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

Assessment of the impacts of climate change on the Grand Saloum transboundary Wetland Complex (Senegal-Gambia)

OUSMANE BADJI

Master Research Program on Climate Change and Marine Sciences

São Vicente
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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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Examiner 1

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Dedication

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To my Mother and Father

Who always boost me in every adventure and challenge, especially this one.

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Resumo

O Grand Saloum (Reserva do Delta de Saloum no Senegal e Parque Budapi na Gâmbia) é o primeiro Complexo Ramsar Transfronteiriço africano. Os ecossistemas neste complexo foram interrompidos por um grande evento extremo (tempestade) em 1987. Este complexo de zonas húmidas está agora sujeito a uma dinâmica significativa caracterizada pela mobilidade costeira. O objetivo deste estudo é avaliar os efeitos do fenômeno climático no Complexo Húmido costeiro usando uma análise GIS multitemporal (1990-2020) e um levantamento socioeconômico. A taxa de variação da linha costeira é obtida através do índice End Point Rate (EPR) usando DSAS. A dinâmica da vegetação foi feita por uma classificação supervisionada no Google Earth Engine (GEE). Os dados do inquérito socioecológico foram analisados com o software SPSS. Os resultados revelaram uma taxa de erosão média anual de 2,44 m / ano e uma taxa de acreção média de 1,84 m / ano. A vegetação costeira próxima à linha de costa mostrou uma diminuição da área de mangue de 16,43% em 2000 para 15,17% em 2005 (1,26% da cobertura total de mangue). A área de mangue aumentou ligeiramente de 16,37% para 16,81% para o ano de 2010 a 2020, respectivamente (0,5% da cobertura total de mangue). Além disso, a pesquisa revelou que a perda de habitat e a remoção da vegetação costeira foram os principais impactos da erosão. O acesso limitado aos recursos do ecossistema e o aumento das dificuldades de trabalho foram os principais impactos devido ao acréscimo. Os principais impactos causados pelas inundações foram a degradação do solo e a perda de habitat. A hipersalinidade levou principalmente à degradação da terra e à perda de recursos do ecossistema. As medidas de adaptação da comunidade local foram baseadas no tipo de costa e na distância de construção da costa. O reflorestamento de manguezais, o plantio de árvores, a reabilitação de diques e a construção de capacidades eram estratégias dominantes em costas arenosas e lamacentas. Essas descobertas revelam a necessidade de fortalecer as estratégias de mitigação e adaptação a fim de abordar os impactos do fenômeno climático no ecossistema e na subsistência local.

Palavras-chave: mudanças climáticas, mudanças costeiras, manguezais, outras vegetações, estratégias de adaptação

Abstract

The Grand Saloum (Saloum Delta Reserve in Senegal and Niumi Park in The Gambia) is the first African Transboundary Ramsar Site Complex. Ecosystems in this complex were disrupted by a major extreme event (Storm) in 1987. This wetland complex is now subjected to significant dynamics characterised by shoreline mobility. The goal of this study is to assess the effects of climate phenomenon in the coastal Wetland Complex using multi-temporal (1990–2020) GIS analysis and a socio-economic survey. The rate of change of the coastline is obtained through the End Point Rate (EPR) index using DSAS. The vegetation dynamic was done by a supervised classification in Google Earth Engine (GEE). The socio-ecological survey data were analysed using SPSS software. The results revealed an annual average erosion rate of 2.44 m/year and an average accretion rate of 1.84 m/year. The coastal vegetation close to the shoreline showed a decrease of the mangrove area from 16.43% in 2000 to 15.17% in 2005 (1.26% of total mangrove cover). The mangrove area increased very slightly from 16.37% to 16.81% for the year 2010 to 2020 respectively (0.5% of total mangrove cover). The survey moreover revealed that loss of habitat and coastal vegetation removal was the main impacts of erosion. Limited access to the ecosystem resources and an increase in work difficulties were the main impacts due to the accretion. The main impacts caused by floods were land degradation and habitat loss. Hypersalinity led mainly to land degradation and loss of ecosystem resources. The local community adaptation measures were based on the type of shore and the distance of build-up from the coast. Mangrove reforestation, tree planting, dike rehabilitation, and capacity building were dominant strategies in sandy-muddy shores. These findings reveal the need for strengthening mitigation and adaptation strategies in order to address the impacts of the climate phenomenon in the ecosystem and local livelihood.

Keywords: climate change, shoreline change, mangrove, other vegetation, adaptation strategies

Abbreviations and acronyms

ADG	Aide au Development Gembloux
DSAS	Digital Shoreline Analysis System
EPR	End Point Rate
GEE	Google Earth Engine
GHG	Greenhouse gases
GIS	Geographic Information System
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Change
ISODATA	Self-Organizing Data Analysis Technique
ISRP	Interactive Survey Reduction Program
IWMI	International Water Management Institute
LaSRC	Land Surface Reflectance Code
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
MCA	Multiple Correspondence Analysis
MEPN	Ministere de l’Environnement et de la Protection de la Nature
MOLOA	West Africa Coast Observation Mission
NDBI	Normalized Difference Built-up Index
NDWI	Normalized Difference Water Index
NOAA	National Oceanic and Atmospheric Administration
ODK	Open Data Kit
RCP	Representative Concentration Pathways
SLR	Sea-Level Rise

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1. Introduction

1.1 Background and Context

Climate change is one of the main contributors to the vast alterations of planet Earth. Overwhelming evidence shows an adverse effect on economic activities across the world. Fluctuations in sea level is one main consequence of climate change. These fluctuations are enhanced by global warming and the melting of land ice (Church et al., 2001). A slower rate of sea-level rise in the human and ecological systems of small islands, low-lying coastal areas, and deltas, enables greater opportunities for adaptation (IPCC, 2007).

African coastal countries that are strongly dependent on coastal and marine resources are facing major challenges. Climate change is considered a threat to wetlands and may disturb mangrove ecosystems (Ellison, 2014). Sea level rise for instance, is considered as a potential threat. The duration and frequency of inundation can harm mangrove ecosystems as well as increase salinity levels beyond the species-specific physiological threshold of tolerance (Friess et al., 2012). In West African coastal countries, the climate change effects become a matter of concern for the management of mangrove ecosystems. Evaluating the long-term changes of the vegetative component of coastal wetlands such as mangrove vegetation is important for the formulation of sustainable alternative livelihoods and adaptation strategies to climate change (Ceesay et al., 2017).

Senegal's coastline extends over a distance of 731 km. The economy of Senegal remains largely dependent on climate-sensitive sectors, particularly agriculture, livestock, and fisheries (Zamudio, 2016). The main problems facing the Senegalese coasts are flooding, coastal erosion, salinization of soils, degradation of mangroves, and changes in fishing regimes (Amara et al., 2018). During the last decades, the Senegalese shoreline has experienced erosion rates between 1 and 2 m per year (Diop et al., 2014; P. W. Bakhoum et al., 2017). Also, the destruction of the Sangomar Point by a storm surge in 1987 was an extreme case that created an island separated from the Palmarin peninsula (MEPN, 2006).

In the Saloum estuary area, sea level rise would result in the disappearance of 27% of the total area, especially in low-lying areas (Niang et al., 2010). Sea level rise may also produce 330 m of erosion in the Northern border between The Gambia and Senegal (Jallow et al., 1996).

1.2 Problem Statement and Research Questions

The Grand Saloum (Saloum Delta Biosphere Reserve in Senegal and Niumi Park in The Gambia) is the first African Transboundary Ramsar Site Complex. This ecosystem has several ecological and economic benefits. Ecosystems in this complex were disrupted by a major extreme event (Storm) in 1987. This wetland complex is now subjected to significant dynamics. Many studies have been carried out in whole or in part on the Saloum Delta mangroves to address problems in different thematic areas, such as the identification of threats and pressures (Drame & Sambou, 2013; Sidibe, 2010). Some studies have confirmed that the variation in climate variables, such as rainfall, influences mangrove dynamics in Saloum (Sow et al., 2019), yet few studies have considered the socio-ecological response of the ecosystem to the climate change effects.

For example, questions such as, “What would be the effect of sea level rise and erosion in the coastal Wetland Complex?” are usually not investigated. Moreover, in the context of a changing climate, there is the need to have regular updates of knowledge on the coastal environment. This study aims to fill some of these knowledge gaps, through geographic information system (GIS) tools and socio-ecological survey to make an assessment of the Grand Saloum complex that can be useful to coastal zone managers.

The main objective of this study was to assess the effects of climate change in the coastal Wetland Complex. To achieve this goal, the specific goals were:

- to quantify how the shoreline in the Grand Saloum complex have spatially and temporally changed during the past 30 years (1990–2020);
- to quantify how the mangrove and other vegetation have spatially and temporally changed during the past 20 years (2000–2020);
- to assess the perception and impacts of coastal climate phenomenon and the adaptation strategies of local communities.

1.3 Structure of work

In addition to the introduction and conclusion, this thesis is divided into four chapters. The first chapter summarizes the literature review; the second illustrates the material and the methodology used. The third chapter presents the results obtained, and finally, the fourth chapter deals with the discussion of the results.

2. Literature review

2.1. Definition of Wetlands

According to the Ramsar convention, wetlands are: "areas of marsh, water, fen or peatland, whether natural or artificial, temporary or permanent, with water that is static or flowing, brackish, fresh, or salt, including marine water depth of which at low tide does not exceed six meters" (Ramsar Convention, 2007).

Wetlands provide numerous valuable functions such as recycling nutrients (Everard, 2016), attenuating floods (Potter, 2011), purifying water, recharging groundwater, and also serve in providing drinking water (Lindsey, 2019). Wetlands are important ecosystems that can provide fish, fodder, fuels, wildlife habitat, buffer shorelines against erosion and recreation to society, as well as control the rate of runoff in urban areas (Kumar & Kanaujia, 2018). The existence of wetlands may be of great significance to some people (IWMI, 2014). Wetlands can even be considered as a cultural heritage for people (Kumar & Kanaujia, 2018).

Many people depend on their resources for food, water, and other materials and their several functions for protecting human health. So a wetland's cultural heritage takes many forms, from paleontological records in sediments and peat, human-made physical structures and traditional water and land-use management practices, to places of religious significance to indigenous peoples and the almost intangible 'sense of place' (Nick Davidson, 2001).

2.2. Sea level rise

Sea-level rise (SLR), caused by climate change, is a global threat. The scientific evidence is now overwhelming. From 1993 to 2003, a faster rate has been observed, about 3.1 [2.4 to 3.8] mm per year. This rate is highly different from the one from 1961 to 2003, with an average rate of 1.8 [1.3 to 2.3] mm per year (IPCC, 2007). Several major factors that currently contribute to sea-level change are identified by the IPCC AR4 Report. These are:

- Ocean thermal expansion;
- Changes in glaciers and icecaps;
- Glacial melt from Greenland and Antarctica;
- A low contribution from snow on land Cryosphere and permafrost (Meisner & Susmita Dasgupta, 2009).

The main factors stated by Cazenave & Cozannet (2014) are land water reservoirs, thermal expansion of sea waters, and freshwater mass exchange between oceans and land ice loss (Fig.1).

The rate of global-mean sea-level rise since 1900 has changed over time, but the contributing factors are still poorly understood (Frederikse et al., 2020). The combined contribution from thermal expansion of the ocean, changes in terrestrial water storage, and ice-mass loss are consistent with the trends and multidecadal variability in observed sea-level on both global and basin scales. Since 1900, ice-mass loss contribution to sea-level (predominantly from glaciers) doubles the thermal expansion one (Frederikse et al., 2020).

Even if the emissions of greenhouse gas (GHG) were stabilized soon, sea levels would continue to rise for many decades (IPCC, 2007). Gornitz et al. (2001) predicted ranges within the 0-1 meter during the 21st century. The IPCC AR4 report has projected, by the end of the 21st century, a sea-level rise between 0.18 to 0.59 meters across different emission scenarios. However, IPCC, 2007 has been criticized for not including the full effect of changes in ice sheet flow (Oppenheimer et al., 2007; Pfeffer & Harper, 2008; Solomon & Alley, 2008).

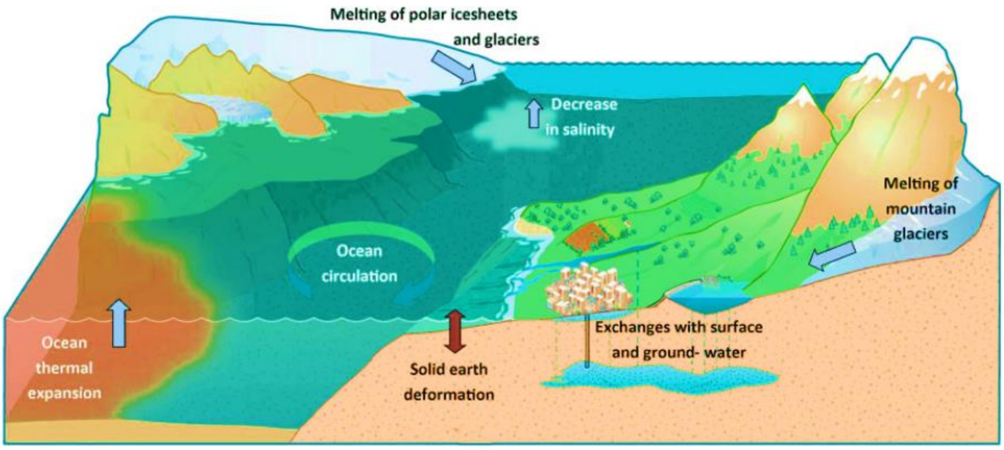

Figure 1: Sketch of the main factors causing sea-level changes. Source: (Robert J. Nicholls & Cazenave, 2010b).

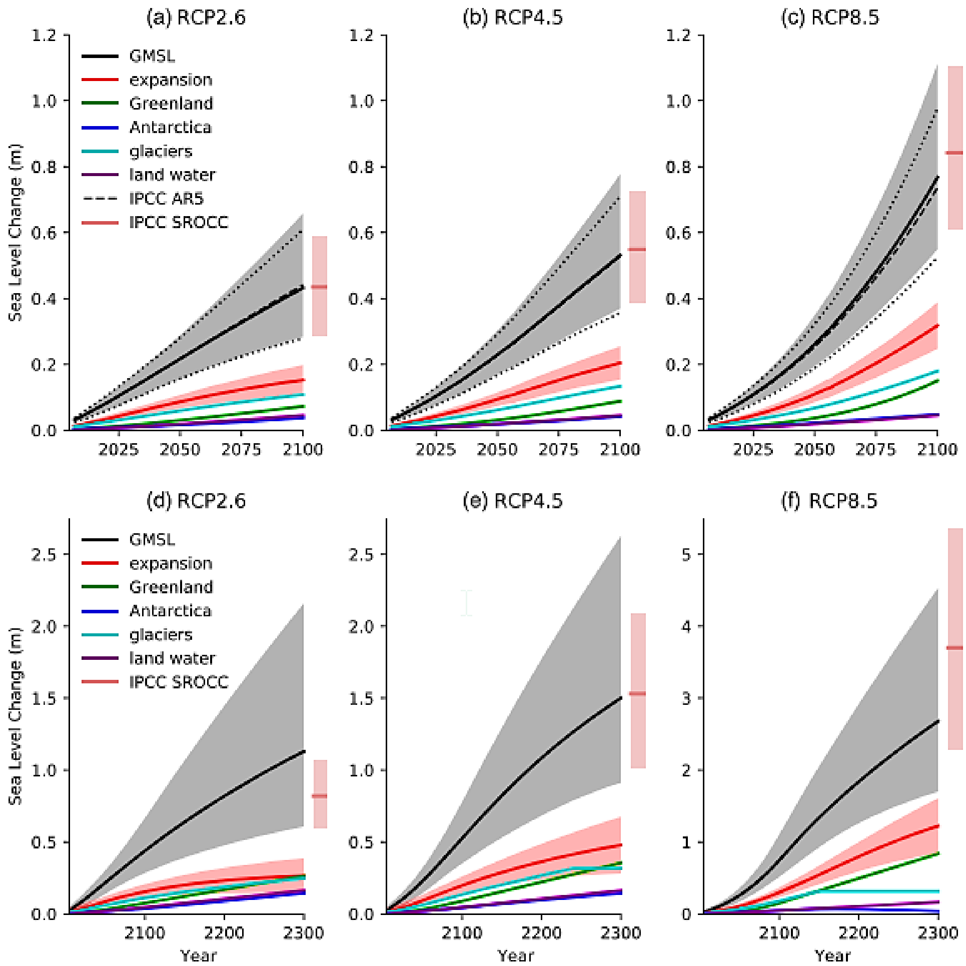

Figure 2:**Projections of global-mean sea-level change for RCP2.6 (left), RCP4.5 (middle), and RCP8.5 (right).** Sea-level components are shown as indicated in the figure legend. The shaded regions show the 5th to 95th percentile range from the 450,000-member Monte Carlo simulation for global thermal expansion (red) and the total (gray). The dashed and dotted lines indicate the 50th percentile and 5th to 95th percentile range from the Monte Carlo simulation presented in IPCC AR5 (Church et al., 2013). The gray shaded bars on the right-hand side of each plot indicate the 5th to 95th percentile range at 2100 or 2300 from the IPCC SROCC (Oppenheimer et al., 2019). All projections are plotted relative to a baseline period of 1986–2005. Note the change of the y-axis scale for panel (f). Source: (Palmer et al., 2020).

An extended 2300 projections illustrate a sea-level rise under all RCP scenarios and with large uncertainties. At these prolonged time horizons, there is a large distinction between scenarios than for the 21st century. For the 2300 projections, the total glacier ice mass becomes exhausted between 2100 and 2300 under RCP8.5 and between 2200 and 2300 under RCP4.5 (Fig.2) (Palmer et al., 2020). Figure 3 is the Mean Sea-Level in the North Atlantic region from satellite Altimetry. This graphic can show that from 1993 to 2020, the North Atlantic is experiencing a sea-level rise of 2.95 mm/year.

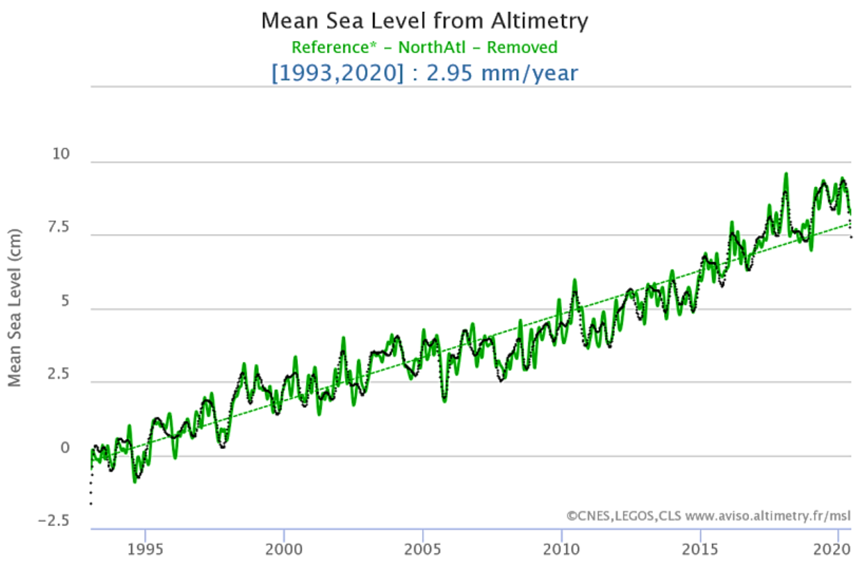

Figure 3: North Atlantic Sea-level rise from satellite altimetry 1993–2020[1].

2.2.1. Sea-level rise impacts

Warming of 2 °C will cause an average sea level rise of 20 cm. If warming still continues above 2 °C, then, by 2100, the sea level will be rising rather than at any time during human civilization (Jevrejeva et al., 2016). Coastal communities experience a rapidly expanding city in the developing world. United Nations Educational, Small island states, Cultural and Scientific Organization, Cultural World Heritage sites, and vulnerable tropical ecosystems will have a very limited time after midcentury to adapt to these rises (Jevrejeva et al., 2016). Global warming is generating a rise in sea level, which results in flooding in low-lying areas and coastal erosion. These effects will be intensified throughout the twenty-first century (Mentaschi et al., 2018; Zhang et al., 2004).

Coastal erosion, extreme marine flooding, or saltwater intrusions in coastal aquifers are expected as worse consequences of sea-level rise. For each type of these impacts, the dynamic response of coastal systems remains highly uncertain. This has motivated numerous studies on the evolution of shorelines, as well as on potential causes, among them, sea level rise (Cazenave & Cozannet, 2014).

[1] Source: https://www.aviso.altimetry.fr

2.2.2. Sea-level rise and wetlands

Understanding the impact of SLR on coastal wetlands must therefore take into account factors that affect the ecological balance of the wetland ecosystem. Those factors are the history of sea levels in regard to the development of coastal gradients, relative geomorphic and sedimentologic homogeneity, the salinity of soil and groundwater, the coastal processes such as tidal range and its stability, and the availability of fresh water and sediment (Alongi, 2008). A rise of 1m SLR may result in a loss of more than 60% of freshwater marsh, Coastal Wetlands, and brackish/saline wetlands (Blankespoor et al., 2014). A large percentage of this loss would take place in East Asia and the Pacific, and the Middle East and North Africa (Blankespoor et al., 2014).

The increased connectivity of the landscape interior to saline coastal waters is due to the construction of drainage ditches for agriculture and channelization for navigation (Bhattachan et al., 2018). Salt moves upgradient because of diffusion, and its effects on vegetation often precede other visible evidence of sea-level rise (Tully et al., 2019). The spatial distribution of forested wetland loss appears more consistent with saltwater intrusion. In this landscape of low topographic relief and shallow groundwater, all hydrologically connected areas are potentially vulnerable to saltwater intrusion (Bhattachan et al., 2018). SLR is threatening high-value vegetated intertidal ecosystems and unless widespread action is taken. Currently, there is no global solution to conserve or adaptively manage these very important intertidal ecosystems (Sadat-Noori et al., 2021).

2.3. Definition Concept of Shoreline and identification

In an article published by Parker (2001), "Where is the shoreline? The answer is not as simple as one might expect”, Parker highlighted all the delicacy of locating and positioning a limit between land and sea in such a space dynamic than the coastline. Coastline refers to the limit reached by high water of spring equinox. The coastline can be materialized according to the coast type by the foot of the cliff or the limit of the terrestrial vegetation. For Guilcher (1951), the coastline corresponds to the “line of the highest seas” in calm weather. However, the real definition of this concept of coastline is problematic and controversial because of the large diversity of identification criteria (geomorphology, tide, vegetation, etc.). Even more recently, for example, Boak & Turner (2005) identified 19 generic coastlines from 45 indicators found in around eighty publications. This diversity of reference lines is reflected, therefore, by the development of many direct or indirect methods to detect and extract a coastline on an iconographic document or in the field in order to retrace the historical evolution of the coastal line.

The identification of a shoreline involves two stages. The first requires the selection and definition of a shoreline indicator that will act as a proxy for the land-water interface (Boak & Turner, 2005). Both the technique for identifying the shoreline position and the assumptions made regarding the definition of the shoreline (shoreline indicators) can induce error when estimating a shoreline position (STOCKDON et al., 2002). To quantify historical rates of change and indicate the dynamics and hazards of the coast, the rate of shoreline change is mostly used by planners, coastal scientists, and engineers (Dolan et al., 1991). The assessment of variations in shoreline position is one of the most important components of Integrated Coastal Zone Management (ICZM). Both assessments of the shoreline and ICZM are important for monitoring erosion processes and evaluating the efficiency of shore protection projects (Pranzini & Simonetti, 2008).

2.4. Shoreline changes in West Africa

West African shorelines have been changing at a fast rate in recent decades (Pennober, 2009). Rates of erosion in the median segment of the Sangomar spit ranged from 0.49 to 14.21 m/yr, with an average of 3.55 m/yr (Sadio, 2017). The accretion noticed vary between 1.58 and 5.31 m/yr, with an average of 2.81 m/yr south of the segment studied. Moreover, Abe et al. (2005) described shoreline dynamics with an accretion of 1.27 m/year in Port-Bouët Bay which emerges in conditions of relative stability. This mobility, highly dynamic in location, is characterised by a globally erosive trend in the Gulf of Guinea and West Africa (Thior et al., 2019).

2.5. Adaptation measures

The IPCC (2001) defines adaptation as an adjustment in social, ecological, or economic systems in response to present or expected climatic stimuli and their effects or impacts. Adaptation refers to changes in practices, processes, or structures to offset or moderate potential damages and take advantage of opportunities linked with changes in climate. In the context of sea-level changes in coastal systems, adaptation options are usually identified as one of three possible approaches (McLean et al., 2001; R. J. Nicholls, 2003).

1. Retreat, which implies that human impacts are minimized by pulling back from the coast after all-natural system effects occurred. This approach involves no attempt to protect the land from the sea.
2. Accommodation, which implies that people continue to occupy the land but make some adjustments to avoid the impacts, for example, by elevating buildings on piles, growing flood-tolerant or salt-tolerant crops.
3. Protection, which aims to protect the land from the sea so that existing land can continue by constructing hard (or semi-hard) structures (e.g., seawalls, sandbags) as well as using soft measures (e.g., beach nourishment).

Adaptation responses to coastal hazards can be of several types and can vary widely between high-density urban cities versus more rural and remote villages and towns. At the local scale, coastal adaptation can involve multiple responses at the same time, including land reclamation, in situ protection using structures, ecosystem-based adaptation, raising elevations, or retreating from the coastline (Robert J. Nicholls & Cazenave, 2010; Oppenheimer et al., 2019). Rural coastal communities often respond to hazards with structures and other responses that can be built quickly and easily using local resources. These can include raising elevations of structures by building on stilts or elevating floors to keep the structures dry during periods of high water levels or heavy rain (Rasmussen et al., 2013; Jamero et al., 2018).

In urban areas, adaptation responses can include technically complex and expensive solutions such as storm surge barriers, land reclamation, or large shore-front levees and seawalls (Aerts et al., 2013). Relocation and planned retreat are also coastal adaptation responses, though these are relatively rare and difficult to implement (Hino et al., 2017).

Ecosystem-based adaptation responses are gaining increasing attention worldwide, particularly due to the multiple benefits they can provide in addition to coastal protection (Bridges et al., 2015). Coastal mangroves, marsh wetlands, and offshore coral reefs can protect shorelines by reducing wave heights and storm surges (Narayan et al., 2016; Storlazzi et al., 2019). These ecosystems also provide valuable co-benefits, including recreation, carbon sequestration, fisheries production, and food and timber production (Sutton-Grier et al., 2015). Ecosystem-based adaptation responses are particularly suitable for contexts where moderate levels of hazard reduction are required in combination with other co-benefits (Arkema et al., 2015).

A living shoreline is a term that includes a range of shoreline stabilization techniques along estuarine coasts, bays, sheltered coastlines, and tributaries (Fig.4). A living shoreline has a particularity that is made up essentially of native material. It incorporates a combination with some type of harder shoreline structure (e.g., oyster reefs or rock sills), vegetation, or other living, natural "soft" elements alone for added stability. Living shorelines control the continuity of the natural land–water interface and reduce erosion while providing habitat value and enhancing coastal resilience (NOAA, 2015).

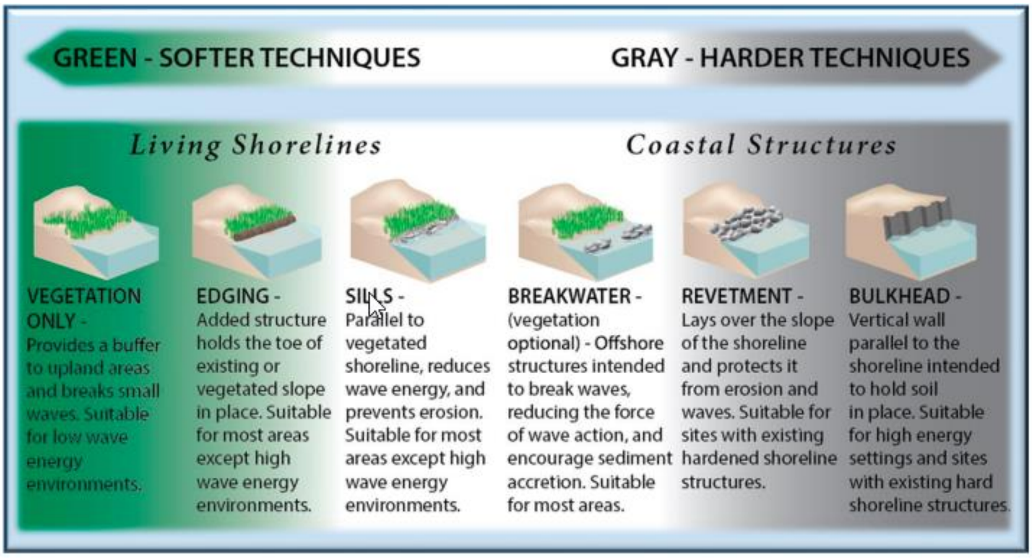

Figure 4: Range in coastal protection approaches from green to gray with those on the left ("living or partially living") Source: (NOAA, 2015).

3. Materials and Methods

3.1. Research design and methods

A combined approach of quantitative and qualitative methods based on remote sensing analyses and a socio-ecological survey was used in this study. The shoreline change was studied through the Digital Shoreline Analysis System (DSAS), an extension to be set up in the ArcGIS software. The mangrove and other vegetation dynamics were accessed using the GEE. A field investigation was done to confirm the points of erosion and accretion. Then a socio-ecological survey was carried out to determine the perception, impacts, and adaptation strategies in the local communities.

3.2. Study area

The Grand Saloum transboundary complex (Fig.5) covers an area of 83,758 ha. It is composed of:

- The Saloum Delta National Park (PNDS) in Senegal, which is located between latitudes 13.583333 and 13.916667, and longitudes 16.466667 and 16.083333. This site was erected by a Decree under the Senegalese law N°76 577 on 28th March 1976 and covered a total of 76,000 ha.
- The Niumi National Park (NNP) in The Gambia, which is located between latitudes 13.516667 and 13.983333 and longitudes 16.933333 and 16.083333, is a coastal strip of 7758 ha erected as a National Park in 1986 and a RAMSAR Site in October 2008. It is the natural southern extension of the Saloum National Park (PNDS) (WOW, 2015).

3.2.1. Climate

The Grand Saloum transboundary complex is marked by a Sudano-Sahelian climate type characterised by rainfall values between 400 and 800 mm with an average temperature of 29° C. The rainfall is generally less in the northern part of the complex (Saloum) and greater in the southern region (Niumi). The Canary current coastal influence is much more prominent on the Senegalese section of the complex. Two main seasons characterise the climate:

- A dry season (cold from November to March, hot from March to June), where the prevailing winds are maritime trade winds, fresh (in a north to north-west direction).
- A dry continental winds (in an east to north-east direction, known as Harmattan).
- A hot, humid rainy season from July to October, dominated by monsoon winds (direction: West and southwest). Annual rainfall in the Saloum Delta has declined from a range of 600-900 mm for the period 1931- 1960 to less than 400-600 mm today. There is a total of

50-60 days of rain per year, with maximum rainfall in August. Recently, in Niumi, there have been reports of increased annual average rainfall from 2000 to 2010, and this certainly might be the same at the whole complex level. Average annual temperatures vary between 26 and 31° C (WOW, 2015).

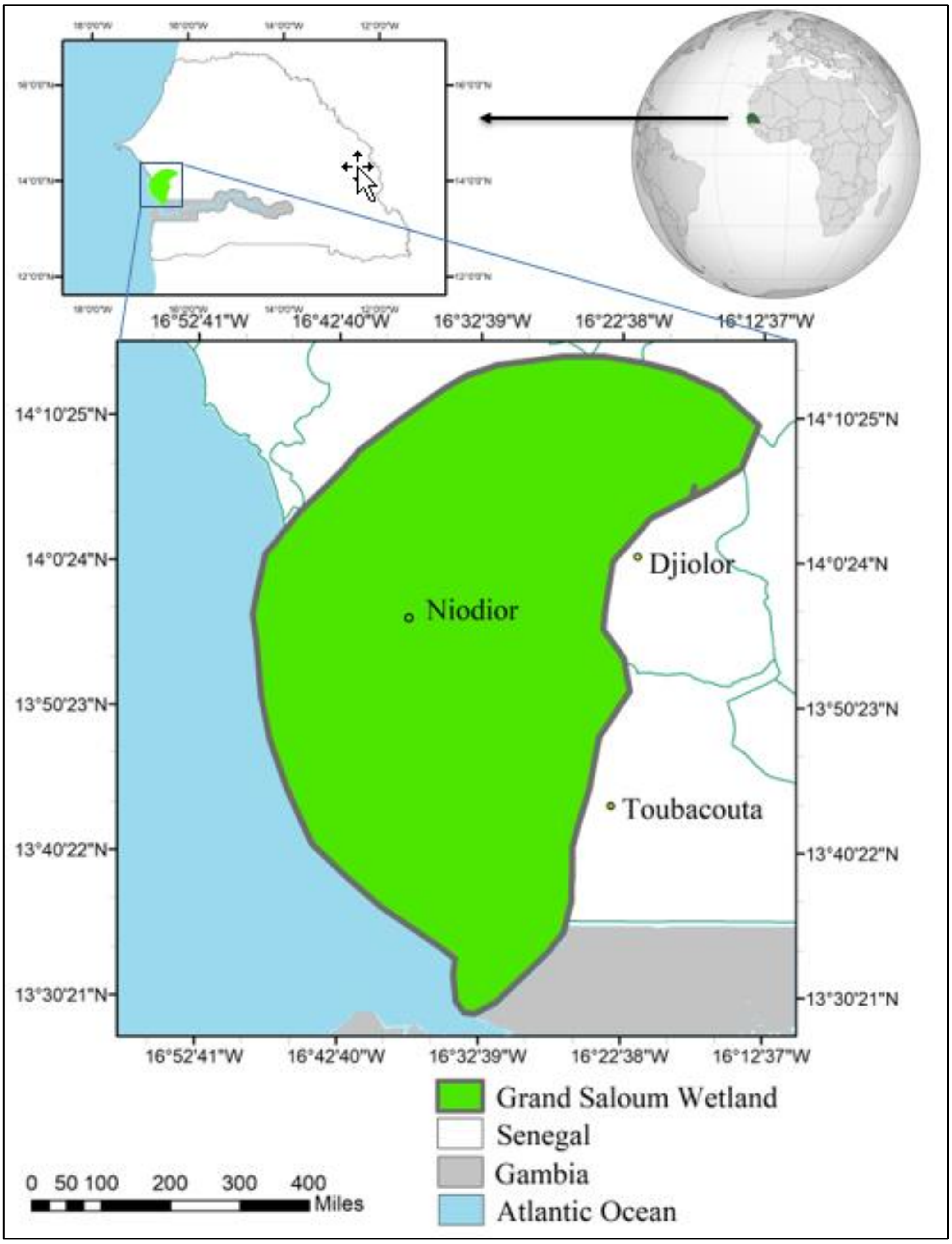

Figure 5: Map of the study area (Saloum-Nuimi Transboundary Ramsar Complex).

3.2.2. Hydrology, geology, and marine dynamics

The Saloum and The Gambia estuaries are located in the western part of the sedimentary basin between Senegal and Mauritania. The landforms of the area are strongly related to its geological history, directly associated with marine dynamics. The Grand Saloum geology is made up of sand with argillaceous or sandy-argillaceous. They are based on a marine oligo-miocen, consisting of sand, marno-limestone, and argillaceous sandstone (Dia, 2012). A topographic map taken from the DEM data (Fig. 6) shows that the Saloum Delta and The Gambia estuary have low elevations. In particular, the Saloum Delta and Niumi are exposed to sea-level rise.

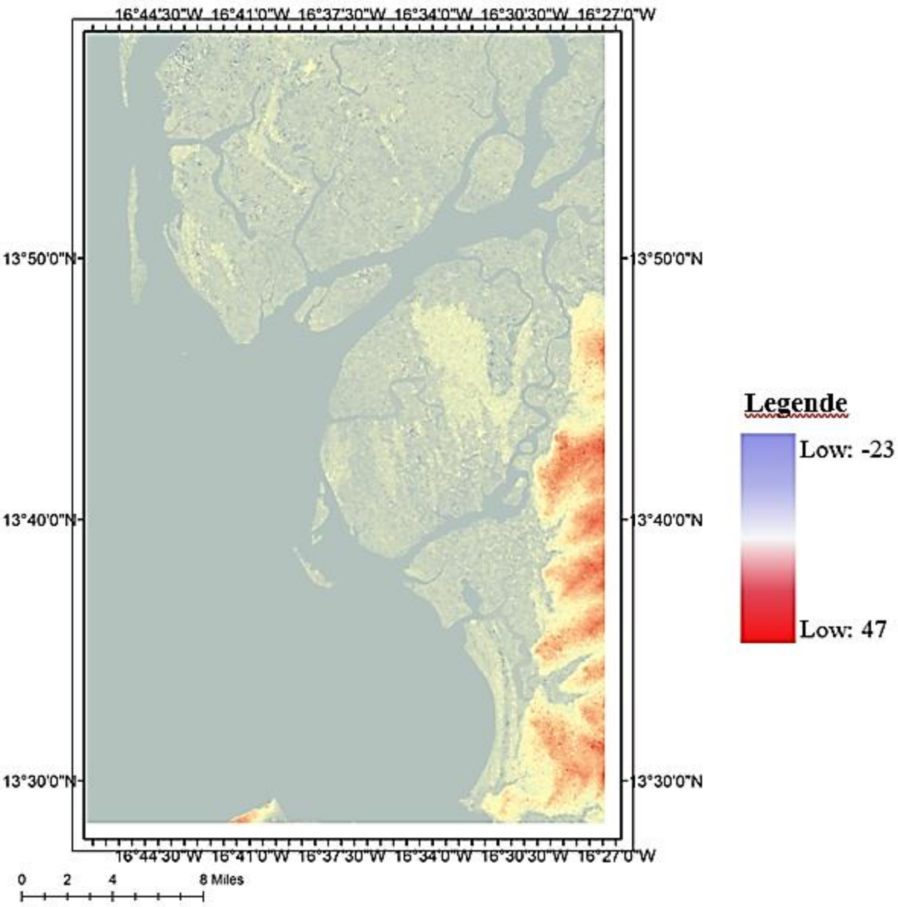

Figure 6: Topographic map of the Grand Saloum.

3.2.3. Biological importance of the study area

➔Aquatic fauna

The Grand Saloum attracts numerous marine fish for feeding and spawning. Marine fish species found in this area are of high economic importance. The upwelling system provides nutrients for marine fishes. It is estimated that the Grand Saloum marine and estuary ecosystems shelter 6 species of turtles, 26 species of cetaceans, 600 species of fish, and more than 200 species of birds (Dia, 2012). The Grand Saloum is classified by international conservation NGOs intervening in West Africa as a site of regional importance for marine conservation. More than 114 fish species spawn and/or nurse in the Saloum and the Gambia mangrove ecosystems. Mature fish then spread out in the Grand Saloum marine ecosystem (Dia, 2012).

Marine birds which are among the greatest biological assets have also been reported. Moreover, the Saloum Delta Bird Island and Bijol Island are among the most important Laridae (royal and Caspian terns and gulls) nesting sites in the world, with more than 60,000 nests each per year (Dia, 2012).

➔Flora

Six main plant species dominate the mangrove ecosystem area *Avicennia germinans*, *Conocarpus erectus*, *Laguncularia racemosa*, *Rhizophora harrisonii*, *Rhizophora mangle*, and *Rhizophora racemosa*. Coastal ecosystems provide many important resources for the local population. Mangroves, for example, are integral to the health and functioning of local fisheries. Leaf litter from mangroves is a food source for a variety of invertebrates that are in turn consumed by other species in the food chain, including fish. The region's mangroves also act as a "nursery" for the spawning of 114 species of fish (Diouf, 1996). Mangroves have important hydrological functions; they may slow or prevent coastal erosion and serve to buffer or mitigate water pollution and flooding. Finally, mangroves are also an important source of fuel and construction wood. The mangroves of The Gambia and the Saloum constitute an important ecosystem for riverbank stability, agricultural production, and fish spawning. Globally, mangrove forests have a high potential for carbon sequestration (Dia, 2012).

3.2.4. Demographic and social context

There are eleven outlying villages, including three located in Bakadadji within the boundaries of the PNDS, with an estimated population of 13,146 inhabitants, according to the 1993 national census of Senegal. The economy of the area is focused on the exploitation of natural resources in wetland zones and often runs along ethnic and gender lines. The Mandingos, Niominkas, and Diolas are the main ethnic groups. A household survey conducted in the Kanuma, which coincided with the study on the Grand Saloum complex, revealed that there is a huge intermixing of ethnicity among the Sérère and Mandingo (Dia, 2012).

3.2.5. Socio-economics

The activities in the entire Grand Saloum Complex Delta are agriculture, forestry, animal husbandry, fishing, and tourism. (Bousso, 1991). Gallup et al. (2019) identified the most important extractive activities within the Delta. The use of dead mangrove wood for fuelwood is the most important extractive use of mangroves. The second most important is Fish, clam, oyster, and shrimp collection. In the last 20 years, annual catches have decreased (from 30,000 to 15,000 t) as has the diversity of species in the catch (Villanueva et al., 2002). Cutting mangrove wood has been estimated around 1500 to 5700 individuals per hectare (Ndour et al., 2012). The annual production of sea food has been estimated to 15,000 tons of fish and shrimp, and 2600 tons of mollusks (ADG, 2012).

3.3. Remote sensing of the shoreline dynamic

3.3.1. Satellite images

Satellite images with different spatial resolutions processed with various change analysis methods are effective for quantifying changes in the wetland (Toure et al., 2018). Accordingly, surface reflectance images from Landsat 5, 7, and 8 (Table 1) between 1990 and 2020 were accessed and processed in ENVI.

Table 1: Landsat images properties.

Dates and time of acquisition	Paths and Rows	Cloud Cover	Sensors	Data Provider:	Bands
1990-12-21 10:47:02	(PATH: 205, ROW: 50) & (PATH: 205, ROW: 51)	0	Landsat 5	USGS	Blue, Green, Red, NIR, SWIR-1, SWIR-2, NDVI, NDBI, NDWI
2000-12-08 11:17:48		0	Landsat 7		
2010-12-28 11:17:22		0	Landsat 5		
2020-12-07 11:27:49		0	Landsat 8		

3.3.2. Image pre-processing

The bands in the surface reflectance images were atmospherically corrected and orthorectified. At any pixel location, the value recorded on a remotely sensed image does not refer to the true ground-leaving radiance at that particular point. One part of the brightness is due to the target of interest reflectance and the remainder from the atmosphere itself. Their contributions are not known a priori, so the objective of atmospheric correction was to quantify these two components in order to use correct target reflectance (Themistocleous et al., 2008). The orthorectification is necessary because of deformations mainly due to camera distortions and acquisition geometry.

The terrain-related geometric distortions that were removed during the orthorecfication stage are related to the image formation process (error tracking), such as distortions caused by the platform, and mainly related to the variation of the elliptic movement around the Earth, instantaneous field of view, topographic relief changes, etc. (Chmiel et al., 2004).

3.3.3. Data analysis and processing

Spectral indices, also known as band transformations, were obtained from the Landsat 5, 7, and 8 surface reflectance images by the following equations (Table 2).

Table 2: Formulas for the NDVI, NDWI, and NDBI calculation.

Index Used	Equations
NDVI	$\boldsymbol{NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}}$
NDWI	$\boldsymbol{NDWI = \frac{\rho_{Green} - \rho_{NIR}}{\rho_{Green} + \rho_{NIR}}}$
NDBI	$\boldsymbol{NDBI = \frac{\rho_{SWIR1} - \rho_{NIR}}{\rho_{SWIR1} + \rho_{NIR}}}$

With: ρ_Green=ToA reflectance of green band, **ρ_NIR**=ToA reflectance of near infrared band.
ρ_NIR=ToA reflectance of near infrared band, **ρ_SWIR1**= short-wave infrared.

Shoreline Detection and analysis

DSAS is one of the most efficient and effective as well as less time-consuming tools in shoreline change analysis compared with the many traditional tools and methods and produces results of better accuracy (Sekovski et al., 2014). It relies on input data such as the date and year and a digitized geometry (in shapefile format) of the shoreline. A series of processes were carried out to analyse the changes in the shoreline, as given in Figure 7.

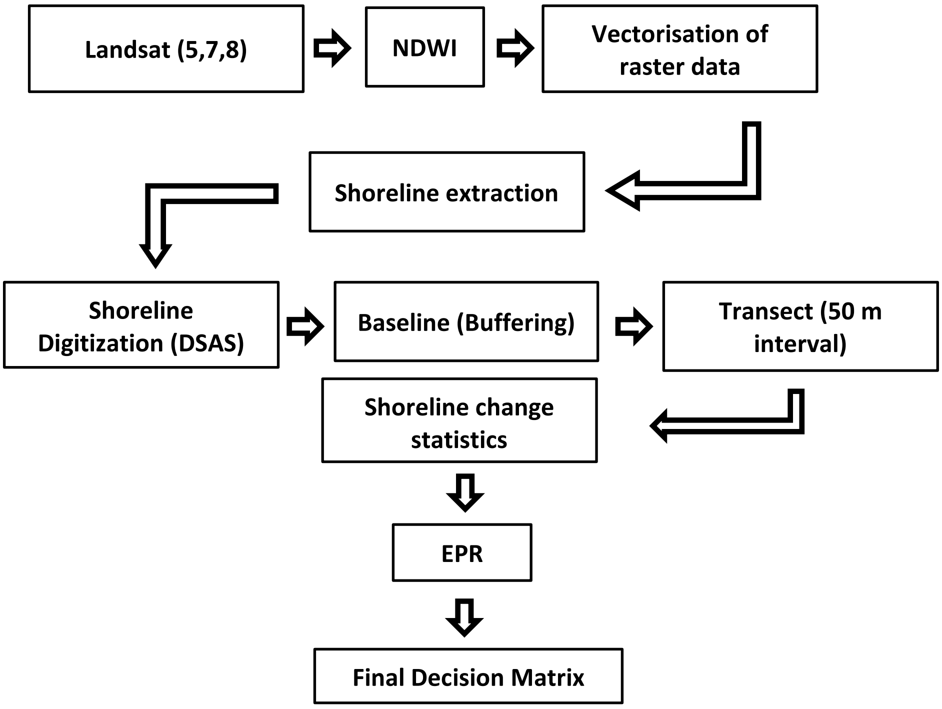

Figure 7: Shoreline detection and analysis process.

➔Segregation of water and non-water feature using a spectral index

NDWI, as defined mathematically in Table 2, was used to determine the water and non-water features. NDWI value ranges from −1 to +1. The NDWI image typically provides positive results for water features and negative for non-water features (McFEETERS, 1996). Only water and non-water features are required to delineate the separation line as a shoreline, and therefore a binary image classification, i.e., 0 and 1, was performed for depicting non-water and water features (Ji et al., 2009).

➔Post-processing of binary raster image

A 3 × 3 mode filter was applied for the post-processing operation that substituted the isolated pixels to the most common neighboring class (either water class or non-water class) to decompose the scattered and isolated pixels (Bartuś, 2014). The jagged boundaries of the water and non-water classes were smoothened by using QGIS clean tool. The shoreline vector was then produced using a raster binary image, and the abutting line of water and non-water class was traced to extract the final shoreline.

➔Shoreline generation

After that, the different time periods shoreline data was fed to the DSAS for further computation of shoreline change for 30 years from 1990 to 2020. In the DSAS tool, shorelines positions are compiled with five attribute fields which include Object ID (a unique number assigned to each), shape (polygon), date (original survey year), and shape length, and uncertainty values. Shorelines of different years were merged as a single feature, which creates a single shapefile of the multiple shorelines. The baseline was generated for calculating the shoreline change by closely digitizing the direction and shape of the outer shoreline. From this process, the rates of shoreline change were generated.

➔Shoreline change statistics

The calculation of the shoreline change was done in the form of End point Rate (EPR). The final decision matrix was prepared on the basis of the results and output. EPR formula (equation 1) was used to present the computational results. The DSAS tool itself chooses the shoreline transects, gives them dependent and independent variables, and automatically calculates (EPR) the rates of erosion and deposition. The accuracy level would be as high as when more years satellite data set has been incorporated (Sekovski et al. 2014). For example, 4 years of satellite images were chosen for the shoreline change analysis. A ± 5 m uncertainty and 95% confidence interval were set as default parameter to calculate the statistics.

$$\mathbf{EPR} = \frac{\textbf{Distance in metres (m)}}{\textbf{time between oldest and most recent shoreline(Year)}} \quad \textbf{Eq. (1)}$$

The EPR values can either be positive or negative, where a positive value represents seaward or offshore movement, and a negative value represents landward movement.

3.4. Remote sensing of the vegetation dynamic

3.4.1. Image classification features

Due to the long record of continuous observation and high spatial resolution, the Landsat series of satellite images are one of the most useful data for biodiversity assessment (Hackman et al., 2017) and widely used in wetland change assessments (Ajaj et al., 2017; Ceesay et al., 2017). The Tier 1 surface reflectance images from the Landsat series of satellites available in GEE were used because surface reflectance gives the most accurate information about the surface characteristics. In addition, three spectral indices (NDWI, NDVI, and NDBI) obtained from the Landsat 5, 7, and 8 surface reflectance images (see Table 2) were used as features. Because the study area is a wetland, the 30m spatial resolution digital elevation model (DEM) from the NASA Shuttle Radar Topography Mission (SRTM) was added to the feature space to distinguish mangrove from other vegetation. Thus, in all the feature space was a 10-band image stack made up of six surface reflectance bands (Blue, Green, Red, Near infrared, SWIR-1, and SWIR-2), three spectral indices, and the DEM.

3.4.2. Image pre-processing

Prior to their ingestion in GEE, the surface reflectance images from the three Landsat sensors were atmospherically corrected using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) or the Land Surface Reflectance Code (LaSRC). Also, the visible bands were bands processed to orthorectified surface reflectance. The bands from Landsat 8 were renamed to match those in Landsat 5 and 7. It was impossible to get cloud-free Landsat images for the study area. As a result, the clouds in all available images were masked. Finally, for each year, the complete collection of images from the Landsat sensors was merged using the median filter. In this way, clean Landsat composites were obtained for each year from 2000 to 2020 for use as inputs to the image classification work.

3.4.3. Training and testing sample collection

Training and testing samples were manually collected using the high-resolution orthophotos on Google Earth (GE). The sample collection protocol was used as the following:

- Generate simple random points within the study area.
- Visually inspect the land use at all points with at least 30m radius homogeneous neighborhood, and accept/reject based on local knowledge.
- Split samples into training and testing sets.

3.4.4. Image classification

A supervised classifier (Random Forest) was used for the land-cover classification on a pixel-by-pixel basis. Apart from its availability in Google Earth Engine, this classifier was selected because they are widely used in land-cover classification (Jia et al., 2014; Yu et al., 2013). The classification workflow is provided in Figure 8 below.

In order to make the map of the land-cover classification of the Grand Saloum the classified maps have been exported from GEE to ArcGIS 10.4. Four (4) classes have been taken into accounts such as mangrove, other vegetation, built and bare sand, and water.

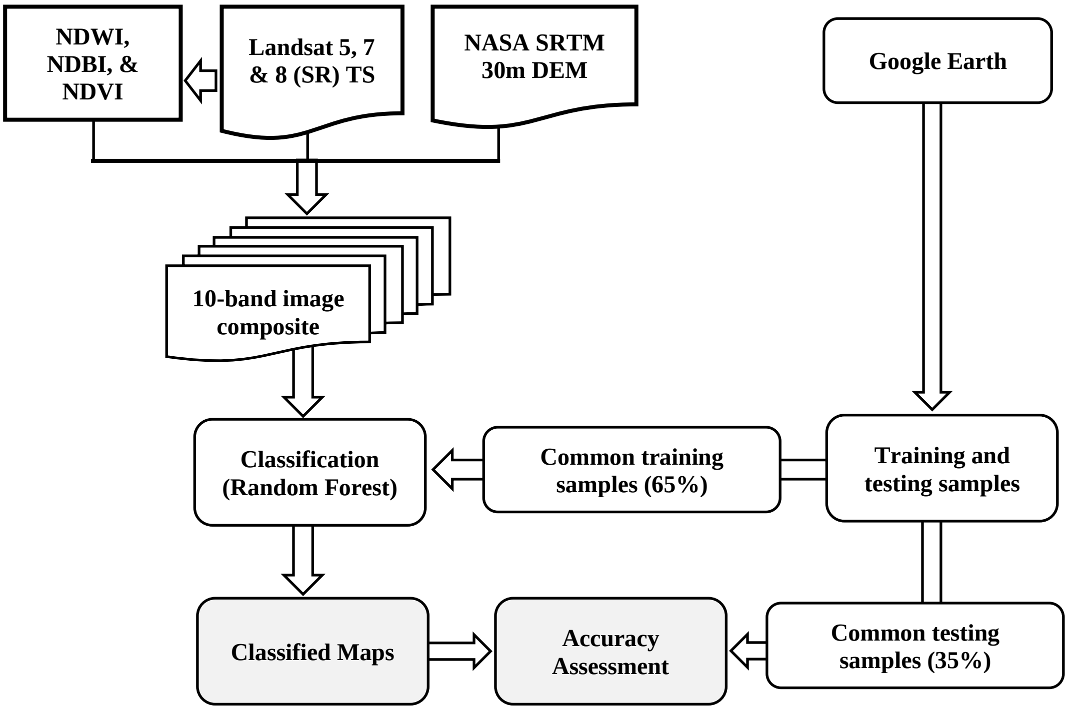

Figure 8: Landsat image classification process.

To access the vegetation close to the shoreline, a buffer has been manually created for a distance of 1km from the shoreline (see appendix 11). Zooming of the classified map along the shoreline has been done to detect areas of great change.

3.4.5. Accuracy assessment

The accuracy was tested using an independent set of samples that were randomly selected from the training and testing samples and computed the confusion matrix for each classified map. The classification procedure was done in Google Earth Engine while testing procedure were carried out in ArcGIS 10.4. For accuracy, 65% of sampling points were used for training and 35% for testing. The accuracy was calculated using the following formula:

$$\textbf{Accuracy}\ (\%) = \frac{\textbf{Total True Value Pixels}}{\textbf{Total Sample Value Samples}}\ \textbf{x 100} \quad \textbf{Eq(2)}$$

3.5. Survey

For this study, four (4) main localities were selected, three (3) on the Saloum side and one (1) on the Niumi side. These villages comprise Djifere, Dionewar, and Djinack Bara in the Saloum and Jinack Kadiata in the Niumi. These localities were selected because of their proximity to the coastline, exposure, and vulnerability, according to the literature review. A semi-structured questionnaire was used according to the method of Bernard (1988). The semi-structured interview guide provides a clear set of instructions for interviewers and can provide reliable, comparable qualitative data. The questionnaire was formulated and administered (Fig.9) to cover three main thematic areas, taking into account the objectives of the study. The thematic areas were:

- The profile of respondents (ratio men women, age, occupation, education level, etc.).
- The local people's perceptions of the coastal climate phenomena and their impacts.
- The adaptation strategies adopted by local communities.

Figure 9: Interview with women working in the fishery sector in Dionewar.

3.5.1. Digitization of survey instrument

Based on the prepared questionnaire, as shown in appendix 10, a digital field data collection form was designed and subsequently deployed on the tablets using the well-tested Open Data Kit (ODK) (Open Data Kit, 2021) methodology. The choice of the ODK is based on its capability to collect and aggregate spatial (or location-based) data and their attributes, including unique IDs, labels, date and time stamps, photos, audio and video recordings, and notes. We implemented the following workflow (Fig.10**)**, which is typical of the ODK data collection framework:

1. Design the digital data collection form based on the proposal questionnaire.
2. Upload the empty digital form on a data aggregate server.
3. Download the empty digital forms on the tablets with the ODK Collect module installed.
4. Collect the field data, even if the tablets are offline (not connected to the internet).
5. Submit the collected data to the Google Drive (when the internet is available) or extract the data directly from the tablets onto hard disks via the ODK Briefcase.

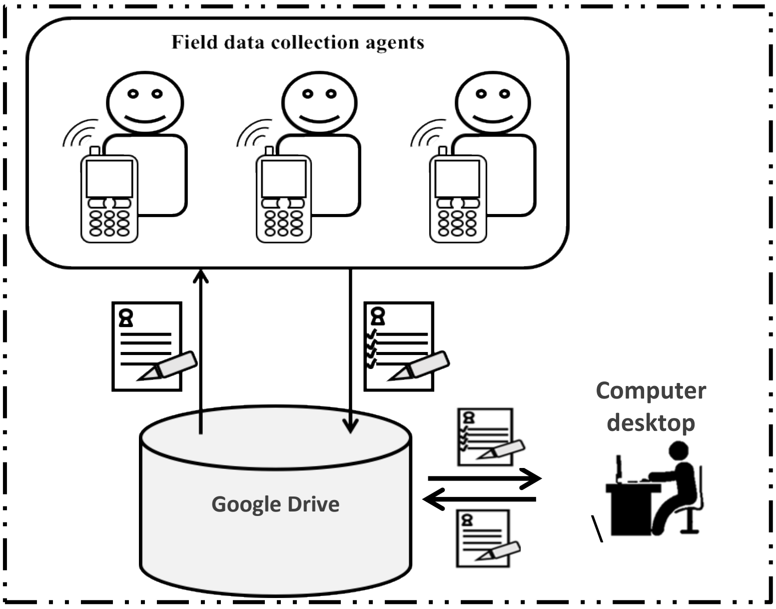

Figure 10: The standardized field data collection workflow.

3.5.2. Sample size and distribution

The simple random sampling approach was used in selecting respondents for the socio-ecological survey. In random sampling, all elements have an equal probability of being selected. Simple random sampling is useful when researchers are interested in associations that would apply to the whole population (sampling method). Based on the statistics of the 2003 population and Housing Census, the NNP area counts 87077 inhabitants. In the SNP 13146 inhabitants were given by the 1993 census. Using Yamane's (1967) formula;

$$\boldsymbol{n} = \frac{\textbf{Population size}}{\textbf{1+Population size}(\textbf{10\%e})^2} \quad \textbf{Eq (3)}$$

Where, n = sample size, N = population size and, e = level of precision or sampling error: ± 10%.

The population size from the Niumi and Saloum census did not provide the particular population size of the vulnerable villages living near the shore. The population size used in this study, covering out of our zone of interest, is for the whole Grand Saloum region. There is a chance that the sample obtained could not represent the true population value. This risk is reduced for a lower confidence level (Israel, 2003). In this case, the sampling error used was 10%. The result obtained as a sample size for analysis was one hundred (100) for the whole Grand Saloum, meaning 25 in each locality. In each locality, we extended the number to 50 respondents.

3.5.3. Survey analysis

The analysis of the social survey was based on descriptive statistical methods. The analyses were done using the Statistical Package for Social Sciences (SPSS) version 23 software. The graphs were performed in Excel. Multiple Correspondence Analysis (MCA) was used to determine significant differences between our sample groups based on the link between the dependent and independent variables.

4. Results

4.1. General observation in the shoreline changes

The studied segment includes the Djiffer coast (Sector E) and goes as far as Dionewar (Sector D), Niodior (Sector C), Bettenty (Sector B), and Djinack Bara and Jinack Kajata Island northern coast of the Gambia (Sector A). Between 1990 and 2020, erosion and accretion occurred in some places and the ecosystem is highly dominated by erosion (see appendix 9). Figure 11 highlights five main sections highly dynamic. Sector A and E show Moderate to High erosion and accretion. The sector B, C, and D are characterised by moderate to high erosion at some points. For this purpose, an annual average erosion rate of 2.44 m is observed and an average accretion rate of 1.84 m.

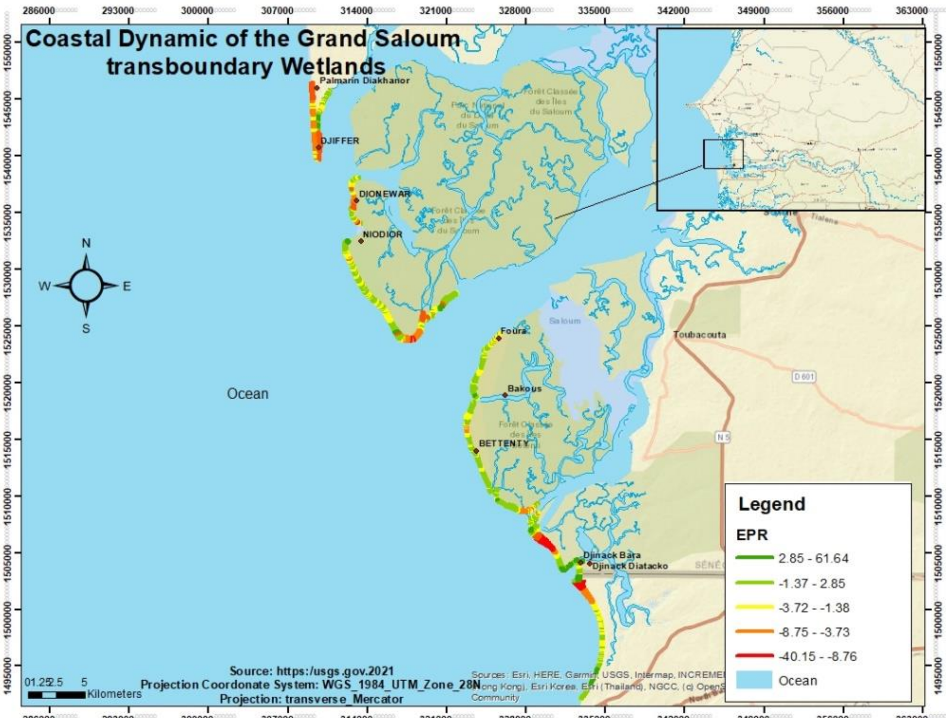

Figure 11: Point of erosion (Red) and accretion (Dark Green) along the Grand Saloum Shoreline.

4.2. Sectorial Analysis

Table 3 shows information related to the rate of change in the shoreline occurring in each section. Sections A and E showed a balance erosion of 4.13 ±0.47 and 1.62 ±0.47 respectively and accretion of 2.82 ±0.47 for both sections. Sections C and D are characterised by High rate of erosion with an average of 2.39 ±0.47 and 2.63 ±0.47, respectively. The average accretion for sections C and D range between 1.45 ±0.47 and 1.018 ±0.47, respectively. Section B doesn't show so much dynamic with an average erosion and accretion of 1.41 ±0.47 and 1.12 ±0.47.

Table 3: Parameters of shoreline dynamics calculated in each transect.

Region	A	B	C	D	E
Transect	1-481	482-914	915- 1276	1277 - 1391	1392 - 1490
Number of transect	481	433	362	114	98
Average Accretion (m/yr)	2.82 ±0.47	1.12 ±0.47	1.45 ±0.47	1.02 ±0.47	2.82 ±0.47
Average Erosion (m/yr)	-4.13 ±0.47	-1.41 ±0.47	-2.39 ±0.47	-2.63 ±0.47	-1.62 ±0.47
Max. accretion (m/yr) (transect)	14.52 ±0.47	2.7 ±0.47	2.8 ±0.47	2 ±0.47	4.98 ±0.47
Max. erosion (m/yr) (transect)	-47.28 ±0.47	-4.53 ±0.47	-12.02 ±0.47	-9.09 ±0.47	-4.02 ±0.47

4.3. Vegetation dynamic

4.3.1. Analysis of the changes in the whole transboundary wetlands

Figures 12 show that from 2000 to 2020 the whole Grand Saloum wetlands experienced an increase in mangrove vegetation and a decrease in the other vegetation. The figures show estimated mangrove coverages of 57867.61 ha and 66840.17 ha in 2000 and 2020 respectively. The coverage of the other vegetation has reduced from 2000 to 2020 with an estimated coverage of 23483.18 ha to 16146.11 ha respectively. The accuracies of the classification vary between 97.51 % and 99.37 % (appendix 8).

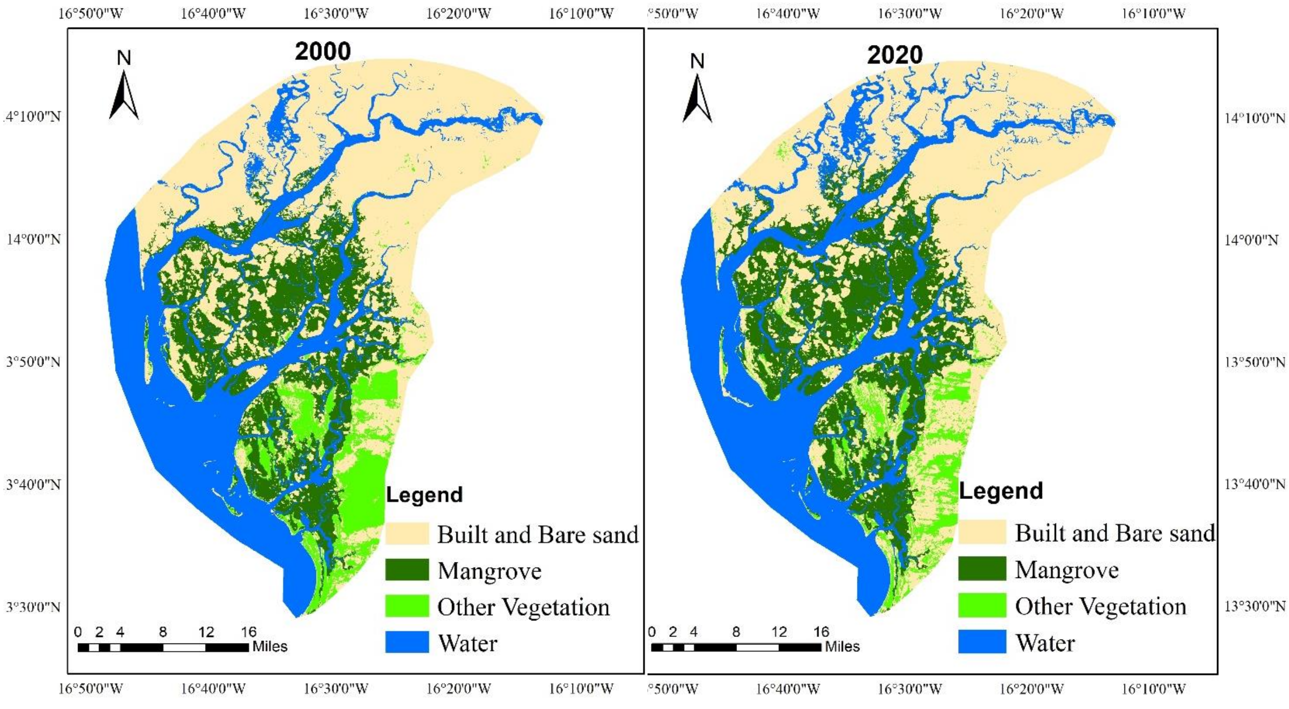

Figure 12: Map of the mangrove and other vegetation for 2000 and 2020.

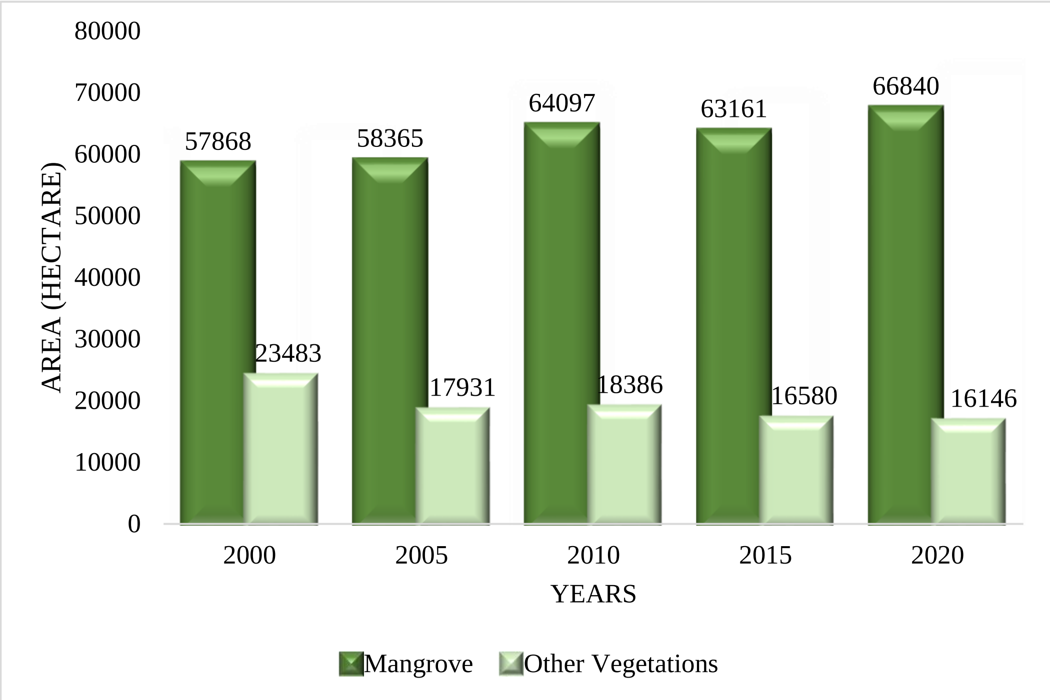

Figure 13: Vegetation dynamics of the Grand Saloum.

The resulting map (Figure 15) from the change detection analysis shows an increase of mangrove northward and a decrease of the other vegetation southward.

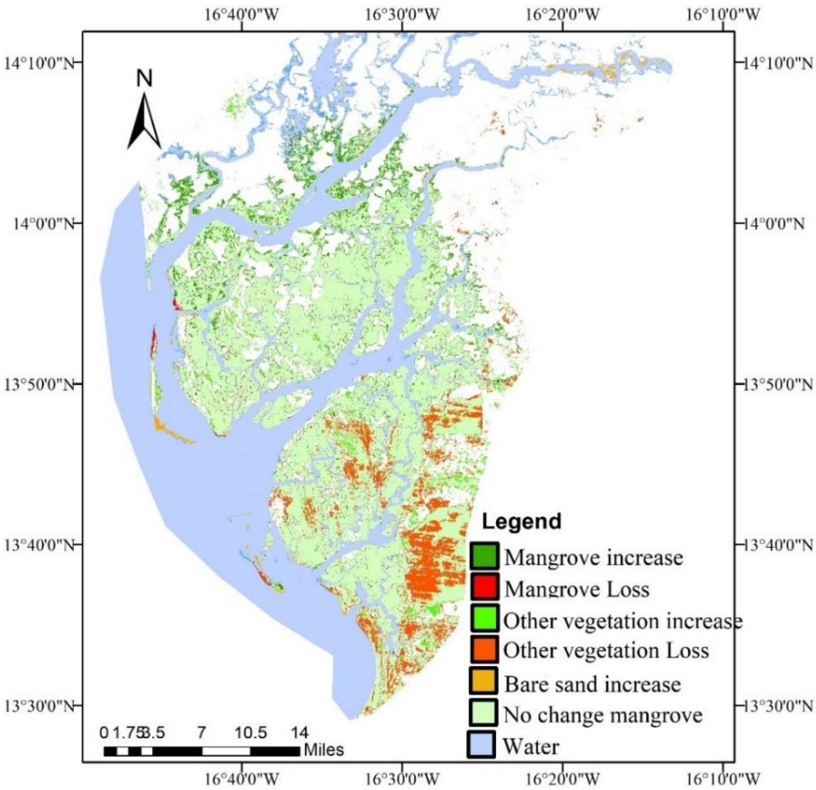

Figure 14: Change detection analysis of the vegetation from 2000 to 2020.

4.3.2. Analysis of the changes in vegetation close to the shoreline

Figure 15 shows the estimated coastal vegetation close to the shoreline. The result shows a decrease in the mangrove area from 16.43% in 2000 to 15.17% in 2005. The mangrove area increased slightly from 16.37% in 2010 to 16.81% in 2020. Regarding the other vegetation cover, a decrease was noticed from 9.52% in 2000 to 6.52% in 2005. From 2005 the other vegetation cover evolved with slightly increasing and decreasing phases.

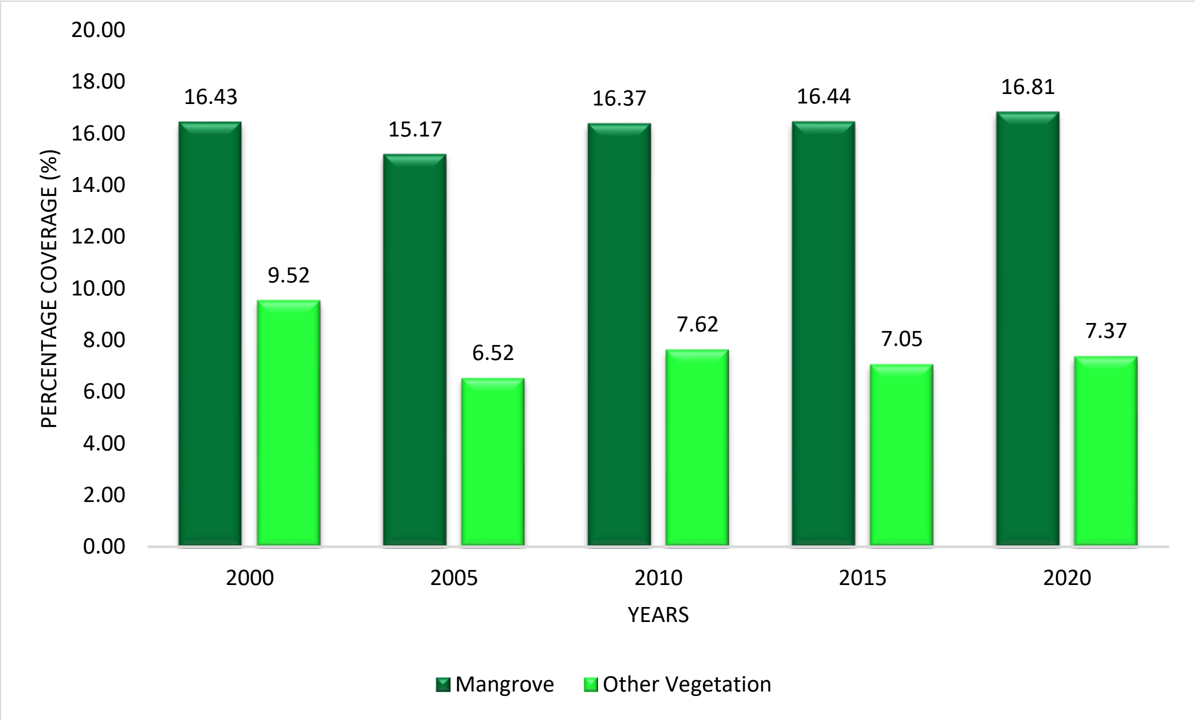

Figure 15: Dynamic of mangrove and other vegetation close to the shoreline from 2000 to 2020.

4.3.3. Change detection

The conversion matrix (Table 4) of the Land-Use Land Cover shows that 3.07% of the mangrove coverage has changed to bare sand area and 3.44% eroded by the water. For the other vegetation, the conversion has been dominated by bare sand with 37.49%. 11.64% of the Built and bare sand has been eroded by water.

The change detection map shows some major changes on both mangrove and other vegetation (Figure 16). In the map, the loss of mangrove is mainly pronounced in sections A and B. Section D is mostly dominated by the loss of the other vegetation.

Table 4: Transition matrix between 2000 and 2020 (In percent).

LULC (%)		Initial year			
		Mangrove	Other vegetation	Built and bare sand	Water
	Mangrove	92.62	2.42	6.06	0.46
	Other vegetation	0.86	58.62	8.86	0.03
	Built and bare sand	**3.07**	**37.49**	73.44	1.89
	Water	**3.44**	1.46	**11.64**	97.61

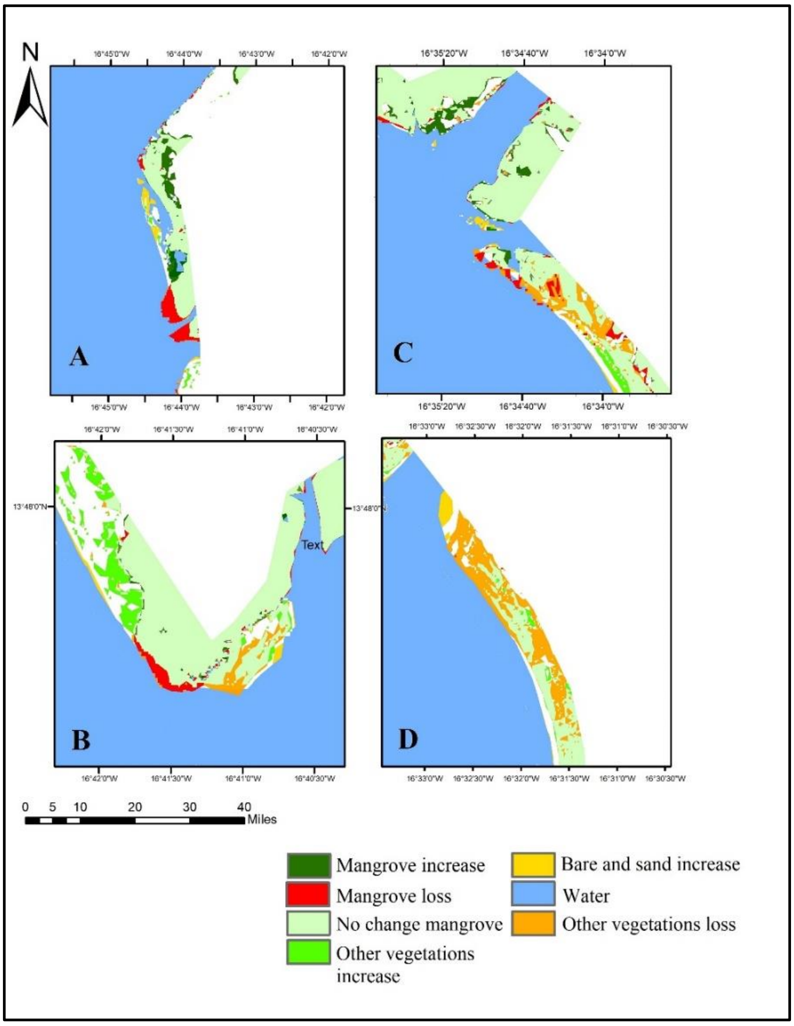

Figure 16: Areas of major change from 2000 to 2020.

4.4. Survey

4.4.1. Local perception

This result shows that 9% of respondents have noticed erosion in each village. Accretion was reported by respondents in Djiffer and Djinack Bara with 9% in each village. Floods are reportedly observed in the Dionewar and Djiffer areas with 9% and 6%, respectively. 9% of respondents from Djinack Bara and Jinak Kajata reported hypersalinity, as shown in figure 17.

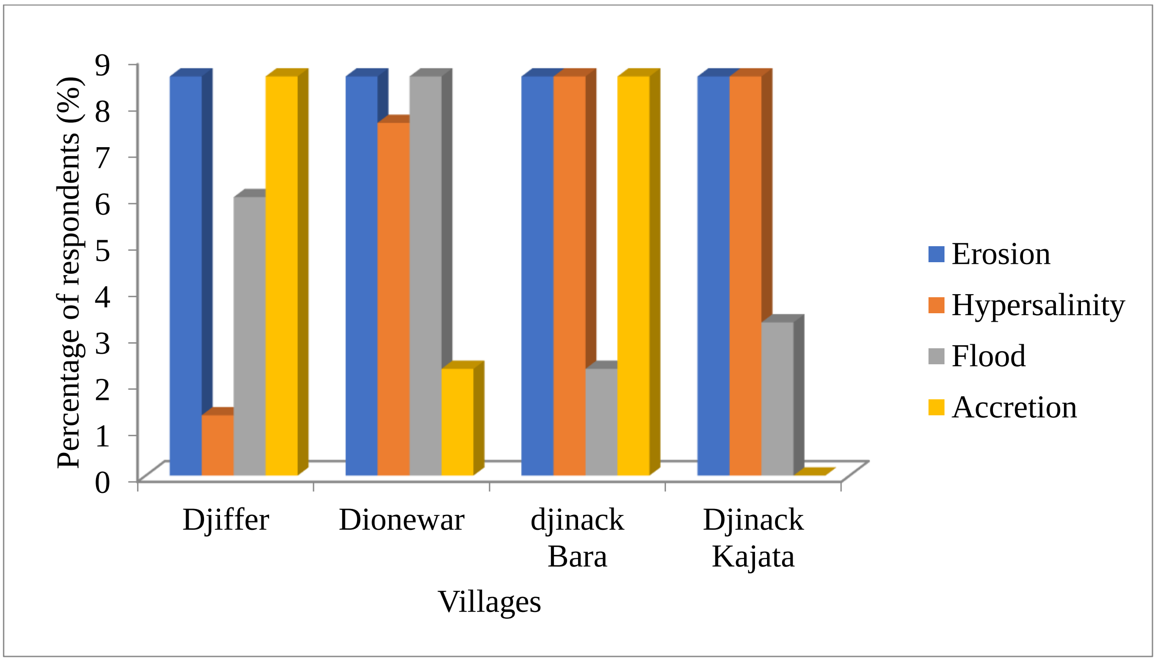

Figure 17: Respondent perceptions on the coastal climate phenomenon.

4.4.2. Impact on the communities

Erosion Impacts

Among the 200 respondents, 45% did not see any impact on their livelihood. 18% of the respondents reported a loss of habitat and coastal vegetation removal (Fig.18). The result shows that 12% from Djiffer said a habitat loss, followed by Dionewar with 5%. 9% of respondents from Dionewar reported an increase in work difficulty in their livelihood activities. 11% from Dionewar reported a vegetation removal. 9% of the respondents from Dionewar reported limited access.

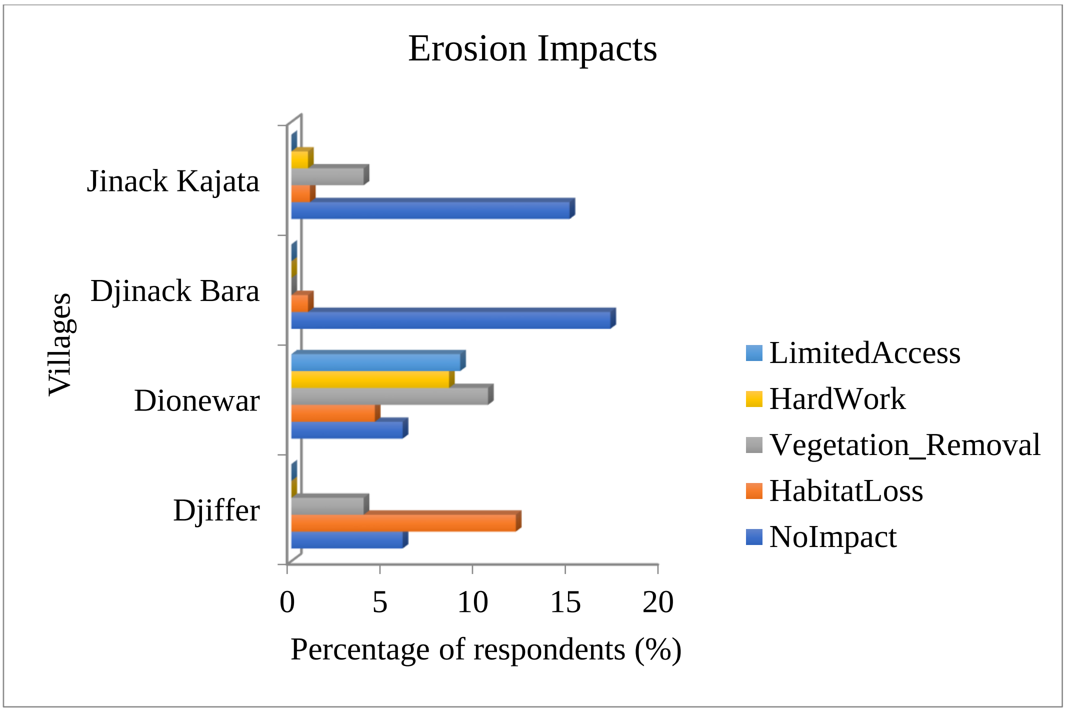

Figure 18: Percentage of respondents impacted by shoreline erosion.

Accretion Impacts

Figure 19 shows that limited access and increase in work difficulty were mainly impacts of accretion. 27% of the respondents from Djinack Bara reported limited access to the resources and 6% said an increase in work difficulty.

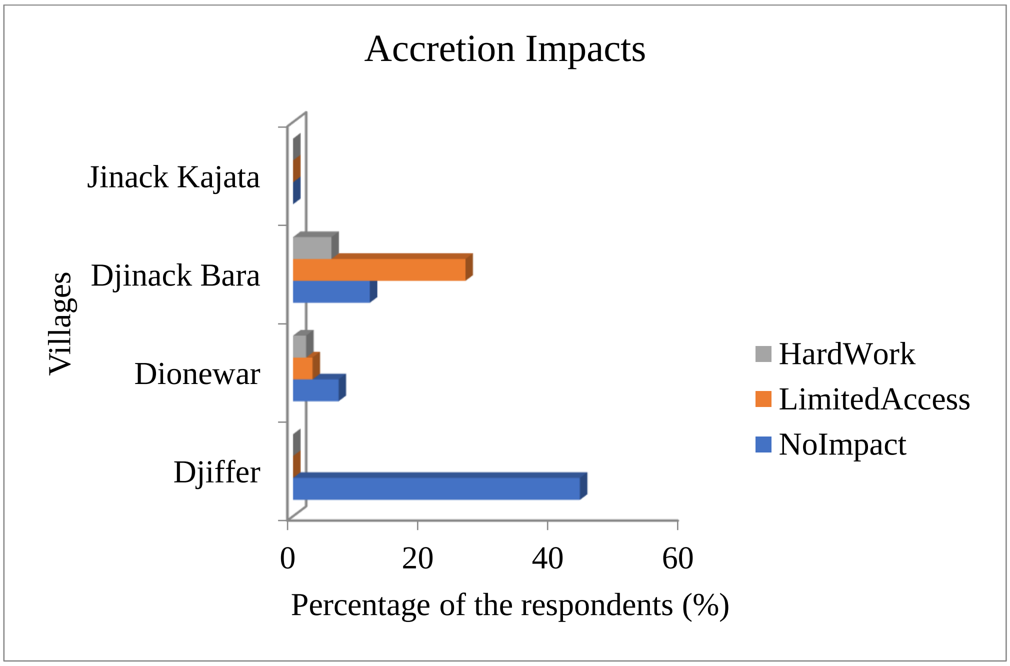

Figure 19: Percentage of respondents impacted by shoreline accretion.

Flood Impacts

Figure 20 shows that 16% of respondents from Dionewar village reported land degradation, 14% said a habitat loss, and 9% reported an increase in work difficulty. 12% of respondents from Djiffer reported a habitat loss.

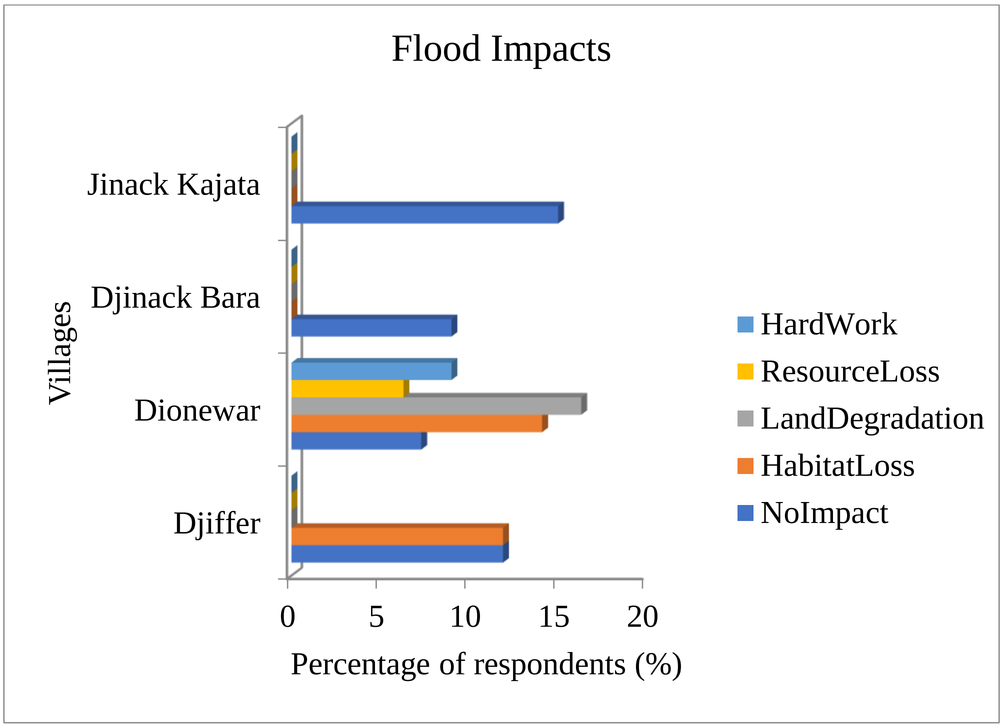

Figure 20: Percentage of respondents impacted by flood.

Hypersalinity impacts

Figure 21 shows that Land degradation has been mainly reported by respondents. 23%, 20%, and 11%, respectively, from Jinack Kajata, Djinack Bara, and Dionewar reported land degradation. 11% and 4% of the respondents respectively from Djinack Bara and Jinack Kajata reported the loss of ecosystem resources.

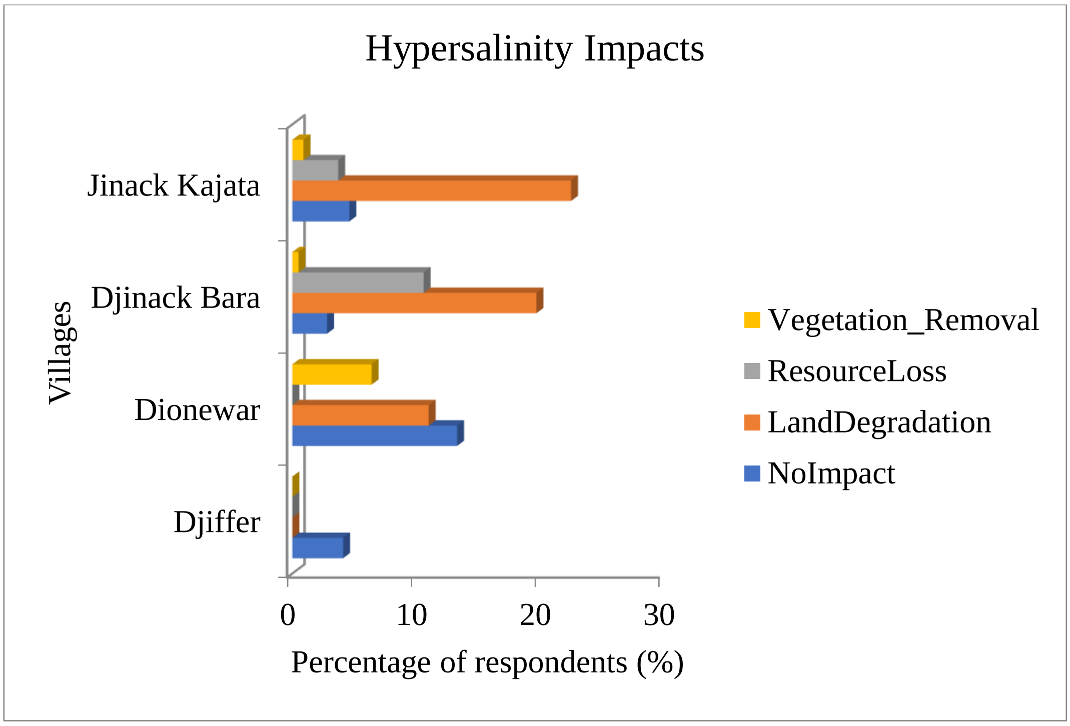

Figure 21: Percentage of respondents impacted by hypersalinity.

4.4.3. Adaptation strategies

Factorial Correspondence Analysis (FCA) (Fig.22) applied to the matrix (village, main activities, and adaptation strategies) reveals the following results: F1 and F2 provide 22.93% and 14.15% of the information respectively. On axis1, this plot shows that in the Dionewar locality, respondents mostly use migration for fishing as an adaptation measure. By contrast, in the Djiffer and Djinack Bara localities, the personal adaptations were mainly full relocation housing and partial retreat, respectively. Only the homeowners' category has settled dikes as a personal adaptation strategy in Djiffer locality. The main community adaptation measures are mangrove reforestation, tree planting, and dike rehabilitation. Capacity building was mentioned as an additional strategy for respondents whose work is collecting bivalves. Regarding the type of shore, two (2) categories of community adaptation measures are identified. In the Dionewar locality with both sandy and muddy shores, we have mangrove reforestation, different from the three other localities with a sandy shore.

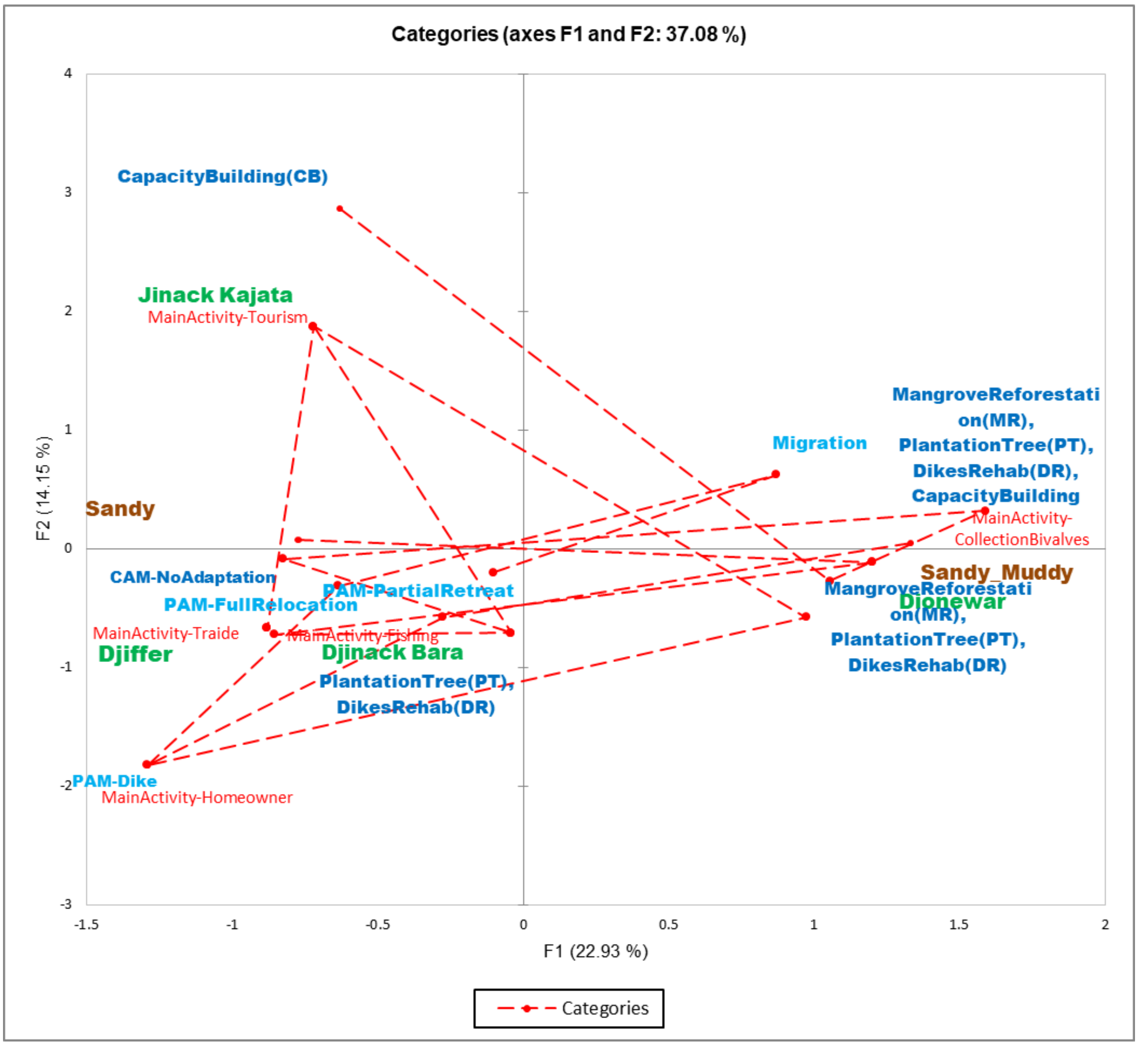

Figure 22: Factorial Correspondence Analysis of the relationship between locality, type of shore, activities, and adaptations measures in Grand Saloum.

5. Discussion

5.1. Shoreline dynamic

Our results show an annual average erosion rate of 2.44 m and an average accretion rate of 1.84 m. This rate of erosion is somewhat closer to the one reported by Diadhiou (2010) with an average rate of erosion of 2.60 m/yr in Palmarin between 1954–2018. By contrast, the rate of erosion is different from Sy, 2007, (as cited in Diadhiou et al., 2016) with 0.09 m/yr and from Diadhiou et al. (2016) with 0.82 m/yr. In the St-Louis region, Faye (2010) found an average rate of erosion of 1,70 m/yr. Exceptional erosion values up to 97–137 m/yr were reported for the langue de Barbarie and Sangomar Point, caused by specific coastal phenomena (Enríquez-de-Salamanca, 2020). The Saloum Delta coast is particularly sensitive to climatic hazards and natural phenomena such as erosion. A major extreme event permanently disrupted this ecosystem in 1987. The breach thus caused by this storm has widened over time and now exposes the villages of the islands to the ocean and, in particular, to the phenomenon of erosion (Bah et al., 2019).

The sectoral analysis has shown an average erosion of 2.82 m/yr in section E. This result is different from Bah et al.(2019)'s value which is 3.43 m/yr. Diadhiou et al.(2016) calculated an average rate of 3.83 m/yr along the Palmarin-Djiffer shore. This difference may be due to the time intervals chosen and the methodology used. No past study highlighted the rate of the shoreline change for sections D, C, B, and A. Nevertheless, our result, showing the dominance of erosion in this region, is conformed to the trend of erosion observed in some sections. Studies conducted in sections C, D, and E estimated a total eroded surface of 3,111,131.88 m^2, together with an accretion surface of 2,286,958.36 m^2. The sediment balance was, therefore, negative, with a deficit of 824 173.52 m^2 in 33 years (Bah et al., 2019). In section A, our results have shown a tendency toward accretion. According to the PWM (2020), Jinack island and the mosaic of islands to the north are essentially shifting shoals of sand, resulting in accretion. Much of this accretion is the result of erosion further south. Anecdotal information stated that the beach in front of Madiyana Camp (Jinack shoreline) had been eroded more than 15m in the past years.

5.2. Vegetation dynamic

The mangroves of the Grand Saloum experienced spatial expansion between 2000 and 2020. Previous findings have confirmed this result (Andrieu et al., 2020; Fent et al., 2019; Lombard, 2021; Sakho et al., 2011). Finding in other wetlands ecosystem over the Gambia, like the

TWNP, has shown a decrease from 1973 to 2012. This decrease is due to the long-term hyper-salinity that cause the lack of mangrove rejuvenation (Ceesay et al., 2017).

The other vegetation experienced loss from 2000 to 2020. Some vegetation cover such as lowland rice fields are exposed to salt intrusion (Dia, 2012). Salt intrusion into potential rice-growing zones is also very active in the Grand Saloum which is impacting the livelihoods of the local communities (WOW, 2015). The spatial distribution of forested wetland loss appears more consistent with saltwater intrusion (Bhattachan et al., 2018).

The results of the vegetation dynamics show that even if, globally, mangrove areas have continuously increased from 2000 to 2020, some parts close to the shoreline are experiencing loss. The Grand Saloum AWP (2020) reported that there are pockets of regression in places such as the coastal fringe exposed to erosion. The main driving forces contributing to the regression of mangrove cover are the rainfall deficit, water salinity, land acidification, coastal erosion, and unsustainable mangrove resource exploitation practices (ADG, 2012).

5.3. Observed Coastal hazards

Our survey has shown that the main climate phenomena identified by local communities were erosion, accretion, flood, and hypersalinity. A previous study, SMFMP (2020), found that the major impacts of climate change in the Grand Saloum were the sea-level rise and accelerated coastal erosion due to the rupture of the Sangomar spit and its impact (reinforcement of the evolutionary process of the landscapes of the Saloum estuary, uprooting of the frontal mangrove, increase in salinity, silting of adjacent mudflats, flooding, etc.).

Coastal erosion is also a natural phenomenon that has a negative impact on mangroves. Indeed, the rupture of the Sangomar spit has led to the degradation or even disappearance of the mangrove that is opposite the new breach because of the strong sea currents and waves that badly hit this part of the estuary. The strong swells noted in recent years, which are a consequence of climate change, often hinder the development of small seedlings, frustrating the reforestation efforts initiated by the populations (SMFMP, 2020).

Our results have shown land degradation as a consequence of hypersalinity. The assessment of the balance sheet of exchanged water flows highlights several characteristics of the system. The results show that recharge and saline intrusion from the Saloum river and the sea constitute the main water supplies (Dieng, 2017). This saline intrusion of seawater leads to the salinization of arable land in coastal areas (Saloum Delta)(ANSD, 2010).

Changing conditions, and especially the increasing salinity, also affect mangroves and certain fish species. In Djirnda, the octopus (*Octopus vulgaris*), a species present during the rainy season, is believed to have disappeared along with the mangrove, which is its breeding ground (Bah et al., 2019).

5.4. Adaptation strategies

Climate-induced relocation and managed retreat are considered as part of the adaptation planning process in many coastal areas. Managed realignment or managed retreat is a coastal management strategy that consists of controlling flooding in the low-lying coastal areas and the abandonment or relocation of assets and people allowing the shoreline to move inland instead of trying to maintain it (Gracia et al., 2018).

Where mangroves occur, they generally reduce erosion and increase sedimentation. The mangroves lower wave energy and slow the flow of water over the soil surface. Therefore, mangroves reduce the water's capacity to dislodge sediments and carry them out of the mangrove area. Slower water flows can allow already suspended sediments to settle out from the water, resulting in increased deposition of sediments (Spalding et al., 2014).

Increasingly, habitat restoration is acknowledged as a critical step in climate adaptation. Healthier habitats are likely to be resilient in the face of frequent disturbances and in the instance of coastal habitats. Healthy habitats with intact coastal processes are more likely to keep pace with sea-level rise and persist long enough to migrate landward. These modified restoration approaches might include breaching of levees to increase sediment deposition or supplementing sediment from elsewhere (Atkinson et al., 2001). Mangrove restoration/rehabilitation reduces wave energy, erosion, and storm surge water levels, thus limiting coastal flooding, saline intrusion into groundwater and farmlands, and damage to property and livelihoods (Ilieva et al., 2020).

6. Conclusions

Sea level rise, one of the consequences of climate change, causes several problems in the coastal ecosystem. Climate phenomena such as erosion, flood, and increased salinity are key problems in coastal wetland areas, particularly in West Africa. Results of different studies conducted in Grand Saloum and of our research show that coastal erosion is accelerating, especially in recent years. In the Grand Saloum, it has increased at an annual average erosion rate of 2.44 m and average accretion of 1.84 m. The mangrove and other vegetation in the wetland have increased between 2000 and 2020 but the vegetation close to the shoreline experiences a loss at some points and did not show a significant increase. Our findings reveal that climate phenomena (erosion, accretion, flood, hypersalinity) have caused damage to habitats, loss of land, damage to mangroves and other vegetation, increased work difficulty, and loss of fishing resources. Adaptation measures found in this study were various and mainly related to the localities, type of shore and the main activities.

Limitations to this study included time constraints and limited budget. Consequently, we could not traverse all the shorelines to verify the point of erosion/accretion. There was also a lack of oceanographical data (wave, tide, sea-level) of the coastal region to use for the shoreline analysis and its relation in the vegetation dynamics.

7. Recommendations

All these identified impacts affect particularly the wetland ecosystem closed to the shoreline, communities, and wetlands management. Knowing these issues addressed in the Grand Saloum, this section might be able to figure out the sustainability measures and mitigation in the form of recommendations. This will profit stakeholders and the community members on the necessary measures and policies needed to combat the impacts of climate phenomena in the coastal zone. The study, therefore, presents the following mitigation and adaptation measures:

- Climate change impact awareness creation and environmental education:

Although the effects of climate change on the coastal and marine ecosystem can be expected and understood by scientists and academics, a large part of the local communities has no access to this information. In this context, Environmental Education (EE) would be a solution by accomplishing a transformative and critical approach to amplify awareness efforts and enhance civil-society action. From this awareness, attitudes, and values that could capacitate a surpassing transformation of this same reality are possible. In such a way, this action will be an alert for all stakeholders on their role in guiding this emergent challenge. It is obvious that Environmental Education focusing on the politicians, media, and even scientists themselves will be a way to clarify the importance of each group in overall public perception.

- Buffering of the shoreline zones

Conservation buffers are pockets or strips of permanent vegetation planted in and around the shoreline zone. This buffering can help solve environmental problems in the community. Since the shoreline is influenced by both oceanic processes and land, there is the need to create a buffer. Buffering is important in wetlands and can beautify the landscape, create habitat for fish and wildlife, and increase the value of the ecosystem.

- Ecosystem recovery approaches

In our findings, tree planting was part of the adaptation strategies. Ecosystem recovery approaches such as the growth of trees will help protect the shore and the beach area from erosion. Vegetation along the coast can protect especially the sandy beach from wave erosion and wind. There are some specific species that can be easily removed from wave action. There is a need to find particular species based on local knowledge that could adapt to the coast and prevent erosion.

- Enforcement of coastal management policies

Policies on coastal conservation measures should be enhanced. People who want to undertake projects along the coast and coastal developers should be issued permits. This will allow developers to follow the necessary guidelines and conservation practices.

- Intensive coastal zone research

Intensive and continued coastal zone research should be promoted, especially in the ocean dynamic, in order to have a better understanding of the resulting effect of the ocean forcing on the coast. Several coastal research centers should be established. Established research centers will help provide solutions to the problems facing the Grand Saloum, such as climate change and related impacts like erosion, sea-level change, and shoreline change.

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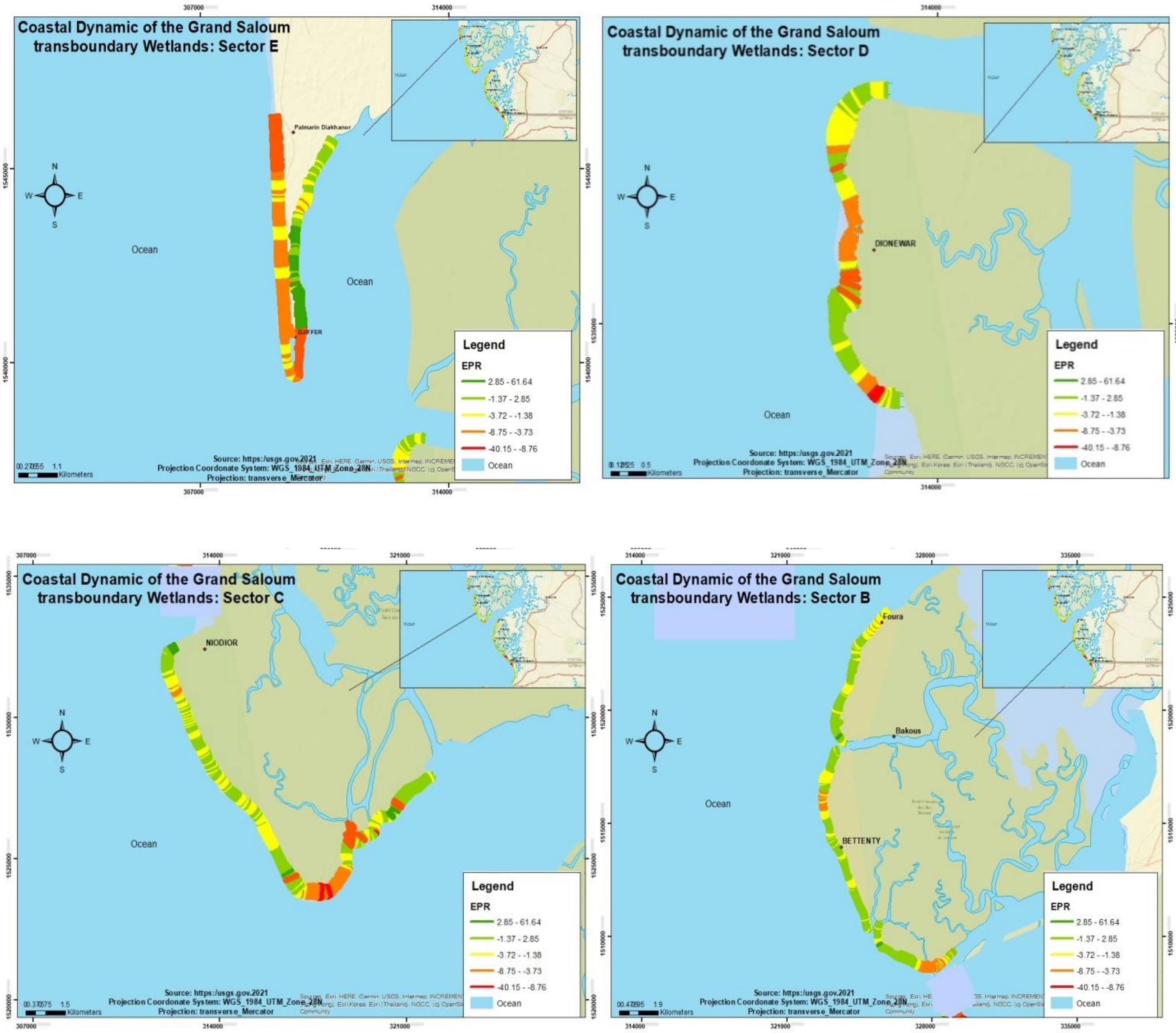
Appendix

Appendix 1: End Point Rate (EPR) showing accretion and erosion levels along the coast.

Appendix 2: Maps showing the points of erosion and accretion in each sector



Appendix 3: Habitat loss due to erosion in Djiffer (Sector A)

Appendix 4: Erosion of mangrove in the Nothern part of Niodior (Sector C)

Appendix 5: Erosion and vegetation removal in Dionewar (Sector D)

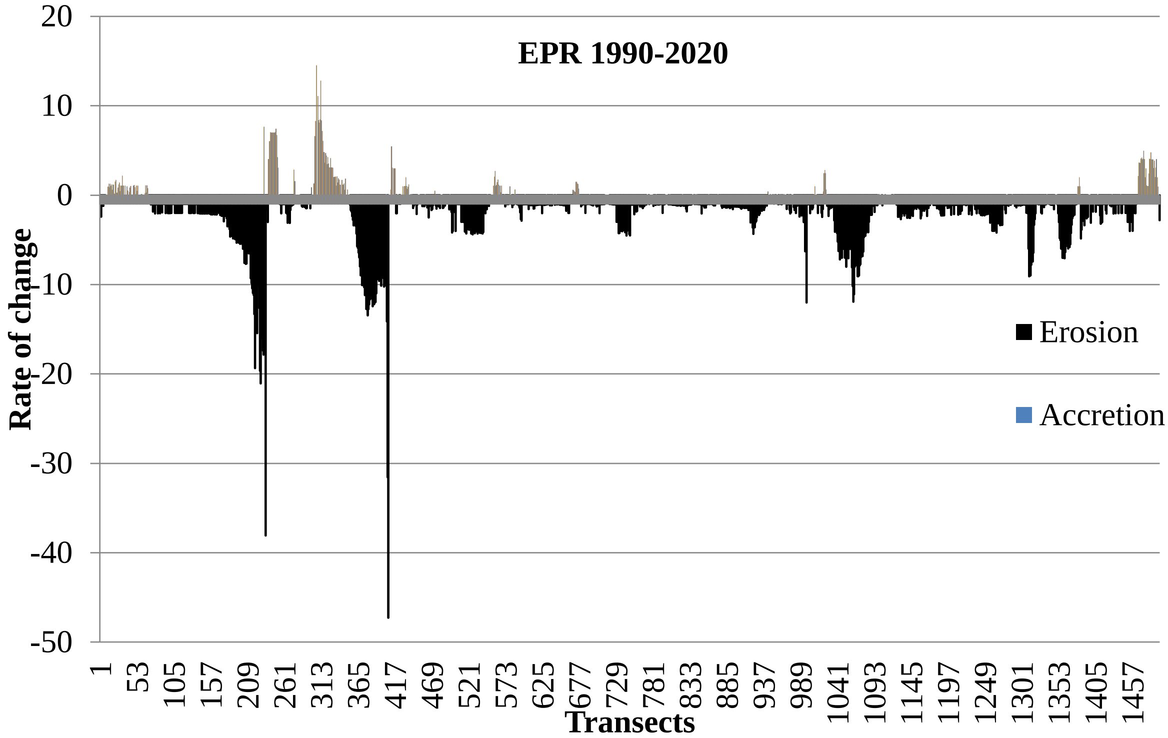
Appendix 6: Dike rehabilitation settles by a houseowner in Djiffer (Sector A)

Appendix 7: Lodge loss due to erosion in Jinack Kajata (Sector A)

Appendix 8: Accuracy Assessment of the classification images

LULC (%)	2000	2005	2010	2015	2020
Mangrove	18.95	19.11	20.99	20.68	21.89
Other Vegetation	7.69	5.87	6.02	5.43	5.29
Built and Sand bare	44.59	46.87	44.11	43.74	42.48
Water	28.77	28.15	28.89	30.15	30.35
Accuracy	**98.75**	**99.37**	**99.37**	**97.51**	**97.51**

Appendix 9: End Point Rate graph of 1990 – 2020



Appendix 10: Questionnaires for local communities

1-IDENTIFICATION
1-1- Name:
1-2- village:
1-3- Gender:
1-4- Age:
1-5- Educational level: Primary, Secondary, tertiary, not studied
1-6- Religion: Christian, Muslim, Animist, Other (Specify)

2-COASTAL LIVELIHOOD STRATEGIES AND DIVERSITY

In this section, we are looking at the different livelihoods activities developed by local communities and what is the degree of diversification.

2- 1- What is your main activity?
- *Agriculture*
- *Animal husbandry*
- *Fishing*
- *Logging*
- *Hunting*
- *Tourism*
- *Beekeeping*
- *Mining Activities*
- *Others (Specify)*

2- 2- Does it generate income? Yes, No
2- 3- In what space do you carry out this activity? :
- *In land,*

- *at coast/sea*
- *others*

2- 4- What are others activities (Selected by priority)?

- *Agriculture*
- *Animal husbandry*
- *Fishing*
- *Logging*
- *Hunting*
- *Tourism*
- *Beekeeping*
- *Mining Activities*
- *Others (Specify)*

3- Coastline and vulnerability

3-1 what phenomena have you noticed during the past few years?

- *Erosion*
- *Accretion*
- *Sea level anomaly*
- *Storm*
- *Increase Salinity*
- *Other*

3-2 How often were these phenomena?
Erosion: High – Medium – Low
Accretion: High – Medium – Low
Sea level anomaly: High – Medium – Low
Storm: High – Medium – Low
Increase Salinity: High – Medium – Low
Other: High – Medium – Low

3-3 How the phenomena observed affect your main activities?

- Erosion: *Ecosystem degradation – Hard work – loss of resources - Other*
- Accretion: *Ecosystem degradation – Hard work – loss of resources - Other*
- Sea level anomaly: *Ecosystem degradation – Hard work – loss of resources - Other*
- Increase Salinity: *Ecosystem degradation – Hard work – loss of resources - Other*
- Storm: *Ecosystem degradation – Hard work – loss of resources – Other*
- Other: *Ecosystem degradation – Hard work – loss of resources – Other*

4 – Adaptation strategies and level of intervention

4- 1 Have you taken adaptation measures by yourself? Yes, No
Which ones?
How successful could you rate each of the adaptation strategies given: (Low- Medium – High)
4- 2 - Have you taken adaptation measures by local communities? Yes, No
Which ones?

- Mangrove reforestation
- Development of aquaculture
- Enrichment plantations of species
- Rehabilitation of dikes
- Capacity building for the integration of climate change in municipal development planning
- Others (Specify)

How successful could you rate each of the adaptation strategies given: (Low- Medium – High)
4- 3 - Are partners (Government and NGO) helping you? Yes, No

Appendix 11: Extraction of the vegetation cover close to the shoreline