it is evident that the primary factors causing the morphological changes are river discharge and wave action. Wave actions and river discharge show a substantial link with the pace of shoreline change, despite the fact that all of these physical factors have affected morphological aspects (shoreline change) (Sadio et al., 2017).

This study backs up the claim made by Guo et al. (2015) that river mouths are dynamic systems that react quickly to variations in wave behavior. Waves dominate the volta delta. River mouth morphology is significantly influenced by wave motions. The evolution of river mouth spits and closure dynamics were impacted by the significant sediment transport and deposition caused by the wave fluxes. knowledge the morphological changes in this dynamic coastal environment requires a knowledge of the interaction between river flow and wave action at the Volta River's mouth.

. Significant erosion and shoreline changes have resulted from the damming's restriction of the sediment supply and the powerful wave action. To address these issues, especially in light of climate change and growing human demands, effective management techniques are required.

Objective three

This section sought to map out some selected coastal communities surrounding the mouth of river Volta and their vulnerability in terms of coastal hazards.

The Volta River's mouth has been dynamic, which has caused man to experience significant erosion in the eastern portions of the Volta owing to the morphological change at the mouth of the river, according to the analysis performed to achieve objectives one and two. (Tsikata 2006; Nairn et al. 1999; Ly 1980). There are at least two instances of coastal flooding there each year (Appeaning Addo et al., 2018). The communities at the River Volta's mouth have been impacted by erosion and floods, as seen by field observations along the eastern portion of the Volta River. The Volta River's eastern section is therefore Ghana's most susceptible coastal area. The study's objective was to map out the coastal communities surrounding the mouth of the Volta River and evaluate their vulnerability to coastal hazard risk using the Coastal Vulnerability Index (CVI), a systematic method for evaluating the vulnerability of coastal zones to a variety of hazards, particularly those associated with climate change, such as storm surges, sea level rise, and coastal erosion (Horton, 2022).

The Coastal Vulnerability Index (CVI) is composed of the Socioeconomic Vulnerability Index (SVI) and the Physical Vulnerability Assessment Index (PVI), though the PVI is the subject of this study.

A quantitative assessment technique called the Physical Vulnerability Index (PVI) was created to determine how vulnerable infrastructure and buildings are to different natural disasters including flooding and wildfires, among other environmental dangers (Catita, 2023). Table 11 shows the creation of a database with physical characteristics that accurately reflect important driving forces behind coastal erosion and floods throughout Ghana's southern eastern coast.

Table 8: Database of Physical Vulnerability Assessment Index (PVI)

communities	Shoreline change	Wave currents	mean tide range	relative sea-level rise rate	coastal slope
Ada Foah	8.3	1.283	0.028	0.0015	0.02
Anyanui	-8.3	1.283	0.028	0.0015	0.03
Dzita	-5.7	1.283	0.028	0.0015	0.025
Srogboe	-8.5	1.283	0.028	0.0015	0.025
Anloga	1.2	1.283	0.028	0.0015	0.03

The coastal vulnerability index is computed as the square root of the geometric mean. Shaw et al. (1998) formula for computing PVI.

PVI=.$\sqrt{a+b+c+d+e}$

Were

a = shoreline erosion/accretion rate

b = mean wave height

c = mean tide range

d = relative sea-level rise

e= coastal slope

Table 9: Computed Physical Vulnerability Assessment Index (PVI). PVI was classified into five vulnerability classes (very low, low, moderate, high, and very high) based on the Jenks natural classification method

Communities	PVI	Ranges	Ranking	Colouring
Srogboe	-1.2	-1.20> -1.19	Very high	Deep red
Anyanui	-1.18	-1.18>-1.17	High	Light red
Dzita	-0.93	-0.9.3> -0.80	Moderate	yellow
Anloga	0.71	0.70 < 0.71	Low	Light green
Ada Foah	1.39	1.38 < 1.39	Very low	Deep green

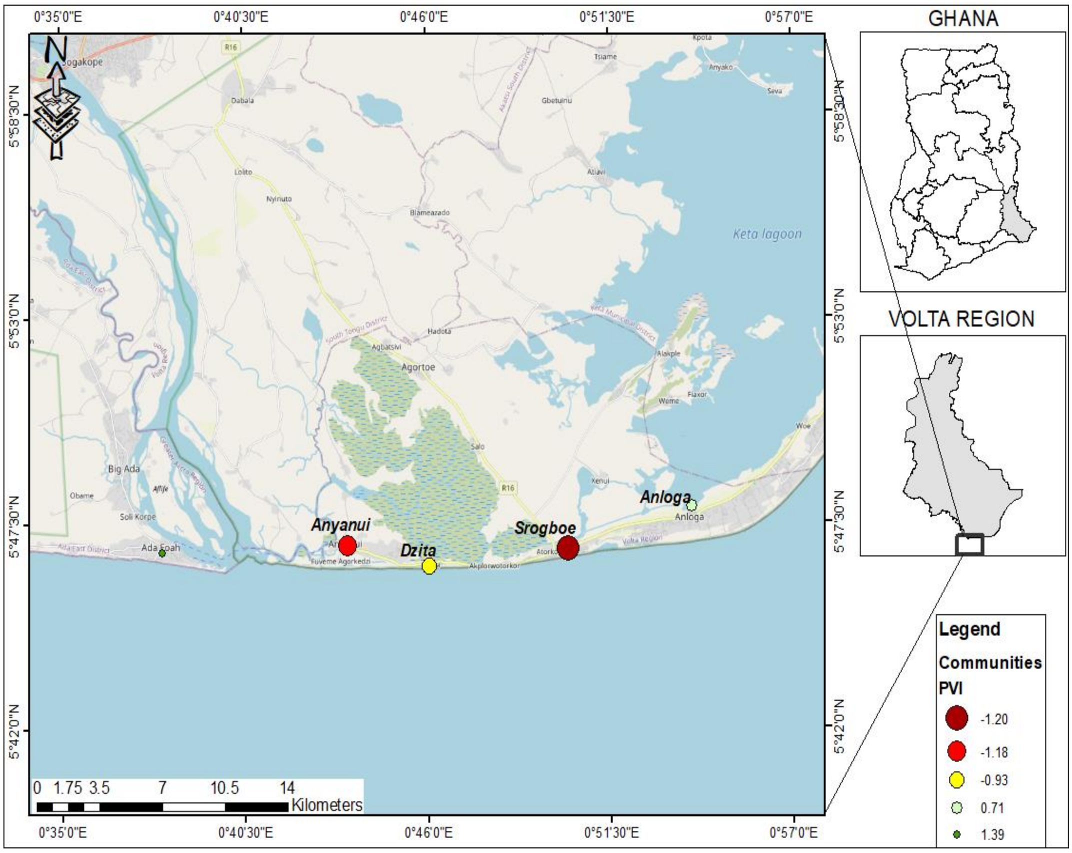


Fig. 16a. Figure 20 depicts the vulnerability level in lines, while the PVI map of some settlements around the mouth of the River Volta on Ghana's east coast is identified with dots.

Source: Department of Geography and Regional Planning, 2024

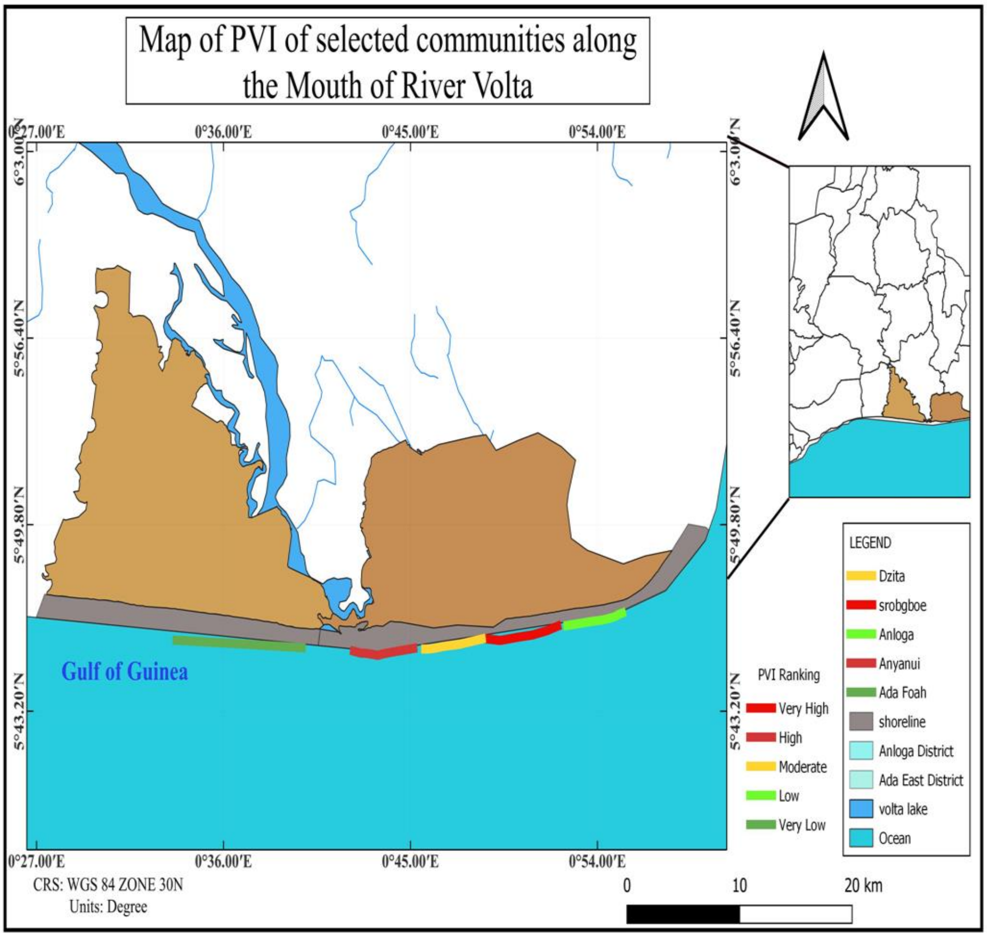


Fig. 16b:. Map of PVI of selected communities around the mouth of River Volta on the eastern coast of Ghana labeled in lines as compared to figure 19 indicated the vulnerability level in dot. Source: Department of Geography and Regional Planning, 2024

The PVI values, which varied from -1.20 to 1.39, were used to identify five vulnerability classes. The following categories applied to these levels: See Figure 3 and Table 2 for additional details. (1) very high vulnerability (-1.20> -1.19); (2) high vulnerability (-1.18> -1.17); (3) moderate vulnerability (-0.9.3> -0.80); (4) low vulnerability (0.70 < 0.71), and (5) extremely low vulnerability (1.38 < 1.39). The main reasons for the coastal vulnerability that persists throughout Ghana's eastern coast are the Volta River's influence and the complex dynamics of the coastal environment of the Volta Delta (Ly

Cheng, 1980; Roest 2018; Boateng 2012). Physical vulnerability is moderate in Dzita and extremely low in Ada Foah, according to the PVI statistics, while it is rather high along Anyanui and Srogboe.

The high vulnerability index of the Anyanui, Dzita, and Srogboe communities around the mouth of the Volta River can be attributed to several interconnected factors that increase their susceptibility to environmental hazards, particularly flooding and erosion. The most vulnerable areas have been identified with deep red followed by light red. These areas require immediate attention for new coastal infrastructure planning, revision of implemented coastal adaptation approaches, or considerations for sustainable and resilient coastal development. There is also a need for adequate coastal adaptation planning and the revision of short--, medium--, and long-term coastal adaptation strategies to address these inevitable coastal hazards.

Summary of objective

According to PVI ratings, the most susceptible settlements around the mouth of the Volta River are Anyanui, Srogboe, and Dzita. Erosion poses a threat to these communities. Due to the collapse of the residents' sources of income and the devastated infrastructure, there was a movement out of the villages. This is supported by studies by Appeaning et al. (2018), which revealed that 90 homes were demolished and 685 individuals were moved in 2011 and 2008, respectively. Thus, the eastern part of the Volta River is the most susceptible part of Ghana's coastline. Field observations along the eastern Volta near Anyanui, Dzita, and Srogboe demonstrate the effects of floods and erosion on these settlements.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Introduction

This chapter is devoted to the summary of the findings, conclusions, recommendations, and suggested areas for future research. The study aims to assess the morphological change at the mouth Volta River and its related challenges.

Summary

In the past years, researchers and technocrats have applied different methods and techniques to extract data from aerial photos or satellite images using remote sensing techniques., to enable them to understand the dynamics of the morphology at the eastern coastline of Ghana specifically the mouth of River Volta (Twumasi & Merem, 2006). Over the past few decades, the mouth of the Volta River has been extremely evolved. The main focus of these changes is the dynamics of the islands and sand spits that occur near the river mouth, which are caused by several factors that have shaped the local morphology, such as river flow, tides, waves, and human-caused modifications over the past few years (coastal protection). As a result, some communities near the mouth are now more vulnerable to coastal risks.

Better management of the system as a whole is made possible by an understanding of the factors that cause such changes as well as the linkages between coastal and delta activities. Even though a lot of research has been done on the Volta River, little attention has been paid to these alterations and the underlying causes responsible for the changes along the Volta shoreline. As a result, there is a dearth of literature about the development and its consequences near the Volta River mouth.

This knowledge gap hinders the formulation of effective strategies and policy for mitigating the adverse effects of these changes and optimizing the management of this critical ecosystem. Therefore, there is a pressing need to conduct a vital study to address the challenges associated with the evolution of the delta at the mouth of River Volta. The study used 90% of remote sensing as the means to achieve the target of the study. Remote sensing involves the utilization of recording devices to gather data from a distance, eliminating the need for direct physical contact with the objects being studied. Results point to the potential complete collapse of infrastructures. It has been established that Ghana's eastern coast is the most vulnerable. At least twice a year, there is coastal flooding there.

Summary of major findings

The following are the major findings of the study:

The study has revealed that the Volta River mouth has undergone significant morphological changes resulting in erosion and accretion at the eastern coastal zone affecting the sand bar and spit.

These rapid changes have occurred over the past decade and have led to increased coastal flooding and erosion along Ghana's eastern coast, occurring at least twice a year.

The underlying factors behind these changes are both natural and anthropogenic. The construction of dams, particularly the Akosombo Dam on the Volta River, has altered the river's discharge and sediment supply, leading to changes in the coastal morpho dynamics and evolution of the river mouth.

Additionally, waves and river discharges have the most physical parameters behind these changes.

The impacts of these changes are felt both in the natural environment and the human communities living along the coast. The rapid elongation of the estuarine sandspits, sandspit intrusion, downdrift erosion, and increased prevalence of floods are some of the coastal hazard changes observed.

Marine life as well as human factors are affected by these changes. Along the residential settlements at the river mouth, erosion is harming the infrastructure and buildings. Because of the significant rate of coastal erosion shown in the results, there is a possibility that these structures could completely collapse, forcing the displaced population to relocate in large numbers and perhaps affecting their socioeconomic standing

Conclusions

The principal findings of the study have led to the following conclusions.

The study's findings demonstrated that the delta and the sand bar and spit near the mouth of the River Volta have undergone morphological modifications.

Findings showed that while both accretion and erosion have been trending upward, erosion has been trending more strongly than accretion.

Natural processes such as tide, wave effects, river discharge, sediment loads, and many more are attributed to this erosion trend. Once more, research showed that the main reasons for the alteration near the mouth of the Volta River are natural elements like the waves and river discharge.

The PVI assessment demonstrates that the field study conducted along the eastern zone segment of the Volta indicates that erosion and floods have affected the settlement near the river's mouth. As a result, Ghana's eastern coastline is now the most susceptible due to the widespread flooding at the Mouth Volta.

Recommendations for policies and practices.

In order to combat the effects of coastal hazards in the eastern coastal community, this section of the study identifies mitigation and sustainability measures in the form of recommendations to stakeholders, including environmental planners, coastal engineers, government officials, and planners. . The following recommendations are based on the conclusions and major findings of the study.

Coastal impact awareness creation and environmental education need to be initiated in the coastal communities. Considering the educational levels and the attitude of the Coastal community, it will only take the commencement of awareness creation and environmental education on the negative community actions against the environment to reduce the coastal hazards incidence and the associated impacts.

As part of the advice, putting ecosystem recovery ideas into practice should be crucial. Methods for restoring ecosystems, such as planting trees, will lessen erosion along the shore and in the beach area. Increasing flora along the shore will shield the sandy beach from the wind.

Decentralization of management policies is necessary once more. The decentralization of these obligations to the community level is required by the EPA's many environmental commitments. The appropriate management training and equipment should be available to members of the coastal community in order for them to monitor the shoreline, its consequences, and wave-induced erosion. Seawater extends along the coast; these places should be planted with salt-tolerant trees.

Coastal protection measures are the last but certainly not the least of the efforts that must be taken. Permits ought to be given to those planning projects along the coast and to coastal developers. This will enable developers to adhere to the relevant regulations and conservation measures.

Area for further studies

Future research should encompass the entirety of the Eastern coastline zone, as this study suggests, as time and resource constraints prevented the study from quantifying the (morphological changes) from the entire Eastern coastal zone. When doing morphological research at a river's mouth, consideration should be given to the community's viewpoint and knowledge, as anthropogenic activities also impact morphological changes. Involving the local population in addressing anthropologic activities that initiate processes that shape the place's morphology is vital.

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