UNIVERSITY OF CAPE COAST

INVESTIGATING COASTAL MANAGEMENT STRATEGIES AND COASTAL INFRASTRUCTURE IN GHANA

BLESSING CHARUKA

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BY

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A thesis submitted to the Department of Fisheries and Aquatic Sciences, School of Biological Sciences, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Doctor of Philosophy Degree in Integrated Coastal Zone Management

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DECLARATION

I hereby declare that this thesis is the result of my original research and that no part of it has been presented for another degree with this university or elsewhere.

Candidate's Signature: …………………………… Date:....... /……./…....

Name: Blessing Charuka

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature: ……..................... Date:…../……./……

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ABSTRACT

Coastal management has emerged as one of the greatest global challenges of the 21st century to adapt to sea-level rise and associated hazards like coastal flooding and coastal erosion. To respond to coastal erosion, different coastal management strategies and coastal infrastructure typologies can be applied to safeguard communities and ecosystems against coastal hazards. The main aim of this study was to investigate the implementation of coastal management strategies and coastal infrastructure in Ghana. Precisely, the study (1) mapped and assessed coastal protection infrastructure along the coast of Ghana using geographic information systems, remote sensing, and in-situ observation; (2) estimated the integrated coastal vulnerability index for the coast of Ghana towards future coastal infrastructural developments; (3) investigated short-term shoreline response to groyne fields and associated environmental impacts at three groyne fields using satellite imagery and remote sensing; and (4) employed in-depth interviews to investigate the socioeconomic impacts of grey infrastructure along the coast of Ghana. Results indicated that: (1) coastal management in Ghana is largely static and reactive using hold-the-line strategies and grey infrastructure for coastal protection; (2) Approximately 20% of the coast was protected using hard-engineered infrastructure between 2000 and 2022; (3) at least 72% of the coast has moderate to very high coastal vulnerability to coastal hazards; (4) shoreline responses to groynes indicate increasing erosion, rapid changes to beach plan form, and terminal groyne effects – severe down-drift shoreline retreat rates; (5) the socioeconomic pitfalls identified include erosion migration, beach access restriction, impacts on artisanal fishing methods, fish landing dynamics, and livelihoods. The outcomes of this study have significant implications for coastal planning, policy-making, and sustainable development of coastal areas in Ghana. In conclusion, the development of shoreline management plans to support adaptive (dynamic) coastal management strategies and hybrid infrastructure is recommended to mitigate reactive, *ad hoc* implementation of grey infrastructure along the coast of Ghana.

KEYWORDS

Coastal management

Coastal infrastructure

Coastal adaptation

Coastal vulnerability

Environmental impacts

Socioeconomic impacts

LIST OF PUBLICATIONS

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3. **Charuka, B.,** Angnuureng D.B., Brempong E.K., Agblorti, S.K.M., Antwi-Agyakwa K.T. Assessment of the integrated coastal vulnerability index of Ghana toward future infrastructure investment plans. *Journal of Ocean and Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2023.106804
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DEDICATION

To my wife Synthia, my children Victoria, Gladwin, and Gladwell, and my mother, Stellah Charuka *nee* Makuve, whose wisdom shaped my journey

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Processing
ATL	Advance the line
BwN	Building with Nature
CVI	Coastal Vulnerability Index
DEM	Digital Elevation Model
EbA	Ecosystem-based Adaptation
EPR	End Point Rate
EwN	Engineering with Nature
GIS	Geographic Information System
HTL	Hold the Line
HWL	High Water Line
ICVI	Integrated Coastal Vulnerability Index
IPCC	Intergovernmental Panel on Climate Change
KSDP	Keta Sea Defence Project
LRR	Linear Regression Rate
LWL	Low Water Line
MR	Managed Realignment
MSL	Mean Sea Level
NAI	No Active Intervention
NbS	Nature-based Solutions
NNBF	Nature and Nature-based Features
PVI	Physical Vulnerability Index

SDG	Sustainable Development Goals
SLR	Sea Level Rise
SMP	Shoreline Management Plans
SVI	Social Vulnerability Index
UAV	Unmanned Aerial Vehicle
UNEP	United Nations Environment Programme
WACA	West Africa Coastal Area

CHAPTER ONE

INTRODUCTION

Coastal areas harbour approximately 40% of the global population (Lubchenco & Haugan, 2023). Consequently, most industrial production, economic, and recreation activities happen in coastal environments (Palmer et al., 2011). At the same time, the coastlines are very dynamic environments that change from time to time, responding to both natural and human anthropogenic activities which contribute to coastal vulnerability (Boruff et al., 2005; Mclaughlin & Cooper, 2010). The increase in sea-level rise and coastal hazards have created demand for coastal protection through various management strategies and coastal infrastructure options (Hill, 2015; Klein et al., 2001; Sutton-Grier et al., 2015).

In Ghana, coastal protection projects commenced in 1999 with the planning and construction of the Keta Sea Defence Project. Subsequently, more coastal protection projects followed with sea defence projects such as Takoradi, Ada, Atokor, Cape Coast and Anomabo. These projects provided the much needed and anticipated coastal protection. Nevertheless, the implementation of coastal protection has also produced several unwanted problems (Angnuureng et al., 2013). However, the investigation of the coastal management and coastal infrastructure implemented along the coast of Ghana is minimal. Furthermore, the environmental and socioeconomic impacts have received little attention. These research gaps have necessitated this study to investigate coastal management strategies and the application of coastal protection infrastructure along the coast of Ghana.

1.1 **Background of Study**

Coastal management has progressed considerably through millennia, triggering innovative coastal adaptation approaches to respond to both human and climate-induced sea-level rise (SLR) and the associated coastal hazards like coastal flooding and erosion. The frequency and severity of coastal hazards have negative impacts on valuable coastal land, people and property (Appeaning Addo et al, 2011; Zhang et al., 2004), prompting the urgent need for proper coastal adaptation planning and management to achieve coastal protection and to balance the environmental and socioeconomic functioning of coastal areas (Wiafe et al., 2013). To protect communities against coastal hazards, different types of coastal protection infrastructure have been implemented in varying geographic contexts.

In the broader context, coastal infrastructure refers to structures, systems, and facilities built along coastlines that provide essential services including coastal defence systems, trade, tourism, fisheries and aquaculture, energy, water, waste management, transport, and telecommunications among other industries (RISK-KIT, 2021; Stevens et al., 2020). In fact, in many countries, industrial and economic production is concentrated along coastal cities. However, in the context of coastal adaptation, coastal (green, grey and hybrid) infrastructure refers to the full range of coastal (adaptation) infrastructure (or coastal defence systems) including hard engineering solutions like jetties and quays, seawalls and revetments, breakwaters and groynes to natural soft-engineered solutions like beaches, dunes, shingle, and coral reefs that provide coastal protection against coastal hazards (Hill, 2015; Klein et al., 2001; Sutton-Grier et al., 2015).

Coastal areas are very dynamic areas where the coastline faces spatial and temporal changes due to natural and human anthropogenic factors (Bush, Pilkey & Neal, 2015). At least, 40% of global population and approximately of 55% of global urban population live in coastal areas (Lubchenco & Haugan, 2023; Stevens et al., 2020). The nexus of overpopulation and the impacts of SLR, coastal storms, flooding, and erosion has positioned coastal adaptation as one of the important subjects of the 21st Century. Of these coastal hazards, coastal erosion is responsible for massive land loss along global coastlines (Luijendijk et al., 2018; Mentaschi et al., 2018), and is also one of the most challenging to manage (Biel et al., 2017; Marshall et al., 2011; Hanson & Lindh, 1993).

In West Africa, coastal erosion is rampant with a mean erosion rate of 1.8 m/year (World Bank, 2019). Along the coast of Ghana, coastal erosion rates vary from -2 m/year to -17 m/year (Boateng et al., 2016; Angnuureng et al., 2013; Appeaning Addo et al., 2008). The impacts include the destruction of coastal land and property, the disruption of the livelihoods of coastal communities, (Appeaning Addo, 2021), threat to heritage sites (Sabour et al., 2020; Vousdoukas et al., 2022), and negative impacts on natural coastal ecosystems. This is further complicated by the lack of coordination among institutions and lax environmental laws (Wiafe et al., 2013). To understand the need for coastal protection, against coastal erosion requires us to look at the spectrum of drivers that contribute to coastal erosion.

1.2 **Key Drivers Influencing Coastal Erosion**

Coastal erosion along the coast of Ghana is attributed to several factors discussed in this section.

1.2.1. Sea level rise

The relative sea-level rise (SLR) is defined as the variation in seawater elevation relative to the mean sea level over a long time (Angnuureng et al. 2018). SLR induce and intensify coastal hazards like coastal storms, coastal erosion and flooding (IPCC, 2021, 2022). Coastal hazards threaten strategic built coastal infrastructure (like roads, railways, water and energy infrastructure), residential properties, coastal ecosystems, and the livelihoods of coastal communities worldwide. As a result, SLR is considered one of the greatest societal challenges of the 21^{st} century for which many innovative coastal adaptation strategies have been designed to respond to the impacts (Bongarts Lebbe et al., 2021; Muis et al., 2016). If current business as usual is maintained, the increase in SLR is irreversible throughout the 21^{st} century and the frequency and severity of impacts is projected to be worse along sandy coasts in low-lying areas (IPCC, 2021, 2022). Consequently, SLR is projected to be the major driver of coastal erosion by 2100 (Oppenheimer et al., 2019), necessitating innovations in coastal adaptation (Bongarts Lebbe et al., 2021; Kirby et al., 2021; Klein et al., 2001; Linham & Nicholls, 2010).

1.2.2. Beach sediment mining

Beach sediment mining is the extraction of sand and pebbles from beaches and inland dunes, largely used in real estate developments for building and decorative purposes. Beach sand mining is a global phenomenon, illegal in developed countries, but omnipresent in developing countries (Bush et al., 2001). In Ghana, sediment mining is one of the leading contributors to coastal erosion on the majority of beaches (Jonah et al., 2017). In their findings, Jonah et al. (2015) established approximately 285, 376 $m^3$of sand was lost annually through tipper trucks at six study sites (Jonah et al., 2015).

Beach sediment mining is highly debated because it conflicts with other economic uses of the coast like fisheries and tourism (Adams et al., 2017), but it remains complex because of: (1) the political and traditional leadership interference, making law enforcement ineffective, and (2) the public perception that coastal sediment is an endowed natural resource to which the community has rights of exploitation. These impasses could be resolved through the use of participatory approaches, engaging stakeholders and communities through educational projects and dialogue meetings (Adams et al., 2017; Jonah et al., 2017).

1.2.3. Construction of sea defence infrastructure

Although coastal protection is a necessary coastal management function, hard-engineered infrastructure also contributes to coastal erosion. The construction of sea defence structures aggravates the erosion of downdrift areas through sediment starvation (Angnuureng et al., 2013). In Ghana, for instance, the Keta Sea Defence Project (KSDP) starved downdrift areas of Kedzi and Hlorve and substantially increased erosion from 3m/year before the construction of

KSDP to 17m/year after the construction (Angnuureng et al., 2013; Alves et al., 2020).

Between 2000 to 2022, more than 15 SDPs have been implemented along the coast of Ghana with a cumulative alongshore beach coverage of at least 100 km based on GIS surveys. These projects include the Blekusu SDP, Keta SDP, Atorkor SDP, Ada SDP, Sakumono (Tema-Accra beach road), Dansoman, Glefe, Mumford, Anomabo, Cape Coast, Elmina, Ankwanda, Adwoa, Dixcove. Ongoing projects include the Axim, Cape Coast, and Ningo-Prampram (Construction Reviews, 2021)**,** but this list is not exhaustive. In 2020 alone, roughly eleven new coastal projects (Mensah Guinea Coastal Protection Project (behind Independence Square), Apam Coastal Protection Project, Kokrobite Coastal Protection Project, Blekusu Coastal Protection Project (Phase II), and Maritime University Coastal Protection Project, all worth US$150 million (GIPC, 2020) had been planned. These structures may eventually starve sediment to downstream beaches, inducing coastal erosion to other beaches and worsening the coastal erosion function.

1.2.4. Port and harbour construction

Ports are primarily constructed to offer a safe harbour for ships to berth, load, and unload cargo. However, port construction disrupts the longshore sediment transport budget, trapping sand and sediments updrift, but starving downdrift areas (Alves et al., 2020). For instance, the construction of the Tema Harbor (opened in 1962) and the Takoradi Port (opened in 1928) is believed to have altered drastically wave patterns, disturbed longshore sediment transport, and intensified coastal erosion to areas like Accra, Ada, and Anlo (Akyeampong, 2001). Since 2012, eleven new fishing harbours have been constructed at major fish landing sites along the coast with an estimated total construction cost of $200 million (Hydro International, 2012). These fishing harbours are Axim, Dixcove, Winneba, Senya Beraku, Elmina, James Town, Gomoa Fetteh, Moree, Mumford, Teshie, and Keta. Three additional fishing harbours, namely Osu, Mfantseman, and Otuam commenced construction in 2021 (Ghanaports, 2021), bringing the total number of new fishing harbours to 15, a nearly 21% increase in new constructions.

With some of the projects near completion, e.g., Axim, Elmina, Mumford, and Moree, it is apparent that, while the new harbours will serve their economic functions, they may significantly alter sediment transport to downstream countries, that is, Benin, Togo, and Nigeria, possibly inducing erosion at some places. Moreover, the full potential of these harbours may not be realised. For instance, a fishing harbour constructed in 2014 to enhance fishing activities and protect the Adjoa Township remains neglected and underutilised. Therefore, the government must look into the economic benefits of these expensive projects.

1.2.5. Damming and illegal mining over river channels

The construction of the Akosombo dam marked a major disturbance of natural sediment supply along the coast of Ghana (Appeaning Addo et al., 2020; Jayson-Quashigah, 2019; Ly, 1980; Roest, 2018). The damming over rivers for hydropower generation, providing water for city consumption and agricultural purposes deprives downstream wetlands of water supply (UNEP, 2007) and obstructs the natural flow of sediments to feed downstream estuaries and beaches

(Bush et al., 2001). Damming threatens deltas through the dual effect of sediment starvation and compaction of muddy sediment which causes local land subsidence (Bush et al., 2001; Pilkey & Cooper, 2014; Oppenheimer et al., 2019), and contributes to approximately 1-2 m SLR per century (Bush et al., 2001).

In his narrative, Akyeampong (2001) describes damming as the most catastrophic human hydrological disruption that transforms terrestrial and riverine ecosystems and threatens coastal wetlands and ecosystems (Akyeampong, 2001). In Ghana, anthropogenic activities on rivers are made worse by illegal and unregulated mineral mining (*Galamsey*) that happens upstream of major rivers. Water from river bodies is blocked for washing gold or channelled for other mining activities. Blocking water channels aggravates downstream erosion and threatens beaches (Luijendijk et al., 2018; Pilkey & Cooper, 2014). In addition, mining introduces fine sediment onto many beaches through the rivers and contributes to suspended sediments. Altogether, damming, unregulated water and mineral mining, and diversion of water channels significantly modify the hydrology of watershed drainage systems to the coasts, contribute to SLR, local land subsidence, and increase coastal erosion (Luijendijk et al., 2018; Mentaschi et al., 2018).

1.2.6. Mangrove deforestation and conversion of coastal ecosystems

Mangroves play an important role in erosion control through wave attenuation and sediment deposition (Powell et al., 2019; Sutton-Grier et al., 2018). However, the increasing urban population and human coastal developments trigger mangrove deforestation for domestic and commercial purposes (Mensah, 2013).

In Ghana, the major contributors to mangrove loss include agricultural land reclamation, urbanization, and salt ponds (UNEP, 2007). Notably, the major salt panning sites, namely Ada Songor Lagoon and Keta Lagoon, are located in the Volta Delta (Wiafe et al., 2013). As a result, mangrove deforestation is high in the Volta Delta estuary, Densu, Ahanta West, and Princess Town (Diop et al., 2014). Other areas with mangrove forests are the Weija, Komenda, Mfantsiman, and Ahanta West (Atta-Quayson, 2018). Since salt production in Ghana is projected to increase to 2.5 million tons annually (Ghana National Strategy Team, 2021), mangrove deforestation for salt pans and agriculture is likely to increase.

1.3 **Statement of the Problem**

Coastal management has emerged as one of the priority areas in the 21st century. In that regard, coastal management has been challenged by both natural factors and human anthropogenic activities leading to rapid coastal changes (Bongarts Lebbe et al., 2021; Bush et al., 2001). Coastal change is a natural continuing process that is inevitable and projected to increase with the frequency and severity of coastal hazards whose impacts are felt worse in low-lying coastal countries (IPCC, 2022, 2021). In Africa, the impacts of coastal changes are already severe with the high cost of land degradation, flooding and coastal erosion especially in West Africa (World Bank, 2018).

In Ghana, the coastal area is increasingly threatened by coastal erosion, tidal waves, and flooding due to its low-lying nature (Wiafe et al., 2013). The mean national coastal erosion rate is estimated to be 2 m/year (Alves et al., 2020, 2022; Angnuureng et al., 2013). The consequences include the destruction of property, and cultural heritage sites, and the inundation of wetlands and coastal ecosystems (Appeaning Addo, 2021; Appeaning Addo, Larbi, Amisigo & Ofori-Danson, 2011).

The Ghanaian coast is largely protected using hold the line policy, implemented using grey or hard-engineered infrastructure (Alves et al., 2020, 2022). The commonest types of grey infrastructure installed are seawalls, groynes, and revetments. However, despite these interventions, studies (Appeaning Addo et al., 2020; Jayson-Quashigah, 2019; Angnuureng et al., 2013) provide evidence of coastal erosion migration to downdrift areas, thus creating new erosion hotspots and coastal management challenges (Alves et al., 2020; Angnuureng et al., 2013; Appeaning Addo et al., 2011). Moreover, coastal hardening is not a panacea as erosion continue to persist, even in protected areas (Bush et al., 2010).

Despite these challenges, studies to appraise the coastal management strategies and implemented coastal infrastructure in Ghana are on microscales and not on national scale (Boateng et al., 2016; Wiafe et al., 2013). Furthermore, there are few records on ecological engineering, innovation and implementation of nature-based infrastructure for coastal protection in Africa. In addition, despite the predominant use of hard-engineered infrastructure, few studies have been made to assess the knowledge gaps in coastal infrastructure typologies implemented in Ghana, their benefits and setbacks, and opportunities for transitioning from hard engineering towards green and hybrid infrastructure (Charuka et al., 2023a).

To close these gaps, this thesis has the main objective to investigate the coastal management strategies and coastal infrastructure in Ghana. It reviews the short, medium, and long-term coastal management policies and provide recommendations for the transition from reactive, static, hold-the-line policies towards proactive, adaptive or dynamic coastal management along the coast of Ghana in line with contemporary global coastal adaptation practices.

1.4 Purpose of the Study

This study investigates the coastal management strategies and coastal infrastructure used for coastal adaptation in Ghana. It establishes different coastal management policies and the types of coastal infrastructure implemented to uphold the policies in Ghana and provides recommendations for improvement in line with contemporary coastal management practices.

1.5 Objectives of the Study

The major aim of this research is to investigate coastal management strategies and the coastal infrastructure typologies used for coastal erosion management in Ghana. The thesis has five objectives to answer the research questions:

(1) Review global coastal management approaches and investigate the application of coastal management strategies (hold the line, advance the line, managed realignment, and no active intervention policies) along the coast of Ghana.

(2) Mapping and assessment of the national spatial distribution of different coastal infrastructures implemented along the coast of Ghana.

(3) Estimate and map the integrated coastal vulnerability of the coast of Ghana and implications for future infrastructural developments.

(4) Investigate shoreline response to groyne fields in Cape Coast, Ada, and Blekusu Phase I and highlight the environmental impacts.

(5) Investigate the socioeconomic impacts of coastal infrastructure on coastal communities in Ghana.

1.6 **Significance of the Study**

Coastal hazards such as flooding and erosion are expected to increase in frequency and intensity in tandem with sea-level rise (IPCC, 2022, 2021). These events have destructive consequences for coastal communities and the impacts are expected to be severe for developing countries with low-lying coasts such as Ghana, increasing coastal vulnerabilities.

The availability of up-to-date and reliable information on coastal infrastructure is fundamental to supporting coastal management decision-making regarding the review of coastal adaptation (Boak & Turner, 2005; Dolan, Fenster & Holme, 1991), and also for coastal real estate evaluations (Linham & Nicholls, 2010; Oppenheimer et al., 2019; Tol et al., 2008). Understanding the morphological and shoreline changes will inform the type of coastal management infrastructure and policies.

Knowledge of contemporary research is essential to understand coastal engineering best practices in integrated coastal zone management (Hughes, 1993), and to enable coastal planners to review their coastal management strategies to adapt to climate change (Mycoo & Chadwick, 2012), to change to adaptive and dynamic coastal management and invest in nature and nature-based coastal infrastructure (Cohen-Shacham et al., 2016; Powell et al., 2019; Bouw & Eekelen, 2020; Bridges et al., 2021). Emphasising the land-sea interactions is essential to assist coastal managers to align their short-term, medium-term, and long-term plans in the face of increasing climate change, increasing sea-level rise and overpopulation, and increased human anthropogenic activities.

In addition, social vulnerability assessment is important to highlight the pitfalls of hard engineering on coastal communities and is very essential to argue quantitative discovery and engage stakeholders. Stakeholder engagement is critical in integrated coastal zone management. The research contributes towards Sustainable Development Goals (SDGs) specifically; SDG 11(Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 17 (Partnerships for goals) thus contributing to the United Nations (UN) Agenda 2030. Since coastal adaptation is a largely capital-intensive and privately profitable niche, SDG 17 is central to coastal adaptation, fostering South-South and Triangular Cooperation.

1.7 **Delimitations of the Study**

Coastal areas are dynamic areas that change from time to time. Similarly, the construction of coastal infrastructure is a continuous process. At the time of the study (January 2000 - December 2022), there were approximately 12 groyne fields along the coast of Ghana. The extent of this infrastructure may change anytime as new infrastructure is implemented, improved, maintained or demolished. In addition, due to limited financial and time resources, there was an arbitrary decision to focus on three major groyne fields.

1.8 Limitations of the Study

Coastal areas are dynamic areas that change from time to time. Time challenges, data losses, and challenges with computing power and electricity load-shedding were common during the study. In addition, due to time limitations, only short-term monitoring was conducted within a period of one year (January – December 2022). However, for short-term studies, at least five years are necessary to give sufficiently detailed information on shoreline and beach responses to installed coastal defences. In addition, the external factors of social, cultural and environmental conditions beyond the researcher significantly impacted the study approach and outcomes of socioeconomic impact assessments.

1.9 Definition of Terms

The majority of definitions used in this thesis are based on UK SMPs (DEFRA, 2006a, 2006b), coastal engineering processes (Reeve et al., 2004, p. 184), the design of groynes in coastal engineering (Kraus et al., 1994; Kraus & Rankin, 2004), the design, monitoring, and maintenance of narrow-footprint groynes (Simm et al., 2020), and other texts on engineering with nature (Bouw & Eekelen, 2020; Bridges et al., 2021; Cohen-Shacham et al., 2016).

Adaptation: Adjusting to new conditions in a way that makes individuals, communities or systems better adjusted to the adverse impacts of climate change (Swanepoel & Sauka, 2019; Mycoo & Chadwick, 2012).

Advance the line: A shoreline management plan policy to build new defences on the seaward side of the existing defence line to reclaim the land (DEFRA, 2006a).

Beach nourishment: The artificial replenishment of a beach with suitable sediment from another source to artificially stabilize the beach and control coastal erosion (Bridges et al., 2021; Capobianco et al., 2002; Klein et al., 2001).

Coastal hazard: A physical phenomenon (e.g., flooding, tsunami, hurricane), that exposes a coastal area to the risk of property damage, loss of life, and environmental degradation (Adger et al., 2005).

Coastal resilience: The ability of socio-ecological systems to absorb and recover from disturbances, and establish a new equilibrium position by retaining or even regaining essential structures, processes or functions (Powell et al., 2019; Adger et al., 2005).

Managed realignment: A shoreline management policy in which the shoreline position is allowed to move backwards or forwards with management controlling or limiting movement (DEFRA, 2006a).

No Active Intervention: A shoreline management plan policy that involves no investment in coastal defences, where vulnerable areas are left to erode naturally (DEFRA, 2006b; 2006a).

Shoreline Management Plan (SMP): A plan providing that shows what coastal adaptation strategy is applied to a specific area or region, consideration the large-scale assessment of the risk to people and the environment (DEFRA, 2006b; 2006a).

1.10 Organisation of the Study

The thesis is organised into seven (7) chapters following the research objectives. Chapter one (1) provides the introduction to the study and presents fundamental contextual information necessary to understand the background of the research, problem statement, purpose of the study, and justification for conducting the research, limitations and delimitations.

Chapter two (2) contains the systematic literature review of contemporary global coastal management strategies and coastal infrastructure typologies and implementation along the coast of Ghana. Coastal management strategies were discussed, and categorised under hold the line (HTL), advance the line (ATL), managed realignment (MR) and no active intervention (NAI) or do nothing approaches. Coastal infrastructure was discussed and classified into green, grey, and hybrid (combined green and grey) infrastructure. The methods for coastal monitoring were discussed and the major gaps in the implementation of the coastal management policy in Ghana were identified, the factors that contribute to the policy-practice disconnect were highlighted, and solutions were proposed to close these gaps.

Chapter three (3) presents the mapping and assessment of coastal infrastructure in Ghana. The maps of national coastal infrastructure distribution along the coast of Ghana were developed using geographic information system (GIS) and remote sensing (RS) to establish the different types of coastal infrastructure installed along the coast of Ghana with the objective to inform coastal management decisions and planning and reviewing of coastal adaptation policies. Results indicated dominant use of the HTL strategy using grey infrastructure, mainly groynes and revetments. Although there are no SMPs, the HTL policy is unarguably evident along the coast of Ghana.

Chapter four 4 estimates and maps the integrated coastal vulnerability of the coast of Ghana to climatic and natural factors by combining physical and socioeconomic variables using the Adaptive Hierarchy Process (AHP) methodology. Coastal vulnerability assessment is considered important to establish the current state of integrated coastal vulnerability, and advise on future coastal infrastructural developments in Ghana.

Chapter five (5) investigates the short-term beach responses to installed groyne fields at Cape Coast (Oasis Beach), Ada East, and Blekusu (Ketu South) using satellite-derived imagery to establish shoreline response at groyne fields and identify the environmental impacts of grey infrastructure.

Chapter six (6) provides analyse of the socioeconomic impacts of coastal grey infrastructure on artisanal fisheries along the coast of Ghana through expert in-depth interviews (IDI).

Chapter seven (7) provides the summary, conclusions, and recommendations to relevant stakeholders for policy action. In addition, the list of references cited in the thesis, and the appendices containing the supplementary figures and tables used in this research are presented.

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a comprehensive synthesis of the relevant literature on coastal management strategies and coastal infrastructure valid to address the research question and objectives of this research. This followed a comprehensive desk research and systematic review of global literature on coastal management policies and coastal infrastructure typologies. In doing so, frameworks, methodologies and research gaps were identified, pointing to the necessity of conducting this study. In addition, national coastal adaptation plans, national guides and international handbooks on integrated coastal zone management were used. Critical synthesis and benchmarking was made on contemporary practices vis a vis national implementation of coastal management in Ghana.

Reviews were also done on subthemes of this topic, including nature-based solutions and ecological engineering, coastal vulnerability assessments, urban costal development, marine spatial planning, environmental and socioeconomic impacts of coastal protection using hard-engineered infrastructure. In summary, this chapter discussed and summarised the existing body of knowledge on coastal management strategies which is important to help readers to understand the background and significance of this research.

One of the greatest global challenges facing coastal management in the 21st century is the adaption to climate-induced sea-level rise (SLR) and the associated coastal hazards such as coastal erosion and flooding. Tol et al. (2008) define adaptation as “the planned or unplanned, reactive or anticipatory, successful or unsuccessful response of a system to change in its environment”. In this regard, reactive (responsive) and proactive (anticipatory) approaches are often used in complementary to each other (Tol et al., 2008), but proactive adaptation approaches are based on the prediction of how ongoing processes may eventually unfold (Linham & Nicholls, 2010; Tol et al., 2008), and aim to respond to both current events and perceived future hazards before. Therefore, coastal managers must establish the appropriate coastal management approach and suitable coastal protection infrastructure to apply under different sea-level rise scenarios to protect the coastlines (IPCC, 2021, 2022).

2.1.Conceptual Framework

The concepts of “coastal management strategies”, coastal infrastructure typologies”, “climate change” and “human impacts” are central to this study. Many theoretical frameworks exist in research, including Integrated Coastal Zone Management (ICZM) (e.g. Wiafe et al., 2013), Ecosystem-Based Management (EBM) (Adaptation Community, 2021; Swanepoel & Sauka, 2019), Risk-Based Management, Sustainable Development Goals (SDGs) Framework (SDSN, 2012), and Climate Change Adaptation frameworks (Klein et al., 2001). Klein et al (2001) clearly outline that the iterative processes of (1) information development and awareness raising; (2) planning and design; (3) implementation, and; (4)

monitoring and evaluation are central to adaptation to climate change and variability.

This research used the ICZM framework by Anton et al. (2012) (Figure 1) was used. ICZM frameworks are important because they provide a holistic approach that integrates the natural and socioeconomic systems (Cantasano & Pellicone, 2014). The objective is to observe the coastal environment, study the impacts of natural and human action on the coastal environment, use the scientific component to investigate the environmental and socioeconomic impacts, and inform policymakers to make appropriate coastal management decisions.

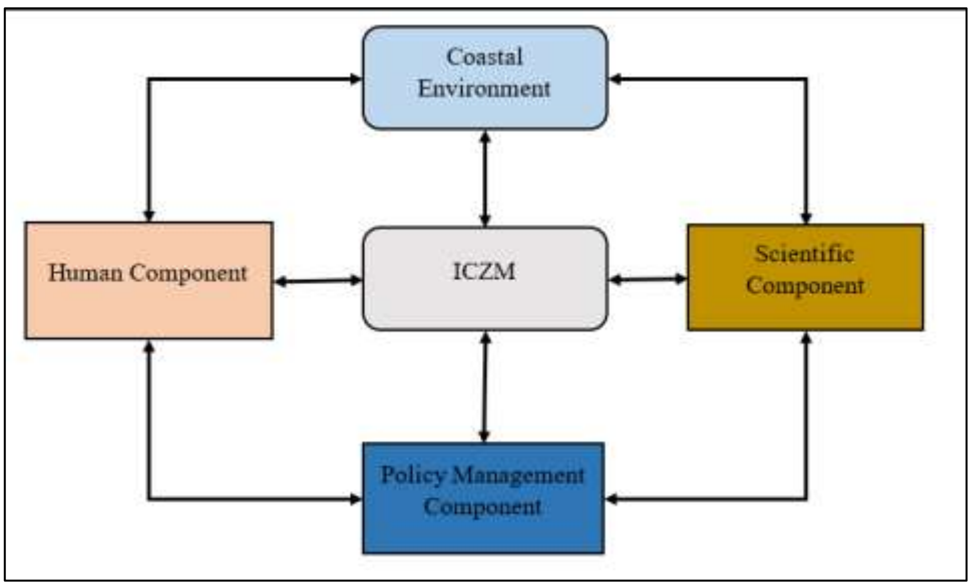

Figure 1: Conceptual framework for integrated coastal zone management (Anton et al., 2022)

The ICZM framework considers both natural, climate and human-induced factors and promotes the sustainable management of coastal areas by considering ecological, social, and economic factors (Cantasano & Pellicone, 2014). In Ghana, the ideal ICZM policy should seek to minimize conflict between coastal development objectives and socioeconomic needs by involving all stakeholders, including governments, universities and government agencies, laboratories, the private sector, non-governmental organisations and local communities (Wiafe et al., 2013).

2.2. Sea Level Rise and Associated Biogeophysical Effects

Sea-level rise is primarily a result of the upsurge in global warming which causes the melting of glaciers, increase in ocean water temperature and thermal expansion of ocean water, and local land subsidence (Wang et al., 2012). Subsidence can be classified as natural subsidence, e.g. earthquakes and tectonic movement, and anthropogenic subsidence (Oppenheimer et al., 2019) which includes illegal and unregulated mining (Luijendijk et al., 2018), and groundwater extraction (Erban et al., 2014). SLR escalates the frequency and severity of coastal storms, flooding, and coastal erosion (Oppenheimer et al., 2019; IPCC, 2021).

SLR biogeophysical effects include the intensification of the frequency and severity of coastal erosion along coastlines (Luijendijk et al., 2018), flooding, threats to coastal infrastructure (Department of Climate Change and Energy Efficiency, 2011; Nazarnia et al., 2020), coastal heritage sites (Sabour et al., 2020; Vousdoukas et al., 2022), the displacement of coastal wetlands and lowlands, destruction of ecosystems, increased salinisation of estuaries, coastal aquifers and contamination of both surface and groundwater (Basack et al., 2022; Moore & Joye, 2021), which contributes to water insecurity in coastal areas.

2.3. Coastal Erosion and its Impacts

Coastal erosion, or shoreline retreat, is the loss of coastal land (sand and bedrock) along the coast, caused by the effect of, among other factors, wind-driven waves, currents, storm surges, and tides (Browder et al., 2019). Coastal erosion is a serious coastal hazard affecting 75% of world coastlines (Pilkey & Cooper, 2014b; Rangel-Buitrago et al., 2018), global sandy coasts (Luijendijk et al., 2018; Mentaschi et al., 2018) and leads to devastating effects such as damage and loss of coastal lands and property (Appeaning Addo, 2021). Coastal erosion is also expected to increase rapidly with sea level rise (Linham & Nicholls, 2010; Pilkey & Cooper, 2014b) over time, and making shoreline change analysis increasingly indispensable.

2.4. The Need for Coastal Protection

Coastal protection is essential for safeguarding both coastal communities and natural ecosystems against coastal hazards. In this regard, coastal protection infrastructure reduces vulnerabilities (exposure and sensitivity) and improves the resilience (adaptive capacity) of communities. This is important considering that approximately 40% of world population live within 100 km of the coasts (Rangel-Buitrago et al., 2018). In West Africa, at least 80% of the regional population live in coastal areas, and approximately 25% of the population of Ghana lives in coastal areas (Alves et al., 2020).

2.5. Coastal Management Strategies

Coastal management has evolved substantially over time in response to climate-induced coastal changes, SLR scenarios (IPCC, 2021, 2022), and technological advancements in coastal infrastructure (Klein et al., 2001; Linham

& Nicholls, 2010; Tol et al., 2008). In literature, coastal management policies are generally classed into three categories, namely: (1) "Protect", "Accommodate", and "Retreat" approaches endorsed by the Intergovernmental Panel on Climate Change Convention (IPCC) (Klein et al., 2001; Linham & Nicholls, 2010; Tol et al., 2008), and; (2) Shoreline Management Plans (SMPs), coined in the United Kingdom by the Department of Environment, Food and Rural Affairs (DEFRA, 2006a, 2006b).

2.5.1. Protect, Accommodate, and Retreat approaches

The "protect" strategy can be implemented either as a reactive response to an event or proactive with planning to protect an area. Nevertheless, by nature, proactive responses have a reactive baseline, that is to say, the occurrence or knowledge of a hazard triggers planning. On the other hand, "retreat" and "accommodation", (Figure 2), employ managed realignment approaches to respond to flooding hazards (Klein et al., 2001; Tol et al., 2008; UNFCCC, 2006).

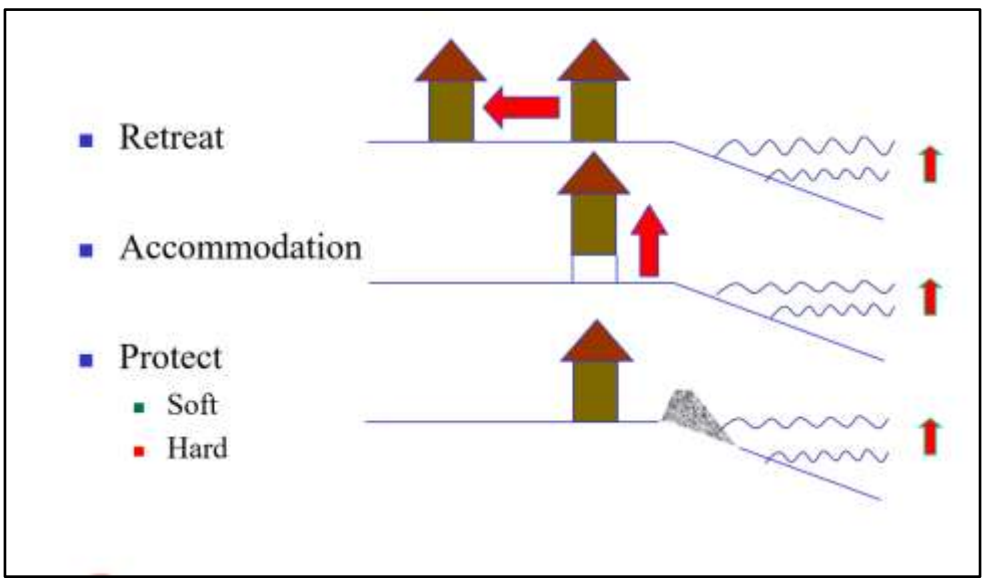

Figure 2: Illustration of the retreat, accommodate and protect approaches (UNFCCC, 2006)

In contrast to accommodation and (managed) retreat, the “protect” approaches may contribute to negative impacts such as impacts on coastal ecosystems and contributing to coastal squeeze.

2.5.2. The UK Shoreline Management Plans

The UKSMPs (strategies, policies or approaches) comprise of four major coastal management strategies for aligning the shoreline in response to coastal erosion, categorised into (1) hold the line (HTL); (2) advance the line (ATL); (3) managed realignment (MR); and (4) No active intervention (NAI) policies (Bridges et al., 2021; DEFRA, 2006a, 2006b). SMPs involve identifying policy options (HTL, ATL, MR, and NAI) for each section of the coast (DEFRA, 2006b, 2006a), but also developing and testing policy scenarios (DEFRA, 2006b; Kirby et al., 2021).

Hold the Line (HTL)

The HTL strategy entails building and maintaining the existing coastal defences in their current positions to maintain the current shoreline in the face of sea-level rise and coastal erosion (DEFRA, 2006a). This may include the use of both hard (groynes and revetments) and soft (vegetation) to hold the line. Despite the modern drive towards green and hybrid infrastructure, future coastal management is expected to be a mix of green and grey assets, and the HTL approach is projected to grow by at least 5.4% in four decades (Beasley & Dundas, 2021). However, the HTL strategy drawbacks include high capital costs, environmental impacts and long-term viability concerns, considering the impacts of sea-level rise and corrosion on hard-engineered structures (Tol et al., 2008; DEFRA, 2006a).

Advance the Line (ATL)

ATL involves building new defences seaward of existing structures to increase protection and reduce stress on current infrastructure (DEFRA, 2006a), and by doing so claim new land (Kirby et al., 2021), typically through beach nourishment, dune restoration, managed retreat by building islands or other infrastructure seaward. ATL is an extremely expensive approach that is rarely practiced, but it has been increasingly used in 21st century for mega coastal land reclamation (Sengupta et al., 2019, 2018, 2023). However, mega coastal land reclamation may have adverse environmental implications. Therefore, ATL should be done by conducting comprehensive assessments and engaging all stakeholders to establish potential impacts and benefits of land reclamation for stakeholders and the environment.

Managed Realignment (MR)

The MR approach involves management decisions to allow the shoreline to move backward but with options to direct its movement in certain areas (DEFRA, 2006a; Kirby et al., 2021). This entails options to remove structures in threatened built areas, moving people and infrastructure away from danger zones (or harm's way) (Dundon & Abkowitz, 2021; Dyckman et al., 2014), and surrender to natural processes. It includes land buyouts and coastal setback zones (Kirby et al., 2021; Sylaios et al., 2015) among other methods that may provide benefits to communities, e.g. from ecosystems services perspective (MacDonald et al., 2020). However, options like relocation require careful economic, social, and environmental assessments rendering all other options unsustainable to dictate relocating people and removal (demolition) of buildings from threatened areas. In many cases, managed retreat demands making difficult strategic decisions and if undertaken without a strategic vision, guiding frameworks, and capacity to manage the retreat, it may put communities at risk (Hanna et al., 2021), and MR may not always be successful, with underlying issues of governance, justice and compensation (Ajibade et al., 2022; Hanna et al., 2021).

No Active Intervention (NAI)

The NAI (or do nothing) does not require investments in coastal defences hence no action is taken to prevent intrusion by natural coastal hazards (Kirby et al., 2021). As a result, NAI is considered ideal in areas where the coastal land has low value, for instance, farmland, places with no people or occupied by few properties, or areas where coastal erosion rates of erosion are very rapid, posing engineering challenges to defend the coasts (DEFRA, 2006a). SMPs have since gained global application, but success is variable based on geographic regions, governance systems, and climatic factors such as relative sea-level rise (SLR).

The IPCC's "Protect", "Accommodate" and "Retreat" approaches, and options for their implementation have been thoroughly discussed in the literature (Klein et al., 2001; Linham & Nicholls, 2010). In this regard: (1) The "protect" strategy entails reducing the risk of an event by decreasing the probability of its occurrence; (2) the accommodate approach entails increasing the society's ability to cope with the effects of the event, and; (3) "retreat" entails reducing the risk of the event by limiting its potential effects (Klein et al., 2001; Linham & Nicholls, 2010).

In all consideration, proactive adaptation needs to be considered. Proactive adaptation comprises five generic objectives aimed at reducing a system's vulnerability, either by minimising risk or maximising adaptive capacity hence: (1) increasing robustness of infrastructural designs and long-term investment; (2) increasing flexibility of vulnerable managed systems; (3) enhancing adaptability of vulnerable natural systems; (4) reversing maladaptive trends, and; (5) improving societal awareness and preparedness (Klein et al., 2001; Tol et al., 2008). In developing countries, proactive coastal adaptation approaches that help to reduce threats from coastal hazards are often lacking.

2.6. Coastal infrastructure:

To implement coastal adaptation approaches, three fundamental types of coastal infrastructure can be identified in literature (Sutton-Grier et al., 2015) and categorised as: (1) Green (soft-engineered), (2) grey (hard-engineered), and (3) hybrid (integrated green and grey) infrastructure. Hill (2015) further described the four categories of coastal infrastructure designs (structural or static walls, dynamic or non-structural walls, static landforms, and dynamic landforms) that can be applied to specific contexts, thus providing a range of alternative implementation options. Categorising coastal infrastructure is essential to support coastal management decision-making when selecting coastal infrastructure, by highlighting the strength and weaknesses, impacts on coastal ecosystems, and long-term response to future sea-level rise of different coastal infrastructure typologies (Hill, 2015). Altogether, different technologies play a crucial role to reduce coastal vulnerability to climate-induced coastal hazards (Klein et al., 2001). In recent times, hybrid infrastructure approaches have become increasingly popular (Powell et al., 2019; Sutton-Grier et al., 2018), indicating a global transition from static, hold the line strategies using grey infrastructure toward dynamic, proactive adaption approach using green and hybrid infrastructure. The understanding of this information is important to inspire transition from reactive, static coastal management to proactive, adaptive management in Ghana.

2.6.1. Grey infrastructure

Grey infrastructure is identified throughout literature as the “traditional” hard-engineering form of coastal protection, unarguably in use for centuries (Hill, 2015; Sutton-Grier et al., 2015). This includes seawalls, revetments, groynes (or groyne fields), breakwaters, jetties, levees and other structures such as roads. Spalding et al. (2014) and Hill et al. (2015) echoes the historic dominance and popularity of grey infrastructure, however gradually losing its supremacy to green and hybrid infrastructure (Chávez et al., 2021; Powell et al., 2019; Sutton-Grier et al., 2015, 2018). In recent decades, there has been tremendous assessment and comparison of grey and green infrastructure, weighing the advantages and disadvantages of both stocks (Browder, Ozment, et al., 2019; Klein et al., 2001; Linham & Nicholls, 2010; Schoonees et al., 2019; Singhvi et al., 2022; Sutton-Grier et al., 2015, 2018).

Incontrovertibly, grey infrastructure provides effective coastal protection. The direct costs associated with grey infrastructure are well known in advance, with standardised, tried and tested designs and standardised implementation (Powell et al., 2019). Therefore, investors have trust and confidence in using grey infrastructure. Importantly, grey infrastructure provides immediate and effective protection against the impacts of SLR like flooding and coastal erosion (Hill, 2015; Klein et al., 2001; Powell et al., 2019; Sutton-Grier et al., 2015).

Nevertheless, grey infrastructure is not without setbacks as its effectiveness declines over time, and lacks adaptive qualities and ecosystem benefits (Sutton-Grier et al., 2015, pp. 141–142). It does not deal with the causes of erosion, reduces sediment supplies to downdrift areas, escalating coastal erosion processes, relocating and regenerating new erosion hot spots and eventually deteriorating coastal scenery (Rangel-Buitrago et al., 2018; Sutton-Grier et al., 2015). In addition, it lacks dynamic protection and ecosystem benefits (Sutton-Grier et al., 2015), contributes to coastal squeeze by limiting the natural landward migration of the shoreline (Pilkey & Cooper, 2014; Powell et al., 2019), and coastal scenery deterioration (Rangel-Buitrago et al., 2018; Sutton-Grier et al., 2015). Moreover, grey infrastructure promotes sediment starvation and erosion migration to downdrift areas, generating new erosion hot spots (Angnuureng et al., 2013; Mycoo & Chadwick, 2012).

The ecological impacts include genetic alteration of marine species and disruption of biodiversity (Powell et al., 2019; Sutton-Grier et al., 2015), non-colonisation by marine species such as fish, epibenthic organisms, and epibiota, and potential invasion by alien species (Bulleri & Chapman, 2010). Disruption of ecosystems and genetic alteration renders ecosystems unable to provide essential ecosystem services like food and nutrient recycling (Bulleri & Chapman, 2010).

In the absence of maintenance, grey stocks become vulnerable to climate change and substantial extra investment will required to sustain coastal defences in highly eroding areas (Kantamaneni et al., 2022). Given this, installed hard-engineered infrastructure could be integrated with nature-based solutions to improve resilience.

2.6.2. Green infrastructure

Green infrastructure are low technology and low-cost approaches that utilise nature-based solutions (NbS) (Bouw & Eekelen, 2020; Cohen-Shacham et al., 2016; Sutton-Grier et al., 2018), also known as nature and nature-based solutions (NNBS) or nature and nature-based features (NNBF) (Bridges et al., 2021), to reduce impacts of coastal hazards. Green infrastructure includes but is not limited to coastal habitats such as sandy beaches, dunes, mangroves, salt marshes, coral and oyster reefs, seagrass beds (seagrass meadows), and other marine habitats that provide both coastal protection and ecosystem services (Bouw & Eekelen, 2020; Bridges et al., 2021; CGIES Task Force, 2015; Spalding et al., 2014; Sutton-Grier et al., 2015, 2018). Salt marshes and mangroves protect coasts by attenuating wave energy, regulating water and sediment flow, reducing coastal erosion, and providing ecosystem services (Spalding et al., 2014).

Although green infrastructure is not as effective as hard-engineered approaches, it is acclaimed to be more sustainable and resilient to climate change impacts because it is less intrusive on the coast, helps to restore and maintain natural landscapes, and minimises environmental impacts while creating environmental opportunities (Mycoo & Chadwick, 2012; Sutton-Grier et al., 2015). Nevertheless, green infrastructure has been less tried in developing countries, creating a research and knowledge gap. In addition, there is evidence that specialised skills and technological capacity for soft-engineered solutions like mega beach nourishment are still lacking in developing countries (Bouw & Eekelen, 2020; Morris et al., 2019).

2.6.3. Hybrid infrastructure

In recent times, the integration of both green and grey assets, or hybrid infrastructure has gained popularity and support for its contribution to the attainment of sustainable development goals (SDGs) and climate change adaptation. Hybrid infrastructure is analogous with terms such as building with nature (BwN) (Bouw & Eekelen, 2020; Cohen-Shacham et al., 2016), nature and nature-based feature or engineering with nature (EwN) (Bridges et al., 2021), and living shorelines (Currin, 2019; NOAA, 2015) that contribute to both coastal resilience and climate (and coastal) change adaptation and mitigation, supporting societal objectives, and providing many opportunities for innovation (Sutton-Grier et al., 2015, 2018).

Recently, NbS have been in the spotlight, gaining popularity and global recognition for climate change adaptation and biodiversity restoration. Notably, at the recently concluded Climate Change Convention (CCC), Conference of Parties (COP27), NbS were accorded recognition and pledges for project funding towards climate change adaptation (IUCN, 2022). Despite this, the current setback for natural infrastructure is the lack of knowledge and effective governance for NbS (Morris et al., 2019), lack of standardisation, challenges with quantification of marine ecosystems protective capacity against coastal hazards such as coastal erosion, storm surges and coastal flooding (Sutton-Grier et al., 2015). For instance, it is difficult to establish a common metric and put a value on ecosystem co-benefits. In addition, while the availability of a broad suite of coastal adaptation approaches increases options for decision-makers, some regions have limited experience with newer coastal adaptation technologies like living shorelines and living breakwaters (Hill, 2015).

2.7. Summary of Research Gaps in Literature

Despite contemporary advances in coastal management research toward hybrid infrastructure, most of the coastal management technologies have been tested in developed countries. Therefore, there has been slow implementation of green and hybrid technologies in developing countries. Consequently, most developing countries have continued with grey infrastructure due to several factors. First, grey infrastructure requires less maintenance. Second, it is appropriate for the build and forget approach, favoured in many developing contexts due to their shrinking capital budgets. Third, the regional and development state of the country (developed or developing context), and policy differences affect the implementation of integrated infrastructure (Hill, 2015; Klein et al., 2001). For instance, some technologies (such as floodgates) are not suited to developing countries (Klein et al., 2001). In addition to technological limits, other limitations include social conflicts, economic, and financial barriers (Hinkel et al., 2018), (Figure 3).

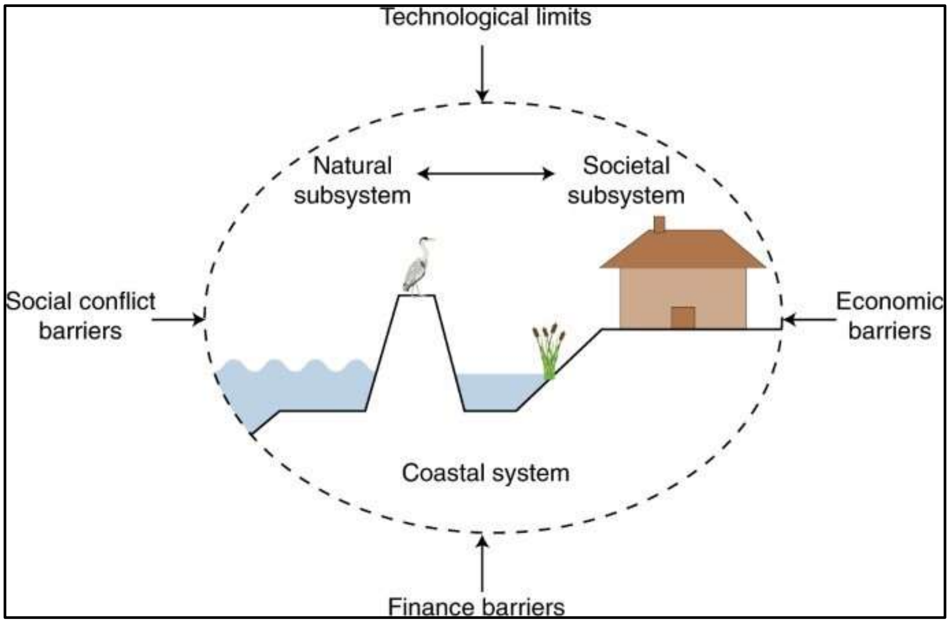

Figure 3: Limitations to coastal adaptation. Source (Hinkel et al., 2018)

In Ghana, for instance, coastal management is predominantly reactive, using hold the line strategies and grey infrastructure without a properly instituted SMP (Wiafe et al., 2013). In addition, the "build and forget" strategy is often favoured, evidenced by the uniform application of rock revetment, seawalls, and groynes.

The fundamental objective that arises is to establish the relation between coastal management policy and coastal infrastructure during the last two decades (2000-2022). In Ghana, for instance, the baseline of the year 2000 coincides with the construction of the Keta Sea Defence Project (1999-2004). In this regard, questions arise: Is there a trend in the transition from hard engineering toward hybrid infrastructure? How does this compare to global implementation of coastal adaptation infrastructure? Different stakeholders have different opinions on what works best and regional, cultural, and political barriers are certain. These knowledge gaps provided a basis for justification of this study.

2.8. Global Distribution of Coastal Management Literature

The country-wise assessment of the literature based on Scopus Database (Figure 4) indicates the combined global outlook of the coastal management literature (Charuka et al., 2023c). The analysis showed that at least 75% of the literature on coastal management policies and coastal infrastructure typologies and their subtypes represents research from developed countries, mainly the USA, Europe, and Australia. Developing countries constitute only 25%, with Africa representing less than 5% of this production. For instance, there are no records on ecological engineering innovation and implementation of nature-based infrastructure for coastal protection in Africa.

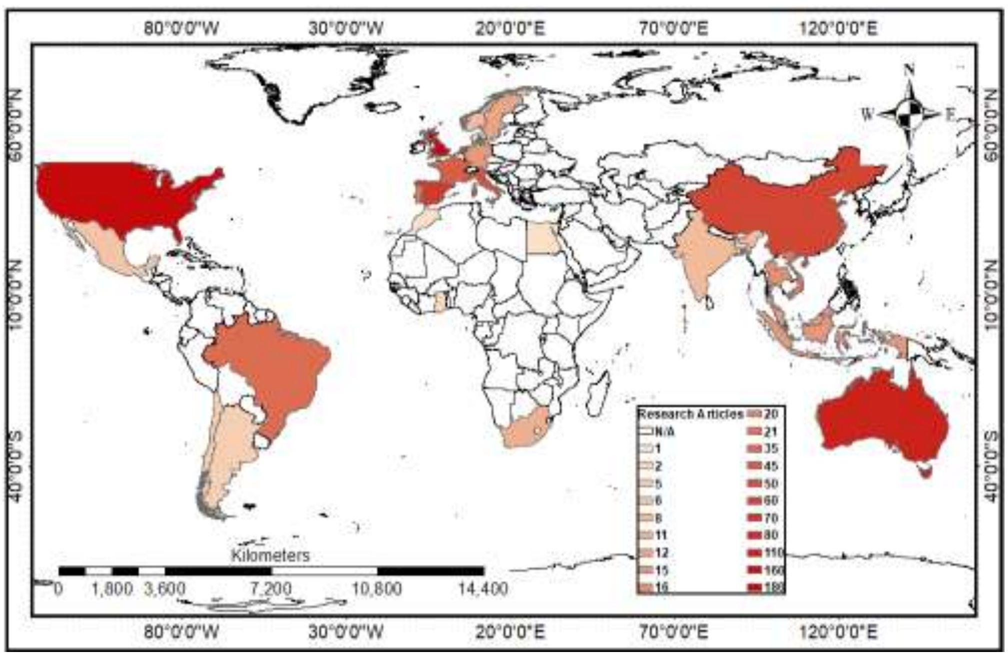

Figure 4: Global review of literature on coastal infrastructure and management policy (Charuka et al., 2023c)

Based on these findings, it can be concluded that although there has been significant advances in coastal management research around the world, research and projects on coastal management policy, including engineering with nature

(EwN), are still underdeveloped in developing countries. In most cases, beach nourishment has been discontinued due to excessive cost (Alves et al., 2020).

2.9. Summary of Coastal Management Approaches

Table 1 summarises the coastal management approaches established in the literature. Determining the appropriate coastal management strategy to apply for a section of the coast depends on factors such as the rate of erosion or shoreline change, the economic value of threatened land, the value of houses and businesses, the presence of road infrastructure, the value of habitats under threat, and the cost of intervention (DEFRA, 2006a, 2006b).

Table 1: *Summary of Coastal Management Strategies*

Category of management strategy	**Coastal management strategy or adaptation policy**	**Implementing technologies**
IPCC coastal adaptation approaches	1. Protect	1. Hard structural options: bulkheads, groynes, seawalls, revetments, levees, floodgates, dikes (Klein et al., 2001). 2. Soft options: Periodic beach nourishments, saltwater intrusion barriers, dune creation and recreation, wetland recreation, and restoration. 3. Indigenous methods: Afforestation, coconut leaf walls, Coconut fibre, stone units, wooden walls, and stone walls (Klein et al., 2001; Linham & Nicholls, 2010).
	2. Accommodation	1. Management preparedness for disasters. Involves creating and increasing society to cope and live with disasters. 2. Emergency planning through early warning systems. 3. Modification of land use through aquaculture and salinity-resilient crops (Klein et al., 2001). 3. Modifying building styles using various technologies like raising housed above ground, increasing the diameter of drainage pipes, improving drainage, and use of desalination plants (Klein et al., 2001; Linham & Nicholls, 2010).
	3. (Managed) Retreat	1. Establish coastal setbacks, 2. Relocate threatened buildings 3. Phased-out or no development in vulnerable areas, creating buffers, managed realignment (Klein et al., 2001; Linham & Nicholls, 2010).
United Kingdom Shoreline Management Plans	1. Hold the line	Building and maintaining the existing coastal defences in their current positions (DEFRA, 2006a, 2006b)
	2. Advance the line	Building new defences on the seaward side of existing structures to claim land, and reduce stress on current infrastructure (DEFRA, 2006a, 2006b).

Table 1, continued

	3. Managed Realignment	Removing structures in built areas under threat, relocating people away from danger zones, and surrendering to natural processes. Approaches include open space preservation, land buyouts, and land-use planning (DEFRA, 2006a, 2006b; Klein et al., 2001).
	3. No Active Intervention	This entails that no action is taken to prevent intrusion by natural coastal hazards, hence no investments are made in coastal defenses (DEFRA, 2006a, 2006b)
Proactive adaptation considerations	1. Increasing robustness of infrastructural designs and long-term investments	Changing the tolerance of loss or failure of investments (*e.g.*, by increasing economic reserves or insurance) (Tol et al., 2008)
	2. Increasing flexibility of vulnerable managed systems	Setting up midterm adjustments and/or reducing economic lifetimes (including increasing depreciation) (Tol et al., 2008)
	3. Enhancing adaptability of vulnerable natural systems	Managed retreat and Managed realignment (Tol et al., 2008)
	4. Reversing maladaptive trends	Introducing setbacks, enforcing development prohibition in vulnerable areas such as coastal floodplains, and eroding cliffs (Tol et al., 2008).
	5. Improving societal awareness and preparedness	Setting up early warning systems for coastal floods due to storm surges (Tol et al., 2008), and beach monitoring. Beach monitoring promotes a shift from a reactive to a proactive coastal adaptation. (Klein et al., 2001; Tol et al., 2008)

Coastal adaptation technologies have varying rewards and shortcomings and the implementation of coastal adaptation is not a "one size fits all". Globally, the success of coastal adaptation is variable due to differences in geography, level of development, and policy differences (Klein et al., 2001; Linham & Nicholls, 2010). Therefore, local factors largely dictate the choice and success of the appropriate coastal adaptation technology.

2.10. Categorisation of Coastal Infrastructure, Strengths, and Weaknesses

Categorising coastal infrastructure (Table 3) is essential to understand their strength and weaknesses, impacts on coastal ecosystems, and long-term response to future sea-level rise and coastal management decision-making (Hill, 2015).

Table 2: *Summary of Strengths and Weaknesses of Coastal Infrastructure Typologies*

Category of coastal infrastructure	Typical examples	Advantages	Disadvantages
Green Infrastructure or soft engineering	• Mangroves, • Salt marshes, • Coral reefs, • Oyster reefs, • Seagrass beds, • Beach recharge, • Sand dunes, • Dune creation, and recreation. • Wetland restoration	• They are acclaimed to be more resilient to climate change impacts (Sutton-Grier et al., 2015) and have the potential to self-recover after storm events (Hill, 2015). • Green infrastructure support ecosystem biodiversity, and hence ecosystem health. Ecosystems like mangroves and saltmarshes provide fisheries habitats (Morris et al., 2019), and improve primary productivity, water quality, and climate change mitigation through carbon sequestration and storage (Bulleri & Chapman, 2010; Hill, 2015; Sutton-Grier et al., 2015). • It minimises environmental impacts while creating environmental opportunities (Mycoo & Chadwick, 2012). • Ecosystems like sandy beaches and dunes provide various functions like storm protection, nutrient cycling, biological filtration and detoxification of coastal waters, acting as nesting and breeding sites, food stores, and nursery for marine organisms such as turtles, birds, and fish, and providing home and food to human beings, plants, and animals (NOAA, 2016; Pilkey & Cooper, 2014; Powell et al., 2019; Sutton-Grier et al., 2015). • Green infrastructure is less intrusive to the coast and helps to restore and maintain natural landscapes (Mycoo & Chadwick, 2012).	• They are not as effective as hard-engineered approaches and are associated with the nonlinearity of coastal protection and associated co-benefits, and success is variable on factors like the type of ecosystem, geography, and severity of storms (Hill, 2015; Powell et al., 2019; Sutton-Grier et al., 2015). • Due to the relative newness of green approaches, there is limited coastal planning expertise in the field (Sutton-Grier et al., 2015) • Green infrastructure projects, such as ecosystem restoration, require a substantial amount of space to implement, and such spatial requirements may not be feasible (Hill, 2015). • It is difficult to quantify coastal protection provided by natural systems (Powell et al., 2019; Sutton-Grier et al., 2015, 2018). • Green infrastructure takes a long time to be fully established to provide the necessary level of coastal protection (Hill, 2015). • There is limited expertise in coastal planning and engineering with nature (Bridges et al., 2021; Hill, 2015)

Table 2, continued

Grey Infrastructure or hard engineering	• Seawalls, • Revetments, • Groynes, • Breakwaters, • Storm surge barriers, • Closure dams, • Levees, • Jetties.	• They are fairly easy to construct using diverse materials like rocks or granite boulders. • They hold the line against coastal erosion (Mycoo & Chadwick, 2012) and provide immediate and effective storm protection (Hill, 2015). • They provide maximum protection against coastal erosion and flooding if well-designed (Alves et al., 2020; Linham & Nicholls, 2010). • They have a global implementation, known engineering standards, level of protection, and lifespan (Hill, 2015; Sutton-Grier et al., 2015). • They already have trusted experts in their design and implementation. Moreover, there is a clear understanding of their functionality and level of protection at different levels of protection (Hill, 2015).	• They lack dynamic protection from changing conditions such as sea-level rise, offer no co-benefits under normal conditions, and their protective capacity weakens with time (Hill, 2015). • They have high initial capital costs. • They hinder the natural sand deposition on the coast (Pilkey & Cooper, 2014) • They cause sediment starvation and erosion migration to adjacent sites (Mycoo & Chadwick, 2012). • They damage habitats during construction leading to loss, migration, and extinction of species (Powell et al., 2019; Rangel-Buitrago et al., 2018; Sutton-Grier et al., 2015). • Defenses like seawalls interfere with natural processes like habitat migration (Linham & Nicholls, 2010) and contribute to coastal squeeze by obstructing the natural landward migration of coastal systems (Linham & Nicholls, 2010; Mycoo & Chadwick, 2012; Pilkey & Cooper, 2014; Zhi et al., 2023). • They affect water colour, genera of organisms living in sediments, and are susceptible to invasion by alien species (Powell et al., 2019; Sutton-Grier et al., 2015).

Table 2, continued

Hybrid infrastructure	• Living shorelines • Groynes and beach nourishment • Buried revetments (Hughes, 1993) • Headland-controlled pocket beaches (Hughes, 1993)	• Hybrid infrastructure is trusted to leverage the advantages of both green and grey infrastructure with focus on sustainable protection and coastal resilience (Hill, 2015; Sutton-Grier et al., 2015, 2018). • Compared to hard-engineered structures, living shorelines have fairly minimum annual maintenance costs after major storm events due to the self-repair capabilities of natural stock. (Powell et al., 2019). • Compared to natural infrastructure, they have a greater level of confidence and trust for investors and stakeholders (Hill, 2015) • They can also be used in areas where there are space limitations.	• Since hybrid approaches are still growing, there is limited data and expertise in coastal planning and engineering with nature (Hill, 2015). • Hybrid infrastructure requires more research and innovation (Hill, 2015). • There is success variability in geography and coastal management policy (Powell et al., 2019; Sutton-Grier et al., 2015). • The costs vary with geographic location and are largely dependent on the frequency of maintenance (Powell et al., 2019). • There is limited data on the cost-benefit ratios for hybrid infrastructure projects (Hill, 2015). This undermines investor confidence and risk appetite.

Based on this analysis, the implementation of coastal protection infrastructure should be done in consideration of the impacts on adjacent landscapes, coastal resilience and sustainability issues.

2.11. Strategies for Coastal Monitoring

Coastal monitoring is essential for identifying and assessing coastal hazards and coastal ecosystems' health and changes over time. In this regard, coastal resilience can be improved by tracking coastal processes and identifying changes and potential hazards. Various methods and technologies are used for coastal monitoring, including satellite imagery, unmanned aerial vehicles (UAVs), GIS surveys, beach profiling and video camera systems (Abessolo et al., 2023; Angnuureng et al., 2022, 2019).

Satellite imagery provides large-scale coverage and allows the assessment of changes in coastal landforms, vegetation, and other parameters like sea-surface temperature and waves. Globally, satellite imagery has been applied to monitor the erosion of global sandy beaches (Mentaschi et al., 2018; Vousdoukas et al., 2022). Likewise, in Ghana, satellite imagery and remote sensing has been applied extensively for coastal monitoring (Appeaing Addo et al., 2012, 2020; Brempong et al., 2023; Jayson-Quashigah et al., 2013), albeit at micro scales. Similarly, UAVs or drones have been used to conduct site-specific studies (Angnuureng et al., 2013, 2019; Brempong et al., 2021; Jayson-Quashigah, 2019). Although these technologies have been applied, national studies using satellite imagery are often hindered by cloud presence along the coast.

Geographic Information Systems (GIS) combine spatial data with attribute data, enabling the creation of detailed maps and analysis of coastal features, such as coastal erosion rates and land use changes. The combination of satellite imagery and powerful, cloud-based GIS has also been used to map the land reclamation of major cities (Sengupta et al., 2018, 2023). In Ghana, GIS and RS have been applied for mapping shoreline dynamics using CoastSat toolkit (Carpenter, 2021) and investigating subsidence and flooding of the Volta using satellite-derived digital elevation models (DEMs) topography (Brempong et al., 2023).

2.12. Coastal Vulnerability Assessments

The Coastal Vulnerability Index (CVI) is useful for identifying high-risk areas, most susceptible to various hazards, such as sea-level rise, coastal erosion, or storm surges and supports policymakers and planners in prioritising areas for making interventions. The CVI integrates various physical, environmental, and socioeconomic factors to assess and quantify the coastal vulnerability of a specific area. The CVI helps planners and communities to understand the extent to which climate change affects coastal communities, ecosystems, and coastal infrastructure, thus enabling the development of adaptive strategies and improving disaster preparedness and disaster risk preparedness. For instance, at-risk communities can be supported to implement early warning systems, evacuation plans, or infrastructure improvements to reduce potential impacts and losses during a disaster. Moreover, the CVI can inform land-use planning and contribute to identifying areas for coastal development, conservation of ecologically sensitive areas, or implementing coastal setbacks for erosion-prone shorelines.

In the wake of increasing SLR and severity of coastal hazards, coastal vulnerability assessments are critical to understanding the risks and challenges faced in coastal areas. The nexus of SLR and human anthropogenic impacts on coastal topology (Bush et al., 2001; Erban et al., 2014) has also contributed to increasing the vulnerability of coastal areas to hazards. A number of national coastal vulnerability assessments have been undertaken for Ghana (Boateng et al., 2016; Wiafe et al., 2013) and specific areas like Accra (Appeaning Addo et al., 2008), but national assessments have not been conducted in the past seven years, creating the area research gap.

Overall, coastal vulnerability assessment provides the foundation for informed coastal management decision-making for risk reduction and sustainable coastal development and to ensure coastal resilience.

2.13. Socioeconomic Implications of Coastal Grey Infrastructure

Despite the primary objective of grey infrastructure to safeguard coastal communities and properties, these structures can also pose significant environmental and socioeconomic pitfalls as has been identified in research (Brayshaw & Lemckert, 2012; Cooper & Pilkey, 2012; Rangel-Buitrago et al., 2018). Coastal infrastructure has notable social and economic impacts on real estate investment and insurance, coastal tourism and social and environmental impacts.

The level of coastal protection affects real estate investment risk and insurance. Coastal real estate is vulnerable to erosion, storm damage, flooding, inundation, and consequential insurance risk (Valerie, 2013). In this, hard-engineered coastal protection contributes to reducing coastal risk and increasing property values by mitigating the risks of coastal hazards and helping to maintain or even increase the value of coastal properties in vulnerable coastal areas, thus increasing investment security for coastal properties protected by these infrastructures. Similarly, hybrid infrastructure aims to integrate both hard and soft stocks to improve coastal resilience

(Browder, Gartner, et al., 2019; Powell et al., 2019; Singhvi et al., 2022; Sutton-Grier et al., 2018).

Similarly, many coastal regions heavily rely on tourism (sea, sun and sand) as a significant component of the local economy. Hard-engineered coastal infrastructure can either enhance the appeal of a coastal area by protecting beaches and waterfronts, attracting more tourists, and boosting the local tourism industry or it can reduce the aesthetic of the beach reducing the local tourism economy (Bush et al., 2001; Pilkey & Cooper, 2014b, 2014a).

Hard-engineered coastal structures can alter coastal ecosystems and natural processes thereby affecting natural habitats and biodiversity, and disrupting natural sediment flow which contributes to increased coastal erosion (Brayshaw & Lemckert, 2012; Cooper & Pilkey, 2012; Jackson et al., 2012; Rangel-Buitrago et al., 2018; Smith et al., 2012). Therefore, there is a need to strike a balance between coastal protection and ecological resilience since most communities rely on habitats for livelihoods.

Coastal infrastructure developments directly or indirectly affect fishing and aquaculture. Grey infrastructure may either disrupt traditional fishing grounds or create new opportunities by providing sheltered areas for aquaculture activities. In many cases, construction may destroy breeding grounds, leading to species migration or extinction of species. To ensure long-term sustainability, proper environmental impact assessments must be undertaken, accounting for environmental and long-term sustainability factors.

2.14. Future considerations in coastal adaptation

In recent years there is a contemporary drive for transitions from grey to green and hybrid coastal infrastructure (Powell et al., 2019; (Bow & Eekelen, 2020; Cohen-Shacham et al., 2016; Sutton-Grier et al., 2018). At the same time, coastal management in developing countries like Ghana remains dominated by hold the line strategies using coastal grey infrastructure. Mostly, the success of coastal adaptation is variable from place to place and local factors largely dictate the choice of the appropriate coastal adaptation technology (Linham & Nicholls, 2010). Other key implementation success factors are stakeholder engagement, public education, and awareness (Bridges et al., 2021; Cohen-Shacham et al., 2016; Klein et al., 2001; Linham & Nicholls, 2010).

2.15. Hybrid infrastructure, scalability, and the Future of Coastal Adaptation

The integration of green and grey infrastructure is essential to enhance coastal resilience (Bridges et al., 2021; Browder et al., 2019; Powell et al., 2019; Sutton-Grier et al., 2015, 2018; Waryszak et al., 2021). Contemporary research on coastal infrastructure is increasingly hybrid-infrastructure centred, e.g. living shorelines (Currin, 2019; NOAA, 2015), BwN (Bouw & Eekelen, 2020), EwN (Bridges et al., 2021; Currin, 2019), and NbS (Chee et al., 2021; Cohen-Shacham et al., 2016; Narayan et al., 2016; Sutton-Grier et al., 2015, 2018). Notably, NbS have taken centre-stage during the past decade in both research and policy-making (2012-2022), (Morris et al., 2019). Evidently, during the 2022 Climate Change Convention (CCC), Conference of Parties (COP) 27, an initiative was accorded to coordinate global efforts to address climate change, land and ecosystem degradation, and biodiversity loss through NbS (IUCN, 2022). Moreover, the United Nations Decade of Ocean Science for Sustainable Development (UN Ocean Decade) supports NbS through the UN Decade on Ecosystem Restoration proclaimed as the decade to "prevent, halt and reverse the degradation of natural ecosystems around the world, for the benefit of people and nature" (UNESCO-IOC, 2022). A study on the development of nature-based coastal defence strategy for Australia by Morris et al. (2019) established that improved scientific knowledge, effective governance, and social acceptance are key to upscaling NbS.

Although there are regional implementation challenges, developing countries may leverage decision-support tools at their exposure (Bridges et al., 2021; Cohen-Shacham et al., 2016; NOAA, 2015). In West Africa, hybrid infrastructure technologies such as beach nourishments have been applied at Ada, Ghana (Bolle et al., 2015), Gambia, and Nigeria, but discontinued due to high costs (Alves et al., 2020). Therefore, beach nourishment is usually problematic in developing countries because it requires periodic top-ups (Klein et al., 2001; Linham & Nicholls, 2010). In addition, the lack of both technology and knowledge on EwN or BwN contributes to minimum implementation. Linham & Nicholls (2010) rated that developing countries have a low degree of experience across different technologies ranging from artificial dunes creation and rehabilitation, storm surge barriers, wetland restoration, and managed realignment (Linham & Nicholls, 2010). To guarantee success and scale, the government can work with development partners to facilitate the implementation of integrated infrastructure and leverage resources, finance, technology, and know-how (Bridges et al., 2021; Browder et al., 2019; Currin, 2019; NOAA, 2015). Engaging policymakers in planning and execution accelerates success. Overall, dynamic coastal management should be considered as the first option before any attempt to consider hard-engineering options (Powell et al., 2019).

2.16. The Need for Institutional Reforms in Developing Countries

The success of any coastal management policy depends on governance and the engagement of public and private stakeholders and civil society in the short-, medium-, and long-term planning for adaptation. In developing contexts, most interventions may have lapsed their design time frames due to the inherent "build and forget" culture, hence the need for revision considering future sea-level rise projections. To improve coastal management policy, recommendations from regional studies (Alves et al., 2020) could help drive policy reforms if all stakeholders are involved. Adaptation is, by large, a social, political, and economic process (Tol et al., 2008). Therefore, there is a need for researchers to work with policy-makers and coastal communities to improve success since contemporary research indicates that bottom-up approaches are favourable and successful (Klein et al., 2001; Linham & Nicholls, 2010).

2.17. Chapter Summary

In this chapter, the major coastal management strategies were identified and discussed. Similarly, three distinct types of coastal infrastructure, advantages and disadvantages were discussed. Overall, there is a significant global advance toward hybrid engineering using nature and nature-based solutions. However, increasing sea-level rise and severe coastal hazards imply that the hold the line and hard engineering will likely continue to be implemented to protect many coastlines. To strike a balance, a mix of green and grey approaches was recommended, at least for the coming four decades.

Several gaps were identified concerning coastal management strategies in developing contexts, which necessitates an investigation of coastal management and infrastructure in Ghana. Despite the global advances towards dynamic coastal management, there is continued reactive implementation of coastal management strategies and the absence of established shoreline management plans has created a culture of build and forget, ad *hoc* implementation of coastal protection interventions. Due to the *ad hoc* implementation of hard-engineered infrastructure, it can be argued that, the hold the line strategy is prevailing. Unfortunately, the spontaneous use of grey infrastructure is linked to unsustainable impacts, mainly coastal erosion migration to downdrift communities, turning natural, stable shorelines into new erosion hotspots and thus complicating the entire coastal management function.

CHAPTER THREE

MAPPING AND ASSESSMENT OF COASTAL INFRASTRUCTURE FOR ADAPTATION TO COASTAL EROSION ALONG THE COAST OF GHANA

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Abstract

Globally, coastal managers are challenged to make informed decisions when selecting coastal infrastructure to respond to climate-induced sea-level rise and associated coastal hazards like coastal erosion and flooding. Classifying the types of coastal infrastructure permits the comparisons of their potential efficiency, environmental and socioeconomic impacts, and long-term response to sea-level rise. At present, information on coastal infrastructure implemented along the coastal area of Ghana is not known thus creating a research gap to catalogue this information. To achieve this, we combined satellite images from Google Earth Pro and the use of ArcGIS capabilities to conduct a national assessment of coastal infrastructure and its distribution along the coast of Ghana. Even though similar approaches have been applied in different geographic contexts, this article focuses on evaluating coastal infrastructure in Ghana. Results show that between 2000-2022, at least 110 km or 20% of the coast of Ghana has been protected using grey infrastructure distributed as groins 40 km (6.5%), revetments and seawalls 50 km (9%), and jetties and port breakwaters 20 km (4.5%). These do not include the numerous private recreational infrastructure that could increase coastal vulnerability. The increasing use of grey infrastructure, particularly seawalls, and revetments along the coast has adverse impacts on overall coastal evolution and causes socioeconomic challenges. This study supports coastal managers to review coastal policy and develop shoreline management plans for the coast of Ghana.

Keywords: Coastal infrastructure, sea-level rise, coastal erosion, grey infrastructure, Ghana

3.1. Introduction

Coastal infrastructure is fundamental to protect coasts against climate-induced sea-level rise (SLR) and associated coastal hazards such as storms, coastal flooding, and erosion. Consequently, coastal managers are challenged to plan to adapt to SLR scenarios (IPCC, 2021; 2022) by choosing the appropriate coastal adaptation policy (Hill, 2015; Powell et al., 2019; Sutton-Grier et al., 2015). In this regard, four generic coastal management policies or strategies can be used for coastal zone protection against erosion, namely, hold the line (HTL), advance the line (ATL), managed realignment (MR), and no active intervention (NAI) approaches as established by the United Kingdom (UK) Shoreline Management Plans (SMP) (DEFRA, 2006b, 2006a; Rangel-Buitrago et al., 2018). These policies can be implemented using any of the three categories of coastal infrastructure, that is, green (natural/soft), grey (hard-engineered), and hybrid (combined green and grey) infrastructure (Hill, 2015; Sutton-Grier et al., 2015).

Grey infrastructure or hard-engineered infrastructure has traditionally dominated shoreline protection, trusted for providing immediate coastal protection and standardised implementation (Hill, 2015; Sutton-Grier et al., 2015). However, contemporary trends in coastal protection support green and hybrid infrastructure because they provide both coastal protection, ecosystem services, and help to build the resilience of coastal communities (Bouw & Eekelen, 2020; Currin, 2019; Hill, 2015; NOAA, 2015; Powell et al., 2019; Sutton-Grier et al., 2018). The paradigm shift from hard engineering to green and integrated infrastructure has challenged coastal planners and managers to make decisions to balance coastal protection and sustainability. However, in Ghana, hold the line strategies and *ad hoc* implementation of coastal works still dominate, largely due to the absence of SMPs (Jonah et al., 2016; Wiafe et al., 2013) among other factors that contribute to increase coastal vulnerability in the wake of increasing SLR and the frequency and severity of extreme coastal hazards (Bongarts Lebbe et al., 2021; IPCC, 2021).

Indeed, SLR, as much as coastal erosion and flooding have emerged as global challenges of the 21st Century for coastal countries (Bongarts Lebbe et al., 2021). Coastal erosion management has generated into a developmental challenge, especially in developing countries. In West Africa, coastal erosion is a major regional developmental challenge that is responsible for the rapid loss of valuable coastal land and properties. It is estimated that, on average, at least $3.8 billion of coastal land is lost annually due to coastal erosion and flooding (World Bank, 2019). In Ghana, the coastline is eroding at an average rate of 2m/per year with some erosion hotspots experiencing erosion as high as 17m/year (Angnuureng et al., 2013). The impacts include damage to transport infrastructure, destruction of coastal land and houses (Appeaning Addo, 2021; Appeaning Addo et al., 2008), threatening port infrastructure and tourism (world heritage) infrastructure like castles and forts (Vousdoukas et al., 2022), and the destruction of natural ecosystems like wetlands, sandy beaches, and dunes (see Figure 5). Coastal erosion also escalates environmental migration and affects the livelihoods of coastal communities (Appeaning Addo & Appeaning Addo, 2016).

Figure 5: A photograph showing the impacts of coastal erosion on natural unprotected beaches (Charuka et al. 2023a).

The figure shows (a) A fast eroding beach at Atiteti beach, Eastern coast (b) Aftermath of tidal flood and severe erosion at Anlo beach, Western coast (c) Once a stable beach, the Brenu beach in Central coast is recently fast eroding, and (d) a threatened community at Ada Foa. at the Volta Estuary.

With approximately 50% of the coastline of Ghana vulnerable to sea-level rise (Boateng et al., 2016; Wiafe et al., 2013), coastal protection becomes a priority to protect coastal communities, land, and property against climate-induced coastal hazards such as flooding and coastal erosion. As a result, since the completion of the Keta Sea Defence Project (KSDP) in 2004, several sea defence projects (SDPs) were implemented along the coast to respond to severe coastal erosion. However, implementation of coastal defences primarily uses hold the line strategy and grey infrastructure for coastal protection without due regard to coastal sustainability aspects, and in most cases, this has caused coastal erosion migration, created new erosion hotspots, and complicated coastal management.

The sustainability of coastal infrastructure has taken centre stage in recent times, triggering rigorous weighing of the benefits and shortcomings of green and grey infrastructure (Hill, 2015; Powell et al., 2019; Sutton-Grier et al., 2018). Although grey infrastructure boasts immediate coastal protection and standardised engineering (Sutton-Grier et al., 2015), it has many unsustainable setbacks. Grey infrastructure causes coastal erosion migration to downdrift areas (Alves et al., 2020; Angnuureng et al., 2013; Appeaning Addo, 2015), restricts horizontal and vertical beach access thereby contributing to coastal squeeze and disappearing, and contributes to reducing beach aesthetics and local tourism (Pilkey & Cooper, 2014). Along the coast of Ghana, the construction of the port and seawall at Takoradi on the West coast, drastically altered wave patterns and induced coastal erosion to areas in Accra, Ada, and Anlo (Akyeampong, 2001). In addition, grey assets lack dynamic coastal protection (Hill, 2015; Powell et al., 2019; Rangel-Buitrago et al., 2018; Sutton-Grier et al., 2015), and are void of ecosystem benefits. These and many other drawbacks have prompted contemporary research and coastal adaptation policies to support natural and hybrid infrastructure that offers both protection and coastal resilience (Bouw & Eekelen, 2020; Bridges et al., 2021; Browder et al., 2019; Cohen-Shacham et al., 2016; Sutton-Grier et al., 2015).

Several SDPs have been implemented between 2004 and 2022 along the coast of Ghana and there are planned and ongoing projects (GIPC, 2020).

Apart from coastal protection infrastructure, coastal settlements are increasing due to population growth and rural-urban migration (GSS, 2021). Moreover, there are tourism and fishing structures that are not appropriately set up along the coast. During the past decade, new fishing harbour projects have been constructed as an economic drive to modernise fish landing sites, but also as a form of coastal protection for the surrounding communities. Nevertheless, despite their intended purpose, the situation has not improved and new areas are emerging as hotspots. One possible reason could be the fact that lessons learnt about the environmental effect of grey infrastructure on the coast, their efficiency, and their characteristics have not been given policy consideration.

In light of the increase in climate-induced coastal hazards and the implemented coastal developments, this research set out to investigate the extent of coastal infrastructure along the coastline of Ghana. The objective is to evaluate the current coastal management strategies implemented in Ghana, focusing on understanding the extent to which these strategies have been implemented and successful in mitigating coastal erosion, preserving critical habitats, or protecting coastal communities from hazards.

3.2.Materials and Methods

3.2.1. Study area descriptions

The coast of Ghana (*Figure 6*) extends from 6°06' N, 1°12'E at the border with Togo to 5°05'N, 3°06'W at the border with Cote D'Ivoire. However, for political administration, the 550km coast is divided into four coastal administrative regions, that is, Western, Central, Greater Accra, and Volta (Wiafe et al., 2013). The coast is divided into three geomorphic regions, namely Eastern, Central, and Western regions.

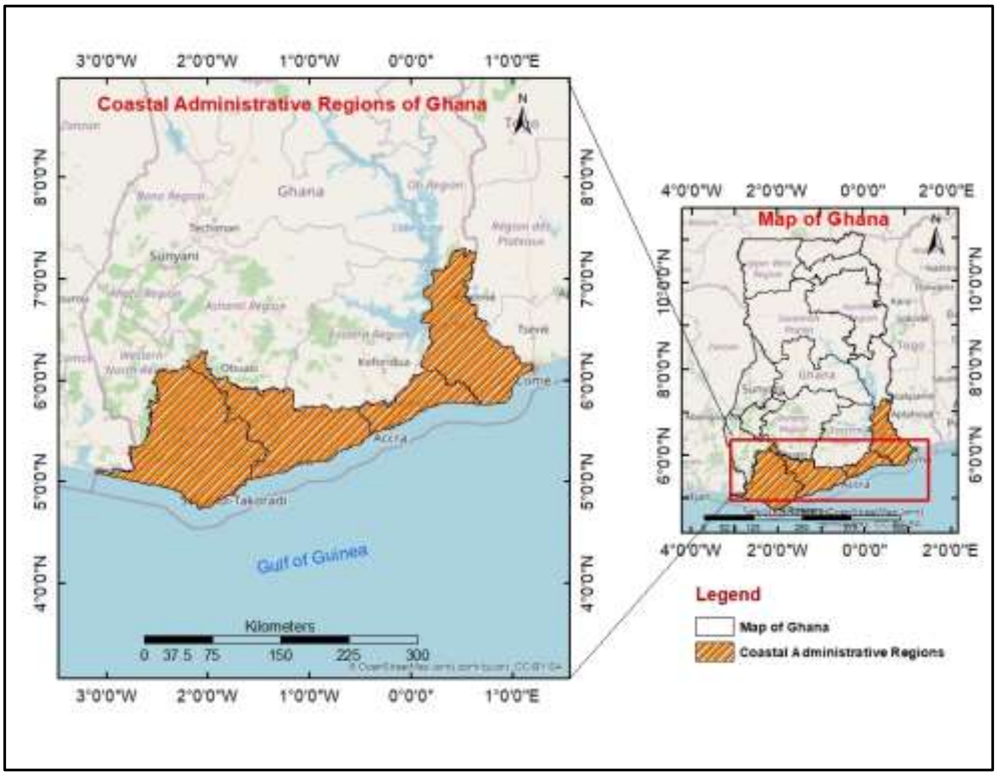

Figure 6: Map of Ghana showing the four coastal administrative regions (Charuka et al., 2023a)

The Eastern coast of Ghana Extends from 6°06' N, 1°12'E at the border with Togo (Aflao) to approximately 5° 43′ 0″ N, 0° 6′ 0″ E, at Prampram, and covers approximately 149 km (Armah, 2005; Boateng et al., 2016). It is characterised by sandy coasts, open sandy beaches that are exposed to relatively high-energy wind-driven waves and influenced by the deltaic estuaries of the Volta River (Wiafe et al., 2013). Therefore, the Eastern coast is relatively more vulnerable to coastal flooding and erosion than other sections of the national coastline. Consequently, the Eastern coast has had more coastal protection projects than other areas of the coast.

The Central coast is the longest geomorphic region and extends from Cape Three Point to Prampram. It is characterized by rocky coasts with bays, sand barriers, and coastal lagoons. The Western coast stretches from New Town at the border with Cote d'Ivoire to Cape Three Point, a distance of 85km. It is characterized by sandy coasts with gently sloping beaches (Armah, 2005; Boateng et al., 2016). The major human anthropogenic activities that contribute to coastal erosion and land degradation along the coast of Ghana are salt panning, mangrove deforestation (UNEP, 2007; Mensah, 2013), and sand mining (Jonah et al., 2016, 2017), damming and unregulated mineral mining (*Galamsey*), and the construction of sea defences (Angnuureng et al., 2013; Alves et al.,2020).

Currently, 25 coastal districts make up the coast of Ghana (Figure 7). Ordinarily, each coastal district (should) have the mandate for coastal erosion management (Wiafe et al., 2013) through multidisciplinary and stakeholder approaches to mitigate environmental and socioeconomic impacts of coastal hazards. However, in most cases, coastal infrastructural projects are implemented by the central government using *ad hoc* reactive approaches without properly studying coastal processes and environmental impacts leading to challenges like coastal erosion migration (Angnuureng et al., 2013; Appeaning Addo, 2021; Wiafe et al., 2013).

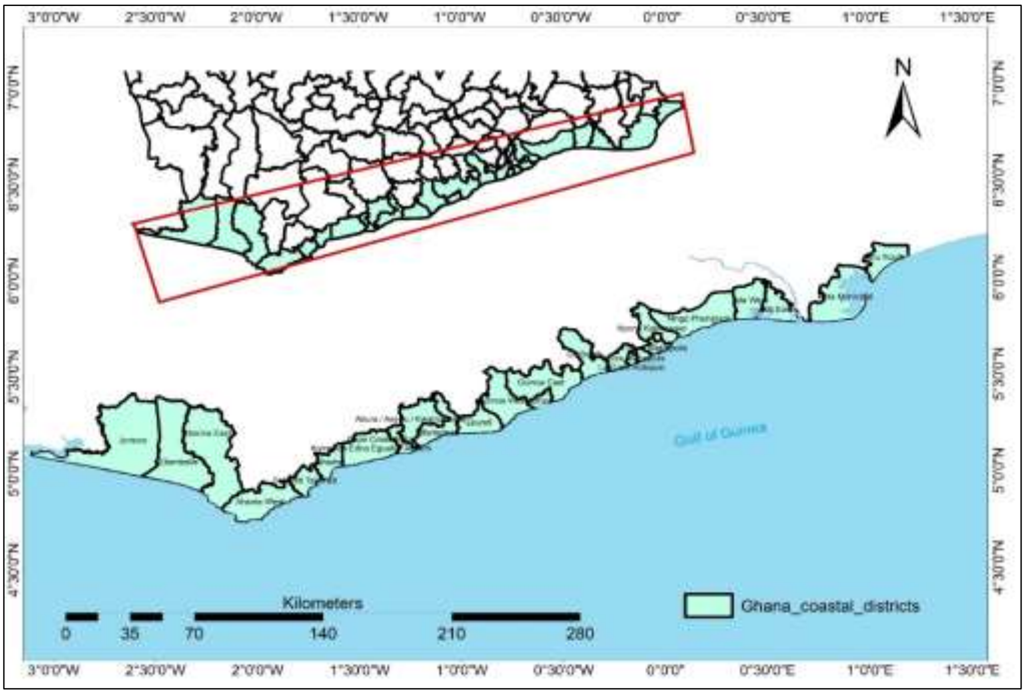

Figure 7: Map of the coastal districts of Ghana (Charuka et al., 2023a)

Given the implementation of coastal defences in most of the coastal regions over the last two decades, a comprehensive understanding of the spatial distribution of coastal protection projects is essential to support coastal management decision-making.

3.2.2. Data collection and processing

Data was collected using various methods including secondary reports, remote sensing, and in-situ observation to identify and classify coastal infrastructure and their attributes (e.g., date of construction, length, breadth, condition, etc.). From Google Earth Pro, the coastal grey infrastructure locations were digitised into Keyhole Markup Language (KMZ) placemark files, and classified into groynes or groyne fields (Figure 8), seawalls, revetments, and jetties (Figure 9).

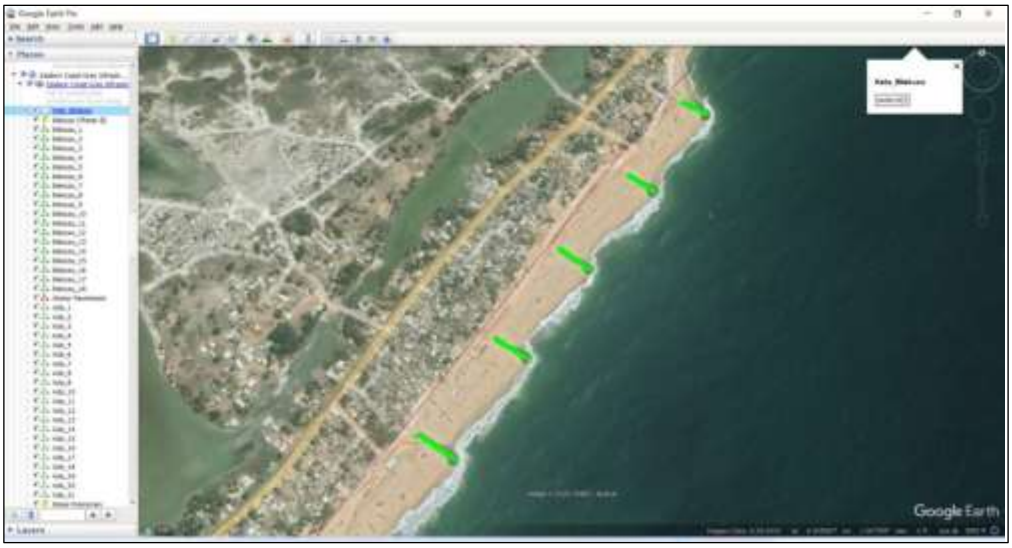

Figure 8: Screenshot showing digitisation of groyne fields at Blekusu (Charuka et al., 2023a)

In addition, the geographic coordinates attributes were retrieved into comma-separated values (CSV) files (See Appendix A and B), and imported into ArcGIS for processing.

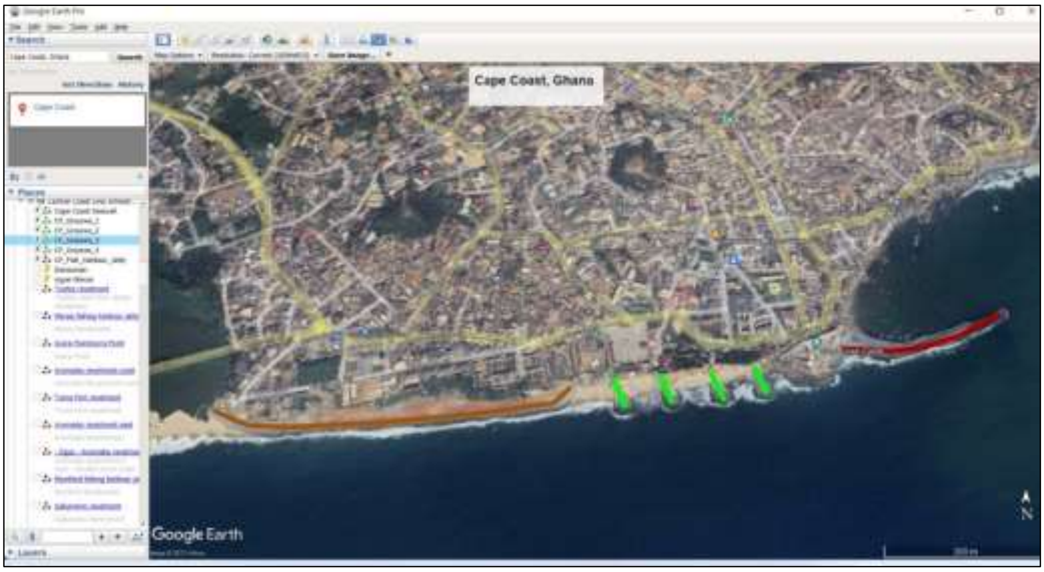

Figure 9: Screenshot showing digitising of the groyne field and seawall at Cape Coast. Source: (Charuka et al., 2023a)

In Ghana, the grey coastal infrastructure is mostly constructed using rock (granite boulders), with exceptions at port areas where concrete is used. The structures were mapped for each of the three geomorphic areas, Eastern, Central, and Western coasts. GIS provided a quicker and simplified methodology for time series analysis, permitting the gathering and analysis of satellite imagery, mapping, and visualisation of the national coastal infrastructure. In addition, original images (Figure 10) were also captured at sites using an unmanned aerial vehicle (UAV). Other primary data relating to the condition of defences were acquired through in-situ observation and interviews.

Figure 10: The groyne field at Blekusu captured using UAV in May 2022 (Charuka et al., 2023a)

The groyne field was implemented to stabilise the Blekusu shoreline against severe erosion. Onsite verification confirmed the types of coastal defences, structural changes over time, and the approximate dimensions and alongshore beach distance covered by hard structures (Table 3). In the table, the different types of coastal grey infrastructure are classified by coastal region and districts showing the totals per district and the alongshore distance covered by revetments, seawalls, and groyne fields.

Table 3: Summary of Different Types of Coastal Grey Infrastructure Classified by Coastal Districts

Coastal Area	District name	Types of coastal grey infrastructure								
		Groynes			**Revetments/seawalls**			**Jetty/Port breakwater**		
		Type	Total	Beach distance	Type	Total	Beach distance	Type	Total	Length
	Ahanta West	Rock	1	10	-	-	2,400	Rock	1	2,175
Western	Sekondi-Takoradi	Rock	1	10	Rock	6	10,000	Concrete	4	5,481
Coast	Shama East	Rock	1	10	Rock	3	7,000	-	-	-
	Komenda Edna Agufo	Rock	12	3,800	Rock	5	6,500	Rock	2	310
	Cape Coast Metro	Rock	4	600	Rock, Gabion	3	4,500	Rock	1	400
	Abura – Asebu	-	-	-	-	-	-	Rock	2	368
Central	Mfantisman	Rock	6	1,200	Rock	3	3,800	Rock	2	268
Coast	Gomoa West	Rock	1	10	Rock	1	500	Rock	1	375
	Gomoa East	Rock	1	10	Rock	1	500	-	-	
	Accra Metropolis	Rock	2	100	Rock	1,662	660	Concrete	1	393
	LaDade Kotopon	-	-	-	Rock	1	300	-	-	-
	Ledzokuku	Rock	2	100	Rock	1	300	-	-	-

Table 3, continued

	Tema Metropolis	-	-	-	Rock	3	5,000	Concrete	1	1,604
	Kpone Katamanse	-	-	-	Rock	1	2,700	Rock	1	268
	Ningo Prampram	Rock	21	6,500	Rock	2	300	-	-	-
Eastern Coast	Ada East	Rock	22	16,000	-		-	-	-	-
	Keta Municipal	Rock	20	2,600	Rock, Gabion	2	3,800	-	-	-
	Ketu South	Rock	18	4,000	-	-	-	-	-	-

At the time of this study, roughly 18 out of the 25 coastal districts had implemented coastal protection projects. Since grey infrastructure along the coast is mostly constructed using granite boulders, no further sub-classification was possible, e.g., wood, concrete or geotextile subclasses.

Data processing involved converting KML files in ArcGIS using the KMZ to Layer conversion tool. Other procedures included importing CSV files in ArcGIS, loading layers, creating shapefiles, and generating maps to visualise locations and the national distribution of coastal infrastructure along the coast of Ghana. Mapping the infrastructure was important to provide a national account and complete panorama of the current coastal infrastructure along the coast of Ghana, necessary to support coastal planning, coastal vulnerability assessments, and review of coastal adaptation plans and to end the *ad hoc* implementations of coastal protection as coastal management solutions in Ghana.

3.3.Results

3.3.1. Grey infrastructure distribution along the Eastern coast of Ghana

The coastal infrastructure locations were mapped according to the three geomorphic areas: Eastern, Central, and Western coasts. The results show that the Eastern coast (Figure 11) is dominated by groyne fields with varying field sizes, with five major groyne systems implemented at Ada, Ningo Prampram, Atorkor, Keta, and Blekusu.

The groyne field at Ada East comprises 22 groynes covering an alongshore distance of approximately 16 km (Bolle et al., 2015). The groynes have an approximate length of 90 m, and an inter-groyne distance of nearly 200m. At Atorkor, the groynes have an average groyne length of 80m, spanning 2.5 km of beach, and interspaced on average at 190m. Similarly, at Blekusu, the groyne field covers approximately 4km of beach, interspaced at approximately 190m. A total of 14 groynes have also been installed at the New Ningo Prampram and 7 groynes at Old Ningo covering a beach distance of approximately 3.5 km and 1.5 km, respectively. This highlights the trend of coastal hardening along the Eastern coast. Work in progress represents ongoing coastal protection projects.

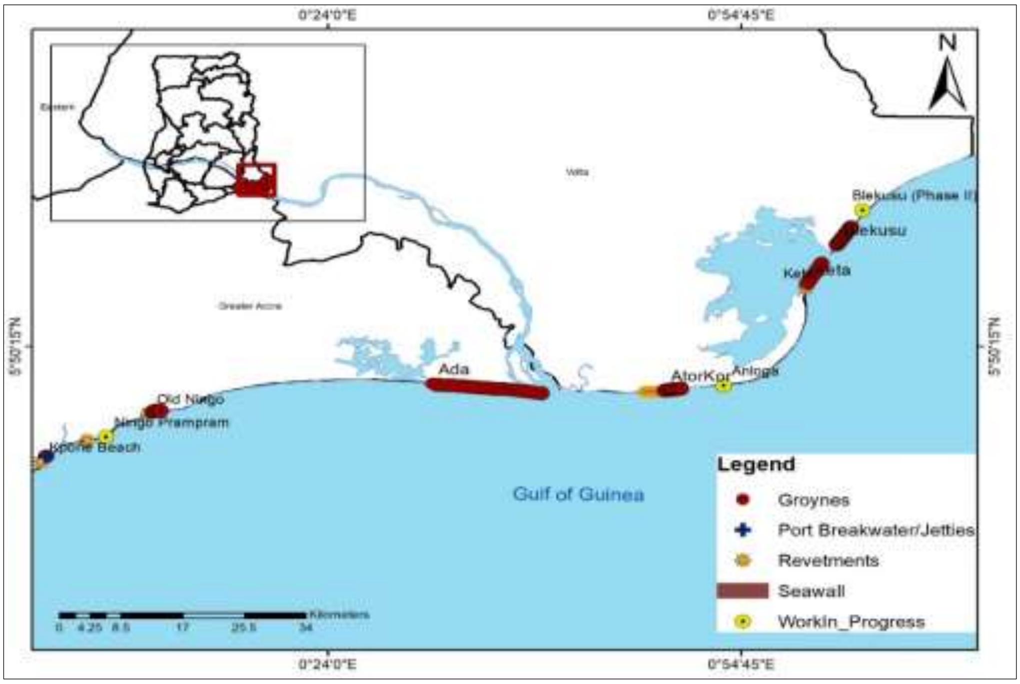

Figure 11: Grey infrastructure distribution along the Eastern coast of Ghana (Charuka et al., 2023a)

3.3.2. Grey infrastructure distribution along the Central coast.

Revetments are by large the dominant coastal grey infrastructure along the Central coast (Figure 12), Revetments are intermittently used to protect the coast from Elmina, Cape Coast, Anomabo, Glefe, and Sakumono, through to Accra and Tema areas. They are implemented solo and sometimes alongside other grey structures. In addition to revetments, groynes were implemented at Cape Coast, Anomabo, and Elmina. At Cape Coast (Oasis beach), the groyne field comprises four giant trapezoidal groynes with an approximate beach coverage of 0.6 km, groyne length of nearly 60 m, an approximate inter-groyne distance of 70 m, and an average height of 2.5 m. Work in progress represents ongoing coastal protection projects

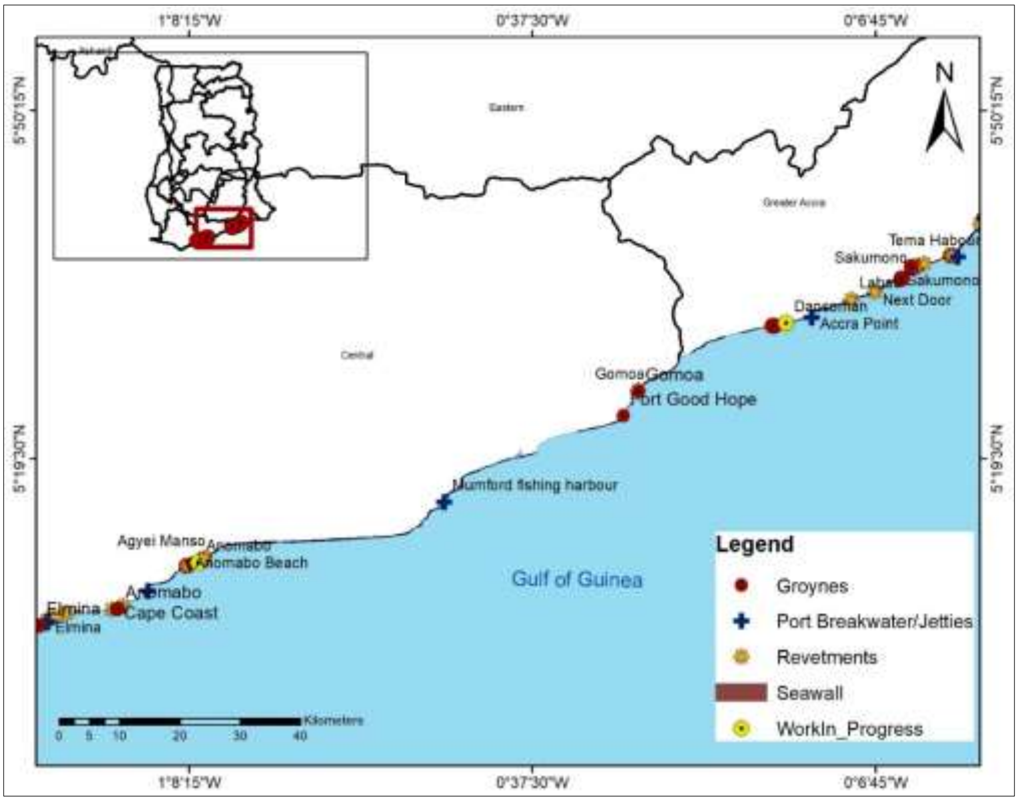

Figure 12: Grey infrastructure distribution along the Central coast of Ghana (Charuka et al., 2023a)

Despite their function to help build up the beach, coastal erosion is persistent between the groynes, seemingly invalidating the primary purpose, that is, to stabilise and build up the beach.

Adjacent to the groyne field at Cape Coast, a seawall was constructed covering a beach distance of approximately 0.8 km. The seawall stretches from Fosu Lagoon to Oasis Beach, completely closing and restricting access to the beach. Similarly, at Anomabo SDP, a groyne system of seven trapezoidal groynes was linked to a one-kilometre revetment to stabilise the Anomabo coast against severe coastal erosion.

3.3.3. Grey infrastructure distribution along the Western coast.

The Western region is the least armoured coast, with major coastal defences along the Axim and Sekondi-Takoradi foreshore and port infrastructure (port breakwaters and jetties) at Takoradi deep port and Sekondi-Takoradi Naval base. This coast experiences significantly low-energy waves and is comparatively less threatened by coastal erosion. Grey infrastructure is concentrated along the Axim and Sekondi-Takoradi areas. The Axim SDP and Sekondi-Takoradi seawall represent the major coastal projects along the Western coast (Figure 13).

However, despite offering immediate protection, the seawall has contributed to restricted beach access and the impacts on coastal local artisanal fisheries need to be fully investigated.

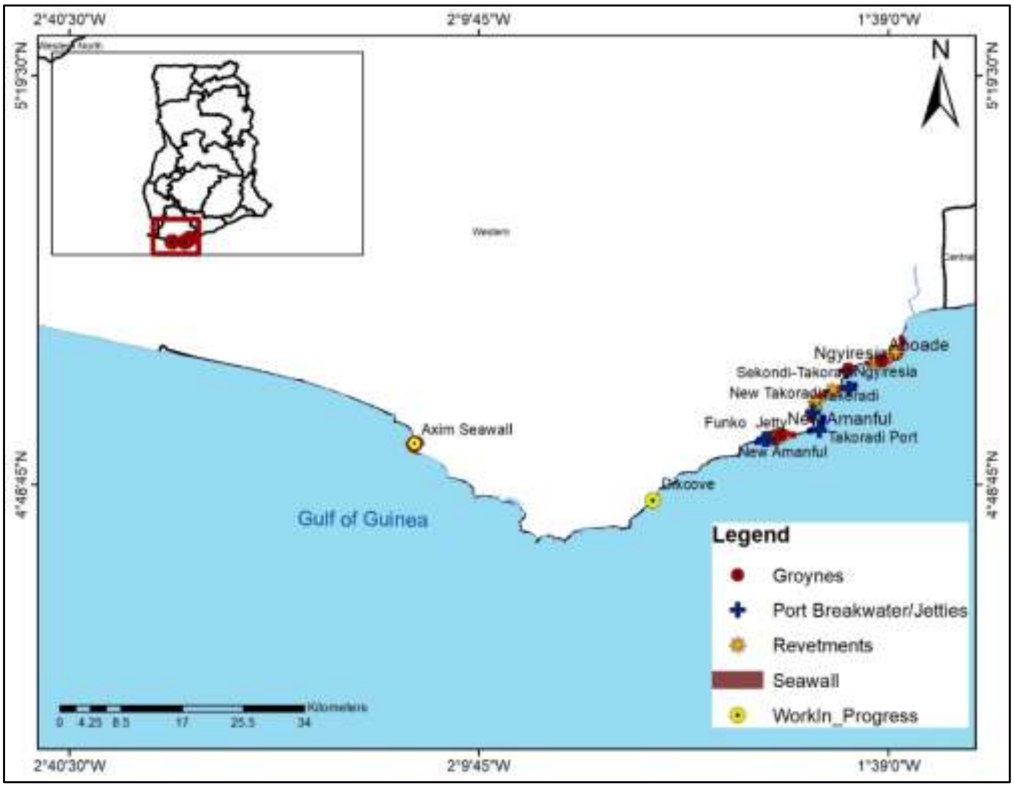

Figure 13: Grey infrastructure distribution along the Western coast of Ghana (Charuka et al., 2023a)

At Axim (Figure *14*), a 5 km sea defence project comprising seawall and revetments is near completion. Protect the community from ongoing tidal wave impacts, enhance beaches for recreation and fishing, and reclaim land for developing tourist facilities. In entirety, the Axim project comprises a combination of groynes, revetments, and breakwaters to shield the coastline and provide the needed protection (Charuka et al., 2023a). Additionally, it focuses enhancing fishing activities, and reclamation of land for the development of tourist facilities to support the local community.

Figure 14: Completion of the construction of the 5km Axim Sea Defence Project

3.3.4. Construction of new fishing harbours and future implications

At least 15 new fishing harbours are under construction along the coast, increasing the number of grey structures. Twelve constructions (Axim, Dixcove, Winneba, Senya Beraku, Elmina, James Town, Gomoa Fetteh, Moree, Mumford, Teshie, and Keta) commenced in 2012 with an estimated total construction cost of $200 million (Hydro International, 2012), and three new fishing harbours commenced in 2021, namely Osu, Mfantseman, and Otuam (Ghanaports, 2021), see Figure 15. These projects were rolled as a government economic drive to modernise fisheries production, provide sanctuary to fishing boats against strong waves, tides, and storm surges, but also to protect the communities at these areas.

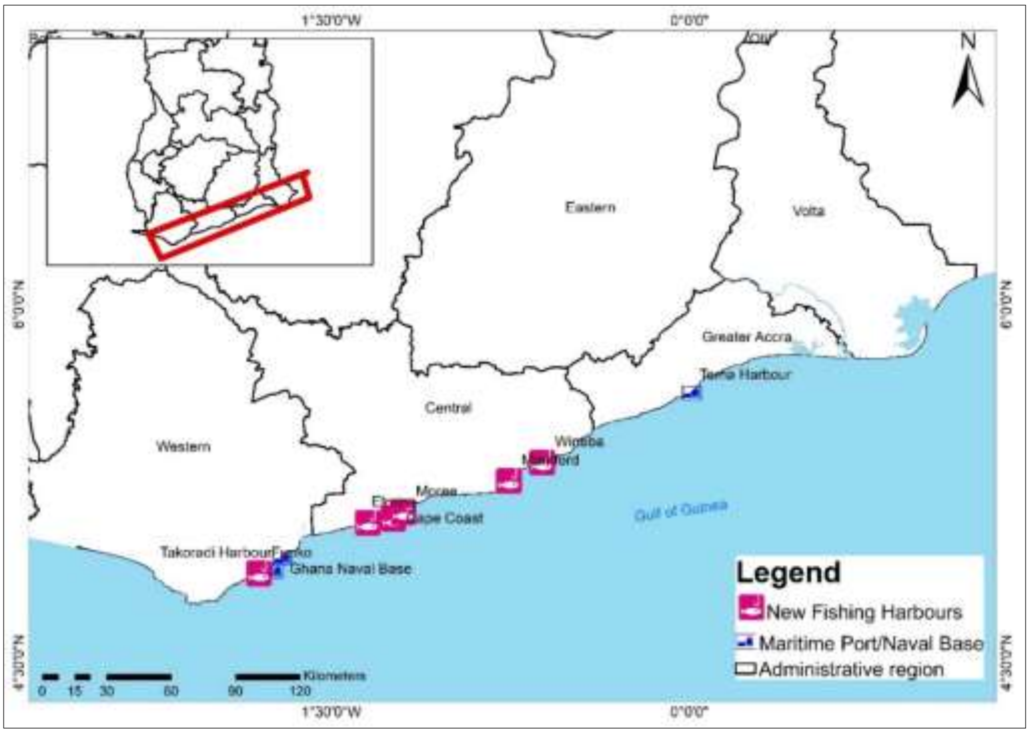

Figure 15: Ports and new fishing harbour infrastructure along the coast of Ghana (Charuka et al., 2023a)

The argument is that the construction of many new fishing harbours may significantly alter coastal processes and sediment dynamics, induce more coastal erosion to downstream communities, and create new challenges.

Among other impacts, the construction of port infrastructure is attributed to the destruction of coastal habitats, alteration of the coastal hydrology and wave patterns (Akyeampong, 2001), and coastal erosion migration to downdrift areas (Angnuureng et al.,2013). It is apparent that the dredging and construction of new fishing harbours will continue to worsen this trend and need further investigation.

3.3.5. Mangrove distribution (coastal green infrastructure) along the coast of Ghana

Mangroves are the most dominant green infrastructure along the coast of Ghana (Figure 16). Mangroves are omnipresent, especially in Ramsar sites such as the Muni Lagoon, Densu delta, Sakumo Lagoon, Songor Lagoon and

Anlo-Keta Lagoon (UNEP, 2007). They are also present in Benya Lagoon (Central coast), Amanzule Wetlands, Half Asssini, Ellembelle, and Whin Estuary (Western coast). Ghana has species of mangroves, namely *Acrostichum aureum, Avicennia germinans, Conocarpus erectus, Laguncularia racemose, Rhizophora harrisonii*, and *Rhizophora racemosa* (UNEP, 2007). Mangrove total area ranges from 137km^2 (UNEP, 2007) to 140km^2 and economic value of $6 million(Ajonina et al., 2014)

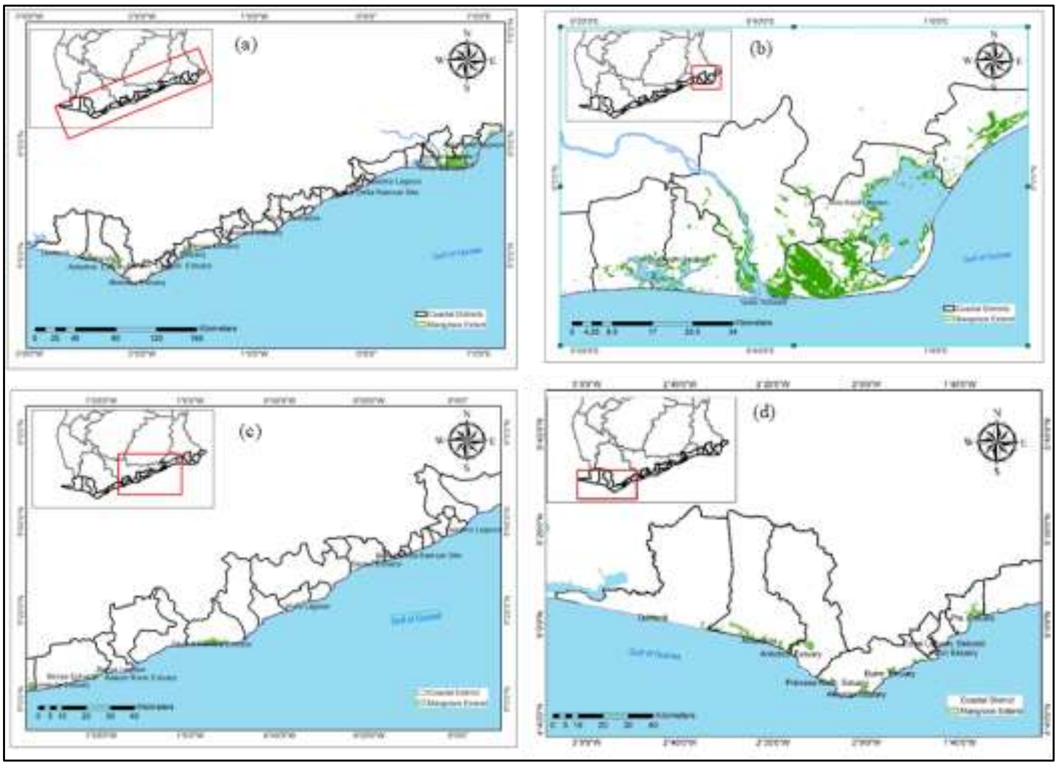

Figure 16: Mangroves extent along the coast of Ghana (a) entire coast of Ghana (b) Eastern coast (c) Central coast and (d) Western coast (Charuka et al., 2023a)

Mangroves are an important natural coastal ecosystem for coastal erosion and flooding protection. They are also central to providing ecosystem services to coastal communities, including the provision of timber, fuel wood, charcoal, and medicine. The protection and regulation functions of mangroves include coastal flooding, erosion, and storm control. Moreover, mangroves and saltmarshes provide many co-benefits such as improving primary productivity, provision of fisheries habitats, improving water quality, and climate change mitigation through carbon sequestration and storage (Sutton-Grier et al., 2015). The detailed research on mangroves in West Africa (UNEP, 2007) and along the Greater Amanzule Wetlands in Ghana (Ajonina et al., 2014) has been well documented. In Ghana, mangroves and other natural infrastructure provide a great opportunity for integrated infrastructure, including living shorelines, but implementation has been slow. Presently, natural and nature-based projects are being piloted using ecosystem-based adaptation, landscape management, and mangrove afforestation and reforestation, but the extent of these projects is yet to be appraised.

3.3.6. Assessment of the distribution of groyne fields along the coast of Ghana

In Figure 17, groyne systems are charted according to the geomorphic region and coastal district, based on the current state of the coastal protection. Results indicate that the majority and largest groynes fields were implemented along the Eastern Coast at Ada East (22 groynes), Ningo Prampram (21 groynes), Atokor (13 groynes), Keta Municipality (Six groynes), and Ketu South (18 groynes), (see Appendix B).

Despite serving their purpose, groyne fields along the Eastern coast are also linked to a chain of erosion migration (Angnuureng et al., 2013). In-situ findings show that since the implementation of the KSDP, coastal erosion has migrated to Blekusu, in Ketu South. After the implementation of the Blekusu (Phase I) coastal protection, new severe erosion hotspots are now being recorded at downdrift places like Agavedgzi, and Denu, creating new demands for coastal protection.

Region/District	# of groynes
Central	**27**
Accra Metropolis	2
Cape Coast Metro	4
Gomoa East	1
Gomoa West	1
Komenda Edna Eguafo	12
Mfantisman	7
Eastern	**82**
Ada East	22
Keta Municipal	19
Ketu South	18
Ledzokuku	2
Ningo Prampram	21
Western	**3**
Ahanta West	1
Sekondi-Takoradi	1
Shama	1
Grand Total	**112**

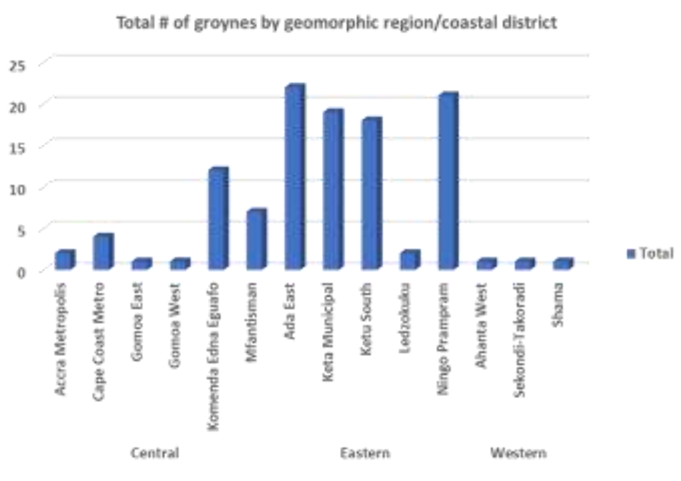

Figure 17: Statistics of groyne fields distribution along the coast of Ghana (Charuka et al., 2023a)

The concentration of groyne fields along the Eastern region is possibly linked to high erosion rates, hence the need to protect vulnerable coastal communities. In terms of cumulative beach coverage, groyne systems cover a distance of approximately 29 km on the Eastern coast compared to 5.1 km and 1.7 km for the Central and Western coasts respectively (Figure 18).

Region/District	Sum of beach coverage(Km)
Central	**5.1**
Cape Coast	0.6
Komenda Edna Eguafo	3.8
Mfantisman	0.7
Eastern	**29.1**
Ada East	16
Keta Municipal	2.6
Ketu South	4
Ningo Prampram	6.5
Western	**1.7**
Ahanta West	0.3
Sekondi-Takoradi	0.7
Shama	0.7
Grand Total of beach coverage	**35.9**

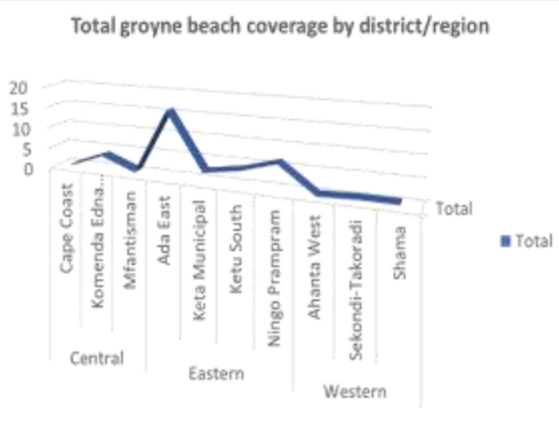

*Figure 18***:** Estimated groyne field beach coverage along the coast of Ghana

3.3.7. Assessment of the distribution of revetments along the coast of Ghana

Revetments are common along the coast of Ghana due to their simplicity and ease of construction using granite rock (Alves et al., 2020). The beach distance coverage by revetments (Figure 19) is charted according to geomorphic coast and coastal district, again, based on the current state of the coastal protection.

Region/Coastal district	Beach Coverage (Km)
Central	**20.86**
Accra Metropolis	0.66
Cape Coast Metro	4.5
Gomoa	0.5
Komenda Edna Eguafo	6.5
Mfantsiman	3.7
Tema Metropolis	5.0
Eastern	**5.0**
Keta Municipal	3.8
Kpone Katamanso	0.3
La Dade Kotopon	0.3
Ledzokuku	0.3
Ningo Prampram	0.3
Western	**23.4**
Ahanta West	2.4
Nzema East	4.0
Shama	7.0
Takoradi	10.0
Grand Total	**49.26**

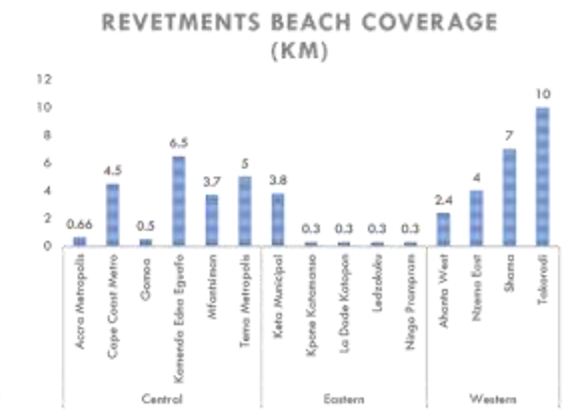

Figure 19: Beach distance coverage by revetments along the coast of Ghana (Charuka et al., 2023a)

Most of the revetments installed typically cover relatively long distances. Howeve r, despite their easy design and implementation, maintenance is required, but the maintenance plans of the installed infrastructure in Ghana are not transparent due to the lack of SMPs and budgetary constraints, factors which ultimately contribute to the faster deterioration of implemented assets.

3.3.8. Tourism infrastructure and demand for coastal protection

Tourism infrastructure (UNESCO World Heritage Sites, castles, forts, beach hotels, and resorts) is increasingly threatened by SLR, necessitating coastal protection along the coast of Ghana. In this study, we mapped 22 UNESCO World Heritage sites comprising 3 castles and 19 forts (Appendix D). These castles are Cape Coast Castle, St. George's d'Elmina Castle, and Christiansborg Castle. The forts include Fort Good Hope, Fort Patience, Fort Amsterdam, Fort San Sebastian, Fort William, and Fort James among others mapped in Figure 20 (a). In addition to castles and forts, the demand for coastal protection is also correlated to the increase in the number of beach-side tourism infrastructure (Appendix C). In this study, we identified a random sample of 100 beach-side resorts Figure 20 (b) which are vulnerable to coastal erosion and in need of coastal protection likely using grey infrastructure.

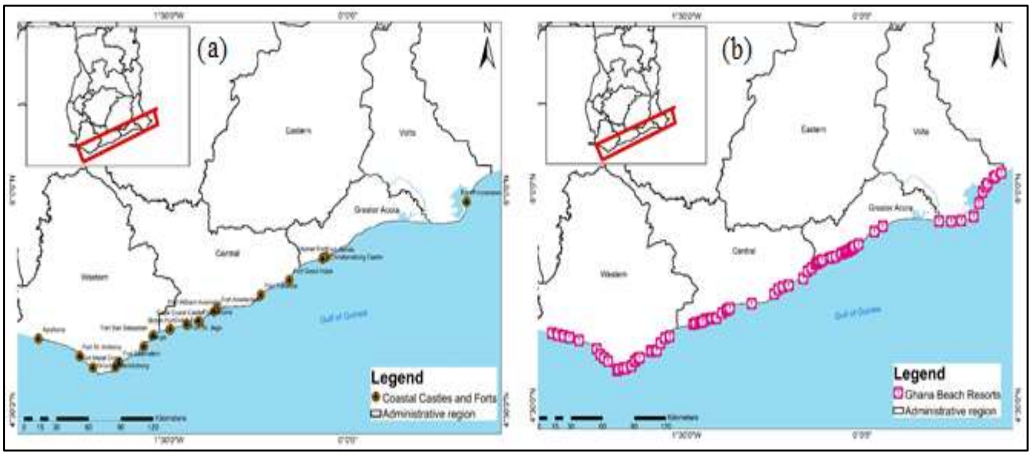

Figure 20: Tourism infrastructure along the coast of Ghana (Charuka et al., 2023a).

Currently, the castles are threatened by SLR and this confirmed recent research that 70% of African heritage sites are threatened by SLR by 2050 (Vousdoukas et al., 2022). Although Elmina Castle, Cape Coast Castle, and Fort Dutch Komenda have significant coastal protection in their neighbourhood. Given the IPCC SLR projections (IPCC, 2021), and persistent erosion and flooding, we envisage the demand for coastal protection to increase. Currently, beachside hotels and resorts like Elmina Coconut Grove, Bay Resort, Cape Coast Oasis beach resort, and Anomabo Beach Resort are protected, but there is high confidence in demand for more coastal protection from onsite interviews.

4. Discussion

Over the past decade, there has been an increase in coastal infrastructure along the coast of Ghana using hard-engineered infrastructure, mostly groynes, revetments, seawalls, and jetties. Most of the defences are implemented using rocks. However, gabion revetments, hybrid groynes, and bags of sand are notable e.g., at Volta Estuary. Wood and concrete installations are rare, possibly due to the associated high costs of construction and maintenance. Revetment and groyne fields are the commonest, and precisely, two accounts of seawalls were identified at Sekondi-Takoradi and Cape Coast.

The increase in coastal grey infrastructure along the coast of Ghana confirms the predominant use of hold the line strategies and the *ad hoc* implementation of grey infrastructure for shoreline protection (Boateng et al., 2016; Jonah et al., 2016; Wiafe et al., 2013). Given that virtually all the hard structures were constructed during the last decade, the entire coast could be protected using grey infrastructure if the rate of coastal hardening persists. Notably, the absence of SMPs is a major concern as some sections of the coast are armoured (hold the line strategy), while other adjacent areas of the coast are unjustifiably unprotected (no active intervention) making them vulnerable to coastal erosion migration. This echoes earlier research on the need for properly instituted SMPs (Boateng et al., 2016; Wiafe et al., 2013). In addition, the current trend of new fishing harbours will further affect longshore transport and induce coastal erosion to previously un-eroding downdrift areas, possibly dictating a new trend in overall shoreline evolution along the coast.

Despite the obvious need for coastal protection, grey infrastructure has many disadvantages documented in research. These include the migration of erosion (Angnuureng et al., 2013), loss of beaches and related utilities such as tourism (Pilkey & Cooper, 2014), invasion of structures by ghost crabs and other alien species that completely alters the species diversity (Glasby et al., 2007; Powell et al., 2019). Locally, grey infrastructure is attributed to the loss of fish landing sites and local beach seine fishing, the migration of sea turtles and other biota that ordinarily thrive live on sandy beaches. Therefore, the environmental and socioeconomic impacts of coastal grey infrastructure need to be fully investigated in future research.

Information about threatened coastal tourism facilities like beachside resorts and cultural heritage sites highlights potential demand for coastal protection. This is essential for economic planning and assessment of coastal vulnerability. Based on this, future implementation must take due consideration of the environmental, social, and economic sustainability aspects and ultimately the sustainability of coastal management in Ghana

Coastal change is inevitable and therefore requires constant planning and monitoring (Currin, 2019; NOAA, 2015). As such, coastal authorities are recommended to consider hybrid engineering with nature and nature-based infrastructure (Bouw & Eekelen, 2020; Cohen-Shacham et al., 2016; Sutton-Grier et al., 2018) for sustainable coastal protection and resilience. Given the national outlook of coastal hardening, the review of the short, medium, and long-term coastal management objectives along the coast of Ghana needs to be adequately addressed to establish SMPs that can effectively solve issues of erosion and flooding and future SLR projections (Alves et al., 2020; IPCC, 2022; 2021). SMPs are necessary to systematically put an end to *ad hoc* coastal engineering using grey infrastructure along the coast of Ghana.

The impacts of hard-engineered infrastructure have already been identified in research (CGIES Task Force, 2015; Rangel-Buitrago et al., 2018; Sutton-Grier et al., 2015), and the endless possibilities of integrating green and grey infrastructure (Bouw & Eekelen, 2020; Browder et al., 2019; Currin, 2019; Sutton-Grier et al., 2018; Cohen-Shacham et al., 2016). Therefore, the institution of proper SMPs (DEFRA, 2006b, 2006a) that are region-specific would support adaptive coastal management and implementation of hybrid infrastructure. Fixing the void of SMPs (Wiafe et al., 2013) and the *ad hoc* and political implementation of coastal works should resolve the "piecemeal", "fix and forget" approaches that are currently at play to improve adaptation to coastal change. Special regard must be given to coastal roads, seaports, coastal aquifers, and other strategic infrastructure that are increasingly vulnerable under current and future SLR scenarios (IPCC, 2021, 2022).

Hybridisation opportunities exist for currently installed coastal protection infrastructure (groynes, seawalls, and revetments) which are currently functional but are vulnerable to future sea-level rise. In this context, options exist for (1) nourishment of groyne fields using dredged material, although this may be hindered by high cost; (2) piloting and implementation of living shoreline at riverine and estuarine areas where road infrastructure, mangrove, and saltmarsh ecosystems already co-exist, e.g. Kakum river estuary, and leverage triple defence benefits (CGIES Task Force, 2015; Sutton-Grier et al., 2015); (3) Restoration of wetlands and mangrove ecosystems using ecosystem-based approaches may be prioritised. To expedite implementation and drive towards hybrid infrastructure, SMPs and Environmental Impact Assessments (EIA) can be aligned with national climate change adaptation plans, such as the Ghana National Adaptation Plan (NAP), (EPA, 2020). This can be done observing other recommendations set out in regional studies on coastal management e.g. West Africa Coastal Area Management (WACA) (Alves et al., 2022, 2020; World Bank, 2017a, 2017b).

5. Conclusion

This study established the intensification of hard-engineered projects along the coast of Ghana during the past two decades (2000-2022). During this time, coastal grey infrastructure was used to protect approximately 20% of the coast against coastal erosion. This study mapped the national distribution of coastal infrastructure along the coast of Ghana which was fundamental to influence changes in coastal management policy and decision-making. The results show that groynes, seawalls, and revetments dominate the coastal infrastructure typologies used to hold the line against the impacts of SLR along the coast of Ghana. Groyne fields particularly dominate the Eastern coast, while revetments are sparsely spread along the entire coast. Despite providing immediate coastal protection, grey infrastructure has a myriad of downsides that include aggravated coastal erosion migration to downdrift areas, irreversible coastline modifications, access restriction to the beach, loss, and damage to natural ecosystems, shortcomings which have impacts to coastal sustainability. The opportunities for adaptive management and hybrid infrastructure were discussed. Considering the severity of coastal erosion and flooding hazards along the coast, we recommend the development of holistic shoreline management plans to end the *ad hoc* implementation of coastal defences along the coast of Ghana.

CHAPTER FOUR

ASSESSMENT OF THE INTEGRATED COASTAL VULNERABILITY INDEX OF GHANA TOWARD FUTURE COASTAL INFRASTRUCTURE INVESTMENT PLANS

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Statement of Contributions of Joint Authorship

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Conceptualisation, established methodology, data analysis, writing original draft,

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Supervised and assisted with manuscript review, and co-author of manuscript.

Angnuureng D.B.: **Co-Supervisor**

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Assisted with filed work, data analysis, manuscript editing and co-author of manuscript

Abstract

Coastal vulnerability assessments are increasingly more important to investigate the exposure of coastal areas to coastal hazards. In recent decades, climate-induced sea-level rise (SLR) and human anthropogenic impacts are exacerbating the frequency and intensity of coastal hazards like storms, coastal erosion and flooding worldwide making coastal vulnerability assessments and coastal adaptation planning a priority. In Ghana, the assessment of the coastal vulnerability index (CVI) during the past decade has been infrequent, site-specific, and not complementary to provide the complete state of national coastal vulnerability during the past decade. This creates uncertainty, with limited information for coastal adaptation planning. To close this gap, we integrated three social variables with six fundamental physical variables to develop an integrated coastal vulnerability index (ICVI) for the coast of Ghana using the analytical hierarchical process (AHP). The ICVI results indicate that 6 coastal districts (18.18%) have very high vulnerability, 10 (30.30%) have high vulnerability, 8(24.24%) have moderate vulnerability, 6(18.18%) have low vulnerability, and 3 (9.09%) have very low coastal vulnerability. Overall, 72% of the coast exhibit moderate to very high coastal vulnerability. The results are significant to update the state of coastal vulnerability and help coastal planners to revise the short-, medium-, and long-term coastal adaptation policies along the coast of Ghana.

Keywords: Coastal vulnerability, coastal adaptation, coastal hazards, analytical hierarchical process, Ghana.

4.1. Introduction

Globally, sea-level rise (SLR) is escalating the frequency and severity of coastal hazards and current research evidence shows that the rise in the global rate of mean SLR is inevitable under different IPCC scenarios (IPCC, 2021, 2022). Consequently, SLR is considered one of the greatest societal challenges of the 21st century, and a major driver of coastal hazards like coastal storms, flooding, and coastal erosion (Bongarts Lebbe et al., 2021). The impacts include damage and loss of land and property, loss of livelihoods, forced environment migration (Appeaning Addo, 2021), threats to strategic coastal infrastructure like roads, water and energy infrastructure (Nazarnia et al., 2020), and threatened heritage sites (Sabour et al., 2020; Vousdoukas et al., 2022). This makes coastal vulnerability assessments a priority coastal management function in the 21st Century.

Coastal vulnerability defines the susceptibility of people and physical infrastructure to coastal change emanating from climate-induced coastal hazards (Boruff et al., 2005; Mclaughlin & Cooper, 2010; Ramieri et al., 2011). In this regard, coastal vulnerability can be assessed on either physical or social parameters, or a combination of the two, but in principle, it is the physical parameters that define overall vulnerability. The socioeconomic parameters are used to compute the social vulnerability index (SVI), which explains vulnerability from a socioeconomic perspective (Mclaughlin and Cooper, 2010), or regional differences in vulnerability to hazards (Boruff et al., 2005). The physical vulnerability index (PVI) is governed by numerous coastal processes, among others, wave height and direction, tides, and relative changes in sea level (Ramieri et al., 2011). However, only the most important variables that are assumed to govern physical vulnerability in an area are usually used to give a quick indication of coastal vulnerability (Palmer et al., 2011). In this regard, the six fundamental variables that are usually believed to strongly influence PVI include: (1) geomorphology; (2) coastal slope; (3) rate of relative SLR (mm/year); (4) shoreline erosion and accretion rates (m/year); (5) mean tidal range (m); and (6) mean wave height (m) (Boruff et al., 2005; Pendleton et al., 2004a; Thieler & Hammar-Klose, 2000a, 2000b). By combining the weighted average of the physical and socioeconomic variables, an integrated coastal vulnerability index (ICVI) can be established (Tano et al., 2018; Mahapatra et al., 2015). The ICVI is a fundamental tool that can be used to estimate the susceptibility of coastal areas to both natural and anthropogenic hazards.

Several methodologies exist to compute the ICVI, but four primary approaches can be distinguished in research (Ramieri et al., 2011). These approaches include: (1) index-based approaches (Armenio et al., 2021; Yin et al., 2012; Mclaughlin and Cooper, 2010; Thieler and Hammar-Klose, 2000a; Pendleton et al., 2004a; Palmer et al., 2011; Tano et al., 2018); (2) indicator-based approaches, (3) GIS-based methodologies (Beluru Jana & Hegde, 2016); and (4) dynamic computer models (Plant et al., 2016). These approaches, advantages and disadvantages have been widely discussed in research (Kantamaneni et al., 2018; Koroglu et al., 2019; Ramieri et al., 2011), thus providing researchers with informed options to estimate coastal vulnerability. In this study, we adopted an index-based approach, due to its simplicity of computation and ease of interpretation (Koroglu et al., 2019), and applied the Analytical Hierarchy Process (AHP), a comprehensive and powerful multi-criteria decision-making tool, especially when considering both qualitative and quantitative factors (Mahapatra et al. 2015; Canul et al., 2020).

In Ghana and West Africa at large, the coastal vulnerability to physical variables is already high due to the low-lying nature of coastlines and exposure to increasing SLR. As a result, adaptation to coastal flooding and erosion has already become a developmental challenge. In addition, human anthropogenic activities such as rapid and unplanned real estate developments (Alves et al., 2020, 2022), damming over rivers (Akyeampong, 2001; Ly, 1980), coastal sediment mining (Adams et al., 2017; Jonah et al., 2017), and the *ad hoc* construction of sea defences along the coast (Angnuureng et al., 2013) contribute to worsening coastal erosion and flooding hazards. This is undermining the attainment of Sustainable Development Goals (SDGs), particularly SDG13, Climate Action and SDG11, Sustainable Cities (World Bank, 2017b). In this regard we refer to SDG13.1(Resilience and adaptive capacity) and SDG 11.5 (Disaster Risk Reduction).

Since 2016, there has not been a national coastal vulnerability assessment for Ghana and implications for future coastal developments. Previously, two studies (Boateng et al., 2016; Wiafe et al., 2013) were conducted. Boateng et al. (2016) estimated CVI using the 1974-2005 shoreline data set and 2000 population data, while Wiafe et al. (2013) excluded the social variables. However, the population of Ghana has increased by 2.1% per annum between 2010 and 2021 (GSS, 2021), coastal districts have been restructured from 25 to 33 districts, and coastal developments and land-use patterns have changed significantly.

This study aims to evaluate the ICVI of the coast of Ghana and explore how the ICVI can be used for decision-making regarding future infrastructure investment plans. The objectives of this study are to: (1) estimate and map the current ICVI for the coast of Ghana; (2) determine the most vulnerable coastal areas where the impacts of climate change, sea-level rise, and human activities are most pronounced and requiring immediate coastal adaptation interventions or revision of adaptation approaches; and (3) provide recommendations for coastal adaptation strategies to achieve sustainable infrastructure developments, and support informed coastal management decision-making to achieve coastal sustainability in Ghana.

4.2. Study area descriptions

This study covers thirty-three coastal districts which make up the coast of Ghana. The coast extends from 6°06’ N, 1°12’E at the Eastern border with Togo to 5°05’N, 3°06’W at the Western border with Ivory Coast (Figure 21).

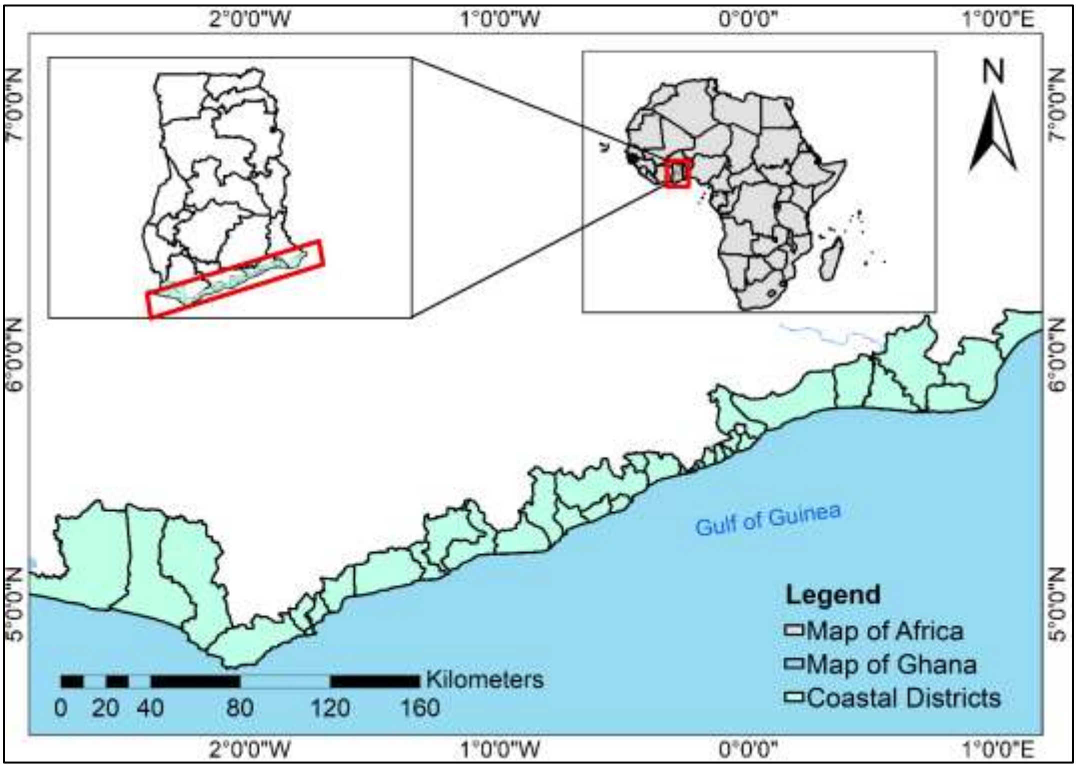

Figure 21: Coastal map of Ghana showing the new 33 coastal districts (Charuka et al., 2023b)

Three geomorphic areas, namely Eastern, Central, and Western coasts, and four coastal administrative regions (Volta, Greater Accra, Central, and Western regions) constitute the coast of Ghana (Armah, 2005; Boateng et al., 2016; Wiafe et al., 2013). The Eastern coast stretches from the Aflao border with Togo to Ningo Prampram and covers about 149km (27%) of the coast. It is characterised by sandy beaches and the deltaic influence of the Volta River Estuary (Armah, 2005; Roest, 2018). The Central coast is the longest geomorphic region and stretches for 316 km (58%) of the national coastline. It is characterised by rocky coasts, bay beaches, sand barriers, and coastal lagoons (Armah, 2005). The Western coast covers about 85km (15%) of the national coastline from Cape Three Points to the border with Ivory Coast (Armah, 2005; Boateng et al., 2016; Wiafe et al., 2013). The major rivers contributing to sediment and influencing coastal processes include the Ankobra River, Pra River, Oti River, Densu River and the Volta River.

4.3. Materials and methods

The main goal of this assessment was to provide sufficient information on the state of integrated coastal vulnerability along the coast of Ghana and identify the coastal areas that are most vulnerable to human and climate-induced coastal changes. To achieve this, we employed the AHP methodology to integrate the PVI and SVI to produce the ICVI (Canul et al., 2020; Mahapatra et al. 2015).

4.3.1. Procedure for assessing coastal vulnerability

The procedure for conducting integrated coastal vulnerability assessments follows four basic steps, namely: (1) identification of key variables that significantly drive coastal processes (Armenio et al., 2021; Mclaughlin & Cooper, 2010; Palmer et al., 2011); (2) ranking of the identified parameters using semi-quantitative scores, usually from 1-5, where 1 indicates very low and 5 indicates very high vulnerability; (3) applying the AHP multi-criteria decision analysis method to give weights to each parameter and generating the weighted PVI and SVI; (4) aggregating the weighted PVI and SVI into a generalised ICVI (Canul et al., 2020; Mclaughlin & Cooper, 2010; Yin et al., 2012). Lastly, the mapping of coastal vulnerability is implemented in a GIS software environment (ArcGIS Desktop) to identify the different areas of coastal vulnerability to SLR. Figure 22 summarises the procedure for conducting coastal vulnerability assessment using the AHP methodology.

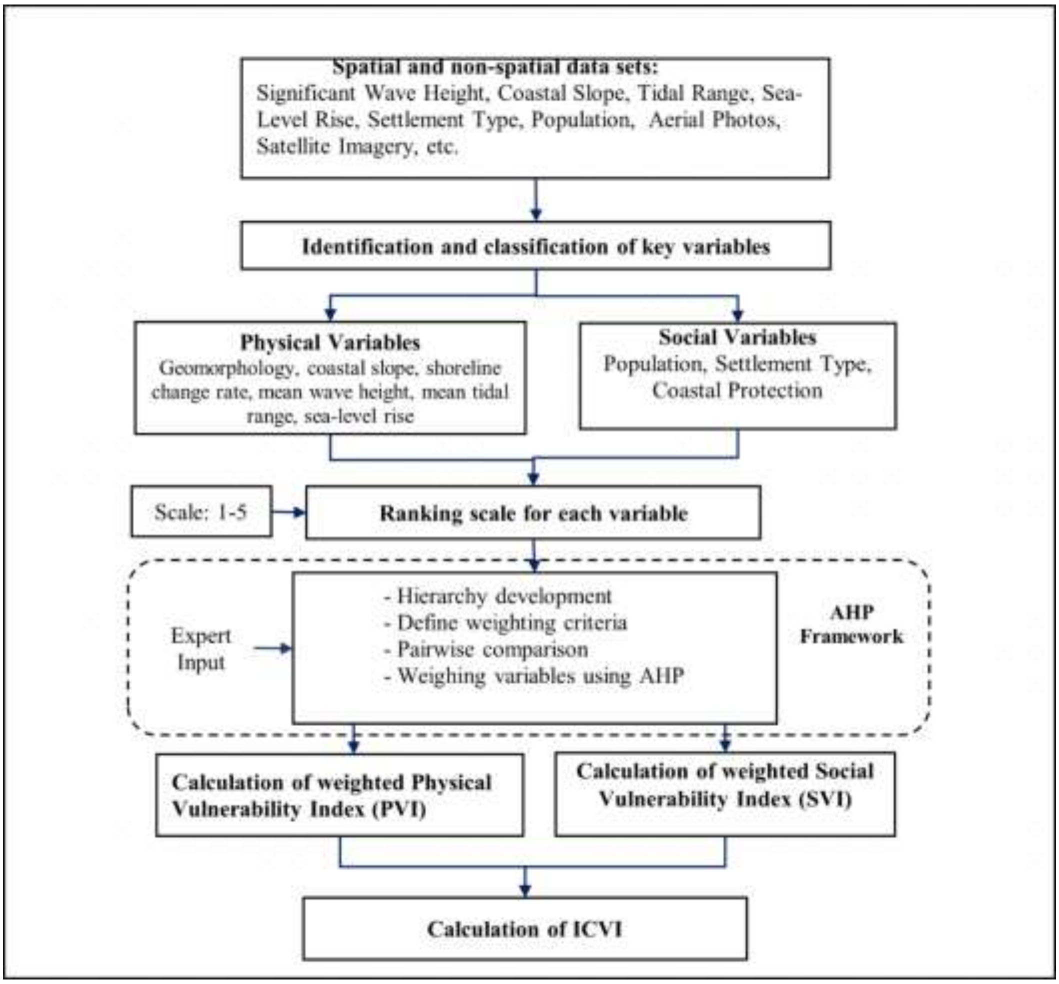

Figure 22: Analytical Hierarchy Process for estimating coastal vulnerability (Canul et al., 2020; Mahapatra et al. 2015)

4.3.2. Selection of physical and social variables for computing ICVI

In this study, we employed six fundamental physical variables (geomorphology, shoreline change rate, coastal slope, mean wave height, mean sea level, mean tidal range) (Pendleton et al., 2004b, 2004a; Thieler & Hammar-Klose, 2000a, 2000b) and three socioeconomic variables (coastal district population, historical disasters, and coastal protection), (Table 4) were used to estimate the ICVI for the coast of Ghana.

Table 4: *Physical and Social Variables Used in Estimating Coastal Vulnerability*

Category	**Variables**		**Measurement Unit**	**Data source**	**Period**
Physical Variables	Geologic or Coastal Characteristics	Coastal Geomorphology	Ordinal value	2005 Orthophoto, Literature: (Wiafe et al. 2013; Boateng et al. 2016).	2005
		Shoreline change rate	m/year	Sentinel 2B (2022), Landsat 7(2000).	2000-2022
		Coastal slope	Percentage (%)	Coastal elevation datasets,	2020
	Coastal Forcing	Significant wave height	Metres	Copernicus monthly averaged reanalysis data(C3S, 2022)	2000-2020
		Mean SLR	mm/year	Regional Sea-level Change (RSLC - IPCC AR6, SSP5-8.5-2050) (Coastal Futures, 2023). Literature: (Boateng et al. 2016; Appeaning Addo 2014)	2000 - 2020
		Mean tidal range	Metres	Literature based on Takoradi tidal gauge, water levels. (Jayson-Quashigah, 2019; Appeaning Addo, 2013)	N/A
Socioeconomic Variables	Coastal protection		Ordinal value	Remote sensing, field/in-situ observation, and verification, Literature (Charuka et al., 2023; Angnuureng et al., 2013)	2000-2022
	Historical disasters		Ordinal value	Literature , (Brempong et el., 2023; Babanawo et el., 2022)expert knowledge	2000-2020
	Population		Number (K)	Populations data from 2010 and 2021 Ghana Census (GSS, 2021; 2010)	2010 - 2021

4.3.3. Physical Parameters

The detailed analysis of the methodology for establishing physical and social variables is discussed to explain parameters and data collection procedure.

Coastal geomorphology

Coastal morphology is an important variable in determining the resilience of a region's coastline to SLR because it expresses the relative erodibility and the degree of resistance of the coast to rising sea levels (Koroglu et al., 2019; Pendleton et al., 2004a). The coastal geomorphology was derived from the 2005 aerial orthophotos (See Figure 23). The coastal geomorphology along the coast of Ghana is characterised by sandy coasts and deltas along the Eastern coast, interchanging rocky shores and bayed beaches along the Central coast, and gently sloping sandy coasts and lagoons along the Western coasts (Boateng et al., 2016; Wiafe et al., 2013).

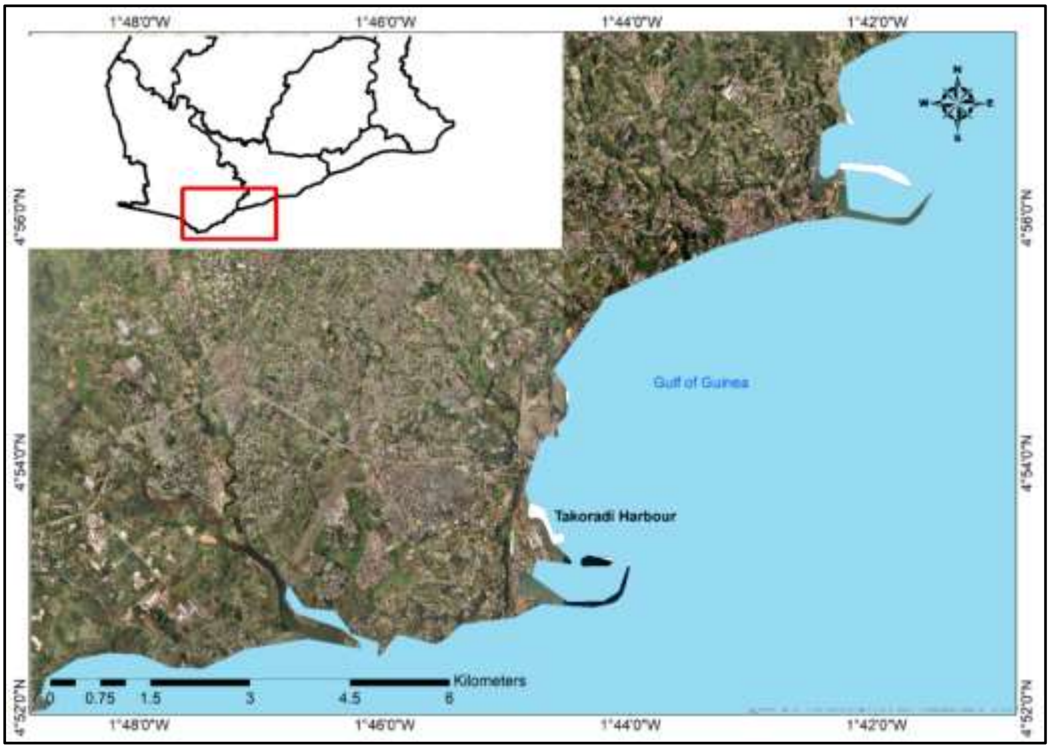

Figure 23: A 2005 Orthophoto showing coastal geomorphology at Sekondi-Takoradi

In addition, estuarine ecosystems such as the Volta River Estuary (Eastern Coast), Densu River Estuary (Central Coast) and Whin and Amanzule River Estuaries (Western Coast) greatly influence coastal processes and morphological changes along the coast (Mensah, 2013; UNEP, 2007).

Coastal slope

Coastal slope explains the relative vulnerability of the coast to inundation and potential rapid coastal erosion (Pendleton et al., 2004a). Typically, areas with narrow beach width have steeper slopes and dissipate less wave energy, but wider and gently sloping beaches have superior wave dissipation capacity which makes them less vulnerable (Palmer et al., 2011; Pendleton et al., 2004a). The coastal slope (of the beach face) along the coast of Ghana is mapped in Figure 24.

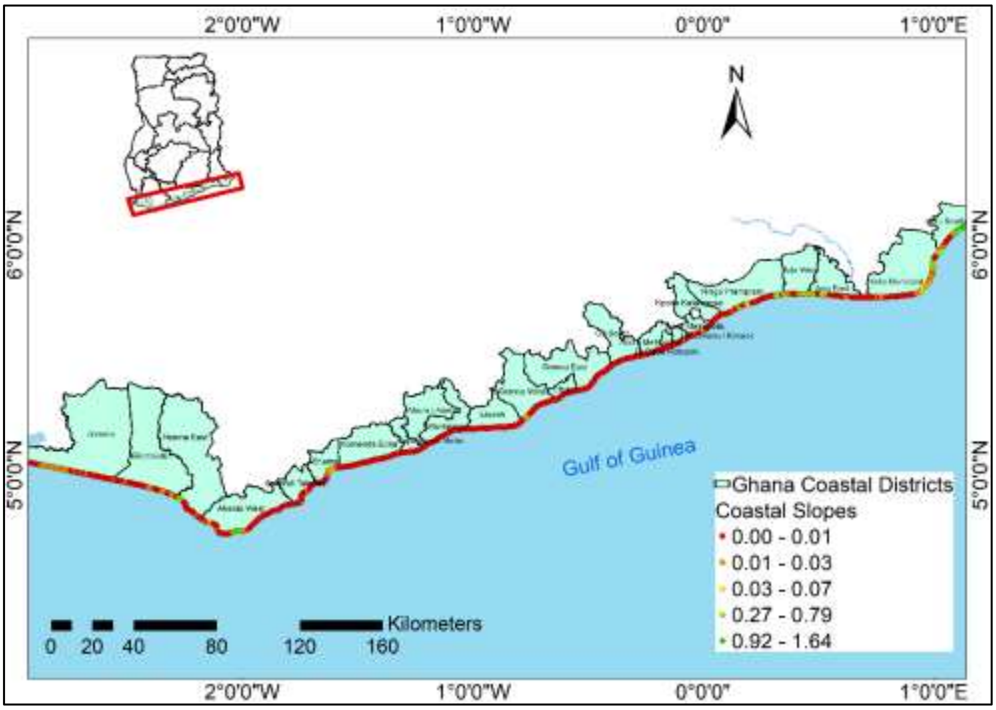

Figure 24: Coastal slopes along the coast of Ghana

Coastal slopes along the coast of Ghana were established to range from 0-1.65 and approximately 92% of the beach face slopes along the coast have slope ratios below 5%, or 1:20, making it highly vulnerable to variations in relative sea level rise.

Sea level rise

The relative change in mean SLR, defined as the variation in seawater elevation relative to the mean sea level over a long time, can reinforce coastal vulnerability (Angnuureng et al. 2018). SLR may significantly alter and influence wind and wave patterns and cause the intensification of coastal hazards like erosion and flooding (Bongarts Lebbe et al., 2021). The cascading effects include coastal flooding, temporary or permanent inundation and loss of wetlands and other ecosystems, processes that intensify saltwater intrusion and groundwater contamination (AGNES, 2021; UNEP-DHI Partnership, 2017). The declining water quality further affects the well-being of coastal communities that are dependent on groundwater resources (Koroglu et al. 2019). The nexus of SLR, flooding, coastal erosion, grey coastal infrastructure, and increasing seaward urban development contribute to coastal squeeze, causing beaches to become narrow and disappear (Pilkey & Cooper, 2014b).

Shoreline change rate

In this study, shoreline change rates were calculated for the period from 2000-2022. The 2022 and 2000 shorelines were extracted from Sentinel 2B and Landsat 7 satellite images respectively. Images were acquired through the USGS Earth Explorer, mosaiced, projected to UTM Zone 30, and digitised along the high-water mark. Subsequent shoreline change analysis was computed in ArcGIS Desktop using the embedded DSAS tool, and mapped to indicate shoreline variability (Figure 25). The shoreline erosion rates were averaged for each coastal district to arrive at a mean value used in the computation of the PVI.

The average national shoreline change rate was -2.24 m/year and the average shoreline change rates are summarised in Table 5. Compared to the rest of the national coastline, the coastal districts of Ada East, Anlo, Keta Municipal, and Ketu South experience relatively higher erosion rates. The average rates for the new coastal districts are given in Appendix 10.

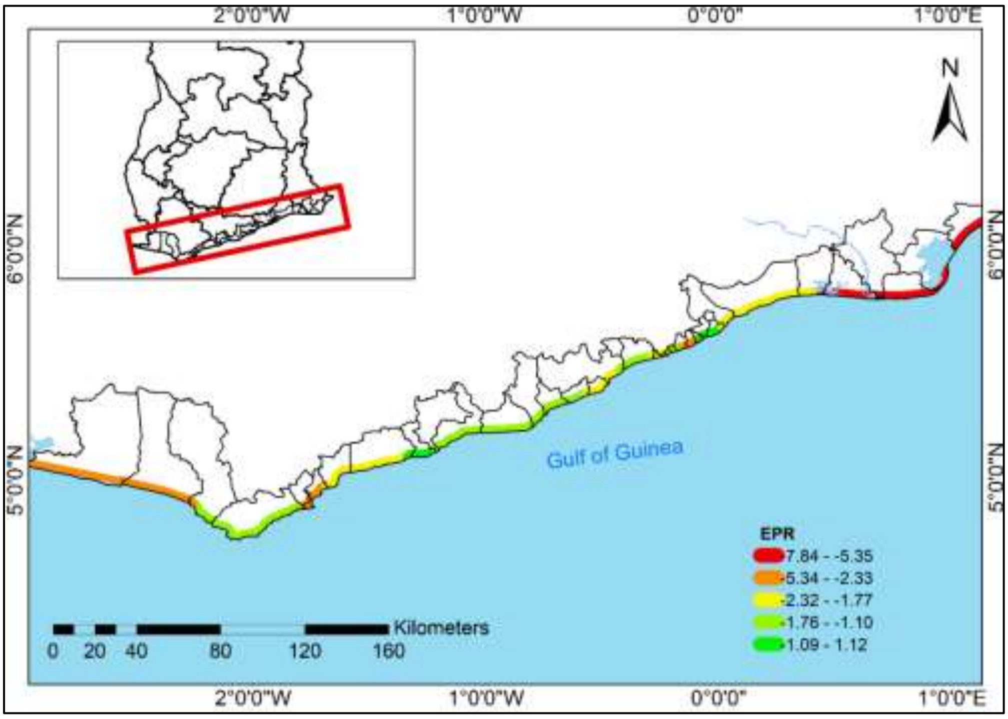

Figure 25: Shoreline change rates along the coast of Ghana from 2000 to 2022

Table 5: *Shoreline Change Rates Along the Coast of Ghana from 2000-2022*

Coastal District	Shoreline change rate (m/year)	Coastal District	Shoreline change rate (m/year)
1. Jomoro	-2.78	18. Ablekuma West	-1.77
2. Elembelle	-2.33	19. Accra Metropolis	-1.78
3. Nzema East	-1.50	20. Korley Klottey	-1.35
4. Ahanta West	-1.42	21. La Dade Kotopon	-1.52
5. Sekondi-Takoradi	-2.14	22. Ledzokuku	2.41
6. Shama	-2.33	23. Krowor	2.41
7. KomendaEdnaEguafo	-1.78	24. Tema West	1.13
8. Cape Coast	1.61	25. Tema Metropolitan	1.13
9. Abura-Asebu	-1.00	26. Kpone Katamanso	-1.95
10. Mfantisman	-1.53	27. Ningo Prampram	-2.06
11. Ekumfi	-0.38	28. Ada West	-2.17
12. Gomoa West	-1.21	29. Ada East	-7.8
13. Gomoa Central	-1.17	30. South Tongu	-19.6
14. Effutu	-1.12	31. Anloga	-5.35
15. Awutu Senya	-1.23	32. Keta Municipal	-4.52
16. Gomoa East	-1.77	33. Ketu South	-7.84
17. Weija Gbawe	-1.25		

Significant wave height

Waves are an important variable that drives coastal processes. The mean significant wave height (MSWH) is considered a proxy for wave energy and a major catalyst of coastal sediment transport, erosion, and deposition rates (Armenio, Mossa, and Petrillo, 2021; Koroglu et al., 2019; Yin et al., 2012; Pendleton et al., 2004a). Wave energy is directly related to the square of wave height (Pendleton et al., 2004a), and is expressed by equation (1).

$$E = 1/8\ \rho g H^2 \tag{1}$$

Where E = energy density, H = wave height, ρ is water density, and g is acceleration due to gravity.

Waves with larger wave heights exert higher energy impact on beaches and induce the transport of larger sediment volumes, increasing coastal erosion and flooding through wave overwash (Koroglu et al. 2019; Pendleton et al. 2004a). In this study, the annual MSWH along the coast (2000, 2005, 2010, and 2020) was computed in MATLAB Software by averaging data acquired from Copernicus Climate Change Service (C3S) global reanalysis monthly averaged reanalysis data (ERA5), from 2000 to 2022 (C3S, 2022) (Figure 26**)**. The results indicate that the MSWH along the coast of Ghana ranges from 0.8 to 1.7m. ERA5 can be regarded as the best proxy to get global reanalysis time series data because it is produced in near real-time and provides an accurate representation (C3S, 2022). The data was obtained for the years for the years 2000, 2010, 2015, and 2020.

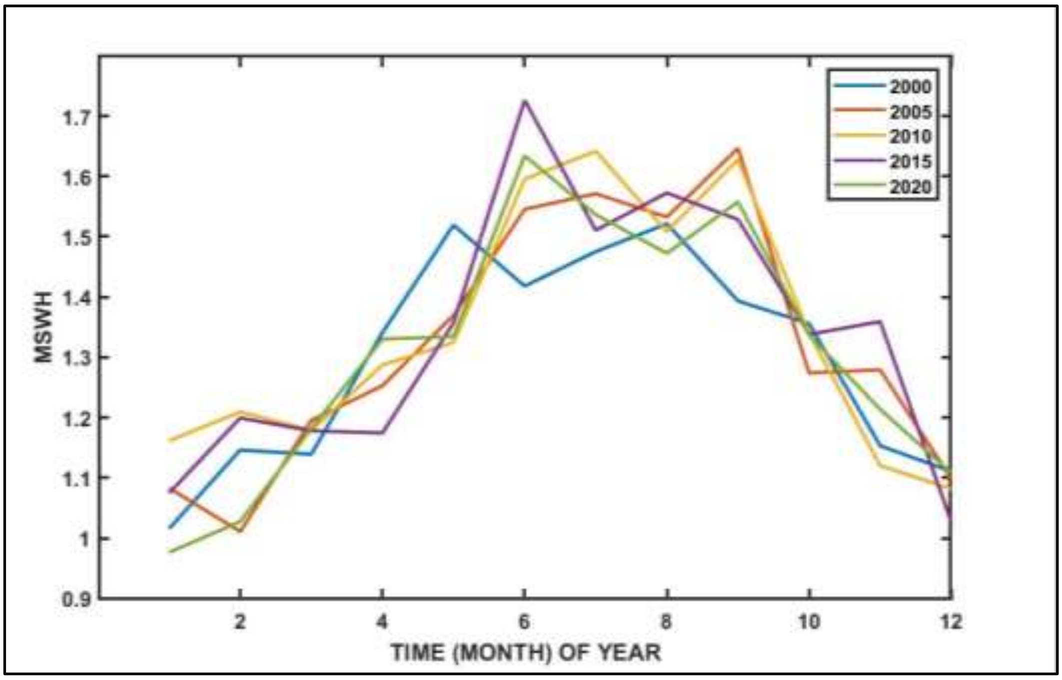

Figure 26: Mean Significant Wave Height along the coast of Ghana for the years 2000, 2005, 2010, 2015, and 2020

The results were classified as: (1) very low (0.82-0.91m), low (0.92-1.00m), moderate (1-1.09m), high (1.09-1.11m), and very high (1.11-1.13m). Thus, H_s is relatively moderate along the Western and Central coast, (H_s=0.8), but increases in height and magnitude from Greater Accra to Volta region, Eastern coast ($H_s \geq 1$). Therefore, significant wave height seems to dictate the erosion rates of the coastal regions of Ghana.

Mean tidal range

The mean tidal range or the average of high and low tides, is an important variable associated with both episodic and permanent flooding due to SLR and storm surges (Armenio et al., 2021; Koroglu et al., 2019; Yin et al., 2012). The coast of Ghana experiences diurnal tides with a mean annual neap tide of 0.58m at Takoradi along the Western coast and a mean annual spring tide of 1.32m at Aflao along the Eastern coast (Armah, 2005). It is known that larger tidal ranges are associated with higher coastal vulnerability and vice versa (Yin et al., 2012). Along the coast of Ghana, the lowest tides are usually recorded annually during the major upwelling (June to September). The mean annual tidal range for the coast of Ghana is 1 m/year (Appeaning Addo, 2014; Boateng et al., 2016).

4.3.4. Socioeconomic Parameters

Coastal population

Coastal areas with high population densities are more likely to have more people injured or killed in the event of coastal hazards. Approximately 25% of the population of Ghana lives in coastal areas. Therefore, the coastal population variable influences the perceived vulnerability of the area (Mclaughlin and Cooper 2010). In this study, the population for coastal districts was acquired from the Ghana Statistical Services (GSS) 2021 Census results (see Appendix 3). Between 2010 and 2021, Ghana’s population increased at 2.1% per annum and surged from 24.6 million in 2010 to 30.8 million in 2021 (GSS, 2021). Given that, we classified the population data from 1 to 5 using the Jenks natural breaks optimisation classification in ArcGIS Desktop as: (1) very low (56,741<N<98,895); (2) Low (98,895<N<

143,012); (3) Moderate (143,012<N<217,304); (4) High (217,304<N<308,697), and (5) Very High (308,697<N>417,334), (See Figure 27).

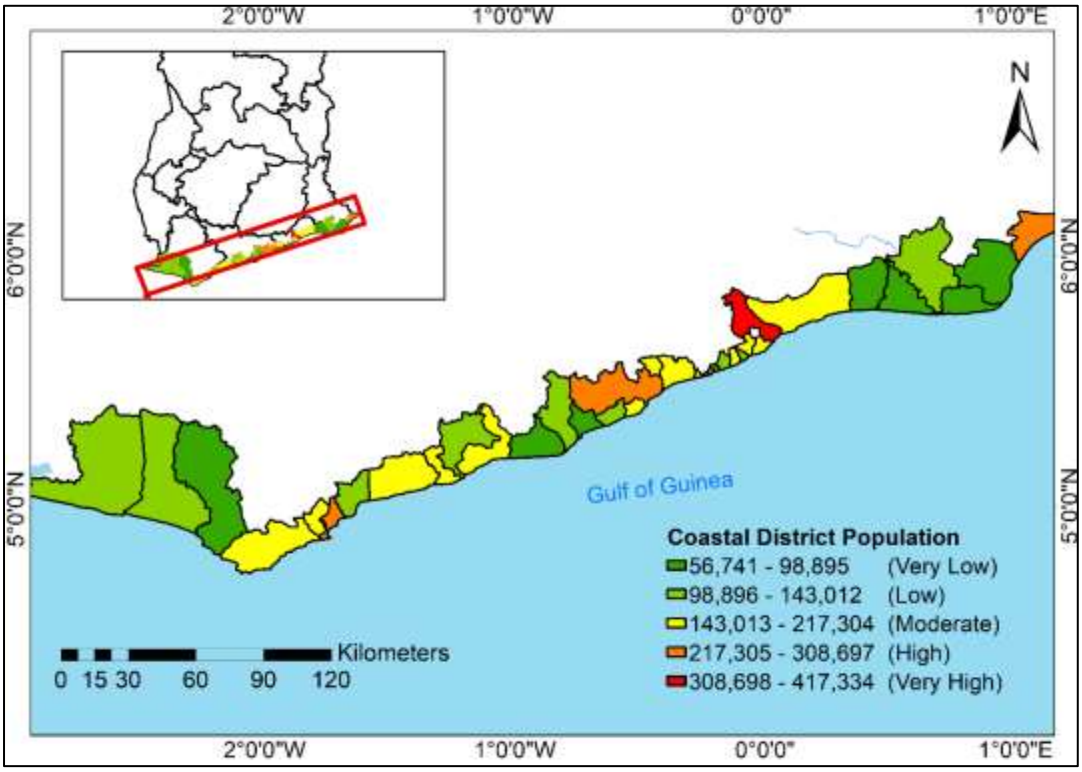

Figure 27: Effect of coastal district population on coastal vulnerability along the coast of Ghana

Results show high population in coastal districts of Takoradi, Accra, and Ketu South and very high SVI in Kpone Katamanso. Further subdivision of districts into smaller districts (from 25 before 2021 to 33 after 2021) indicates relative increase in population density in these coastal areas (Figure).

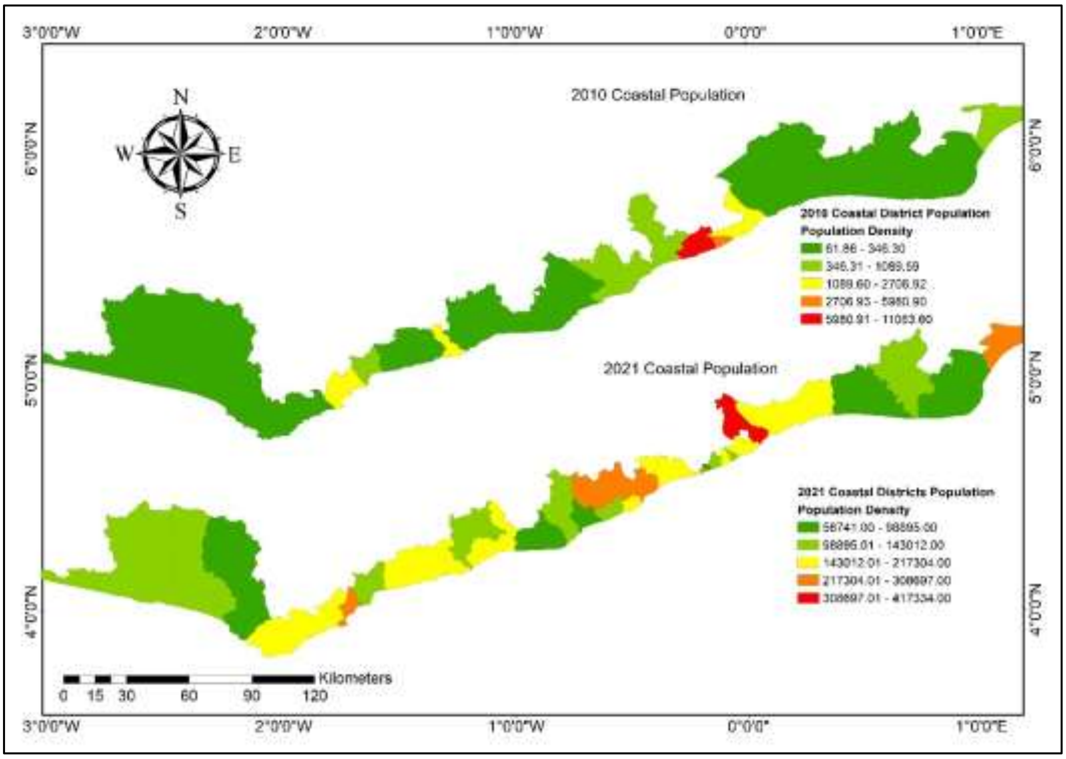

Figure 28: Map of changes in Ghana's coastal population (2010 – 2021)

Historical disasters

The frequency and severity of past occurrences of coastal hazards and their impacts on socioeconomic conditions provide valuable insights into an area's vulnerability to future occurrences. In this study, we also considered the historic frequency, and severity of previous disasters along the coast of Ghana, mainly severe erosion and flooding (Angnuureng et al., 2013; Babanawo et al., 2022; Brempong et al., 2021, 2023). Realising that areas that are historically prone to hazards provide valuable insights into vulnerability. These areas are likely to be affected in the future, and the socioeconomic impacts are likely to be repeated or worsened. Historical disaster provides the lens to understand the socioeconomic functioning of society, coordination and response to past coastal disasters, community resilience (Babanawo et al., 2022, 2023), and is important to support future emergency planning. Based on findings from literature and expert interviews, the major hotspots include Ketu South, Keta

(Brempong et al., 2023), Anlo, Ada along the Eastern coast, Shama, Anlo, and along the Central coast, and Takoradi along the Western Coast.

Coastal protection

The coastal protection parameter was added to differentiate protected and unprotected areas. Over the past decade, coastal protection increased along the coast of Ghana (Figure 29). Naturally, protected areas are perceived to be less vulnerable than those that are not protected. In this regard, the alongshore length of the beach covered by each coastal protection infrastructure was considered.

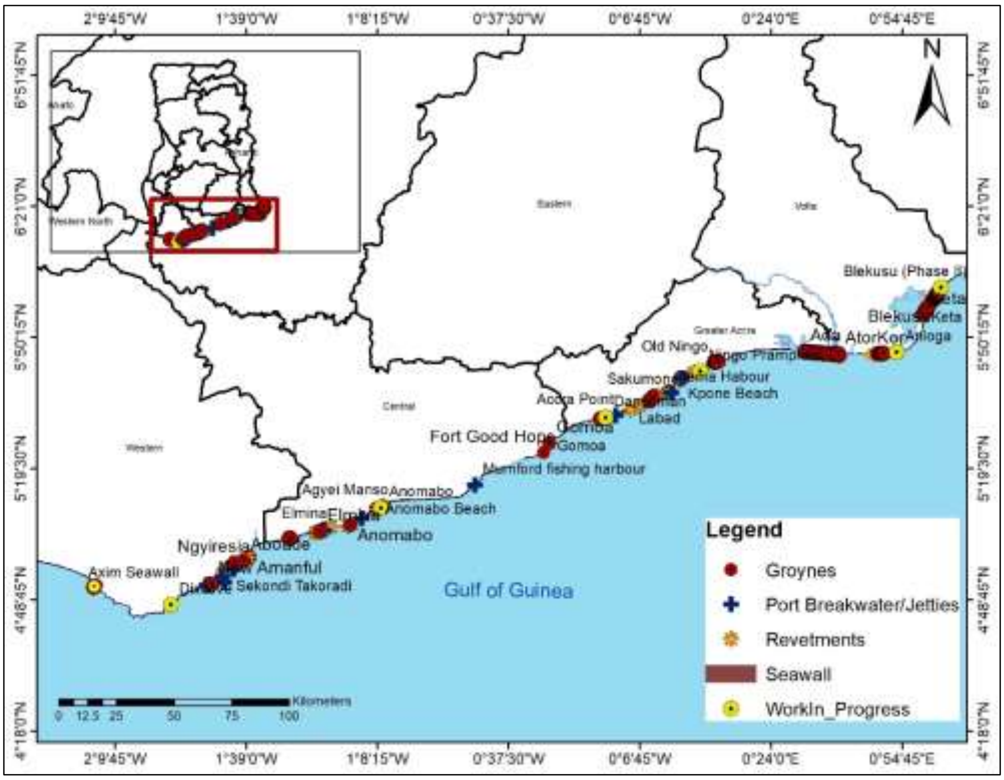

Figure 29: Visualisation of coastal infrastructure along the coast of Ghana.

Coastal protection was calculated as the ratio of the alongshore beach distance covered by defences per district relative to the total shoreline length in kilometres. Approximately 20% of the coast is currently protected using grey infrastructure, mainly groyne fields, revetments, seawalls and jetties

(Charuka et al., 2023). Coastal protection works have increased considerably during the last two decades (2000-2022). Coastal protection was calculated as the ratio of the alongshore beach distance covered by defences relative to the total shoreline length in kilometres. Consequently, the vulnerability of the coast, after factoring coastal defence projects is presented in Figure 30.

These variables were subsequently weighted using the AHP methodology, integrated, and used in the computation of PVI and SVI. The final ICVI was computed by averaging the PVI and SVI.

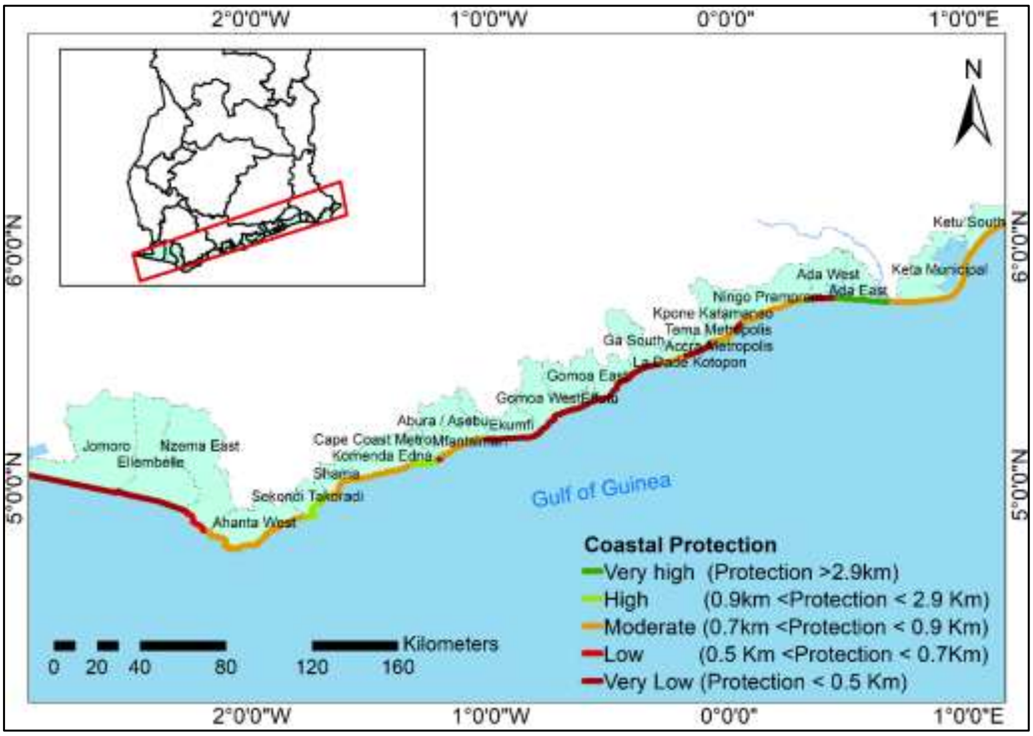

Figure 30: Impact of coastal infrastructure on coastal vulnerability along the coast of Ghana

4.3.5. Computation of ICVI using AHP methodology

The CVI is meant to provide a relative indication of coastal vulnerability, which is not absolute (Palmer et al., 2011). The composite CVI can be defined as either the square root of the product of all the variables divided by the number of variables (Thieler and Hammar-Klose 2000a; 2000b; Pendleton et al. 2004a; Koroglu et al. 2019) or it can be expressed as the sum of differentially weighted variables using the deterministic Analytical Hierarchy Process (AHP) methodology (Canul et al., 2020; Yin et al., 2012). In this study, the AHP approach was applied and the variables were ranked based on their perceived importance using the Saaty (Saaty, 2001, 2008; Saaty & Sodenkamp, 2008) rating scale (Table 6).

Following seven interviews with experts on coastal management, a pairwise comparison of variables was performed. The pairwise comparison (Table 7) involves assigning perceived relative importance and their reciprocals to variables in the comparison table.

Table 6: *Saaty Rating Scale Used in Computing CVI Following AHP*

Intensity of importance	**Definition**	**Explanation**
1	Equal Importance	Two factors contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one factor over another
5	Strong importance	Experience and judgment strongly favour one factor over another
7	Very Strong importance	Experience and judgment strongly favour one factor over another. The importance is demonstrated in practice.
9	Extremely important	The evidence of favouring one factor over another is the highest possible validity
2,4,6,8	Intermediate values	Compromise is needed

Table 7*: Physical Parameters Pairwise Comparison Matrix*

Criteria	Geomorphology	Coastal slope	Shoreline change rate	Mean wave height	Mean tidal range	Sea level rise
Geomor-phology	1.000	2.000	3.000	5.000	5.000	5.000
Coastal slope	0.500	1.000	3.000	5.000	5.000	7.000
Shoreline change rate	0.333	0.333	1.000	3.000	2.000	6.000
Mean wave height	0.200	0.200	0.333	1.000	3.000	4.000
Mean tidal range	0.200	0.200	0.500	0.333	1.000	2.000
Sea level rise	0.200	0.143	0.167	0.250	0.500	1.000
Checksum	2.433	3.876	8.000	14.583	16.500	25.000

To guarantee consistency, the matrices are normalised and weighted. To obtain the normalised pairwise comparison matrix (Table 8), each value in the pairwise matrix is divided by the checksum of the pairwise matrix, and the criteria weights were calculated by averaging each row of each normalised pairwise matrix.

Table 8*: Computed Normalised Matrix for Physical Variables*

Criteria	Geomor-phology	Coastal slope	Shoreline change rate	Mean wave height	Mean tidal range	Sea level rise	Criteria weight
Geomorphology	0.411	0.516	0.375	0.343	0.303	0.200	0.358
Coastal slope	0.205	0.258	0.375	0.343	0.303	0.280	0.294
Shoreline change rate	0.137	0.086	0.125	0.206	0.121	0.240	0.152
Mean wave height	0.082	0.052	0.042	0.069	0.182	0.160	0.098
Mean tidal range	0.082	0.052	0.063	0.023	0.061	0.080	0.060
Sea level rise	0.082	0.037	0.021	0.017	0.030	0.040	0.038
Checksum	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Similarly, a pairwise comparison was conducted for socioeconomic variables (Table 9), using the same procedure applied to the physical variables.

Table 9: *Social Parameters Pairwise Comparison Matrix*

Criteria	District population	Historical disasters	Coastal protection
District population	1.000	5.000	7.000
Historical disasters	0.200	1.000	3.000
Coastal protection	0.143	0.333	1.000
Checksum	1.375	5.500	11.000

In the same way, the normalised table for socioeconomic variables was computed (Table 10).

Table 10: *Computed Normalised Matrix for Socioeconomic Variables*

Criteria	District Population	Historical disasters	Coastal protection	Criteria Weight
District population	0.745	0.789	0.636	0.72
Historical disasters	0.149	0.158	0.273	0.20
Coastal protection	0.106	0.053	0.091	0.08
Checksum	1.000	1.000	1.000	1.000

The subsequent steps involved computing the Consistency Ratio (CR), calculated by dividing the Consistency Index (CI) by the Random Index (RI) following the same methodology applied (Canul et al., 2020). Table 11 shows the RI values for variables 1 through 9.

Table 11*: Randomly Generated Index Numbers 1 To 9*

Number	2	3	4	5	6	7	8	9
Random Index	00	0.52	0.90	1.12	1.24	1.32	1.41	1.45

To compute the Consistency Ratio (CR) the Consistency Index (CI) was computed by dividing the criteria weights by the weighted sum value for the matrix through equation (2):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

Where is the average of sum values over criteria weights, CI = consistency index, and *n* = number of variables. Finally, the CR was computed by dividing the CI by the RI (Table 12).

Table 12: *Computation of Consistency Ratio (CR)*

Variables	Physical Variables	Socioeconomic Variables
N	6	3
λ_{max}	6.43	3.05
Consistency Index	0.07	0.03
Random Index	1.24	0.52
Consistency Ratio	0.07	0.06

Since the CR < 0.10, which is a standardised ratio that indicates reasonable consistency in the pairwise comparison matrix, we can continue with the decision-making process using AHP. Subsequently, the AHP formula is applied to get the PVI (Equation 3) and SVI for each coastal district.

$$PVI = \sum_{i=1}^{6} F_i * W_i \quad (3)$$

Where F_i is the vulnerability ranking of factor *i*, and W_i is the weight of physical factor *i*.

Similarly, the SVI (Equation 4) is computed in the same manner for PVI:

$$SVI = \sum_{i=1}^{3} F_i * W_i \quad (4)$$

Where F_i is the vulnerability ranking of social factor *i*, and W_i is the weight of social factor *i*.

Lastly, the ICVI (Equation 5) for the coast was computed by averaging PVI and SVI since the two indices have already been weighted and computed through the AHP process following e.g. (Mahapatra et al., 2015), hence

$$ICVI = (PVI + SVI)/2 \quad (5)$$

The coastal vulnerability was computed and mapped for 33 coastal districts along the coast from Jomoro to Ketu South in East-West direction in an ArcGIS Desktop environment.

4.4. Results

4.4.1. Estimating the PVI for the coast of Ghana

The composite PVI was computed by averaging the physical parameters indices for each coastal district. The total PVI for the coast of Ghana was 80.34. Based on AHP computations, the total PVI scores were classed into 5 vulnerability levels ranging from 2.71 to 4.47, classed as: (1) very low vulnerability (2.71 - 3.06); low vulnerability (3.07 - 3.41); moderate vulnerability (3.71 – 3.76); high vulnerability (3.76 - 4.11); and very high vulnerability (4.11 – 4.47) (Figure 31).

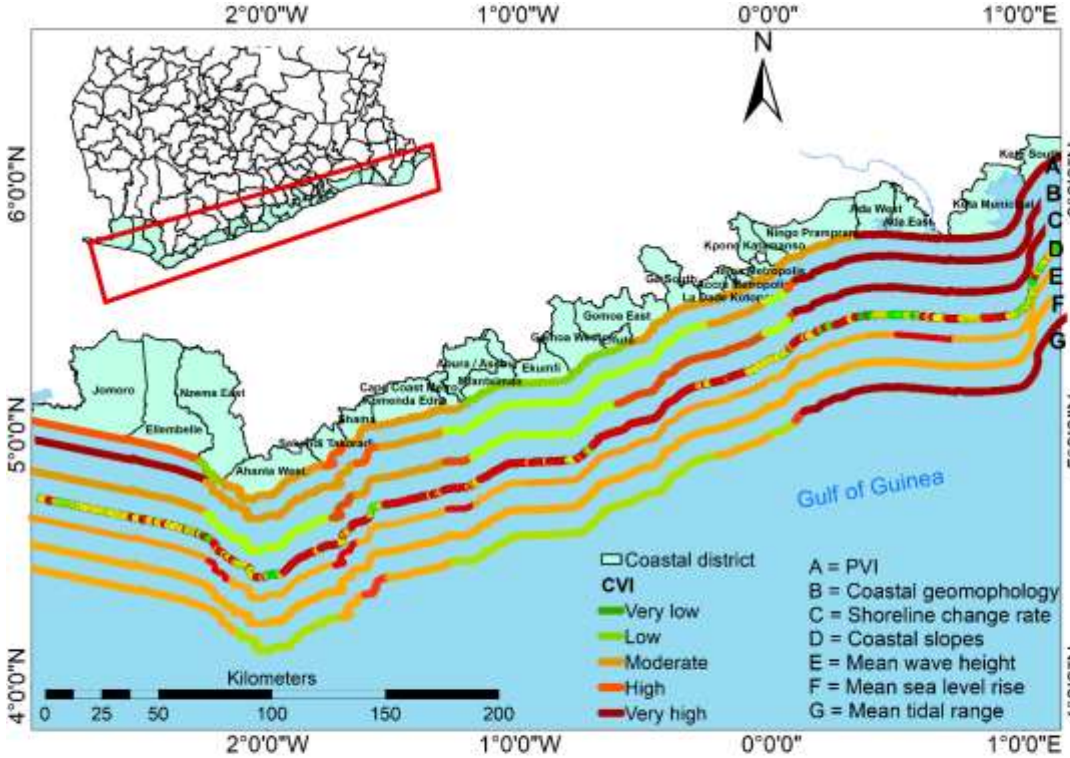

Figure 31: State of physical coastal vulnerability along the coast of Ghana

The PVI results indicate that physical vulnerability is very high along the Eastern coastal districts of Ada East, South Tongu, Anlo, Keta, and Ketu South, the Western districts (Sekondi-Takoradi, Jomoro and Ellembe) and Central coast (Cape Coast). Overall, the Central coast experiences low to moderate PVI.

4.4.2. Estimating the SVI for the coast of Ghana

The SVI scores for each coastal district ranged from 0.70 (very low) to 1.89 (very high). The SVI score was computed to be 34.82. The results were classified using the natural breaks (Jenks) classification and mapped in an ArcGIS Desktop environment (Figure 32), to explain the impacts of hazards on society.

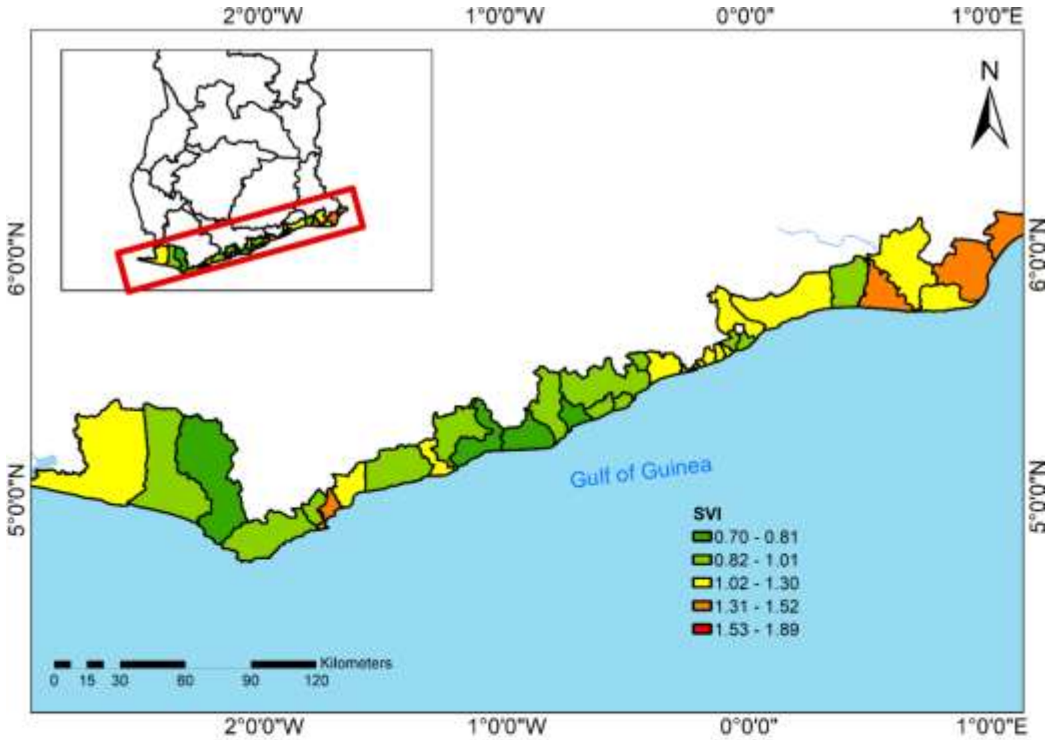

Figure 32: The effect of social parameters on coastal vulnerability along the coast of Ghana

From the results, it can be observed that the SVI was mainly influenced by high population growth. In this regard, 72% of SVI is explained by high population densities (and coastal developments) while historic disasters and level of protection explain about 20% and 8% respectively. In Ghana, high SVI were recorded in areas like Sekondi-Takoradi, Cape Coast, Accra Metropolitan, Ningo Prampram, and Kpone Katamanso coastal districts.

4.4.3. Estimating the ICVI for the coast of Ghana

The ICVI for the coast of Ghana was calculated by integrating the PVI and SVI (Equation 5), giving a total ICVI score of 74.36. The district ICVI values were classified using natural break classification, in ArcGIS environment to represent the different vulnerability levels (Figure 33).

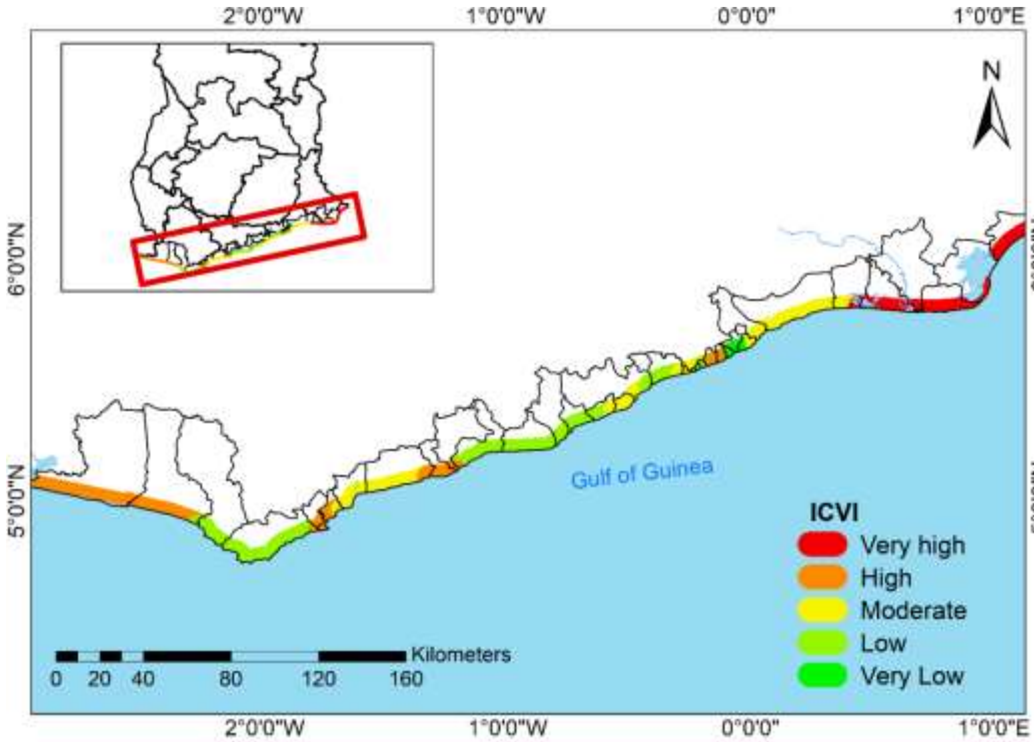

Figure 33: State of Integrated Coastal Vulnerability along the coast of Ghana

The ICVI results indicate that 6 coastal districts (18.18%) have very high risk, 10 (30.30%) have high vulnerability, 8(24.24%) have moderate vulnerability, 6(18.18%) have low vulnerability, and 3 (9.09%) have very low vulnerability. In this regard, the districts of Ada East, Anloga, Keta, and Ketu South exhibit very high vulnerability. Consequently, at least 72% of the coast exhibits moderate to very high coastal vulnerability.

4.5. **Discussion**

This study provided an opportunity for a comprehensive evaluation of the ICVI in Ghana. In this regard, the most vulnerable areas have been identified. These areas also require immediate attention for new coastal infrastructure planning, revision of implemented coastal adaptation approaches, or considerations for sustainable and resilient coastal development.

4.5.1. Significance of study to coastal vulnerability assessments in Ghana

The CVI helps to predict the susceptibility of coastal areas to both the impacts of climate change and human interference. This is important to inform decision-makers about vulnerable coastal areas, and where to plan for and implement coastal adaptation measures to reduce vulnerability (Yin et al., 2012; Koroglu et al., 2019; Mclaughlin and Cooper, 2010). The application of AHP methodology to compute ICVI by integrating physical and social variables helps to understand the coastal system's susceptibility to coastal forcing parameters, but also its ability to adapt to coastal change (Mclaughlin and Cooper 2010; Pendleton et al., 2010). AHP methodology provided the opportunity for multi-criteria analysis of parameters and provide better results. Applying this to the context of Ghana, not only contributes to the advancement of knowledge in Ghana, but also improves the approach from two previous national assessments of coastal vulnerability studies (Boateng et al., 2016; Wiafe et al., 2013), and provides the opportunity for further research incorporating more socioeconomic variables. In addition, our attempt to evaluate coastal vulnerability for each coastal district, improved previous studies (Boateng et al., 2016) by highlighting changes in coastal population, which has increased by 2.1% per annum since 2010 (GSS).

4.5.2. Vulnerable coastlines in Ghana

Coastal vulnerability remains very high along the Eastern coastal districts of Ghana particularly Ada East, South Tongu, Anlo, Keta Municipality, and Ketu South mostly due to the influence of the Volta River and the complex dynamics of the coastal ecosystem of the Volta Delta (Boateng, 2012; Ly, 1980; Roest, 2018), but also human anthropogenic activities like sediment mining (Jonah et al., 2015, 2016, 2017). In addition to the construction of sea defences (Angnuureng et al., 2013) and mangrove deforestation (Mensah et al., 2013), the increase in coastal vulnerability along the Eastern coast may be largely attributed to the construction of the Akosombo Dam as identified in previous research (Ly 1980; Appeaning Addo et al. 2020; Boateng et al. 2012). Coastal vulnerability has also increased at Jomoro and Sekondi-Takoradi (Western Coast) and Cape Coast (Central Coast). Other significant new hotspot areas included Ningo Pram Pram where new coastal protection works have been installed to reduce vulnerability to erosion hazards.

4.5.3. Future coastal infrastructure and investment prioritisation

The identification of vulnerable coastlines can help the governments and respective agencies to use the ICVI to develop resilient and sustainable infrastructure and better protect the most vulnerable coastal areas. The priority should be to move away from reactive adaptation and static measures towards dynamic or adaptive management (Bongarts Lebbe et al., 2021; Chee et al., 2021; Frohlich et al., 2022). For instance, currently installed groyne fields need integration beach nourishment to improve their efficiency and protect buildings and strategic infrastructure.

Investments in the development of CGI like mangroves, salt marshes and wetland restoration among other NbS is important to encourage living shorelines and other coastal vegetation that provide ecological benefits (Bridges et al., 2021; Cohen-Shacham et al., 2016; Currin, 2019).

It is also important to review designs and to protect strategic infrastructure like coastal roads, rails, and bridges with sea-level rise in mind to enhance their longevity and functionality (Department of Climate Change and Energy Efficiency, 2011; Nazarnia et al., 2020). Adaptive planning and coastal setback measures must be implemented to protect vulnerable coastal areas and encourage sustainable infrastructural development and land use in Ghana.

4.5.4. Pitfalls and environmental impacts from coastal grey infrastructure

Over the past two decades, the construction of sea defences has contributed to chronic coastal erosion migration to adjacent unprotected natural sandy coasts, creating new erosion hotspots. This confirms previous studies where Keta SDP transferred erosion to Kedzi area (Roest, 2018; Angnuureng et al., 2013). In recent years, the Ada groyne fields induced erosion and created new erosion hotspots at Fuveme and Atiteti. Similarly, Blekusu groyne field has severely transferred erosion to areas like Agavedzi, and Salakope. Therefore, it can be argued that in recent years, coastal defences have indirectly contributed to chronic erosion migration, structural erosion and ultimately the increased coastal vulnerability of naturally unprotected beaches especially along the Eastern coast.

4.6. Conclusions

The CVI is fundamental to providing knowledge of the current state coastal vulnerability to coastal hazards. Integrating PVI and SVI into ICVI is essential to understand both physical vulnerability and society's exposure to hazards. This is important to inform decision-makers on priority (high coastal vulnerability) areas, and communicate with stakeholders and general public about coastal hazards, and also influence adequate coastal adaptation planning and the revision of short, medium and long-term coastal adaptation strategies to address inevitable coastal changes. The AHP methodology provided a flexible multi-criteria approach to estimate ICVI, providing a better approach to understanding coastal vulnerability. Although physical parameters dominated the explanation of ICVI, the inclusion of socioeconomic variables provided the opportunity to understand the susceptibility of the coastal communities to coastal hazards, most importantly due to increasing coastal populations.

In future research, the integration of both physical and social parameters remains critical to understanding the integrated coastal vulnerability of the coast of Ghana under future sea level rise. Historical disaster information helps to understand the socioeconomic functioning of society, coordination and response to past disasters and supports future emergency planning.

Based on the results, the Eastern coast of Ghana continues to exhibit highest ICVI compared to the moderate and low ICVI along the Central, and Western coasts respectively. In addition, growing populations and insatiable demand for coastal real estate developments will, if left unplanned or unregulated, trigger encroachment into coastal ecosystems like wetlands. Therefore, we recommended not only the development of shoreline management plans to improve adaptation to coastal forcing variables, but also the enforcement of environmental laws to avoid human encroachment into buffer zones and protected areas.

4.7. Recommendations for future coastal infrastructure investment plans

Coastal vulnerability is defined as a function of: (1) coastal characteristics (resilience and susceptibility); (2) coastal forcing (variables that contribute to susceptibility), and; (3) socio-economic factors (variables explain impacts of morphological changes on society) (Mclaughlin & Cooper, 2010). To this effect, the importance ICVI studies is threefold: (1) identify and monitor changes in coastal vulnerability over time and space; (2) improve local knowledge about underlying processes of coastal vulnerability; and (3) support the development of strategies for reducing coastal vulnerability by developing resilient designs (Palmer et al., 2011). Therefore, the ICVI is important for reflecting highly vulnerable areas, adaptation planning, improving public awareness of factors that contribute to hazards, e.g., sand mining and damming, and taking measures to reduce vulnerability and improve resilience. Based on the findings of this study, we recommend the following:

1. The development of national shoreline management plans (DEFRA, 2006a, 2006b) to determine how each section of coast will be protected in the short, medium and long-term plans, especially at district level, and the implementation of appropriate coastal adaptation infrastructure to protect at-risk areas (Hill, 2015; Klein et al., 2001; Linham & Nicholls, 2010; Sutton-Grier et al., 2015). The expertise and capacity of district administrations to execute these functions should be evaluated since coastal engineering projects are highly technology-driven and expensive.

2. The alignment of coastal management policy and the national development plans, and importantly leveraging the national adaptation plan (NAP) to improve coastal adaptation and resilience. Integrating coastal adaptation into national climate adaptation is important to support the development of strategies for reducing coastal vulnerability (Palmer et al., 2011).
3. Hybridisation of coastal infrastructure to prevent chronic erosion migration and improve coastal adaptation. Over the past two decades, the coastal management approach has been reactive, hold the line policy using gey infrastructure, mainly groynes and revetments made from granite boulders. To reverse this trend, proactive adaptation and hybrid coastal protection using nature-based solutions to improve coastal resilience must be prioritised.

CHAPTER FIVE

INVESTIGATING SHORT-TERM SHORELINE RESPONSES TO GROYNE FIELDS ALONG THE COAST OF GHANA.

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Statement of Contributions of Joint Authorship

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Supervised, methodology, manuscript review, editing, and co-author of manuscript.

Abstract

Groyne fields are among the commonest coastal grey infrastructures implemented to protect coastal communities and properties against erosion worldwide. In Ghana, between 2000 and 2023, at least twelve groyne fields have been implemented along the 550 km coastline using granite rocks. However, studies on short-term shoreline responses at groyne fields have received little attention despite increasing groyne system implementation. To close this gap, we employed a combination of field surveys, satellite imagery, and GIS to evaluate short-term shoreline variability and environmental impacts of groyne fields at Ada, Blekusu and Cape Coast between 2000 and 2023. First, we employed high-resolution Planetscope Imagery to obtain satellite-derived shoreline positions. Second, an unmanned aerial vehicle was flown at sites between March and October 2022 to collect high-resolution imagery on variability and sediment volume changes. Results indicate that, during this period, erosion persisted at Ada (LRR -5 m), Blekusu (LRR = -3 m), with accretion at Cape Coast, (LRR = 0.78 m). The observed environmental pitfalls include: (1) severe shoreline migration at the terminal groynes (terminal groyne effect) at Blekusu and Ada that altered shoreline geometry; (2) rapid change of beach plan form (formation of saw-shaped beaches). The findings are crucial to support coastal decision-makers to revise coastal adaptation approaches and to consider hybrid infrastructure for coastal protection along the coast of Ghana.

Keywords: Groyne fields, grey infrastructure, coastal erosion, coastal adaptation, shoreline responses, environmental pitfalls, Ghana.

5.1. **Introduction**

Different types of coastal grey infrastructure - seawalls, revetments, breakwaters, and groynes – can be used to protect shorelines against coastal erosion. In recent times, SLR has intensified, aggravating frequency and severity of coastal hazards and ultimately increasing demand for coastal adaptation infrastructure (Bongarts Lebbe et al., 2021; Kirby et al., 2021; Mallette et al., 2021; Nazarnia et al., 2020; Hill, 2015; Sutton-Grier et al., 2015; Mycoo & Chadwick, 2012; Linham & Nicholls, 2010; Tol et al., 2008; Klein et al., 2001). In this regard, groynes are one of the commonest grey infrastructures implemented for shoreline protection globally.

Groynes are shore-perpendicular structures built to trap sediment and prevent coastal erosion. Many types of groynes are identified in literature including: (1) piled; (2) narrow-footprint; (3) gravity; (4) hybrid structure; (5) permeable; (6) and bulk/rubble-mound groynes (Simm et al., 2020). Bulk/rubble-mound groynes are commonly built using armour rocks with straight, Y, T, and L-shape designs depending on factors such as sediment type, rate of longshore drift, and tidal currents (Simm et al., 2020). In Ghana, virtually all groynes fit into the latter typology and typically made with granite rock boulders.

Functionally, the purpose of groynes is twofold: (1) maintaining the beach behind them; and (2) controlling the amount of sand moving alongshore (Kraus et al., 1994). In this regard, the detailed modern functional design of groynes, including parameters governing beach response to groynes and functional properties attributed to groynes has been thoroughly studied, e.g. in the United States (Kraus et al., 1994; Simm et al., 2020), and so are the guidelines for maintenance and lengthening of groynes (CSE, 2013). A list of findings and recommendations for the modern functional designs of groynes was synthesised by Kraus and Rankin (2004).

Similarly, the parameters governing beach response to groynes are well documented, and typically established as a function of the characteristics of at least 27 parameters that include: (1) groynes length and permeability, (2) beach and sediment, (3) wave, wind, and tides (Kraus et al., 1994). Findings from these studies indicate that shoreline responses at groyne fields is variable depending on key factors like groyne length, permeability, and length of groyne fields (Kraus et al., 1994; Kraus & Rankin, 2004; Simm et al., 2020). Typically, an increase in permeability decreases the efficiency of the groynes, and different groyne permeabilities produce different equilibrium beach plan forms (Kraus et al., 1994). Consequently, the efficiency of the groyne field is high with maximum sediment trapping but rapidly diminishes with an increase in permeability (i.e. 100% permeability nullifies the function of the groyne) (Kraus et al., 1994).

The design of groynes is an evolving process and periodic groyne maintenance and lengthening of groyne systems is recommended for optimal efficiency (CSE, 2013). Groyne lengthening is important because it increases the impact of the structure on the shoreline (CSE, 2013; Kraus et al., 1994). The success of groynes is judged when the groyne is successful in preserving the position of the (local) shoreline, herein defined as the "preservation of shoreline position in a groyne compartment or next to a groyne such that the shoreline never recedes landward of half the effective groyne length" (Kraus et al., 1994).

The environmental pitfalls of shoreline stabilisation have been researched on a global perspective and includes failed coastal stabilisation in Kwazulu Natal, South Africa (Smith et al., 2012), modifications to Tweed River Mouth on Gold Coast in Australia that interrupted longshore transport and contributed to coastal erosion migration to other beaches (Cooper & Pilkey, 2012), and the proliferation of hard-engineered structures like groynes, gabions, and seawalls in Puerto Rico that contributed to the narrowing and loss of beaches (Jackson et al., 2012). In West Africa, several installed defences have succumbed to wave action, and beach nourishment has been discontinued due to high costs (Alves et al., 2020). In their study, Pilkey and Cooper (2014a) attribute the extinction of natural beaches due to human anthropogenic activities. The inexhaustible list of human anthropogenic actions includes sandy beach mining, construction of coastal hard structures, and pollution (Pilkey & Cooper, 2014a).

Specifically, the environmental impacts of groynes - like all hard-engineered coastal infrastructure - have been established in literature and include: (1) Sediment trapping updrift and starvation to downdrift coast, leading to, (2) coastal erosion migration to downdrift coasts (Angnuureng et al., 2013), (3) shoreline migration at terminal groynes, and (4) the formation of beaches with saw-teeth beach plan forms (CSE, 2013; Hughes, 1993; Kraus & Rankin, 2004; Reeve et al., 2004; Simm et al., 2020). These are processes that ultimately affect shoreline evolution and geometry. In their findings, Angnuureng et al (2013) established that the groyne fields at Keta caused downstream sediment starvation and created new erosion hotspots at downdrift areas like Blekusu, Agavedzi, and Adina foreshore. Despite these impacts, globally, studies on short-term local changes – years to decades – influenced by various grey structures are scarce (Ells & Murray, 2012).

In Ghana, at least 12 groyne fields have been implemented at places like Cape Coast Oasis Beach (4 groynes), Anomabo (7 groynes), Old Ningo (8 groynes), New Ningo (14 groynes), Ada East (22 groynes), Atorkor (13 groynes), Keta (6 groynes), and Blekusu Phase I (18 groynes) (Charuka et al., 2023), making groyne fields a prominent coastal infrastructure. However, except for Angnuureng et al. (2013) and Angnuureng et al. (2022), there are no studies on shoreline responses at groyne fields nor the synthesis of the environmental impacts of grey infrastructure along the coast of Ghana even though groyne fields are very common.

To close this gap, we leveraged high-resolution PlanetScope satellite and UAV imagery to assess short-term shoreline responses at three groyne fields. The objectives of this study are to: (1) measure shoreline position at groyne fields and establish the influence of groynes on beach morphology; (2) investigate sediment volume dynamics; and (3) assess environmental pitfalls on neighbouring coastlines. Studying groynes is important to gain a thorough understanding of how groyne systems alter natural coastal processes and coastal ecosystem dynamics. In this study, the focus was more on shoreline responses (stability). The findings are important to support coastal decision-makers in revising implemented solutions and considering adaptive management and hybridisation of coastal infrastructure in Ghana.

5.2. Materials and Methods

5.2.1. Study Areas

The study covers three groyne fields along the coast of Ghana namely, Cape Coast, Ada East, and Blekusu. Site selection was informed by the previous studies on coastal infrastructure (Charuka et al., 2023) and integrated coastal vulnerability assessment (Boateng et al., 2016).

Cape Coast

Constructed in 2019, the groyne field at Cape Coast Oasis Beach (Figure 34) comprises of four gigantic trapezoidal groynes at the beachfront of Oasis Beach Resort. Each groyne has an approximate length of 65 m, a height of roughly 3.5 m above mean sea level (at construction) and an average width of 10 m. The giant groynes are constructed from piled granite boulders, assembled in a shore-perpendicular, North-South direction.

Figure 34: The groyne field at Cape Coast (Oasis Beach Resort). Source: Google Earth, 2022

The dominant wave direction at Cape Coast is mainly SSW, with H = low (0.92 - 1.00 m). Littoral transport is in West-East direction and the historic average shoreline change rate is -1.12 m/year.

Ada

The Ada groyne field was constructed in 2013 to counter persistent coastal erosion and protect communities from wave overtopping (Bolle et al., 2015). The groyne field covers 16 km along the beach, making it the longest groyne field along the coast of Ghana (Figure 35). It comprises 22 groynes, 90 m in length, interspaced at approximately 700 m. The groynes are constructed from piled granite rocks assembled in a shore-perpendicular direction. However, despite the present protection, Ada remains a highly eroding sandy beach and erosion hot spot (Jayson-Quashigah, 2019; Jayson-Quashigah et al., 2013).

Figure 35: The Ada groyne field, comprising 22 groynes. Source: Google Earth

The dominant wave direction at Ada is mainly from SSW direction, with H_s = moderate (1m – 1.09m). Littoral transport is high in West-East direction. Over the past decades, the groyne field at Ada is largely attributed to the coastal erosion migration to adjacent areas of Fuveme, Atiteti, and Anyanui, which have been hard hit by erosion and frequent flooding.

Blekusu

The Blekusu (Phase I) coastal protection comprises 18 groynes (Figure 36) at the foreshore of Blekusu community, Ketu South district, along the Eastern coast of Ghana. The groyne field stretches for approximately 4 km, bound by the coordinates (5.984186°N, 1.031531°E and 6.009447°N, 1.049286°E). The average length of each groyne is 90 m, with a uniform width of about 10 m and the inter-groyne distance is approximately 200 m.

Figure 36: Blekusu (Phase 1) groyne field comprising 18 groynes

The predominant wave angle (α) at Blekusu is mostly SSW; 180°≤α≤200°, with a mean of α = 190°. The wave angle, α, is an important determinant of the littoral transport rate. Littoral transport moves in a West-East direction, trapping sediment westward and inducing erosion on the East side of the groynes. Groyne spacing is of vital importance as it contributes to the efficiency of the system (CSE, 2013; Kraus et al., 1994; Kraus & Rankin, 2004; Simm et al., 2020). The dominant wave direction is mainly South to SSW directions with H_s = high (1m – 1.13 m).

5.2.3. Data collection and processing

(i) Data acquisition from satellite imagery.

High resolution satellite data was acquired from Planet Earth Explorer (https://planet.com/explorer/) daily scenes annually in October from 2017 to 2022 (Figure 37).

The satellite images were geometrically corrected and projected to UTM 30N in ArcGIS Desktop to eliminate spatial distortions and match a single geographic reference system. The description of satellite imagery used for shoreline extraction is tabulated in Table 13.

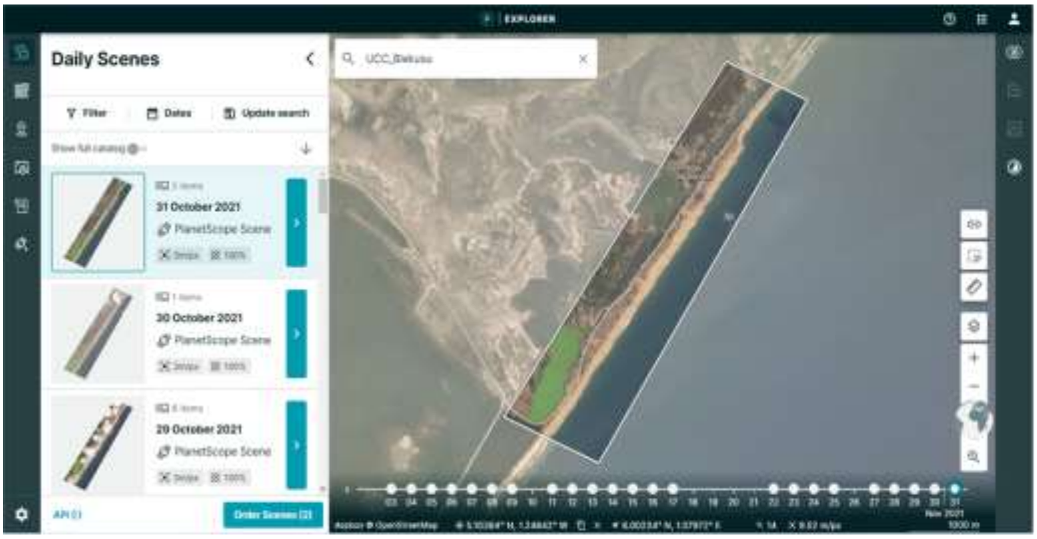

Figure 37: Acquisition of satellite images from Planet Explorer

Table 13: *Description Of Satellite Imagery Used for Shoreline Extraction*

Study Area	No. of groynes	Platform	Resolution	Map Projection	Date Acquired	Cloud Cover (%)
Ada	4	PlanetScope	3m	UTM 30N	04/11/2022	0.00
			3m	UTM 30N	04/11/2022	0.00
			3m	UTM 30N	04/11/2022	0.00
			3m	UTM 30N	04/11/2022	0.00
			3m	UTM 30N	04/11/2022	0.00
Cape Coast	22	PlanetScope	3m	UTM 30N	01/22/2023	0.10
			3m	UTM 30N	01/22/2023	0.13
			3m	UTM 30N	01/22/2023	0.00
			3m	UTM 30N	01/22/2023	0.51
			3m	UTM 30N	01/22/2023	0.00
Ada	18*	PlanetScope	3m	UTM 30N	01/22/2023	0.10
			3m	UTM 30N	01/22/2023	0.19
			3m	UTM 30N	01/22/2023	0.60
			3m	UTM 30N	01/22/2023	0.00
			3m	UTM 30N	01/22/2023	0.00

(ii) **Data acquisition using UAV**

An unmanned aerial vehicle (UAV), DJI Phantom 4 Pro was flown over the three study areas once every two months for one year from March 2022 to September 2022 to monitor short-term shoreline responses to groynes. Drone Deploy software (https://www.dronedeploy.com) was used to plan flight paths with flight altitude set to 100 m to achieve a wider beach coverage following Jayson-Quashigah (2019). Four flights were made for each site. The detailed flight descriptions are given in Table 14.

Table 14: *Study Sites and Dates of Drone Flights*

Name of Site	Geographic boundaries	Flight Dates	Mean flight duration	Images Captured
Cape Coast	5.102717°N, 1.244746°W- 5.103135°N, 1.242189°W	1. 21/03/2022 2. 09/05/2022 3. 15/07/2022 4. 03/09/2022	30 minutes	500
Ada	5.769937°N, 0.665380°- 5.782566°N, 0.534417°E	1. 21/03/2022 2. 21/05/2022 3. 11/07/2022 4. 20/09/2022	45-60 minutes	650
Blekusu (Phase I)	5.984186°N, 1.031531°E - 6.009447°N, 1.049286°E	1. (Lost Data) 2. 22/05/2022 3. 12/07/2022 4. 21/09/2022	45-60 minutes	700

Approximately 650 images were captured during each flight at Ada East, 700 at Blekusu, and 500 at Cape Coast. Flights were made during the high tide and tide times were acquired from (https://www.tide-forecast.com).

5.2.4. **Processing UAV imagery.**

Data from UAV was cleaned in Agisoft Metashape software to remove blurred and overexposed pictures taken outside the defined flight path to reduce errors during the construction of Digital Elevation Models (DEMs) and orthophotos following Jayson-Quashigah (2019). Images were processed based on Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms embedded in the Agisoft Metashape software (Jayson-Quashigah, 2019). This involved sequential alignment of photos, building dense cloud, building DEM, and generating orthomosaics. All orthophotos were georeferenced to the Ghana meter grid using a 2005 orthophoto.

5.2.5. **Shoreline extraction**

Different proxies – the High-Water Line (HWL) mark, the tidal datum-based Mean High Water (MHW) or Mean Sea Level (MSL) mark – can be used to extract shorelines from remotely sensed data (Dolan et al., 1991; Boak & Turner, 2005; Appeaning Addo et al., 2008). Nonetheless, contemporary advances in remote sensing, image processing (Boak & Turner, 2005), and machine learning using open-source software such as Google Earth Engine, Coastsat toolkit and Python (Vos et al., 2020, 2019; Castelle et al., 2021), allow automatic shoreline extraction and time series analysis of shoreline change, or the use of Bayesian Network (BN) models to predict shoreline evolution (Plant et al., 2016). In this study, shorelines were manually digitised from orthophotos on the HWL.

5.2.6. **Shoreline change rate estimation**

Shoreline change analysis was done using the Digital Shoreline Analysis System (DSAS) extension in ArcGIS software. Shorelines were merged and referenced to a baseline. Consequently, transects were uniformly cast at 10 m intervals at each site to calculate changes. In DSAS, several statistical methods can be used for shoreline change rate estimation. These include the Linear Regression Rate (LRR), End Point Rate (EPR), Net Shoreline Movement (NSM), Average of rates (AOR), Jack Knifing (JK), among others (e.g. Dolan et al., 1991; Boak & Turner, 2005). The LRR computes the shoreline change rate by fitting a least square regression to all shoreline positions. LRR is the simplest, detailed, most reliable based on accepted statistical concepts (Boak & Turner, 2005) and therefore most reliable methodology (Deepika et al., 2014). The NSM computes the distance between the oldest and most recent shorelines for each transect and the EPR can be established by dividing NSM by the time elapsed between the oldest and most recent dates (Deepika et al., 2014). In this study, both the NSM and LRR were used. The LRR, (Equation (6), was employed to calculate change rates for satellite-derived shorelines between 2017 and 2022 following (Jayson-Quashigah, 2019).

$$Y = \beta_0 + \beta_1 X_i + \varepsilon \qquad (6)$$

Where Y equals all observed values for the dependent variable, β_0 is the Y intercept or constant or bias, β_1, is the slope or coefficient, X_i is the observed values of the independent variable, and ε is the error component.

The NSM (Equation 7) was also used to compute net shoreline movement (2015-2022) and to compute short-term shoreline response to the groyne field by establishing variation in distance (in metres) from UAV-derived shorelines.

$$NSM = S_b - S_a \qquad (7)$$

Where S_a and S_b are the recent and older shorelines respectively.

5.2.7. **Error estimation in shoreline changes**

Manual digitisation of shoreline position from orthophotos generated from UAV imagery and the georeferencing of images is intrinsically associated with errors. The errors: ground sampling distance, (E_p), georeferencing error (E_g), and tidal range error (E_t) were used to compute the total positional error, (E_r) using Equation 8 (Jayson-Quashigah, 2019).

Shoreline uncertainties were estimated based on previous studies (Appeaning Addo et al., 2012; Brempong et al., 2021; Hapke et al., 2011).

$$E_r = \sqrt{(E_p{}^2 + E_g{}^3 + E_d{}^2 + E_t{}^2)} \quad (8)$$

Where (E_p) is the ground sampling distance, (E_g) is the georeferencing error, E_d is the total digitising error, and (E_t) is the tidal range error. In this study, E_p was 0.6, E_g was 0.6, E_d was 0.5, and E_t was 1. The total horizontal positional error was 1.40 m

Subsequently, the annualised error (E_x) was estimated to account for uncertainties in the shoreline rate of change at each transect using equation (9). (Appeaning Addo et al., 2012; Brempong et al., 2021; Jayson-Quashigah, 2019).

$$E_x = \sqrt{(E_p{}^2 + E_g{}^3 + E_d{}^2 + E_t{}^2)}/T \quad (9)$$

Where E_1, E_2,... Ez are the total shoreline position errors for each year and T is the period (T = 5 years) of analysis. In this study, the annualised error was 0.23m.

5.3. **Results**

The three groyne fields exhibited varying shoreline responses and morphological changes presented in this section

5.3.1. **Cape Coast**

Shoreline responses using satellite photogrammetry

The LRR for Cape Coast for the five years (2017-2022) based on satellite imagery from Planet Explorer was established to be -1.18m/year (Figure 38).

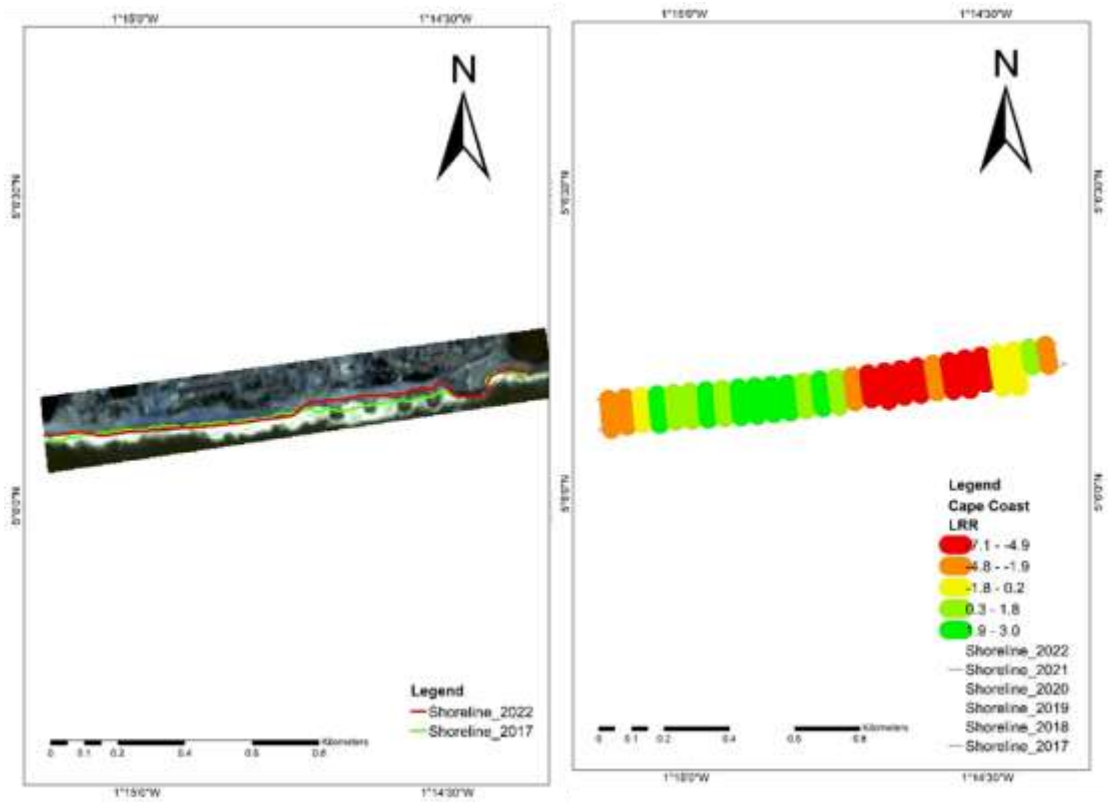

Figure 38: Shoreline change responses at Cape Coast between 2017 and 2022

In 2019, the commencement of the construction of the Cape Coast Seawall led to the seaward land reclaim of approximately 50-60 metres of land, part of which was used to construct roads during the construction, confirmed through georeferencing with a 2005 aerial orthophoto overlay. This could easily be mistakenly accounted as accretion.

Shoreline response using UAV imagery.

Shoreline changes were calculated over a total of 373 transects, cast over a distance of 4 km The mean LRR at Cape Coast between March and September was 0.78 m/year (Figure 39).

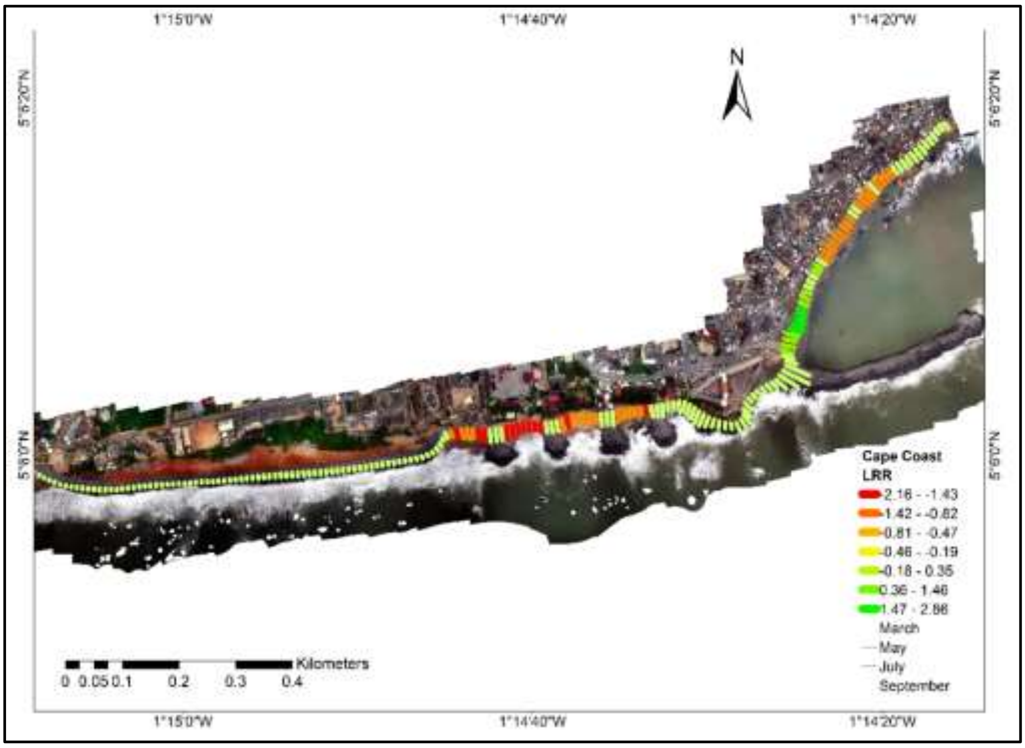

Figure 39: Linear Regression Rates for Cape Coast between March and September

Although the entire beach is stabilised by the seawall and four-groyne field, results indicated that there is gradual erosion between the groynes.

At the same time, the detailed investigation of the shoreline distance movement between March and September 2022 indicated that the mean NSM ranged from -0.24m to -0.56m (Figure 40).

The mean NSM was -0.24 m between March and May 2022, -0.48 m between May and July, and -0.55 m between July and September. Altogether, the mean NSM between March and September was -0.24 m, (Figure 41). Although the seawall stabilised the beach from Fosu lagoon, the results indicate that coastal erosion was persistent between the groynes at Oasis beach.

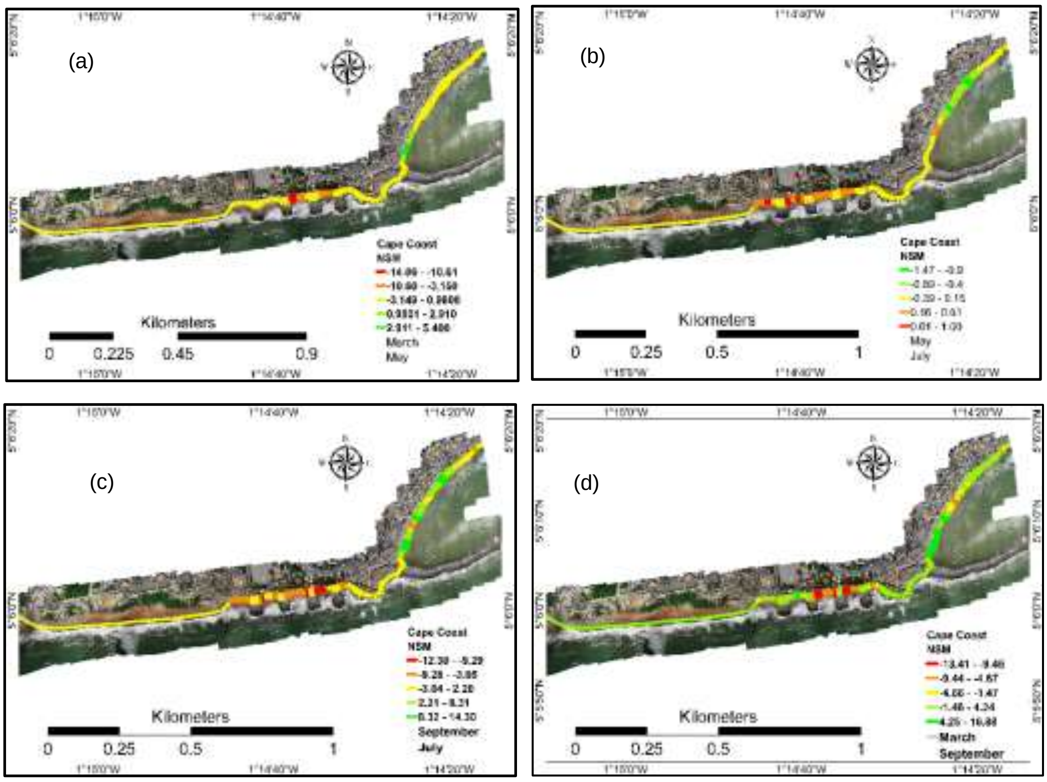

Figure 40: Shoreline movement at Cape Coast between March and October 2022. The figure shows rates between (a) March-May, (b) May-July, (c) July-September, and (d) March-September 2022

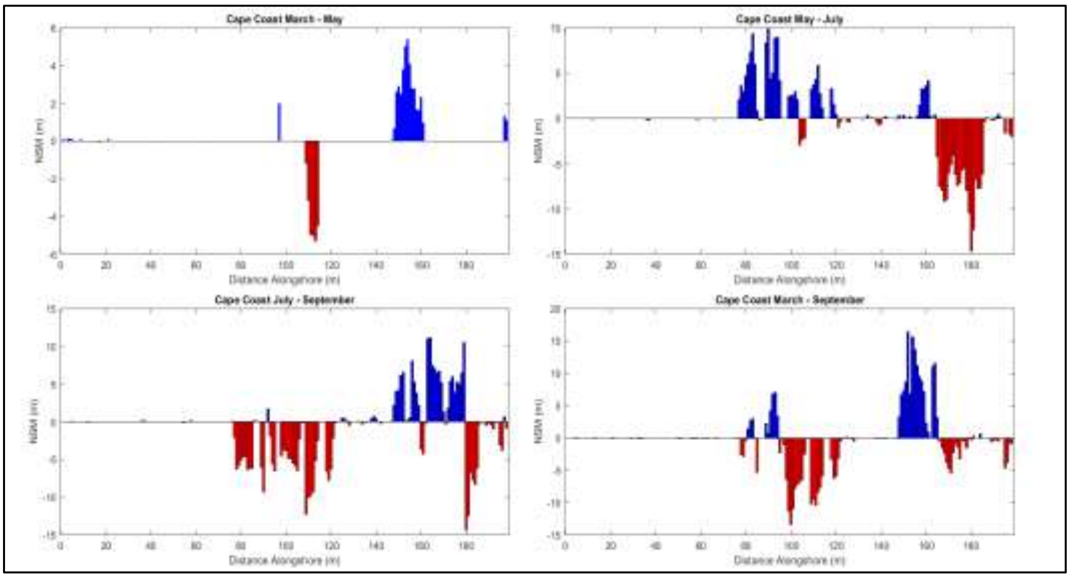

Figure 41: Erosion and accretion trends at Cape Coast, March – September 2022

5.3.2. **Ada East**

Shoreline responses using satellite photogrammetry

The LRR results over five years (2017-2022), using Planet Explorer data sets was -5.53 m/year (Figure 42). During this period, the mean shoreline movement was 34.6 m and the maximum distance movement was 49.3 m (Appendix E).

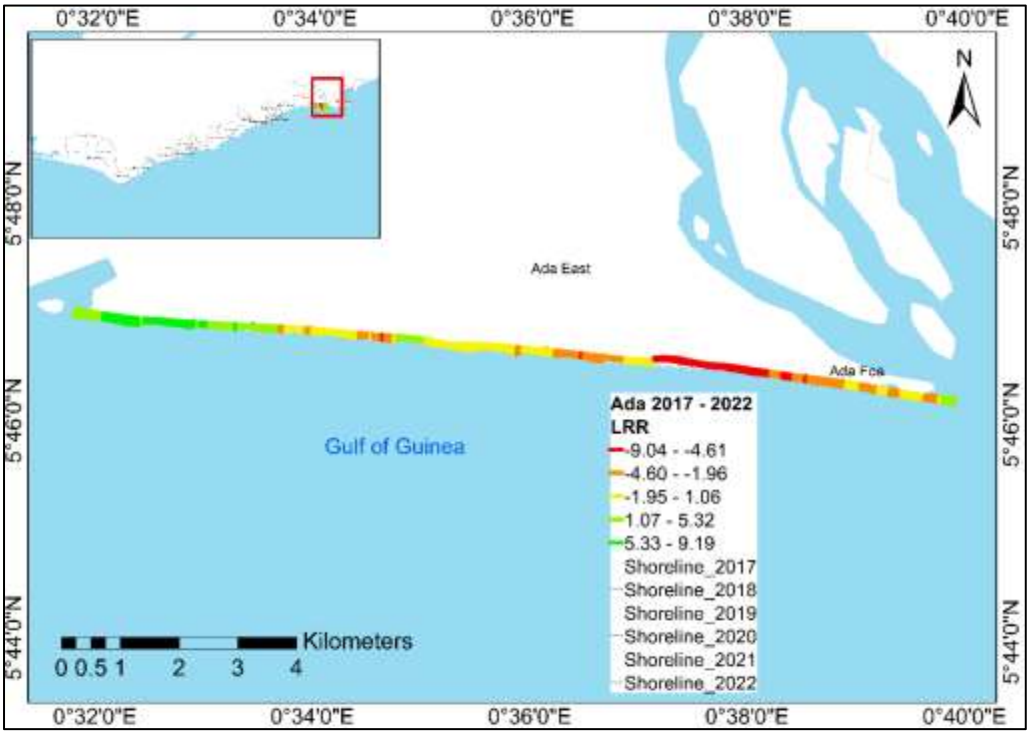

Figure 42: Shoreline changes at Ada between October 2017 and October 2022

Shoreline changes using UAV imagery

A total of 1021 transects were cast over a distance of 4 km. The mean LRR results for Ada was -5 m/year (Figure 43). During this period, Ada exhibited the highest shoreline change rate of all three sites.

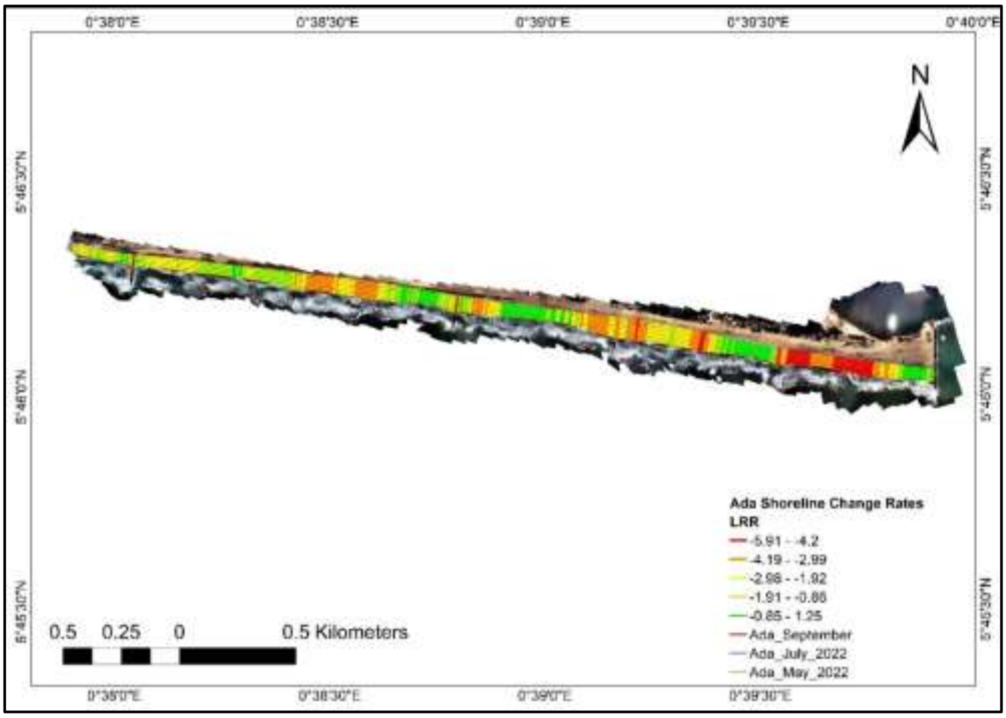

Figure 43: Shoreline changes for Ada from May to September 2022

The NSM between May and July was 4.68 m, between July and September was 6.28 m and, 3.96 m between May and September 2022 (Figure 44).

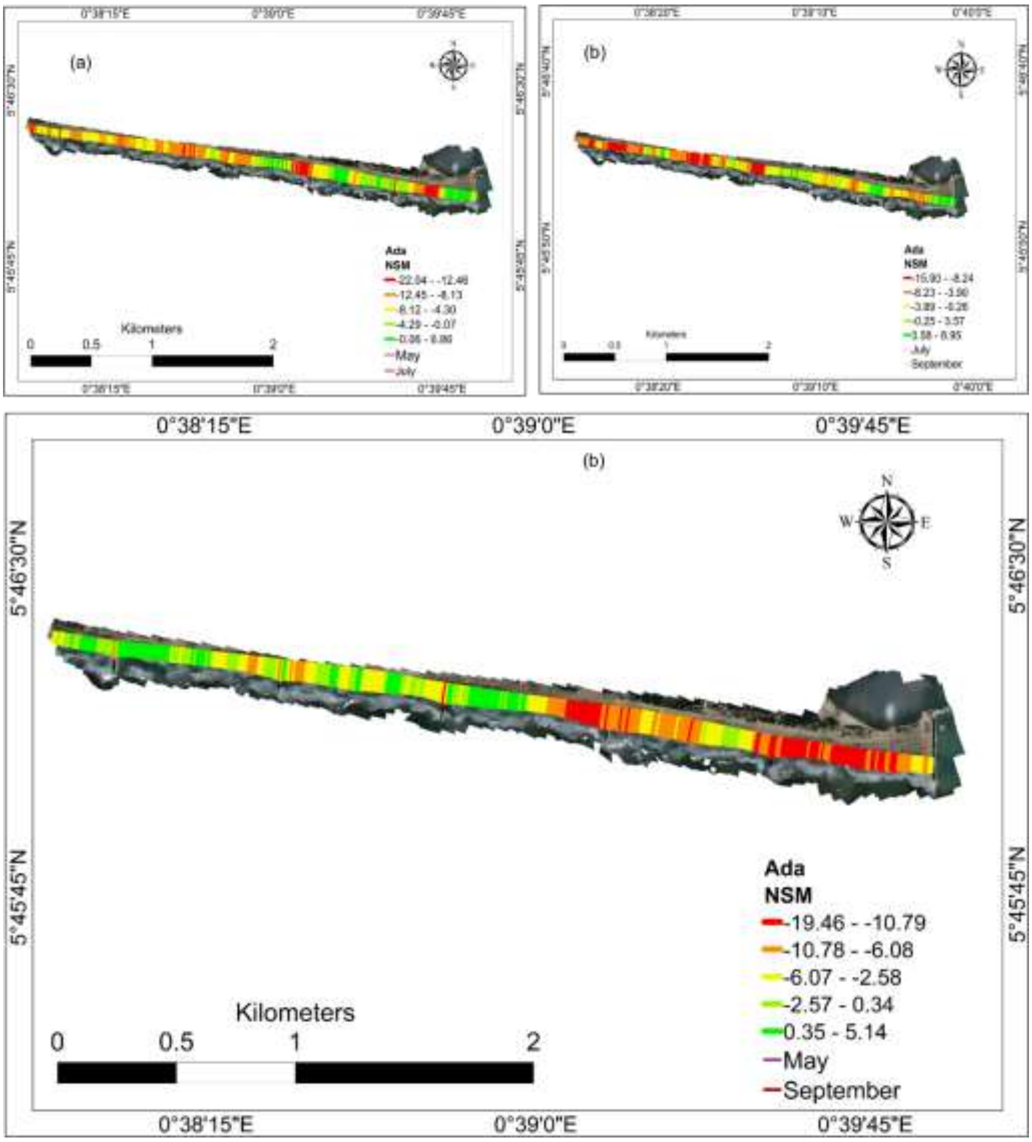

Figure 44: Net shoreline distance movement at Ada from May – September 2022

The variation in erosion and accretion trends is shown in (Figure 45).

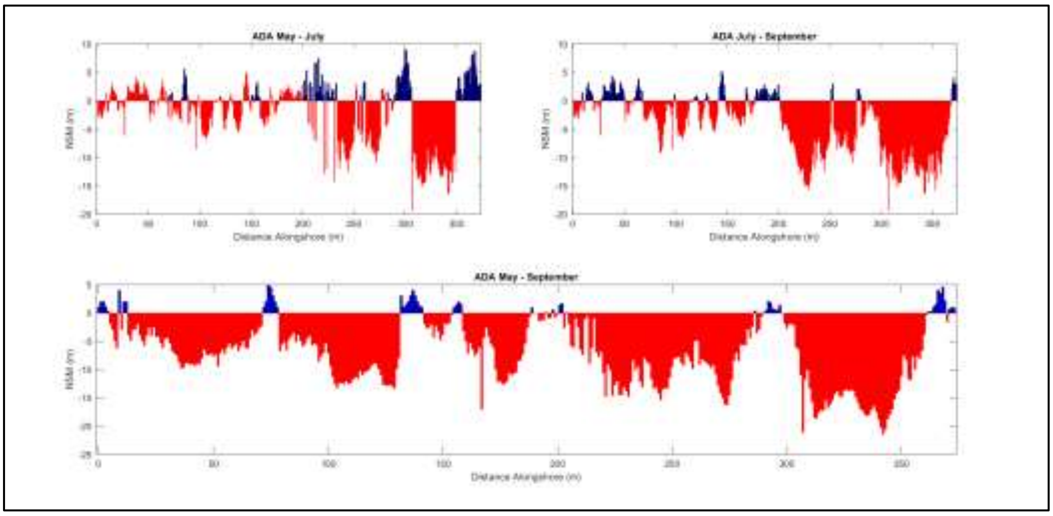

Figure 45: Erosion and accretion at Ada between May and September 2022

5.3.3. **Blekusu**

Shoreline responses using satellite photogrammetry

The LRR results over five years (2017-2022) using Planet data sets was -established to be -7.8 m/year. During the construction of the groyne field, approximately between 80 and 90 metres of land was reclaimed seaward (Figure 46a). Consequently, beach nourishment and accretion dominated the 2018 to 2021 period as the beach stabilised. However, coastal erosion was notable between 2021 and 2022, as the beach responded to the groyne system, seen through the saw-shape beach form and terminal groyne effect (LRR = -8-m), (Figure 46b).

In terms of environmental impact indications, the migration of shorelines beyond the terminal groynes is evident. In addition, there is already evidence of change to the beach form (saw-tooth beach formation) and coastal erosion spillover to downdrift communities like Agavedzi and Salakope.

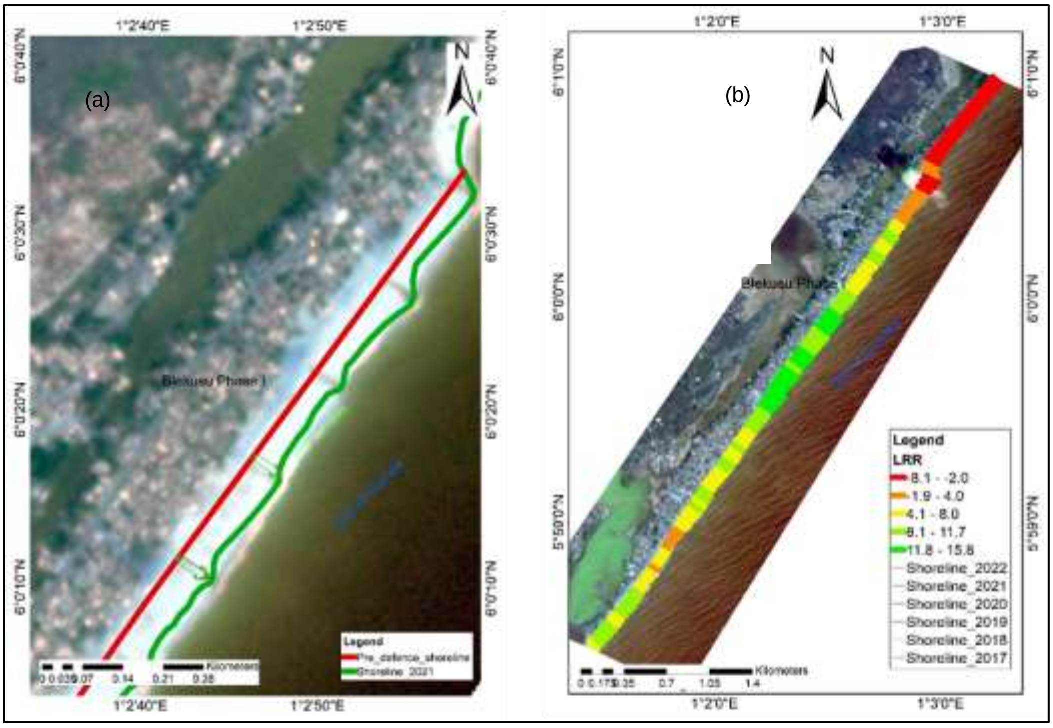

Figure 46: Shoreline changes at Blekusu between 2017 and 2022. The figure shows (a) land claim during construction and (b) shoreline responses to the groyne field

Shoreline change analysis using UAV imagery

Approximately 411 transects were cast over a distance of 4,100 m, and spaced at 10 m. The mean LRR from May to September was -2.58 m/year.

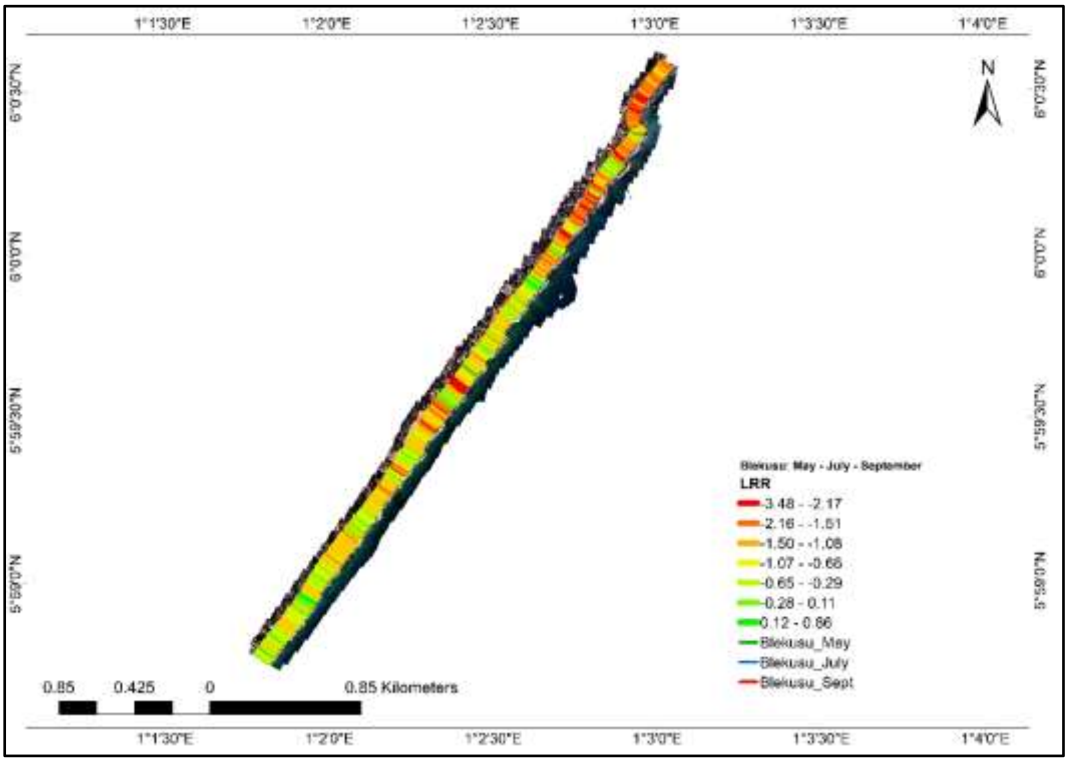

Figure 47: Shoreline change rates at Blekusu from May to September 2006

Blekusu recorded the second-highest shoreline change rate during this period, after Ada. At the same time, analysis of the NSM indicated that the mean distance movement between May and July was -1.63 m, -1.92 m between July and September, and -2.02 m between May and September 2022 (Figure 48).

At Blekusu, despite the accretion trend in May, erosion dominated the beach from May through to September (Figure 49).

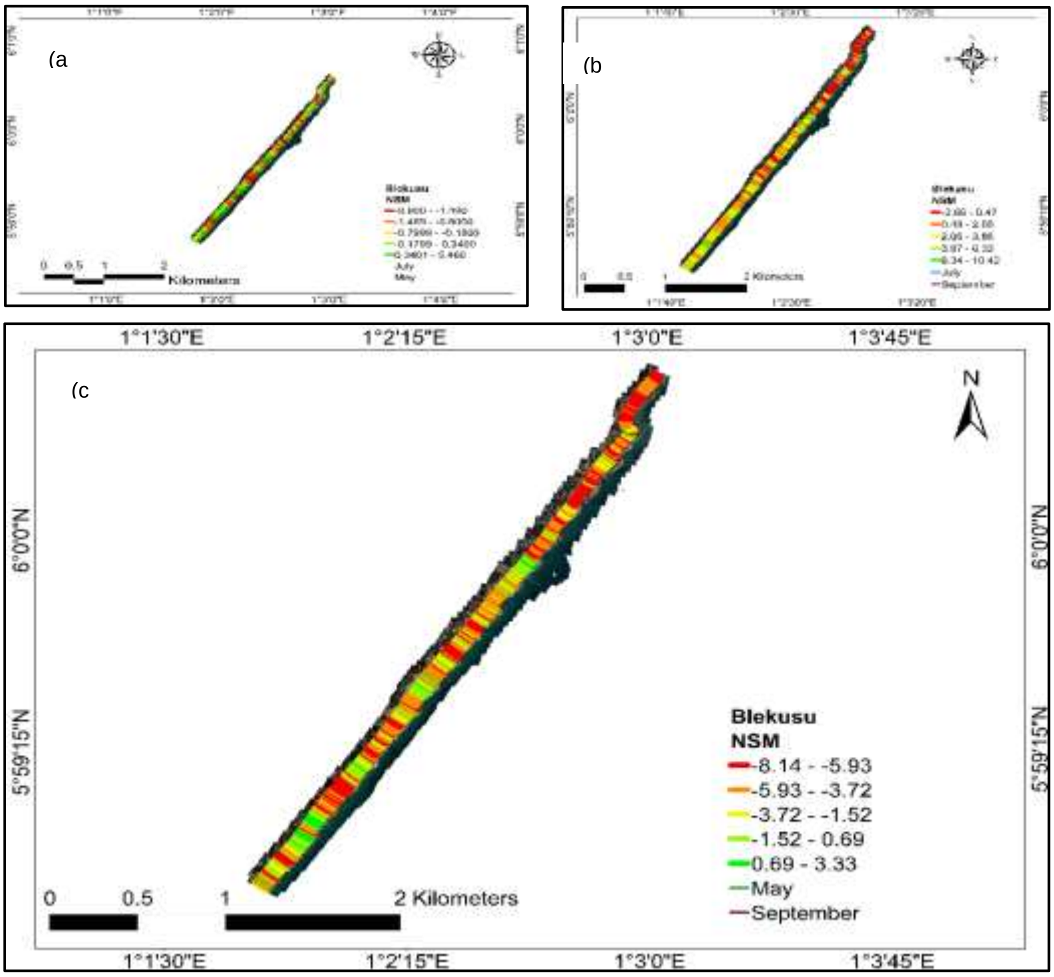

Figure 48: Net shoreline movement at Blekusu from May and September 2022

The erosion and accretion trends at Blekusu are shown in Figure 49.

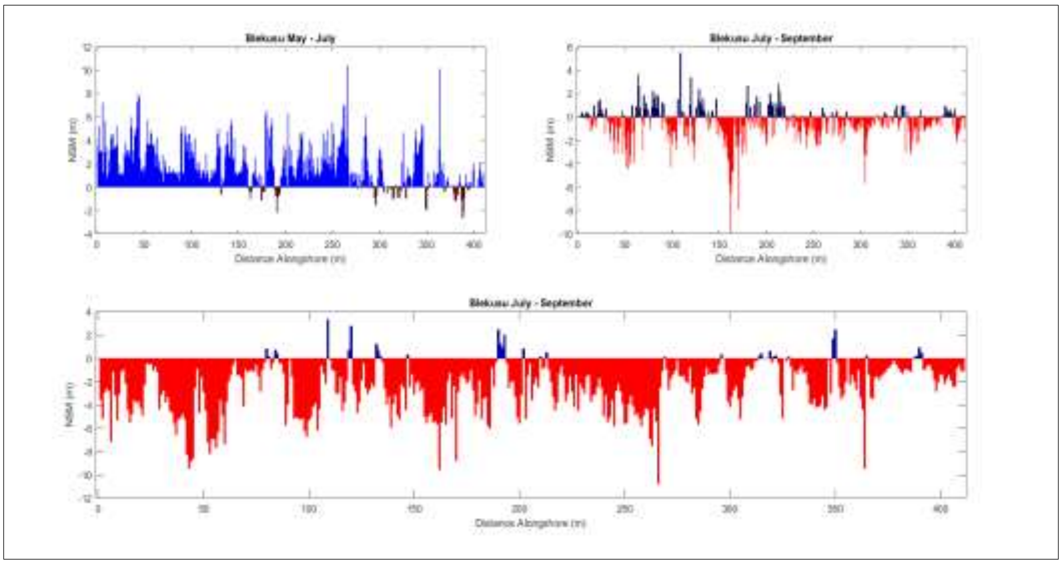

Figure 49: Erosion and accretion at Blekusu (May and September 2022)

Summary of shoreline changes

The summary of shoreline change rates between March and September 2022 for the three beaches is presented in Table 15.

Table 15: *Summary of Shoreline Responses at Groyne Fields*

Data Acquisition Method	Month/Year	Shoreline change rate (m/year)		
		Ada	Blekusu	Cape Coast
Satellite (Planet Data)	10/2017 - 10/2022	-5.53± 0.40	-7.11± 0.40	-1.13 ± 0.40
UAV (DJI Phantom 4)	03/2022 - 05/2022	*Data loss	*Data loss	-5.23
UAV (DJI Phantom 4)	05/2022 - 07/2022	-4.68	-0.63	-0.14
UAV (DJI Phantom 4)	07/2022 - 09/2022	-6.28	-1.92	-0.55
UAV (DJI Phantom 4)	05/2022 - 09/2022	-3.96	-2.02	-0.24

*Data and equipment was lost during flight

5.4.**Discussion**

Different results were obtained at the three study sites pointing to the uniqueness of each beach and hence differing beach responses to groynes (Kraus et al., 1994; Simm et al., 2020). Increasing erosion between groynes at Cape Coast (approximately -0.8m/year) is of major concern as the beach has not built up for some time. This could point to one solution – beach nourishment – to encourage the build-up and stabilisation of the beach. However, nourishment is a costly temporary solution associated with ecological disruptions (Cooper & Pilkey, 2012).

At Blekusu, some environmental pitfalls were observed. First, erosion intensified at the terminal groyne with a maxim shoreline movement of -8 metres in six months. Second, coastal erosion migrated to adjacent naturally unprotected and uneroding sandy coasts at Agavedzi and Salakope, creating new erosion hotspots within a year and triggering a national outcry for more coastal protection at beaches. While the increased erosion between May and July at Blekusu could be attributed to the onset of the wet season, it provides sufficient basis to argued that there was notable erosion despite coastal protection.

The Ada groyne field deteriorated rapidly with the cessation of beach nourishment. Currently, the groynes are immersed in water and it is inarguable that the permeability of groynes is almost entirely compromised (permeability ~ 98%). Again, the reduction in groyne sediment trapping capacity at Ada may be attributed to less maintenance and the termination of beach recharge considering that beach sediment trapping at a groyne field is a function of length, height, and spacing (USACE, 2002; SCE, 2013). As these parameters deteriorate, the functional capacity of the groyne system is reduced, causing a narrow beach (CSE, 2013). Therefore, urgent attention is required at Ada, possibly with beach nourishment, groyne lengthening, and revision of groyne spacing. Furthermore, the installation of the groyne field at the Volta Estuary and interaction with estuarine and ocean processes could have led to the disappearance of the sand bar at the mouth of the estuary.

Finally, since most extreme coastal events and coastal erosion occur as a series of episodic events (Hughes, 1993), both short-term and long-term monitoring of shoreline responses at these groyne fields is recommended to inform coastal management decisions (groyne maintenance (lengthening and repair), or hybridisation through beach nourishment. Alteration of groynes design (L, T, and Y forms) (Simm et al., 2020) can be considered to encourage downdrift sediment discharge and reduction of beach loss.

5.5. **Conclusion**

Groyne fields are one of the most common coastal grey infrastructures implemented along the coast of Ghana to protect coastal communities and properties against coastal erosion. In this study, the results of short-term shoreline responses at groyne fields indicated varying erosion and accretion rates and hence different shoreline responses to groyne fields. Comparatively, Ada had the highest erosion rate with the highest shoreline movement of 49.25 m compared to 37.4 m and 35.9 m for for Blekusu and Cape Coast in the same period. However, many factors of longshore and cross shore parameters were not included in this study and this warrants further research to establish not only shoreline responses, but total beach response to the groyne field. Both short and long-term monitoring is required to fully understand the functioning of the implemented groyne fields and the environmental impacts. Some environmental impacts were identified, mostly shoreline migration and changes to beach plan forms. To provide a lasting solution, the implemented groynes could be augmented with hybrid solutions such as beach nourishment to improve efficiency, but being wary that nourishment is a temporary process that can be a very expensive solution, especially in the context of developing countries.

CHAPTER SIX

SOCIOECONOMIC PITFALLS OF COASTAL GREY INFRASTRUCTURE AND IMPLICATIONS FOR ARTISANAL FISHERIES AND COASTAL MANAGEMENT POLICY IN GHANA.

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Statement of Contributions of Joint Authorship

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Agblorti S. K.M. **Principal Supervisor**

Supervised and assisted with manuscript review, and co-author of manuscript.

Angnuureng D.B. **Co-Supervisor**

Conceptualisation, supervised , manuscript review, editing, and co-author of manuscript

Abstract

Throughout the history of coastal development, human alteration of the coastline has negatively affected the coastal environment and society. Over the past two decades (2000-2022), coastal grey infrastructure was dominantly used to protect the Ghanaian coastline in response to severe coastal erosion. However, grey infrastructure caused unwelcome environmental and socioeconomic impacts. Furthermore, in a developing country where artisanal fisheries and coastal tourism are the backbone of coastal livelihoods, it became necessary to investigate the socioeconomic pitfalls of coastal stabilisation on livelihoods. To achieve this, we employed in-depth interviews (IDI), televised video interviews, and published reports to establish current and historic socioeconomic impacts. The findings reveal the major impacts from grey infrastructure on (1) artisanal fisheries operations, mostly beach seine fishing; (2) changing fish-landing dynamics;(3) loss of beach access and; (4) ecological status. There is a clear concern about the non-inclusion of coastal communities in the planning and implementation of coastal protection projects. It is recommended to have stakeholder engagement and inclusion in the planning and implementation of coastal adaptation approaches in Ghana.

Keywords: Human alterations, grey infrastructure, socioeconomic impacts, in-depth interviews, artisanal fisheries, community livelihoods, Ghana.

6.1. Introduction

Throughout the history of coastal development, human alteration of the coastline through human modification of the coastline to protect coastlines using different coastal infrastructures has negatively affected the coastal environment and society (Bush et al., 2001; Chávez et al., 2021; Cooper & Pilkey, 2012). In this respect, different coastal grey (hard-engineered) infrastructure have historically been used to provide trusted, immediate, and effective protection from coastal hazards (Klein et al., 2001). However, despite offering effective local protection, grey infrastructure has produced negative environmental and socioeconomic impacts (Hill, 2015; Sutton-Grier et al., 2015, 2018; Tol et al., 2008).

The environmental impacts include coastal erosion migration (Angnuureng et al., 2022; Angnuureng et al., 2013), contributing to the loss of beaches through coastal squeeze (Cooper & Pilkey, 2012; Pilkey & Cooper, 2014b), ecological impacts (Chapman & Blockley, 2009; Powell et al., 2019), loss of beach aesthetics (natural beautiful beach scenery). Both shore-parallel and shore-perpendicular structures contribute to beach degradation and these have been addressed in varying global contexts (Brayshaw & Lemckert, 2012; Bush et al., 2001; Cooper & Pilkey, 2012; Pilkey & Cooper, 2014a, 2014b; Smith et al., 2012).

Shore-parallel installations include structures such as revetments and seawalls constructed parallel to the shore to refract wave action. Despite protection, these structures tend to restrict traditional fishing operations yet artisanal fisheries contribute at least 90% of capture fisheries, about 10% of employment in Ghana (Wiafe et al., 2013). Therefore, artisanal fishing constitutes a major proportion of coastal communities' livelihoods globally. In addition, shore-parallel structures affect coastal tourism (sun, sea and sand) (Pilkey & Cooper, 2014a) and leisure activities and other economic sectors that depend on the beach's scenic value.

Meanwhile, shore-perpendicular structures include groynes and jetties. These structures function by trapping sediment updrift but inhibit sediment transport to downstream beaches. Although many studies have been conducted at different geographic scales globally, studies on the socioeconomic pitfalls of coastal stabilisation and protections in Ghana remained underexplored. In a developing country where artisanal fisheries are the backbone of coastal community livelihoods, coastal grey infrastructure has undoubtedly created negative socioeconomic impacts that necessitated investigation.

This paper employed in-depth interviews (IDIs) and recorded (televised) interviews to investigate both current and historic socioeconomic impacts of coastal grey infrastructure and the implications for artisanal fisheries, coastal tourism and overall coastal management policy in Ghana.

6.2. Methodology

6.2.1. Study Area

In total, 25 interviews were conducted over a total of eight locations, including Axim, Anomabo, Takoradi, Cape Coast, Artokor and Bkekusu (Figure 50).

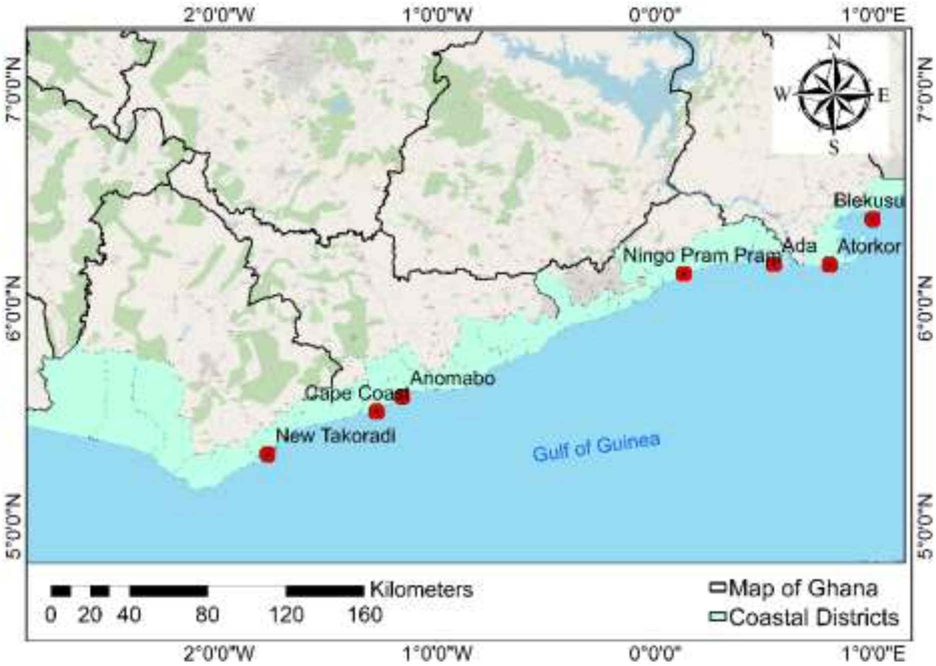

Figure 50: Interview locations along the coast of Ghana

6.2.2. Sociodemographic Information

Based on the 2021 Ghana Statistics Services Census (GSS, 2021), the population of Ghana increased at a rate of 2.1% per annum from 25.6 million in 2010 to 30.8 million in 202 (GSS, 2021). In this regard, the coastal population increased from 5,905,910 in 2010 to 6,907,616 in 2021, representing approximately one million increases in coastal population in Ghana. Based on these dynamics, the coastal areas in Ghana continue to be the main destination of rural-to-urban migration. For instance, Jonah et al. (2016) indicated that the population of Cape Coast doubled from 82,291 in 2000 to 129,169,894 in 2010 (Jonah et al., 2016). Most of the migrants to coastal areas are affected by the availability of employment opportunities from industries and fishing. Since fishing is the dominant economic activity along the coast of Ghana, disturbances in the fishing operations may have negative impacts on the fish supply and value chains in Ghana, a tendency that is likely to affect coastal livelihoods.

6.2.3. Sampling Method

Purposive sampling was used to find experts for in-depth interviews. Snowballing approach, based on the referals given (Creswell & Creswell, 2018; Creswell & Poth, 2018; Creswell et al., 2011; Creswell & Plano Clark, 2011). The IDIs were ended when saturation was reached from the information emerging from the interviews (Boyce & Neal, 2006). Interviewees were informed about the interview by telephone and reminded a day before the interview dates.

6.2.4. In-Depth Interviews (IDIs)

IDIs serve the purpose of collecting large amounts of qualitative data about the behaviour, attitudes, and perceptions of the interviewees (Creswell & Creswell, 2018; Creswell & Poth, 2018; Creswell & Plano Clark, 2011; Creswell et al., 2011; Boyce & Neal, 2006; Crotty, 1998). To provide complete information, IDIs typically rely on multiple sources of information (Boyce & Neal, 2006), pointing to a rich ecosystem of participants.

A total of 25 IDIs (Table 16) were conducted with among others, senior scientists from universities, government agencies, policymakers, senior researchers and project managers working with non-governmental organisations, coastal project site engineers, beachside resort owners/managers, and community assemblymen to investigate the socioeconomic pitfalls of coastal stabilisation along the coast of Ghana. An interview guide (Appendix G) was made comprising questions and probes that guided the interview process.

Table 16: *In-Depth Interviews and Their Locations*

Interviewee	**Type of organisation**	**Locations**	**Number**
Community leader	Coastal Community	Blekusu	2
Coastal Engineer	Coastal Engineering	Ningo Pram Pram	1
Community leader	Coastal Community	New Takoradi	1
Community member	Coastal Community	Ada Foa	1
Environment manager	Government Institution	Cape Coast	2
Fisheries manager	Fisheries Commission	Cape Coast	1
Fisherman	Fisheries Representative	Axim	2
Fisherman	Fisheries Representative	Blekusu	2
Project managers	Government Institution	Anomabo	3
Owner/Manager	Beach Front Hotel/ Resort	Anloga	1
Owner/Manager	Beach Front Hotel/ Resort	Cape Coast	1
Owner/Manager	Beach Front Hotel/ Resort	Elmina	1
Senior Researcher	Civil Society	Takoradi	1
Senior Researchers	University	Cape Coast	2
Senior Researchers	University	Accra	1
Program Manager	NGO/Charity	Multiple	3
Total			**25**

Interviews were conducted face-to-face, with open-ended questions, allowing the researcher to solicit rich and detailed responses and make probes to follow-up questions (Creswell & Plano Clark, 2011; Boyce & Neal, 2006). In the case of beachside resorts, interviews were conducted on-site. Interviews with chief fishermen and community leaders were conducted at their convenient locations, usually at the beachfront. Each interview lasted in the range of 30-45 minutes with a mean duration of 35 minutes.

The interview process followed procedural actions namely: setting up the IDI environments with stakeholders by explaining the purpose of the interview, the reason why the stakeholders were chosen, and the expected duration of the interview, following Boyce and Neal (2006). Subsequently, informed consent was sought from interviewees verbally, by reading out the document to them. The confidentiality statement was also read out, including the consent to have the interview recorded.

6.2.5. Ethical Clearance

The data was collected in accordance with research standards and code of practice. Ethical clearance was obtained from the University of Cape Coast, Institutional Review Board (IRB), Ethical Approval ID UCCIRB/CANS/ 2022/02 (Appendix F). During the interviews, pseudonyms were used for all participants. Participants were informed and consented to the recording of the interviews. The interviews were audio recorded, and the audio recordings were saved using the naming convention; Date_NameofPlace_IDIName.

6.3. Data Analysis

IDI responses were audio recorded, transcribed and analysed using deductive thematic analysis. The process involves reading of the transcribed text data and coding of the text into themes. The themes were then analysed to find certain keywords that reflect the socioeconomic impacts (Figure 51). After reading the transcripts, the categories (Boyce & Neal, 2006) were established based on important criteria, including: (1) frequency of words or phrases, (2) new (surprising) information, and (3) important information based on literature and relevance to research objectives. This was mainly aimed at establishing underlying information.

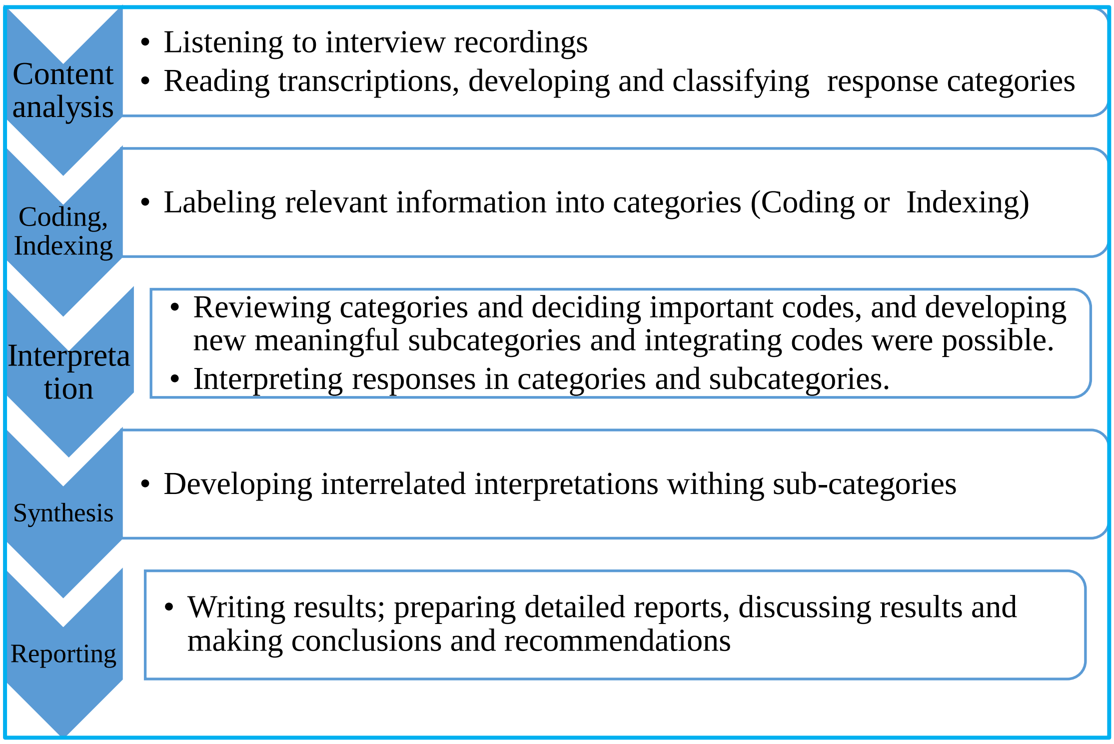

Figure 51: IDIs Deductive content analysis procedure used for data analysis

The thematic analysis of keywords was done using a basic word cloud analysis tool, https://wordclouds.ethz.ch/. Word cloud tools are basic text mining techniques used to detect text frequency, trends and patterns to provide insight for large data sets. Data transcriptions were uploaded to the portal for text mining. The text parsing options included the number of words to generate, word count and parsing options per line, among other options for text parsing options. This feedback was important to identify common themes.

6.4. Results

The study revealed varying socioeconomic impacts explained in this section.

6.4.1. Categories of socioeconomic impacts

A detailed thematic analysis was performed to establish the major keywords that arose from the investigation (Figure 52). Based on the word cloud result, the major pitfalls concerned damage to fishing nets, the effect on fishing methods, particularly beach seine fishing, changes to traditional fish-landing dynamics and reduced livelihood income. Issues regarding beach access, beach aesthetics and local tourism had low priority among respondents.

Figure 52: Word cloud of socioeconomic impacts emphasised in IDIs

6.4.2. Impacts of artisanal fishing methods, fish landing dynamics

Although respondents echoed the importance of hard protection, interviewees at Cape Coast and Atorkor felt that shore-parallel revetments and seawalls had negative impacts on traditional fishing and fish landing dynamics. At Cape Coast, a woman (50) said:

"The fishermen used to land some fish here at Fosu Lagoon. But after

the seawall, they no longer come. We now have to go to Elmina. I am getting old and I cannot cope with the pressure (competition) at Elmina landing beach."

Similarly, along the Eastern coast, Artokor (Ablekuma), is a traditional fishing community largely dependent on beach seine fishing for livelihood. However, the installation of the 3.8 km revetment (Figure 53) has largely affected beach seine fishing. This is complicated by the proximity of a seaside road to the revetment which makes it barely impossible to pull nets in front of oncoming traffic

Figure 53: Atorkor revetment adjacent to the Anloga - Anyanui road

The impacts on traditional methods like beach seine fishing have immediate impacts like livelihood income reduction.

A fisherman (55) said:

> *"The sea defence is good, but the revetment also threatens our fishing methods. We are completely dependent on the sea for survival. The sea*

is our only way of life, both men and women in this community. When the men catch less fish, it means there is less fish on the market for those who process and for people to buy. So we are now having problems with rising fish prices because there is no more fish."

Another fisherman (48) said:

"The sea defence has changed the way we catch and land fish in this community"

6.4.3. Challenges with anchorage of boats with outboard engines

Fishermen representatives interviewed at New Takoradi indicated that:

"The major problem now is to have anchorage of our boats. Because of the revetments and seawall, sand no longer comes to our shores. We have resorted to making artificial anchorage for our boats, but it is a challenge. Sometimes the boats drift with the current and end up getting damaged."

Likewise, respondents at Cape Coast indicated that they have a psychological fear that the rock may drift and land on their navigating routes and damage their engines.

6.4.4. Beach access disruption and loss of beach aesthetics

Although the beauty of the beach was the least among respondents, people were concerned the sea defence compromised beach access and diminished beach aesthetics. Figure *54* shows that the seawall at Cape Coast has not only reduced beach access but prevented natural use of the beach like fish landing near Fosu Lagoon.

Figure 54: Cape Coast seawall and groyne field

In addition to the natural beach aesthetics that are lost, there seem to be no working plans for the maintenance of rocks as they deteriorated. A coastal engineer who also designed and implemented some of the coastal defences said:

"It is true, we now have a major challenge to use the beach at some beaches. At Atorkor – these are some of the projects where stakeholder engagement was not properly done to understand the community's main source of livelihood. Traditionally, the culture of maintenance is dire in Africa. The maintenance of rocks may not be activated. Ada is now a problem. It seems a good job was not done. Now the solution may only be a new system as maintenance could be more expensive."

6.4.5. Ecological impacts

In Cape Coast, some fishermen expressed concern over the emergence of new species of crabs that residents said they would not consume. At the same time, some respondents think the local ghost crab population has declined. The residents associate this with many reasons ranging from the dredging operations using mechanical equipment to the boulders that are brought to the beach from inland locations. Consequently, this is perceived to have caused the invasion of new species and the disappearance of local species. The people vowed they would not eat the invasive new species.

6.4.6. Stakeholder participation in coastal protection

Respondents cited the absence of government-stakeholder engagement in the planning and implementation of coastal defence projects.

A fisherman (60) interviewed at Blekusu said:

> *"In terms of stakeholder consultation – regarding involvement of the community - we have absolutely no knowledge of who implements the coastal defences in this area. We wake up only to see the project is going on. But we don't know who is conducting the work. What we appreciate is that we are getting the protection we expected for a long time. We are not involved in the processes. Maybe some are involved, but I don't know of that to my knowledge."*

A project engineer (48) - names and location withheld for anonymity - who was interviewed stated:

> *"The ideal scenario is that stakeholders should be involved in coastal planning and implementation from the beginning. But since these are contacts between government, financiers and engineering firms, that is not always the case. So planning may be done with the government and project implementing partners. In terms of stakeholder engagement, we have to embrace the new paradigm of making local communities part of the entire process from planning to implementation. Communities*

are supposed to be involved, but yes, that may not be the case everywhere. I think we have to learn from these developments to improve our approaches to coastal planning and management to avoid falling back to the behaviours of the past decades."

A young fisherman (30) interviewed at Cape Coast showed his discontent with the government's approach to implementing coastal works and stated:

"We are not involved in any process. We are not told. We saw them coming here with their equipment and workers and started working without telling us. These workers come from somewhere else. All we can do is to watch. As youth I feel that we should have benefited from some of the jobs from these projects. There are many ways we can contribute, but from this, we are not important. We are not happy."

Communities interviewed stated they have no voice on the type of coastal infrastructure implemented (seawall, groynes or jetties), in the box.

Responses on political implementation of defences:

"They don't consider us relevant." — female, age 56

"The government [of Nana Akufo Addo] doesn't care about us." — male, age 44

" We know they are waiting for elections. We are ready for them" — male, age 50

Another engineer said:

"In terms of stakeholder engagement, we have to embrace the new paradigm of making indigenous people part of the entire process from planning to implementation. Traditionally, the local communities are not included in decision making but this has to change to avoid falling back to the behaviours of the past Century."

6.4.7. Politicisation, incomplete projects and coastal erosion migration

Many interviewees cited the political implementation of coastal works. Uncompleted coastal projects have catalysed erosion migration. A community member who appeared in a televised interview (Figure 56) attributed the coastal erosion migration to the political implementation of defences, but also the inherent local syndrome that an incoming political administration does not want to continue with projects that were initiated by a former administration. He said:

> *"The thing (erosion problem) started in 2012 when the sea started coming to our shores and destroying the buildings. The previous governments (former administration), that is NDC time, constructed only for 2km and they reached here, in 2016 the previous government was out and the new one (NPP) came and worked up to here. So after that the direction (of the erosion) turned to us and the pressure (wave action) started destroying our properties."*

Figure 55: Televised interview on coastal erosion impacts at Dansoman Community (Citi News Room, 2022)

Consequently, grey infrastructures have induced serious erosion to adjacent beaches, creating new erosion hotspots and generating psychological stress, a sense of insecurity, and uncertainty for unprotected communities. The political implementation (using sea defence construction as a political campaign), it seems, has infuriated the traditional leadership as political parties do not honour their promises. In a recording of a televised interview, a traditional leader of Dansoman said:

> *"The NPP government has deceived us. The NDC started but could not complete the project, but the NPP government hasn't commenced anything. A year ago, government officials visited the area and promised that the sea defence wall would be completed, but as of now, nothing has been done. The residents are angry because they believe the government and the Chief have deceived them….. It is obvious they are waiting for another election year to come and deceive us. We want (the President) to get his officials to come and build the sea defence wall."* (Citi News Room, 2022)

These findings highlight some of the socioeconomic challenges inherent in the implementation of grey infrastructure in Ghana. These pitfalls require urgent policy attention to improve coastal governance and sustainable coastal maagement in Ghana.

6.5. Discussion

The process of engaging coastal communities to understand their perceptions and experiences contributes to improving community knowledge and fostering community awareness of coastal hazards and their involvement in coastal management decision-making. Evidence from this study indicates that shore-parallel structures (seawalls and revetments) present more social impacts to coastal communities than shore-perpendicular structures (groynes). For instance, community members indicated groynes provide the opportunity to utilise the built beach and inter-groyne spaces for launching and anchorage of boats while revetments and seawalls do not. Given the results, it is imperative to engage communities in coastal planning decisions to understand their preferences and the likely impacts of coastal defences on their livelihoods.

6.5.1. Implications for artisanal fisheries and community livelihoods

In all measurable respects, artisanal fishing is the backbone of coastal community livelihood support in Ghana and contributes 10% (Wiafe et al., 2013). Therefore, any disruption to fishing methods and fish-landing dynamics has negative consequences on the livelihoods of peasant communities in smaller towns along the coast of Ghana. Good human health and well-being is attached to livelihood income. Therefore, coastal planners must consult communities to establish the appropriate typology to protect the beach. It is believed that shore-parallel structures present more social impacts to coastal communities than shore-perpendicular structures. Conversely, shore-perpendicular structures like groynes provide the opportunity to utilise the beach built between the groynes for recreational purposes and economic uses such as launching and anchorage of boats.

6.5.2. Coastal governance at risk with exclusion of stakeholders

Results show that stakeholder consultation (inclusive approach) during the planning and construction of coastal protection projects in Ghana was absent and therefore affects good coastal governance principles. Community members interviewed confirm that usually the coastal protection plans have already been finalised, and it is difficult to disprove political implementation of hard structures since grey infrastructure takes decades to able to prove they destroy beaches (Bush et al., 2001). This timespan can even be longer if installed defences have a defined maintenance plan. Therefore, in the absence of scientific evidence, buy-in political support to vote for the prohibition of coastal hardening is difficult (Bush et al., 2001). In Ghana, grey infrastructure is usually built using granite rocks since these materials require less maintenance and are less affected by ocean processes. In other findings, interviewees expressed that politicians may favour the protection of areas with high value, usually at the expense of downstream rural coastal communities that eventually bear impacts like coastal erosion migration. This was evident in Takoradi where initial protection of port areas migrated erosion to residential areas of New Takoradi, which were later protected using seawalls and revetments.

6.5.3. Less government support for community resilience

Interviewees expressed little or no government support to address the effects emanating from coastal stabilisation, mainly coastal erosion migration. Overall, the resilience of affected communities can be measured as a function of community support (10 out of 10 people interviewed), support from NGOs (8 out of 10) and government support (2 out of 10). Community support plays a major role, especially during flooding events. For instance, 5 out of 10 interviewees at Blekusu expressed that during the height of the tidal waves, water levels in flooded houses can reach 1m threatening property and leading to cases of loss of lives, especially children. Alternative livelihoods sources are meagre with 9 out of 10 people interviewed expressing they have no alternative livelihood other than fishing, or jobs in the community fishing value chain.

6.6. Conclusion

This study used in-depth interviews to explore the socioeconomic impacts linked to coastal grey infrastructure in Ghana. The major socio-economic impacts established include (1) impact on artisanal fisheries on traditional methods like beach seine fishing and fish landing dynamics; (2) impacts on boat anchorages; (3) reduced or lost beach access; and (4) political implementation and exclusion of stakeholders. The political implementation led to white elephants, incomplete projects, and chronic erosion migration. Other pitfalls included the loss of beach aesthetics which could potentially affect local coastal tourism indirectly affect the source of livelihood for coastal communities.

Findings from this study also indicate that the socioeconomic impacts of coastal hardening have not been given due consideration. In the context of this study, shore-parallel infrastructures (revetments and seawalls) posed more socioeconomic impacts than shore-perpendicular structures (groynes). Mostly stakeholders and coastal communities were not consulted. Engaging stakeholders to investigate the socioeconomic impacts and potential disruptions provides the opportunity to engage policymakers and recommend sustainable solutions such as nature-based solutions that minimise negative impacts on the environment and communities. Since the future coastal adaptation is envisaged to comprise integrated hard and soft or hybrid protection, the engagement and inclusion of all stakeholders in the planning and implementation of coastal adaptation approaches is essential if good governance is to be attained in integrated coastal management in Ghana.

6.6.1. Policy recommendations

The major challenge along the coast of Ghana is the absence of SMPs (Wiafe et al., 2013). This leads to the spontaneous *ad hoc* implementation of hold the line strategy using grey infrastructure like revetments, seawalls, and groyne. Based on findings, from IDIs, the following are recommended:

- Engagement of stakeholders to establish livelihoods and potential socioeconomic impacts before implementation of coastal protection. In many instances, the livelihoods of artisanal fisheries and coastal communities were not considered in the planning and implementation of coastal protection projects.
- Institution of SMPs to facilitate dynamic protection using soft protection and managed retreat, e.g., coastal setbacks.
- Cessation of political implementation of coastal engineering projects to avoid unplanned implementation and irrecoverable environmental damages to natural coastlines.

CHAPTER SEVEN

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

7.1. Overview

This study set out to investigate coastal management strategies and coastal infrastructure provided in Ghana. It began by conducting a comprehensive analysis of global coastal management strategies and infrastructure and zoomed into their application in Ghana. The insights from the contemporary global coastal management practices and coastal infrastructure typologies growing importance of coastal management and adaptation to coastal hazards in the 21st century. Categorisation of coastal management strategies and coastal infrastructure enabled assessment of their advantages and disadvantages and limitations for adaptation in different geographic contexts. Contextualising this to Ghana provided the opportunity to understand the coastal management regime in Ghana. Findings from the literature identified several coastal management gaps and showed that coastal management in Ghana was reactive and *ad hoc* in nature.

The mapping of coastal infrastructure confirmed that that different types of grey infrastructure have been implemented along the coast Ghana between 2000 and 2023, with approximately 20% of the coast protected. Grey infrastructure was classified into seawalls, revetments, groyne fields, and jetties. Several SDPs were implemented along the Eastern coast including Ningo Prampram (24 groynes), Ada Foah (22 groynes), Atorkor (13 groynes), Keta (system of 6 groynes) and Blekusu Phase I (18 groynes). Similarly, several projects were implemented along the Central coast including revetments and groynes at Elmina Coconut Groove Beach (5 groynes), Elmina

Lemon Beach seawall, Cape Coast Oasis Beach groyne field (4 groynes), Anomabo groynefield (7 groynes). A system of revetments and jetties were also installed along the Central and Western coasts. Key SDPs include Axim SDP, Sekondi-Takoradi seawall and SDP, and Komenda SDP (system of groynes and revetments). Ongoing SDPs include Dansoman SDP, Blekusu Phase II, and Axim SDP which is near completion.

The assessment of integrated coastal vulnerability indicated that coastal vulnerability along the coast of Ghana has increased during the past decade despite the increase in coastal protection. This was mostly evident along the Eastern coast of Ghana with coastal districts of Eda East, Anloga, Keta Municipal, and Ketu South with indices indicating high coastal vulnerability. In addition, social vulnerability has increased in sync with population growth and coastal developments.

The monitoring and assessment of the environmental pitfalls of grey infrastructure was important to inform coastal management decision-making. In this study, the assessment of shoreline responses at groyne fields showed that although coastal groyne fields protect their sites, major environmental impacts were happening including: (1) shoreline migration at the terminal groyne (terminal groyne effect), especially at Blekusu Phase I and Ada; (2) modification of normal beach plan form causing the formation of saw-shape beaches, (3) coastal erosion migration to adjacent coasts, creating new erosion hotspots. At Ada, groyne fields altered the natural interaction of the sea and the Volta Estuary and induced coastal erosion up to Fuveme. The cessation of beach nourishment at Ada likely aggravated the deterioration of the groyne system which completely compromised groyne permeability and has entirely nullified the function of groynes.

The socioeconomic impacts of coastal grey infrastructure have not been given due consideration in Ghana. The major socioeconomic impacts identified include loss of beach access, restricting artisanal fishing methods like beach seine fishing by limiting the spaces where fishers can deploy their nets, potentially reducing their catch, changing fish-landing dynamics and reducing community livelihood income. Other pitfalls include loss of beach aesthetics which could potentially affect local tourism, another source of livelihood for coastal communities. In this regard, shore-parallel infrastructures (revetments and seawalls) were found to have more socioeconomic impacts than shore-perpendicular structures (groynes).

Many opportunities exist for nature-based infrastructure, including mangrove reforestation and afforestation, dune creation, and living shoreline constellation. However, many knowledge and policy gaps continue to hinder the adoption and upscaling of nature-based solutions or ecological engineering. These include political implementation of coastal protection, knowledge gaps in hybrid and green infrastructure, skills and expertise gaps, stakeholder preferences, and perception and priorities of NbS with respect either protection or ecosystem services. The major pitfall would be to have rushed pilot nature-based infrastructure projects without careful studies on both the assumed and realisable protection and ecological benefits from green and nature-based solutions.

Demand for grey infrastructure is inevitable to protect coastal communities and their properties given increasing SLR and the severity of coastal hazards. This is true considering that strategic coastal infrastructure such as roads, water and energy infrastructure will need to be protected against coastal erosion, flooding (wave overtopping). In this regard, it is important that coastal adaptation must be aligned with National Adaptation Plans (NAPs) to enhance sustainable development of the coastal areas.

7.2. Conclusions

This study investigated and identified the coastal management strategies and typologies of coastal infrastructure implemented in Ghana. Results from empirical investigation of the coastal management strategies and the mapping of different types of infrastructure along the coast show that approximately 20% of the coast of Ghana was protected using grey infrastructure primarily used to implement grey infrastructure, particularly revetments, seawalls, jetties and groynes. In addition, although there are no officially declared SMPs, the hold the line policy was used to implement virtually all coastal defences along the coast, without considering other integrated coastal management practices such as beach nourishment and engaging coastal communities in ecosystem-based approaches like mangrove tree planting.

Despite the increase in coastal protection, coastal vulnerability assessment indicated that at least 54% of the coastal of Ghana have moderate to very high coastal vulnerability to coastal hazards. In addition, coastal grey infrastructure continues to contribute to environmental and socioeconomic challenges.

It was also established that the implementation of hard-engineered infrastructure along the coast caused several socioeconomic impacts. Moreover, these socioeconomic impacts have not been given due consideration. In most cases, stakeholders were not included in the planning and implementation of coastal defences, a trend which violates good coastal governance.

7.3. Recommendations

Based on the research findings from this study, the following actions are recommended:

i. The comprehensive mapping and updating of the national database of coastal infrastructure to inform the revision of coastal management policies.

ii. Comprehensive monitoring of protected sites to understand total beach responses to installed coastal defences to verify effectiveness and environmental impacts.

iii. The periodic national assessment of coastal vulnerability that incorporates multiple social and physical parameters to inform coastal adaptation policy and coastal development planning.

iv. The establishment of holistic and adaptive shoreline management plans to determine how each section of the coast will be protected in the short, medium and long-term plans, especially at the district level.

v. The engagement and inclusion of all stakeholders in the planning and implementation of coastal adaptation approaches. Stakeholder engagement is fundamental to achieving good coastal governance in Ghana.

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APPENDICES

Appendix A: Revetments distribution along the coast of Ghana

Place	Region	District	Lat	Long	Length (m)
New Amanful (west)	Western	Takoradi	4.874809	-1.78553	642
New Amanful (east)	Western	Takoradi	4.875139	-1.78283	1,029.00
Takoradi Harbour	Western	Takoradi	4.900486	-1.74673	999
Takoradi Harbour	Western	Takoradi	4.918045	-1.74033	971
New Takoradi	Western	Takoradi	4.907111	-1.74226	723
New Takoradi	Western	Takoradi	4.930817	-1.71936	5,224.00
Aboade (1)	Western	shama	4.967489	-1.66504	1,387.00
Aboade (2)	Western	shama	4.969628	-1.65398	1,580.00
Aboade (3)	Western	shama	4.979597	-1.64026	695
Elmina Lemon Beach	Central	Komenda Edna	5.074769	-1.37991	900
Elmina Coconut Gro	Central	Komenda Edna	5.077742	-1.37015	600
Elmina Habour	Central	Komenda Edn	5.079428	-1.35784	1,486.00
Elmina Habour	Central	Komenda Edna	5.087375	-1.34874	889.5
Elmina Habour	Central	Komenda Edna	5.092867	-1.33748	2,467.00
Cape Coast	Central	Cape Coast Metro	5.097153	-1.31924	373
Cape Coast	Central	Cape Coast Metro	5.102439	-1.25218	754
Cape Coast	Central	Cape Coast Metro	5.108364	-1.23562	237
Anomabo Beach	Central	Mfantsiman	5.167014	-1.14009	1,962.00
Anomabo Beach	Central	Mfantsiman	5.172233	-1.12323	409
Agyei Manso	Central	Mfantsiman	5.179153	-1.11342	1,256.00
Gomoa	Central	Gomoa	5.4244464	0.466411	186
Gomoa	Central	Gomoa	5.425181	-0.46708	206
Glefe	Central	Accra Metropolis	5.51808	-0.27791	1662
Labad	Eastern	La Dade Kotopon	5.559333	-0.14909	296
Next Door	Eastern	Ledzokuku	5.570919	-0.11412	264
Sakumono	Eastern	Tema Metropolis	5.608022	-0.05293	1,120.00
Sakumono	Eastern	Tema Metropolis	5.612397	-0.04011	2,921.00
Greenwich Meridian	Eastern	Tema Metropolis	5.624397	6.67E-05	900
Kpone Beach	Eastern	Kpone Katamanso	5.671086	0.043361	225
Pram Pram (1)	Eastern	Ningo Prampram	5.701603	0.100744	114
Old Ningo (1)	Eastern	Ningo Prampram	5.740636	0.177208	177
AtorKor (1)	Eastern	Keta Municipal	5.772619	0.807367	2735
Keta	Eastern	Keta Municipal	5.92155	0.993536	760

Appendix B Groynes fields distribution along the coast of Ghana

Groynes and groyne fields in Ghana					
Place	**Region**	**District**	**Lat**	**Long**	**Length (m)**
New Amanful	Western	Ahanta West	4.875156	-1.78451	75
Ngyiresia	Western	Sekondi-Takoradi	4.9574	-1.69923	175
Aboadze	Western	Shama	4.9676	-1.65823	321
Elmina Lemon Beach	Central	Komenda Edna Eguafo.	5.078908	-1.36227	66
Elmina Lemon Beach	Central	Komenda Edna Eguafo.	5.079092	-1.36128	65
Elmina Lemon Beach	Central	Komenda Edna Eguafo.	5.079292	-1.36005	65
Elmina Lemon Beach	Central	Komenda Edna Eguafo.	5.079347	-1.35891	63
Cape Coast, Oasis Beach	Central	Cape Coast Metro	5.102906	-1.24473	73
Cape Coast, Oasis Beach	Central	Cape Coast Metro	5.103081	-1.24391	75
Cape Coast, Oasis Beach	Central	Cape Coast Metro	5.103058	-1.24291	72
Cape Coast, Oasis Beach	Central	Cape Coast Metro	5.103219	-1.24204	70
Anomabo	Central	Mfantisman	5.170089	-1.13215	75
Anomabo	Central	Mfantisman	5.170483	-1.13094	70
Anomabo	Central	Mfantisman	5.170864	-1.12955	71
Anomabo	Central	Mfantisman	5.171106	-1.1282	74
Anomabo	Central	Mfantisman	5.171461	-1.12693	75
Anomabo	Central	Mfantisman	5.171692	-1.12559	71
Anomabo	Central	Mfantisman	5.172233	-1.12323	71
Fort Good Hope	Central	Gomoa East	5.387606	-0.48884	55
Gomoa	Central	Gomoa West	5.424	-0.46577	55
Glefe	Central	Accra Metropolis	5.520704	-0.26567	67
Glefe	Central	Accra Metropolis	5.520841	-0.2642	72
Club 1900 Beach	Eastern	Ledzokuku	5.590103	-0.07417	65
SMTC Ghana	Eastern	Ledzokuku	5.606947	-0.05838	65
Ada East	Eastern	Ada East	5.783314	0.528722	78
Ada East	Eastern	Ada East	5.782419	0.534475	88
Ada East	Eastern	Ada East	5.782	0.540428	82
Ada East	Eastern	Ada East	5.781258	0.548203	80
Ada East	Eastern	Ada East	5.780942	0.554892	98
Ada East	Eastern	Ada East	5.780503	0.561217	75
Ada East	Eastern	Ada East	5.780261	0.567661	80
Ada East	Eastern	Ada East	5.7798	0.5735	115
Ada East	Eastern	Ada East	5.779586	0.579464	81
Ada East	Eastern	Ada East	5.778542	0.585192	90
Ada East	Eastern	Ada East	5.778008	0.591792	83
Ada East	Eastern	Ada East	5.777306	0.598142	83
Ada East	Eastern	Ada East	5.777153	0.604581	88

Ada East	Eastern	Ada East	5.776297	0.610961	88
Ada East	Eastern	Ada East	5.776294	0.618694	152
Ada East	Eastern	Ada East	5.774319	0.634311	69
Ada East	Eastern	Ada East	5.775164	0.628083	70
Ada East	Eastern	Ada East	5.773486	0.640622	60
Ada East	Eastern	Ada East	5.772531	0.646722	68
Ada East	Eastern	Ada East	5.771542	0.652975	65
Ada East	Eastern	Ada East	5.7709	0.659306	95
Ada East	Eastern	Ada East	5.771406	0.665417	100
AtorKor	Eastern	Keta Municipal	5.774039	0.818178	79
AtorKor	Eastern	Keta Municipal	5.774219	0.819639	70
AtorKor	Eastern	Keta Municipal	5.774406	0.821142	77
AtorKor	Eastern	Keta Municipal	5.774617	0.822631	74
AtorKor	Eastern	Keta Municipal	5.774725	0.824031	75
AtorKor	Eastern	Keta Municipal	5.774825	0.825478	79
AtorKor	Eastern	Keta Municipal	5.775211	0.827211	75
AtorKor	Eastern	Keta Municipal	5.775494	0.828978	84
AtorKor	Eastern	Keta Municipal	5.775667	0.830819	81
AtorKor	Eastern	Keta Municipal	5.775817	0.832628	76
AtorKor	Eastern	Keta Municipal	5.775994	0.834439	81
AtorKor	Eastern	Keta Municipal	5.776278	0.836258	81
AtorKor	Eastern	Keta Municipal	5.776683	0.838494	85
Keta Sea Defence	Eastern	Keta Municipal	5.927161	0.995508	217
Keta Sea Defence	Eastern	Keta Municipal	5.933008	0.998536	231
Keta Sea Defence	Eastern	Keta Municipal	5.939211	1.001864	189
Keta Sea Defence	Eastern	Keta Municipal	5.944922	1.005972	227
Keta Sea Defence	Eastern	Keta Municipal	5.950739	1.00985	163
Keta Sea Defence	Eastern	Keta Municipal	5.956189	1.013261	163
Blekusu	Eastern	Ketu South	5.984186	1.031531	82
Blekusu	Eastern	Ketu South	5.985542	1.032697	71
Blekusu	Eastern	Ketu South	5.987033	1.033717	78
Blekusu	Eastern	Ketu South	5.988453	1.034869	73
Blekusu	Eastern	Ketu South	5.989856	1.035942	76
Blekusu	Eastern	Ketu South	5.991378	1.036853	74
Blekusu	Eastern	Ketu South	5.992972	1.038128	78
Blekusu	Eastern	Ketu South	5.994419	1.038986	70
Blekusu	Eastern	Ketu South	5.99575	1.040342	73
Blekusu	Eastern	Ketu South	5.997244	1.041258	72
Blekusu	Eastern	Ketu South	5.998778	1.042169	79
Blekusu	Eastern	Ketu South	6.000314	1.043186	70
Blekusu	Eastern	Ketu South	6.001781	1.044094	76
Blekusu	Eastern	Ketu South	6.003267	1.045275	83
Blekusu	Eastern	Ketu South	6.004917	1.045978	77
Blekusu	Eastern	Ketu South	6.006206	1.047211	72
Blekusu	Eastern	Ketu South	6.007872	1.048181	65
Blekusu	Eastern	Ketu South	6.009447	1.049286	61

Ningo Pram Pram	Eastern	Ningo Pram Pram	5.742761	0.182311	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.743866	0.183816	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.744627	0.185405	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.74509	0.187166	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.74505	0.189007	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.744959	0.190789	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.744804	0.192583	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.727478	0.148642	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.727941	0.1509	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.728468	0.152996	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.72865	0.154151	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.729501	0.157028	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.73035	0.158931	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.731146	0.160763	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.731844	0.162736	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.732449	0.164348	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.733939	0.166002	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.735091	0.167803	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.735619	0.169612	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.736349	0.171137	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.738048	0.172686	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.73909	0.174272	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.74028	0.176209	90
Ningo Pram Pram	Eastern	Ningo Pram Pram	5.741348	0.17799	90

Appendix C Beach resorts sampled

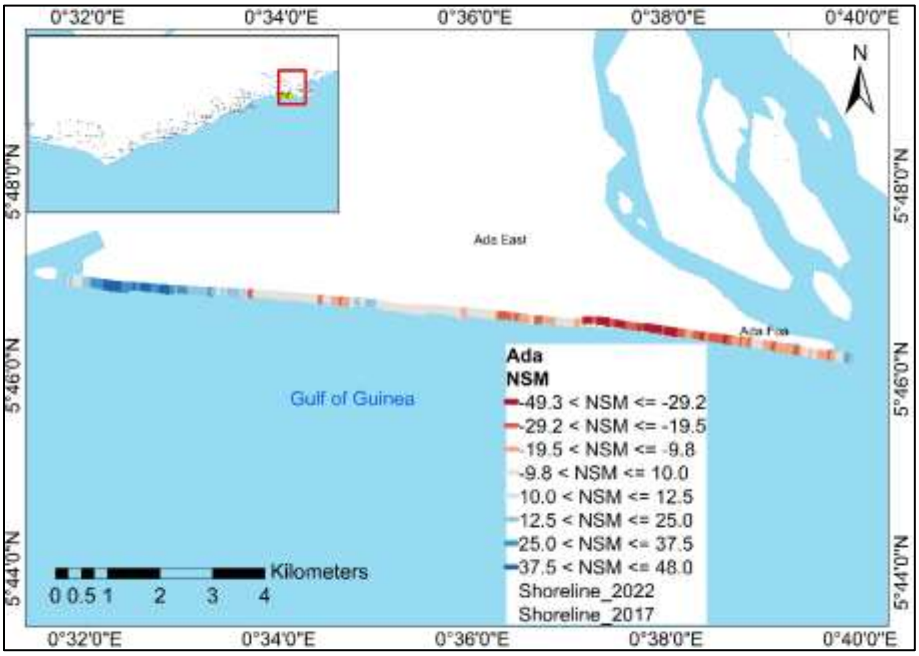
Beach resort/hotel	Long	Lat	Beach resort/hotel	Long	Lat
Akwida Inn	-2.02555	4.758682	Breeze Beach Resort	-0.94352	5.20425
Royal Elmount Hotel	-1.33562	5.094575	Tuna Fish	5.25331	5.25331
Elmina Beach Resort	-1.337	5.093251	Mumford Atlantic	-0.75078	5.270512
Heritage Beach	-1.29554	5.099863	Blue Diamond Beach	-0.71821	5.303202
Coconut Grove Resort	-1.37018	5.078368	Rippels Lodge	-0.67763	5.319865
Beyin Eco Beach Camp	-2.59341	4.987403	St Charles Beach	-0.62837	5.33005
Tenack Hotel, Nzulezu	-2.58313	4.985483	Sunflower Lodge	-0.50523	5.377329
Tenack Beach Resorts	-2.64534	4.999305	White Sands	-0.46863	5.42705
Beyin Beach Resort	-2.59656	4.987779	Big Blue Resort	-0.4332	5.447325
Tenack Beach Resorts	-2.54533	4.978942	Kuvuki Beach	-0.39971	5.477852
Venice View Beach	-2.4974	4.969195	Wakanda Beach	-0.3833	5.48451
Maaha Beach Village	-2.41538	4.9498	Casa Palmera	-0.38503	5.483596
Ankobra Beach Resort	-2.26488	4.890595	Elva's Palace	-0.39184	5.481085
Axim Beach Resort	-2.23463	4.851565	Phoenix Beach	-0.38184	5.485249
Lou Moon Resort	-2.20168	4.828717	Serenity Spa	-0.36959	5.491969
Keda's Lodge	-2.16901	4.806567	Kokrobite Beach	-0.36663	5.491977
Cape Three Points	-2.09084	4.740325	Jah Guide	5.497833	5.497833
Cape Three Points	-2.07692	4.749348	Premier Beach	-0.34835	5.500992
Ocean Village	-2.04085	4.754026	The Luxury Beach	-0.34113	5.504576
Ezile Bay Ecolodge	-2.03844	4.756191	Bojo Beach	-0.32737	5.5077
Safari Beach Lodge	-2.01358	4.757718	First Class Commey	-0.27811	5.518997
Ceto Beach	-1.96851	4.771891	Dansoman Beach	-0.26092	5.521866
Ahanta Ecolodge	-1.94016	4.802722	Korle Beach	-0.22634	5.528807
Busua Inn	-1.93892	4.806312	Osu Beach	-0.17934	5.549166
Busua Beach Resort	-1.93574	4.808644	Dreamland	-0.15117	5.558802

The Hideout	-1.91285	4.825696	Labadi Beach	-0.13835	5.562053
Fantas Folly	-1.8982	4.82902	Pork Junction	-0.13075	5.564451
Lupita Blom Resort	-1.80499	4.877301	Next door beach	-0.11683	5.57
Funko Beach	-1.797	4.873796	Peninsula Beach	-0.09491	5.583232
Africa Beach	-1.76612	4.876015	Teshie	-0.09869	5.579457
Viena City Beach	-1.75205	4.87917	La Plage	-0.09437	5.583894
Sekondi Beach	-1.72017	4.930767	Blackmama Beach	-0.09067	5.584958
Vevaag Logdge	-1.68118	4.965547	Shining Beach	-0.08845	5.586121
Asemba Guest Lodge	-1.64303	4.977805	Audrey's Garden	-0.08154	5.58777
Albeta's Palace	-1.44142	5.060903	Club 1900	-0.07636	5.589599
Charlestina Beach Resort	-1.4399	5.062253	Best Western Plus	-0.06971	5.596471
Ayiko Beach Resort	-1.43834	5.062988	Adom Guest House	-0.04974	-0.06971
Brenu Beach Resort	-1.42186	5.068215	Nautilus Beach	-0.03364	5.613338
The Beach House	-1.39044	5.07301	The Plams	0.101801	5.701412
Elmina Bay Resort	-1.37833	5.075125	The C Resort	0.174198	5.738139
Stumble Inn	-1.37659	5.075457	Azizanya Coconut Gr	0.65316	5.773784
Akomapa Village	-1.36828	5.078691	Meet Me There	0.755773	5.772383
Shilon Guest Logdge	-1.36034	5.07987	Reddington Chalets	0.842736	5.777819
Hutchland Beach	-1.29485	5.099958	Woe	0.947733	5.805766
Da Breeze	-1.28304	5.100497	Aborigines Beach	0.994981	5.897684
Assasse Pa	-1.25424	5.102273	Azizadzi	1.024797	5.975634
Oasis Beach	-1.24307	5.103537	Agavedzi	1.050671	6.013097
Moree Paradise	-1.19487	5.138822	Adina	1.067261	6.032548
Biriwa Beach Resort	-1.15731	5.156856	South Beach Resort	1.116819	6.07223
Comfort Beach Resort	-1.14734	5.164325	Hedzrarawo	1.134174	6.083116
Anomabo Beach Resort	-1.12945	5.170934	Atlantic Breaze Beach	1.184791	6.106833

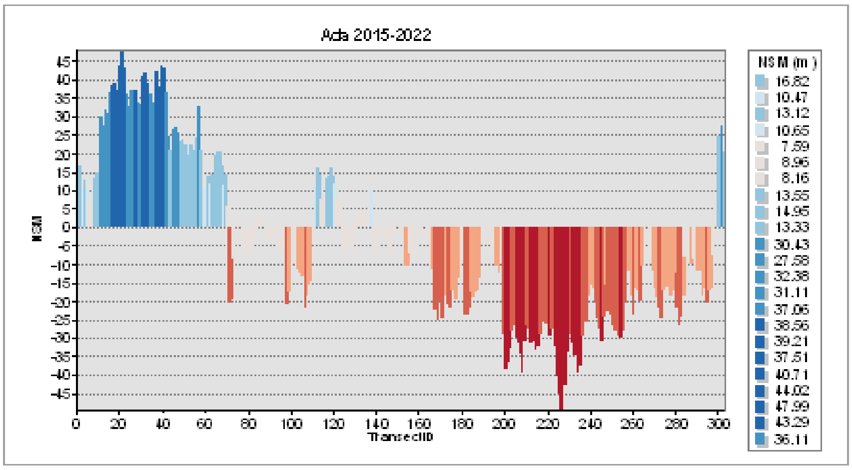
Appendix D Coastal cultural heritage sites at risk

Heritage Sites	**Long**	**Lat**
Cape Coast Castle	-1.241041	5.103524
St. George's d'Elmina Castle	-1.347964	5.082689
Christiansborg Castle	-0.18272	5.5467
Fort Good Hope	-0.489886	5.387435
Fort Patience	-0.728184	5.286231
Fort Amsterdam	-1.093064	5.192413
Fort St. Jago	-1.350825	5.08486
Fort San Sebastian	-1.629196	5.010773
Fort Metal Cross	-1.944939	4.793394
Fort St. Anthony	-2.244349	4.868001
Orange	-1.707322	4.935627
Groot Fredericksborg	-2.133914	4.791099
Fort William Anomabo	-1.119103	5.174119
Fort Victoria	-1.249233	5.106757
Ussher Fort	-0.208352	5.538436
Fort James	-0.211426	5.533578
Apollonia	-2.590025	4.987167
British Fort	-1.489604	5.05
Dutch Fort	-1.486008	5.052135
Fort Batenstein	-1.917189	4.82427
Fort Prinzensten	0.993616	5.921865

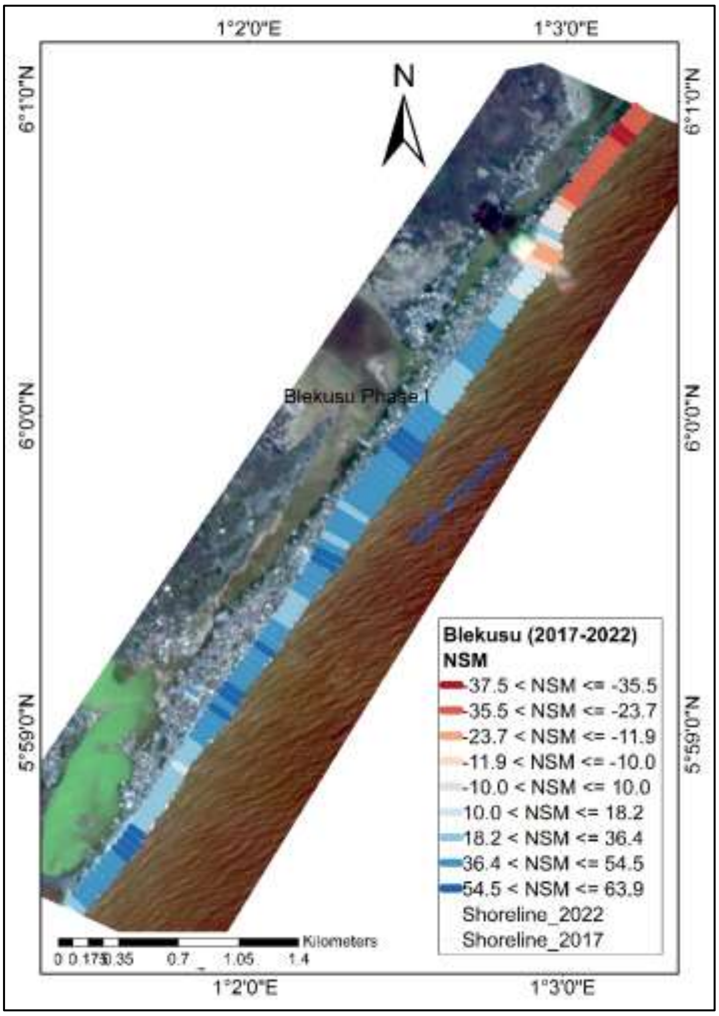
Appendix E Summary of Net Shoreline Movement (2017-2022)
ADA



ADA		**Distance (m)**	
Total No. of Transects			303
Maximum negative distance		49.2	
Maximum positive distance		47.9	
Total sum of all transects		-1045.9	
Mean distance movement		34.6	
Total no. of negative transects			190
Total no. of positive transects			113

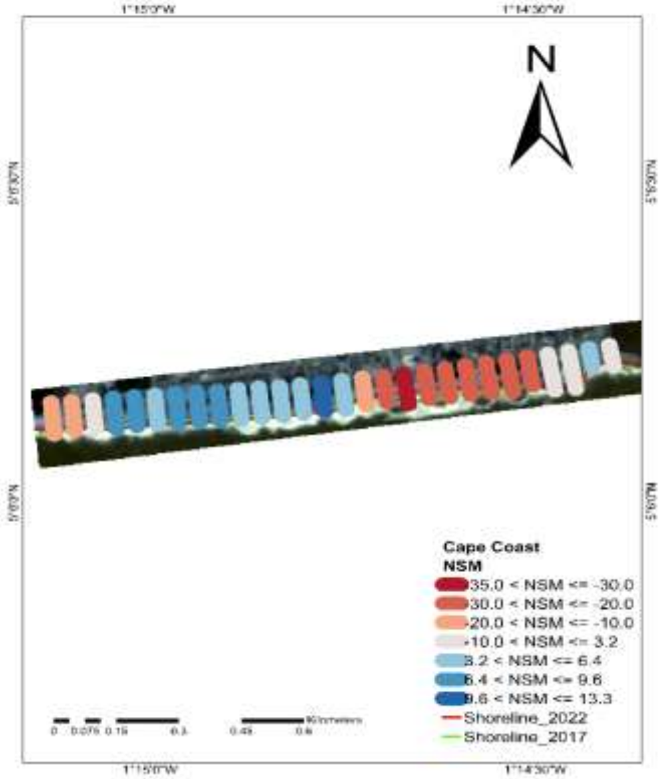


BLEKUSU

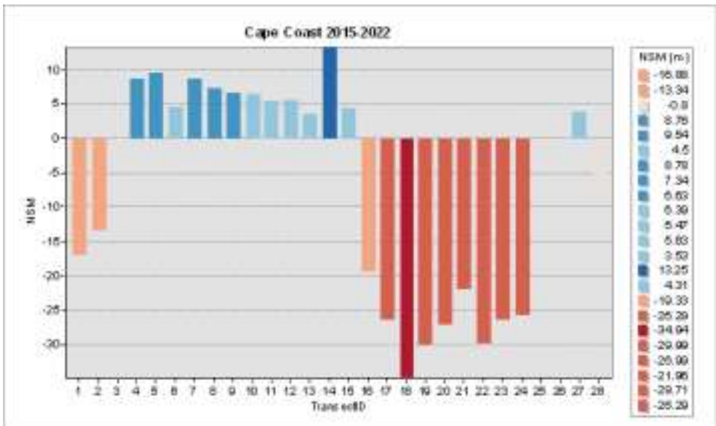


BLEKUSU	Distance (m)	
Total No. of Transects		115
Maximum negative distance	37.4	
Maximum positive distance	63.8	
Total sum of all transects	-3205.4	
Mean distance movement	27.8	
Total no. of negative transects		20
Total no. of positive transects		95

CAPE COAST



CAPE COAST	Distance (m)	
Total Transect		30
Maximum negative distance	-35.0	
Maximum positive distance	13.3	
Total sum of all transects	-192.6	
Mean distance movement	-6.8	
Total no. of negative transects		13
Total no. of positive transects		18



Appendix F Ethical Clearance used to conduct in-depth interviews

UNIVERSITY OF CAPE COAST

INSTITUTIONAL REVIEW BOARD SECRETARIAT

TEL: 0558093143 / 0508878309
E-MAIL: irb@ucc.edu.gh
OUR REF: UCC/IRB/A/2016/1269
YOUR REF:
OMB NO: 0990-0279
IORG #: IORG0009096

1TH MARCH, 2022

Mr. Blessing Charuka
Department of Fisheries and Aquatic Sciences
University of Cape Coast

Dear Mr. Charuka,

ETHICAL CLEARANCE – ID (UCCIRB/CANS/2022/02)

The University of Cape Coast Institutional Review Board (UCCIRB) has granted Provisional Approval for the implementation of your research titled **Assessment of Coastal Engineering Practices for Coastal Erosion Management in Ghana.** This approval is valid from 1th March, 2022 to 28th February, 2023. You may apply for a renewal subject to submission of all the required documents that will be prescribed by the UCCIRB.

Please note that any modification to the project must be submitted to the UCCIRB for review and approval before its implementation. You are required to submit periodic review of the protocol to the Board and a final full review to the UCCIRB on completion of the research. The UCCIRB may observe or cause to be observed procedures and records of the research during and after implementation.

You are also required to report all serious adverse events related to this study to the UCCIRB within seven days verbally and fourteen days in writing.

Always quote the protocol identification number in all future correspondence with us in relation to this protocol.

Yours faithfully,

Samuel Asiedu Owusu, PhD
UCCIRB Administrator

ADMINISTRATOR
INSTITUTIONAL REVIEW BOARD
UNIVERSITY OF CAPE COAST

Appendix G In-Depth Interview Guide

This In-depth Interview Guide was developed following Boyce and Neal (2006) to establish the socioeconomic pitfalls of coastal grey infrastructure and implications for coastal management policy in Ghana. The IDI is divided into introduction, informed consent, IDI questions, and closing remarks.

Introduction

Dear respondent

I want to thank you for taking the time to meet with me today. My name is Blessing Charuka. I am a PhD Candidate with the Africa Centre of Excellence in Coastal Resilience (ACECoR) at the University of Cape Coast. I would like to talk to you about socioeconomic pitfalls of coastal grey infrastructure along the coast of Ghana based on your experiences.

The interview should take less than an hour. I will be recording the interview fully capture your responses. All responses will be kept confidential and may only be shared with research team members. I will ensure that any information we include in our report does not personally identify you as the respondent.

Remember, you don't have to talk about anything you don't want to and you may end the interview at any time. Do you have any questions about the process? Are you willing to participate in this interview?

________________ ______________ ______________

Interviewee Witness Date

Interview Questions

1. 1. Can you describe the major socioeconomic problems faced by the communities due to hard-engineered structures?
    a. *Can you give me an example?*

b. Can you explain that further? 2. What are the major impacts of specific structures livelihoods? *a. Would you give some examples* 3. What are the specific impacts on artisanal fisheries and livelihoods? *a. Would you explain that further?* 4. Has (groynes, seawall, revetment) affected beach access and coastal tourism? *a. In what ways?* *b. Please would you elaborate further* 5. What are the specific impacts on human health and wellbeing? *a. Can you describe specific examples of psychological impacts* 6. Are communities included in the planning and implementation regarding coastal protection? *a. May you give examples?* 7. What are the policy gaps regarding implementation of coastal protection projects? a. *In what ways do you think the situation can be revised?* 8. Which types of coastal infrastructure do you prefer? (revetments, seawalls, groynes, jetties) *a. Please give reasons.* 9. What adaptation approach should be continued/discontinued? a. *Why? Please justify your answer.*
Closing Is there anything more you would like to add? I'll be analysing the information you and others gave me and submitting a draft report to the organization in one month. I'll be happy to send you a copy to review at that time, if you are interested. Thank you for your time

Appendix H Ghana coastal district population (GSS, 2021)

Coastal district	Population
Jomoro	126,576
Ellembele	120,893
Nzema East	94,621
Ahanta West	153,140
Effia Kwesimintisim	173,973
Sekondi Takoradi	245,382
Shama	117,224
Komenda Agufua	166,017
Cape Coast Metro	189,925
Abura Asebu	124,465
Mfantisman	168,905
Ekumfi	56,741
Gomoa West	129,512
Gomoa Central	83,610
Efutu Municipal	107,798
Awutu Senya	161,460
Gomoa East	308,697
Weija Gbawe	213,674
Ablekuma West	153,490
Accra Metropolis	284,124
Korley Klottey	68,633
La Dade Kotopon	140,264
Ledzokuku	217,304
Krowor	143,012
Tema Metropolis	177,924
Kpone Katamanso	417,334
Ningo Prampram	204,673
Ada West	76,087
Ada East	76,411
Keta Municipal	78,862
Ketu South	253,122

Appendix 10 Shoreline Change Rate 2000 -2022