UNIVERSIDADE TÉCNICA DO ATLÂNTICO
INSTITUTO DE ENGENHARIA E CIÊNCIAS DO MAR

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE

Master Thesis

ANALYSIS OF SHORELINE EVOLUTION IN SUPPORT OF MARINE AND COASTAL MANAGEMENT IN THE GAMBIA

DAWN OREDOLA PRATT

Master Research Program on Climate Change and Marine Sciences

São Vicente
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Analysis of Shoreline Evolution In Support of Coastal and Marine Management in The Gambia

Dawn Oredola Pratt

Master's thesis presented to obtain the master's degree in Climate Change and Marine Sciences by the Institute of Engineering and Marine Sciences, Atlantic Technical University in the framework of the West African Science Service Centre on Climate Change and Adapted Land Use

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Panel defense

President

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Examiner 1

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Examiner 2

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Dedication

This thesis is wholeheartedly dedicated to my parents Mr. George A. Pratt and Mrs. Gloria C. Pratt, who have been ever-present and have remained my constant source of inspiration.

I specially dedicate this work to my brother Mr. Aidan Pratt and Master George Williams, and I hope this inspires them to give life their best shot despite the challenges they may face.

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Resumo

As praias de todo o mundo são flageladas por problemas associados à erosão e deposição costeiras. Na Gâmbia, a erosão costeira é um desafio significativo exacerbado pelas pressões crescentes das alterações climáticas e da subida do nível do mar, pela acção das ondas naturais e pelas actividades humanas que levam à degradação costeira e à perda de biodiversidade. Este estudo analisa a evolução da linha costeira na Gâmbia ao longo de 32 anos, 1986-2018, utilizando a teledetecção. Investiga o efeito da acção das ondas e das actividades humanas na faixa costeira ao longo de Banjul até Bald Cape (Células 3 a 6). As imagens multi-temporais Landsat foram utilizadas para a extracção de linhas costeiras utilizando o Sistema Digital de Análise de Linhas Costeiras (DSAS), uma extensão do ArcGIS. Os movimentos espaço-temporais da linha de costa e a taxa de alterações estatísticas foram analisados durante dois períodos, 1986-2002 e 2002-2018. O período 1986-2002 registou uma taxa de variação média de -1,76 m/ano com uma altura média de onda significativa de 0,45m, enquanto que uma taxa de variação média de 2,79 m/ano foi registada para o período 2002-2018 com uma altura média de onda significativa de 0,46m. As estatísticas acumuladas de DSAS calculadas para estes períodos revelam que a maior parte das linhas costeiras acumularam activamente ao longo do tempo. Contudo, prevaleceu uma tendência erosiva contínua ao longo das células 4 e 6 com taxas de erosão de -5,2 m/ano e -1,33 m/ano, respectivamente. As variações sazonais e mensais da altura média significativa das ondas produziram uma erosão assimétrica da linha de costa, alterando as tendências do movimento de sedimentos na zona costeira próxima. As alterações da linha de costa nestas áreas devem-se principalmente à exploração mineira não regulamentada da costa, ao transporte de sedimentos de longo curso, e às estruturas de defesa costeira. Estruturas artificiais tais como groynes, revestimento e quebra-mares ao longo da costa alteram os processos costeiros naturais, provocando alterações na linha de costa ao reduzir significativamente o material sedimentar da praia. Assim, a monitorização frequente das linhas costeiras é essencial para compreender o dinamismo costeiro que orientará planos eficazes de gestão marinha e da zona costeira para conter os perigos e a degradação costeira, a perda de biodiversidade e a perda de recursos terrestres e económicos na zona costeira.

Palavras-chave: Erosão Costeira, Acreção, Análise da Mudança da Linha Costeira, Sistema Digital de Análise da Linha Costeira (DSAS), Gestão Costeira, A Linha Costeira da Gâmbia

Abstract

Beaches worldwide are plagued with problems associated with coastal erosion and degradation. In the Gambia, coastal erosion is a significant challenge exacerbated by the increasing pressures of climate change and sea-level rise, natural wave action, and human activities leading to coastal degradation and biodiversity loss. This study analyzes shoreline evolution in The Gambia over 32 years, 1986-2018, using remote sensing and GIS techiques. It investigates the effect of wave action and human activities on the coastal stretch along Banjul to Bald Cape (Cells 3 to 6). Multi-temporal Landsat imagery was used for the extraction of shorelines using the Digital Shoreline Analysis System (DSAS), an extension of ArcGIS. The spatio-temporal shoreline movements and the rate of statistical changes were analyzed for two periods, 1986-2002 and 2002-2018. The period 1986-2002 recorded an average rate of change of -1.76 m/yr with a mean significant wave height of 0.45m, while an average rate of change of 2.79 m/yr was recorded for the 2002-2018 period with a mean significant wave height of 0.46m. The cumulative DSAS statistics computed for these periods reveal that most shorelines have actively accreted over time. However, a continuous erosive trend was prevalent along cells 4 and 6 with erosional rates of -5.2 m/yr and -1.33 m/, yr respectively. Seasonal and monthly variations of the mean significant wave height have produced asymmetric shoreline erosion by changing the trends of sediment movement in the nearshore area. The shoreline changes in these areas are mainly due to unregulated coastal mining, longshore sediment transport, and coastal defense structures. Artificial structures such as groynes, revetments, and breakwaters along the coast alter the natural coastal processes, causing shoreline changes by significantly reducing the sediment material from the beach. Therefore, frequent monitoring of shorelines is essential to understand coastal dynamism that will direct effective marine and coastal zone management plans to curb coastal hazards and degradation, biodiversity loss, and land and economic resources loss in the coastal area.

Keywords: Coastal Erosion, Accretion, Shoreline Change Analysis, Digital Shoreline Analysis System (DSAS), Coastal Management, The Gambia’s Shoreline

Abbreviations and acronyms

CMSP	Coastal Marine Spatial Planning
CZM	Coastal Zone Management
DSAS	Digital Shoreline Analysis System
ENVI	Environment for Visualising Images
EPR	End Point Rate
ETM+	Enhanced Thematic Mapper Plus
ICZM	Integrated Coastal Zone Management
MSP	Marine Spatial Planning
MWP	Mean Wave Period
NEA	National Environment Agency
NDWI	Normalised Difference Water Index
NSM	Net Shoreline Movement
OLI	Operational Land Imager
SLR	Sea Level Rise
SCA	Shoreline Change Analysis
SWH	Significant Wave Height
TM	Thematic Mapper
UTM	Universe Transverse Mercator
UAV	Unmanned Aerial Vehicle
WGS	World Geodetic System

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1. Introduction

1.1 Background and Context

Coastal zones are areas of prime environmental, economic and social importance. They form one of the most densely populated and developed zones globally and host critical infrastructures and ecosystems. About 50% of the global population lives within 150 km of the global coastlines (Syvitski et al., 2005; Mentasch et al., 2017). Historically, coastal zones have been an attraction to humans due to their enormous and varied ecosystem services.

To a large extent, coastal zones are increasingly being threatened by a combination of human activities and environmental pressures. Climate change and climate-related changes to weather patterns, storm intensity, frequency, and accelerated sea levels combined with storm swell are likely to increase coast challenges such as habitat degradation, loss of biodiversity, and coastal erosion (IPCC, 2014). These pressures drive physical processes such as erosion, deposition, flooding and sea-level variations which continually alter the shoreline (Murali et al., 2009). The increasing dynamics associated with the erosional process have become a significant concern in countries with limited engineering capacity (Aarninkhof et al., 2010).

Coastal erosion is a global phenomenon resulting from several natural processes and environmental factors acting collectively on the morphology of coastal environments (Petrakis et al., 2014). The retreating shorelines, anthropogenic activities, and global SLR due to climate change are likely the underlying causes of coastal erosion (Nicholls et al., 2007). Coastal erosion and deposition have always existed and contributed to shaping the present coastlines, and human activities have mainly intensified this effect. Impact studies have revealed that low-lying coasts, low reef islands, and coral atolls are highly vulnerable to the potential impacts of sea-level rise (Maul, 1993). In addition, there is likely to be an increase in coastal erosion and inundation of densely populated low-lying areas, such as and the Greater Banjul Area in The Gambia (Jallow et al., 1996).

The Gambia, with a coastline of 80km, is among the most vulnerable countries to coastal erosion and SLR globally, mainly due to its geographic location, with some areas lying below sea level (Nicholls et al., 2019). Besides the natural coastal erosion processes, beach sand mining is also a severe threat to the coastal vegetation cover and marine biodiversity. The risk associated with climate change hazards and the consequent impacts on the socio-economic development in coastal communities in The Gambia is increasing.

Shoreline change represents a vital step in understanding the dynamism and evolution of the coastal areas, and these changes affect economic development and land-use management. Therefore, shoreline evolution has drawn great attention worldwide and could serve as an effective tool for stakeholders to understand and reduce coastal erosion risk and minimize social, physical, and economic loss (Fuad and F. 2017). According to Williams et al. (2020), the study of shoreline variation and forecast plays a vital role in coastal zone management and is even more relevant in climate change and SLR.

Traditionally, the conventional field survey methods coupled with aerial photographs were used for the mapping and monitoring of shoreline changes (Cendrero 1989). In recent years, remote sensing data has been extensively used in shoreline change studies due to its synoptic and repetitive coverage, high resolution, multispectral capabilities, and its cost-effectiveness in comparison to conventional techniques (Lillesand, Kiefer, and Chipman 2015).

1.2 Problem Statement

The coastal zone has been one of The Gambia's most valuable assets as it serves several ecological, socio-cultural, and economic purposes. This zone generates revenue from commercial fishing activities, port and marine transportation, agriculture and serves as a hotspot for tourism and real estate development. This area comprises unique coastal ecosystems, supports a rich biological diversity, and contains valuable natural resources. However, the Gambia's coast is at risk of erosion because of its low elevation and geographical makeup. According to Gomez et al., (2020), 90% of the households are vulnerable to coastal erosion, and 74% of the households do not have sustainable adaptation strategies to coastal erosion.

Coastal erosion in The Gambia is a significant challenge exacerbated by the increasing pressures of climate change and anthropogenic activities, including intense storm surges, flooding, altered wind patterns, offshore bathymetric changes, and reduced fluvial sediment input, leading to ecosystem losses (Pirazzoli et al., 2004; Regnauld et al., 2004). This has an enormous impact on the physical the socio-economic vulnerability of the coastal communities and negatively affects lives and livelihoods. Analysis of environmental challenges in The Gambia has revealed that the coastal zone is characterised by various anthropogenic activities, including legal and illegal sand mining (Fatajo, 2010; National Environment Agency, 2010b). This has contributed to coastal erosion and has resulted in coastal and land degradation and habitat fragmentation, which leads to the loss of biodiversity and ecologically sensitive areas (Steiner, 2019).

Effective adaptation to the effects of coastal erosion on people, the built environment, and infrastructure requires in-depth knowledge of the hazard distribution and the risk it poses at different scales (UNDRR, 2017). Limited understanding of longshore transport of sediments, storm surge, SLR, and several uncertainties in predicting future coastal dynamic conditions hampers the ability to project long-term coastal evolution. Additionally, adequate hydrodynamic datasets and approaches are insufficient to track and understand the oceanic evolution and predict how it will change in the future. Hence, there is a need to investigate the extent of coastal erosion and the corresponding shoreline changes and their impact on the coastal environment to facilitate the design of tailored management measures to curb the effects of coastal erosion.

1.3 Research Questions

The specific enquiry which this research seeks to address include:

- To what extent has The Gambia's coastline evolved over time and at what rate?
- How do the prevailing winds and waves and their seasonal climatology affect the dynamics of the coast?
- What management measures/policies can be put in to address challenges associated with coastal degradation effectively?

The knowledge derived from answering these questions will give insight into the processes that drive the coast's ongoing erosion and historical evolution.

1.4 Relevance and Importance of the Research

Coastlines are dynamic features that change their morphology and position temporally in response to natural processes such as sea sea-level, waves, tides and currents, and human activities related to the construction of coastal protection structures (Moore and Griggs, 2002). The complexity of coastal zones makes them inherently difficult to understand and manage. However, adequate, quality, and timely information can support better decisions. A well-designed coastal zone information system could be significant as a decision-support tool to aid the development of integrated and sustainable coastal management strategies, which could be incorporated in national and local level policies (Jonah et al., 2016).

Several studies have suggested that the coastline of The Gambia is retreating (Jallow et al., 1996; Bijl, 2011). However, existing historical shoreline evolution databases have not been updated since 2009 to identify the extent of shoreline change spatio-temporally; and the rate of change statistics along the coastal from Banjul to Bald Cape. Therefore, analyzing and understanding the dynamism and variability of the coastline is vital to scientists and policy-makers in environmental management and resource protection. Shoreline mapping and data highlighting long-term changes and recent evolution trends increases the capability for adequate decision making and will potentially drive enhanced public awareness of coastal changes in The Gambia. It will also support the implementation of an Integrated Coastal Zone Management scheme that will minimize coastal hazards, loss of land, and economic resources and also put forward measures that can be implemented to protect the coast from risks associated with unmonitored coastal dynamism..

1.5 Objectives of the study

This research aims to provide reliable data and valuable information on coastal dynamism and the extent of shoreline change, to support effective coastal zone management and adaptation practices in The Gambia. This is crucial in building sustainable and multidisciplinary coastal management foundations, thereby supporting socio-economic development.

Therefore, the study's general objective is to conduct a shoreline change assessment over the West Coast Region of The Gambia to determine the extent of shoreline evolution, and to investigate the effects of surface waves and human contribution to the change.

Specifically, the research seeks to:

- Analyse spatio-temporal shoreline changes from 1986 to 2018;
- Investigate the effect of surface waves on the dynamism of the shoreline;
- Assess the perceptions of stakeholders on factors contributing to coastal erosion; and
- Propose management strategies/policies in addressing coastal erosion.

1.6 Structure of the study

The study is presented in chapters from chapter 1 through to chapter 6. The first chapter introduces the coastal zone and discusses its challenges, such as coastal erosion. It progresses to chapter two, which delves into literature and gives an overview of the related works about the objective of this research. In chapter three, the data and various methods employed in the analysis are discussed. The results obtained from the data analysis are presented in chapter four, followed by the subsequent chapter, which discusses the results realised and explains the trend and variations observed from the analysis. Finally, chapter six details a conclusion on the study and gives recommendations for the sustainable management of the coastal zone.

2. Literature review

Coastal erosion can be defined as the process of wearing away materials from a coastal profile due to imbalances in the supply and transportation of materials from a specific section (Marchand, 2010). Specifically, coastal erosion is considered a natural process that breakdowns the rock and the sediments at the shoreline, above and below the water surface (Arnott and Ollerhead, 2011). Coastal environments form the interface between the land and the ocean (Martinez et al., 2007). The buffer area between permanent land and water is occasionally submerged due to tides, waves, storm surge, rain, surface runoff, and rivers in the estuarine zones. This area defines the coastal zone, which is highly dynamic and protects coastal natural hazards by absorbing energy and momentum fluxes from the ocean (Martinez et al., 2013) and hosts a wide range of marine bio-systems (Schlacher, 1998). The coast undergoes constant modification as rivers, near-shore currents, and waves move sediments inside, outside, and within the nearshore zone (Antolinez et al., 2016). Additionally, morphological evolution of the coast tends to accelerate under extreme events such as storms, which drives intense erosion, leading to irreversible changes (Ciavola and Coco, 2017).

2.1 The Coastal Zone

A coastal zone is an interface between the land and sea, including the areas of land influenced by the sea nearby and the sea influenced by the land nearby (Boateng, 2006). The action of waves and winds along the coast results in the activity of erosion and deposition of sediments continuously. The rates of erosion and deposition vary considerably over time along such zones (Nelson, 2015). The energy reaching the coast can become high during storms, and such high energies leave coastal zones highly vulnerable during natural hazards. The balance of these interactions provides a unique domain for coastal ecosystems, climate, geomorphology, human habitation, and, importantly, regimes of dynamic physical, chemical, and biological processes. These zones are significantly important as most of the world's population inhabit the area (Crossland et al., 2005). Thus, a clear understanding of the interactions between the oceans and the land is essential in understanding the hazards associated with coastal zones.

The resources and amenities of the coastal zone are crucial to our societal needs. While it represents about 20% of the world’s surface area (Costanza et al. 1997), the coastal zone performs various ecosystem services, as shown in *Figure 1.*

Figure 1: Ecosystem services of sandy beaches (Modified from Defeo et al., 2009).

The coastal zone also comprises a series of unique ecosystems adapted to the dynamics and high levels of energy, sediments, and nutrients that stimulate high biological productivity and diversity of species in various ecosystems, encompassing distinctive communities of coastal plants and animals (Crossland et al., 2005).

2.2 Coastline/ Shoreline

A coastline is a line marking the intersection of the water surface with the shore, and it is the landward limit of the effect of the highest storm waves on the coast (Dolan et al., 1991). The coastline's continual change over time results from cross-shore and alongshore sediment movement in the littoral zone, mainly due to the dynamic nature of water levels at the coastal boundary due to waves, tides, and currents, and storm surge (Boak and Turne, 2005). This change in the coastline is also associated with the sea-level change and geomorphic processes of erosion and accretion and human activities (Muthukumarasamy *et al*., 2013).

The instantaneous shoreline is the position of the land and water interface at one particular time. Thus, the coastline must therefore be considered temporally (List and Farris, 1999; Morton, 1991), noting that the most significant and possibly incorrect assumption in many coastline investigations is that the instantaneous coastline represents average conditions (Smith and Zarillo, 1990). A coastline may also be considered over a slightly longer time scale, such as a tidal cycle, where the horizontal or vertical position of the shoreline may vary depending on the beach slope, tidal range, and prevailing wave and meteorological conditions (Boak and Turne, 2005).

Geomorphic processes such as erosion, deposition, longshore transport of sediments, periodic storms, inundation, and sea level change continuously modify the shoreline (Jose et al., 2018). Coastlines belong to the landward side, and coastal belts may be very wide or narrow and vary with reference to their slope, beach profile, rock types, climate, and vegetation (Balasubramanian, 2011).

2.3 Coastal Erosion

The coastal landforms are complex, dynamic, and delicate environments that interface between terrestrial and marine forces. Coastal hazards such as erosion, seawater inundation, storm surge, and environment instability are significant problems associated with this environment. Coastal erosion is a natural process, and it is a major problem for developed shorelines in all parts of the world today. The shoreline's landward displacement caused by the waves and currents' forces is termed coastal erosion (Senevirathna et al., 2018). Many studies have tried to link coastal erosion with maritime climate, sediment transport, and SLR parameters. However, it is somewhat unclear to what extent these factors influence coastal erosion (López, et al., 2017). This problem is expected to accelerate in the future due to global warming, which most likely will cause a sea-level rise and increase the number of storm events across the globe (Muthukumarasamy *et al*., 2013).

Erosion, which is derived from the Latin word erosio is defined as the encroachment of land by the sea over a sufficiently long period to eliminate the impacts of weather, storm events, and local sediment dynamics such as sand waves (Vinayaraj *et al*, 2011). Coastal erosion mainly occurs when wind, waves, and longshore currents transport sand from the coast and deposit it in a different location; another beach, the abyssal ocean bottom, an ocean trench, or onto the landside of a dune. This removal of the sand from the sand sharing system results in permanent changes in beach shape and structure (Prasad and Kumar, 2014). The coastal sediments or deposits, together with those arising from inland erosion and transported towards the ocean by rivers, are redistributed along the coast, providing material for dunes, beaches, marshes, and reefs.

Coastal landforms are unique and dynamic; however, urbanization and rapid population increase due to abundant natural resources have affected their delicate balance. They are currently being threatened by the intensive use of coastal spaces, mainly due to the artificial land uses in these areas (Pinto et al., 2009). Human activities such as sand mining and construction are equally associated with negatively impacting the shoreline, making coastal erosion a severe problem in recent times (Prasad and Kumar, 2014).

2.4 Sediments Transport

Coastal sediments comprise pieces of solid material that may be moved due to water motion due to waves or currents but do not float (Van Rijn 1998). Coastal sediments, commonly sand grains, cobbles, gravel, coral fragments, and shell fragments, occur along the entirety of The Gambia coastline, with a wide range of origins, structures, sizes, and chemical compositions (Jallow et al., 1996). Sediment is produced at the coastline. It develops through weathering and erosion of rock, shells, or shell fragments, organic debris, or chemical precipitation. They are generally delivered to the coast by river flows, wave action, and currents. (NCCARF, 2016).

High energy waves, fast-flowing rivers, and strong currents can lift and carry larger and heavier sediments than low energy waves. Once the water calms, the larger, heavier sediments are deposited, while the smaller and lighter sediments continue their journey, further separated or sorted according to their texture. The fine sediments, mud, clay, and silt sink much slowly, hence washin away fastest and settling in very calm waters. Sand sediments, on the other hand, can be carried by much stronger flows, even though it sinks quickly to the bottom, and are picked again and again by strong waves (Wang and Luo, 2014).

The decline of river currents as they enter the ocean at the coast and the landward push by waves determines that the coastal margin is a preferred location for coastal sediments to be deposited (Van Rijn, 1998). Waves, currents, and tides redistribute sediments accumulating near the coast. However, sediment accumulations may affect water motions, and with sufficient feedback, this provides the basis for the development of coastal landforms (Woodroffe, 2003).

2.5 Wind and Wave Influence on Coastal Erosion

According to UK Environment Agency (2009), coastal landforms are dynamic systems that function over a range of temporal and spatial scales. Dominant physical factors such as wave height, wave energy, tidal range, and littoral drift shape coastal landforms (Seenipandi et al., 2012).

Wind can influence the processes of coastal geomorphology in diverse ways, including wind stress on the surface of the water during major storms, storm surge, and inducing the sea breeze effects. Storm surge results from the frictional wind stress on the water surface, inducing

a current in the surface water. Empirically, the resulting current in the top few centimeters of the sea surface will be about 2% of the wind velocity (Komar, 1976).
The storm surge effect enhances the beach erosion process along open sandy dune coastlines by raising the water table in the beach and lowering intergranular friction between the sand grains, so that the pore water pressure from the raised water table induces the sand from the lower beach face to flow out into the surf zone. Wind-generated surge also piles up tidal waters inside estuaries, tidal inlets, and river mouths, often leading to saline flooding of adjacent low-lying coastal land. Due to the onshore winds and storm surge, the tidal cycles within the estuaries are altered to a much higher than normal tides and reduced low tide (Masselink and Pattiaratchi, 1998).

Changes in the prevailing wind direction may significantly affect coastal conditions and lead to significant deformations of the shore morphology and changes in the direction of the long-shore drift. We have numerous examples of this all over the globe. This will likely result in the lateral displacement of the line denoting the sea/land interface without any real vertical change in sea level (Mörner, 2005).

2.6 Human Interference on the Coastal Zone

Human activities and interference with the coast have a long history that has affected coastal morphology and shoreline position due to induced erosion. This influence began with early agriculture in the late Stone Age and accelerated with intensified human activities, including sand mining and construction of engineering along coasts.
Coastal engineering interference with several coastal processes often leads to negative implications for the sustainability of the beach environment. Overall, coastal protection is a complex matter, and consideration needs to be given to several factors, some of which often remain unknown or uncertain (Finkl and Makowski, 2010). While it seems obvious that fishing utilizing explosives are likely to generate disastrous effects on coastal stability, it seems quite unforeseeable that even the harvesting of thousands of sea cucumbers and other marine life from the coast may lead to severe coastal erosion (Mörner and Matlack-Klein, 2017). Human interference with the coastal runoff, the sediment supply, land-sea configuration, and installation of coastal protection structures have a significant and even dominant effect on coastal erosion (Syvitski et al.2005; Young et al., 2009).

2.7 Shoreline Change Analysis

Shorelines change analysis (SCA) is a broad descriptor that has been used since the 1970s to express the methods and approaches used to define and quantify changes in the location of shorelines (Burningham and Fernandez-Nunez, 2020). The study of shoreline change represents a vital step in understanding the dynamism and evolution of the coastal area. It provides stakeholders with insight to do better at reducing the risk of coastal erosion and minimizing social, physical, and economic loss (Fuad, 2017).

Shoreline changes in the coastal areas which arise from wave action and alongshore currents and are responsible for accretion and erosion of coasts are easily detected and computed using geospatial techniques and automatic calculations by the extension tool in ArcGIS (Nassar et al., 2019). The Digital Shoreline Analysis System (DSAS) extension tool in ArcGIS and developed by the United States Geological Survey (USGS) is used to calculate the rate of shoreline change statistics from a time series of multiple shoreline positions. The software is proposed to assist the shoreline change-calculation process and give the rate-of-change information and the arithmetical data essential to set up the consistency of the computed results (Murali et al., 2013). DSAS is also appropriate for any general-purpose that calculates positional transformation over time, such as assessing glacier limits in chronological aerial photos and land use/land-cover changes (Thieler et al., 2009). It has three main components that define a baseline, generate orthogonal transects that determine separation along the coast, and compute rate-of-change like Linear Regression Rate (LRR), End Point Rate (EPR), and several other computations.

Globally, qualitative and quantitative analysis of shoreline spatio-temporal variations has been addressed by several studies (Nassar et al. 2019; Addo, Jayson-Quashigah and Kufogbe, 2012). The End Point Rate (EPR) statistical technique combined with the satellite imageries is an accurate and reliable method for shoreline change computation and analysis (Sebat and Salloum 2018).

2.8 Strategies to addressing Coastal Management

The recognition of the potential effects of climate change and human pressures on coastal zones results in a growing need for a sustainable and efficient adaptation policy (European Environment Agency, 2006). The science of sustainability has emerged out of the interdisciplinary focus on atmosphere, combining aspects of sustainable development and environmental science. It utilises a notion of human and natural systems by examining interactions and feedback processes while encouraging innovative methods such as the combination of quantitative and qualitative methodologies, involving a mix of fieldwork with remote sensing technologies (Kate et al., 2001).

The implementation of sustainable strategies for coastal management demands a paradigm shift in the approach of project development and design, away from a traditional defensive approach. This promises to minimise impacts and, if necessary, effect mitigation and compensation towards a pro-active approach, aiming to optimise system opportunities, including benefits for nature and society (Ehler, 2003).

Coastal governance is of paramount importance in the implementation of coastal management strategies. It entails wielding power and authority in society to influence and enact policies and decisions concerning public life and economic and social development (Ehler, 2003). In relation to integrated coastal management (ICM), governance refers to the structures and processes used to govern public and private behavior in the coastal area and the resources and activities it contains. ICM highlights how specific resources or portions of the coastal zone are managed to achieve desired objectives. According to Ehler (2003), coastal management should follow the ICM policy cycle for effective management (*Figure 2*).

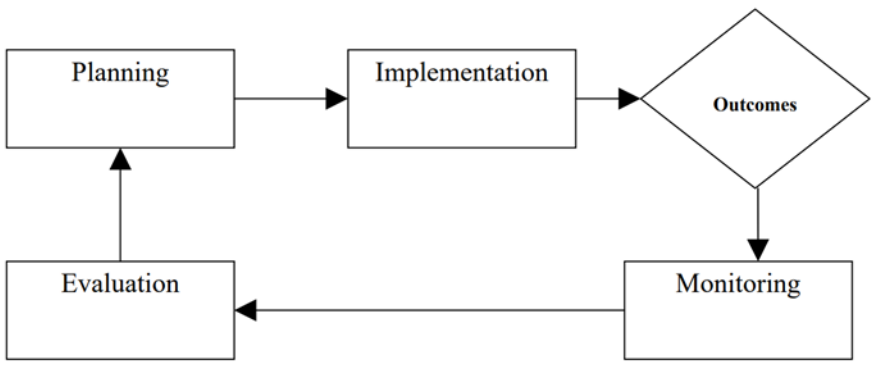

Figure 2: The Integrated Coastal Management Policy Cycle (Source: Ehler, 2003).

The coastal zone of The Gambia is prone to flooding and coastal erosion. The River Gambia, which runs through it, is both a source of livelihoods for communities and, at the same time, can become an environmental hazard severely affecting the capital, Banjul, and almost half of the country. In an attempt to curb the situation, the Global Environment facility supported a UN Environment-led project titled "Adoption of an Ecosystems Approach for Integrated Implementation of Multilateral Environmental Agreements at National and Divisional Levels" (UNEP Report, 2017). This project aimed to strengthen the national institutional framework for integrated management of global environmental priorities, and integrate global environmental and ecological issues into divisional level planning and implementation by identifying potential solutions to environmental issues, such as coastal erosion and flooding, thus enhancing community livelihoods.

Additionally, the Government of The Gambia in 2004 implemented a beach nourishment program along the coastline of The Gambia. This was aimed at reclaiming lost land to boost tourism, protect important structures from being lost, and protect biodiversity. However, concerns have been raised in recent times about the effectiveness of the adaptation action at protecting the coastline, as most of it has been lost again through the reclamation of lands by the ocean (Amuzu et al., 2018). There is the need to appraise further options and arrive at a more effective line of action to take to elude maladaptation in the coastal zone of The Gambia.

3. Data and Methods

The study was carried out using a combination of qualitative and quantitative data. Chapter three gives a detailed breakdown of the research methodology, covering data acquisition, processing, and analysis. The chapter first provides an overview of the study area and further discusses the data analysis tools employed to extract and compute the needed result for the study.

3.1 Study Area

This study was carried out over the coastal zone of The Gambia in West Africa, particularly cells 3, 4, 5 and 6 (*Figure 3).* The selection of the study sites was based on key factors such as their ecological value, the economic and natural resources that are linked to these areas that could be threatened, and the various cultural values and livelihoods that could be affected due to the unmonitored dynamism of the coast, that can potentially lead to environmental degradation, biodiversity loss and loss of natural resources.

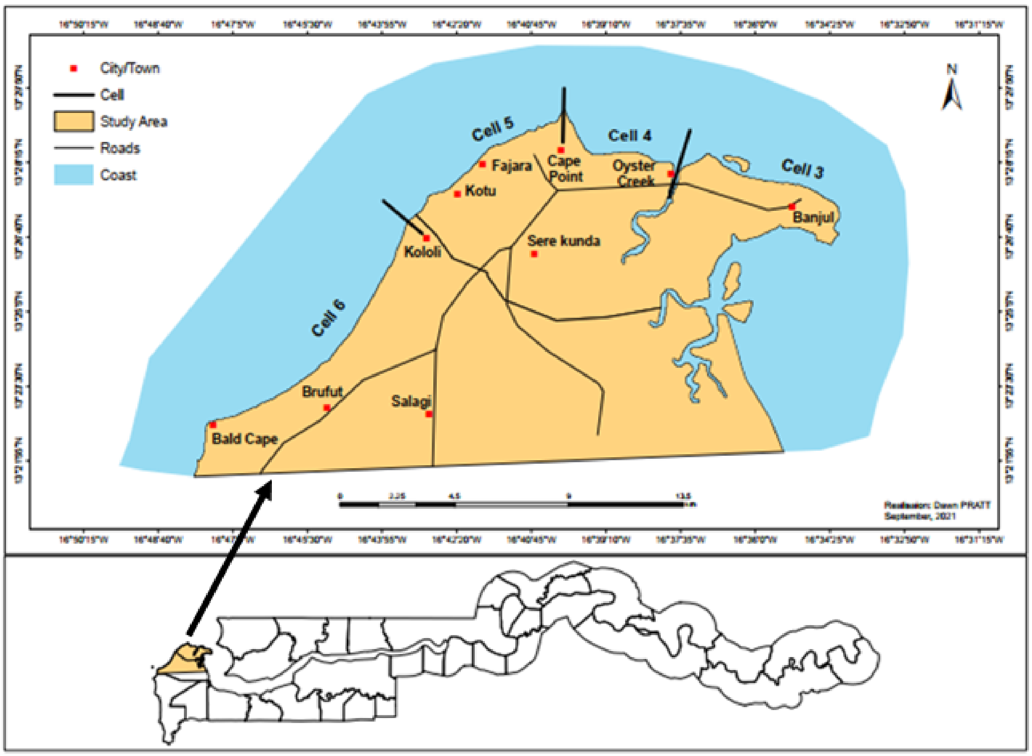

Figure 3: Map of the study area highlighting coastal cells 3 to 6.

The Gambia, bordered by Senegal on the north, east and south, and the Atlantic on the west (*Figure 4*) is located between latitude 13°N and longitude 15°W and has a coastline running along the West African coast, from the mouth of the Allahein River to between Buniadu Point and the Karenti Bolon; a total length of 80 km (Jallow et al., 1996). The study was carried out over cell 3 through to cell 6. Banjul (Latitude 13°26′25N and Longitude 16°34'29W) and Bald Cape (Latitude 13°21′30N and Longitude 016°48'11W) represent the limits of the coastline used for this study, with a total coastline length of about 33 km.

Figure 4: Map of The Gambia (Sourced from https://www.accessgambia.com)

The country is majorly semi-arid with two distinct seasons, wet and dry. The wet season runs between June to October; whereas, the dry season is from December to April. Most regions within The Gambia are currently experiencing a slight increase in temperature while rainfall patterns are irregular and highly variable. During the dry season, the influencing factors are the Saharan anticyclone which causes subsidence and hence, surface warming with northeasterly and or easterly wind-flow. The passages of mid-level troughs from the Atlantic Ocean occasionally accompanied by the sub-tropical westerly jet brings along unusually breezy and cool northerly and or northwesterly wind-flow. With regards to the rainy season, the critical factors in development of a wet mode depends on the development of a low-level equatorial southwesterly or southerly monsoonal flow, northward displacement of the Inter-Tropical Discontinuity/Inter-Tropical Convergence Zone (ITD/ITCZ) and the African Easterly Jet (AEJ) including easterly wave activities.

3.1.1 Banjul Port to Oyster Creek (Cell 3)

The coastline within this unit extends from Banjul, the capital, to Oyster Creek (*Figure 5*). This cell is a 13.5 km stretch of land, with the highest point, approximately 2 m above mean sea level (Jallow et al., 1996). A considerable number of government institutions and private businesses are located in Banjul. It is also home to important cultural, economic and social sites such as the National Cemetery, The National Assembly, The State House, National Museum hotels, Mile two central prison and an oil mill, with few Ministries located less than 300m from the coastline (Amuzu et al., 2018). The area between Banjul Point and the sand-spit east of Oyster Creek consists of narrow beaches with damaged groynes and local revetment protections. Barrier spit and island systems trend eastward into The Gambia River and are the main geomorphological features in this unit.

Figure 5: Sandy beach along Banjul to Oyster Creek (Source: NEA, 2012).

3.1.2 Cape Point to Fajara (Cell 4)

This coastal cell stretches over a distance of 3.5 km. It is characterized by actively eroding cliffs and restricted pocket shorelines running west from Cape Point to Fajara (*Figure 6*). The upper layer of sandstone is liable to disintegration by runoff spillover, and, where unprotected, the underlay is liable to disintegration by wave action. Besides threats of coastal erosion, this area is also prone to frequent flooding from the stream openings present in the area (Amuzu et al., 2018). The cell constitutes a line of important overseas organizations, private properties, consulates, and the Bakau fish-landing site, among others. So far, considerable damages to hotels and residential buildings along this coastal cell's shoreline have been recorded.

Figure 6: Eroding cliffs along the Cape Point to Fajara coastal stretch highlighted in a) and b) (Source: NEA 2015, 2016).

3.1.3 Fajara to Kololi Point (Cell 5)

Kololi Point is a prominent geomorphological feature in this unit, and shoreline retreat is evident by the wave-cut cliffs. The shoreline of this coastal cell spans 5km, and it is expansive and mostly uninterrupted towards the north, while the southern part is narrow and underdeveloped (Figure 7).

Figure 7: Beach profile along Fajara to Kololi Point (Source: NEA, 2017).

3.1.4 Kololi to Bald Cape (Cell 6)

This 11km shoreline between Kololi Point and Bald Cape (*Figure 8*) is mainly characterised by tourism-related facilities and the demarcated tourist development area. No coastal protection works were present in this cell as of 2018, except for local sandbag revetments in front of the hotels. Besides the ongoing challenge of coastal erosion in this area, the shoreline is also susceptible to frequent river flooding from the Kotu creek (Bijl, 2011). Farmlands along Kotu Creek will probably experience adverse effects of prolonged flash floods and saline interruption, reducing the productivity of farmlands in this area in support of agricultural activities. Although some parts area has been embanked, other sites are still exposed and likely to be at risk of coastal erosion in the short term.

Figure 8: Coastline along Fajara to Kololi Point highlighted in a) and b) (Source: NEA, 2010).

3.2 Data

3.2.1 Shoreline Satellite Data

In assessing the long-term shoreline change of the coast of The Gambia, multi-temporal Landsat satellite imagery that offered the land-use information at different LANDSAT missions (Chander et al. 2009) for 32 years were used. TM, ETM+, and OLI images were downloaded from the United States Geological Survey website (https://earthexplorer.usgs.gov/) for 1986, 2002, and 2018 respectively. Landsat imagery has synoptic and repetitive data coverage, with multi-spectral resolution capabilities to observe, measure, and distinguish between land and sea surface geophysical features, proving valuable for studies related to the coastal area and coastal zone management (Moore 2000; Mishra et al. 2019).

The imageries considered for this analysis were selected at a 16-year interval based on the lowest cloud cover over the study area. According to (Lima et al. 2019) pre-monsoon, March-April, or post-monsoon season; September to October, satellite data are cloud and haze-free and best preferred due to reduced or minimal atmospheric errors. A uniform spatial resolution of 30 meters was maintained for all datasets to avoid scale transformation error. All the satellite imageries are in UTM projection coordinate system with zone node 28N and WGS 84 datum. The details of the satellite data used are recorded in Table 1.

Table 1: Specifications of satellite data

Date of Acquisition	Satellite/Sensor	Path/Row	Projected Coordinate System	Spatial Resolution	Land Cloud Cover
24/01/1986	Landsat 5 (TM)	205/51	UTM_1984_28N	30m	0
18/04/2002	Landsat 7 (ETM+)	205/51	UTM_1984_28N	30m	0
22/04/2018	Landsat 8 (OLI)	205/51	UTM_1984_28N	30m	0

3.2.2 Wave and Wind Climate Analysis

To estimate the effect of wave climate over the coast of The Gambia, ERA5 monthly averaged data on single levels from 1979 to present was used to download bulk wave parameters (significant height *Hs*, wave period *T*). This data was derived from Copernicus Climate Change Service from the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides hourly global estimates for a large number of atmospheric, ocean-wave and land-surface quantities. The data was download from January 1986 to December 2018. Significant wave height and mean wave period data were extracted from the ECMWF data server with a horizontal resolution of 0.5°x 0.5° and a monthly temporal resolution.

The wind climate data was also acquired from the ERA5 monthly averaged data on single levels from 1979 to the present was used to download wind parameters (wind speed, u-component of wind, and v-component of wind) for 1986-2018. Monthly reanalysis data was downloaded from January 1986 to December 2018 with a horizontal coverage of 0.2° x 0.2° (22.2km).

3.3 Methods

In analysing the shoreline changes along the coastal cell of The Gambia, the following tasks were performed: study area definition, data acquisition, image pre-processing in ENVI, shoreline extraction from each image using NDWI indexing approach, and finally, shoreline change detection using DSAS in ArcGIS. *Figure 9* shows the methodology adopted in this study to detect the shoreline changes.

Figure 9: Flow Chart of Research Methodology

3.3.1 Image Pre-processing in ENVI

The raw satellite imagery usually contains many defects varying from radiometric distortion, geometric distortion, and the presence of noise due to variations in the attitude and velocity of the sensor platform. Thus, they cannot be used without undergoing corrections. The following pre-processing steps were performed to prepare the images for processing: radiometric calibration and atmospheric correction. Radiometric calibration and atmospheric correction were conducted according to Schroeder et al. (2006) using ENVI.

ENVI is a remote sensing software used in the processing and analyses of geospatial imagery. Using the software, radiometric calibration was performed according to the radiance of each image; thus, making it possible to compare multi-temporal imagery. Radiometric calibration employs algorithms and a series of processes that improve Landsat data. This is done by converting the Digital Number (DN) data values to spectral radiance and then to reflectance. This is accompanied by the removal of atmospheric effects, which are due to absorption and scattering.

Atmospheric correction of the images was carried out to remove products artifact (Pons et al. 2014) and the effects of the atmosphere such as clouds and aerosol properties to produce surface reflectance values. Atmospheric correction significantly improves the interpretability and use of an image to minimize the effects of alteration in radiometric values generated by interpolation during a geometric correction.

Fast Line-of-sight Atmospheric Analysis of Hypercube (FLAASH) tool is a first-principles atmospheric correction tool that corrects wavelengths in the visible through near-infrared. It was also employed in data processing and shortwave infrared regions were used to reduce the effect of the atmosphere (such as surface albedo, surface altitude, water vapor column, aerosol and cloud optical depths, surface, and atmospheric temperatures) effectively, to enhance the image information with better accuracy and to calibrate the sensors and superimpose the different images.

3.3.2 Shoreline Detection and Extraction using NDWI

Normalized Difference Water Index (NDWI) was used to extract water features from Landsat TM, and ETM+ images as Green and Near Infrared bands of the satellite images are common bands at all Landsat sensors. NDWI has greater accuracy for delineating water features than other indices (McFeeters, 1996). NDWI works by getting the maximum water reflectance by green band wavelength and minimizes low reflectance of Near-Infrared by water feature (Roy et al., 2018). Bands 2 and 4 were used for TM and ETM+ images, whiles bands 3 and 5 were used for OLI images. The extraction was done using the signatures of each ground target among the spectral bands and the band ratio between two spectral bands. McFeeters (1996), proposed a threshold binary image classification ranging from -1 to 1 for delineating surface water features from the raw digital number of Landsat and defining the discrete separation line as the shoreline, where all positive NDWI values are classified as water and negative values as non-water features. The NDWI is expressed as follows in equation 1:

$$NDWI = \frac{Green - NIR}{Green + NIR} \qquad \text{(Eq. 1)}$$

Where *Green* is the reflectance of the green band, and *NIR* is the reflectance of the near-infrared band.

This index is intended to maximize water reflectance by using the green wavelengths, minimize the low reflectance of NIR by water features, and take advantage of the high reflectance of NIR by vegetation feature. Thus, enhancing water features with positive values and suppressing vegetation and soil to negative values.

3.3.3 DSAS Analysis in ArcGIS

The basis software used in determining shoreline rate-of-change is the Digital Shoreline Analysis System (DSAS). DSAS is an extension tool in ArcGIS, a Geographic Information System (GIS) software developed by the Environmental Systems Research Institute (ESRI). There are several methods to calculate shoreline change in DSAS, such as Shoreline Change Envelope (SCE), Net Shoreline Change (NSM), End Point Rate (EPR), Linear Regression Rate (LRR) change, and so on. DSAS allows the calculation of the rate of change statistics for a time series of shorelines. Shoreline change rates are calculated in DSAS using the distances between the reference baseline and each shoreline intersection along a transect. The shoreline boundaries were extracted from the false colour composite of Landsat imageries of TM, ETM+ and OLS representing 1986, 2002, and 2018 respectively. Satellite imagery of different periods was digitalized in shapefile and imported in DSAS to calculate and analyse the shoreline change rate. DSAS uses a measurement baseline method to calculate rate-of-change statistics for a time series of shorelines (Leatherman and Clow, 1983). The baseline was computed manually and served as the starting point for all transects cast by the DSAS tool. In this study, the DSAS was executed in five steps: shorelines preparation, baseline creation and buffering, transects generation, computation of distances between baseline and shorelines at each transect, and finally, the calculation of the rate of shoreline change (Thieler et al. 2005).

The temporal shoreline, 1986, 2002, and 2018 were merged into a feature class and kept in a personal geodatabase with required attributes to measure shoreline change along each transect. A buffer line of 200m was created along the onshore side, and to create a measurement point, transects intersect each shoreline, and the measurement points are used to calculate shoreline change rates. Transects were automatically generated perpendicular to the baseline at 200m intervals with 100m transect spacing. The intersections of transects and the shorelines along the defined baseline were then used to calculate the rate of change statistics.

The DSAS executes statistical operations, namely Shoreline Change Envelop (SCE), Net Shoreline Movement (NSM), and End Point Rate (EPR), to measure the shoreline change rate of the study area. The measured shoreline change rates have been interpreted for four (4) cells; Banjul Point to Oyster Creek (Cell 3), Cape Point - Fajara (Cell 4), Fajara - Kololi Point (Cell 5), and Kololi Point-Bald Cape (Cell 6) based on the coastal configuration. Hence, all these segments were represented by 360 transects placed perpendicular to the shoreline with 50m intervals, and their corresponding statistical values have been described for the transects of individual cells.

3.3.4 Shoreline Change Analysis

The discrete shorelines were extracted, and a geo-database was prepared using ArcGIS 10.8 software. The landward shoreline movement with respect to the position of reference baseline is considered erosion. At the same time, the seaward shift indicates accretion at each transect of the individual cells, and the statistical values of the measurement have been denoted as negative (-) for erosion rate and positive (+) for accretion rate (Anders and Byrnes 1991). The SCE and NSM computation operation values in DSAS are used to measure the distance of the long-term net shoreline change in meters between 1986 and 2018. The rates of shoreline change were calculated by measuring the distance between shoreline positions through time and along a given transect (Dolan et al., 1991). The EPR statistical measurements reveal the short-term change rate per year during the period of study. The SCE is estimated as the distance between the shoreline farthest from and closest to the baseline at each transect. This measurement represents the total change in shoreline movement for all discrete shoreline positions and is unrelated to their dates. The entire shoreline movement was represented for all shoreline positions, and their rate of erosion and accretion along the coast has been considered with respect to baseline positions. The SCE is expressed as equation 2:

$$S_d = d_f - d_c \qquad \text{(Eq. 2)}$$

Where S_d is the shoreline change distance in metres (m), d_f is the distance between the baseline and farthest shoreline (m) at a specific transect; d_c is the distance between the baseline and closest shoreline (m) to a particular transect.

The NSM is associated with the dates of only two shorelines. It is estimated as the distance between the oldest, and youngest shorelines at the point of intersection in each transect. Equation 2 is used to calculate the NSM and it is generally expressed as equation 3:

$$NSM = Dt_2 - Dt_1 \qquad \text{(Eq. 3)}$$

Where Dt_2 is the distance of the earliest (first) shoreline for each transect, Dt_1 is the distance of the latest shoreline for each transect.

The End Point Rate (EPR) statistics was used in estimating the extent of shoreline changes. EPR is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline (Forster and Savage, 1986). The EPR is a statistical method for estimating the rate of shoreline change per year. It is calculated by taking the difference between the first (closest) and last (farthest) shoreline to the baseline at a specific transect and dividing by the number of years used for the study. In DSAS analysis, the EPR statistic is performed by dividing the distance of net shoreline movement (NSM) at transects by the total period of interval elapsed between the oldest and most recent shorelines. The trends of the EPR values represent the rate of erosion and accretion processes in the coastal zone. The EPR is estimated using Eq. 4, which is expressed as:

$$\mathrm{EPR} = \frac{\mathrm{D_1} - \mathrm{D_2}}{\mathrm{t_1} - \mathrm{t_0}} \qquad \text{(Eq. 4)}$$

Where D_1 and D_2 are the distances between the shorelines and the baseline, and t_0 and t_1 represent the dates of the two shoreline positions.

3.3.5 Wave and Wind Climate Analysis

In assessing the wind sea and wave climate over The Gambia, the climatology of the ERA-5 significant wave height was processed monthly and seasonally, following the World

Meteorological Organisation standards. For the northern hemisphere, seasons are named DJF (December to February; Winter), MAM (March to May; Spring), JJA (June to August; Summer), and SON (September to November; Fall). For the monthly analysis, months are labeled 1 to 12, indicating the months of the year from January to December. Spatial distribution of the mean significant wave height was generated and overlaid by the mean wind direction. The climatology of the wind was analysed using the wind speed and u and v components of the wind. The wind speed was computed using equation 5:

$$w = \sqrt{u^2 + v^2} \qquad \text{(Eq. 5)}$$

Where w is the wind speed, *v* is the zonal component and *u* is the meridional component of the wind. From the wind climate data, the wind rose was also computed. Wind direction increases clockwise such that an eastward wind is 0°, a northward wind is 90°, a westward wind is 180°, and a southward wind is 270°. The statistics of the various parameters were also calculated.

3.3.6 Questionnaire Survey

Structured questionnaires were purposively administered to a total of 14 subject experts, comprising coastal zone managers and professionals involved in coastal protection, for approximately 10 minutes per person. The questions to the subject experts focused on the history of the erosion problem in The Gambia, and their perceptions on the causes of shoreline change. The main objective of implementing the questionnaire was to acquire a cross-reference to different stakeholder experiences of shoreline evolution and management and ground truthing of the satellite data used in the realisation of the shoreline evolution map. Seven of the respondents were managers involved in planning and policy evaluation, and the other seven were involved in coastal monitoring and community outreach. In addition, three interviews were conducted with two programs officers involved in coastal monitoring from The National Environment Agency and the Great Institute. These interviews were conducted to investigate the technical reasons behind the planning and construction of shoreline management structures along the coast.

4. Results

The study results demonstrated that coastal cells of The Gambia had experienced a general shoreline movement, both landward and seaward, in all the three periods analyzed in this study. A summary of the net movement and the rates of change along these coastlines within the study periods are presented below.

4.1 Summary of Shoreline Change Statistics: 1986-2002

The shoreline of the study area is about 33 km and is divided into four segments called cells. Cell 3 runs through Banjul to Oyster Creek; cell 4 covers Cape Point to Fajara, cell 5; Fajara to Kololi Point, and cell 6 covers Kololi Point to Bald Cape (Table 2).

Table 2: Cell identification and their corresponding DSAS transect numbers.

Cell No.	Cell Name	Transect ID	Shoreline Length (km)	Coast Type
3	Banjul point – Oyster Creek	278-360	13.5	Beach
4	Cape Point - Fajara	216-277	3.5	Cliff
5	Fajara – Kololi Point	141-213	5	Beach
6	Kololi Point – Bald Cape	1-140	11	Beach

The DSAS results on the rates of shoreline changes calculated at 100m transect distance across the coastal cell of The Gambia between 1986-2002 is presented in *Figure 10*. Overall, this indicates that the erosion rate and the overall shoreline movement increased continually from 1986 to 2002, with an average EPR of -1.76 ± 0.87 m/yr and an average NSM distance of -28.5 m. It was observed in each period that there was continuous erosion, and a remarkable increase in end point rate and net shoreline movement occurred within the 1986-2002 period. The DSAS summary of the shoreline change analysis based on the EPR and NSM between 1986 and 2002 is shown in Table 2.

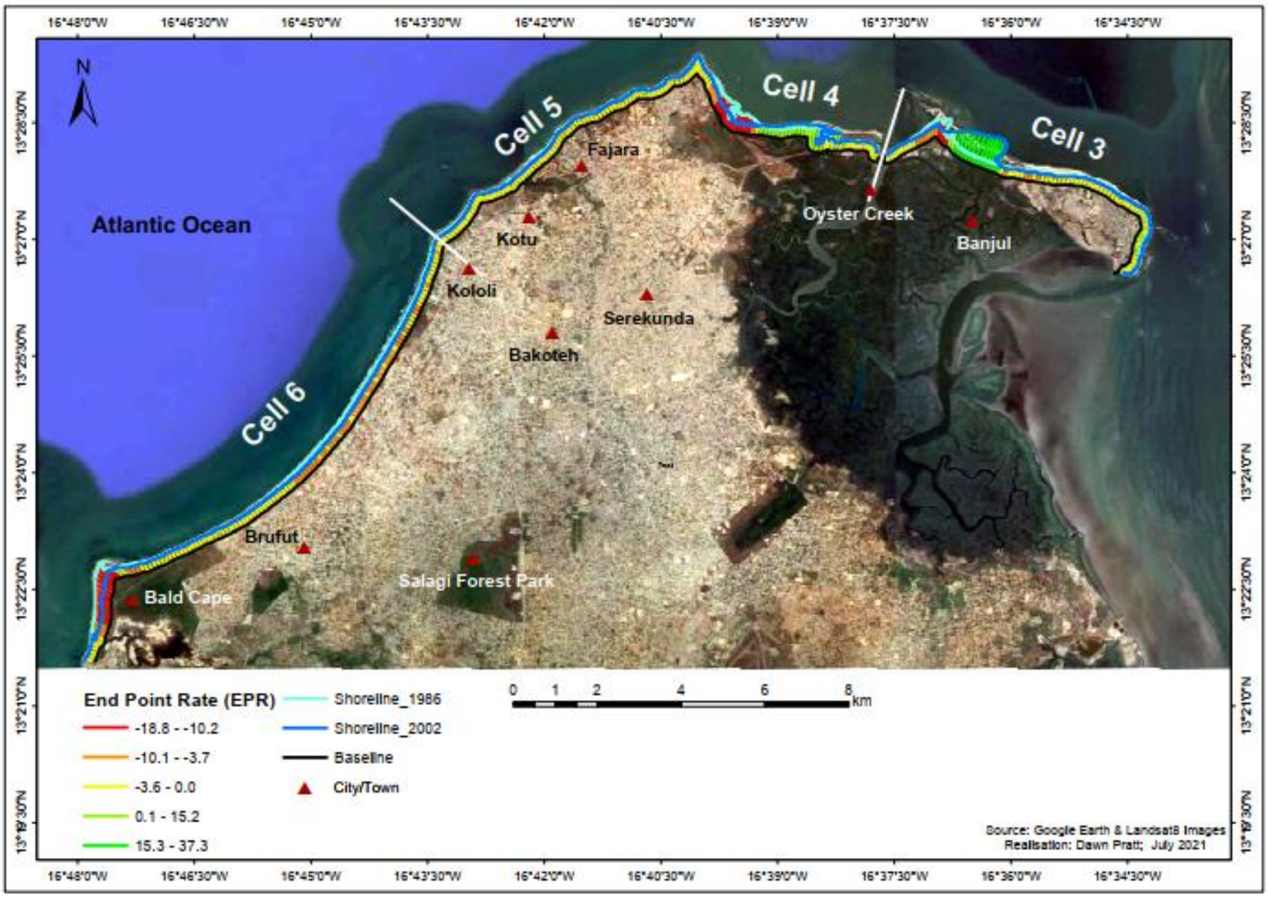

Figure 10: Shoreline Change Map of End Point Rate: 1986-2002

4.1.1 Cell 3

Cell 3 (Banjul – Oyster Creek) proved to be the most dynamic, recording the highest shoreline movement of -305.2 m to 605.7 m (*Figure 12)* and an EPR ranging between -18.8 m/yr to 37.3 m/yr during this period (Table 3). Trends indicated that seaward shoreline shifts were highest around the Hamza Military Barracks and the coastal stretch opposite the Mile 2 prison, experiencing a high accretion rate with an EPR of 37.3 m/yr along the 299th transect. This cell recorded an average rate of change of 3.81 m/yr with an average NSM of 61.90 m. Transects 279-288 (*Figure 11*) recorded a landward shift with an average NSM of -144.5m and an average EPR of -8.9 m/yr, indicating moderate erosion. In contrast, the remainder of the transects in this cell recorded low erosion rates between -0.1 to -3.6 m/yr.

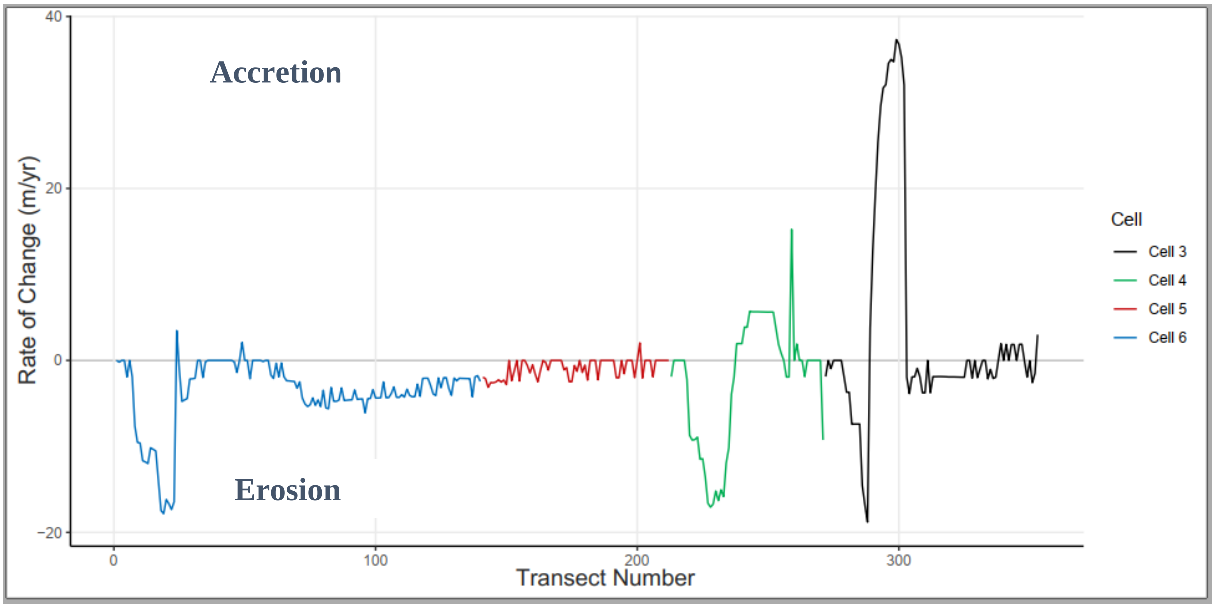

Figure 11: End point rate (EPR) of 1986-2002

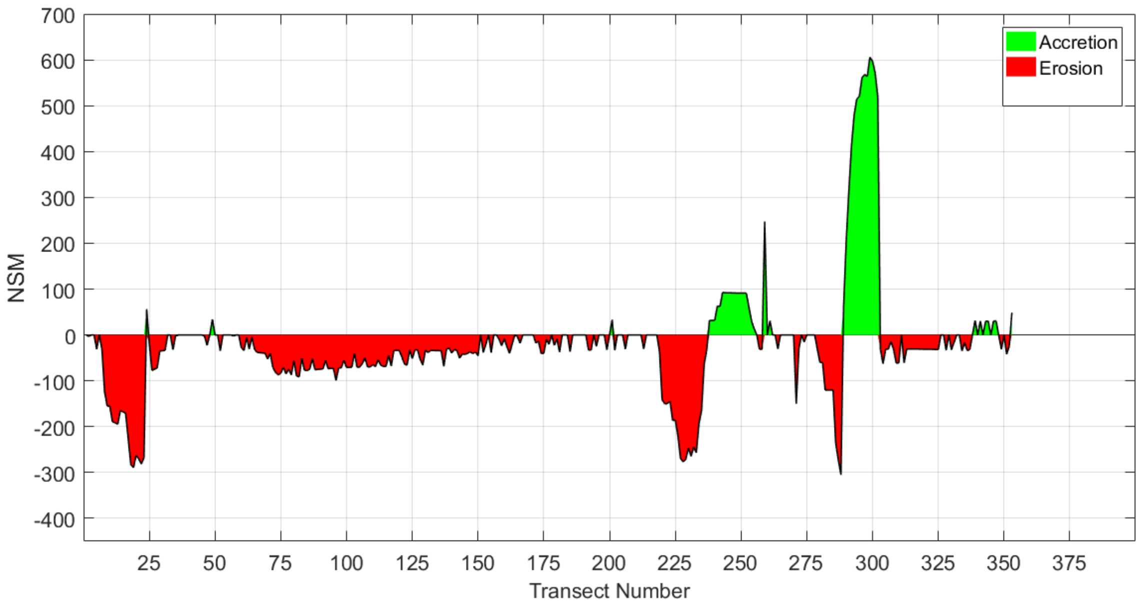

Figure 12: Net shoreline movement (NSM) of 1986-2002

4.1.2 Cell 4

Within Cell 4 (Cape Point – Fajara), a similarly positive and negative shoreline movement trend was observed with an average NSM of -51.2m (Table 3). Transects 213-237 experienced a moderate erosion rate at an average of -10.9 m/yr around the Sun Beach Hotel through to Ocean Bay Resort, while a low accretion rate of 4.3 m/yr was observed between transects 238-255 (*Figure 11*). Aside from transect 259 that recorded the highest rate of change of 15.2 m/yr, rest of the shoreline within this cell eroded at a low rate of less than 2.6 m/yr.

Table 3: Shoreline change statistics using End Point Rate (EPR): 1986-2002.

S/N	Attribute	Cell 3	Cell 4	Cell 5	Cell 6
1	Total Transect	82	59	72	140
2	Mean Shoreline change rate EPR (m/yr)	3.81	-3.15	-1.7	-4.5
3	Mean Net Shoreline Movement Rate (m)	61.9	-51.17	-27.6	-72.9
4	Mean Accretion Rate (m/yr)	19.74	4.68	2.04	2.78
5	Mean Erosion Rate (m/yr)	-3.46	-9.68	-1.8	-4.62
6	Maximum Accretion Rate	37.32	15.24	2.04	3.47
7	Maximum Erosion Rate	-18.8	-17.06	-3.13	-17.83
8	Number of Accreting Transect	21 (25%)	20 (34%)	1 (4%)	2 (2%)
9	Number of Eroding Transect	46 (56%)	24 (41%)	37 (51%)	113 (81%)
10	Overall Trend	Accretion	Erosion	Erosion	Erosion

4.1.3 Cell 5

The shoreline along Cell 5 (Fajara - Kololi Point) was recorded the least shoreline movement and the least erosion rate during this period. This cell recorded an average NSM of -27.6 m and an average shoreline change (EPR) of -1.70 m/yr (Table 3).

4.1.4 Cell 6

Cell 6 (Kololi Point – Bald Cape) recorded the most critical rate of change as the entire stretch of the shoreline experienced erosion except for transects 24 and 49. This cell experienced a rate of change of -4.5 m/yr with an average erosion rate of -4.60 m/yr, accounting for 81% of all transects in the cell (Table 3). The highest rates of erosion were observed around the Tanji Bird Reserve through to Tanji.

4.2 Summary of Shoreline Change Statistics: 2002-2018

The shoreline analysis result of the rate of shoreline change over this period is presented in Figure 13. Overall, 357 transects were generated along the shoreline for this analysis. A net accretion trend was observed, with a NSM ranging between -409.8 and 420.5 m and an average net shoreline movement of -44.7 m (*Table 4*). The mean rate of change recorded was 2.79 ± 0.88 m/yr, with an EPR ranging from -25.6 to 26.3 m/yr. A total of 219 transects (84%) underwent accretion, of which 77.5% was statistically significant, whiles 15.7% of the remaining transects recorded statistically significant erosion (*Table 4*).

Table 4: Shoreline change statistics using End Point Rate (EPR) and Net Shoreline Movement (NSM): 2002-2018.

S/N	Attribute	Cell 3	Cell 4	Cell 5	Cell 6
1	Total Transect	83	62	73	139
2	Mean Shoreline change rate EPR (m/yr)	2.17	4.73	1.22	2.74
3	Mean Net Shoreline Movement Rate (m)	34.79	75.67	16.94	43.86
4	Mean Accretion Rate (m/yr)	6.38	8.7	1.8	3.1
5	Mean Erosion Rate (m/yr)	-16.47	-4	-1.6	-1.52
6	Maximum Accretion Rate	26.26	18.78	5.71	12.25
7	Maximum Erosion Rate	-25.6	-8.48	-2.28	-2.12
8	Number of Accreting Transect	62 (75%)	35 (57%)	24 (33%)	98 (71%)
9	Number of Eroding Transect	14 (17%)	16 (26%)	5 (7%)	8 (6%)
10	Overall Trend	Accretion	Accretion	Stable	Accretion

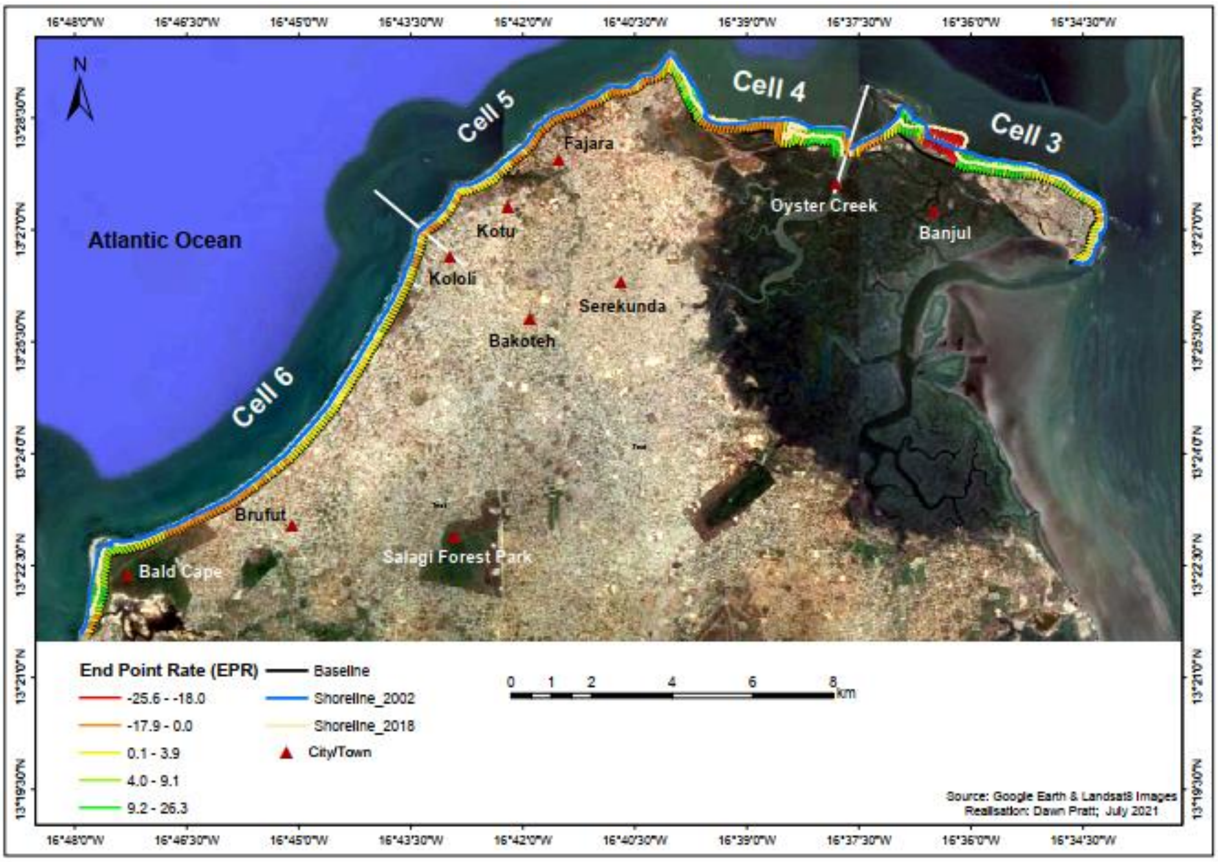

Figure 13: Shoreline Change Map of End Point Rate: 2002-2018

4.2.1 Cell 3

This cell experienced the most shoreline shift, both landwards and seawards, with an overall accretion trend during this period (*Figure 14*, *Figure 15*). An average NSM of 34.8 m and a rate of change (EPR) ranging between -25.6 and 26.3 m/yr was recorded (*Table 4*), indicating a slightly higher accretion rate as opposed to erosion. 83 transects were generated in this cell, of which 62 (75%) experienced accretion at an average rate of 6.38 m/yr. 17% of the remaining transects eroded at a rate of -16.47 m/yr, leaving just 3% of the shoreline stable. The highest accretion rates of >10 m/yr were recorded along the shoreline close to Radio Syd and along Toll point, while the most erosion of 20.5 m/yr occurred along the Hamza Barracks between transects 296-306 (*Figure 14*). The rest of the shoreline within this cell accreted at a lower rate of ≤ -3.9 m/yr.

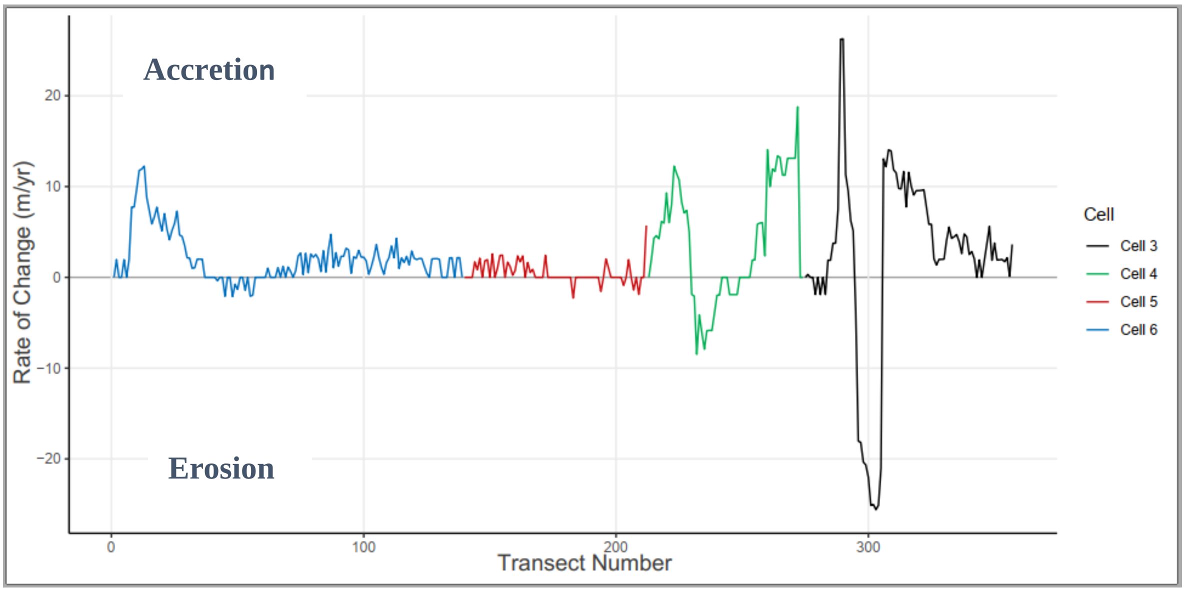

Figure 14: End Point Rate (EPR) 2002-2018

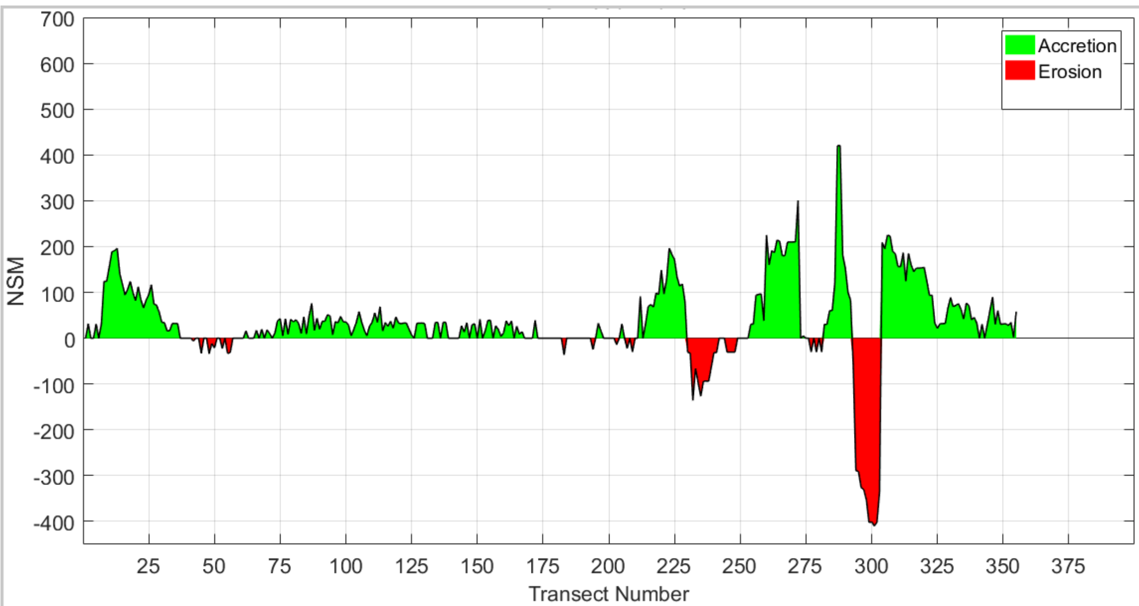

Figure 15: Net Shoreline Movement: 2002-2018

4.2.2 Cell 4

A net accretion trend was observed along the shorelines of this cell, with accretion being dominant at the extremes and erosion being observed along the center of the cell. This cell recorded a mean shoreline rate of change of 4.73 m/yr and an average NSM of 75.67 m (*Table 4*). A total of 62 transects were generated within this cell, of which 35 (67%) experienced accretion with a mean accretion rate of 8.70 m/yr. The accreted shoreline segment of the cell included the rocky cliff of Cape Point Beach between transects 214-229 and the segment preceding the Denton Bridge between transects 254-272. The mid-segment recorded an average erosion rate of -4.0 m/yr.

4.2.3 Cell 5

This cell remained the most stable with minimal shoreline change across all 73 transects and recorded a net positive shoreline shift with a mean shoreline change rate of 1.22 m/yr (*Table 4*). An average NSM of 16.9 m and a mean accretion rate of 1.80 m/yr were observed, with 60% stability along the cell. Fajara experienced moderate erosion, while a lower accretion rate was observed around Kotu (≤ 3.9 m/yr).

4.2.4 Cell 6

A total of 139 transects were generated in this segment, of which 98 (71%) recorded a positive shift, making this cell the most accreted during this period. This cell recorded a positive NSM of 43.9 m and an EPR ranging between -2.12 and 12.25 m/yr (*Figure 14*). Trends indicate that accretion was highest around Bald Cape coastal stretch all through to Tanji. Transects 42-56; the shoreline along Brufut recorded minimal erosion with an EPR of -2.74 m/yr, while 24% of all transects remained stable and the rest of the coast accreted at a rate of ≤ 3.1 m/yr. This cell experienced an overall accretion trend during this period.

4.3 Cumulative Summary of Shoreline Change Statistics: 1986-2018

The shoreline analysis result of the rate of shoreline change over this period is presented in Figure 16. Based on the rate of shoreline changes EPR method, the coastal stretches of the study area were classified into five categories based on their rates of change. The categories include; high erosion (≥-4.3 m/yr), low erosion (-4.2 to 0 m/yr), stability (-0.1 to 1.4 m/yr) and low accretion (1.5 to 5.1 m/yr) and high accretion (> 5.2 m/yr).

Table 5: Cumulative shoreline change statistics using End Point Rate (EPR): 1986-2018.

S/N	Attribute	Cell 3	Cell 4	Cell 5	Cell 6
1	Total Transect	83	64	73	140
2	Mean Shoreline change rate EPR (m/yr)	3.26	1.73	-0.43	-1.34
3	Mean Net Shoreline Movement Rate (m)	105.1	63.22	-26.83	-37
4	Mean Accretion Rate (m/yr)	3.91	4.45	1	1.35
5	Mean Erosion Rate (m/yr)	-1.35	-5.2	-0.78	-1.33
6	Maximum Accretion Rate	13.36	14.06	1.19	3.26
7	Maximum Erosion Rate	-1.86	-11.04	-1.57	-6.17
8	Number of Accreting Transect	63 (78%)	41 (64%)	5 (7%)	7 (5%)
9	Number of Eroding Transect	09 (11%)	16 (25%)	32 (7%)	96 (69%)
10	Overall Trend	Accretion	Accretion	Stability	Erosion

There is a variation in the mean EPR of accretion and erosion in all four cells across 1986, 2002, and 2018. A mean accretion rate of 3.91 m/year was found in cell 3 (Banjul-Oyster Creek), the highest accretion rate amongst all four cells, whereas cells 4 and 6 recorded similar rates of accretion rates of 1.61 m/yr and 1.35 m/yr, respectively (*Table 5*). Cell 5 comprised the most stable shorelines and recorded the lowest accretion rate of 1 m/yr.

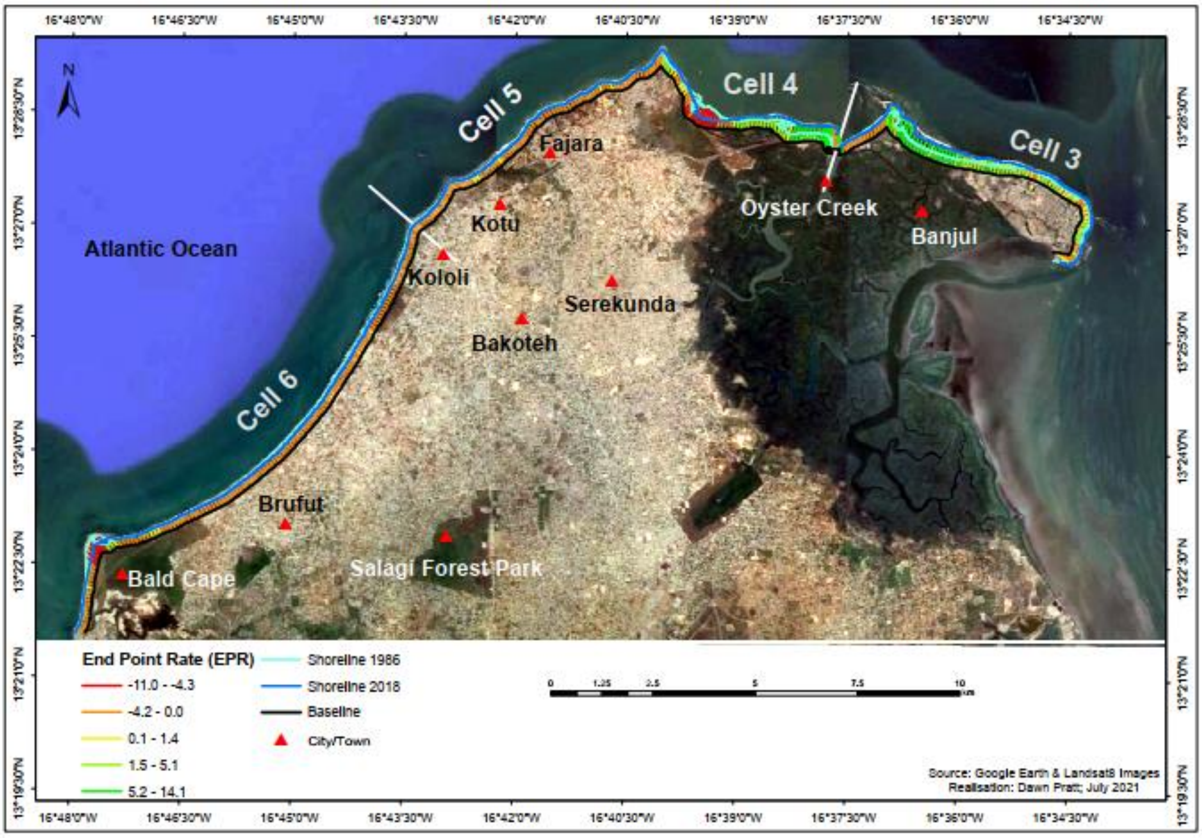

Figure 16: Shoreline Change Map of End Point Rate: 1986 -2018.

Overall, a total of 360 transects were generated for this analysis, and a net accretion trend was observed with a NSM ranging between -356.1 and 453.3.5 m (*Figure 18*) and an average movement of 25.1 m. The mean rate of change recorded was 0.78 ± 0.44 m/yr, with an EPR ranging from -11.04 to 14.06 m/yr (*Figure 17*). A total of 116 transects (44%) underwent accretion at a rate of 4.78 m/yr, while 47% of the eroded transects recorded statistically significant erosion at a rate of -1.66 m/yr.

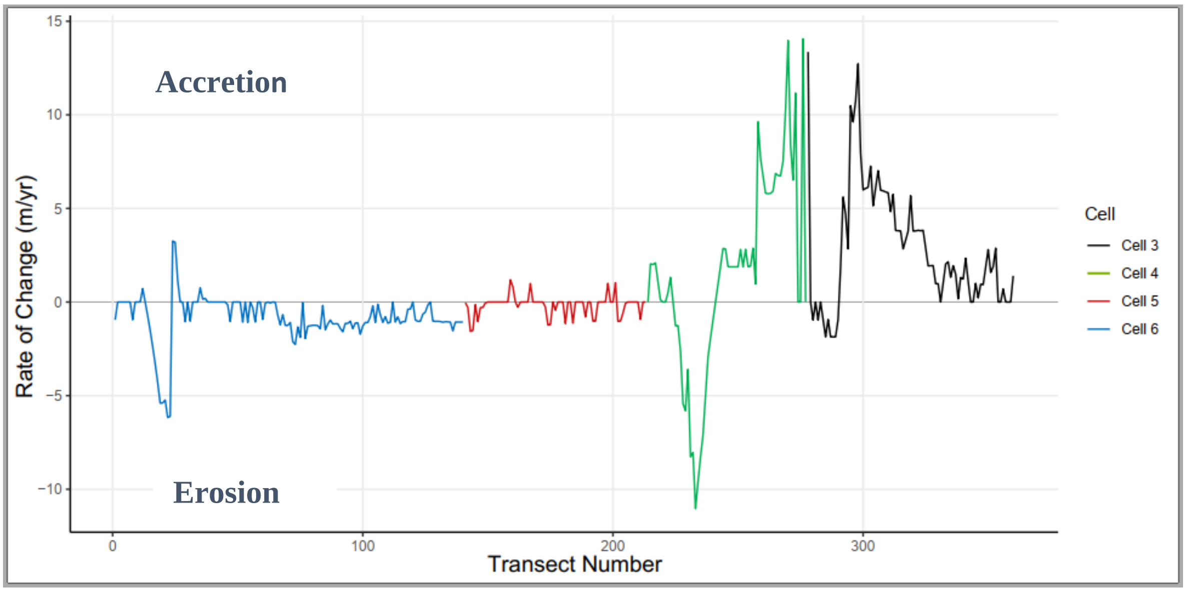

Figure 17: End Point Rate (EPR) 1986-2018.

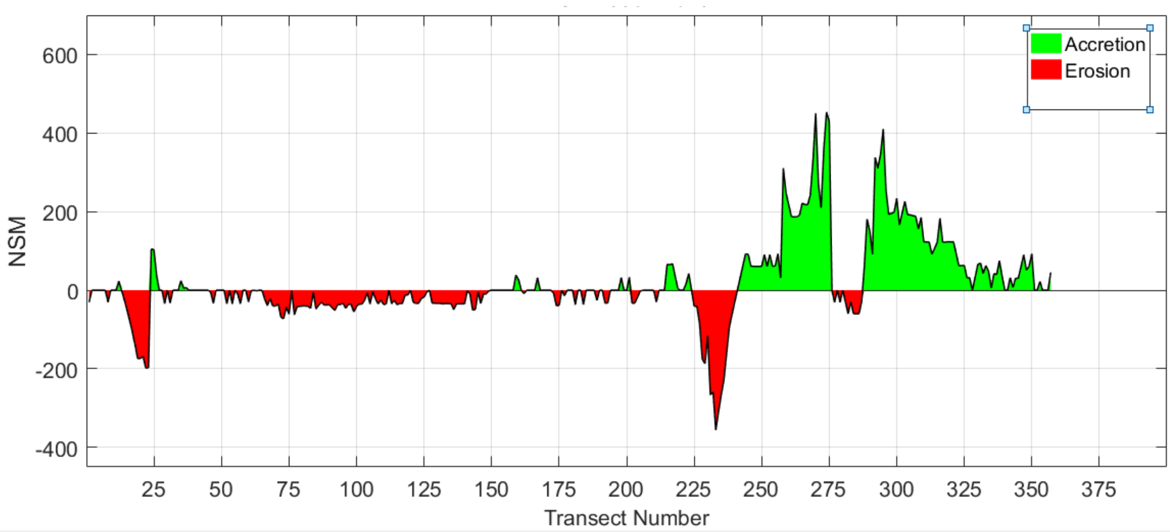

Figure 18: Net Shoreline Movement: 1986-2018.

The segments experienced a twitch in the erosion trend as cell 4 recorded the highest rate of -5.2 m/yr, with a mean shoreline change of 1.73 m/yr. Cells 3 and 6 experienced a similar erosion rate at -1.35 m/yr and 1.33 m/yr, respectively, whereas cell 5 recorded a low rate of -0.78 m/yr and a low shoreline change rate of -0.43 m/yr. The entire study area experienced an average shoreline change of 0.78 ± 0.44 m/yr. The maximum mean shoreline change rate was found along cell 3 and cell 5 recorded the minimum value amongst all the cells.

This study found that about 50% of the shoreline along the study area; cells 3 and 4 precisely, are actively accreting while 25% (cell 6) is gradually eroding though at a low rate of -0.84 m/yr and the remaining 25% (cell 5) has remained consistently stable all through the study period. The statistics of the various cell are shown in *Table 5*.

4.4 Stakeholder Perception on Shoreline Evolution

4.4.1 Characteristics of Respondents

The 14 stakeholders who participated in the questionnaire survey were between the ages of 20 to 45 years and have worked directly and indirectly with the coastal area for about 2-10 years.

Figure 19 displays the distribution of their ages. The age range of 31-39 years constituted the highest frequency - representing 50% percent of total respondents, followed by 20-30 and 40-45 years, each comprising 29% and 21% of respondents, respectively. The group falls within the active working-class group employed in different sectors of management. The group was able to provide valuable information concerning the historical and current observations along the coastal zone.

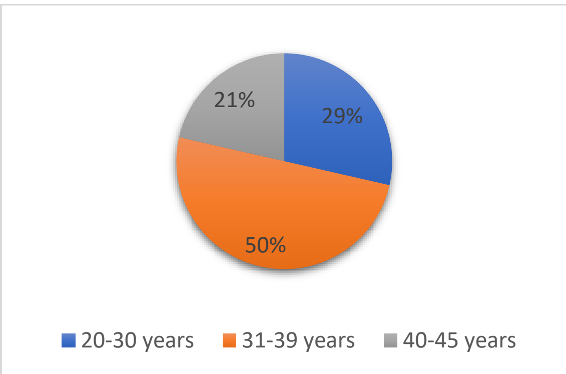

Figure 19: Age distribution of respondents

The relatively older respondents from the ages of 40 to 45 provided detailed insights into the historical development of the erosional problem in the study area.

4.4.2 Stakeholders' Perception on Accreting Coastal Cells

In assessing the rate of change and validating results obtained, the respondents were asked to state the observed accretion trend along each cell as of 2018. From the statistics shown in *Figure 20,* all four cells experienced a degree of accretion. However, cells 3 and 6 have shown the most significant accretion rate based on the responses from the stakeholders as compared to cells 4 and 5, which may have experienced an accretion rate of a smaller magnitude.

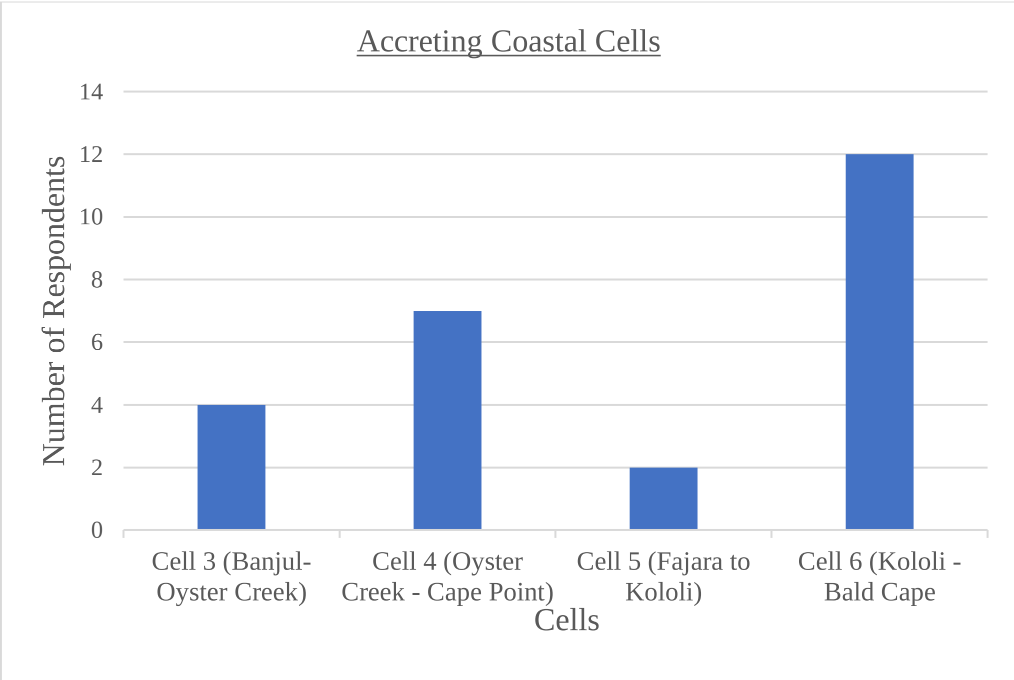

Figure 20: Stakeholder's perception of accretion in each cell

4.4.3 Stakeholders' Perception on Eroding Coastal Cells

A similar approach was adopted in assessing the negative rate of change across each cell. The 14 respondents were tasked to state the observed erosional trend along each cell as of 2018. From the statistics shown in *Figure 21,* all the cells along the study area recorded a certain level of erosion. Cells 3, 5, and 6, in particular, showed the most significant erosional rate based on the responses from the stakeholders. Cell 4 may have experienced a slightly lower rate as compared to the rest of the cells hence the low statistics.

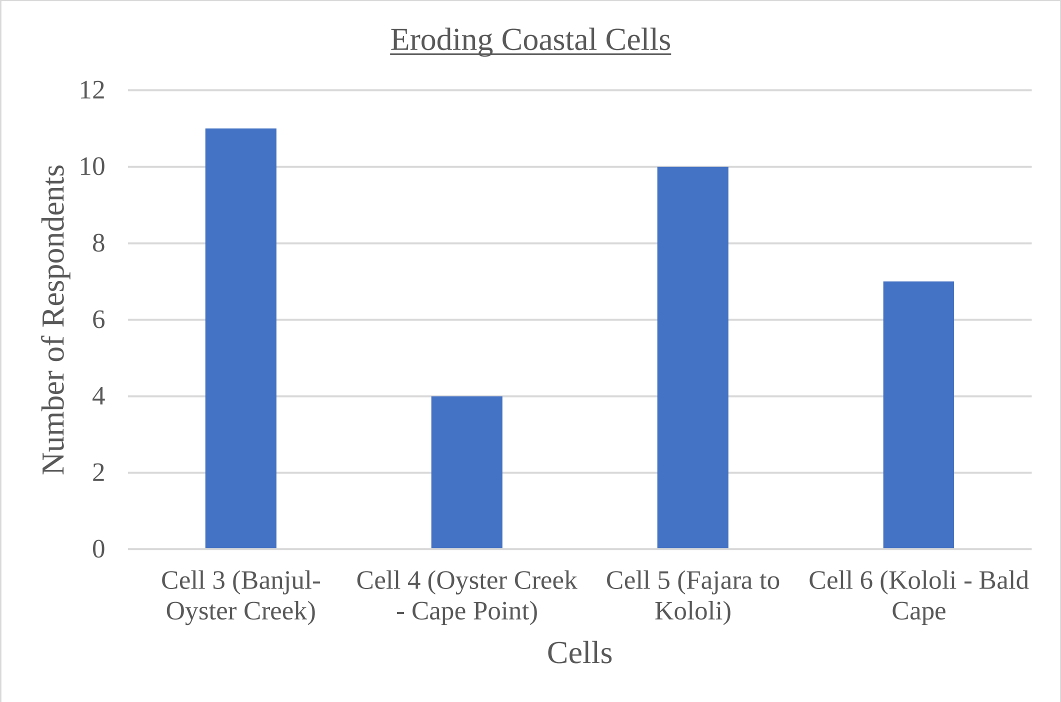

Figure 21: Stakeholder's perception on erosion along each cell

4.4.4 Stakeholders' Perception on Factors Contributing to Coastal Erosion

Several factors contribute to coastal erosion. For this study, stakeholders were asked to give their opinions on the possible factors contributing to the erosion based on the following criteria: inadequate monitoring, lack of national coastal framework, lack of public awareness of coastal issues, climate change, increased tourism and recreation, complex natural environment, lack of scientific understanding, technical limitations, limited statutory stakeholder participation, urbanisation, multitude of users and activities in the coastal zone, lack of public involvement and multitude of users and activities in the coastal area.

Figure 22 shows that most of the possible causes of coastal erosion and degradation selected by the respondents are tied to lack of national coastal framework, lack of public awareness of coastal issues, climate change, technical limitations, multitude of users and activities in the coastal zone and lack of public involvement among others.

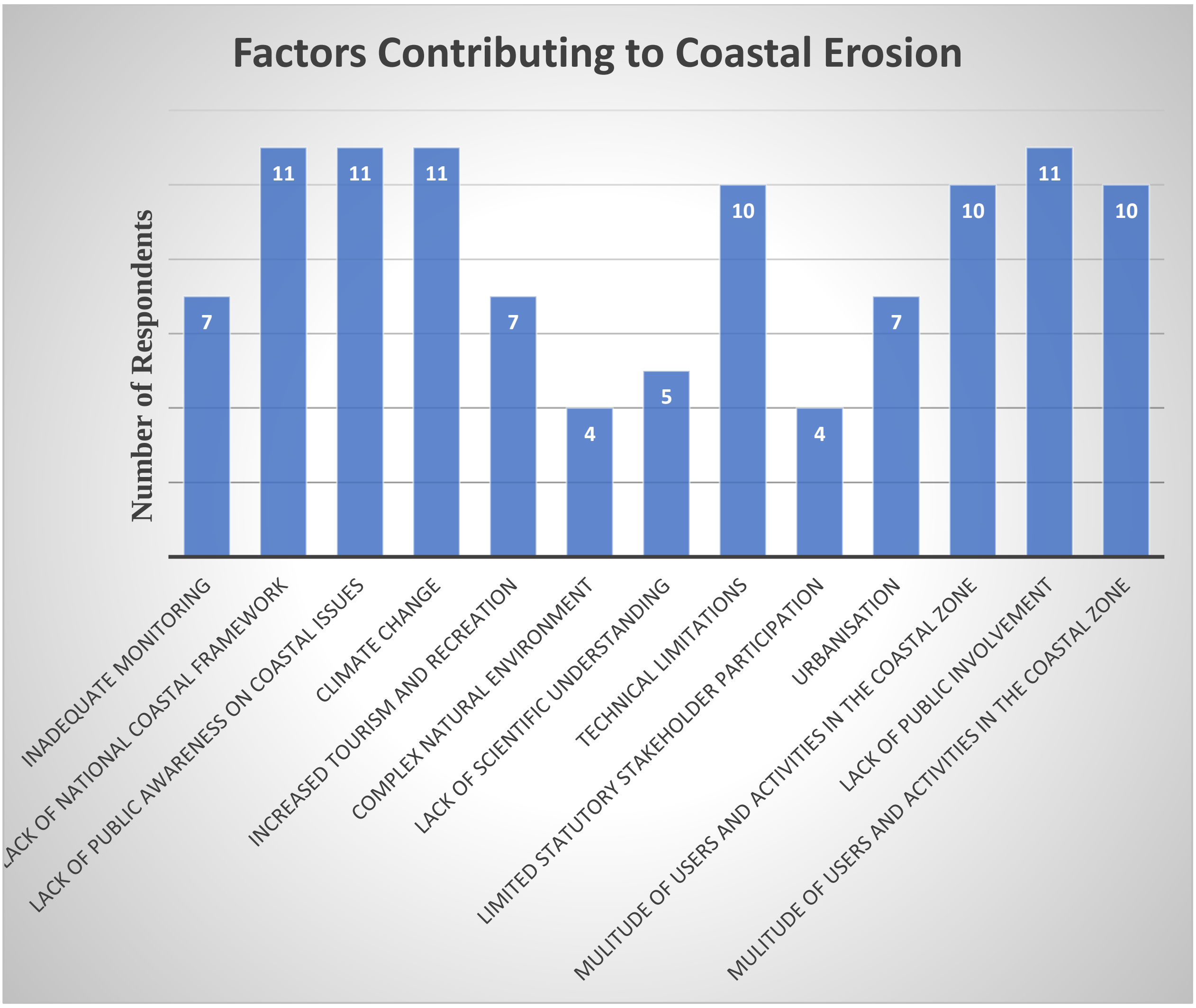

Figure 22: Stakeholder's perception on factors contributing to coastal erosion

4.5 Wave and Wind Climate Analysis

The time series of the wind speed, significant wave height (SWH), and mean wave period for the period 1986-2018 is presented in Figure 23. Winds over the area generally flow between 0.8 - 9.5m/s in strength (*Figure 24*). The strongest and the weakest winds were observed in January and September, respectively.

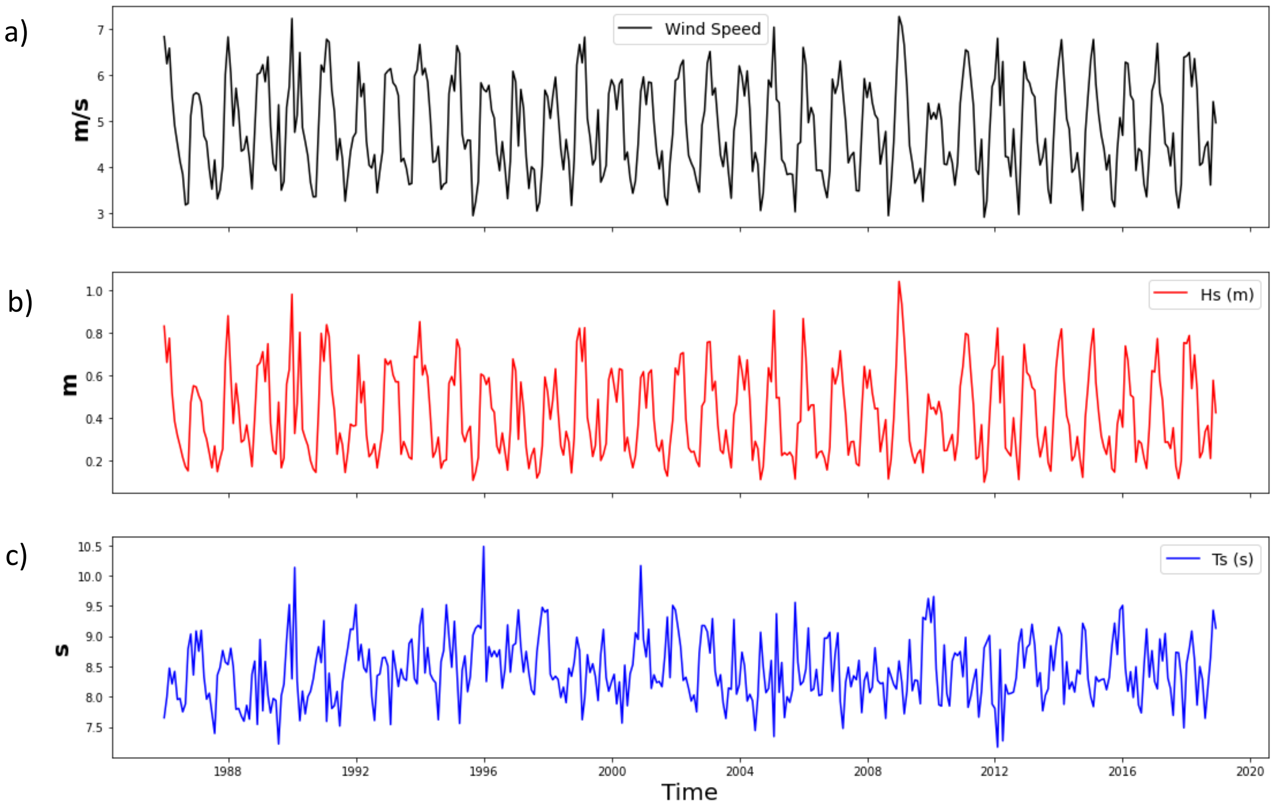

Figure 23: Time series of a) mean wind speed, b) mean significant wave height (H_S), and c) mean wave period (T) between 1986-2018.

The average wind speeds over the study area are 4.85m/s (*Table 7).* DJF (winter) is the stormiest season when the highest wind speeds are recorded compared to the other seasons. The prevailing wind directions along the coastal stretch are predominantly from the west - W (30%) and west-south-west- WSW (29%) direction, between the range of 4.5-7.0 m/s. The calmest winds predominantly blow from the west and southwest direction with an occurrence of 11% over the area, whiles the the strongest winds blew only 1% of time time over the area (*Figure 24*)

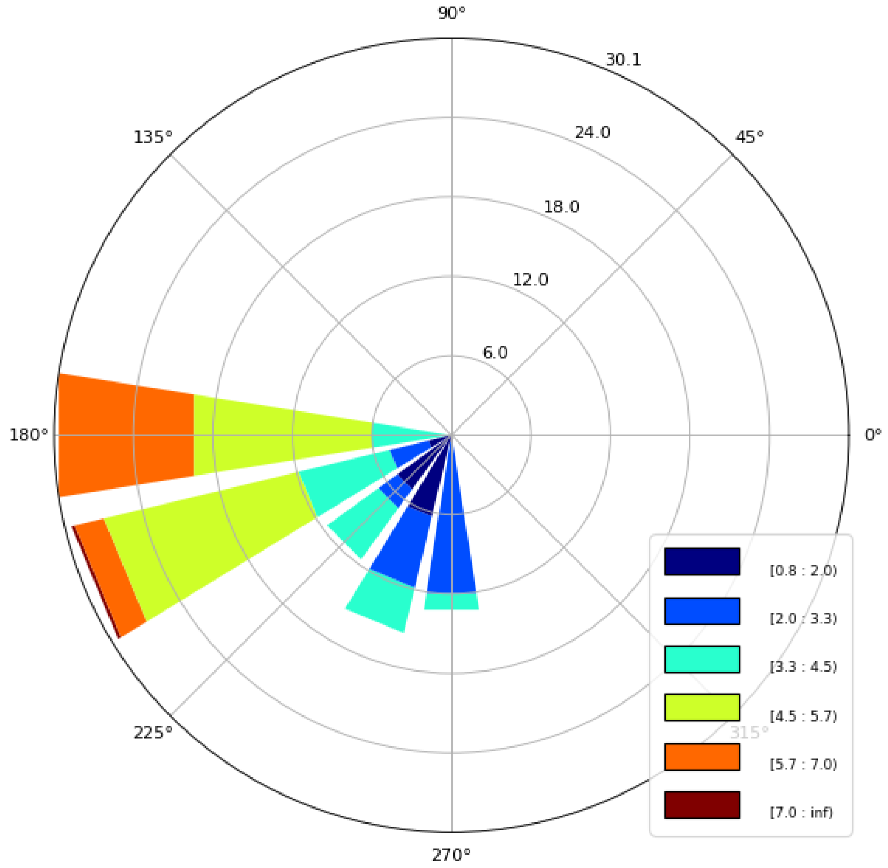

Figure 24: Wind rose representing the wind speed and various wind directions over 1986-2018.

Table 6: Maximum, minimum, and mean values of wave parameter (1986-2018)

Wave Parameter	Minimum	Maximum	Mean	Standard Deviation
Significant Wave Height (Hs (m))	0.02	1.55	0.42	0.24
Wave Period	2.74	11.23	8.44	1.268

Table 7: Maximum, minimum, and mean values of wind parameters (1986-2018).

Wind Parameter	Minimum	Maximum	Mean	Standard Deviation
Wind Speed	1.35	9.43	4.85	1.495
Wind Direction	180	270	235.43	35.379

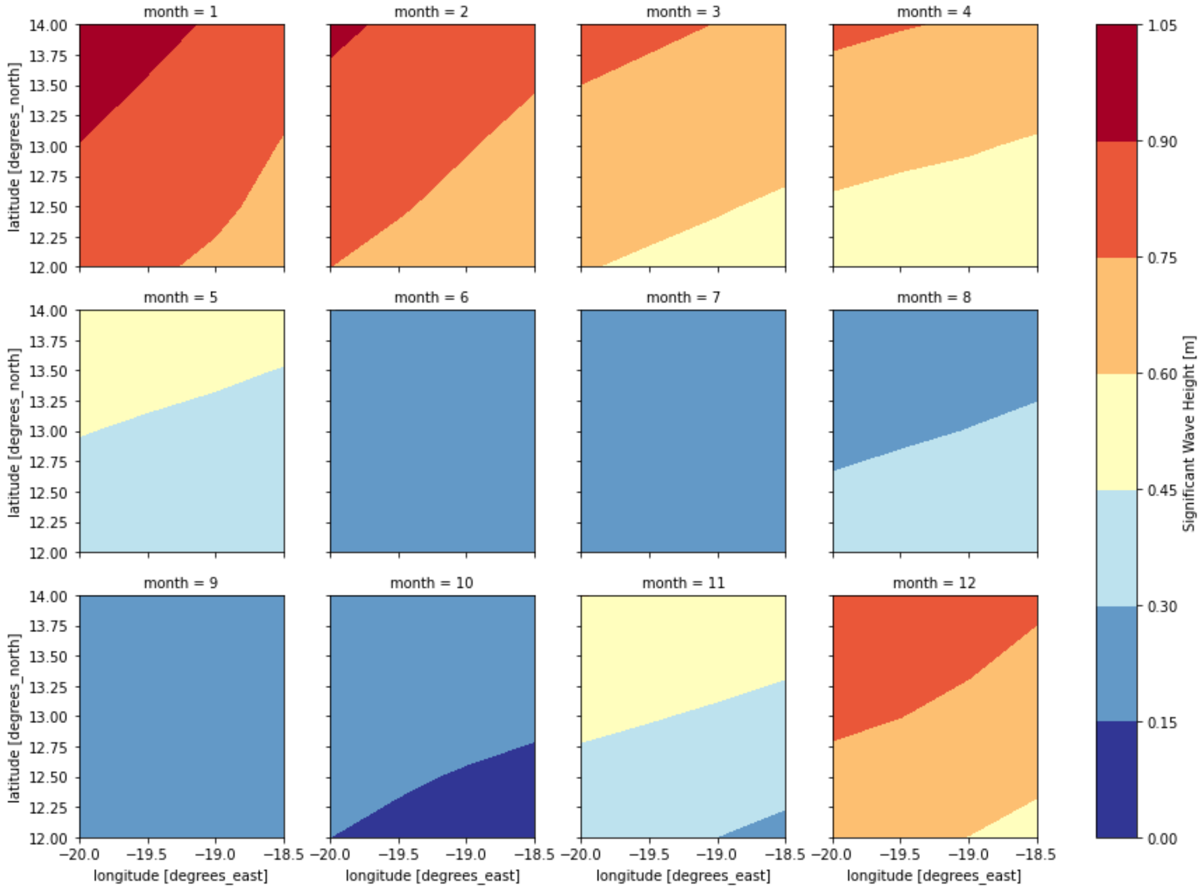

Figure 25: Mean monthly significant wave height (1986-2018).

The corresponding generated significant wave heights ranged between 0.02 m and 1.55 m with periods between 2.74 and 11.23 seconds (*Table 6).* An apparent monthly variability of the SWH is observed, as December to April recorded the highest, while the lowest SWH was observed in September and October (*Figure 25).*

Seasonal variability in significant wave height is shown in Figure 26 and Figure 27, illustrating that JJA (June to August) and SON (September to November) are the seasons with the lowest mean SWH whiles DJF has the highest over the two periods analysed (1986-2002, and 2002-2018).

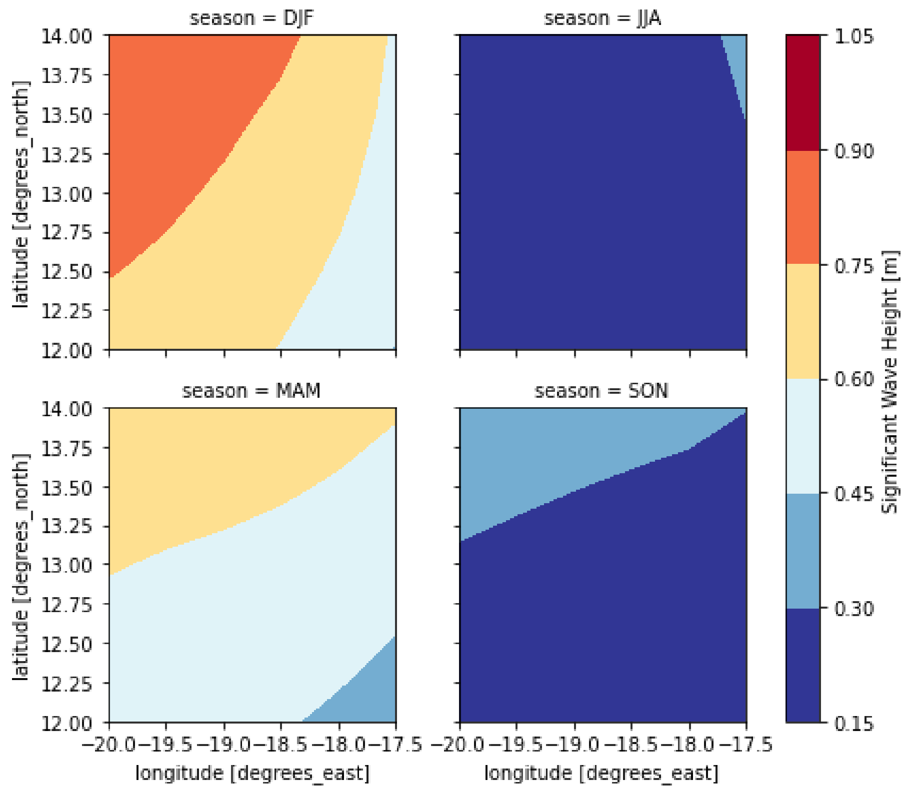

Figure 26: Seasonal variation of mean Significant wave height (1986-2002)

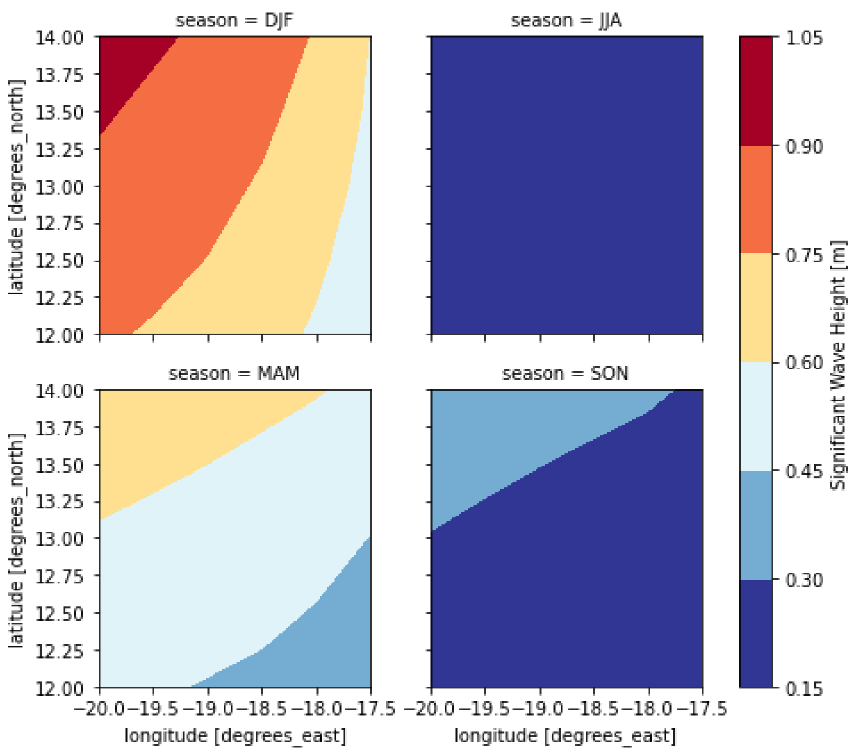

Figure 27: Seasonal variation of mean Significant wave height (2002-2018)

The SWH overlaid with the wind direction shows that the wind direction over 1986-2002 and 2002-2018 was predominantly southwards, with a mean SWH of 0.44 m/s for both periods, with a slightly higher wave height variation in 2002-2018 (*Figure 28, Figure 29*).

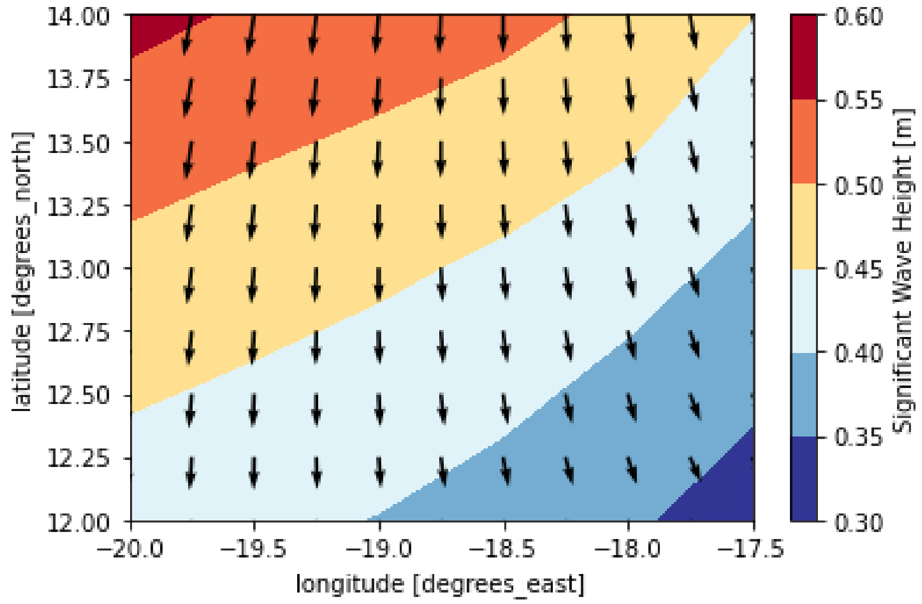

Figure 28: Significant wave height overlaid with wind direction (1986-2002).

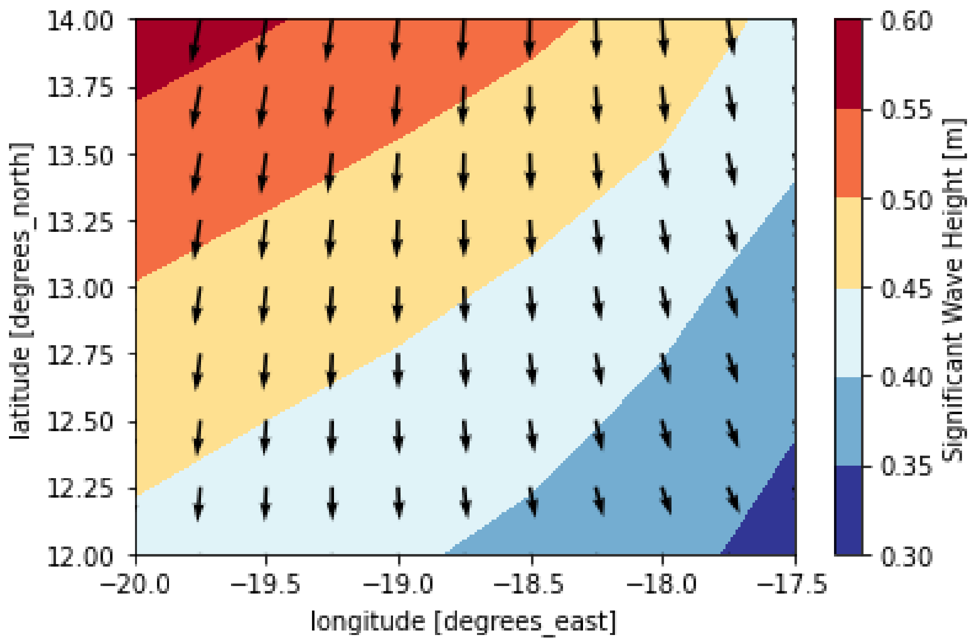

Figure 29: Significant wave height overlaid with wind direction (2003-2018).

5. Discussion

In the study, negative and positive values for shoreline changes indicate recession and progression, respectively. These two phenomena were analyzed and discussed temporally.

5.1 Significant Shoreline Changes with 1986-2002

Wave events coupled with longshore current, construction of artificial structures, and modification of beach landforms have contributed to coastal degradation in the study area (Bijl, 2011). The erosive trend observed within cell 3 (Banjul to Oyster Creek) was due to the development of the sand-spit, extending 50 m east (Jallow et al., 1996) of Oyster Creek in the 1980s. This is likely due to a relatively large sediment supply combined with a period of oblique wave action on the shoreline. This led to the local accumulation of sand in the spit thus greatly reducing the down-drift sediment transport to the east of the spit which agrees with Alonso et al (2002) and Pilkey and Thieler (1992), that factors exacerbating coastal erosion include beach morphology and location, relative sea-level change, wave action, sediment transport and net longshore drift. The deprivation of sediment from the main sand supply gave rise to a substantial reduction in sand hence the erosion along the rest of the Banjul shoreline. The erosional trend along the coast during this period was due to an annual net sand loss from the coast in a longshore direction and the effect of SLR.

The remainder of shorelines within this period experienced longshore transports with moderate natural gradients. The observed sizeable erosive trend is majorly due to sand mining from the beach. The annual volume of sand lost from the beach due to mining was similar to the volume lost due to the gradient in the longshore transport along the entire coast of Gambia. However, the deficit due to the gradient in the longshore transport is spread along the entire coast of Gambia, while the deficit due to sand mining was created very locally, throughout several kilometres around cell 6. This locally increased the natural sand deficit by a factor 3 to 4, resulting in erosion rates of the order of 4 to 5m per year in cell 6 (Delft Hydraulics, 2000).

An erosional trend is evident along the cliff between Cape Point and Fajara (cell 4). Undercutting the toe of the cliff by the waves may take years, after which a significant part of the cliff slides off. Natural protection of the toe of the cliff has been formed by relatively resistant fragments which form a small groynes. Between some protruding headlands along the cliffs, narrow sandy pocket beaches are present. The morphology of the cliffs indicates that the cliff has been exposed to wave attacks and has contributed to the retreat in this cell on a geological time scale. However, there is also apparent evidence of erosion due to the runoff of the rainwater. At many locations, large channels scoured through the cliff can be observed (Bilj, 2011).

5.2 Significant Shoreline Changes with 2002-2018

The Royal Haskoning coastal protection project funded by the African Development Bank (ADB) in 2004 embarked on a 1,400,000 m³ sand redistribution and beach nourishment to protect and re-stabilize a 3 km coastline within cells 3 and 6 (Royal Haskoning, 2000). A soft solution of beach restoration and rehabilitation was employed, using small-scale local beach nourishment at reasonable levels to curb the high rate of erosion caused by the sand mining activity in these areas. In contrast, in cells 4 and 5, a revetment along the coast was used to reduce the action waves at the toe of the cliff (Royal Haskoning, 2000). Contrastingly, cell 3 recorded high recessive rates along the sand-spit, which is likely due to sand dredging for nourishing neighboring cells. The entire coastal cells experienced high accretion rates due to coastal defense intervention carried out in 2004 in the form of beach nourishment along all cell 6 and revetment along the shoreline of cell 4, which is mainly a cliff.

The frequent erosion and accretion process along the coastal area within short-term periods is mainly due to unregulated coastal mining and wave action (Chandrasekar et al., 2000). Artificial structures such as groynes, revetments, and breakwaters along the coast disturb natural coastal processes such as wave direction and littoral current, causing shoreline changes by removing the sediment material from the beach (Masselink and Short 1993).

5.3 Cumulative Shoreline Evolution: 1986- 2018

Wave-induced longshore transport is considered the dominant sediment transport mechanism along the study area. The cumulative shoreline trend of the coastal cells studied reveals that coast erosion remains a challenge especially along cells 4 and 6 which agrees with the National Environment Agency report (2010) stating that recent measurement reveal that the nourishment along the beaches have decreased from about 150 meters at project completion to 26 meters in February 2010, and further to 16 meters in July 2010, despite having an expected lifetime of 10 to 15 years. This indicates that coastal erosion is a significant challenge along cell 6, which could be due to the action of waves and similar pressures from anthropogenic activities.

The two leading causes of erosion in the country are wave action and human actives. The natural coastal processes that prevail today are the impacts of alongshore currents or the littoral drift. The oblique wave pattern hitting the shoreline washed it away. Coupled with anthropogenic interference such as sand mining results in accretion rates failing to equate with the erosion rate, causing substantial sediment loss. The principal mechanism for erosion in the country's northern coast is the effect of littoral drift (Jallow et al., 1996). This process entails the transportation of sediment, sand, clay, and silt particles by the combined action of wave agitated particle motions perpendicular to the wavefronts in combination with downstream transport by wave-induced alongshore current in the downwind direction (DHI, Port Consult 1997). This generates a thin layer of sediments on the seabed surface, transported downstream in a zigzag-like pattern. The waves approaching the northern coast of Banjul from a westerly direction produce a littoral drift towards the east. As it approaches the east coast of Banjul, a littoral drift towards the west is generated.

The cumulative shore change trend is mainly attributed to coastal intervention structures implemented to curb erosion. The groynes placed in cell 3 are not entirely effective in controlling the longshore sediment transport issue along this coast. The coast stretches between Fajara to Kololi (cell 5) is plagued with permanent erosion due to artificial structures. In the open beach, the revetment and groynes interfere with the waves and act as wave breakers, leading to longshore sediment transport and erosion (Robinson 1980). Artificial structures like breakwaters, groynes, and seawalls divert the action of waves, resulting in erosion and accretion in the adjacent cells. The result reveals that the erosion and the accretion pattern along the Banjul to Bald Cape stretch are mainly controlled by the wave energy behavior, which determines the sediment movement in the study area.

Gambia’s coasts is composed of loose sediments, which account for 97%, while only 3% are rocky (Prlecuemoa, 2010). Coastal cells that are positioned directly facing the wave action experience greater littoral sediment transport, leading to erosion. However, deposition takes place at the adjacent zone by longshore drift, forming headlands as beaches or dunes (Van Wellen et al. 2000). This was the case of cell 3 between the 1986 to 2002 period. The coastal cell developed a sand spit from the transported littoral sediments due to the erosional wave action over cell 4. However, a substantial amount of sand has been evacuated from the coastal headlands due to unregulated mining activities, which have caused severe erosion along cells 3 and 6, particularly during the 1986 to 2018 period. The rate of erosion of these zones is estimated to be -3.46 and -4.62 m/yr, respectively.

Figure 17 shows that the coastal cells have experienced an average rate of severe erosion and accretion along cells 4 and 6, with low accumulation along cells 5 and 6. Cell 4 recorded an erosion rate three times higher than cell 3, while the accretion rate of cell 3 was four times higher than that of cell 3. The findings are in line with the Royal Haskoning (2000) report on the Feasibility study on the erosion problem.

5.4 Stakeholder's Perception on Factors contributing to Coastal Erosion

The results indicate that majority of stakeholders/respondents have noticed the shoreline evolution over the study area. Coastal zone professionals believe that the contributing factors to erosion are the lack of a National coastal framework and technical limitations for timely management. The lack of public awareness regarding the coastal zone, the ecological values they provide, and the damages attached to coastal erosion also sit high amongst other selected attributes on the list (*Figure 22)*. This indicates that public awareness of the benefits and hazards of the coastal zone needs to be communicated to the local communities.

5.5 Wind and Wave Climate Analysis

Winds are the most common causes of observed ocean waves (Lyons 1994). The winds over the study area are generally southwesterly trade winds with their strength lying between 0.8 – 9.5 m/s. The temporal pattern does not seem to suggest any well-defined uniformity but marginally indicated an increasing strength during the winter season (DJF). Seasonal variations in wind speed and SWH have produced an asymmetric shoreline erosion by changing the trends of sediment movement in the near-shore area (Chauhan et al. 1996; Benumof et al. 2000; Georgiou and Schindler 2009; Saravanan et al. 2011).

The coastal dynamic of an area is mainly influenced by the action of the wave along the coast, which controls its erosional and retreating trend (Nafaa et al. 1991; Anil Cherian et al. 2012). *Figure 25* shows the monthly spatial variation of the mean SWH along the coastal area. For the entire coast, the calculated mean SWH ranges from 0.05 to 1.55 m. Cell 4, oyster Creek to Cape Point, is noted for higher wave height because of its geographical location and coastal configuration. The coast is located at the southernmost tip of the coastal zone, with forces acting on the landforms from various directions. The steep slope at its peak can decrease the discharges of littoral sediment by diverting the waves (Wang 1998). This cell experienced the highest rate of erosion of -9.68 m/yr between 1986 to 2002. This area has been protected since 2004 using revetments intervention.

Oceanographic and meteorological parameters in conjunction with geologic factors affect shoreline changes (Nikolakopoulos et al. 2019). From this study, it is uncertain the extent to which significant wave height drives shoreline change over the study area. However, a strong positive correlation between the SWH and the wind speed indicates that SWH and wind speed are strongest between DJF and MAM. This would likely imply that destructive waves with weak swash but strong backwash that is powerful enough to transport sediment material from the coast occur during this period, causing the coast to erode significantly over time.

5.6 The Effects of Human Activities on Coastal Erosion

Human activities along the coast are diverse and can occur extensively. Increasing human activities is a significant challenge along the coastal zone with regard to coastal management. Human developments, urbanisation and shoreline stabilization activities, and tourism are great contributors to exacerbating the shoreline change rates due to beach nourishment and coast-protection structures (revetment, break water, groynes) which alter coastal processes, sediment transport and invarably affects shoreline position.

Sand has been mined within these areas since the 1980s but due to the adverse impacts posed on the fragile ecosystems, together with a sand budget deficit, it has been moved to other locations, hence transferring the problem to neighbouring cells and leading to an overall change in the coastal morphology. Hard engineering coastal protection structures on the other hand block off the longshore sediment transport and alter local hydrodynamic conditions along the coast. Beach nourishment, for instance, artificially causes rapid and temporary shoreline accretion (Morton and Miller, 2005). It is understandable that when sediments input exceeds sediments output, beaches will accrete or widen. Since these coastal land use activities were identified in the Banjul-Bald Cape area, it is reasonable to relate them to these areas' accretion and erosional trend. According to Esteves et al. (2002), these anthropogenic activities might affect local sand balance and intensify natural shoreline changes.

In most cases, hard coastal engineering structures initially protect the area they are intended to protect (Carter, 1991), but eventually, the quality of the structure deteriorates and fails to serve its purpose. Since the coastline is generally eroding, when it catches up with the wall, the beach slope steepens in front of the wall. This happens because the seawall, which is a rigid structure does not allow the beach to take up sand stored on the beach berm, as is the natural storm response. Therefore, the beach cannot dissipate the force of the incoming waves, and eventually, the wall falls over. This explains why the defense structures have failed to serve their purpose in the long term.

5.7 Coastal Management and Adaptation Strategies

The overview of the various coastal management initiatives in The Gambia has demonstrated varying patterns, reflecting the socio-economic, political, and institutional complexity of each cell in the coastal zone. Addressing the coastal priorities will require a concerted and multidisciplinary approach on many fronts. Interventions are needed at the national, regional, and local levels, and targeted interventions would address specific problems, while institutional interventions would aim to improve the overall effectiveness of all ICZM interventions either by providing the institutional backing to facilitate project delivery or the means for minimizing overlaps and avoidable conflicts.

Although several initiatives in integrated coastal management have been successfully implemented in The Gambia, there seems to be a gap in the learning process and in the effectiveness of the systems by which successes and challenges of the applied interventions can be shared. Regional dialogue and cooperation would equally be vital, and this requires the development of appropriate mechanisms that will eventually translate to sustainable coastal zone management in The Gambia.

5.8 Coastal Erosion Management Implications

The primary response to coastal erosion in most countries worldwide is the protection of properties while paying limited attention to natural processes (Cooper et al., 2016). Like many countries, the one-dimensional preference for hard coastal protection structures exists in The Gambia, and this has caused severe impacts on the natural coastal ecosystems. Since 2004, various hard engineering and stabilisation schemes have been constructed along The Gambia’s coastline in response to coastal erosion. These include groynes, revetments, and breakwaters (Stancheva, 2013). The construction of these coast-protection structures for shoreline armoring has had many adverse effects, leading to the redirection of wave action, reduction in sediment supply, and alteration of the natural coastal environments. Recurrently, shoreline armoring has been planned with minimal regard for the long-term cumulative effects (Griggs, 2005; Stancheva et al., 2012; Cooper et al., 2016).

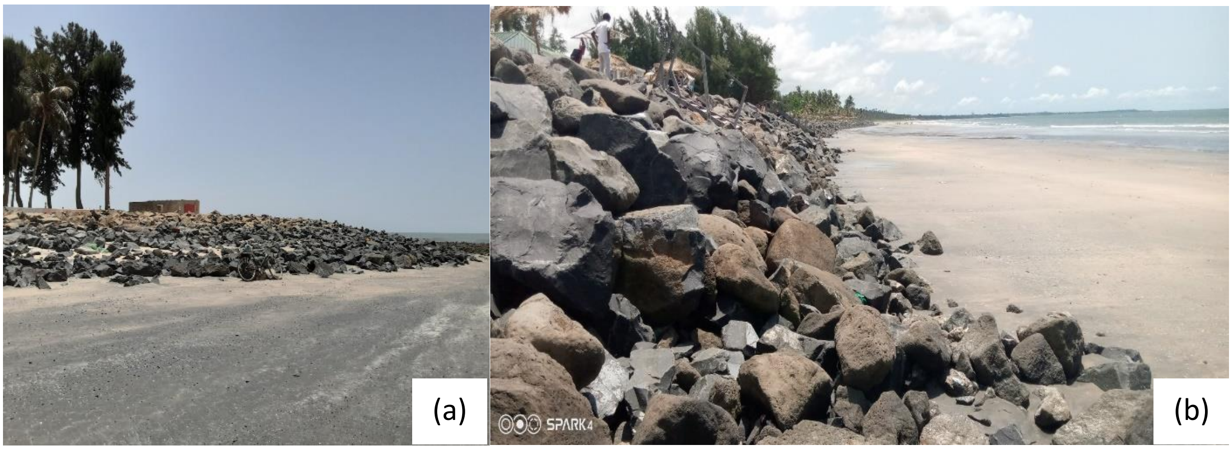

Figure 30: Construction of revetments along the coast as a coastal erosion measure: a) Cell 3, and b) Cell 6 (Source: NEA, 2018)

In most cases, hard structures initially protect the area it is intended to protect (Carter, 1991), but eventually, the quality of the structure deteriorates and fails to serve it purpose. Since, the coastline is generally retreating, when it catches up with the wall, the slope of the beach steepens in front of the wall. This happens because the seawall, which is a rigid structure, does not allow the beach to take up sand stored on the beach berm, as is the natural storm response. Therefore, the beach cannot dissipate the force of the incoming waves, and eventually, the wall falls over. This most likely explains why coastal defense structures have failed to serve their purpose after a short while. Thieler et al. (2001) noted that the most important causes of human-induced erosion are the interruption of sediment sources (armoring of coastal banks) and the interference with alongshore sediment transport (groynes).

5.9 Proposed Strategies for Managing Coastal Erosion

The identified types of beach and rates of shoreline change present coastal managers with several management options. Each category exhibits different peculiarities that must be addressed independently if all the coastal mining, dredging and structural intervention issues are successfully managed. This requires an understanding of the activities being undertaken and how they are done, the purpose of the products, and the underlying reasons behind these practices. Addressing poor coastal zone practices from such narrow perspectives may lead to effective management strategies to deal with the entire practice. This may require the commitment and collaboration of coastal managers with various state and non-governmental stakeholders, including the National Environment Agency, Local Governments, The Gambia Maritime Authority, The Gambia Police Force, and other relevant stakeholders.

Integrated coastal zone management and a conservation plan for The Gambia will be pertinent to tackling issues regarding the anticipated SLR due to climate change, storm surges, flooding and erosion, and coastal habitat fragmentation due to coastal degradation. In enhance effective ICZM implementation in The Gambia, it will be vital to consider the following proposed tenets:

- **Addressing critical uncertainties for climate change and the coastal marine environment in an ICZM scheme**:

It is paramount for ICZM to kick start with a holistic knowledge about the state of the marine and coastal environment and its available resources that will inform the present state of these systems and assist with predicting future conditions. The current practice of haphazard responses to coastal zone problems hails from the fact that little to no adequate database exists on dynamic coastal processes, requiring a survey of the coastal zone. Thus, the development of standard procedures, measuring techniques, data storage, and management capabilities could be put in place for the data collection, including topography, physical, geological processes, biological assessment, water resources, socio-economic activities, and other relevant information which will efficiently assist the monitoring of the coastal activities and processes. It will also improve the understanding of the marine environment and its role in global processes by promoting scientific and in-depth coastal dynamics research and systematic monitoring. According to the data collected, the coastal zone could also be divided into several ecological niches based on their functions and according to the data collected.

- **Monitoring and data collection**:

An essential component of integrated coastal zone management will entail conducting reliable research and routine data gathering to create a database of meteorological parameters, sea-level variations, oceanographic and coastal dynamic information, bathymetry, hydrographic mapping, and demographic socio-economic data. The relevant stakeholders could be identified and tasked with collecting, assembling, and analysing relevant marine and oceanographic data.

- **Capacity building**:

A developing country like The Gambia lacks technical and administrative capacity in data collection and coastal and marine for ICZM. This lack in capacity would likely make it more challenging for The Gambia to successfully undergo an effective ICZM, which is needed to reduce coastal degradation and biodiversity. An effective regional and global response to coastal and marine studies will require the full participation of developing nations with adequate technical capacity. In this regard, capacity building in the marine sciences for enhanced coastal management is necessary to establish and strengthen national oceanographic commissions.

- **Stakeholder arrangements**:

An implementable and effective coastal zone management policy should embrace a well-articulated institutional and stakeholder arrangement. The government should first evaluate the technical and financial capacity of the designated national institutions and government departments participating in ICZM. Considering the diverse nature of ICZM, the institutional arrangements should embrace (i) marine environmental and resource evaluation unit, (ii) socio-economic and land use planning unit, and (iii) legal, institutional sectors as well as local settlers.

- **Management policies**:

Effective and implementable legislations must be in place for the effective management and conservation of coastal and marine resources. Most of the existing laws in many countries are difficult to implement due to their incompatibility with national goals and objectives (Cicin-Sain, 1993). The management of coastal erosion, for instance, must be given priority. While environmental laws may discourage the degradation of resources, policies should not be compromised in curbing the problem.

- **Strengthening Regional and International Cooperation:**

The strengthening of international ties will promote institutional arrangements necessary to support the implementation of the program areas to integrate sectoral activities. This will provide information exchange and better linkages among bilateral and multilateral national, regional, and other organizations, promoting regular intergovernmental review within the UN system of ocean/coastal issues; and promoting effective cooperation among the UN. Understanding that the role of international cooperation is to support and supplement national efforts, there is a need to improve coordination and strengthen links among them and ensure that a multi-sectoral approach to marine issues is presented at all levels.

- **Marine Spatial Planning (MSP):**

Marine Spatial Planning (MSP) is a phenomenon gaining popularity among African coastal states within the Atlantic Region. Several African countries engaged in diverse projects to implement marine spatial plans to effectively manage their coastal and marine areas (Sagoe et al., 2021). It is a promising ecosystem-based management tool that could be implemented in The Gambia to manage the coastal and marine areas. MSP seeks to achieve ecological, economic, and social objectives that usually have been specified through a political process (IOC/UNESCO, 2017). In this regard, greater efforts should be geared towards including MSP as part of national policy, informing governments and stakeholders of its benefits and potential to strengthen institutional capacity and bridge all gaps.

6. Conclusion and Recommendations

6.1 Conclusion

The analysis of shoreline change using multi-temporal Landsat imageries (1986–2018) demonstrates that the study area, Banjul to Bald Cape, has experienced a varying degree of erosion along different cells/segments of the beach over time. In the absence of long-term monitoring of the dynamics and evolution of the beach through cross-shore profile surveys and volumetric analysis, shoreline analysis that cuts across different periods proves to be an essential tool in understanding the shoreline's evolution. The use of GIS and remote sensing tools in obtaining statistical data through the application of DSAS is a robust and effective way to determine the stability or vulnerability of the coast. This study has considered factors that potentially alter the shoreline, either independently or in a combined manner. The significant positive linear correlation of the wind speed and wave height implies that natural processes and human activities contribute the most to the modification of the coast. This study therefore draws the attention of stakeholders to the realisation that the one-directional approach to coastal management may not effectively tackle challenges associated with coast erosion and degradation, as hard coastal engineering structures only shift the problem downdrift rather than ensuring a permanent solution.

6.2 Recommendation

Seasonal mapping and monitoring of shoreline evolution using an unmanned aerial vehicle (UAV) would be an effient and cost effective approach for routine monitoring of shoreline change. This innovative coastal engineering application highlights the enormous potential of drones to improve and potentially revolutionize the forthcoming coastal zone monitoring.

Additionally, Integrated Coastal Zone Management system, a multidisciplinary approach to addressing the complexity of issues affecting the coastal zone and the marine environment is an effective management scheme. However, new management frameworks and governance structures are essential for ensuring that coastal communities and the nation reaps long-term benefits and services that healthy oceans and coastal zones can provide. In this regard, integrating marine spatial planning (MSP) into the nation's coastal management strategy plan is recommended to ameliorate the current practices and bring about an effective and sustainable environment and resource management. MSP provides governments, local communities, and marine sectors a transparent, equitable, and participatory process to navigate critical challenges, develop effective and durable solutions, and plan for the future. Coastal Marine Spatial

Planning (CMSP) will identify areas most suitable for various types of activities to reduce conflicts among users, minimize environmental impacts, facilitate compatible uses, and preserve critical ecosystem services to meet economic, environmental, security, and social objectives. In practical terms, CMSP provides a public policy process for society to determine better how the ocean and coasts are sustainably used and protected now and for future generations.

6.3 Future Studies

For an in-depth understanding of the shoreline evolution along each cell, a comprehensive study on the hydrodynamics of the coast, looking at the seasonal changes, wave energy and longshore sediment transport should be explored as a means of routinely monitoring the dynamics of the coast, which when left unmanaged will lead to significant shoreline shift, ecosystem loss and habitat fragmentation, as well as loss of natural resources. This will further guide policymakers on the most suitable coastal defense intervention that will be most effective in protecting the coast against wave and tidal activities.

7. References

Aarninkhof, S.G.J., Van Dalfsen, J.A., Mulder, J.P.M. & Rijks, D. Sustainable Development of Nourished Shorelines. Pianc Mmx Congress Liverpool UK 2010

Amuzu, J., Jallow, B.P., Kabo-bah, A.T., Yaffa, S. The socio-economic impact of climate change on the coastal zone of the Gambia. *Nat. Resour. Conserv*. 6 (1) 24. (2018) DOI.org/10.13189/nrc.2018.060102.

Anfuso, G., Martinez, J.A., Rangel-Buitrago, N. Bad erosion management: the southern Sicily case study. In: Pilkey, O., Cooper, A. (Eds.), Pitfalls of Shoreline Stabilization. *Springer, New York*, pp. 215e233. (2012)

Anfuso, G., Williams A.T., Cabrera Hernández, J.A., Pranzini, E. Coastal scenic assessment and tourism management in western Cuba. *Tourism Management, 42(), 307–320*. (2014) doi:10.1016/j.tourman.2013.12.001.

Antolinez, J.A.A., Mendez, F.J., Camus, P., Vitousek, S., González, M., Ruggiero, P., Barnard, P.L. A multiscale climate emulator for long-term morphodynamics (MUSCLE-morpho). *J. Geophys. Res. Ocean*.121, 775–791 (2016). DOI: 10.1002/2015JC011107.

Arkema, K.K., Guannel, G., Verutes, G., Wood, S.A., Guerry A. Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change,* vol.55, issue.10, 2013. DOI : 10.1038/nclimate1791.

Ashton, A., Murray, A. B. & Arnoult, O. Formation of coastline features by large-scale instabilities induced by high-angle waves. Nature414, 296–300 (2001).

Banica, A., Bastard, J., Kosiek, M. Integrated Coastal Zone Management (ICZM): a framework to tackle environmental issues? *Danish Approach. Centre for Environmental Studies*. (2003).

Barnard, P. L. Coastal vulnerability across the Pacific dominated by El Niño/Southern Oscillation. *Nat. Geosci.8*, 801–807 (2015).

Bijl, E. “The cause of coastal erosion on a nourished beach in Kololi, The Gambia". MSc Thesis. Delft University. (2011)

Biliana, Cicin-Sain. Sustainable development and integrated coastal management. 21(1-3), 11–43. (1993) doi:10.1016/0964-5691(93)90019-u.

Bird, E.C.F. Coastline changes. A global review. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 219 p. (1985)

Boak, E.H. & Turner, I.L. Shoreline Definition and Detection: A Review. *Journal of Coastal Research*. 688-703. West Palm Beach, Florida. (2015)

Borrero, J. C. Field Data and Satellite Imagery of Tsunami Effects in Banda Aceh. Science (80).308, 1596–1596 (2005).

Carter, R.W.G. Sea level changes in B.E. McWilliams, Climate Change; studies on the implications for Ireland. Government of Ireland, Department of the Environment. Dublin 1st and 2nd editions (1991)

Ciavola, P. & Coco, G. Coastal storms: processes and impacts (John Wiley & Sons, 2017). 10. Harley, M. D. et al. Extreme coastal erosion enhanced by anomalous extratropical storm wave direction. *Sci. Rep.7*, 6033 (2017). 11. Kay, R. & Alder, J. *Coastal Planning and Management*. Taylor & Francis. DOI: 10.1007/s13398-014-0173-7.2 (2005).

Cooper, J.A.G., O'Connor, M.C., McIvor, S. Coastal defences versus coastal ecosystems: a regional appraisal. *Mar. Policy*. (2016) http://dx.doi.org/10.1016/ j.marpol.2016.02.021.

Costanza, R., d' Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., an den Belt, M. The value of the world's ecosystem services and natural capital. *Ecological Economics*, 25(1), 3–15. (1998) Doi: 10.1016/s0921-8009(98)00020-2

Crossland, C. J., Baird, D., Ducrotoy, J.-P., Lindeboom, H., Buddemeier, R. W., Dennison, W. C., … Swaney, D. P. The Coastal Zone — a Domain of Global Interactions. *Global Change — The IGBP Series, 1–37.* (2005) doi:10.1007/3-540-27851-6_1

Dionne, J.-C. (1978). *Komar, P.D. (Beach Processes and Sedimentation, Englewood Cliffs (New Jersey), Prentice-Hall, xii et 429 p., 218 fig., 18, 5 x 24 cm, $33.30. Géographie Physique et Quaternaire, 32(2), 178.* (1976) doi:10.7202/1000349ar

Dolan, R., Fenster, M.S., Holme, S.J. (1991). Temporal analysis of shoreline recession and accretion. *Journal of Coastal Research*, 7(3), 723-744. Fort Lauderdale (Florida). ISSN 0749-0208

Esteves, L. S., Toldo Jr., E. E., Dillenburg, S. R., & Tomazelli, L. J. 2002. Long- and Short-Term Coastal Erosion in Southern Brazil. Journal of Coastal Research, Special Issue 36, ISSN 0749-0208 , 273-282

Fuad, M. A. Z., and D. A. M. F. 2017. "Automatic detection of decadal shoreline change on northern coastal of Gresik, East Java – Indonesia." *IOP Conference Series: Earth and Environmental Science* 98: 012001. doi:10.1088/1755-1315/98/ 1/012001

Gomes, C., Silva, A. N., Taborda, R., Santos, F., Rebelo, L., & Medina, A. (2019). Drivers of island beach evolution: insights from an island-scale study at Boa Vista (Cabo Verde). Earth Surface Processes and Landforms. doi:10.1002/esp.4709

Gomez, M.L., Adelegan, O.J., Ntajal, J., Trawally, D. Vulnerability to coastal erosion in The Gambia: Empirical experience from Gunjur. *International Journal of Disaster Risk Reduction*. 45 (2020) 101439 doi.org/10.1016/j.ijdrr.2019.101439.

Government of Finland, UNEP and PAP/RAC: Assessment of Integrated Coastal Management in Africa. Split, Croatia, Priority Actions Programme Regional Activity Centre, UNEP/MAP, 1998, pp viii + 72.

Hanslow, D. J. (2007). Beach Erosion Trend Measurement: A Comparison of Trend Indicators, SI 50 Proceedings of the 9th International Coastal Symposium, 588 – 593. Journal of Coastal Research. Gold Coast, Australia, ISSN 0749.0208.

Himmelstoss, E.A., Henderson, R.E., Kratzmann, M.G., Farris, A.S., 2018. Digital Shoreline Analysis System (DSAS) Version 5.0 User Guide. In: Open-File Rep. 2018- 1179. 126.

Intergovernmental Panel on Climate Change, Climate Change 2013 the Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013. Retrieved from, www.camb ridge.org.

IOC/UNESCO. (2017). Marine Spatial Planning. http://msp.ioc-unesco.org/about/marinespatial-planning/

IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., & Minx, J. C. (Eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jallow, B.P. Vulnerability of the coastal zone of The Gambia to sea level rise and development of response strategies and adaptation options. *Climate Research.* Vol. 6: 165-177 (1996)

Jonah, F.E., Mensah, E.A, Edziyie, R.S, Agbo, N.W, Adjei-Boateng, A., (2016). Coastal Erosion in Ghana: Causes, Policies, and Management. *Coastal Management*, 44:2, 116-130, DOI: 10.1080/08920753.2016.1135273.

Jose, M., Pereira, G.F., S. Bairavi. Shoreline Mapping and Coastal Change Studies along Chennai Coast Using Remote Sensing and GIS. International Journal of Scientific Research in Science and Technology. *International Journal of Scientific Research in Science and Technology* (2018) Mar-Apr;4(5) : 1394-1398 DOI:10.32628/IJSRST1845360

Keqizhang, Bruce C. Douglas, and Stephen P. Leatherman. (2004). Global warming and Coastal Erosion. *Climatic Change* 64: 41–58. Kluwer Academic Publishers. The Netherlands.

Leatherman, S.P. (2017). Coastal erosion and the United States national flood insurance program. Ocean Coast Manag.156 35–42.

Leatherman, S.P., Clow, B., 1983. UMD shoreline mapping project. IEEE Geosci. Remote Sens. Soc. Newsl. 22, 5–8.

Limber, P. W, List, J.H, Warren, J. D. (2007). Investigating Methods of Mean High Water Shorelines from Lidar Data and the Relationship between Photo-derived and Datum-based Shoreline in North Carolina. http://dcm3.enr.state.nc.us/.

List, J.H. and Farris, A.S., 1999. Large-scale shoreline response to storms and fair weather. Proceedings of the Coastal Sediments '99 (Long Island, New York), pp. 1324-1337.

López, M., Pagán. J.I., López, I., Aragonés, L., Tenza-Abril, A.J., & García-Barba, J. Factors Influencing The Retreat Of The Coastline Int. J. Comp. Meth. and Exp. Meas., Vol. 5, No. 5 (2017) 741–749: doi:CMEM-V5-N5-741-749

Marchand, M., Sanchez-Arcilla, A., Ferreira, M., Gault, J., Jiménez, J. A., Markovic, M., Sutherland, J. (2011). Concepts and science for coastal erosion management – An introduction to the Conscience framework. *Ocean & Coastal Management, 54(12), 859–866.* doi:10.1016/j.ocecoaman.2011.06.005

Martinez, M. L. Intralawana, A., Vázquezb, G., Pérez-Maqueoa, O., Suttond, P., Landgrave, L., (2007). The coasts of our world: Ecological, economic and social importance. Ecol. Econ.63, 254–272. 3. doi.org/10.1016/j.ecolecon.2006.10.022.

Masselink, G. And Pattiaratchi, C., 1998. Morphodynamic impact of sea breeze activity on a beach with beach cusp morphology. *Journal of Coastal Research,* 14(2), 393-406. Royal Palm Beach (Florida), ISSN 0749-0208.

Mentasch, L., Vousdoukas, M.I., Pekel, J-F., Voukouvalas, E., Feyen, L. Global long-term observations of coastal erosion and accretion. Scientific reports. 8:12876 (2018). DOI: 10.1038/s41598-018-30904-w.

Moore, L. J.; Ruggiero, P., and List, J.H. Comparing Mean High Water and High Water Line Shorelines: Should Proxy-datum Offsets Be Incorporated into Shoreline Change Analysis? *Journal of Costal research*, 22(4), 894-905. West Palm Beach (Florida), ISSN 0749-0208. (2006)

Mörner N-A. Sea level changes and crustal movements withspecial reference to the eastern Mediterranean.Z Geomorphologie137:91–102. ((2005))

Morton, R.A. Accurate shoreline mapping: past, present, and the Coastal Sediments '91 (Seattle, Washington), pp. 997-1010. (1991)

Morton, R.A., Miller, T.L., 2005. National Assessment of Shoreline Change: Part 2, Historical Shoreline Change and Associated Land Loss along the U.S. South East Atlantic Coast. U.S. Geological Survey. Open-file Report 2005-1401, Retrieved in pdf from: https://pubs.usgs.gov/of/2005/1401/ofr-2005-1401_print.pdf (last Accessed on 06 February 2017).

Murali, R.M., Shrivastava, D., & Vethamony, P. Monitoring shoreline environment of Paradip, east coast of India using remote sensing. Current Science, Vol. 97, No. 1, 10 July 2009

Nicholls, R. J. & Cazenave, A. Sea-level rise and its impact on coastal zones. Science (80- 328, 1517–1520 (2010).

Nicholls, R.J., Hinkel, J., Lincke, D., Van der Pol, T. Global Investment Costs for Coastal Defense through the 21 St Century, The World Bank, 2019, https://doi.org/ 10.1596/1813-9450-8745.

Nicholls, RJ, Wong, PP, Burkett, VR, Codignotto, J, Hay, J, McLean, R, Ragoonaden, S, and Woodroffe, CD, Coastal systems and low-lying areas, in Parry, ML, Canziani, OF, Palutikof, JP, van der Linden, PJ, and Hanson, CE (ed) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge, UK, Cambridge University Press, 2007, 315-356.

Omar Defeo, Anton McLachlan, David S. Schoeman, Thomas A. Schlacher, Jenifer Dugan; Alan Jones; Mariano Lastra, Felicita Scapini, *Threats to sandy beach ecosystems: A review. , 81(1), 1–12.* (2009) doi:10.1016/j.ecss.2008.09.022.

Paterson, S.K. O'Donnell, A. Loomis, D.K. and Hom, P. The Social and Economic Effects of Shoreline Change: North Atlantic, South Atlantic, Gulf of Mexico, and Great Lakes Regional Overview. *Human Dimensions of Natural Resource Management Research Unit Department of Natural Resources Conservation University of Massachusetts, Amherst*, MA 01003. (2010)

Petrakis, Stelios & Karditsa, Aikaterini & Alexandrakis, Giorgos & Monioudi, Isavela & Andreadis, Olympos. *Conference:* Coastal Landscapes, Mining Activities & Preservation of Cultural Heritage, Milos island, Greece (2014)

Pilkey, O. H. & Cooper, J. A. G. Society and Sea Level Rise. *Science* (80-.).303, 1781–1782 (2004).

Pirazzoli, P. A., Regnauld, H., & Lemasson, L. Changes in storminess and surges in western France during the last century. Marine Geology, 210(1-4), 307-323. (2004)

Prasad, D.H. and Kumar, N.D. Coastal Erosion Studies—A Review. International Journal of Geosciences, 5, 341-345. (2014) doi.org/10.4236/ijg.2014.53033

Rangel-Buitrago, N. G., Anfuso, G., & Williams, A. T. Coastal erosion along the Caribbean coast of Colombia: Magnitudes, causes and management. *Ocean & Coastal Management, 114, 129–144.* (2015) doi:10.1016/j.ocecoaman.2015.06.024

Roy, S., Mahapatra, M., & Chakraborty, A. Shoreline change detection along the coast of Odisha, India using digital shoreline analysis system. *Spatial Information Research*. (2018) doi:10.1007/s41324-018-0199-6.

Roy, S., Mahapatra, M., Chakraborty, A. Shoreline change detection along the coast of Odisha, India using digital shoreline analysis system. *Spatial Information Research*. (2018) doi:10.1007/s41324-018-0199-6.

Schlacher, T., Raffaelli, D. & Hawkins, S. Intertidal Ecology. Estuaries 21, 365 (1998).

Schleupner, C. Spatial assessment of sea level rise on Martinique's coastal zone and analysis of planning frameworks for adaptation. *Journal of Coastal Conservation*, 11(2), 91–103. (2007) doi:10.1007/s11852-008-0010-2

Seenipandi,K., Ramachandran, K.K., Chandrasekar, N. Modeling of coastal vulnerability to sea-level rise and shoreline erosion using modified CVI model. *Remote Sensing of Ocean and Coastal Environments.* Pages 315-340 (2021)

Sem, G. The Impact of Climate Change on the Development Prospects of the Least Developed Countries and Small Island Developing States; WHO: Geneva, Switzerland, 2009.

Senevirathna, E. M. T. K., Edirisooriya, K. V. D., Uluwaduge, S. P., & Wijerathna, K. B. C. A. *Analysis of Causes and Effects of Coastal Erosion and Environmental Degradation in Southern Coastal Belt of Sri Lanka Special Reference to Unawatuna Coastal Area. Procedia Engineering, 212, 1010–1017.* (2018) doi:10.1016/j.proeng.2018.01.130

Smith, G.L. and Zarillo, G.A.. Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. *Journal of Coastal Research,* 6(1), 111-120 (1990).

Steiner, A. Climate Change, Environment, and Sustainable Development in Africa. African Economic Development, 93–110. (2019) doi:10.1108/978-1-78743-783-820192006

Syvitski, J.P.M., Vorosmarty, C.J., Kettner, A.J., Green, P. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308(5720), 376–380. (2005)

Thieler, E. R., O'Connell, J. F., & Schupp, C. A. The Massachusetts Shoreline Change Project: 1800s to 1994, Technical Report. September 4, 2001: A USGS Administrative Report, generated in collaboration with the WHOI Sea Grant Program and Cape Cod Cooperative Extension, to the Massachusetts Office of Coastal Zone Management (CZM) pursuant to National Oceanic and Atmospheric Award No. NA970Z0165 (2001)

United Nations Development Programme Republic of the Gambia Project Title: Enhancing Resilience of Vulnerable Coastal Areas and Communities to Climate Change UNDAF Outcomes (From Gambia UNDAF 2012-2016): Outcome 1: Capacities, Institutions Strengthen, 2016.

United Nations Environmental Program, Options for Ecosystem-Based Adaptation in Coastal Environments. Retrieved from, https://www.sprep.org/attachments/bem/PEBACC/EbA_resources/Options_for_Ecosystem-based_Adaptation_in_Coastal_Environments_UNEP.pdf. (2016)

United Nations Office for Disaster Risk Reduction.. *Words into Action Guidelines: National Disaster Risk Assessment Hazard Specific Risk Assessment*. https://doi.org/10.1007/978-94-007-4123-2_1 (2017)

Van Rijn, L.C. Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Amsterdam: Aqua Publications - I11 (1993)

Vinayaraj, P., Johnson, G., Dora, G.U., Philip, C.S., Kumar, Williams, R.G., Micallef, A.T., Anfuso, A., Gallego-Fernandez, G.J. B.,. Andalusia, Spain: An Assessment of Coastal Scenery. *Landscape Research, 37(3), 327–349*. (2014) doi:10.1080/01426397.2011.590586.

Wang, K. and Luo, S. Petrology and Sedimentary Environments of the Hongshuizhuang Formation in the Kuancheng Region, Hebei. *Sedimentary Geology and Tethyan Geology*, 34, 29-35 (2014)

Williams, S.J. and Gutierrez, B.T. Sea-level rise and coastal change: Causes and implications for the future of coasts and low-lying regions. U. S. *Geological Survey Woods Hole Science Center. Shore & Beach* Vol. 77, No. 4. (2009)

WIOMSA. Shoreline Change in Tanzania and Kenya: Assessment Procedures and Mitigation Strategies for Management. *WIOMSA Manuals* No. 00. Zanzibar. (2010)

X.H. Wang, X., Xu, S.G. Pearson, G. Xue, R.J Morrison, D. Liu, P.Sh. Integrated Coastal Zone Management Research in Australia and China. *LDM Journal*. Volume 2.

Pinto, P., Cabral, P., Caetano, M. and Alves, M.F. Urban growth on coastal erosion vulnerable stretches. *Journal of Coastal Research*, SI 56 (Proceedings of the 10th International Coastal Symposium), pg – pg. Lisbon, Portugal, ISBN (2009)

Appendix

Questionnaire Administered

This survey questionnaire targeted Coastal Management and Protection Professionals at the National Environment Agency, Department of Fisheries, Maritime Department and the Geology Department of The Gambia. It consists of 22 questions.

1. Gender?
- Male
- Female

2. What age category do you belong?

- 20 - 30
- 31-39
- 40-45
- 46-54
- 55-65
- 66 years and older

3. How would you describe your present association with the coastal area regarding your profession/organisation you represent?
   - Manager (involved in planning, policy, or evaluation)
   - Practitioner (involved in management, engineering, consultancy, monitoring, or education)
   - Scientist (academic, student or, researcher)
   - Non-statutory stakeholder (landowner, special interest group)
   - Community group
   - Other (please specify)

………………………………………………………………………..

4. How long have you been engaged in the field of coastal monitoring and management (in any capacity)?

…………………………………………………….

5. Which of the following best describes the focus of your work presently?
   - Nationwide
   - Regional (please specify region) …………………………………………………
   - Local Government (please specify area) ……………………………………………………
   - Other (please specify) …………………………………………………….
6. Which of the coastal cells are presently at risk of coastal erosion?

- Cell 3
- Cell 4
- Cell 5
- Cell 6

7. What was the situation 16 years ago in the cell(s) selected above?
    - Cell 3 - (Erosion, Stable, Accretion)
    - Cell 4 - (Erosion, Stable, Accretion)
    - Cell 5 - (Erosion, Stable, Accretion)
    - Cell 5 - (Erosion, Stable, Accretion)

8. Which of the coastal cells is accreting presently?
    - Cell 3
    - Cell 4
    - Cell 5
    - Cell 6

9. What was the situation 16 years ago in the cell(s) selected above?
    - Cell 3 - (Erosion, Stable, Accretion)
    - Cell 4 - (Erosion, Stable, Accretion)
    - Cell 5 - (Erosion, Stable, Accretion)
    - Cell 6 - (Erosion, Stable, Accretion)

10. What type of coastal features are most at risk of erosion (E.g., beach, estuary, dunes, tidal flat, cliffs)

11. What is the grain/sand size along each cell? (E.g., very fine, fine, coarse)

12. On a scale of 1 - 5, 1 = ‘little to none’ and 5 = ‘extreme,’ how would you rate the risk of coastal inundation/flooding in each cell?

13. Is a strong one-directional longshore sediment transport present along the coastal cells?

14. What type of coastal feature is mostly at risk of coastal inundation? (E.g., beach, estuary, tidal flat, cliff)

15. What means have been used to prevent or remediate coastal erosion in these cells?\
    - Hard engineering/structures (Sea walls, groynes, others)
    - Soft engineering/structures (Sandbags, others)
    - Coast reorientation
    - None

16. In your opinion, what are the environmental challenges involving erosion and inundation in the coastal area?

17. What are some of the activities that have contributed to increasing the risk of erosion presently?
    - Lack of scientific understanding
    - Technical limitations
    - Inadequate monitoring
    - Lack of national coastal framework
    - Limited statutory stakeholder participation
    - Lack of public involvement
    - Lack of public awareness of coastal issues
    - Climate change
    - Increased tourism and recreation
    - Urbanisation
    - Coastal defense issues
    - Mulitude of users and activities in the coastal zone
    - Complex natural environment
    - Others

18. What are some of the activities that have contributed to increasing the risk of erosion over the last 16 years?

19. What are the main challenges in implementing coastal management practices in relation to coastal erosion and inundation?

20. What implementation/management measures been put in place to tackle coastal erosion in the coastal cells?

21. When was this done?

22. What do you or your organization think is the best approach to educating the public about these coastal changes?
    - Social media
    - Flyers
    - Community forums
    - News
    - Documentary
    - Other (please specify) ……………………………

END OF SURVEY