FACULTY OF HUMANITIES AND SOCIAL SCIENCES

DEPARTMENT OF GEOGRAPHY

West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL)

Doctorate Programme in Climate Change and Disaster Risks Management

Coastal erosion dynamics of Dakar, Senegal

Thesis Submitted in partial fulfillment of the requirements for the degree of **DOCTOR OF PHYLOSOPHY** in Climate Change and Disaster Risks Management

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August 04, 2023

Dedication

I dedicate this work to my lovely mother Aissatou SARR and my late father Bassirou POUYE, my wife Awa DIONE, my son Mohamad Ibn Ibrahima POUYE, my brothers Modou POUYE, Ousmane POUYE, Babacar POUYE and Omar POUYE, my sisters Yacine POUYE and Fatima POUYE.

Acknowledgements

It is with great pleasure and gratitude that we express our appreciation and thanks to all those who contributed to the completion of this thesis.

This work could not have been completed without the advice, suggestions and requirements of our thesis supervisors, Professor Pessièzoum ADJOUSSI, Professor Jacques André NDIONE, Professor Jan BLÖTHE, Dr Amadou SALL, to whom we express our gratitude and consideration.

We thank WASCAL and the Federal Ministry of Education and Research of Germany which sponsored this work, particularly WASCAL Lomé, namely Professor Komi AGBOKA, Professor Prosper BEGEDOU, Deputy Director, Dr. Idrissou our scientific coordinator, our wonderful office assistant Mrs. Séfako SEGBE and all the staff.

We thank all the professors of the University of Lomé, in particular those of the Department of Geography, for the efforts they make for better training of students. We thank the administration of the Centre des Œuvres Universitaire de Lomé (COUL).

We also thank the staff of the Centre de Suivi Ecologique (CSE) de Dakar.

We also thank all the staff of the Institute of Social Sciences of the Environment and Geography of the Albert-Ludwigs University of Freiburg, Germany.

We thank madam TIMERA, Secretary of the Faculty of Human Sciences of the Cheikh Anta Diop University of Dakar for her support, advice and guidance she always gave us since our first year at the university.

We would also like to thank all those who participated in the success of this thesis, in particular, my graduates: Doukoro DIARRA, Madou SOUGUE, Nadège DOSSOUMOU, Yao KOMLAGAN, Kissi ABRAVI, Asaa Abunkudugu AKUNAI, Muhammad Leroy GOMEZ, Marcel KOUAKOU, Dr Peter OYEDELE, and Hassane BASSIROU.

I thank particularly Mrs. Aissatou NDIAYE for her support.

Summary

The advancing sea resulting from sea level rise, combined with the effects of climate change and hydrodynamic agents, is affecting the coastal morphology of the Dakar region. As a result, a reduction of coastal areas is observed in some coastal zones, causing human displacement inland and disrupting economic activities such as fishing and tourism. Coastal erosion makes the coasts of the Dakar region physically and socio-economically vulnerable. This study analyses the dynamics of the coastline from 1990 to 2040 using Geographic Information System techniques and shows that the region records average retreats of about -0.44 m/year, 0.21 m/year and -0.11 m/year respectively on the northern, western and southern coasts. These dynamic rates are expected to be about -4.4 m/year (for the north coast), 2.1 m/year (for the west coast) and -1.1 m/year by 2030 (south coast). By 2040, they are estimated to be around -8.8 m/year (north coast), 4.2 m/year (west coast) and -2.2 m/year (south coast). These predicted dynamic rates will result in a loss of coastal areas, estimated at 861273 m^2 in 2030 and 1256493 m^2 in 2040. These forecasts depend on the behavior of hydrodynamic agents and coastal characteristics. They also provide information on the level of vulnerability to coastline dynamics. The physical and socio-economic vulnerability of the Dakar region to coastal erosion was also studied using the Coastal Vulnerability Index method. It is shown that different vulnerability indexes are noted on the northern (94), western (10) and southern (23) coasts. Although the Dakar region is physically vulnerable to coastal erosion, it is essential to note that this vulnerability is accentuated by human activities which make it socio-economically vulnerable. This physical and socio-economic vulnerability also will negatively affect the economic land value of the coast in 2030 and 2040. Thus, the estimate of economic loss by the use of an econometric model shows that the Dakar coastline will record an estimated loss of 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040. These forecasts would make it possible to prevent the impact of coastal erosion by installing protective infrastructure in the most exposed areas. Whether the Dakar region coastline is economically confronted with coastal erosion, abnormal settlements, pollution, sand exploitation aggravate economic losses. Several adaptation measures have been implemented. However, despite the efforts of the Senegalese government to combat coastal erosion, the coastline continues to retreat.

Keywords: Coastal dynamic, Shoreline change, Erosion impacts, Vulnerability, Economic losses, adaptation measures.

Abbreviations and acronyms

ACCC: Adaptation to Climate Change in Coastal Areas

AIC: Akaike Information Criterion

AIDS: Acquired Immunodeficiency Syndrome

AF: Adaptation Fund

ANACIM: Agence Nationale de la Météorologie et de l'Aviation Civile

ANSD: Agence Nationale de la Statistique et de la Démographie

AQI: Air Quality Index

BIC: Bayesian Information Criterion

BFEM: Brevet de Fin d' Etude Moyenne

CCOD: Commission de contrôle des opérations domaniales

CDM: Clean Development Mechanism

CGQA: Centre de Gestion de la Qualité de l'Air

CI: Condition Index

CICES: Centre international du Commerce extérieur du Sénégal

CNDOSN: National Centre for Oceanographic Data and Information

CN: Condition Number

CO2: Carbon Dioxide

COMNACC : Comité National sur les Changements Climatiques

CPDN: Contribution Prévue Déterminée Nationale

CROD-T: Centre de Recherche Océanographique Dakar-Thiaroye

CSE: Centre de Suivi Ecologique

CVI: Coastal Vulnerability Index

DEEC: Direction de l'Environnement et des Etablissements Classés

DNA: Designated National Authority

DPM: Direction des Pêches Maritimes

DSAS: Digital Shoreline Analysis System

EC: Expected Contributions

EPR: End Point Rate

ETM: Enhanced Thematic Mapper

FAO: Food and Agriculture Organization

FCFA: Francs Communautés Financières d'Afrique

GCF: Green Climate Fund

GDP: Gross Domestic Product

GEF: Global Environment Facility

GGE: Greenhouse Gas Emissions

GHG: Green House Gases

GIS: Geographic Information System

GPS: Global Position System

HIV: Human Immunodeficiency Virus

IAGU: Institut Africain de Gestion Urbaine

ICZM: Integrated Coastal Zone Management

ICS: Industrie Chimique du Sénégal

IFRCARCS: International Federation of Red Cross and Red Crescent Societies

IMF: International Monetary Fund

INDC: Intended Nationally Determined Contribution

InSAR: Interferometric Synthetic Aperture Radar

IOC: Intergovernmental Oceanographic Commission

Ipar: Initiative Prospective Agricole et Rurale

IPCC: Intergovernmental Panel on Climate Change

ISRA: Institut Sénégalais de Recherche Agricole

ITCZ: Intertropical Convergence Zone

JICA: Japan International Cooperation Agency

LPSEDD: Letter of Policy for the Environment and Sustainable Development Sector

LRR: Linear Regression Rate

MDGs: Millennium Development Goals

MEDD: Ministère de l'Environnement et du Développement Durable

MEEDM: Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer

MEF: Ministère de l'Economie et de Finance

MEFP: Ministère de l'Education et de la Formation Professionnelle

MEPN: Ministère de l'Environnement et de la Protection de la Nature

MNDWI: Modified Normalized Difference Water Index

MOLOA: Mission d'Observation du Littoral Ouest Africain

MPEM: Ministère de la Pêche et de l'Economie Maritime

MSL: Mean Sea Level

MWH: Mean Wave High

NACOMCC: National Committee on Climate Change

NAP: National Adaptation Plan

NAPA: National Action Plan for Adaptation

NASA: National Aeronautics and Space Administration

NDCs: Nationally Determined Contributions

NDEC: Nationally Determined Expected Contribution

NDVI: Normalized Difference Vegetation Index

NDWI: Normalized Difference Water Index

NGOs: Non-Governmental Organization

NIS: National Implementation Strategy

NOAA CO-OPS: National Oceanic and Atmospheric Administration Center for Operational Oceanographic Products and Services

NSM: Net Shoreline Movement

NSDP: National Sustainable Development Policy

NCCP: National Climate Change Policy

OHLM: Organismes d'Habitation à Loyer Modéré

OLI: Operational Land Imager

OLI/TIRS: Operational Land Imager/Thermal Infrared Sensor

PA: Parcelles Assainies

PADDUS: Projet d'Appui à la Décentralisation et au Développement Urbain au Sénégal

PDU: Plan Directeur Urbain

PNUE: Programme des Nations Unies pour l'Environnement

POLMAR: National Plan for the Fight against Marine Pollution

PRL: Projet de Reboisement du Littoral

PSE: Plan Sénégal Émergent

RPHAE: Recensement de la Population de l'Habitat, de l'Agriculture et de l'Elevage

SAPs: Structural Adjustment Programmes

SCE: Shoreline Change Envelop

SDGs: Sustainable Development Goals

SICAP: Société immobilière du Cap-Vert

SIE-Sénégal: Système d'Information Energétique du Sénégal

SNDEC: Senegal's Nationally Determined Expected Contribution

SNDES: Stratégie Nationale de Développement Economique et Social

SN-HLM: Société Nationale des Habitations à Loyer Modéré

SOS: Save Our Souls

SWIR: Short Wave Infrared

TM: Thematic Mapper

UEMOA: Union Economique Monaitaire Ouest Africaine

UN: United Nations

UNDP: United Nations Development Programme

UNDRO: United Nations Disaster Relief Office

UNFCCC: United Nations Framework Convention on Climate Change

UNEP: United Nations Environment Programme

UNISDR: United Nations International Strategy for Disaster Reduction

UNSO: United Nations Sudano-Sahelian Office

USAID: United States Agency for International Development

USGS: United States Geological Survey

VIF: Variance Inflation Factor

VDN: Voie de Dégagement Nord

WASCAL: West African Science Service Centre on Climate Change and Adapted Land Use

ZAC: Zone d'Aménagement Concertées

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PART I: STUDY ORIENTATION, CONCEPTUAL FRAMEWORK, LITERATURE REVIEW, GENERAL PRESENTATION OF DAKAR REGION, AND METHODOLOGICAL APPROACH

Chapter 1: Study orientation

I. Context

Climate change is a meaningful phenomenon which challenges the economic development and the prowess of our environment. It is severe in many parts of the world. Most areas in the world are vulnerable to its impacts such as sea-level rise, advanced sea, coastal erosion, biodiversity decreasing, lands salinity, the disappearance of human establishments, ocean acidification, fishing reduction, and an unbalance between water offerings and water demand, etc. However, it would be accurate to say that due to their low adaptation capacities, developing countries are the most vulnerable to the impacts of climate change. Senegal is among the most vulnerable West African countries to the impacts of climate change. It is a developing country, and its economic activities, such as agriculture, fishery, tourism, etc., are affected. Coastal erosion is the most threatening disaster in Senegal apart from the flood. Therefore, the Dakar region, like most coastal cities in the world, is not safe from its impacts. Advanced sea resulting from the rise in sea level affects the coasts (Pouye et al. 2022).

The evolution of the coast of Dakar region in previous studies (Dennis et al. 1995; Faye 2010; Bakhoum et al. 2018) showed that there is indeed an advanced sea which is probably due to the variations in oceanic water linked to tectonic plaque; melting ice caps in polar zones; dilation of sea waters; variations in the geoid; and modification of continental crust. As a result, the coastline retreats. Therefore, this situation leads to the reduction of coastal areas, coastal flooding, human displacement toward inland, and disruption of economic activities such as fishery and tourism. Human activities along the coast accentuate these threats through sand mining, pollution, and illegal settlements (Pouye 2016). According to Niang et al. (2012), scenario-based studies have predicted land losses in Dakar by 2050. These losses will be estimated at 0.21 to 1.79 km², i.e., 3.8 to 28.5% of the total beach area. By 2100, they will be between 0.77 and 3.95 km², i.e., 12.2 to 62.8% of the total beach area.

In a study on changes in climatic conditions and rising sea levels on the north coast of the Cape Verde peninsula, Pouye (2016), stated that 'to fight against coastal erosion impacts, the Senegalese government adopted adaptation measures such as building protective walls, reforestation, protective dykes, rock fill, breakwaters, etc.' Among these protective measures, some are more effective depending on their quality, duration of resistance against hydrodynamic agents and the type of coast where they are installed. However, it should be noted that these protective infrastructures constitute a significant constraint on sedimentary exchanges between continents and oceans.

II. Justification

The justification for conducting a thesis on coastal erosion dynamics in Dakar, Senegal, is anchored in the imperative to fill critical knowledge gaps and advance our understanding of this complex phenomenon. Dakar's coastal erosion represents a unique and intricate challenge, shaped by a convergence of natural and anthropogenic factors. In this section, we elucidate the scientific rationale for embarking on this comprehensive research endeavor.

This thesis on the coastal erosion dynamics of Dakar, Senegal, hints at several research gaps in previous studies. Previous research on coastal erosion dynamics often provides a broad overview, focusing on general coastal processes. However, Dakar's coastal erosion is influenced by a unique combination of factors, including rising sea levels, climate change effects, hydrodynamic forces, and specific geological and geomorphological characteristics. These nuances are often overlooked or insufficiently explored in broader coastal studies. Many existing studies lack comprehensive, long-term data for the Dakar region. This gap results in a lack of precise understanding of how erosion dynamics have evolved over time and across different parts of Dakar's coastline. Without this information, it's challenging to predict future trends accurately. Traditional research methods may not capture the intricate processes driving coastal erosion and the losses of coastal areas due to erosion in Dakar. The thesis highlights the use of new Geographic Information System (GIS) techniques and predictive modeling to fill these gaps.

Previous studies have primarily focused on the physical aspects of coastal erosion, overlooking its broader societal and economic impacts. This thesis highlights that the physical and socioeconomic vulnerabilities of the Dakar region to coastal erosion require a holistic assessment that considers the dependency ratio, level of education, gender aspect and population density of district municipalities. While some studies might have touched upon the economic effects of coastal erosion, a comprehensive evaluation of the economic losses associated with erosion is often lacking. This research gap means that decision-makers and policymakers may not have access to the necessary data to understand the economic implications fully.

To fill these gaps, the primary strength of this thesis lies in its specialized focus on Dakar's coastal erosion dynamics. By concentrating on this specific region, the research acknowledges and delves into the unique factors shaping erosion, including the interplay of natural and anthropogenic drivers. It aims to provide a detailed and context-specific understanding of coastal erosion in Dakar. This thesis extends its research horizon from 1990 to 2040, allowing for a comprehensive examination of coastal dynamics over five decades. This extended temporal coverage enables the identification of historical trends and the development of future projections. Previous studies with shorter temporal scopes may not have captured these long-term patterns. The application of GIS techniques and predictive modelling sets this research apart. These advanced tools enable a more precise and data-driven analysis of coastal geomorphological processes. By adopting innovative methodologies, this thesis enhances the depth and accuracy of its findings, filling a gap in the utilization of modern research techniques in coastal erosion studies. One of the key innovations of this thesis is its holistic approach to vulnerability assessment. By considering both the physical and socioeconomic vulnerabilities and by integrating new parameters in the vulnerability assessment, the research recognizes that the impacts of coastal erosion extend beyond the physical environment. This approach provides a more complete understanding of the socioeconomic vulnerability of the coast of Dakar region. Another innovative aspect of this thesis is its in-depth evaluation of the economic impacts of coastal erosion. By estimating economic losses associated with erosion, this research goes beyond surface-level analysis and provides quantitative data on the potential economic impacts. This information is critical for decision-makers and policymakers in devising effective strategies to mitigate the economic consequences of coastal erosion. Previous studies may not have delved into economic assessments to the same extent, making this research a valuable contribution to understanding the full scope of the issue.

III. Aim and Objectives

This study aims to analyze the dynamics of the coastline from 1990 to 2040, the processes contributing to these coastal dynamics, the vulnerability of the Dakar region to coastal erosion, the economic impacts and adaptation measures. The specific objectives are to:

1) Examine climatological, hydrodynamic, human, and geological parameters which contribute to coastal erosion in the Dakar region;

2) Analyze the past and present, and future coastal erosion dynamics;

3) Assess the physical coastal vulnerability;

4) Assess socio-economic coastal vulnerability;

5) Evaluate the economic impact of coastal erosion;

6) Document adaptation strategies and suggest ways of improving them.

IV. Significance of the Study

The following points depict the significance of the study:

- The study would provide a clear overview of coastal erosion, its impacts in Dakar, Senegal, and all the different processes that mediate this erosion.

- The study results would provide evidence to enable different economic actors and populations to make decisions about the impacts of coastal erosion on their activities and the coastal environment. For this, actors would be better equipped with knowledge of sustainable adaptation and mitigation strategies.

- It would provide essential information to relevant institutions in Senegal, such as the Ministry of Tourism, Ministry of Industry, Ministry of the fishery, Ministry of High Education, and the Direction de l'Environnement et des Etablissements Classés (DEEC) and Non-Governmental Organisations (NGOs) working in this area.

- The research would also provide additional literature about coastal erosion in Dakar, Senegal and open up a new pathway for future research.

V. Scope of the Study

This thesis covers twenty six district municipalities along the coast of the Dakar region. This choice of these district municipalities can be justified because they are more vulnerable to coastal erosion due to their nearest position to the sea. There are diverse economic activities in Dakar coastal areas, such as fishing and tourism, and the awareness of different actors about coastal erosion and its impacts and adaptation strategies is considered very timely and pertinent in a way to contribute to the global discourse on sustainable development goals (SDGs), particularly SDGs 11, 13 and 14.

VI. Expected results

The expected results can be resumed by the following points:

- **Analyse the climatological, hydrodynamic, geological, and human factors that contribute to coastal erosion in the Dakar region**
    - Determining and analysing climatological patterns and trends in the Dakar region from 1990 to 2040.

- ❖ Evaluation of the hydrodynamic processes that contribute to coastal erosion, such as wave patterns, tidal movements, and currents.
- ❖ Analysing the impact of geological and geomorphological parameters on coastal dynamics.
- ❖ Analysing how human activities such as urbanisation, tourism, the construction of coastal infrastructure, sand mining, and unplanned settlements affect erosion.

➢ **Examine the processes of historical, current, and future coastal erosion**

- ❖ Analysing historical trends in coastal erosion using data from 1990 to 2020.
- ❖ Quantifying the rate of coastal advance or retreat over the research period.
- ❖ A projection of the processes of coastal erosion between 2030 and 2040.
- ❖ The location of possible erosion areas and regions at risk for future severe erosion.

➢ **Determine the socioeconomic and physical vulnerability of the coast**

- ❖ Evaluation of physical vulnerability, taking into account aspects such as geomorphology, geology, existing protective infrastructures, slope, relative sea level, shoreline displacement, tidal range, swell range, wave height, distance between settlement and the sea.
- ❖ Socioeconomic vulnerability analysis that considers factors like population density, dependency ratio, gender ratio and education level.
- ❖ Integration of physical and socio-economic vulnerability indices to identify regions most at risk.

➢ **Evaluation of the economic impact of coastal erosion**

- ❖ Analysis of economic sectors affected by coastal erosion in Dakar, such as fisheries and tourism.
- ❖ Estimation of potential future economic losses.

➢ **Recommend the appropriate adaptation strategies for better resilience**

- ❖ Identification of existing coastal protection and adaptation measures in the Dakar region.
- ❖ Proposal of new or improved adaptation strategies based on the enhancement of capacity building of the institution in charge of coastal erosion management, the research findings and implication of local communities in coastal erosion management.
- ❖ Recommendations for policymakers and stakeholders to enhance coastal resilience and reduce vulnerability to erosion.

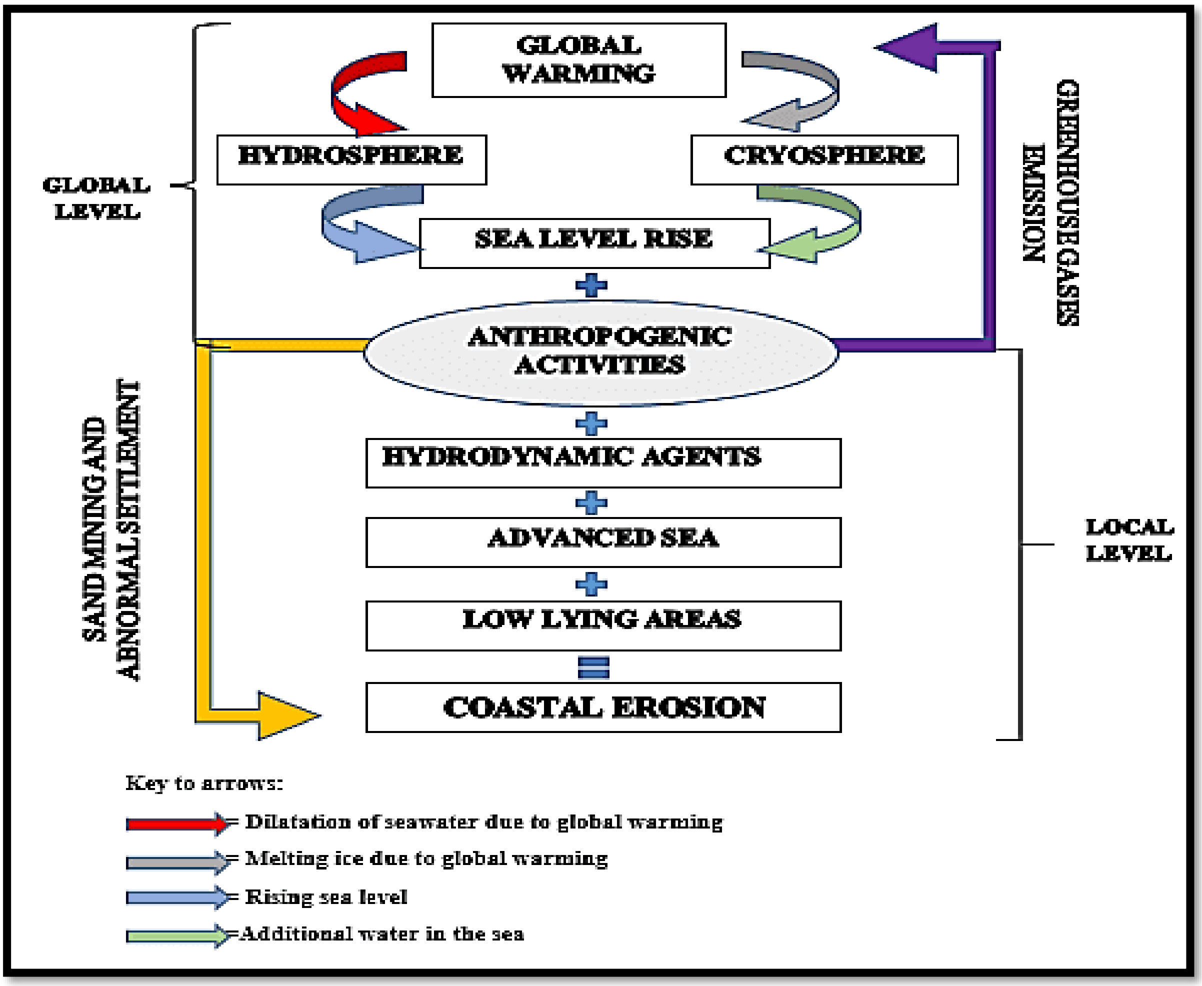
The chapter 2 addresses the conceptual framework and literature review.

Chapter 2: Conceptual framework and literature review

I. Conceptual framework

The term "global warming" refers to the rise in the planet's average surface temperature brought on by a rise in greenhouse gases such carbon dioxide, methane, and water vapour. One of today's most important environmental challenges is the increase in global temperatures (Zhang 2023). Burning fossil fuels has resulted in extraordinary increases in the atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases since the industrial revolution got underway at the beginning of the 19th century. As a result, these gases have significantly raised ocean and atmosphere temperatures (Stocker 2013 in Zuo et al. 2021).

The figure 1 is about the conceptual framework used in this study. It resumed all processes that can intervene in coastal erosion in Dakar region.



Source: Personal work

Figure 1: Conceptual framework

The effects of this global warming on the cryosphere result in ice melting and seawater dilution, which produce sea level rise and coastline retreat in the majority of coastal regions worldwide. One of the most severe consequences of the rapid melting of the polar ice caps in recent decades, driven on by global warming, according to a study by Kurniawan et al. (2021). Over time, the ice and snow caps at the pole have decreased due to the greenhouse effect, which is getting worse. Additionally, seawater dilation caused by global warming has an impact on the hydrosphere. Seas become hotter as a result of rising global temperatures, which results in a phenomenon known as thermal expansion of water. It results in an increase in the water's volume. Warming oceans and thermal expansion are responsible for almost half of the observed global sea level increase on Earth (NASA 2023).

The effects of sea level rise on the coasts are amplified by human activities like sand extraction and unusual settlement. Sea level rise, other climatic ocean changes, and negative consequences from anthropogenic activity on ocean and land all have an impact on coastal ecosystems. Due to the influence of other climate-related factors, it is still difficult to attribute such effects to sea level rise (Michael et al. 2019). For instance, the weather and marine phenomena, especially waves and coastal currents, have a significant impact on the changes that such coastal regions experience. The amount of clastic materials available to these dynamic agents, which make up the active coastal sedimentary prism, must also be taken into account (Sanlaville 2001). However, it is also still difficult to attribute these effects to sea level rise because of the influence of non-climatic causes such infrastructure development and habitat degradation brought on by humans (Michael et al. 2019). Low-lying coastal communities are now more exposed and vulnerable to extreme sea level events and sea level rise as a result of historical and current demographic and settlement trends as well as anthropogenic subsidence. In general, human-induced changes in low-lying coastal areas can be quick and quickly transform coastlines, exceeding the effects of sea level rise (Michael et al. 2019). Additionally, the consequences of climate change's effects on hydrodynamic agents like wave, wind, and tide amplify the effects of sea level rise on the coasts.

Due to its geographical position in the sea and the fact that the Dakar region is mainly composed of low-lying areas, coastal erosion is the most threatening disaster which challenges communities apart from the flood. In this study, all processes that intervene in coastal erosion in Dakar are analyzed.

II. Literature review

Climate change, sea level rise and coastal erosion

Climate change is a meaningful phenomenon which challenges the economic development and prowess of our environment. It is severe in many parts of the world. Most areas in the world are vulnerable to the impacts of climate change, such as advancing seas, coastal erosion, decreasing biodiversity, land salinity, the disappearance of human establishments, ocean acidification, fishing reduction and an unbalance between water supply and water demand, etc. The long-term and immediate impacts of climate change include its massive global effects and implications for small changes in the earth's orbit. Human actions have an effect on the atmosphere, ecology and seas, which results in a warming of the planet and an increase in air and marine temperatures. Extreme weather, heat waves, storms and flooding, forest fires, reduced safety, economic troubles, long-term effects on human health and the ecosystem, risks to water and food resources, and altitudinal and tree line shifts are all effects of climate change that we are currently experiencing (Bhatt 2021).

Furthermore, climate change will accelerate the loss of biodiversity and dwindling freshwater and land resources and increase societal vulnerabilities, particularly in areas where the economies are highly dependent on natural resources (IPCC 2022). West Africa makes a very small contribution to global climate change, but because of its position and poor capacity for adaptation, it is extremely sensitive to the consequences of climate variability and change. As they rely on rainfed agriculture and ecosystem services, inhabitants in the dry parts of West Africa, in particular, suffer unfavorable effects from rising temperatures and fluctuating rainfall patterns. In various West African nations, flooding is another typical hazard brought on by the environment (Teye 2022).

In this context, one of the most important effects of climate change on the coastal areas of many countries is sea-level rise. An increase in temperatures is anticipated in addition to the increasing sea levels (between 0.09 and 0.88 m by 2100). The sea level has risen by around 15 cm over the previous century, but due to melting land ice and warming ocean waters, the rate of rise has recently accelerated, and it is anticipated that the sea level will rise by another 30 cm over the next 50 years. The greenhouse effect has primarily been held responsible for this accelerating rate of sea-level rise. The ocean surface is predicted to warm by an extra 2 to 4 °C if atmospheric CO_2 doubles during the next 100 years (Duxbury et al. 2002). The expansion of warming water will also affect the sea level by raising it an additional 60 cm for each degree of increase in the average ocean temperature. As a result, the coast's edge will move inland from hundreds to thousands of meters along low-lying coasts, and coastal erosion will be accelerated.' Also, sea-level rise, wind velocity, height waves, and height tides changes are among the effects of climate change in coastal areas. Nevertheless, it would be essential to note that the impacts of possible responses to sea-level rise vary at the local and regional scales due to variations in local and regional parameters. When combined with the coast's low-lying nature and low socio-economic and institutional development level, these parameters would suggest that West Africa is vulnerable to sea-level rise. Large land areas could be lost; the most threatened land is wetland areas within deltas or around estuaries and lagoons (Nicholls and Mimura 1999).

The rising sea level causes an aggravation of temporary submersion; extension of permanent submersion on low-lying areas; lagoon shores; maritime marshes; coral reefs; reinforcement of erosion actions on cliffs and beaches; increased salinization of estuaries; and reduction in the volume of freshwater aquifers (Sanlaville 2001). The consequences of such a natural phenomenon affect the economy through the reduction of agricultural productivity and marine biodiversity, the risk of flooding of port and road infrastructure and the destruction of tourism facilities (MEPN/DEEC 2010). When combined with the coast’s low-lying nature and low socioeconomic development, these parameters would suggest that West Africa is vulnerable to sea-level rises. Large areas of land could be lost, and most of the threatened land is wetland areas within deltas or around estuaries and lagoons (Nicholls and Mimura 1999).

One of the effects of sea-level rise is coastal erosion. It is the most threatening disaster in Senegal apart from flooding. In Senegal, most tourist facilities could be destroyed, and up to 180 000 people could lose their homes. Such impacts suggest that vulnerability to sea-level rise will increase substantially over the next few decades unless these changes are carefully planned. Therefore, the planned relocation of development inland out of the coastal zone can only be a partial solution. At the local level, the Dakar region contains the highest concentration of towns and industries along the coast, including 26 km of highly developed erodible coastline. Inundation and erosion are the significant visible consequences of sea-level rise in this area. Dakar region itself is situated on a rocky headland, but much of the surrounding metropolitan area is vulnerable to erosion given sea-level rise. Shoreline retreat is already a problem, with recession rates at Rufisque between 0.45 and 2.46 m/year (1959 to 1980). Far from being negligible, saltwater intrusion into Senegal's aquifers and surface waters is one of the damages of sea-level rise, threatening water resources unless offset by increased rainfall. This could damage agricultural production in several areas. Besides, salinization and other changes are promoted by sea-level rise and climate change (Dennis et al. 1995). Most tourist facilities are endangered, and up to 180,000 people could lose their homes (Nicholls and Mimura 1999). Such impacts suggest that vulnerability to sea-level rises will increase substantially over the next few decades. At the local level, the coastal dynamics of the Dakar region show that there is indeed an advance in the sea, which is probably due to variations in oceanic waters aggravated by the effects of hydrodynamic agents, such as wave, tide, wind, geomorphologic and topographic conditions. Therefore, a reduction of coastal areas, human displacement toward inland and the disruption of economic activities (fishing, recreation and hotel and industrial activities) are noted. These threats are accentuated by humankind through sand mining, pollution and illegal settlements along the coast (Pouye et al. 2022).

It was also noted that other parameters are involved in coastal erosion processes. Due to climatic and hydrodynamics factors such as waves, wind, drift, tides, etc., coastal areas are the most dynamic zones in the world. Depending on the degree of porosity and the nature of sediment that composes the coast, they are subjected to changes. The drive factors for these changes are the geological and geomorphological, hydrodynamic, biological, climatic and anthropogenic conditions.

Geologic conditions, characterized by the sediment structure type, arrangement, resistance and isostasy, are the basis of morphological processes and the development of coastal relief. In contrast, geomorphologic conditions are determined by climatic factors such as precipitation, rainfall and wind. These geologic and geomorphologic conditions are the generator of the forms of typical relief and sediment supply (Łabuz 2015). In addition, hydrodynamic factors such as waves and wind play an important role in coastal environmental change. If a wave breaks into weak or soft materials, the forward-moving water's force easily cuts into the littoral. It causes erosion, and the retreat of the shoreline is rapid. Wind is an essential key parameter in hydrodynamic conditions and generates swell, waves and sea currents. It contributes to this erosion and performs two kinds of erosional work: deflation and abrasion. Deflation is the removal of particles, largely silt and clay, from the ground by the wind. It acts on loose soil or sediment. The second process of wind erosion, abrasion, drives sand-sized particles against an exposed rock or soil surface, wearing down the surface by the impact of the particles (Strahler 2013).

Physical vulnerability of Dakar region to coastal erosion

Owing to the lack of common shared language and the difference in scientists' backgrounds, there is no universal definition for vulnerability which refers to the propensity of exposed elements such as physical or capital assets, as well as human beings and their livelihoods, to experience harm and suffer damage and loss when impacted by single or compound hazard events (UNDRO 1980; Smith 1981; Blaikie et al. 1996; UNISDR 2009; Birkmann 2006; Cutter et al. 2003; Cutter and Finch 2008; Wisner et al. 2012; Birkmann et al. 2013; Rana and Routray 2018). The methodological Guide for Assessing Vulnerability to Climate Change at the Community Level (Coastal Zones) states that vulnerability is a function of risks, hazards, exposure and adaptation options and responses (Fall and Correa 2011).

Many assessment approaches characterize vulnerability according to the degree of susceptibility or fragility of communities, systems or elements at risk and their capacity to cope under hazardous conditions (Birkmann et al. 2013 in Mwale et al. 2015). Therefore, in the final report of ECOFYS (2016), a vulnerability assessment is defined as an evidence-gathering activity to assess who or what is vulnerable, to what, and under what circumstances. For example, older people (the who) are more susceptible to high temperatures (the what); hence in the event of a heatwave (the circumstance), they will be more vulnerable. It considers social vulnerabilities that can be determined by factors such as economic diversity, demographic, income, education, critical thresholds, social cohesion/capital, equity, governance, policy priorities and biophysical vulnerabilities, which can be determined by factors such as climate change and variability, including extremes, land use, habitat quality, water availability, critical thresholds, frequency, duration, and magnitude. The all-encompassing motivation behind the vulnerability assessment is to illuminate decision-makers about the possible dangers and openings introduced by climate change. It gives a way to assess the effects related to various sizes of environmental change, alongside proof to look at changed variation reaction procedures and strategy choices. A vulnerability assessment may form part of a broader adaptation policy cycle that is used to support policy-makers (Moss et al. 2010 in ECOFYS 2016).

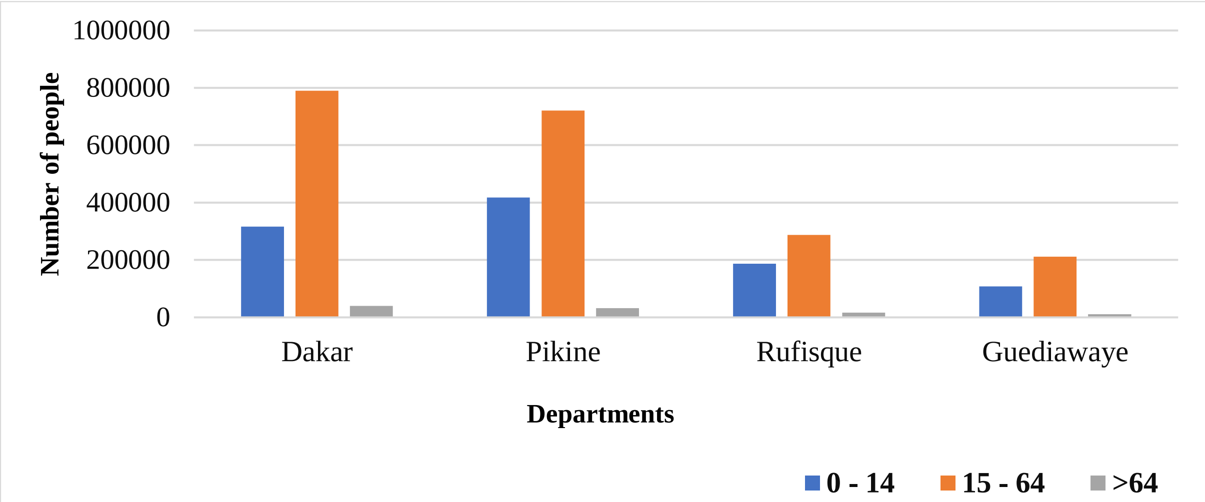
The vulnerability of Senegal's coasts has always been the subject of scientific investigation. Since the 1990s, studies have attempted to estimate the vulnerability of the world's coastal zones to a sea level rise of 0.5 and 1 meter and a coastline length of 68.5 km for all sectors such as cities (34), industries (3), cities with dykes (7), tourist areas (21.5) and fishing villages (3).

For each sector, adaptation options were defined. It was estimated that 1,350 km of coastline would need to be protected at a total cost of US$1,596 million. On this basis, Senegal was ranked 45th among countries vulnerable to accelerated sea-level rise, out of 181 countries examined (IPCC 1992). In the second study, which considered a maximum sea level of 6 m, it was estimated that the area at risk would be 7,450 km^2 and that about 3.7 million people would live there in 2020 (Hoozemans et al. 1993). These results ranked Senegal as the 8th most vulnerable country in the world. The costs of protection were re-evaluated at US$ 3,623 million, i.e., an annual cost of 1.72% of the Gross National Product. Finally, the study estimated the surface area of coastal ecosystems at risk: 20,600 ha of salt marshes, 104,100 ha of intertidal zones and 364,300 ha of mangroves. The third study (Dennis et al. 1995) used 4 scenarios of sea level rise (0.2, 0.5, 1 and 2 m by 2100) and determined the area of land likely to be lost, the populations and economic value at risk and the costs of protection (MEPN 2006).

Socio-economic vulnerability of Dakar region to coastal erosion

According to Rahadiati et al. (2019), vulnerability is a low resistance of a community facing threats that influence the disaster risk level. It can be considered from the economic, environmental, and socio-cultural factors and social conditions such as poverty, social pressure, and a less than strategic environment, which may decrease the community's resistance to facing threats. Coastal vulnerability assessment focuses on how climate change will impact coastal communities and the ecosystem service they provide. These services may incorporate natural resources and infrastructures (Oloyede et al. 2022). Primarily, coastal vulnerability induced by climate change was based on natural processes and less on socio-economic aspects (Giorgos Alexandrakis et al. 2014). This study assessed socio-economic vulnerability of the coasts of Dakar region to erosion using indicators such as population density, dependency ratio, gender ratio and education level.

Dakar region has a superficies about 550 Km^2, e.g., 0.28% of the national area. Its population has grown from 3,630,324 inhabitants in 2018 to 3,732,282 inhabitants in 2019. As the most populous region, Dakar has been home to 23% of Senegal's population since 2013. This population is unequally distributed in departments such as Dakar, Pikine, Guédiawaye and Rufisque. Pikine remains the most populous department with a population of 1,392,875 inhabitants, i.e., 688,777 women and 704,098 men. The department of Dakar has a population of 1,363,444 inhabitants, e.g., 689,221 men and 688,539 women. The department of Guédiawaye has a population of 392,190 inhabitants, i.e., 197,795 men and 194,395 women, and the department of Rufisque has a population of 583,773 inhabitants, i.e., 291,353 men et 292,420 women (ANSD 2021). According to ANSD (the 2013 census), the distribution of the population of the Dakar region by age shows that the population aged 0 to 14 is about 1,028,141 inhabitants, e.g., 33% of the total population of Dakar (3,137,649 inhabitants). People aged 15 to 64 years are 2,010,290 inhabitants, e.g., 64%, while people older than 64 years are 98,764 inhabitants, e.g., 3% of the total population of Dakar (ANSD 2014) (Figure 2). As the capital of Senegal, the Dakar region hosts over 50% of economic activities and most of the administrative infrastructures.



Source: (ANSD 2014)

Figure 2: Age distribution of the population of the Dakar region

Consequently, the concentration of the population is becoming denser and denser, increasing the need for urbanization and allotments. The allotment and allocation of land plots remain more focused on the department of Rufisque, which still has unused land. Nevertheless, building permits continue to be issued throughout the Dakar region. The Act III of decentralization marks the total disappearance of the administrative entity 'rural community', which implies complete urbanization of the Dakar region since 2013 following the adoption of Law 2013-10 on Act III of decentralization. Before this reform, there had been urban growth since the first population and housing census (1976) due to the Dakar region's economic influence and geographical position. Practically, only the department of Rufisque has had rural areas. This situation has not changed too much since the urbanization rate of this department only went from 77.30% to 77.40% from 1976 to 2013. The other departments have been fully urbanized since 1976. As regards water and sanitation, the challenge remains above all in the accessibility of quality water and adequate drainage systems. As a result, water production fell from 114,799,595 m^3 in 2017 to 82,789,094 m^3 in 2018, which explains the numerous water shortages. As for sanitation, the access and wastewater treatment rates have evolved positively, rising from 31% to 32% and from 54% to 60%, respectively, between 2018 and 2019. On the other hand, the water depollution dropped by 2 points with 39% in 2018 and 37% in 2019 (ANSD 2021).

The economic impact of coastal erosion in Dakar region

Dakar region, like most of the world's capitals, is not safe from the impacts of climate change and coastal erosion because of its geographical position and its low-lying (Pouye 2022). Advanced sea resulting from the rise in sea level is affecting the coasts. Dakar's current and expected coastal dynamic shows that there is indeed an advanced sea due to variations in oceanic waters aggravated by the effects of hydrodynamic agents such as waves, tides, and wind. Therefore, this situation reduces coastal areas; human displacement toward inland; disruption of economic activities such as fishing, recreation, hotel, and industry activities. Mankind accentuates these threats through sand mining, pollution, and illegal settlements (Pouye 2016). According to Niang et al. (2012) scenario-based studies have predicted land losses in Dakar by 2050. These losses will be estimated at 0.21 to 1.79 km^2, i.e., 3.8 to 28.5% of the total beach area. By 2100, they will be between 0.77 and 3.95 km^2, i.e., 12.2 to 62.8% of the total beach area. At one time, knowledge of the economic value of the beach was minimal, beyond that suggested by property values. There needs to be more scientific information on the economic value of the beach to assess the effectiveness of investing exorbitant amounts of money in beach erosion management (Edwards and Gable 1991). So far, this economic value of beach erosion was sometimes assessed by the cost of protective infrastructures without considering income losses (Alexandrakis et al. 2015). Therefore, with the use of econometric models, this challenge is resolved. The evaluation is no longer linked to the protection infrastructures but to the revenues generated by economic activity such as tourism and the economic value of coastal properties. In a study, Alexandrakis et al. (2015) estimated the value of eroded beaches through the hedonic pricing model, where the beach value is determined by its width and tourism business. Some studies argued that the value of the properties is relative to beach width. Brown & Polakowski (1977), in a study, indicate that the value of a property decreases with distance from the water. The effect of beach quality, as determined by beach width, on property values in two South Carolina coastal towns is investigated by Pompe and Rinehart (1995). In addition, in a study, Landry et al. (2003)

emphasized the complexity of the relationship between property value, the erosion rate, and distance from erosion reference. Property owners appreciate shorter distances to the reference erosion feature for recreational and amenity reasons. They also value the protection against storm surges and the risk of erosion, fostered by a larger beach width, a more considerable distance to the reference erosion feature, and a decreased erosion rate.

The importance of assessing the economic value of beaches is to evaluate coastal management policies and projects (Lew and Larson 2008). It may identify coastal areas needing protective infrastructure based on physical and socio-environmental vulnerability, coastal dynamism rate, and beach width reduction. Further, this study uses an econometric model (multi-linear regression) which points out the impacts of Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to town, CVI, Number of Buildings, Number of Hotels, Number of Industries, Number Fishing Points and Road Length on beach value along the coast of Dakar region. Geographic Information System technics were used to determine independent variables through spatial data.

Adaptation strategies against coastal erosion in Dakar

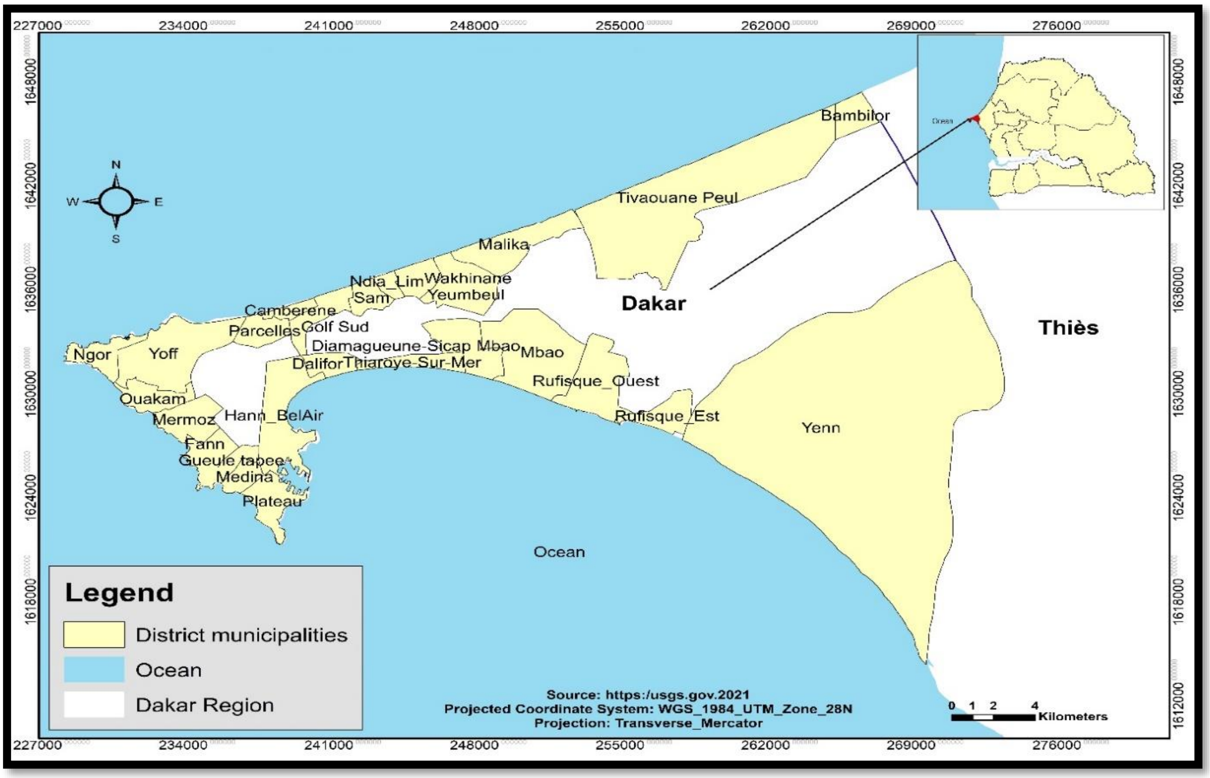
Since a long time ago, human beings have been challenged sometimes by the inconveniences of nature (floods, volcanic eruptions, earthquakes, storm surges, drought). However, they have always found ways to adapt to these obstacles to survive and improve their living conditions. Therefore, to protect against coastal erosion, several means are used: protective walls, groin fields, reforestation, dykes, riprap, beach nourishment, dune restoration, beach draining systems, and breakwaters. Among these means, some are more effective depending on their quality, their resistance duration against hydrodynamic conditions (swell, winds, sea currents, waves), and the type of coast where they are installed. However, despite the advantages that these infrastructures provide to communities in terms of the preservation of coastal ecosystems, it should be noted that they can be a hindrance to the exchange of sediments between continents and oceans. In addition, some of these protective infrastructures are very expensive. Consequently, in some coastal regions doing nothing is the easiest coastal management option. This situation is generally the case in areas with no people, so nothing economical or institutional value should be protected. Today there is a practice of non-intervention/no action in West Africa, but this is not an act of addressing coastal problems in a planned manner. Many sections of the West African coast are under natural and manmade threats without any coastal management plan in place. This is not what the "do nothing" approach preaches: dealing with natural phenomena, possibly losing land to the sea, but without loss of infrastructure or even lives. While this is the cheapest and most environmentally friendly option for many parts of developing regions such as West Africa, one must weigh the costs (for people, tourism, industries, infrastructure) against the benefits (the advantages of letting the area return to its natural processes). If the costs greatly outweigh the benefits, for example, by relocating people or losing valuable facilities, other options must be considered. This situation is not practiced in West Africa. Not all problems have been addressed because governments have no financial resources to conduct detailed research. Otherwise, they would surely do something. It is therefore advisable to consider this practice. Do due diligence and do nothing (Alves et al. 2020). According to Stewart et al. (2011), long-term coast management is an essential and challenging task. Some challenges coastal managers face include maintaining and protecting public access and natural character, protecting people and properties from natural hazards, and sustainable planning and use of natural and physical resources. Pouye (2016) stated that faced with this coastal erosion, the Senegalese government adopted adaptation measures depending on the means at its disposal: Protective walls, reforestation, protective dykes, riprap, etc. Among these protective measures, some are more effective depending on their quality, their duration of resistance against hydrodynamic parameters and the type of coastline where they are installed. However, it should be noted that these protective infrastructures constitute a significant constraint on sedimentary exchanges between continents and oceans. To better manage coastal erosion and pollution, 26 additional developments and preservation projects have been inventoried for an estimated budget of more than 30 billion francs CFA. Such expense could have been avoided if the legislation developed in Senegal had been applied. For example, the Law n°76-66 of 2 July 1976 defines the natural public domain with the shores of the sea and the artificial public domain with the numerous urban infrastructures built or planned. This Law is completed by the Merchant Navy Code (Law n°2002-22 of 16 August 2002) ; Law No 83-05 of 28 January 1983 of the Environmental Code specifies that marine environments must neither be a source of erosion nor degradation, Law No. 83.71 of 5 July 1983 on the Hygiene Code ; Law no 88-06 of 26 August 1988 on the Mining Code which stipulates in Article 3 that ‘all useful mineral substances contained in the subsoil of the Republic of Senegal are the property of the State ; Law no 98-03 of 8 January 1998 and Decree No 98-164 of 20 February 1998 regulate mining, including sand extraction ; Decree no 89-907 of 5 August 1989, setting out the modalities for its application, was replaced by Law No 2003-36 of 24 November 2003 on this Mining Code ; Law N°2001-01 of 15 January 2001 on the

Environment Code and its implementing Decree N°2001-282 of 12 April 2001 constitute the fundamental legislative and regulatory framework governing activities with environmental impacts ; Decree no 89-907 of 5 August 1989, setting out the modalities for its application, was replaced by Law No 2003-36 of 24 November 2003 on this Mining Code and Law No 2002-22 of 16 August 2002 on the Merchant Navy Code (Quensière et al. 2013). The chapter 3 addressed the general presentation of Dakar region.

Chapter 3: General presentation of Dakar region

Introduction

Geographically, Dakar is a peninsula. It is located in West Africa between 17° 10 and 17° 32 west longitude and 14° 53 and 14° 35 north latitude. It covers an area of 550 km² or 0.28% of the national territory. It is bordered to the east by the Thiès region and by the Atlantic Ocean to the north, west and south (Pouye 2016). Our study area is all coastal zones in the Dakar region (133,69 kilometers) (Bakhoum et al. 2018), i.e., 18,91% of the total coast of Senegal and the delimitation is based on the different type of coast: sandy coast in the northern and southern part and rocky coast in the western part. This study area is divided into these coastal segments. This choice is justified by the fact that the geomorphologic, geologic, topographic conditions and the level of vulnerability are not the Dakar region covers an area of about 550 km², e.g., 0.28% of the national territory. It is bordered east by the Thiès region and north, west and south by the Atlantic Ocean (Pouye 2016) (Figure 3). This general presentation of the Dakar region focuses on two different points: The physical and human aspects. The figure 3 is the location map of Dakar region and the district municipalities along the coast.



Source: personal work

Figure 3: Location map of the Dakar region

I. Physical presentation

Dakar region, known as the peninsula of Cape-Verde due to its geographical position from the sea, is characterized by its geology, geomorphology, climate, hydrodynamic agents and vegetation.

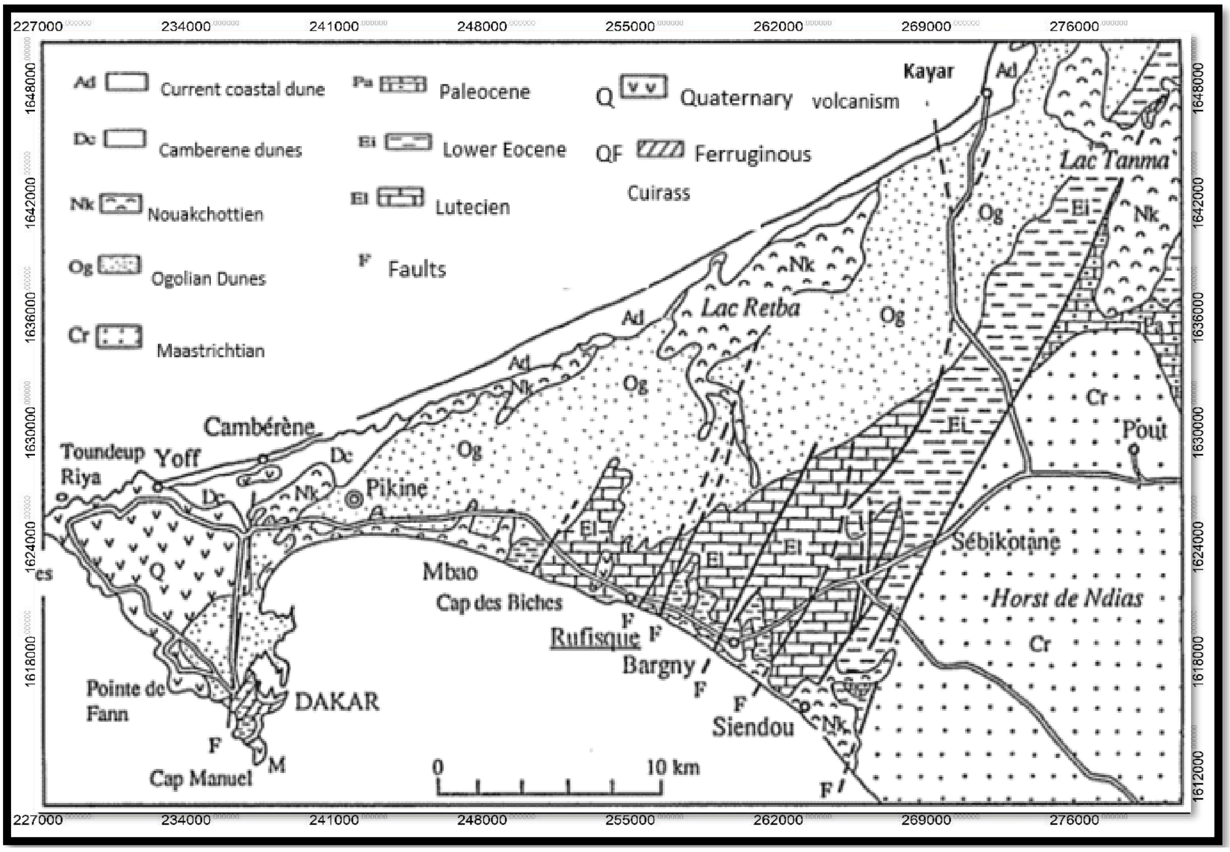
I.1 Geology and geomorphology of Dakar

According to Adjoussi (2001), three different activities determine the geologic history of the Dakar region: volcanic activities and marine transgressions and regressions, which were observed from the pre-quaternary period up to the quaternary period. Significant faults mark this geology. In addition, in a study, Sane and Yamagishi (2004) stated that "These faults formed two horsts: The Dakar and Ndias horst. Dakar plateau 50 m high above sea level consists mainly of Tertiary volcanic such as basaltic, tuffaceous, and sedimentary rocks. The Ndias horst reaches a height of 105 m and is formed of quaternary volcanic deposits. The morphology of the two horsts is accentuated by the occurrence of recent volcanic cones composed of both volcanic ash and basaltic lavas. The horsts develop indented, cliffy shorelines that preserve a less degraded structure. On such shorelines, the direct impact of waves is consequently reduced". The outcrops present in this region, from secondary to quaternary age, are the witnesses part of the geodynamic history of the Senegalese-Mauritanian basin and can be related to four main periods (Niang 1996): From the Upper Cretaceous to the Paleocene; end of the Paleocene to the middle Eocene Upper Eocene to the Pliocene, Pliocene to the Holocene, Middle Miocene and the Pliocene to Holocene period. According to Niang (1996), during the Upper Cretaceous to Paleocene period, the Senegal-Mauritanian basin experienced detrital sedimentation marked by Campano Maastrichtian clayey sandstone series in the area outside Ndias, and there was also a significant marine regression marking the end of the Maastrichtian. After this regression, a transgression of the Paleocene favored clayey-marl deposits except in the area of the Ndias dome.

After this period from the Upper Cretaceous to the Paleocene, the period from the end of the Paleocene to the Middle Eocene is marked by clay-marl facies and two transgressions are noted: the first one in the Lower Eocene and the second one in the Middle Eocene, with the establishment of clayey, marl and calcareous series. This period ends at the end of the middle Eocene, marked by a tectonic episode that will cause a rejection of the horst and graben structure of the Cape Verde peninsula accompanied by uplift, emersion and tilting along an E-W axis of the Ndias horst. On the other hand, the period from the Eocene to the Pliocene is marked by continental detrital sedimentation. It is characterized by sandy-clayey ruby and azoic formations of terminal continental. The last transgression occurs in the Middle Miocene. During this period, the basic Tertiary, Oligo-Miocene volcanism of the Dakar-Thiès region was also established, represented by lava and tuffs whose deposit mode is closely linked to tectonics. A vast erosion surface was set up from the terminal Miocene to the Pliocene.

And finally, the Pliocene to Holocene period, characterized by sedimentation strongly influenced by climatic fluctuations, is at the origin of two levels of ferruginous armour in the lower Pliocene: the primary Pliocene armour and the secondary armour of ancient Plio-Pleistocene age, which forms the Dakar plateau. This secondary cuirass formation is covered by the formation of sub-basaltic sands, which are thought to be ancient continental dunes or coastal sediments of aeolian origin brought by coastal drift, and it is at this time that the quaternary volcanism of the mammals dates from the lower Pleistocene (Niang-Diop 1996).

The following map is about the geological map of the Dakar region.



Source: Niang-Diop, 1996

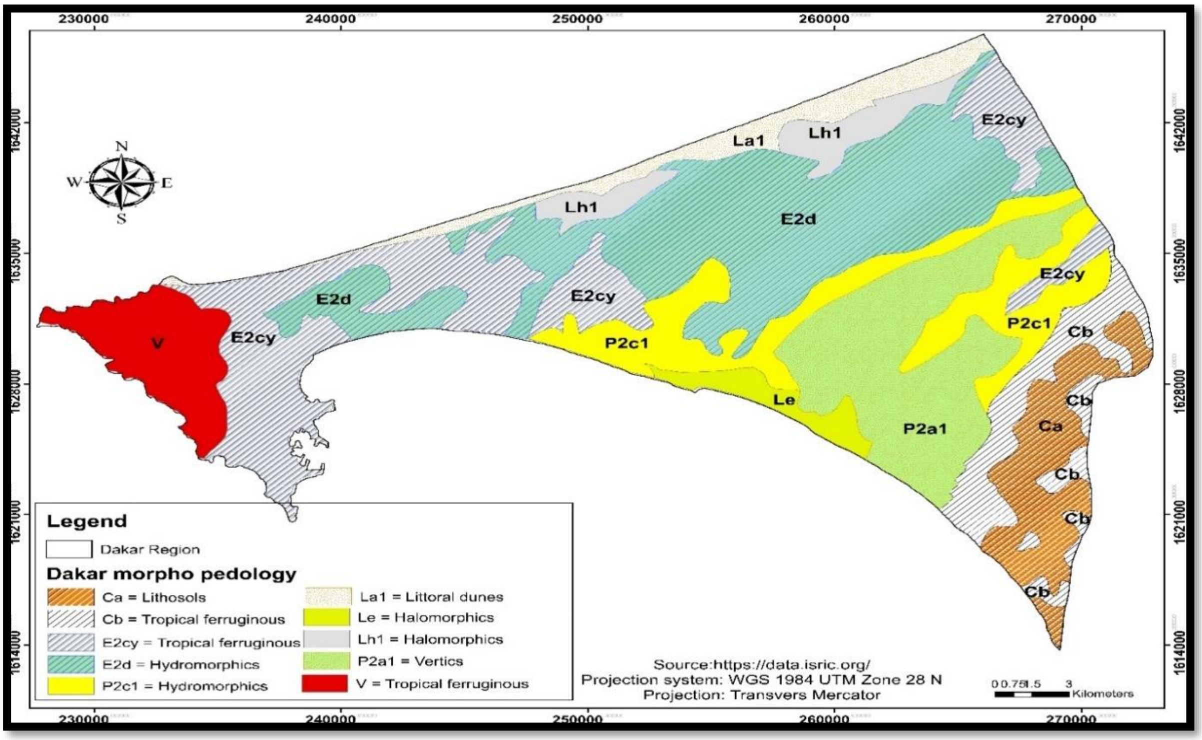
Figure 4: Geological map of the Dakar region

Regarding the geomorphological structure of Dakar region, resulting from the evolutionary dynamics of geological formations, they are recognized in the graben. The coastal dunes are arranged along the north coast and consist of two influential groups: living dunes behind the high coast and young dunes behind the living dunes (Figure 4) (Adjoussi 2001). These dunes are set up by N-S oriented littoral drift from 4000 years B.P. after the Flandrian transgression. The Ogolian Erg (22m-15 m B.P.) is situated in the focal and northern part of the Dakar region. It incorporates longitudinal dunes running in the NE-SW direction, isolated by dame interdune corridors. The substratum of the limestone plateau of the Bargny-Rufisque district is made of limestone and Marl of Eocene age. In the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion (Sane and Yamagishi 2004).

I.2 The morpho pedological characteristics of Dakar

Five formations characterize the morpho pedological conditions of the Dakar region: Recent volcanic formation, formation of Maastrichtian sandstone (Cretaceous), formation on marl-limestone rocks (Paleocene-Eocene), recent Ergs and littoral formations.

The figure 5 is about the morphopedological characteristics of the Dakar region.



Source: USAID Project/ RSI N 685 - 0233

Figure 5: Morpho pedological map of the Dakar region

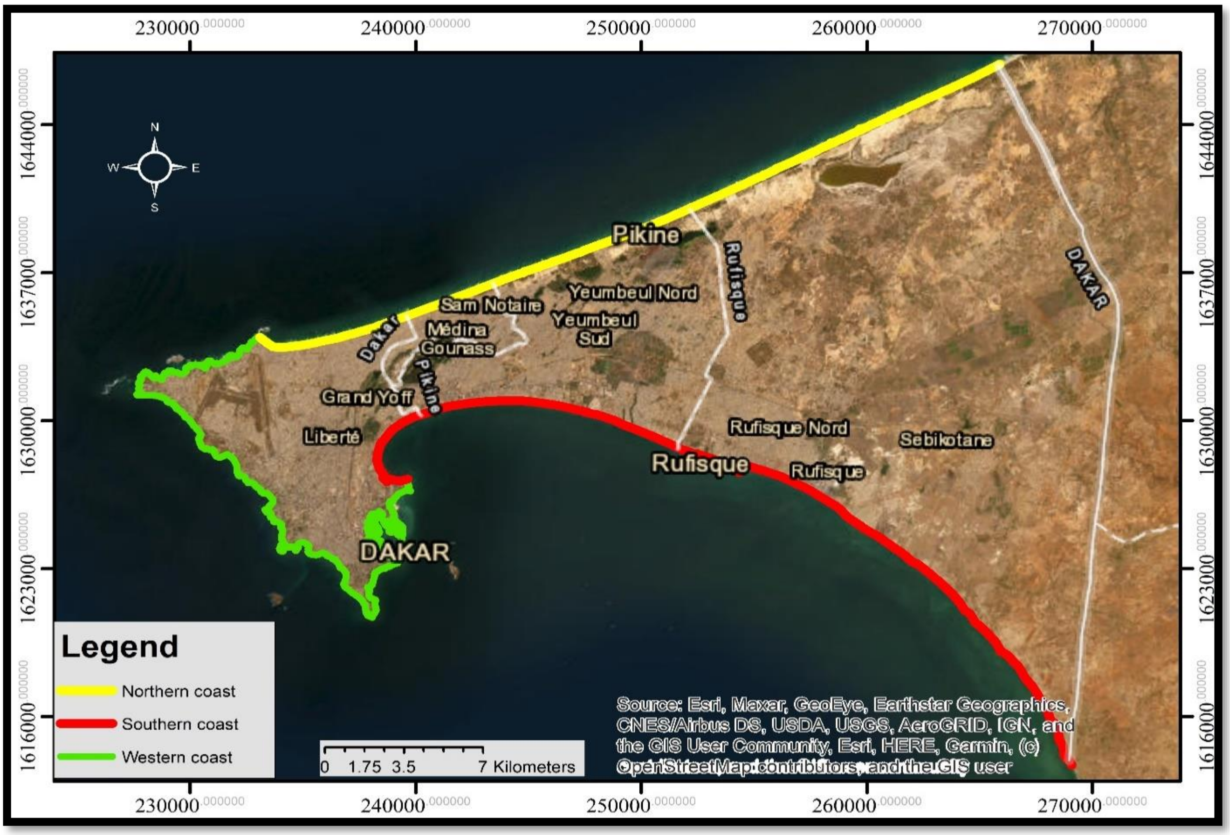
The recent volcanic formation is composed of a Basaltic spread, a low leaching tropical ferruginous soil on complex material in the head of the Dakar region. The formation of Maastrichtian sandstone (Cretaceous) can be found in trays and small valley zones and is composed of two types of sediment: Lithosols and regosols, on cuirass dismantled on sandstone which can be found in the tray zones at the centre of Dakar and in the north close to the coastal dunes and tropical ferruginous soils with little or no leaching, on colluviums which appear in small valley zones. The formation of marl-limestone rocks (Paleocene-Eocene) can be found in the tray, alluvial plain, cliff zones and the edge of the plateau and is composed successively by the vertic hydromorphic soils on clayey marly-limestone material, strongly tirsified; deep hydromorphic soils on sandy-clayey alluviums; hydromorphic soils on various materials; erosion rendzina on marl-limestone rocks and hydromorphic soils on limestone colluvium. The recent Ergs are composed of the dunes from the inside and coastal dunes: Hydromorphic soils in the Niayes area and low leaching tropical ferruginous soils.

Three types of sediments characterize the littoral formations: Sharp coastal dunes and marine beaches - Raw mineral soils; Semi-fixed coastal dunes - Raw mineral soils and Holomorphic soils on clayey material - Hydromorphic soils on clayey material - Slightly evolved soils on exuding sands (Figure 5) (USAID Project/ RSI N 685 - 0233).

I.2.1 Different types of coasts in Dakar

According to Duxbury et al. (2002), the coasts of the world are areas where the land meets the sea. Coastal areas are not static. Tides, winds, waves, earthquakes, changes in sea level, changes in the position of the continents, and changes in climate all shape and reshape the world's coast and will continue to do so. In Senegal, with a coastline of about 706.72 km, three different types of coasts are noted: The rocky coasts are limited to the Cape Verde peninsula and a few capes to the South of Dakar; Mangrove estuaries characterize most of the mouths of its major rivers, such as the Senegal River, where the mangrove is a relic, Saloum and Casamance; Most of the littoral is composed of sandy coast and forms two major groups separated by the Cape Verde peninsula (Diaw 1992).

The northern coast, called the grand coast (from Saint-Louis to Yoff), is backed by a powerful dune system and is almost straight. It is under the predominant influence of the Northwest swells, which induce a coastal drift, directed towards the south and strongly fed since the estimates of sedimentary transits parallel to the coast vary between 200,000 and 1 500,000 cubic meters per year. These recent and current dunes, with raw mineral soils, have isolated saline lakes that are witnesses of the last transgression. Barrier beaches and holomorphic soils border them. Whether the north and south coasts are sandy, the southern coast (from Hann to Djiffere) is a segmented coast in a succession of capes and bays whose arrangement is controlled by tectonics. A shallow barrier beach backs the sandy beaches. This coast is subject to a northwest swell whose energy is reduced due to refraction and diffraction around the Cape-vert peninsula. Although a south-eastward coastal drift is present and the estimates of sediment transport indicate that the provision is much less important than along the northern coast, 10,500 to 300,000 cubic meters per year (Niang-Diop 1996). The Dakar region is characterized by three different coasts: The North, West, and South coasts (Figure 6). The north and south coasts are sandy coasts while the west coast is a rocky coast. The following map is about the Different types of coasts in the Dakar region.



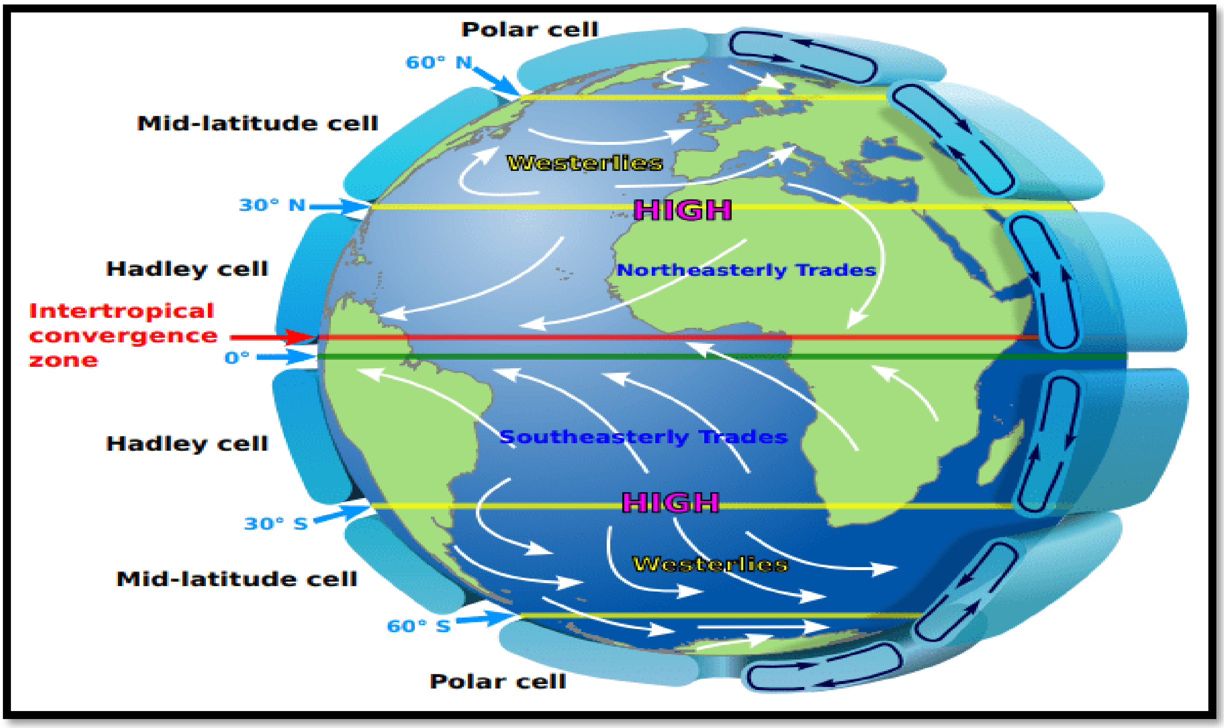
Source: http:/usgs.gov.2021

Figure 6: Different types of coasts in the Dakar region

To sum up, these geologic, geomorphologic and morpho pedologic conditions play an important role in the Dakar region's morphology and natural coastal erosion dynamic, which is accentuated by other key physical parameters such as climate parameters.

I.3 Atmospheric circulation

The general atmospheric circulation is generated by three phenomena: solar radiation, rotation, and earth revolution. The exchange of energy between the sun and Earth is generated by solar radiation. Therefore, some regions receive more heat energy than others. Atmospheric pressure, i.e., the weight of air above a place in High latitudes due to the energy deficit, will register a settlement of the air at ground level, resulting in the existence of high-pressure zones called anticyclone zones where the high polar pressures are noted. However, in the tropical zone, important solar radiation will result in upward movements, which means that the air will tend to rise, and this phenomenon will require the existence of low pressures. These are called tropical low pressure or intertropical low pressure. From solar radiation, a circuit of air will be carried out from high pressure to low pressure, in other words, from the polar zones to the tropical zones. This circulation is linked to thermal factors, i.e., heat. Therefore, tropical zones, i.e., low latitudes, are considered energy-exporting surplus zones, whereas high latitudes, characterized as polar zones, are energy importing deficit zones (Hartmann, 2007). The figure 7 is about the general atmospheric circulation and different cells of the Earth.



Source: By Kaidor - Own work based on File: NASA depiction of Earth global atmospheric circulation.jpg, CC BY-SA 3.0, (*File: Earth Global Circulation - En. Svg - Wikimedia Commons*, n.d.).

Figure 7: Global atmospheric circulation and different cells of the Earth

This figure shows that the air circulation in the atmosphere is split into three different cells in each hemisphere: The Hadley (Tropical and intertropical zones), Ferrell (Latitudinal zones) and polar cells (Polar zones). The Ferrell cells are not driven by temperature and flow opposite the Hadley and polar cells. Acting like a gear. These circulating cells transport heat from the equator to the poles and result in semi-permanent areas of high and low pressure due to the rise and descending parts of the circulation cells giving us our climatic zones (Remote Sensing Notes - Docsity, n.d.).

The rotation of the Earth introduces variations in the atmospheric circulation through the way that the Earth is exposed to the sun but also a deviation of winds by the Coriolis force. As a result, the winds leaving the tropical high-pressure areas are deflected to the right in the northern hemisphere and eventually form a westerly wind called the Jet Stream (Archer et al. 2008).

Just as part of three cells, the global circulation pattern is at a point because of the Earth's rotation. The turn of the Earth instigates an obvious move to one side in the Northern Hemisphere and the left in the Southern Hemisphere. This is the Coriolis effect which is the way that the Earth's surface pivots faster at the equator than at the poles. This Earth is more extensive at the equator, so it has further travel in one day. The consequence of this implies that as air moves from the equator, it doesn't move in a straight line relative to the Earth's surface (Dummies, n.d.). Instead, it appears to an observer on the ground to move in a slightly curved direction, but there is no physical force causing this deflection. As the climate turns with the Earth, it is only because of air moving from an area that is moving quickly to a region that is moving more slowly. This deflection is a major factor in why winds blow anticlockwise around low pressure and clockwise around high pressure in the Northern hemisphere and vice versa in the Southern Hemisphere, so when flowing towards the north pole, the air is deflected toward the east. When travelling southwards back towards the equator, it is deflected westwards (Figure 7). The same result occurs in the southern (Met Office 2018).

The circulation is roughly from high tropical pressures to intertropical low pressures in the tropical zone. Tropical high pressures can form a continuous anticyclone belt on the surface where permanent cells such as the Azores anticyclone or seasonal cells such as the Sahara-Libyan anticyclone or the Australian anticyclone.

❖ When the geographical equator is confused with the meteorological equator, trade winds circulations are observed on the surface in both meteorological hemispheres.

❖ When the geographical equator shifts away from the meteorological equator, two circulations can be distinguished: trade wind circulations which are prolonged by a monsoon circulation.

In the upper tropical troposphere, three strong wind cores can be distinguished. Two of these wind cores (North African East Jet and South African East Jet) are individualized in the middle layers on either side of the meteorological equator. They are centered around 3000 to 4000 meters above sea level, while the third wind core (Tropical East Jet) is found in the upper troposphere (10,000 to 14,000 meters above sea level) (Met Office 2018).

I.3.1 Climate characteristics of Dakar region

The climate of the Dakar region is characterized by aerial, thermal and water conditions. This type of climate is Canarian and is strongly influenced by geographical and atmospheric conditions. By the presence of a seafront surrounding almost the whole Dakar region, it is characterized, during the year, by a microclimate marked by the influence of the sea trade winds; hence the existence of a fresh and quasi-permanent and relatively high humidity of around 25%. However, the harmattan, Saharan continental trade wind, is felt weakly in the dry season further away from the coast. The minimum temperature varies between 17° and 25° C from December to April and from 27° to 30° C from May to November (Sogué Diarisso et al 2004). In addition, located in the coastal Sahelian domain, the Dakar region is characterized by low amounts of rainfall between 100 and 500 mm, and the average annual temperatures do not exceed 30°C (Sagna 2007).

I.3.1.1 Airline conditions

The main climatic features result from a combination of geographical and climatic conditions. Geographical conditions are expressed by the latitude that gives the tropical areas and by the advanced position of West Africa in the ocean, which determines the different climatic conditions between the coastal region and the inland countries. Aerologic conditions are expressed by alternating over the country of three flows whose movements are facilitated by the flatness of the relief (Sagna 2007).

I.3.1.2 Maritime trade wind

Originating from the Azores anticyclone, the maritime trade winds have north to north-east and east direction constantly moist and cool. It is marked by a low daily thermal amplitude. Due to its vertical structure, which blocks the development of clouds, it cannot dump rainfall.

However, its humidity can be deposited overnight in the form of dew. Its domain concerns a coastal fringe which diminishes in the south with the rise of the monsoon but which is maintained almost all the year along the Dakar-St. Louis axis. Towards the interior, it dries out quickly, acquiring characteristics close to the harmattan, which separates it from the discontinuity of the maritime trade winds (Sagna 2007).

I.3.1.3 Harmattan

The harmattan is the final branch of the Saharan continental trade wind and is characterized by a large drought linked to its continental course and very high thermal amplitudes. It is cool at night and hot by day. It often carries sand particles and dust that constitutes the "dry mist". Harmattan cannot generate rainfall and it is accompanied by a very high evaporation capacity. As it approaches the coast, harmattan passes over the layer of humid wind air trade maritime, reinforcing the upper drought. It helps to prevent precipitation from Atlantic humidity (Sagna 2007).

I.3.1.4 Monsson

Benefiting from a very long trajectory which makes it humid, the monsoon is a result of the St-Helena anticyclone in the South Atlantic. It blows over the country during the summer period depending on the southeast-northwest direction, and it dries out relatively as a function of its inward penetration. It is characterized by a low thermal amplitude but with temperatures generally higher than those of the trade winds maritime. The monsoon enters the territory in April and gradually extends until July and August, when the northern coast is subject to the trade winds maritime and monsoon. It withdraws very slowly in September, then abruptly in October, the month in which the trade winds re-establish their domination (Sagna 2007).

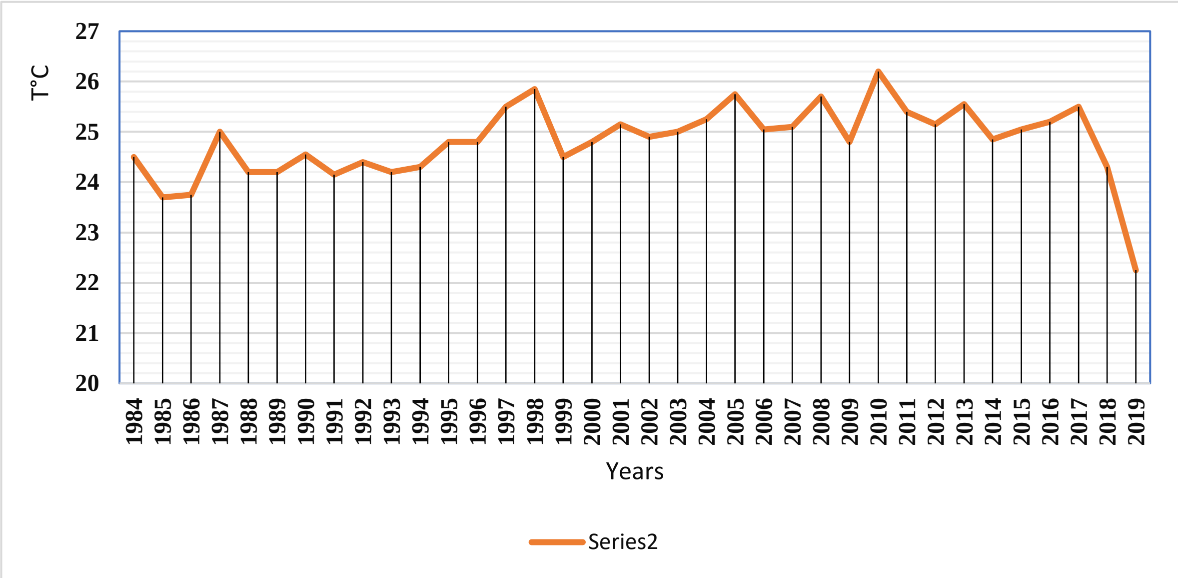
I.3.2 Temperature

Due to the maritime trade winds and its location in the coastal Sahelian area, the Dakar region undergoes average annual temperatures that do not exceed 30°C from 1984 to 2019. The average annual maximum temperature is around 30°C, and the minimum temperature annual average is 25°C. It is softened by the effect of the maritime trade winds (Sagna 2007).

The areas along the coast are the coolest region of Senegal due to the quasi-permanence of the maritime trade winds. The thermal amplitude, both diurnal and annual, follows the same progression. It is weak on the coast and progresses towards inland. In the Northwest of the country near the coast, the thermal regime only reaches a maximum (September-October) and a minimum in January (Sagna 2007). Climatic data from the Dakar-Yoff weather station shows that the average annual temperatures over the last 30 years are marked by highs and lows. These variations were observed between 1984 and 1992, with the highest (28.1°C) and (26.6°C) average, i.e., a periodic average (1984-1992) of 25.7°C. Most of the years in this period have nine or ten wet months, from October to June. The year 1987 has the most variations in temperature with a thermic amplitude of 25°C. 1993-1998 is marked by an evolution of annual maximum temperatures (28.8°C), the highest of this period.

From 1999 to 2019 is the hottest period in the last twenty years. It groups the highest averages: 28.5°C, 28.8°C, 29°C and 29.3°C (Figure 8).

The figure 8 is about the annual average temperature of Dakar region from 1984 to 2019



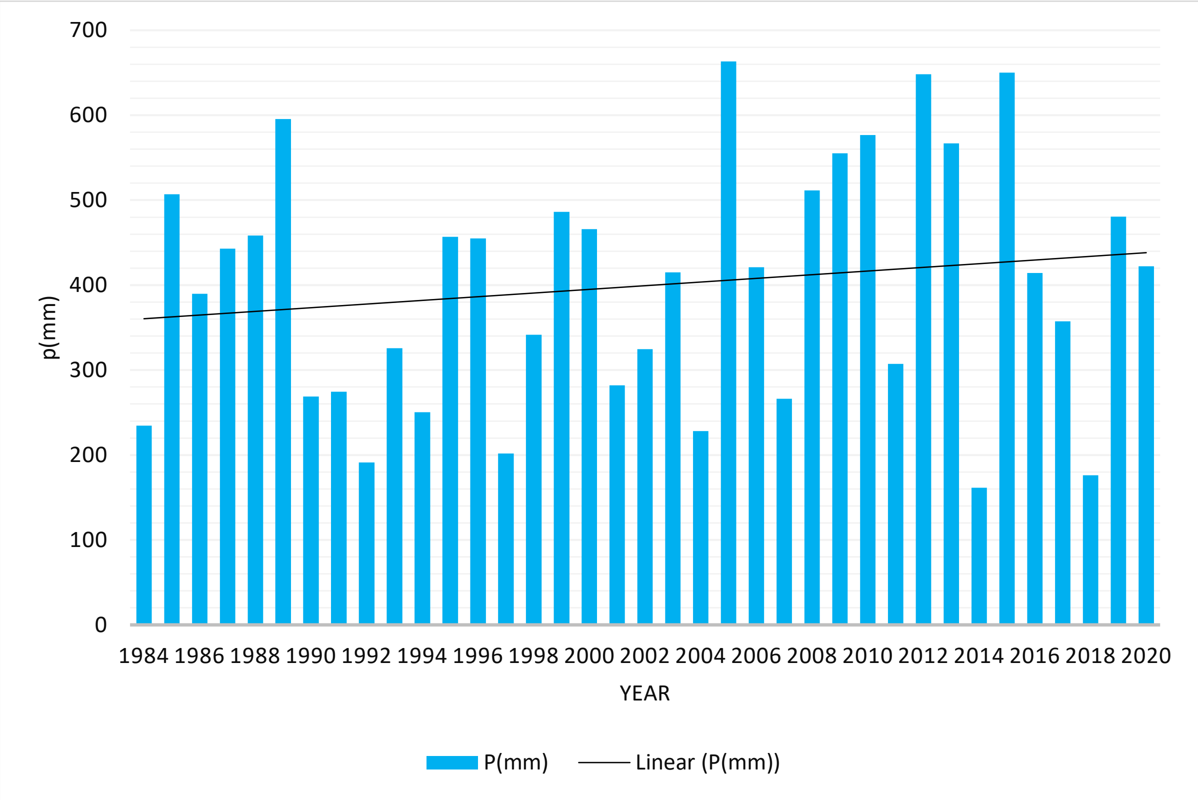
Source: ANACIM, 2019

Figure 8: Annual average temperature of Dakar region from 1984 to 2019

The climate of the Dakar region can be determined by airline conditions which are the trade wind maritime, harmattan and the monsoon. In coastal areas, the wind is among the key factor in the coastal system generating swell, sea currents and waves and plays an important role in coastal sediment transport. However, the perturbation of these airline conditions in coastal zones accentuates coastal erosion through increased storm surge frequency, coastal flooding, dune retreats, dune disappearances, etc. As a result, the coastline moves backwards, causing a disturbance in coastal zones. In general, we have an increasing temperature trend from 1984 to 2019. This is one of the effects of current climate change and is mainly caused by the variation of solar radiation, disturbances of arbitrary parameters, the action of volcanism in the stratosphere and greenhouse gas emissions into the atmosphere by humankind (CO2, CH4, N2O, H2O, and aerosols). It manifests through global warming, sea-level rise, irregular rainfall patterns, increased floods, drought, melting ice caps, seasonal shifts, disturbance of plant inflorescence, etc. Far from being negligible, rainfall is an important element in climate characteristics.

I.3.3 Rainfall

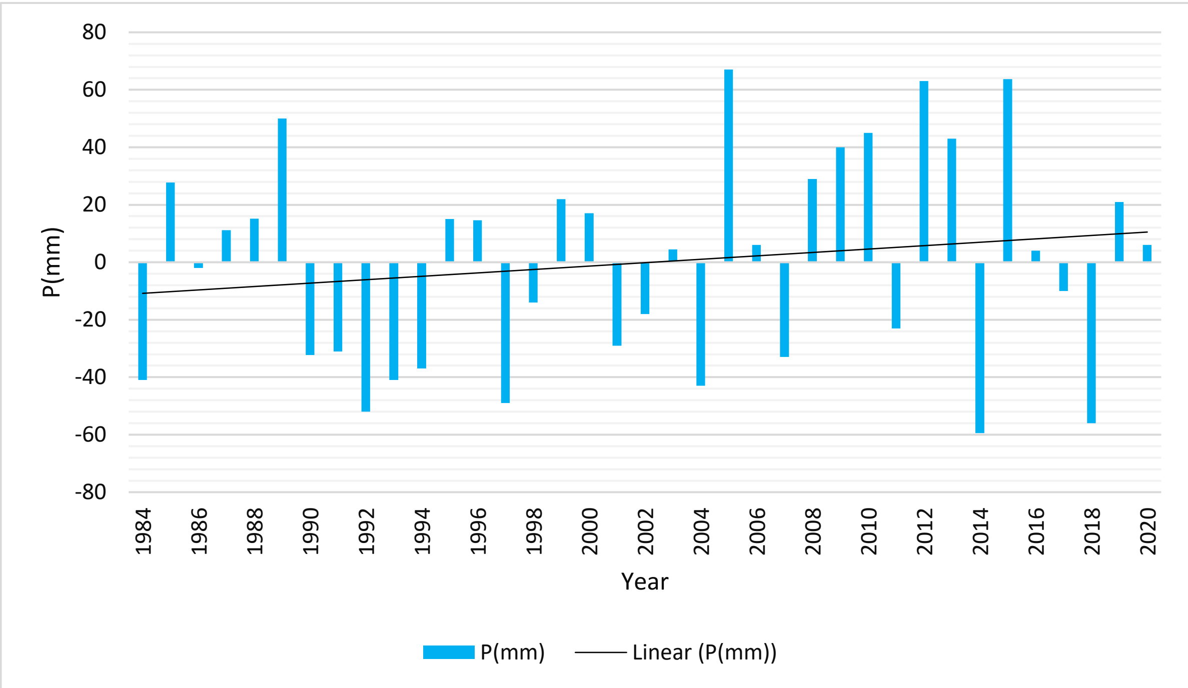
Due to its location in the sub-Saharan zone, the Dakar region is subject to two seasons: dry and rainy seasons. The dry season is characterized by a rarity of pluviometry and is generally observed between November to May. The rainy season is started in June and ends in October. It is characterized by rainfall which often causes flood events. The figure 9 is about the annual average rainfall evolution from 1984 to 2020, showing the global trend in precipitation in this period.



Source: ANACIM, 2020

Figure 9: Annual average rainfall of Dakar region from 1984 to 2020

In this figure, different variations in the annual average can be noted. Therefore, the highest annual monthly average exceeding 500 mm concern 9 years: 1985, 1989, 2005, 2008, 2009, 2010, 2012, 2013 and 2015 recorded respectively 507mm, 595mm, 663mm, 512mm, 555mm, 577mm, 648mm, 567mm and 650mm. The lowest annual and monthly average rainfall didn't exceed 200mm and concerned the years 2012, 2014 and 2018, respectively, 191 mm, 161 mm, and 176 mm (Figure 10). The figure 10 shows the annual percentage deviation in rainfall. It allows identifying the exceed and deficit years in pluviometry and the general trend of this period.



Source: ANACIM, 2020

Figure 10: Histogram of percentage deviations of the annual rainfall of the Dakar region from 1984 to 2020

Rainfall data from 1984 to 2020 in the Dakar region are subject to analysis and can be divided into two periods:

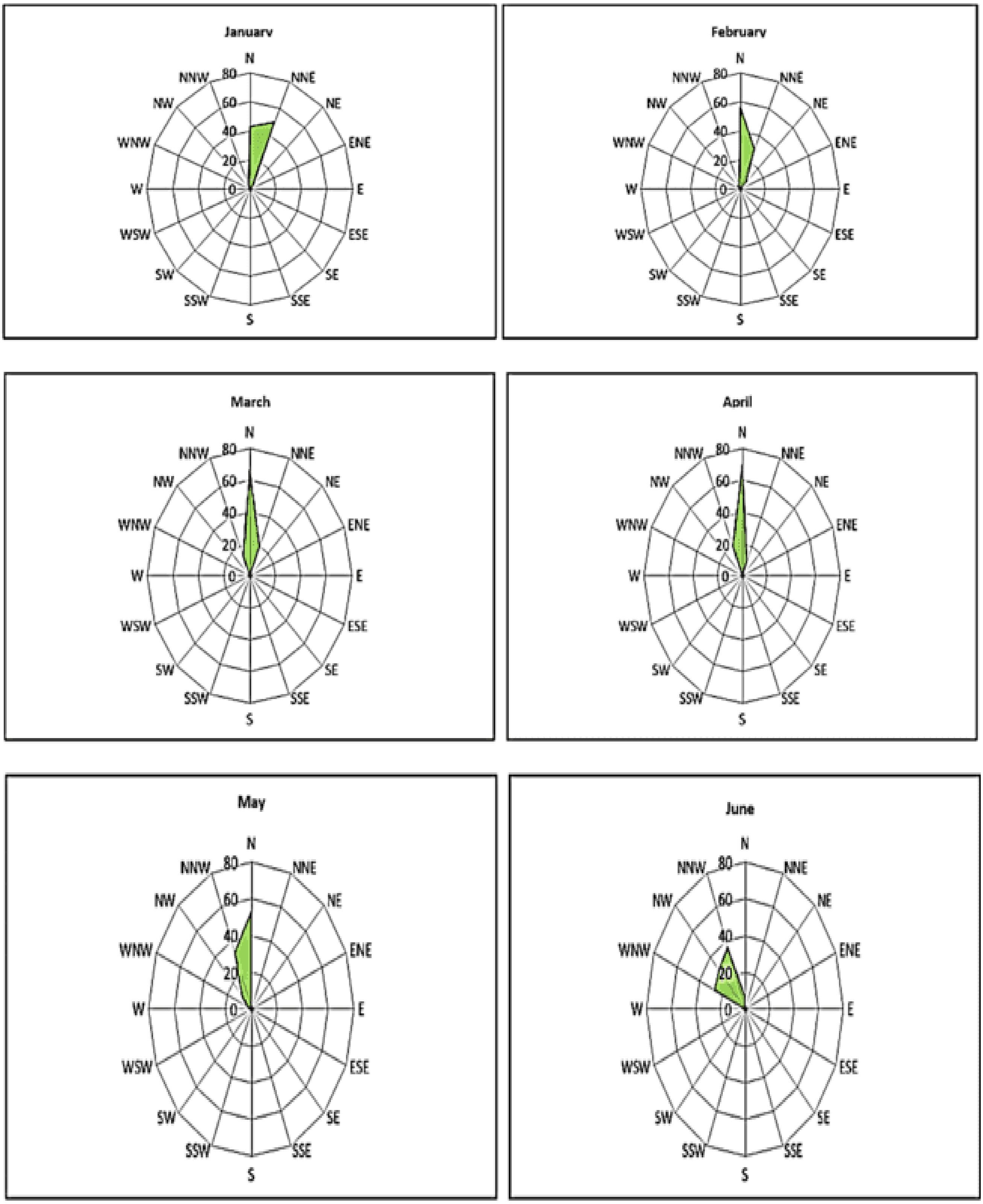
- From 1990 to 2000: the total amount of rainfall is globally in deficit with a succession of discrepancies deficits from 1990 to 1994 and annual averages not exceeding 400 mm.

- From 2001 to 2020: this period generally exceeds 12 excess years over 20 years with an annual average of 421.4 mm (Figure 9).

The climate variability can be seen in total rainfall recorded from 1984 to 2020. The standard deviations of precipitation for the Dakar-Yoff station can vary considerably from year to year. Therefore, according to Sagna (1995), this great variability is due to the types of disturbances that bring most of the rain to Dakar: grain lines and disturbances cyclonic. One of their main characteristics is that they are random. The passage of two-grain lines can take several days. In addition, the frequency of ascents in the Intertropical Convergence Zone and cyclonic disturbances are particularly high. It can cause a succession of cyclones of precipitation for several hours or days. Therefore, this rainfall variability is another natural cause of flooding in the Dakar region. According to the IFRCARCS (2019), flooding is the most frequent climate-related disaster in Senegal, particularly in the Dakar region. Several deaths have been reported during flooding in the Dakar region, with many injuries since 2005, when a long drought ended. This year's floods have taken a heavy toll on urban dwellings, which have suffered extensive material damage. Many roads in the Dakar region have become impassable, causing several accidents, traffic jams and disruptions. Human displacement is one of the most severe damages which causes flooding. Consequently, flooding affects the livelihood of displaced people by developing certain diseases such as malaria and other water-borne diseases. In addition, it would be true to say that these impacts of flooding adding to the impacts of hydrodynamic conditions in coastal zone accentuate the vulnerability of people living along the coast to coastal erosion, reducing their adaptation capacities.

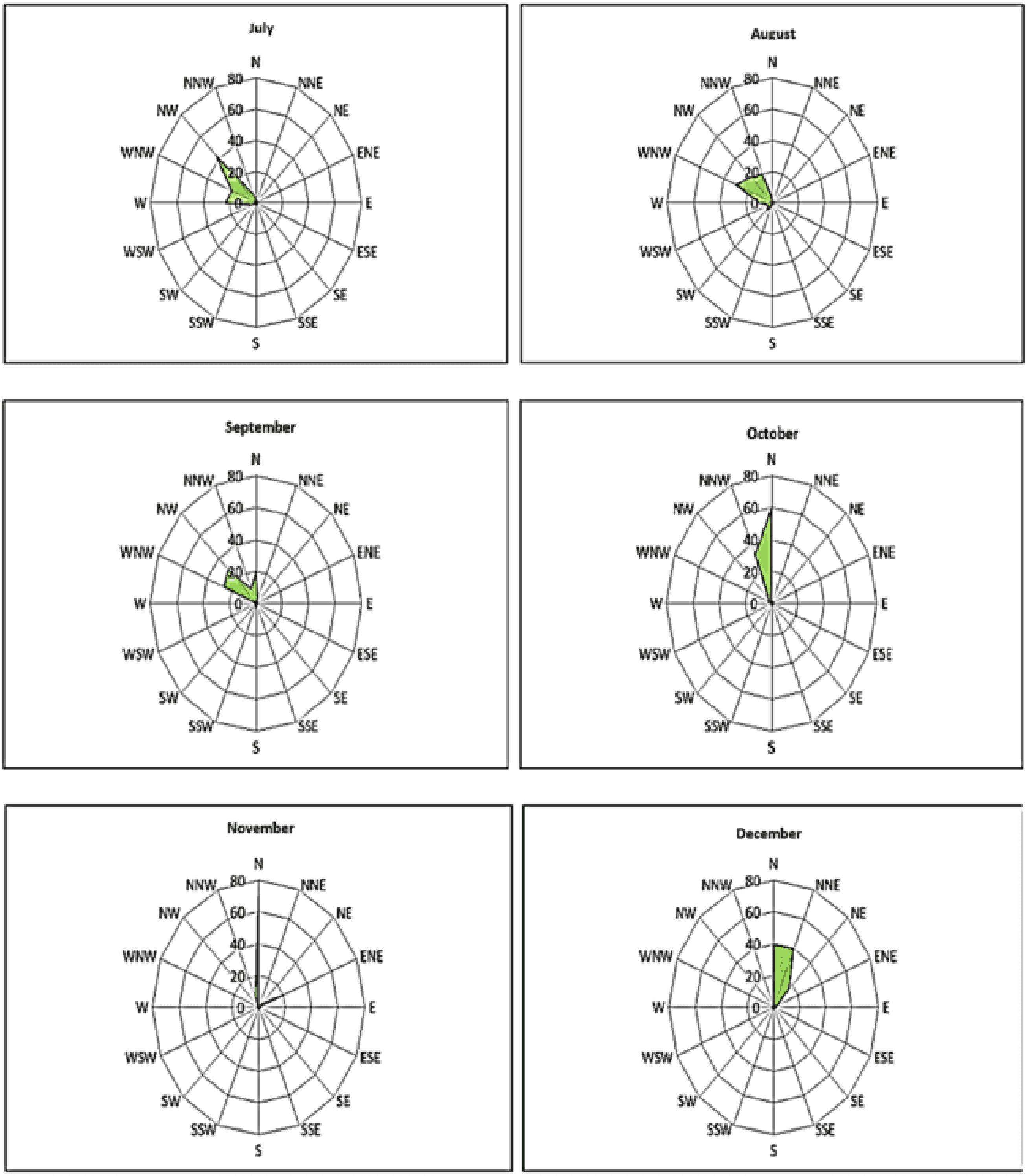
I.3.4 Winds

The wind has two characteristics: direction and speed. The direction is determined by the cardinal points (North, East, South and West), and the speed is expressed in m/s. From these points, it would be true to say that there are winds from the North, South, East and West. Height directions compass rose, composed of four principal directions and four secondary directions instead of the one with four directions, is used because climatologic science deals with height directions compass rose (Sagna, 1995). The figure 11 shows the height directions wind compass from 1984 to 2020. It is about the monthly average of wind direction over the year from 1984 to 2020.



Source: ANACIM, 2020

Figure 11 A: Wind compass of Dakar region from 1984 to 2020



Source: ANACIM, 2020

Figure 11 B: Wind compass of Dakar region from 1984 to 2020

For the wind analysis from 1984 to 2020, the classification of winds according to their directions and the determination of their frequencies are used. As a result, an average wind year comprises the 12 months of representative winds from 1984 to 2020. These months can be divided into three wind seasons:

- The wind season from November to February covers four months and is dominated by winds from the North-East quadrant. It is characterized by maximum temperatures which do not exceed 30°C and a maximum relative humidity of up to 70%.

- The second wind season covers three months (March, April, and May) and is dominated by the north maritime trade winds. It is characterized by temperatures exceeding 30°C and marks winter and summer transitions.

- The third season also covers three months (July, August, and September) with predominantly westerly winds. These winds, better known as monsoons, are the generator of winter rainfall exceeding 300 mm. It should be noted that two transition months exist: the first is the month of June, which marks a separation between the first and the second season, and the second is October which marks the separation between the first and the third.

I.4 Hydrodynamic characteristics

According to Sanlaville (2001), weather and marine phenomena, particularly waves and coastal currents, play a decisive role in changes those coastal areas are subject to. It is also necessary to consider the volume of clastic materials at the disposal of these dynamic agents and which constitute the active coastal sedimentary prism. The hydrodynamic agents are the swell, wave dynamics, sea current, coastal drift, tide, mean sea level, and wind.

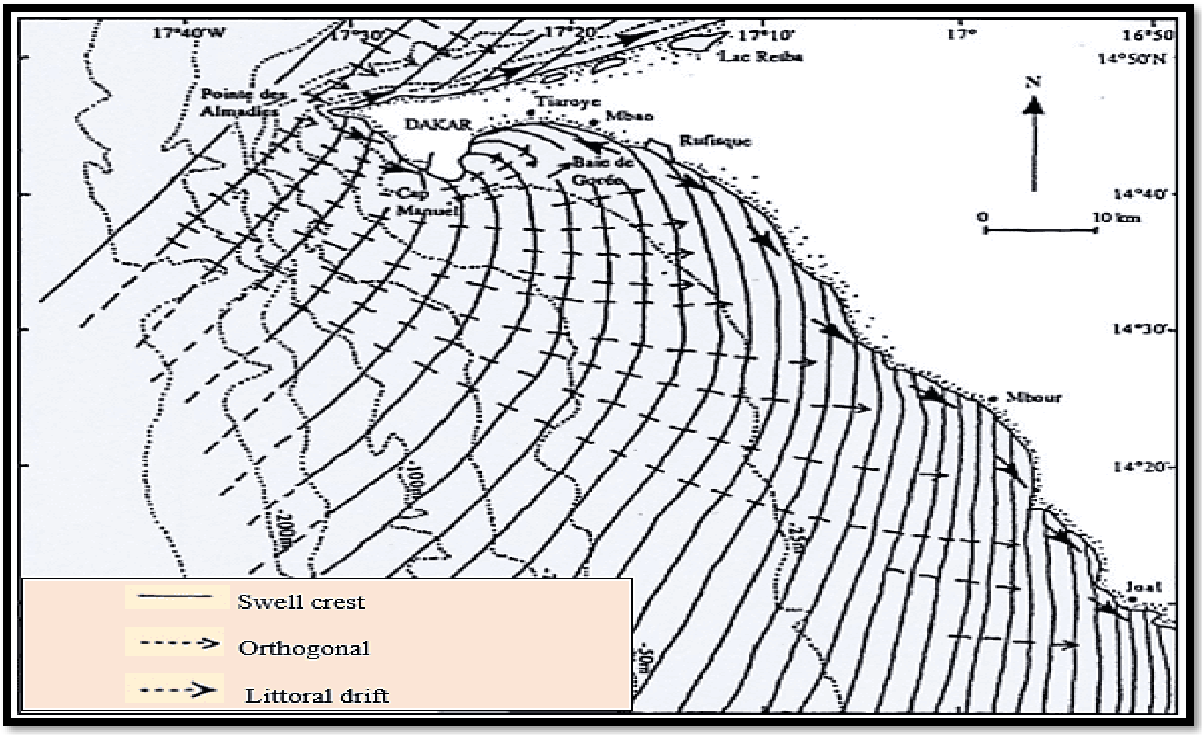
I.4.1 Swell and wave dynamics

When swell approaches the coast, its characteristics change. Its camber increases. It breaks: it is the wave. When the swell characteristics change close to the coast, it influences the bottom and acts on sediment transport. Waves and swells generated by wind and currents are the two most important forces that influence and determine the dynamic behavior of beaches (IBE and Quelennec 1989 in Adjoussi 2001). Its period is between 1 and 30 seconds. It is therefore characterized by: Its trough H or its amplitude $\alpha = H/2$; its wavelength - L - separating two successive crests; its period T; its celerity C; its camber $V = H/L$.

Some indications about the swell: its trough does not exceed about fifteen meters on the globe. Its wavelength varies from a few tens to a few hundred meters. Its period varies from 1 s to 30 s. The camber does not exceed 14% (Diaw et al. 1992). In some literature (Masse 1968; Riffault 1980; Sall 1982; Nardari 1993; in Niang-Diop 1996), it is stated that the Cape-vert peninsula receives three long swell types. Northwest swell (N320° to 20°E), South-west swell (N180° to 200°E) and the West swell (N270°)

- **Northwest swell (N320° to 20°E)**

The figure 12 shows the Dakar region's northwest swell crest and littoral drift.



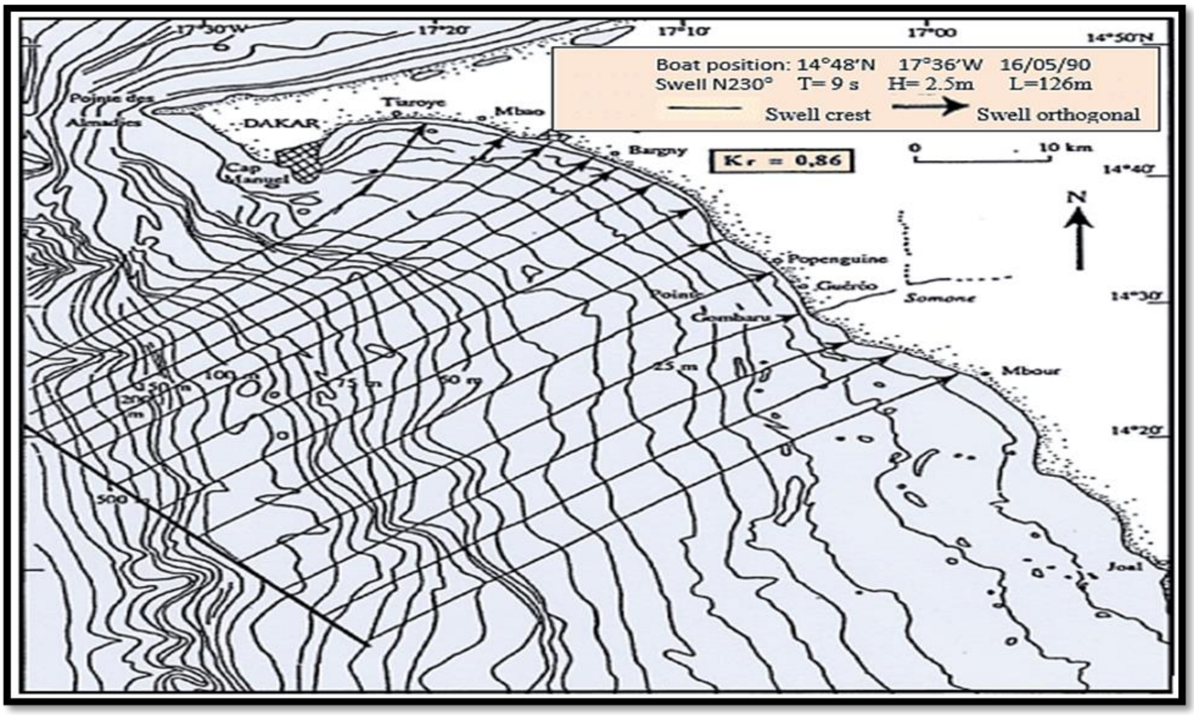
Source: Guérin, 2003

Figure 12: wave and induced coastal drift (northwest swell) of Dakar region

The northwest swell is present throughout the year. In its propagation, it meets some obstacles (Almadies and Bel-Air headlands and Cape-Manuel), which it bypasses. Due to these obstacles, the wave of the northwest swell is subject to three successive diffractions causing the change in its direction. Due to the rise of the continental shelf, the northwest swell also is subject to refraction phenomena. Its propagation is slowed when the water level becomes less than half the height of the swell wavelength. The crest lines tend to position themselves in parallel to isobaths. This swell corresponds, at a depth of 13 m to directions from the South (N150° to 210°E) once it arrives in the Bay of Gorée. These changes in the orientation of the swell planes are accompanied by a dispersion of energy in the Bay of Gorée, which is already fluctuating according to the importance of the refraction phenomena (especially on the shoal zone between Mbao and Bargny) (Guérin 2003).

- **Southwest swell (N180° to 200°E)**

The figure 13 shows the southwest swell crest, its direction, and its influence on the southern coastal shape.



Source: Guérin, 2003

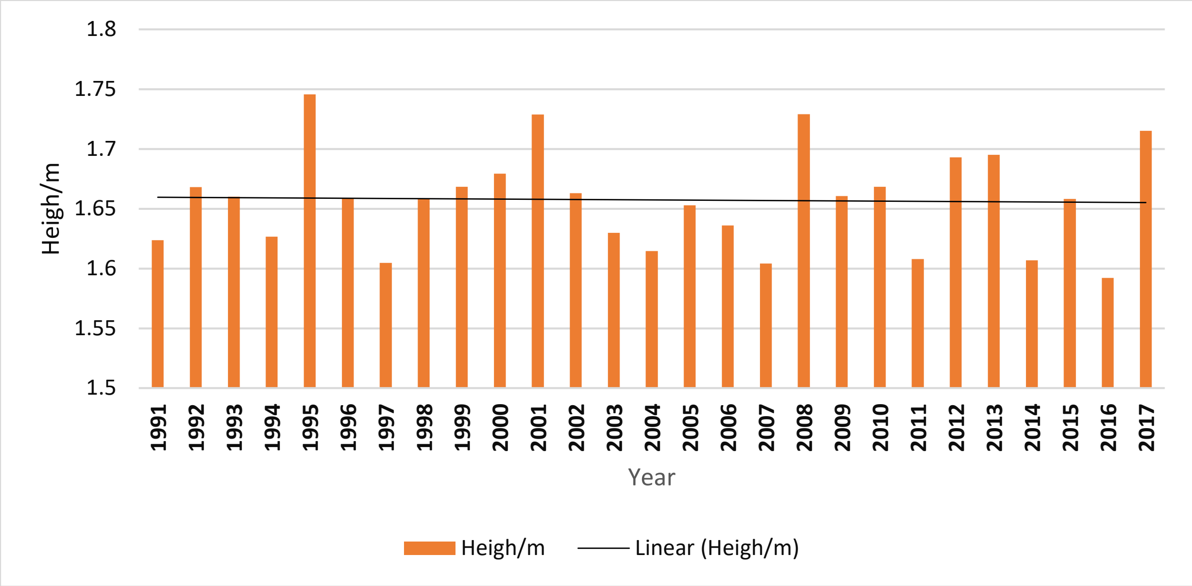
Figure 13: Wave and induced coastal drift (southern swell) of Dakar region

Originating in the South Atlantic, the southwest swell is most noticeable during the rainy season. Offshore, its energy is lower than the northwest swell (11 kW.m^{-1} vs 18 kW.m^{-1}) (Nardari 1993 in Guérin 2003). They reach a depth of 13 m with a minimum direction of N200°. Due to its low frequency and low energy offshore, the importance of this type of swell has been minimized. However, it does generate moderate (1.75m) to strong (2.75m to 3.75m) energetic swells.

- The West swell (N270°)

The west swell remains exceptional. It comes from the cyclones of the sea of the Caribbean and may appear during October, November, or December. Its average energy is about twice as high as the Southwest swells (22.7 kW. m^{-1}) (Nardari 1993 in Guérin 2003).

The figure 14 shows the annual height of swell from 1991 to 2017 and the general trend.



Source: ANACIM, 2017

Figure 14: Histogram of annual swell height per meter from 1991 to 2017

In this figure, it is noted that the height of the swell of the Dakar region from 1991 to 2018 does not exceed 2 meters. The highest height swell was about 1.74 recorded in 1995, and the lowest is about 1.60m (Figure 14). In more concrete terms, Guérin (2003) states that the swells of the Cape Verde peninsula are short (less than 7.5 s). Their heights are less than 2 m, characteristic of the Atlantic Ocean. However, there has been a decline sensitive to the averages of period and height during wintering. This period is characterized by the absence of the northwest swell, with the predominance of southern sector swells. The southwest swell has values close to the northwest swell and is not strong enough to maintain averages of 7 m and 1.7 s during the rainy season.

I.4.2 Sea currents

In Senegal, three masses of water follow on the coast during the seasons. These waters modify the logical sediment behavior;

- from June to August, the waters are linked to the northern edge of the equatorial counter-current. They are hot (27 to 28°C) and salty (36°/00);

- from August to December, the warm Guinean waters (28°C) and desalinated (35°/00) replace the previous ones. They are influenced by the inflow of water from the south;

- from December to May, the north-eastern trade winds dominate and drive away the surface waters, replacing them with deeper, colder, and less salty waters (35,5°/00). The temperature of the coastal waters during this period is between 4° and 4.5°. The drop in temperature due to the rise of deep water is the upwelling common to all the West African coast from December to May, a period when the trade winds and swell of the N.W (UNEP 1985).

I.5 Oceanic circulation

Ocean circulation can be conceptually divided into two components: a fast surface circulation, driven by winds, and a slower, wider circulation, driven largely by water density. By blowing over the ocean, the winds exert a frictional force on its surface, forcing the development of surface ocean currents. As the Earth rotates, these currents flow perpendicular to the wind direction, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (Glossary n.d.). When such currents meet, zones of convergence or divergence of water appear, giving rise to upwelling (deep waters rise to the surface) or downwelling (surface waters sink to the depths). This wind-driven circulation is by far the most dynamic and energetic. It also controls most small-scale phenomena (Shah et al. 2019). The northwest African frontage is part of the tropical Atlantic. It is characterized by two zonal superficial oceanic circulations related to trade winds which move latitudinally between 5° N (January) and 15° N (August) at the same time with the Inter-Tropical Convergence Zone (ITCZ). Three different currents are distinguished in this zone:

❖ The north-equatorial current transport westward cold and salty water of Canary currents. Linked to the North-Est trade winds, it reaches its maximum intensity during the boreal winter when the ITCZ occupy its most southerly position. It is the cold water along the Senegalese coasts (Mix et al. 1986 in Niang Diop 1995).

❖ The south-equatorial current transport westward Benguela (Angola's getaway to the Atlantic) cold water. Linked to the South-Est trade winds, it is reinforced during the boreal summer. Following the monsoon expansion and the ITCZ ascent toward the north.

❖ The north-equatorial counter-current interposes between the north and south equatorial currents, linked to the ITCZ, which transport cold and salty water (tropical water) eastward generated in the west Atlantic edge and form the Guinean current. Tropical water invades the Senegalese coast during this period.

This zonal circulation determines the westward transfer of superficial water, causing a water deficit along the Senegalese continental shelf. This deficit is balanced in two manners: The first one is by the meridian circulation-controlled trade winds with advection of heat and salty tropical water toward the north in the dry season (from November to May) heat and desalinated Guinean waters. This geostrophic current reaches a speed average of 20 $cm.s^{-1}$ attaining its maximum intensity in April-May (about 50$cm.s^{-1}$). The second is by the ascent of deep water or upwelling, which is generated in the dry season under northeast trade winds. (Johnson et al. 1975; Wooster et al. 1976; Mittelstaedt 1983 in Nang-Diop 1995).

I.5.1 Upwelling

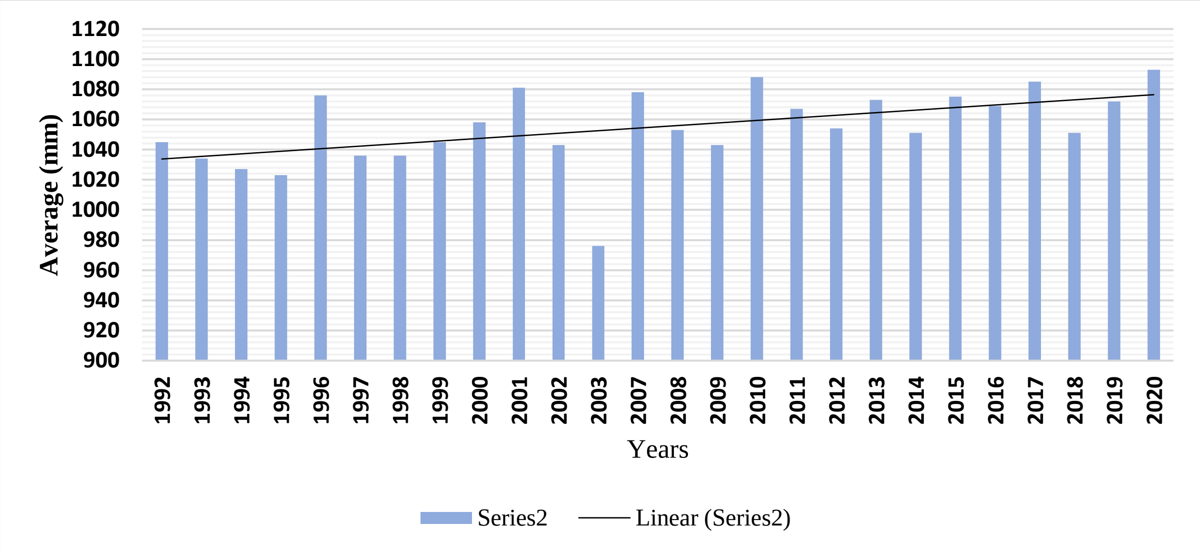
In the Marine Glossary, Upwelling is defined as the vertical motion of water in the ocean by which subsurface water of lower temperature and greater density moves toward the ocean's surface (Hydrothermal Processes | Encyclopedia.com n.d.). Upwelling occurs most commonly among the western coastlines of continents but may occur anywhere in the ocean. Upwelling results when winds blow nearly parallel to a continental coastline and transport the light surface water away from the coast. Subsurface water of greater density and lower temperature replaces the surface water and exerts a considerable influence on the weather of coastal regions. Carbon dioxide is transferred to the atmosphere in regions of upwelling. This is especially important in the Pacific equatorial regions, where 1-2 GtC/year may be released into the atmosphere (Glossary n.d.). Upwelling also results in increased ocean productivity by transporting nutrient-rich waters to the ocean's surface layer (www.Marine-Conservation.Org.Uk, n.d.). This Upwelling phenomenon is observed on Senegalese coasts from December to May and generates high seasonal variations of the superficial oceanic water temperature. Consequently, a rise of the isotherm of 19ºC is noted, representing the thermocline, a layer of water ocean with a greater temperature gradient than the layer below and above it. This rise of the isotherm reaches the water surface of Dakar in February and corresponds to a maximum vertical extension (200 to 225 meters) of water mass observed from January to Marsh. A second maximum vertical extension of the water mass of about 200 meters is also observed from September to October. (Verstraete 1985 in Niang-Diop 1995). According to Ndoye (2016), this upwelling phenomenon can be divided into two seasons:

❖ A cold season of the advective type is characterized by low upwelling from November to January and low and irregular winds. This period corresponds to the installation of trade winds.
❖ Strong winds characterize a cold season with strong upwelling from February to April. This period becomes the principal motor of horizontal and vertical circulations of continental shelf water.

I.5.2 Coastal drift and tide

The coastal drift is a current parallel to the coast. It is induced by the waves that arrive obliquely to the shore. It is active in the surf zone. Coastal drift is the main cause of sedimentary transit on the coast. Its speed varies between 60 and 80 cm/s. In some literature (Barusseau 1995; Soumare 1996 in Adjoussi 2001), it is stated that "a speed of 20 cm/s is necessary to determine a transit". It has an SW-NE direction on the northern coast of Dakar and an N-S direction at the head of the peninsula and its sheltered southern coast. Its competence is often reinforced by the tide, a periodic movement that affects the general level of the seas and oceans.

The figure 15 is about the annual daily average tide of the Dakar region from 1992 to 2020.



Source: uhslc.soest.hawaii.edu/data

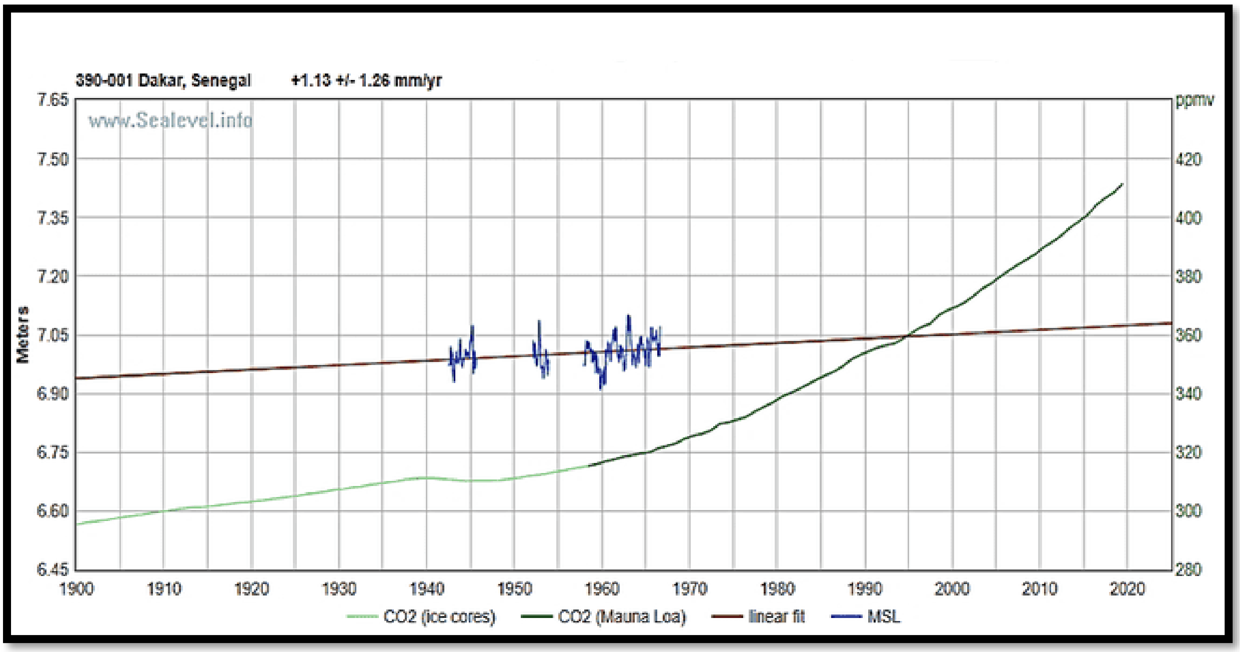
Figure 15: Annual daily average of the tide in the Dakar region from 1992 to 2020

Tide is caused by the difference in gravitational forces resulting from the change of position of the Sun and Moon relative to points on Earth. The movement of the tide is manifested by an apparent rise (the flow) and a fall in the water level of sea level (the ebb) (Gill 2015). The Senegalese coast is affected by a semi-diurnal tide which consists of a sequence of high and low water twice a day: two highs and lows, about the same level. The tide generates very fast local currents, which are able to erode the seabed and transport an important quantity of sediment (Adjoussi 2001). The annual daily averages of tide recorded in Dakar show that the trend line of tide increased from 1992 to 2020 with a mean daily tide of 1,055 mm (Figure15).

I.5.3 Mean Sea level of Dakar

In the Marine Glossary, mean sea level is defined as the average level of the sea over some time, taking into account periodic changes due to tides and other fluctuations (such as wind waves) (www.Marine-Conservation.Org.Uk, n.d.). Sea level is one of the most important parameters in climate change research and can be used in operational oceanography applications; and it is very useful in harbor operation and coastal engineering. It is important to note that the uses of sea level data for science and practical purposes are interdependent. For example, knowledge of long-term sea-level rise needs to be input into the engineering design of coastal structures, many of which will have a lifetime of many decades or a century. In addition, insight into the rate of sea-level rise may also help understand complex coastal processes, such as sedimentation and erosion (Woodworth et al. 2007). In the Dakar region, historical sea level data is downloaded from the Permanent Mean Sea Level website (www.psmsl.org/data/ 2021). Two-period records are noted: from 1940 to 1970 (Figure 16) and from 1990 to 2020 (Figure 17).

The figure 16 is about the Mean Sea Level of Dakar region from1940 to 1970.

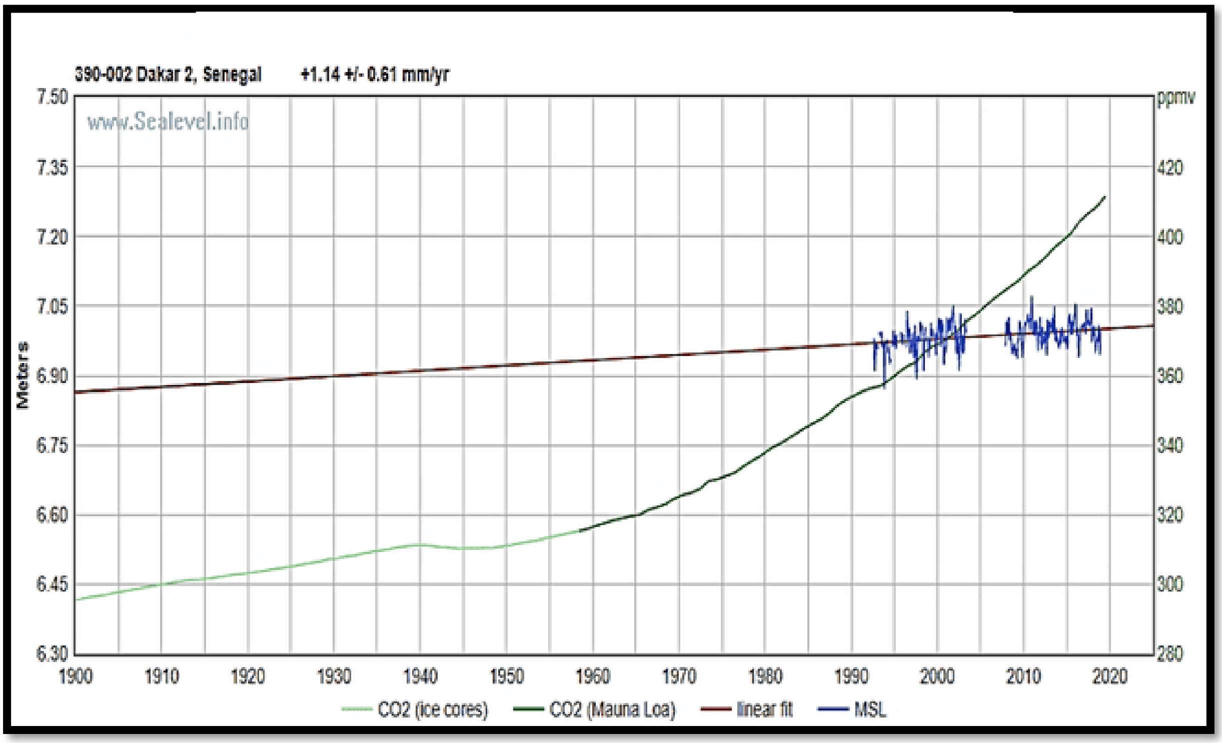


Source : Sealevel.info/MSL_graph.php?id=390-001 2021

Figure 16: Mean Sea Level of Dakar region from1940 to 1970

The mean sea level (MSL) trend at Dakar, Senegal, is +1.13 mm/year with a 95% confidence interval of ±1.26 mm/year, based on monthly mean sea level data from 1942/8 to 1966/9. The plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is shown, in red, along with its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by NOAA CO-OPS (Figure 16) (Sealevel.info/MSL_graph.php?id=390-001 2021).

The figure 17 is about the Mean Sea Level of Dakar region from 1990 to 2020.



Source: : Sealevel.info/MSL_graph.php?id=390-001 2021

Figure 17: Mean Sea Level of Dakar region from1990 to 2020

The mean sea level (MSL) trend at Dakar 2, Senegal, is +1.14 mm/year with a 95% confidence interval of ±0.61 mm/year, based on monthly mean sea level data from 1992/9 to 2018/12. The plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. By default, the long-term linear trend is also shown, in red, along with its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by NOAA CO-OPS. (Figure 17) **:** (Sealevel.info/MSL_graph.php?id=390-001 2021).

I.6 Vegetation

The maritime fringe called "Niayes" extends from Dakar to Saint Louis. The great Niayes of Dakar is "the green lung of Dakar". It is an area that benefits from a favorable climate to the development of numerous plant productions and economic interests (IAGU 2007). Therefore, this agricultural production is threatened by disappearance due to coastal dynamics and urbanization. Several projects of dune fixation by planting filaos (Casuarina equisetifolia) were undertaken in the past to halt the decline of dunes. Planted in 1948 on the northern coast of Senegal, the filao is a shrub of the Fabaceae family originating from the Pacific. This nitrogen fixer can be used as a windbreak and firewood and is very effective in retaining even sandy and degraded soils. Particularly adapted to the climatic conditions of the Niayes, it produces an important litter which is very sensitive to fire. These plantations are being deforested in the Dakar region because of the high land ownership and demography pressure. This risk leads to a vulnerability for existing land assets and agricultural economy which depends on this area, and the unique ecosystem that represents the Niayes. Despite its utilities, the Niayes region is deforested. Therefore, several development projects aim to improve its management. In the recent past, efforts have been undertaken by the Senegalese government with the support of UNDP-UNSO, Canadian and American cooperation to fix the dunes along the northern coast of Dakar by reforesting 12,000 ha between 1974 and 1990. From 2001 to 2006, Senegalese government with the support of the Japanese cooperation has launched a reforestation project on the littoral (PRL) which has the specific objective of planting 2037 ha of forests in 10 years in Thiès and Louga regions (PRL - Projet de reboisement du littoral | Ministère de l'Environnement et du Développement Durable 2001). In 2006, SOS Sahel launched a project to plant one million trees against desertification in the regions of Louga and Thiès. The objective was to renew the ageing filaos that protect the agricultural basin and fragile ecosystem of the Niayes. The result in 2009 is the maintenance of 8 ha of dunes stabilized by the reforestation of 8,330 filaos. Reforestation continues through an integrated reforestation program. In 2011, in the Thiès region, ISRA was working with local people on a forest regeneration project to broaden the genetic basis of the filaos. In the Dakar region, there was a virtual absence of reforestation between 1986 and 2010 (Ndoa 2012, Quensière et al. 2013).

Partial conclusion

In summary, due to its geographical position, the Dakar region has a Canarian climate influenced by geographical and atmospheric conditions. It is crossed by the maritime trade winds from the Azores anticyclone from North to North-East sector. It is a fresh, moisture wind which explains its stability. The harmattan also is noted. The trade wind's trajectory is entirely continental and comes from the Maghrebian anticyclone. It warms up and dries out as it crosses the Sahara zone to reach Senegal. These two flows from the northern hemisphere are opposed to the monsoon flow from the Saint Helena anticyclone, which takes over Cape Verde from July to September. When it is continental, the monsoon is generally accompanied by abundant rainfall. As a result, Senegal, particularly the Dakar region, is experiencing two seasons. The dry and wet season. These climatological conditions play an important role in the geomorphology conditions of the Dakar region, which is composed of the massive de Ndias in the south part, which corresponds to the Maastrichtian horst. It is a relief of hills and trays often cuirassed, covered with lithosols and ferruginous soils. Along the coast, red sandstone mounds are bordered by cliffs. In the Rufisque-Bargny area, low plateaus extend over a surface that overlaps the limestone and marl Eocene. Most of the Dakar is occupied by fixed continental dunes. Since the climatic conditions combined with the geomorphological aspects play an important role in the shape of the Dakar region, it would be true to say that the hydrodynamic agents play the key role in the coastal morphology of Dakar through the erosion or accretion accented by humankind's activities through the high density, high demographic pressure, economic activities, pollutions, etc.

II. Human presentation

Introduction

Like most coastal cities, the Dakar region is characterized by its high population, which is estimated in 2020 to 3 835 019 inhabitants, i.e., 23% of the entire population of Senegal (16 705 608 inhabitants) according to the Agence National de la Statistique et de la Demographie (ANSD). The political and economic capital of Senegal, is the headquarters of numerous international organizations. Due to the high economic and demographic concentration, Dakar is a crucial business center and an important cultural and human melting pot. It is the primary outward opening, thanks to an international harbor and airport (ANSD 2005). Its geographical position, climate, infrastructure, buildings, biodiversity, fish resources, population, etc., confer multiple advantages on other regions of the country (Quensière et al. 2013).

II.1 Population

The population of the Dakar Region is estimated at 3 835 019 inhabitants, i.e., 23% of the national population. The density indicator is generally used, considering its concentration, dispersion, and distribution. It expresses the ratio of population to land area and measures the pressure exerted by men on a given space. Dakar region concentrates the highest population density, services, infrastructure, decision-making power, and wealth. The importance of Dakar's attractiveness can be appreciated because of the extremely high population density in the city. Indeed, it remains the most densely populated and has an exceptional density of 6 972 inhabitants/km^2, whereas the average density of the country is 85 inhabitants/km^2 (ANSD 2021). The table 1 is about the age and gender distribution in each department in Dakar region.

Table 1: Age and gender distribution in each department in Dakar region

Age	DAKAR		PIKINE		GUEDIAWAYE		RUFISQUE	
	SEXE							
	Male	Female	Male	Female	Male	Female	Male	Female
0-4 years	57 408	55 556	75 182	72 318	18 967	17 967	33 313	31 653
5-9 years	54 014	52 546	73 371	70 897	18 862	18 166	33 441	31 581
10-14 years	47 478	49 031	63 215	62 899	16 595	16 829	28 986	27 866
15-19 years	48 395	56 252	58 187	61 245	15 751	17 031	24 359	24 467
20-24 years	64 210	68 437	61 930	62 522	17 714	18 775	22 759	23 712
25-29 years	71 193	66 077	60 027	56 988	17 252	17 545	21 289	22 066

30-34 years	57 412	51 588	49 727	45 192	14 394	13 988	18 019	18 015
35-39 years	45 408	40 263	37 340	34 608	11 239	10 793	14 396	14 986
40-44 years	34 025	31 221	28 250	27 425	8 451	8 212	11 771	11 753
45-49 years	25 955	25 345	21 312	22 940	6 105	6 716	9 605	10 108
50-54 years	22 590	21 654	19 608	20 391	5 180	6 095	8 318	8 659
55-59 years	17 394	16 630	15 177	14 599	4 232	4 755	6 619	6 603
60-64 years	13 595	12 820	12 130	10 851	3 542	3 775	5 311	5 019
65-69 years	7 542	7 812	6 388	6 029	1 960	2 075	2 918	3 024
70-74 years	5 098	5 227	4 687	4 643	1 444	1 552	2 044	2 191
75-79 years	3 018	3 394	2 554	2 445	843	870	1 242	1 390
80-84 years	1 853	2 311	1 569	1 616	492	614	780	984
85-89 years	847	1 137	740	709	256	280	407	507
90-94 years	328	463	236	364	61	116	141	190
95-99 years	205	214	151	185	45	64	60	103
100-104 years	13	45	30	58	12	22	11	16
105-109 years	13	22	11	16	2	9	4	5
110-114 years	3	14	5	22	2	6	2	1
TOTAL	**577 997**	**568 056**	**591 827**	**578 964**	**163 401**	**166 258**	**245 796**	**244899**

Source: ANSD, 2014

The population of the Dakar region can be distributed by age and gender. Considering these two parameters, a distribution has been made into three generations: the first comprises people aged between 0 and 29 years old, representing the young population; the second comprises people aged between 30 and 64 years old. The third generation represents the elderly (65 to 114 years of age). An urban population is noted and dominated by young people aged between 0 to 29. This portion of population has been evaluated in 2014 at 2,006,324 people i.e., 1,003,898 males and 1,002,426 females. It represents 64% of the total population of the Dakar region, with 520,832 people under the age of 15. There are 1,032,109 people aged between 30 and 64, i.e., 33% of the total population: 527,105 men and 505,004 women. For those aged between 65 and 114, there are 98,762 people, or 3% of the total population, with 48,017 men and 50,745 women. Even if the growth in the population of the Dakar region is a challenge in terms of education, health, security, etc., it would be accurate to say that the occupation of this population of Dakar, particularly in coastal areas, is more and more alarming.

II.2 Occupation processes of Dakar

To organize land use in cities, the government has drawn up urban plans called "Plan Directeur Urbain (PDU)". The public authorities have been involved since 1970 in the development of serviced plots (Parcelles Assainies (PA) and Zone d'Aménagement Concertées (ZAC)), production of low-cost housing (SICAP and SN-HLM) and support for housing cooperatives. Since 2009, the habitat policy has been based on a sectoral policy letter to facilitate access to decent housing for the middle classes and disadvantaged people. The sectoral policy letter for the housing sector aims to sustainably develop urban space through the development and application of appropriate planning tools, to consistently implement actions that facilitate access to housing and the conditions for occupying the various economic functions, social and cultural production. Therefore, the Dakar region presents a particular situation, with 48.8% of households living in low-rise houses, 41.7% in upstairs houses and 5.7% in buildings. Furthermore, 85.6% of households living in buildings and 81% living in houses upstairs live in Dakar (ANSD 2014).

Housing and land remain a problem in terms of access (satisfying demand), management (controlling the evolution of urbanization) and costs (price inflation and land speculation) because of increasing demand for housing, dwindling land reserves, exponential growth in land and housing prices, high taxation, expensive building materials and difficulties in accessing credit. Peripheral neighborhoods are growing by automatic extension. These irregular extensions are narrow and winding streets and heterogeneous size plots. Spatial occupation is characterized by spontaneous settlement, generally in the departments of Pikine and Rufisque, as well as in localities known as traditional villages such as Ouakam, Yoff and Ngor. However, to prevent irregular occupation and anticipating slums, the town and country planning departments have had recourse to Para public and private developers (OHLM, SN-HLM, SICAP, SCATURBAM, etc.) and then to the option of concerted development; this first option excluding the poorest populations. After a 10-year pilot phase as part of the " Projet d'Appui à la Décentralisation et au Développement Urbain au Sénégal" Project (PADDUS), financed by French cooperation, the "Zone d'Aménagement Concertée" (ZAC) procedure has entered its operational phase with a first experience in Mbao/Gare, in the Dakar region. Today, a major ZAC program is underway on the initiative of the Ministry of Urban and Regional Planning in the suburbs of Dakar (Diamniadio), and in recent years the State has developed, directly or through private operators, several sites in Dakar, such as Grand Yoff Sud, Hann Maristes, Nord

Foire and the Mbao area. But in 2007, we witnessed the transformation of numerous land reserves for housing (CICES reserves, LSS Stadium, catchment area, pyrotechnics, etc.) (MEF 2008)

II.2.1 Coastal occupation

The urban population growth in Dakar is the consequence of the rapid occupation of the coast. Consequently, this immediate occupation causes problems in the marine environment. Littoral urbanization has become a reckless phenomenon reflecting the importance of water proximity. The dynamics of the coastal occupation show two types of evolution: on the one hand, the advance of the dwellings towards the sea, and on the other hand, the advance of the sea towards the dwellings. In addition, there has been a reduction or even disappearance of vegetation cover in the Dakar region in favor of the built environment, for example, the retreat of the filao in Guédiawaye department which has a surface area of 12.9 km² and a density of 22,108 inhabitants per km². In addition, the Niayes of Pikine, an area of market gardening, has evolved to a considerable extent towards the built environment because of the strong demographic growth in the Dakar region and its suburbs (Pouye 2016).

II.2.2 Occupation law and regulation

In Senegal, laws and regulations clearly define space occupation. Three different domains can be noted: the national domain, State domain and titles of private individuals. These three influential groups make up the Senegalese land tenure system. Two legal laws can be noted: Law 64-46 of June 17 1964, and Law 76-66 of July 2 1976 (Quensière et al. 2013).

The national domain, a vast area, comprised more than 95% of Senegalese soil governed by Law 64-46 of June 17 1964. It was divided into four categories of land: urban areas, classified areas, pioneer areas and terroir areas. At the same time, the State domain is subdivided into public and private domains (Ipar 2021). Law 76-66 of July 2 1976, defines the natural public domain with the sea shores and artificial public domain with numerous urban infrastructures built or planned to be built (Adjoussi 2001), and it should be noted that this Law has been supplemented by the "Code de la Marine Marchande" (Law n°2002- August 22 August 16 2002) defines the maritime public domain. Nevertheless, this text suffers from not only the ambiguities as regards the determination of the physical limits of this domain (imprecision in the definition of the level of the highest tides) but also the occupation modalities and exploitation of this Zone (which are defined by the State but with possibilities of portion declassifications of maritime public domain) (CSE 2010).

The titles of private individuals were established based on the July 26, 1932, decree reorganizing the land ownership regime in francophone West African countries. Based on this text, final and unassailable land titles are issued. It organizes land ownership by providing holders with a guaranteed right on buildings. Nevertheless, the antiquity of these laws and the Sustainable Development Goal oblige the adoption of new laws to correct the shortcomings of the previous laws:

The law n° 2007-16 about the creation and fixing rules of organization and functioning of the Special Economic Zone provided for the delimitation of an area of about 10,000 hectares between Diamniadio and Mbour and fixed the missions and powers of a High Authority which has full authority and latitude to dispose of all the lands of the Zone, through any means it considers necessary.

The purpose of Law Nº 2008-43 of August 20, 2008, on the Urban Planning Code is to harmonize the disposition of Law Nº. 88-05 of June 20, 1988, on the Urban Planning Code with those of Law Nº 96-07. It does not lead to an upheaval in the dominant land tenure system. Land reserves can be constituted by registering land in the national domain as far as the State is stationed for:

- The realization of future development operations in urban areas;

- The preservation and development of natural areas and

- The development of tourist areas. These are exclusively public utility projects, which suggests no change in the national domain's legal regime for land registration.

The bill Nº 06/2011 on the land ownership regime only concerns the national domain. It does not call into question either the prerogatives of the decentralized authorities in terms of land management or the situation of the occupier of the national domain, which remains governed by the provisions of Law Nº 64-46 of June 17 1964. Nor does it overturn the land ownership regime. The bill Nº 07/2011 on transforming residence permits and similar titles into land titles does not concern the national or public domain. It concerns only land that should generally have depended on the private domain of the State. It authorizes the free and informal conversion into land titles of irregular administrative titles subject to reimbursement of the costs incurred by the State from the first transaction following the initial transfer (Ipar 2021).

The situation in the Dakar region can be seen as an interweaving of national ownership (regime of urban areas) and state ownership (regime of the inalienable public domain and regime of the private domain, which unfortunately remains the property of the State). In-state cases, the powers of the administrations are not the same. Therefore, reforms are needed in Dakar to give the elected Regional Council real power to control land use and infrastructure. The decree of December 31 1996, on the modalities for transferring powers to local authorities in matters of state ownership, does not seem to settle the issue. It may also be noted that the legal rules on town planning, transport management, industrial risks and land use planning in the Dakar region constitute an essential part of positive Law. However, they often contradict each other and are not always respected in the field. For example, the 2008 town planning code gives the general prescriptions for town planning and land use, but the administration has issued authorizations violating these prescriptions. This caused a flood in many neighborhoods. Due to its cross-cutting nature, land use planning involves local authorities and several ministries (environment, urban planning, transport, and infrastructure). The regulations are not very clear concerning the distribution of attributions. The most eloquent example is coastal planning (Quensière et al. 2013).

The coast of the Dakar region is undoubtedly the most vulnerable part and the one that raises even more questions about the application of legal rules in force. The project of the law on the coast is still under study, but it is confronted with many political and financial stakes that condition the coastal actors. In the meantime, the rules for classification and downgrading of the public maritime domain are still governed by article 19 and following the 1976 law on the Code of State Domain; despite the intervention of the "Commission de Contrôle des Opérations Dominantes" (CCOD), villas and hotels continue to spring up along the coast; Coastal erosion and the advance of the sea are continuing as a result of climate change and human activities (Quensière et al. 2013). Space occupation has long been one of the concerns of the Senegalese government. Laws and regulations on land use in Senegal should allow for a normal development adequate to current development standards. However, the non-application of these laws constitutes one of the main constraints to excellent environment management, management of risks such as floods and coastal erosion, and the smooth running of economic activities such as fishing, industry, transport, etc.

II.3 Economic activities

By economic activity, one must retain the work performed by a person to produce or participate in producing goods and services intended for sale or use in producing goods and services household self-consumption. As defined in national accounts, the person engaged in economic activity provides labor for producing goods and services, whether they are traded, in return for a wage or salary in cash or in-kind or for profit. Illegal or underground activities are excluded from the economic sphere (ANSD 2014). It should be noted that Senegalese economic activities, whether in industry, the tertiary sector, or crafts, are concentrated mainly in the Dakar region. Today, the industrial sector, traditionally oriented towards the food, chemical or textile industries, the wood and furniture sector and refining, meets difficulties. As elsewhere, the textile industry suffers from Chinese imports. Senegal's chemical industries (ICS) have been in a severe crisis (Wikipedia 2020).

Its importance can therefore be assessed by its significant electricity consumption compared to other sectors of activity. For example, the Energy Information System of Senegal states that the industrial and tertiary sectors account for 66 and 75% of national electricity consumption, respectively. The informal sector has been assessed in the diagnoses, whether for crafts, taxis or dugout canoes (taken into account in the agriculture and fishing sector). Many households in Dakar derive all or part of their income by running an informal production activity. The Bay of Hann, Rufisque, Soumbédioune and Yoff are the prominent localities in the Dakar region where fishing activities represent an important part of Dakar's economic income. There is also essential agricultural production which absorbs a considerable part of Dakar's active population. There is also a monopolization of services in all economic activities. Most banks and money transfer agencies are in Dakar. Concerning the transport, two elements characterize transport in the Dakar region. Firstly, an undeniable asset is the Port of Dakar. It is halfway between Europe and South America, from North America to Southern Africa. These qualities mean that it handles 90% of Senegal's trade with the outside world and that this traffic corresponds to more than 70% of the country's customs revenue. The other element is its geographical location. The main difficulty of the port of Dakar is linked to its confinement in a densely built urban structure that must be crossed to move goods (Quensière et al. 2013).

In the results of the third general census, it emerges that the population potentially active is that of individuals aged 15 years or older who have reached the legal age to participate in the production of goods and services. This population amounts to 7728868 inhabitants, i.e., 71% of the population aged over six years. It should be noted that 49.5% of this population is inactive, and 29.3% of this population is concentrated in Dakar, with a low sex ratio of 30.1%, with 208 employed men for every 100 women. In addition, more than 3 out of 5 men are employed, i.e., 62.8%. In Senegal, nearly three men out of 20, i.e., 15.2% and 17.1% of the unemployed, i.e., 1,000,904 inhabitants, live in Dakar. The proportion of unemployed women is 99977, i.e., 18.5%. The total number of unemployed (170927 inhabitants) live in Dakar (ANSD 2014). Despite economic activities being the pillar of the Senegalese economy. It should be true to say that, certain economic activities such as energy, industry, transport etc., are the generator of pollution particularly in Dakar region.

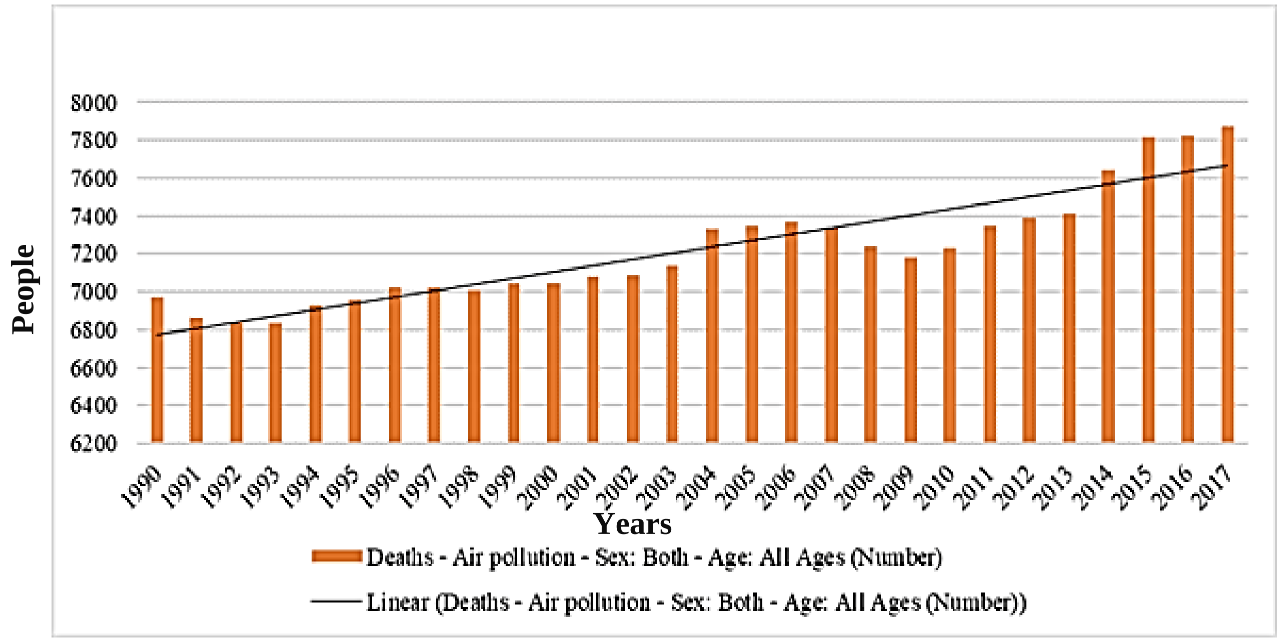
II.4 Pollution in Dakar

According to the Air Pollution - Our World in Data website (Air Pollution - Our World in Data n.d.), over 7000 people died from pollution in Senegal. Therefore, the Dakar region, like most of the coastal cities in the world, particularly in developing countries, is subject to air, marine and environmental pollution. This fact can be justified by the high concentration of economic activities such as industries, electricity production and transport based on hydrocarbon consumption generate air pollution. For example, according to the SIE-report 2014, 1,687,316 tons of hydrocarbons were imported in 2013 for nearly one billion euros and represent about 25% of total imports for electricity production and transport consumption (Tchanche 2018).

II.4.1 Air pollution

In Dakar, air pollution is generally due to industry activities, particularly the energy production, transport sector and daily biomass combustion of the population. In the report of the determined contribution at the national level in Senegal (2019), the public electricity generation fleet is essentially thermal, i.e., 93% of installed capacity, and the dominant fuel is fuel oil, accounting for 75%. Between 2010 and 2030, it has been forecasted that the Gross electricity production was multiplied by 2.9 compared to 4.3 for CO2 emissions. This relative increase in CO2 emissions will be faster than the one from the production of electricity due to the intense penetration of coal at the expense of fuel oil/diesel. The air quality of Dakar is measured by the Centre de Gestion de la Qualité de l'Air (CGQA) implanted since 2010 through the Air Quality Index (AQI), which indicates the daily air quality. It provides information on the level of air pollution and the health impacts that can result after a few minutes or days of exposure to air pollution. (denv.gouv /12/26/2020). According to Demay (2011), significant air pollution has adverse effects on human health, environment and biodiversity and has a role in climate change. Mortality due to air pollution affects many people. For example, in Senegal, over 7000 people die because of air pollution (Figure 18); the most affected are those over 65 years old and other vulnerable people.

The figure 18 is about Annual number of deaths caused by air pollution in Senegal from 1990 to 2017.



Source: Air Pollution - Our World in Data n.d.

Figure 18: Annual number of deaths caused by air pollution in Senegal from 1990 to 2017

II.4.2 Marine pollution

Concerning marine pollution by wastewater discharges, Dakar city and suburbs discharge 180,000 cubic meters of wastewater per day despite the lack of drinking water supply. Most of which are discharged directly into the sea without any prior treatment. This wastewater contains mineral and organic materials, chemicals toxic to marine life and heavy metals (lead, mercury, etc.). Most industries use storm drains or municipal sewers to dispose of their wastewater. Using these collectors causes operating difficulties due to chronic obstruction of the pipes by large-caliber solids and pollution of the marine and coastal environment (MEPN 2010).

Source: Pouye, 2021

Figure 19: Discharge of wastewater into the sea by pipes in Cambérène

Partial conclusion

In summary, the Dakar region has a population of 3,835,019 inhabitants, an exceptional density of 6,972 inhabitants/km^2, and the average density of the country is 85 inhabitants/km^2 (ANSD, RPHAE 2020). It is characterized by rapid population growth. In terms of land use, Dakar is home to neighborhoods and slums. Housing and land remain a problem of access. For example, satisfying the demand is still delicate. Management is a challenge in terms of controlling the dynamics of urbanization. Far from being negligible, costs (price inflation and land speculation) also remain a challenge. Several factors explain this situation: the constant increase in demand for housing, reduction in land reserves, exponential growth in land and housing prices, administrative red tape, high taxation and cost of building materials, difficulties in accessing credit. Being the capital of Senegal, Dakar region host the most important economic activities such as trade, industry, services, fishing, transport, etc. As a result, people are partly forced to live in this area. According to Sane and Yamagishi (2004), this concentration of population has led to a construction boom and then to excessive extraction of sand from the beaches and dunes. Consequently, there is a deficit in terms of sediment balance along the coast. Furthermore, pollution also is one of the most critical environmental challenges in the Dakar region. The chapter 4 addresses the methodological approach used in this thesis.

Chapter 4: Methodological approach

Introduction

Different methods of data collection and analysis techniques are used to achieve the aim of this study. The research begins with documentation. After that, field survey was conducted. Some models are used for the future coastal erosion dynamics forecast, coastal vulnerability assessment and economic evaluation impacts.

I. Documentary research

The documentary research started in October 2019 at the University of Cape Coast in Ghana library. Other university libraries were visited for this documentary research: The University of Lomé, university Cheikh Anta Diop of Dakar, Centre de Suivi Ecologique (CSE), Ministry of Environment, ENDA Third World, Institute of Earth Sciences, National Agency for Statistics and Demography (ANSD) and the Oceanographic Research Centre. The articles from scientific journals were consulted.

The documentary research allowed the elaboration of the proposal and all essential information related to this thesis. It has also given us a comprehensive understanding of coastal erosion, its causes, consequences and adaptation strategies. This documentary research explored the different ways of thinking about coastal erosion issues and establishing the research problem.

I.1 Sampling

A sampling technique known as the quota method is used to select respondents to the questionnaires. Accordingly, twenty-six district municipalities along the coast of Dakar are chosen. A quota method is used. For this method, the number of people living in these district municipalities is determined. The quota of each district municipality for the total sample was estimated at 700 people.

The table 2 is about the number of people in the different district municipalities along the coast of Dakar region.

Table 2: Number of people living in the district municipalities along the coast of Dakar

District municipalities	Population	Frequency (%)	Sample
Mermoz/ Sacre-Coeur	29798	1.658705	12

Ngor	17383	0.967624	07
Ouakam	74692	4.157728	29
Yoff	89442	4.978786	35
Fann/Point E/ Amitie	18841	1.048784	07
Gueule Tapee/Colobane/Fass	52267	2.909441	20
Medina	81982	4.563525	32
Plateau	34713	1.932298	14
Hann/ Bel Air	67961	3.783047	26
Camberene	52420	2.917958	20
Parcelles Assainies	159498	8.878451	62
Golf Sud	92345	5.140381	36
Ndiareme Limamoulaye	35171	1.957793	14
Sam Notaire	78660	4.378606	30
Wakhinane Nimzatt	89721	4.994317	35
Keur Massar	201653	11.22501	78
Malika	32130	1.788515	13
Yeumbeul Nord	168379	9.372812	66
Daliford	30418	1.693217	12
Mbao	96320	5.36165	37
Thiaroye Mer	52773	2.937607	21
Bambilor	44962	2.502808	18
Tivaouane Peulh-Niagha	41123	2.28911	16
Yene	24795	1.380213	10
Rufisque Est	70125	3.903506	27
Rufisque Ouest	58890	3.27811	23
TOTAL	**1796462**	**100**	**700**

Source: (ANSD 2014)

We point out the sample of each district municipality, in other words, the number of people representative of each locality. For example, for the district municipality of Yoff, we focused on 35 people who are representative of the 89442 people living in the locality compared with our total sample (700 people).

Formula 1: Sampling technique

$$\mathbf{Yoff} = \mathbf{89422} * \mathbf{700} / \mathbf{1796462} = \mathbf{35}$$

I.2 Data collection and analysis

Quantitative and qualitative data are used in this study.

I.2.1 Climatological data

Climatological data (rainfall, wind, temperature etc., from 1984 to 2020) and hydrodynamic data (swell and some daily tides (from 1982 to 2020) have been collected from the "Agence Nationale de l'Aviation Civil et de la Météorologie de Dakar" (ANACIM). Hourly and Monthly tide data of the Dakar region have been downloaded from the website of the Sea Level Center of the University of Hawaii (Uhslc.soest.hawaii.edu/data/ n.d.). These data were subjected to studies with software such as Excel, ArcGIS, etc., allowing us to analyze the trend of climatic and hydrodynamic parameters.

For the climatological data, formulas were used to consolidate the argumentation. Data about the hydrography were analyzed using the percentage, deviation and percentage deviation.

Formula 2: Percentage, Deviation, and Percentage Deviation

$$\mathbf{Percentage} = \mathbf{P(mm)/Average}$$
$$\mathbf{Deviation} = \mathbf{Percentage} - \mathbf{100}$$
$$\mathbf{Percentage\ Deviation} = \mathbf{\%P(mm)} - \mathbf{Average\ P(mm)}$$

I.2.2 Sea level data

In the Coastal Vulnerability Assessment Report of Timor-Leste (UNDP 2018), Sea Level Rise is defined as an increase in the mean level of the ocean surface. Relative sea-level occurs when there is a local increase in the ocean level relative to the land, which might be caused by the ocean rising, the land subsiding, or both. In areas with rapid land level uplift (e.g., seismically active areas), relative sea-level can fall. This parameter indicates how the global (eustatic) sea-level rise and local isostatic or tectonic land motion affect a portion of the shoreline. Sea level data were collected from the oceanographic centre research of Dakar, and the website of Permanent Service of Mean Seal Level (www.psmsl.org/data/ 2021) helping us to analyze the evolution of sea level from 1940 to 2020.

I.2.3 Coastal dynamic analysis in Dakar region using GIS approach

Like most of the world's capitals, the Dakar region is not safe from the impacts of coastal erosion because of its geographical position and low-lying areas. The advanced sea resulting from sea-level rise combined with the effects of climate change affects the coastal morphology of the Dakar region. This situation is accentuated by the disturbance of hydrodynamic agents such as waves, tide, wind, etc. Consequently, this reduces coastal areas, and causes human displacement toward inland, disruption of economic activities such as fishery, hostelry, industry, etc. Human activities accentuate these threats through sand mining, pollution, and illegal settlements along the coasts.

The coastline dynamic depiction was done using the GIS approach. Historical Landsat images from 1990 to 2020 provided by the Glovis website (Glovis.usgs.gov/ n.d.) are used. The shoreline velocity is evaluated between two dates, and the End Point Rate (EPR), a statistical method, is used to calculate shoreline velocity in the Digital Shoreline Analysis System (DSAS) software which is an extension of Arc GIS. After computing the coastline rate, the simulation of the coastline is automatically performed using the Buffer tool. Predicting future shoreline positions is evaluated using the velocity V=Distance/Elapsed time between 2020, 2030 and 2040. Suppose the year 2020 is taken as the origin, with a rate of change in coastline retreat equal to X meters. In that case, it will emerge that assuming this average constant rate of change at that date, the coastline will retreat to a distance of Y meters in 2030 concerning its current position (Arnaud et al. 2019).

The study of shoreline dynamics is generally conducted in coastal countries. Therefore, since it is an essential parameter in studying the impacts of climate change in coastal areas, scientists are more interested in littoral studies seeking deep existential knowledge. To study the impacts of climate change along the coast, one can refer to the coastline dynamics. This section aims to elaborate how the coastal dynamics in the Dakar region from 1990 to 2040 was depicted. It can play an essential role in addressing the issue of coastal erosion in Dakar. To achieve the objective of this section, the Geographic Information System (GIS) approach, which is among the most current methods to determine coastline dynamics, is used through the processing of images, classification, coastline delineation, computation of the coastline dynamics using ArcGIS and Digital Shoreline Analysis System (DSAS) software.

1.3.3.1. Coastline delineation

The coastline is sometimes assimilated into the shoreline. However, there are nuances and complexity both in practice and semantics (Faye 2010). In a study, Chand and Acharya (2010) state that "the shoreline is the boundary between land and water body. The term is considered synonymous with coastline, but it considers different, so the precise definition of shoreline is considered as the line contacting between the mean high-water line and the shore". According to Bird (2008), “The coastline is defined as the edge of the land at the limit of normal high spring tides; the subaerial land margin, often marked by the seaward boundary of terrestrial vegetation. It is taken as the cliff foot at high spring tide level on cliff coasts. The shoreline is the water's edge, moving to and fro as the tides rise and fall so that there is a low-tide, a mid-tide, and a high-tide shorelines. Shorelines thus move to and fro as the tide rises and falls, whereas coastlines are submerged only in exceptional circumstances (e.g., during storm surges).”

Delineating the coastline from time-series images is one of the most valuable and complex approaches in remote sensing. In the past, the coastline was extracted manually from areal images. However, due to the lack of objectivity and inaccuracy of results, new techniques have been developed: the incorporation of the edge tracing algorithm for Synthetic Aperture Radar (SAR) imagery, image segmentation method for radar and optical satellite imagery, a coherence thresholding method for interferometric SAR (InSAR), a combined method integrating image segmentation, region growing and edge detection for multispectral imagery, an active contour method for polarimetric SAR images (Annex: Table 2), the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) methods (Dai et al. 2019).

In this study, the shoreline is considered as the limit between the continent and sea and its delineation was done using the classified and digitalized MNDWI images.

1.3.3.2. The use of the Modified Normalized Difference Water Index (MNDWI)

To better dissociate the land surface and sea, the Modified Normalized Difference Water Index (MNDWI) has been used in this study. For that, the band rationing technique is used by employing the bands 2 and 5 for Landsat 5 TM and Landsat 7. For Landsat 8, the bands 3 and 6 were used. In MNDWI, the highest value is +1, and the lowest is -1. The threshold value for classification is 0. The formulas below are about the computation of the MNDWI for Landsat

5 TM, Landsat 7 ETM+ and Landsat 8 OLI.

Formula 3: MNDWI

For Landsat 5 TM and 7 ETM+

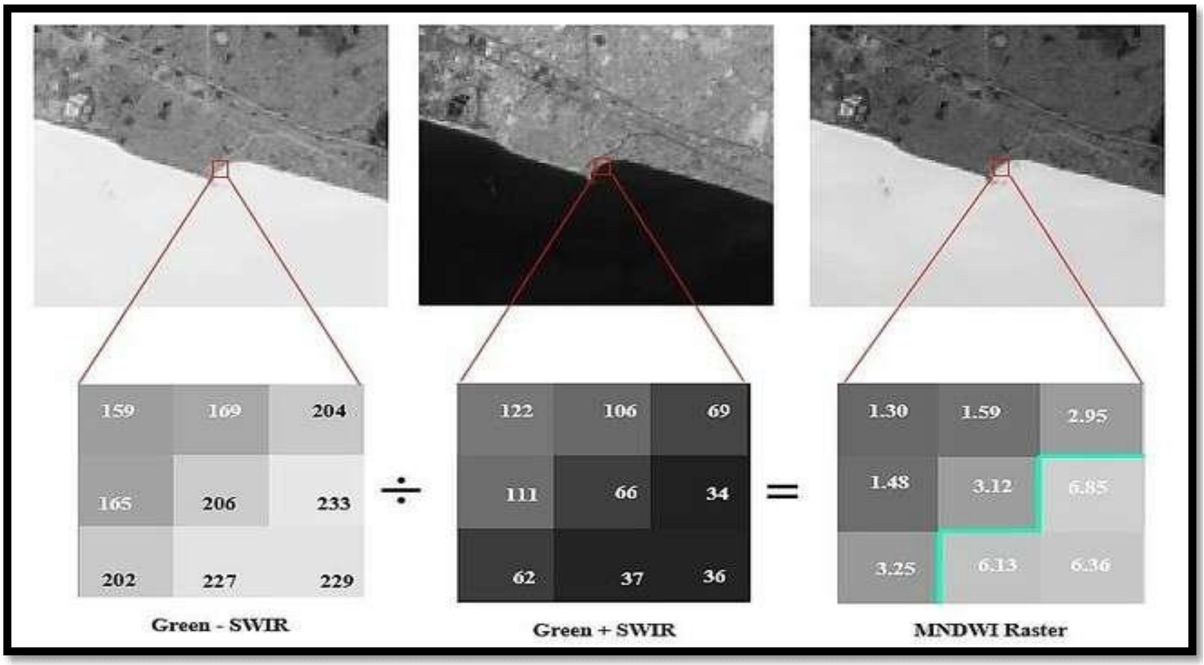
$$\mathbf{MNDWI} = \mathbf{Band\ 2\ (Green) - Band\ 5\ (SWIR)/Band\ 2(Green) + Band\ 5(SWIR)}$$

For Landsat 8 OLI

$$\mathbf{MNDWI} = \mathbf{Band\ 3(Green) - Band\ 6(SWIR1)/Band\ 3(Green) + Band\ 6(SWIR1)}$$

The Modified Normalized Difference Water Index (MNDWI) originates from the Normalized Difference Water Index (NDWI), which is calculated using two near-infrared channels. These two indices are enhancement techniques through band rationing. According to Gao (1996), the NDWI is used for remote sensing vegetation liquid water interacting with solar radiation. In a study, McFeeters (1996) stated that this NDWI takes benefits the condition where the presence of features that have higher near-infrared reflectance and lower red-light reflectance, e.g., terrestrial vegetation) will be enhanced, while those with low red-light reflectance and very low NIR reflectance (e.g., water) will be suppressed or eliminated. This NDWI is modified by substituting a middle infrared band such as Landsat TM band 5 for the near-infrared band used in the NDWI to enhance and extract water information in the water region where the background is dominated by build-up land area. The MNDWI is more suitable than the NDWI because it reduces or even removes build-up land and vegetation noises (Xu 2006). In an MNDWI image, one can delineate the boundary between land and sea through the pixel values (Figure 20).

The figure 27 shows the pixel values resulting from rationing the band of a Landsat-OLI image used to delineate the shoreline.



Source: Personal work

Figure 20: Band rationing of Landsat-OLI imagery of the Rufisque department for delineating the shoreline

1.3.3.3. Image classification

Landsat images for each year (1990, 2000, 2010 and 2020) from the MNDWI calculation were used to depict the coastlines. For that, the MNDWI images were classified into two landcover classes to distinguish the land and sea (Figure 28). After that, these classified images were converted to vector layers from which the coastlines were digitalized. The figure 21 shows how the MNDWI technique can be used to better differentiate land and sea by classifying an MNDWI image into two classes (land and sea).

Source: Personal work

Figure 21: The classified image base on the MNDWI of the southern coast of the Rufisque

department (Dakar region)

The classification of the MNDWI image was done following this procedure in ArcGIS:
To obtain a usable classified MNDWI image in ArcGIS, one should go to Layer properties and then choose Method (Manual) in Classified.

1.3.3.4. The digitalization of the coastline

The digitalization of the coastlines of the Dakar region from 1990 to 2020 was done using the classified MNDWI images for the years 1990, 2000, 2010 and 2020. The following procedure was employed: Go to Search window in ArcGIS -> Search for Convert raster to polygon -> In input features, load the raster to convert -> In Field (optional), put value -> In Output polygon features, put the name -> Ok -> Convert the polygon to vector layer -> Go to search window -> Search for convert polygon to line -> In input features, load the adequate polygon to convert -> In output feature, put the name -> Ok. After obtaining the vector lines, select the one corresponding to the shorelines.

I.2.4 Coastline dynamics calculation using the Digital Shoreline Analysis System (DSAS)

The coastline dynamic is an essential parameter in studying the evolution of the coast. It is not static, whatever the coast types, and is difficult to apprehend. According to Guariglia et al. (2006), the coastline position can be cyclical, long-term, or random due to specific events. The cyclical changes in the coastline are linked to seasonality or tidal conditions. The long-term variations are due to the rising sea level or sand storing along the coast. The random variations are due to wave conditions, storms, or floods. In this random variation, the coastline can change in a brief period. The analysis of the coastline dynamics of the Dakar region from 1990 to 2020 is performed in the DSAS software, which is an extension of ArcGIS. It is based mainly on four different components: The Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), and Linear Regression Rate (LRR).

❖ The Net Shoreline Movement is the distance between the most recent and oldest shorelines for each transect and is measured in meters (m).

❖ The shoreline change Envelope (SCE) reports a distance (in meters), not a rate. The SCE value represents the most significant distance among the shorelines intersecting a given transect. As the total distance between two shorelines has no sign, the value for SCE is always positive. The transect rate file may be clipped to this span for display purposes (Himmelstoss et al. 2018).

❖ The End Point Rate (EPR) statistical method is computed by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and the youngest shorelines.

❖ The linear regression rate-of-change statistic can be determined by fitting a least-squares regression line to all shoreline points for a transect. The regression line is placed so that the sum of the squared residuals is minimized. It is the slope of the line. The method of linear regression includes these features: all data are used, regardless of changes in trend or accuracy, the method is purely computational, the calculation is based on accepted statistical concepts, and the method is easy to employ (Dolan et al. 1991; Crowell et al. 1997 in Himmelstoss et al. 2018). To perform a study of the shoreline dynamics of the Dakar region using a GIS approach, a database which is composed of different Landsat images from 1990, 2000, 2010, and 2020 is used:

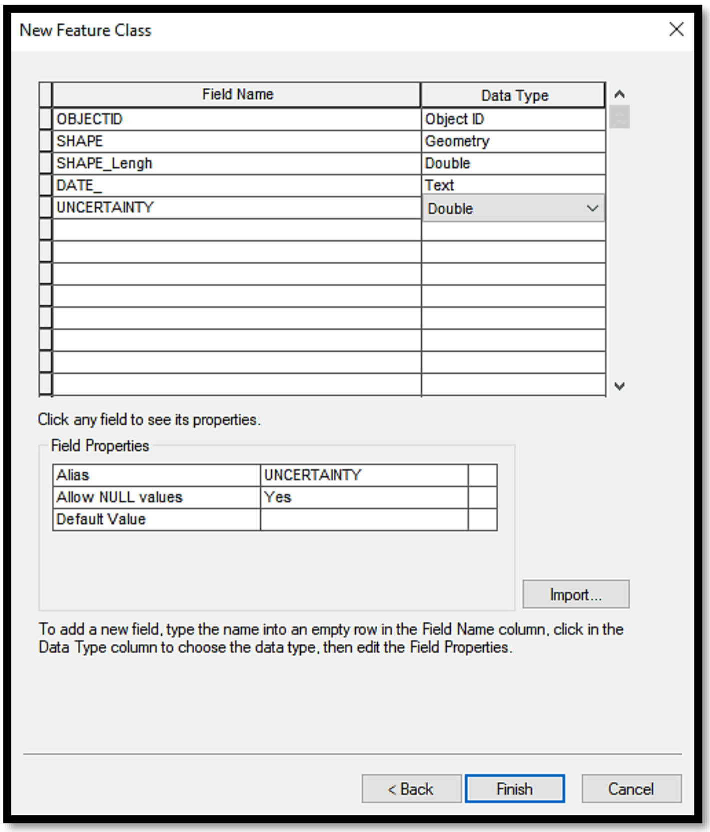
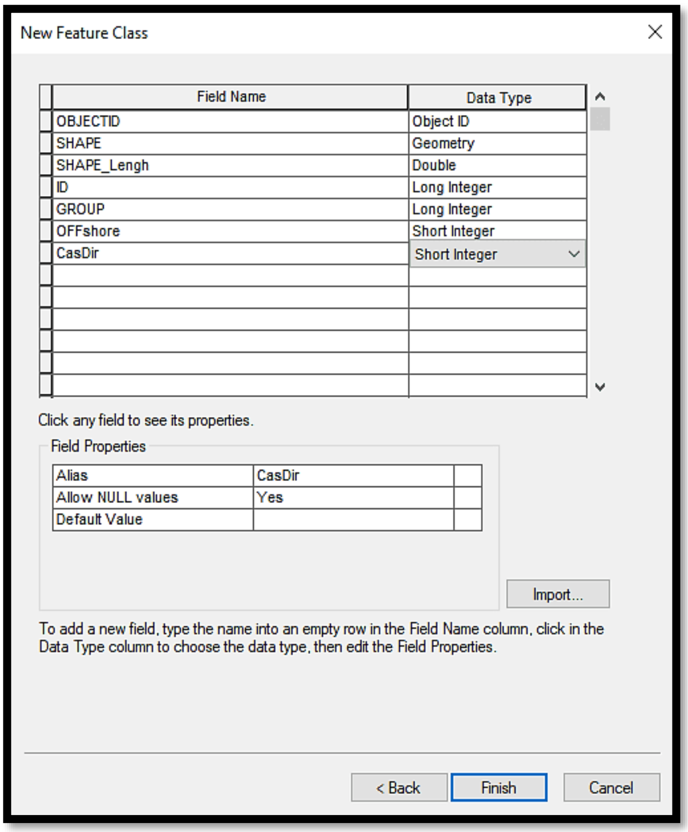
- ❖ Landsat 5 TM acquired by 05/12/1990, resolution of 30m
- ❖ Landsat 7 ETM acquired by 05/30/2000, resolution of 30m
- ❖ Landsat 5 TM acquired by 10/25/2010, resolution of 30m
- ❖ Landsat 8 OLI_TIRS acquired by 11/02/2020, resolution of 30m

These images were pre-processed before depicting the coastlines. This pre-processing of images allows not only to make them more readable but also to enhance their quality. After the processing, they are digitalized in order to depict the coastline. Therefore, based on these coastlines, the shoreline velocity is evaluated between two dates, for example, 1990 and 2020. For that, the statistical method is computed by dividing the distance of shoreline movement by the time elapsed between the oldest and the youngest shorelines using the Digital Shoreline Analysis System (DSAS) software which is an extension of ArcGIS (Himmelstoss et al. 2018).

I.2.5 Application

In this study, two different software are required to conduct the coastline dynamic calculation: ArcGIS and DSAS. Shorelines and baselines extracted from satellite images constitute the primary data used. The coastline dynamic was done using the DSAS toolbar through the Default Parameters, Cast Transects, transect layer selection, and Calculate rate windows. The table 3 provides information on the shoreline and baseline feature classes used to calculate coastline dynamics in the DSAS.

Table 3: Information related to the feature classes for baseline and shoreline

<table>
<tr><th>Feature class for shoreline</th><th>Feature class for baseline</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Source: Personal work in DSAS.V5

I.2.6 Shorelines and Baseline integration

First, after digitalizing the coastline for the years 1990, 2000, 2010 and 2020, we merge them to combine different coastlines as one shapefile layer. After that, a baseline was created using the buffer polygon from the merged coastlines using the buffer tool. Then, we created a DSAS file through ArcCatalog, where the shoreline and baseline geodatabase were created. The following procedure was used: Right-click on **DSAS file** -> Go to **New** -> **Personal Geodatabase ->** Right click on **Personal Geodatabase** -> Go to **New** -> **Feature class** -> In name, put **Shoreline or Baseline** -> In type of feature, choose **line feature** -> Click on **Next** -> Choose the **adequate coordinate system** -> file the **table** -> Click **on finish**.

After creating the shoreline and baseline geodatabase, we digitalize them using the Merged coastlines and their buffer polygon layers.

- **The digitalization of the shoreline in the DSAS geodatabase file**

The attribute table of the shoreline was edited by integrating the date of each shoreline and attribute 0 to UNCERTAINTY. The table 4 is about the integration of information related to the shoreline in the DSAS.

Table 4: Edited table of the Western coast's shoreline of Dakar from 1990 to 2020

Table

Shoreline_1990_2020_WC

OBJECTID *	SHAPE *	DATE_	UNCERTAINTY	SHAPE_Length
1	Polyline	05/12/1990	0	32862.11974
2	Polyline	05/30/2000	0	33957.803101
3	Polyline	10/25/2010	0	31006.348973
4	Polyline	07/02/2020	0	32958.664867

0 (0 out of 4 Selected)

Shoreline_1990_2020_WC

Source: Personal work in DSAS.V5

- **The digitalization of the baseline in the DSAS geodatabase file**

After that, the attribute table of the baseline was edited by attributing 1 to the **ID** and **Group_** cells and 0 to the **OFFshore** and **CasDir** cells. The table 5 is about the integration of information related to the baseline in the DSAS.

Table 5: Edited table of the Western coast's baseline of Dakar from 1990 to 2020

Table

Baseline_1990_2020_WC

OBJECTID *	SHAPE *	ID	GROUP_	OFFshore	CasDir	SHAPE_Length
1	Polyline	1	1	0	0	31076.40682

1 (0 out of 1 Selected)

Baseline_1990_2020_WC

Source: Personal work in DSAS.V5

I.2.7 Coastline dynamic calculation

Numerous researches on the prediction of the coastal dynamic have been carried out. An example is a study by Fenster et al. (1993), in which he stated that, ' Several methods have been used to predict beach loss as a function of time or sea-level rise (Pilkey et al. 1989; Pilkey and Davis 1987). These studies include: (1) Extrapolation of calculated long-term erosion rates; (2) Superimposing Sea level rise on various coastal plain and barrier island slopes; (3) Comparing the offshore ramp slope to the shoreface retreat rate (Everts 1987); (4) Using the Bruun rule (Bruun 1962); and (5) Using variations of the Bruun rule (e.g., DEAN and Maurmeyer 1983; Dubois 1990).' The most common used for future shoreline change prediction was an extrapolation of a constant rate of change value due to its simplicity, and the fact that the sediment transport is not taken into account, and the method is the Endpoint Rate (EPR) or Linear Regression (LR) (Fenster et al. 1993).

The shoreline velocity in the Dakar region between 1990 and 2020 was evaluated using the EPR method, which is a statistical method. It computes the dynamic coastal rate by dividing Net Shoreline Movement (NSM) by the time elapsed between the oldest and youngest coastlines. The advantage of this statistical method is that it computes the dynamic rate easily and does only require two shoreline dates (Himmelstoss et al. 2018). The negative values of the End point Rate (EPR) indicate erosion rates, whereas the positive ones correspond to accretion rates.

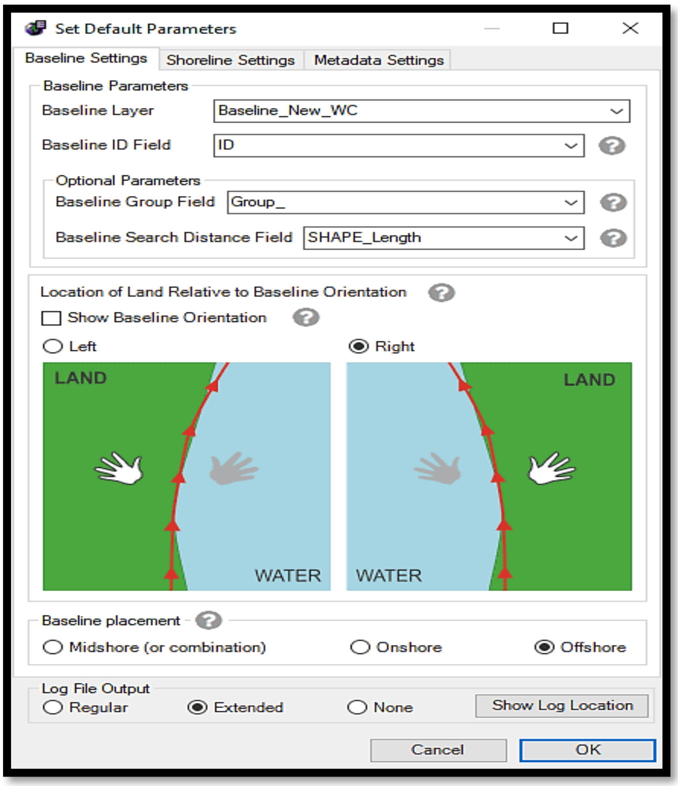
Formula 4: End Point Rate (EPR)

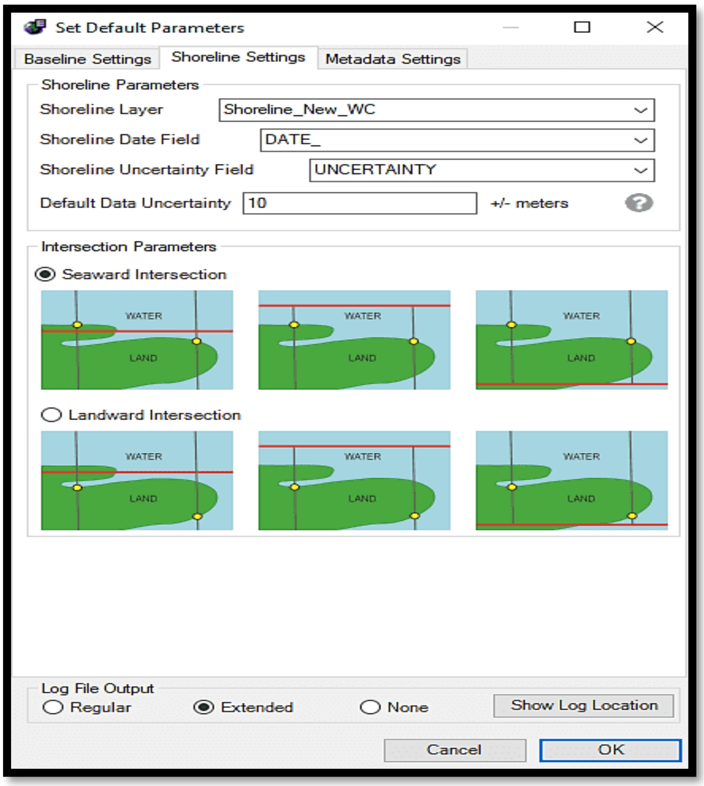
$$\mathbf{EPR = NSM/Time\ Between\ oldest\ and\ Recent\ coastline}$$

Where: NSM= Net Shoreline Movement

After the digitalization of the shoreline and baseline in the DSAS geodatabase file, the DSAS toolbar is used to compute the coastline dynamic of the Dakar region by sitting the default Parameters window, which specifies the name of the file for the baseline and shoreline inputs and sets the metadata inputs (Himmelstoss et al. 2018).

Table 6: Information in the Set Defaults Parameters tables of the Western coast of the Dakar region

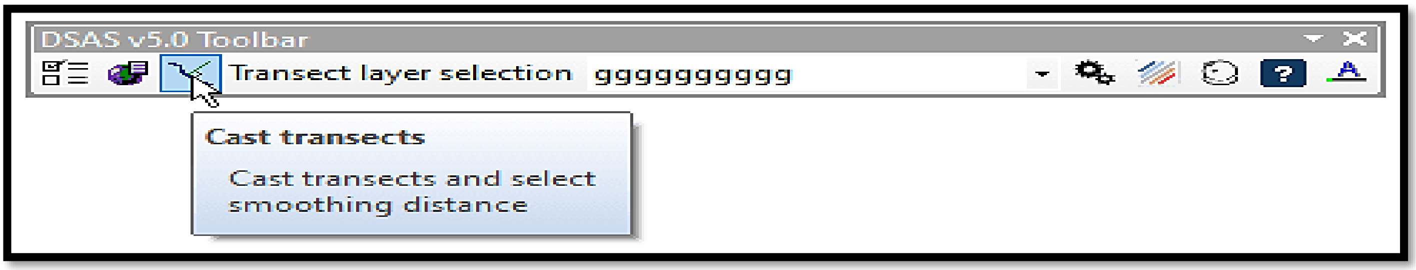


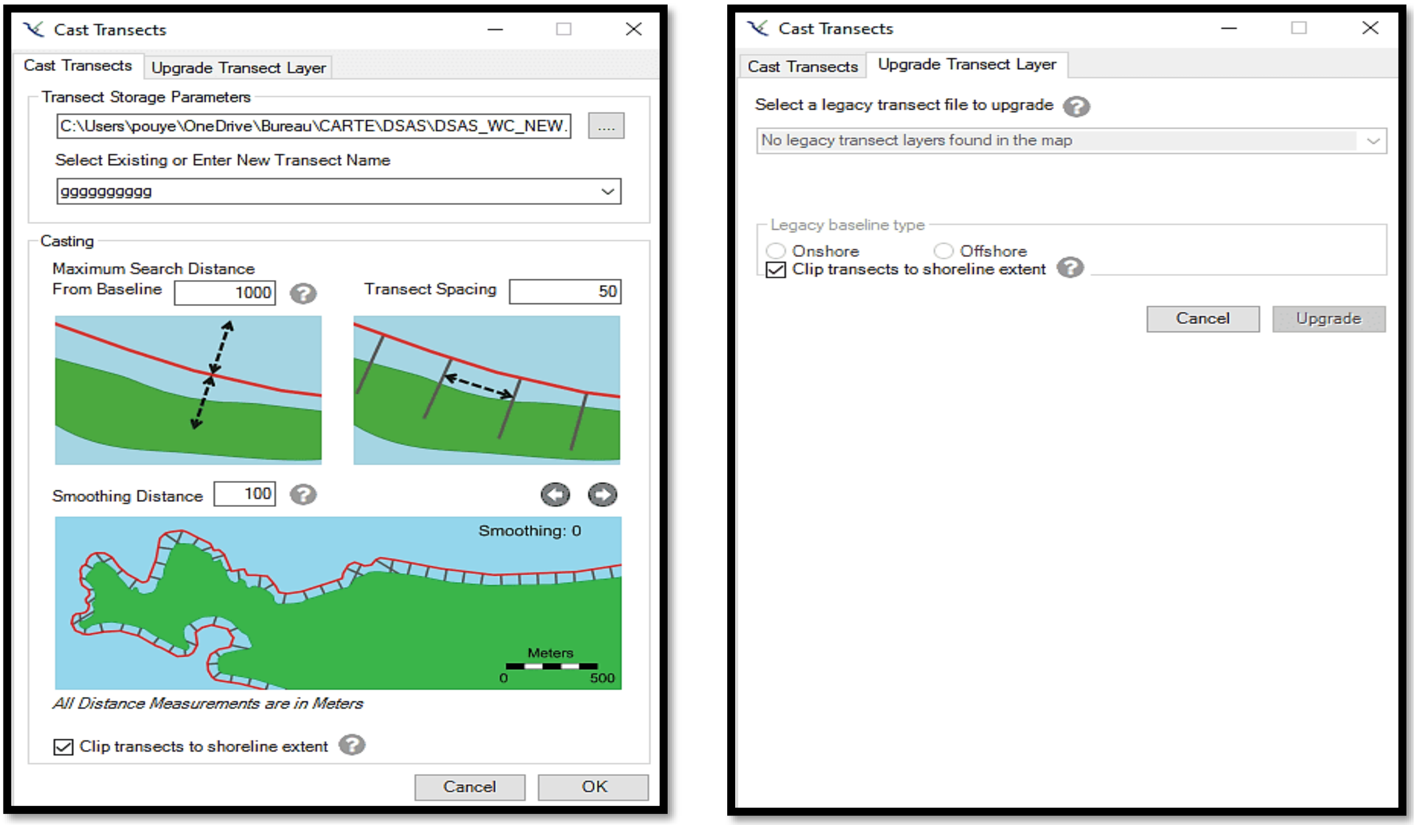


Source: Personal work in DSAS.V5

After setting the default parameters, the Cast window generates a new (or overwrites an existing) transect feature class based on the user-specified settings (Himmelstoss et al. 2018). In this Cast transects window, the distance from the baseline, transect spacing and smoothing distance are determined.

Table 7: Information in the Cast transects tables of the Western coast of the Dakar region

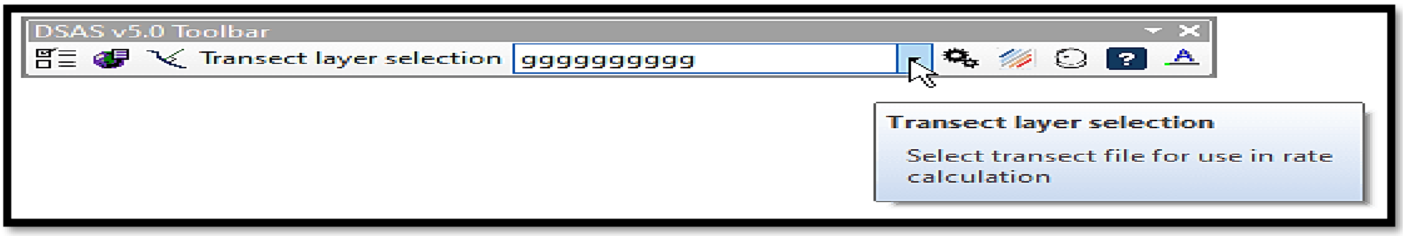




Source: Personal work in DSAS.V5

After sitting in the Cast Transects window, the adequate transect layer is selected to compute the dynamic of the coastline. The table 8 is about the transect selection for calculating the shoreline dynamic.

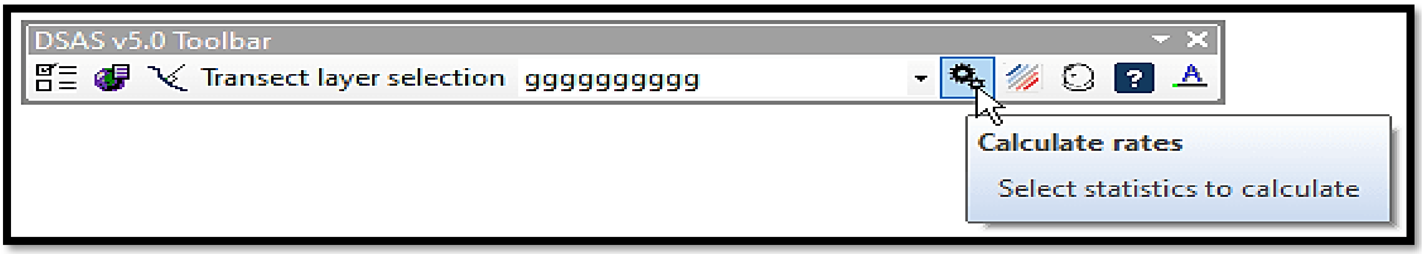
Table 8: Selection of transect layer for computing the dynamic of the coastline

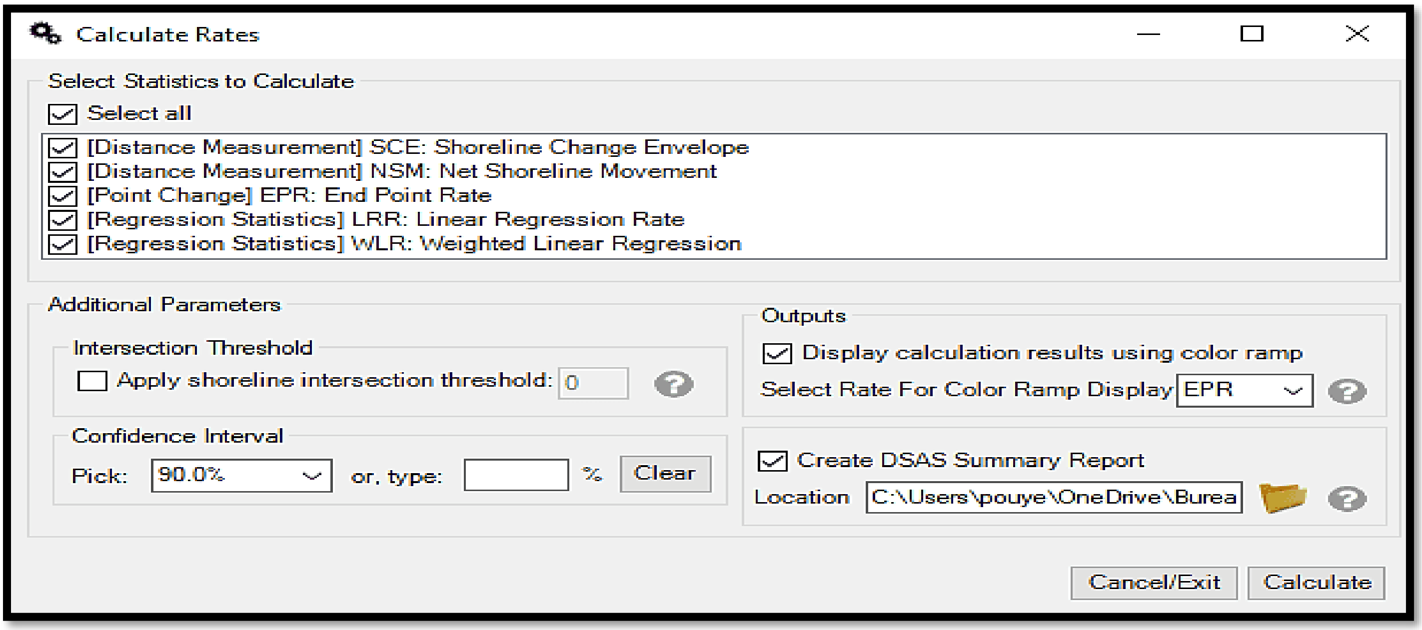


Source: Personal work in DSAS.V5

After selecting the adequate Transect layer, the dynamic coastline rate is computed through the calculated rate window. The table 9 is about the necessary information to compute the dynamic rate of the coastline.

Table 9: The calculation of the dynamic coastline rate through the EPR or LRR





Source: Personal work in DSAS.V5

I.2.8 The prediction of future coastline positions and estimated lost area in the Dakar region in 2030 and 2040

In the DSAS, the prediction of future shorelines is based on the Kalman filter model. It combines observed and model-derived shoreline positions to predict future shoreline positions with uncertainty (Himmelstoss et al. 2018). According to Durrant-Whyte (2001), the Kalman filter ascertains new estates of the state of interest by taking a weighted average of a prediction based on the previous estimate and new observation. A simulation is automatically performed using the Buffer tool based on the current velocity rate to predict the future coastlines' velocity rates. The purpose of predicting the future shoreline positions of the Dakar region in 2030 and 2040 is to find out the future lost coastal areas and infrastructures to alert the policymakers to consider these localities in coastal management policies. This shoreline position prediction is evaluated using the formula of velocity:

Formula 5: Velocity

V=Distance/Elapsed time between 2020 and 2030

If the year 2020 is taken as the origin, with a rate of change in the retreat of the coastline equal to X meters, it will emerge that assuming this average constant rate of change at that date; the coastline will retreat to Y meters in 2030 depending on its current position.

With uncertainty, the DSAS software automatically performed the forecasted lost areas in 2030 and 2040. In contrast, the forecast of lost areas in 2030 and 2040 was performed using the following procedure in ArcGIS: Since the positions of 2020, 2030 and 2040 coastlines are known, they are merged using Arc Toolbox. After that, we convert the merged layer, which is a vector layer, to a polygon layer from which the lost areas are determined by digitalization.

I.2.9 Estimation of uncertainty

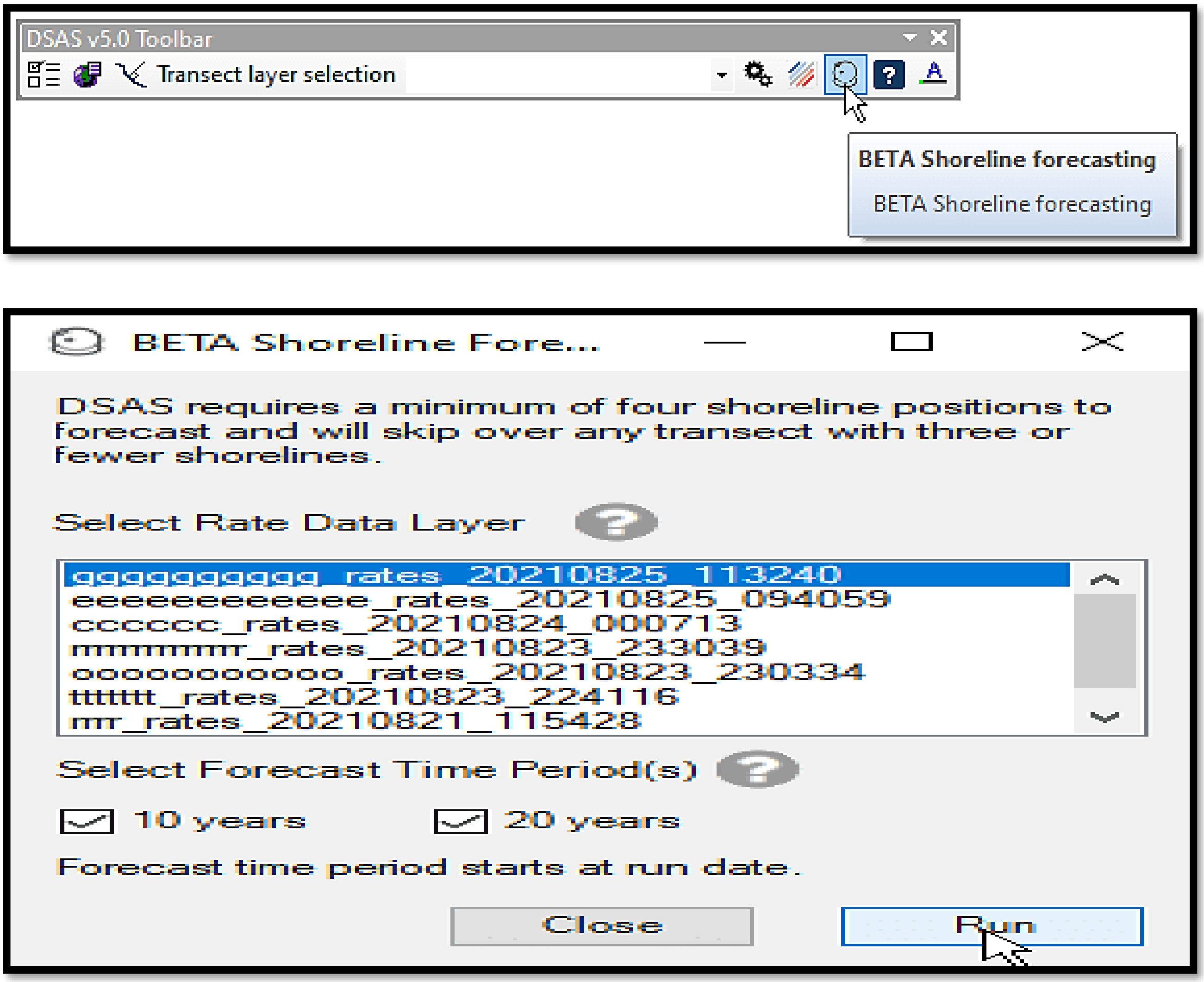
All measurements are subject to error, and analysis is integral to any scientific experiment. The analysis of error is the evaluation of uncertainties, allowing scientists to estimate their results' accuracy and reduce uncertainties if necessary (Taylor 1997). In this study, the estimation of the shoreline dynamic uncertainty using the end point rate of two shoreline positions (1990-2020) is computed by adding their squares. The square root of the summation of squares is divided by the number of the year (30 years) between the two shorelines to determine the uncertainty of the End Point Rate (EPRunc) (Himmelstoss et al. 2018).

Formula 6: EPR uncertainty calculation

$$\mathbf{EPR_{unc}} = \sqrt{\frac{(\mathbf{uncy\ A})\mathbf{2} + (\mathbf{uncy\ B})\mathbf{2}}{\mathbf{date\ A} + \mathbf{date\ B}}}$$

The table 10 is about the selection of the information in order to predict the future coastline position.

Table 10: Future shoreline position forecast in 2030 and 2040 using the DSAS



Source: Personal work in DSAS.V5

A minimum of four coastlines is required to predict the future shoreline position in the DSAS. After computing the dynamic of the coastline, the prediction of future shoreline positions is performed through the BETA Shoreline forecasting window.

I.2.10 Limits of the Digital Shoreline Analysis System (DSAS)

Despite the advantages of the End Point Rate (EPR) method, some limits are noted: In the Digital Shoreline Analysis System (DSAS). The Geological Survey Open-File Report, it is stated that if there are more than two shorelines, certain additional information provided by shorelines can be omitted. Some gap is also noted, for example, the changes in sign, magnitude, or cyclical trends (Himmelstoss et al. 2018) and the inability of the software to determine the forcing of morph dynamics (Oyedotun 2014).

I.3 Assessment of physical vulnerability through the Coastal Vulnerability Index (CVI)

To assess the physical vulnerability of the Dakar region to Sea Level Rise, the Coastal vulnerability index CVI is employed. It is inspired by the one used by Kotinas et al. (2021) in the Modelling Coastal Erosion study applied in Marathon Bay, Greece. It encompasses data from eight variables contributing to coastal vulnerability to erosion and flooding. These eight variables are relief or topography, lithology or rock type, geomorphology, sea level, vertical land movements, horizontal coastline changes (erosion or accretion), tidal variability and wave height. The use of new parameters is noted in this study: The existing protective infrastructures, which play an essential role in determining the adaptative capacity to cope with coastal erosion and the distance between the sea and settlement, which is an important parameter to evaluate the level of exposure of communities to coastal erosion.

It would be essential to note that these physical parameters used cannot be utilized in every coastal context because the coastal conditions leading to erosion in one place can be different elsewhere. These variables are calculated by using the square root of their product. The variables are also ranked from 1 to 5 and divided by the total number of variables. The variables are the critical drive factors of the physical coastal vulnerability in the Dakar region. It should also be noted that these quantitative and qualitative variables have different units.

I.3.1 Variables used

This study uses ten variables: slope, geomorphology, geology, existing protective infrastructures, relative sea level, shoreline displacement, tidal range, swell range, wave height and distance between settlement and the sea.

I.3.2 Slope

The susceptibility of the coast to immersion by flood and the quickness of shoreline retreat are influenced by the area's relief (Kotinas et al. 2016). In this study, data about the slope of the Dakar region were obtained by downloading the Digital Elevation Model through the Copernicus website and using ArcGIS software (see Figure 10 in annex). The coastal slope of the Dakar region is used to determine the level of exposure of the coast to inundation. The coastal slope of the Dakar region can be divided into three sections. On the northern coast, from Yoff to Malika, the slope is lower than 1 %, whereas from Tivaouane Peuhl to Mbambilor, it does not exceed 4 %. On the southern coast from Hann Bel-air to Rufisque, the slope is lower than 1 %, whereas on the coast of the district municipality of Yéne slope is between 0 to 39 %. The slope of the western coast (from Ngor to Plateau) is between 3 to 41.9 %.

I.3.3 Geomorphology

According to Sane and Yamagishi (2004), the accompanying geomorphological units are recognized in the graben. Coastal dunes arranged along the northern coast include two influential groups: the live coastal dunes spread out at the rear of the high seashore, and the youthful rises loosen up behind the live coast sand rises. These are set up by N-S-oriented littoral drift. The Ogolian Erg is situated in the focal and northern part of the Dakar region. It incorporates longitudinal dunes running in the NE-SW direction, isolated by dame interdune corridors. The limestone plateau of the Bargny-Rufisque district, whose substratum is made of limestone and Marl of Eocene age. In the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion (Pouye 2022). The coastal geomorphology of the Dakar region is one of the conditions determining its susceptibility to erosion or not. It is characterized by sand in the hole north coast and south coast from Hann Bel-Air to Rufisque Ouest. Cobble beach and medium cliff coast characterized the coast from Rufisque Est to Yene. The cliff characterizes the western coast (see Figure 12 in annex).

I.3.4 Geology

Three different activities determine the geologic history of the Dakar region: volcanic activities, marine transgressions, and regressions (Pouye 2022). Marine transgressions and regressions observed from the pre-quaternary period up to the quaternary period marked traces still visible in the Dakar region. They are made up of mainly Nouakchott deposits (5500 years B.P.). These deposits are sands or grey marl rich in coastal fauna with limestone bets of an average thickness of 100 meters. The brown marl deposits are also visible in the northern part of Dakar. As a result, the limestone and limestone soils are currently the framework and substratum of Dakar (Adjoussi 2001). Geologically, from the Mesozoic to the Quaternary age, the overall advancement of western Senegal is portrayed by significant faulting framed two horsts (in Dakar's surrounding region). In Dakar city, the southern horst shapes the Dakar plateau 50 m high above the ocean level. It comprises essentially tertiary volcanic, for example, basaltic, dolerite and tuffaceous rocks, and sedimentary rocks. The Ndiass horst arrives at 105m and is framed by Quaternary volcanic deposits. The morphology of the two horsts is emphasized by the occurrence of recent volcanic cones made out of both volcanic debris and basaltic magmas. The horsts create intended, cliffy shorelines that safeguard a less corrupted structure. On such shorelines, the wave's immediate effect is reduced, which slows erosion. Between the two horsts is an enormous graben overwhelmed by Quaternary residue, which shows the lowest topographic point since altitudes rarely rise 5 m above sea level. Long after the tertiary volcanism, severe disintegration of the horsts happened during the early Quaternary. Mechanical change of the igneous rocks happened by common enduring of the dolerite facies and separation of the rock along joints, causing the formation of erratic blocks. Chemical changes started with the decay of individual grains. This phenomenon is notable in tropical areas (Sane and Yamagishi 2004).

Generally, the coast of Dakar region is geologically characterized by sedimentary and volcanic rocks at the western and southern coasts and fine unconsolidated sediments at the northern and southern coasts (see Figure 14 in annex).

I.3.5 Existing protective infrastructures

The protective infrastructures against coastal erosion were installed along the coast of the Dakar region. Plantation which fixes the dunes, riprap and protective walls and gravel are noted in some coastal segments in the Dakar region (see Figure 16 in annex). The existing or not protective infrastructures are a helpful variable to determine local communities' vulnerability and adaptative capacity to cope with coastal erosion.

I.3.6 Relative Sea level

Since the sea level plays an essential role in the coastal dynamic, it can indicate the vulnerability to the coastline retreat leading to a sharp decrease in beaches, mainly observed in the Dakar region. The southern and northern coasts appear among the most vulnerable compared to the west coast because of the low-lying areas in these coastal zones. Indeed in 2050, based on the hypothesis of accelerated sea-level change, almost 50% of the beaches will be lost. On the northern coast, the damage will be less critical (loss of between 40 and 46% of the current beach area) (MEPN 2002 in Pouye 2016).

I.3.7 Shoreline displacement

The shoreline displacement is an indicator which informs on the vulnerability to coastal erosion and is determined by the End Point Rate using the DSAS tool, which is an extension of ArcGIS software. Four Landsat images (1990, 2000, 2010, and 2020) were employed. Dakar region records the respective average rate retreats about -0.44 m/year, 0.21 m/year, and -0.11 m/year, respectively, on the northern, western, and southern coasts. These rates are linked to the nature of the coasts and the hydrodynamic agents' behaviors and provide information about the level of vulnerability (Figure 37).

I.3.8 Tidal Range

Tide is linked with both permanent and episodic inundation events. An extensive tidal range determines the spatial extent of the coast. Areas with large tidal waves have broad, near-zero relief intertidal zones and are susceptible to permanent inundation following sea-level rise. Besides, they are susceptible to episodic flooding associated with storm surges, particularly if these coincide with high tide. It is estimated based on existing oceanographic data (Figure 15).

I.3.9 Swell Range

Generated by wind and currents, swell is one of the most important forces that influence and determine the dynamic behavior of beaches. In the Dakar region, from 1991 to 2018, the height of the swell does not exceed 2 meters. The highest height swell was about 1.74 m, recorded in 1995. Guérin (2003) states that the swells of the Cape Verde peninsula are short (less than 7.5 s). Their heights are less than 2 m, characteristic of the Atlantic Ocean. However, there has been a decline sensitive to the averages of period and height during wintering. This period is characterized by the absence of the northwest swell, with a predominance of southern sector swells (Figure 14).

I.3.10 Wave Height

Waves and longshore currents transform the shoreline via shoreline transport. This variable indicates the number of beach materials that may be moved offshore and, as a result, be permanently removed from the coastal system. The risk variable assigned to wave height is based on each coastal area's maximum significant wave height. For this variable, we decided to examine significant values of the waves, which are closely related to the force of marine erosion.

I.3.11 Distance between settlements and the sea

The distance between the settlement and the sea is valuable in assessing vulnerability. It is one of the indicators which informs about the level of exposure of local communities to coastal erosion. The distance between the settlement and sea for each transect was determined using Google earth, GPS visualizer and ArcGIS. The high urban population growth in Dakar is the consequence of the rapid occupation of the coast, which reflects the importance of the settlement's proximity to the sea. The coastal occupation dynamic shows two types of evolution: The advance of the dwellings toward the sea and, on the other hand, the advance of the sea towards the dwellings. In addition, vegetation cover has been reduced or disappeared in the Dakar region in favor of the settlement. For instance, the retreat of the filao due to road construction on the northern coast particularly in the department of Guédiawaye accentuate the vulnerability. The southern coast is more vulnerable than the department of Guédiawaye due to the distance between the houses and the sea which does not exceed 100 meters (Pouye 2016).

I.3.12 Coastal Vulnerability Index calculation

The Coastal Vulnerability Index (CVI) used in this study is inspired by Kotinas et al. (2016) in the Modelling Coastal Erosion study applied in Marathon Bay, Greece, previously proposed by Thieler and Hammar-Klose in 1999. It encompassed data from eight variables contributing to coastal vulnerability to erosion and flooding. These eight variables are relief or topography, lithology or rock type, geomorphology, sea level, vertical land movements, horizontal coastline changes (erosion or accretion), tidal variability and wave height. The use of new parameters is noted in this study: The existing protective infrastructures, which play an essential role in determining the adaptative capacity to cope with coastal erosion and the distance between the sea and settlement, which is an important parameter to evaluate the level of exposure of communities to coastal erosion. The CVI is calculated using the square root of the product of variables. The variables are also ranked from 1 to 5 and divided by the total number of variables. It would be essential to note that these variables are the key driving factors of the physical coastal vulnerability and are both quantitative and qualitative and have different units. ArcGIS, DSAS, Google Earth Pro and GPS Visualizer were used in this study.

Formula 7: Coastal Vulnerability Index calculation

$$\mathbf{CVI} = \sqrt{\frac{(\mathbf{a} * \mathbf{b} * \mathbf{c} * \mathbf{d} * \mathbf{e} * \mathbf{f} * \mathbf{g} * \mathbf{h} * \mathbf{i} * \mathbf{j})}{\mathbf{10}}}$$

Where:

a- Geomorphology (Landform) ; **b-** Geology ; **c-** Existing protective infrastructures ; **d-** Slope ; **e-** Relative sea level ; **f-** Shoreline displacement ; **g-** Tidal Range ; **h-** Swell Range ; **i-** Wave Height ; **j-** Distance between settlement and the sea

I.3.13 Slope calculation

In this study, the coastal slope is determined through a DEM downloaded from the Copernicus website. It is calculated by measuring the distance from each shoreline segment to the points with a contour over 4 meters. The slope is obtained by dividing the rise by distance and multiplying by 100. To calculate coastal slope, three steps should be performed: A selection of coastal areas over 4 meters altitude, segmentation of shoreline in small parts and distance from each part of the shoreline to the nearest points with an elevation of 4 meters.

- **Selection of coastal areas over 4 meters altitude**

To select the coastal areas that have an elevation over 4 meters, a DEM (which is a raster with an elevation value for each cell) of the Dakar region was employed using the following procedure in ArcGIS: The tool Arc toolbox is opened, and in Spatial Analyst tool, Conditional was chosen. In the Input conditional raster, the DEM must be set. In expression, a value over 4 meters will be created. For that, the expression 'Value>4' should be created. In Input True Raster or Contour value, the number '1' must be set. To better identify the file, it should be named 'Over4meters' in the Output raster. To calculate the distance from each shoreline segment to Contour of 4 meters, the raster file should be converted to vector (polygon) through Arc toolbox and named 'Over_4merters_Polygon'.

- **Segmentation of shoreline in small parts**

After the conversion, the nearest distance between the small part of the shoreline and the altitude over 4 meters will be estimated. For that, the shoreline of the year 2020 is considered and split by using the following procedure: Arc toolbox->Data Management tool->Features->Split line At vertices. The shoreline will be set in Input Features, and the file should be named 'Split_Shore' in the Output features class.

- **Distance calculation**

Since the necessary layers were created, the distance from each part of the shore to points that have an elevation of 4 meters is calculated through the following procedure: Arc toolbox->Analysis Tools->Proximity-> Near. The ‘Split_Shore' created is set in the Input feature, and the polygon represents the areas with an altitude over 4 meters ('Over_4merters_Polygon’) will be set in Near features. The distance is automatically calculated by pressing Ok.

Formula 8: Slope calculation

$$\mathbf{Slope = 4 \,/\, Distance \ * 100}$$

The slope is calculated by dividing the rise (4 meters) by the distance. First, a new field was created in the attribute table of the 'Split_Shore' layer, named 'slope'. The Add Field option from table options is selected to perform slope calculation. The new field's name is specified as 'Slope' and Type as Double. The following procedure was employed: Right-click on 'Slope' and select the Field Calculator and the expression 'Slope = 4 / NEAR_DIST *100’ for calculating the slope.

I.3.14 Geomorphology

Data about the geomorphology of the coast of the Dakar region have been collected through the USAID Project/ RSI N 685 – 0233. Many types of sediment have been identified: sandy beach, Cobble beach, cliff and medium cliff coast (see Figure 12 in annex). These geomorphologic conditions have different resistivity to erosion. The layers ‘Geomorphology. shp' of the coasts of the Dakar region was created and added to the workspace. Each shoreline part is attributed to a geomorphologic feature by joining the information of the two layers ('Split_Shore’ and ‘Geomorphology. shp') through the Spatial Join Tools, which is in Arc Toolbox->Analysis Tools->Overlay->Spatial Join. The layer 'Split_Shore’ is set in Target Features and the layers ‘Geomorphology. shp’ in Joint Feature. The Output file should be named ‘Split_shore_geom’. Only the information about the Geomorphology and slope is kept by unchecking 'Keep all target features'. Since the two layers do not correspond in the 'Match option (Optional)', 'WITHIN_A_DISTANCE' is chosen, and in 'search radius', 50 meters is set (see Figure 13 in annex).

I.3.15 Geology

The Dakar region's coastal geology is a variable contributing to the susceptibility to coastal erosion. Sedimentary rock characterized the coasts of Gueule Tapée, Medina, Fass, Rufisque Est and Yéne. From Ngor to Mermoz, the cliff determined the coast. Fine unconsolidated sediments characterized some northern areas on the southern coast (from Hann Bel-Air to Rufisque Est and from Rufisque Est to Yene) (see Figure 14 in annex). The layers ‘Geology. shp' of the coasts of the Dakar region was created and added to the workspace. Each shoreline part is attributed to a geologic feature by joining the information of the two layers ('Split_shore_geom’ and ‘Geology. shp') through the Spatial Join Tools, which is in Arc Toolbox->Analysis Tools->Overlay->Spatial Join. The layer 'Split_shore_geom’ is set in Target Features and the layers ‘Geology. shp’ in Joint Feature. The Output file should be named ‘Split_shore_geom_geol'. Only the information about the Geomorphology, Geology and slope is kept by unchecking all target features. Since the two layers do not correspond in the 'Match option (Optional)', 'WITHIN_A_DISTANCE' is chosen, and in 'search radius', 50 meters is set (see Figure 15 in annex).

I.3.16 Existing protective infrastructures

To incorporate the existing protective infrastructures in the CVI assessment, each shoreline part should be assigned to existing protective infrastructure or no existing protective infrastructure (see Figure 16 in annex).. For that, the coastal areas that have a protective infrastructure or not were inventoried. First, the vector layers (polygon) for protective infrastructures were created. After that, the information was joined to the layer (‘Split_shore_geom_geol’ and ‘Protective infrastructures. shp') through the Spatial Join Tools, which is found in Arc Toolbox->Analysis Tools->Overlay->Spatial Join. The layer 'Split_shore_geom’ is set in Target Features and the layers ‘Protective infrastructures. shp’ in Joint Feature. The Output file should be named ‘Split_shore_geom_geol_Protec'. Only the information about the Geomorphology, Geology, protective infrastructures, and the slope is kept by unchecking 'Keep all target features'. Since the two layers do not correspond in the 'Match option (Optional)', 'WITHIN_A_DISTANCE' is chosen, and in 'search radius', 50 meters is set (see Figure 17 in annex).

I.3.17 Sea Level Change

Since 1982, the sea level of Dakar has been recorded through tides gauges. These sea-level data records were not regular because of the temporal breaking down of the tide gauges and other inconveniences. For example, data about 2004, 2005 and 2006 were not recorded (missing data). Therefore, the mean sea level (MSL) trend at Dakar 2, Senegal, is +1.14 mm/year with a 95% confidence interval of ±0.61 mm/year, based on monthly mean sea level data from 1992/9 to 2018/12 (Figure 16 and 17). The plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. By default, the long-term linear trend is also shown, in red, along with its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by NOAA CO-OPS**.** To account for sea-level change, data should be added to the layer's attribute table 'Split_shore_geom_geol_Protec'. For that, a new file is created by selecting Table Option and Add field and then creating the new field named 'RSL'. The following procedure was employed to incorporate information about the sea level: Right-click on 'RSL'-> Field calculator->Provide the expression "RLS' = 1.14' mm. Consequently, each transect is attributed to the value of 1.14 mm (see Figure 18 in annex).

I.3.18 Shoreline displacement

Quantifying shoreline movements is usually performed by a ''baseline and transect'' method using manual or automatic (computer) techniques (Dolan et al. 1978; Clow and Leatherman, 1984). In a GIS environment, the user constructs a baseline by drawing a reference line either onshore or offshore of the historical shorelines in the GIS. Then, transect lines are cast perpendicular to the baseline at a user-specified spacing along the baseline. The transects are intersected with the shorelines to produce points, which identify the locations of historical shoreline positions along each transect. The statistics are calculated for each transect and stored in a data table. The corresponding EPR was attributed to each transect (see Figure 19 in annex) in the attribute table by joining the information of the layer 'Split_shore_geom_geol_Protec' and 'Intersects' based on their spatial information through the Spatial Join Tools, which is found in Arc Toolbox -> Analysis Tools -> Overlay -> Spatial Join. The layer 'Split_shore_geom_geol_Protec' is set in Target Features, and the layers 'Intersects' in Joint Feature. The Output file should be named 'Split_shore_Semi_FINAL'. Since the two layers do not correspond in the 'Match option (Optional)', 'WITHIN_A_DISTANCE' is chosen, and in 'search radius', 120 meters is set. The file will contain the information about the coastline dynamic for each transects created after pressing Ok (see Figure 19 in annex).

I.3.19 Mean Tidal Range

Senegalese coasts are affected by a semi-diurnal tide composed of a high water-low water sequence twice daily: 2 highs and two lows, about the same level. The tide generates swift local currents, eroding the seabed and transporting an essential quantity of sediment (Adjoussi 2001).

The annual daily averages of tide recorded in Dakar show that the trend line of tide increased from 1992 to 2020 with a mean daily tide of 10.55 cm. To consider tide, data should be added to the layer's attribute table ‘Split_shore_Semi_FINAL'. For that, a new file is created by selecting Table Option and Add field and then creating the new field named 'Tide'. The following procedure was employed to incorporate information about the tide: Right-click on 'Tide'->Field calculator->Provide the expression "Tide'= 10.55' cm. Consequently, each transect is attributed to the value of 10.55 cm (see Figure 20 in annex).

I.3.20 Swell Range

In the Dakar region, it is noted that the height of the swell from 1991 to 2018 does not exceed 2 meters. The highest height swell was about 1.74 mm recorded in 1995, and the lowest was 1.60m. In more concrete terms, Guérin (2003) states that the swells of the Cape Verde peninsula are short (less than 7.5 s). Their heights are less than 2 m, characteristic of the Atlantic Ocean. However, there has been a decline sensitive to the averages of period and height during wintering. This period is characterized by the absence of the northwest swell predominance of southern sector swells. The southwest swell has values close to the northwest swell and is not strong enough to maintain averages of 7 m and 1.7 s during the rainy season. Furthermore, the mean high swell from 1991 to 2018 is about 1.65 m. To consider the coastal vulnerability assessment well, data should be added to the layer's attribute table ‘Split_shore_Semi_FINAL’. For that, a new file is created by selecting Table Option and Add field and then creating the new field named 'Swell Range'. The following procedure was employed to incorporate information about the sea level: Right-click on 'Swell Range'->Field calculator->Provide the expression "Swell Range'= 1.65' mm. Consequently, each transect is attributed to the value of 1.65 m (see Figure 21 in annex).

I.3.21 Mean Wave Height

To account for Mean Wave High, data should be added to the layer's attribute table ‘Split_shore_Semi_FINAL’. For that, a new file is created by selecting Table Option and Add field and then creating the new field named 'MWH'. The following procedure was employed to incorporate information about the Mean Wave High: Right-click on 'MWH'-> Field calculator->Provide the expression "MWH" = 1.75' m. Consequently, each transect is attributed to the value of 1.75 m (see Figure 22 in annex).

I.3.22 Distance between settlement and sea

The corresponding ‘Distance between settlement and sea’ was attributed to each transect in the attribute table by joining the information of the layer ‘Split_shore_Semi_FINAL' and 'Distance between settlement and sea' based on their spatial information through the Spatial Join Tools, which is found in Arc Toolbox -> Analysis Tools -> Overlay -> Spatial Join. The layer 'Split_shore_Semi_FINAL' is set in Target Features and the layers ' distance between settlement and sea' in Joint Feature. The Output file should be named 'Split_shore_FINAL'. Since the two layers do not correspond in the 'Match option (Optional)', 'WITHIN_A_DISTANCE' is chosen, and in 'search radius', 120 meters is set. The file will contain the information about the distance between settlement and sea for each transect created after pressing Ok (see Figure 23 in annex).

I.3.23 Ranking values for CVI calculation

The ranking values for CVI are made based on the different variables (Table 17). The scale is from 1 to 5, indicating each variable's vulnerability level. The ranking values were done first by creating a new field for each variable in the file 'Split_shore_FINAL’ and then the ranking value.

- The fields were created by selecting 'Table Option' and 'Add field'. In Name, CVI_ plus the name or abbreviation of the variables is set and Type set as 'integer'. These names should be CVI_Slope, CVI_Geom, CVI_Geol, CVI_EPI, CVI_SLC, CVI_EPR, CVI_MTR, CVI_Swell, CVI_Wave and CVI_Dist.
- To rank the values of a variable for example ‘Slope’, the following procedure was employed: Selection Menu->Select by Attributes->In Layer option, the file ‘Split_shore_FINAL’ must be set->Double click on Slope->Set the expression ‘Slope>32’ (for the Index 1 (Very low))->Ok->Right click on ‘CVI_Slope'-> Calculator-> Assign the value '1'->Ok. As a result, all coastal areas with a slope over 32 will be highlighted in blue. The same procedure was done for Indexes 2, 3, 4 and 5.

I.3.24 General Coastal Vulnerability Index calculation

To compute the general coastal vulnerability, index the following procedure was used: Right click on ‘Split_shore_FINAL’->Open Attribute table->Table option->Add Field->In Name, CVI is set->In Type, Double is selected. The expression (‘‘Sqr (([CVI_Slope] * [CVI_Geom] * [CVI_Geol] * [CVI_EPI] * [CVI_SLC] * [CVI_EPR] * [CVI_MTR] * [CVI_Swell] * [CVI_Wave] *

[CVI_Dist]) **/ 10))** was employed. The Coastal Vulnerability Index (CVI) is computed by pressing Ok. To visualize the CVI in a map, the following procedure was employed: Double click on 'Split_shore_FINAL'->Symbology->Quantities->Graduate colours ->In Value, CVI is set, and in Normalization, none->In Classes, 5 is set for representing the expression (Very Low, Low, Medium, High, Very High)->the Color Ramp should be from Green to Red->Ok.

The table 11 shows the variables used to calculate the coastal vulnerability index and the ranking of the level of vulnerability from 1 (very low) to 5 (very high).

Table 11: Coastal Vulnerability Index (CVI) variables

CVI	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
Variables	1	2	3	4	5
Coastal slope	>32	16 - 32	8 - 16	4 - 8	0 - 4
Geomorphology	Rocky, cliffed coasts, Fiords, Fiards Artif. Constructions	Medium Cliffs, Indented coasts	Low cliffs, alluvial plains, beach rocks, dunes (mixed material)	Cobble beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mudflats, Deltas, Mangrove, Coral reefs
Geology	Plutonic Volcanic High-medium grade metamorphic	Low grade metamorphic Sandstones and Conglomerates	Most sedimentary rocks	Coarse, poorly sorted unconsolidated sediments	Fine unconsolidated sediments Volcanic ash
Existing protective infrastructures	The forest which fixes the dunes	Riprap	Protective walls and breakwater	Gravel	No protective infrastructure
Relative level sea change (mm/yr.)	<1,8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.2	>3.2
Shoreline erosion/ accretion(m/yr.)	>2.0	1.0-2.0	-1.0 – +1.0	-1.1 – -2.0	<-2.0
Mean Tide range(m)	>6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	<1.0
Mean Swell Range (m)	<2.0	2.5 - 3	3 – 3.5	3.5 - 4	>4
Mean Wave Height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	>1.25
Distance between settlements and sea (m)	1149 - 2053	589 - 1149	267 - 589	96 - 267	0.72 - 96

Source: (Personal work inspired to (Thieler, E., Hammar-Klose, 1999 in Kotinas et al. 2016)

Legend: CIV= Coastal Vulnerability Index

I.4 Assessment of socioeconomic vulnerability of Dakar to coastal erosion

In this study, four variables represent the socio-economic vulnerability of district municipalities along the coast of the Dakar region. These variables include population density, dependency ratio, gender ratio and education level. Like the CVI assessment, the socio-economic vulnerability assessment is calculated using the square root of the product of variables. The variables are also ranked from 1 to 5 and divided by the total number of variables.

I.4.1 Population density

The population density is computed based on the number of populations living in district municipalities along the coast divided by the superficies of these district municipalities. The higher the population density of a district municipality is, the more exposed in the context of exposure to coastal hazards is this district municipality. The density was calculated for district municipalities by dividing the populations by the surface areas to calculate the vulnerability index for density. The population density was calculated using the following formula.

Formula 9: Population density

$$\textbf{Population density} = \textbf{Number of populations}/\textbf{Land area}$$

I.4.2 Dependency ratio

The number of children under age 14 plus the number of people who are above 65 determined the non-working population. The district municipalities with high dependency ratios are more vulnerable to the impacts of coastal erosion because the working population are more preoccupied with the pick-up charge of the non-working population.

The table 12 shows each indicator's details, description, measurement, source, constraints and explanations. It should be essential to note that this method to assess the socioeconomic vulnerability of the Dakar region based on non-physical parameters is inspired by the Coastal Vulnerability Assessment Report of Timor-Leste (UNDP 2018). It was contextualized in the Dakar region.

Table 12: Indicator characteristics for vulnerability assessment based on non-physical aspects

INDICATOR	DESCRIPTION	PROXY DATA	MEASUREMENT	INDICATOR SOURCE	EXPLANATION
Socio-economic	Population Density	This component indicates the number of people potentially impacted by hazards in the area.	The ratio between population and area	Agence Nationale de la Statistique et de la Démographie	A higher ratio indicates higher vulnerability, as more people would be affected by climate change.
	Dependency Ratio	This indicator shows the number of people of the non-working age compared to those of the working age.	Dependency ratio measures the number of dependents, population aged zero to fourteen and over the age of sixty-five concerning the total population aged fifteen to sixty-four.	Agence Nationale de la Statistique et de la Démographie	A higher ratio indicates higher vulnerability, as the population faces higher burdens in supporting the non-working population.
	Gender Ratio	The ratio between women and men determines the level of adaptability because women often face social constraints, receive less education and are excluded from political and household decision-making processes.	Gender ratio between men and women	Agence Nationale de la Statistique et de la Démographie	A higher gender ratio indicates higher vulnerability as a more significant part of the population would be vulnerable to the effects of climate change.
	Education Level	Education level in the context of adaptation to climate change defines how somebody prepares for and responds to the impacts of climate change.	The ratio between people who receive secondary education with people who do not receive secondary education	Field survey	In this study, people not receiving secondary education are more vulnerable.

Source: Inspired from Coastal Vulnerability Assessment Report of Timor-Leste (UNDP, 2018)

Formula 10: Dependency ratio

$$\text{Dependency Ratio} = \frac{\text{Total number of children under age 14} + \text{Total number of senior citizens above age 65}}{\text{Total number of 15 to 65}} X\ 100$$

I.4.3 Gender ratio

Naturally, women's primary responsibility of caring for the house and children is warranted. They stay home and are primarily under instructed than men. They are generally dependent on men. Consequently, they are more vulnerable to the impacts of climate change. In this study, the district municipalities with a high number of women are more exposed to the impacts of coastal erosion. The gender ratio was calculated by dividing the number of male populations by the female populations multiplied by 1000. The following formula was used.

Formula 11: Gender ratio

$$\text{Gender Ratio} = \text{Male population}/\text{Female Population} * 1000$$

I.4.4 Education level

Based on the field survey results, the number of populations receiving education in our study area varies between 44 and 88%. Education level is an important parameter that indicates the awareness of the population living in district municipalities along the coast about the impacts of climate change and the ability to cope with it. Data about education level was collected from the field survey. The table 13 is about the socio-economic variables used in this study and the ranking of the level of vulnerability.

Table 13: Socio-economic Coastal Vulnerability Index (CVI) variables

CVI	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
Variables	1	2	3	4	5
Population density (People/km^2)	142 - 650	650 - 7565	7565 - 14524	14524- 27475	27475 - 43222
Dependency ratio (%)	2 - 4	5 - 6	7 - 8	9 - 11	12 - 20
Gender ratio (%)	34 - 35	36 - 37	38 - 39	40 - 43	44 - 46
Education level (%)	76 - 88	68 - 75	57 - 67	51 - 56	44 - 50

Source: (Personal work inspired from (UNDP 2018)

I.4.5 Integration of socio-economic data in ArcGIS

The Integration of socio-economic data was done using the following procedure. First, the shapefile representing different district municipalities was loaded in ArcGIS. It is named 'District municipalities'.

❖ **For Population density**

For the population density, the integration of data was done by integrating first data about population and superficies. The integration of data about population was done by Right clicking on 'District municipalities'-> Open Attribute table -> Table option -> Add Field->In Name, 'Population' is set ->In Type, Integer is selected -> Ok -> right click on 'District municipalities' -> Edit Feature -> Start Editing -> Fil the corresponding population number for each district municipality. The integration of data about superficies was done by Right clicking on 'District municipalities'-> Open Attribute table -> Table option -> Add Field->In Name, 'Superficies' is set ->In Type, Integer is selected -> Ok -> right click on 'District municipalities' -> Calculate geometry -> in Property, Area is set -> Ok. The superficies of each district municipalities is automatically calculated. To calculate the population density, the formula 10 was employed by right clicking on 'District municipalities'-> Open Attribute table -> Table option -> Add Field->In Name, 'Density' is set ->In Type, Integer is selected -> Ok -> right click on 'Density' -> Field calculator -> the expression '[Population] / [Area]' is set -> OK. To note that Area equal to superficies (see Figure 24 in annex).

❖ **For Dependency ratio**

For the Dependency ratio, the integration of data was done by integrating first data about people who are under 14, those who are over 65 and the total number of populations from age group of 15 to 65. The integration of data about population under 14 was done by Right clicking on 'District municipalities'-> Open Attribute table -> Table option -> Add Field->In Name, 'under 14' is set -> In Type, Integer is selected -> Ok -> right click on 'District municipalities' -> Edit Feature -> Start Editing -> Fill the corresponding under 14 population number for each district municipality. The integration of data about population over 65 was done by Right clicking on 'District municipalities'-> Open Attribute table -> Table option -> Add Field->In Name, 'Over 65' is set -> In Type, Integer is selected -> Ok -> right click on 'District municipalities' -> Edit Feature -> Start Editing -> Fill the corresponding over 65 population number for each district municipality. To calculate the dependency ratio, the formula 10 was employed by right clicking on ‘District municipalities’-> Open Attribute table -> Table option -> Add Field->In Name, ‘Dependency ratio’ is set ->In Type, Integer is selected -> Ok -> right click on ‘Dependency ratio’ -> Field calculator -> the expression ‘[Under 14] + [Over 65] / Total number of populations from age group of 15 to 65* 1000’ is set -> OK (see Figure 25 in annex)..

❖ **For Gender ratio**

For the Gender ratio, data about male population and female population were integrated. The integration was done by Right clicking on ‘District municipalities’-> Open Attribute table -> Table option -> Add Field->In Name, ‘Male’ is set ->In Type, Integer is selected -> Ok -> right click on the layer ‘District municipalities’ -> Edit Feature -> Start Editing -> Fil the corresponding number of male populations for each district municipality. The integration of data about female population was done by Right clicking on ‘District municipalities’-> Open Attribute table -> Table option -> Add Field->In Name, ‘Female’ is set ->In Type, Integer is selected -> Ok -> right click on ‘District municipalities’ -> Edit Feature -> Start Editing -> Fil the corresponding number of female populations for each district municipality. To calculate the Gender ratio, the formula 11 was used by right clicking on ‘District municipalities’-> Open Attribute table -> Table option -> Add Field->In Name, ‘Gender ratio’ is set ->In Type, Integer is selected -> Ok -> right click on ‘Gender ratio’ -> Field calculator -> the expression ‘[Male] / [Female]*1000’ is set -> OK. The computation of dependency ratio is automatically performed (see Figure 26 in annex)..

❖ **For Education level**

Data about education level was joined: Right click on ‘District municipalities’-> Open Attribute table -> Table option -> Add Field->In Name, ‘Education level’ is set -> In Type, Integer is selected -> Ok -> right click on ‘District municipalities’ -> Edit Feature -> Start Editing -> Fil the corresponding value for each district municipality (see Figure 27 in annex).

I.4.6 Ranking values for socio-economic vulnerability index calculation

The socio-economic vulnerability index's ranking values are based on the different variables (Table 12). The scale ranking is from 1 to 5, indicating each variable's vulnerability level. The ranking values were done first by creating a new field for each variable in the file ‘District municipalities’ and then ranking the value. The fields were created by selecting 'Table Option' and 'Add field'. In Name, CVI_ plus the name or abbreviation of the variables is set and Type set as 'integer'. These names should be CVI_Pop_Dens, CVI_Depend, CVI_Gender and CVI_Educ. To rank the values of a variable for example 'Population density, the following procedure was employed: Selection Menu->Select by Attributes->In Layer option, the file ‘District municipalities’ has to be set->Double click on ‘Density’ -> Set the expression ["Density" >=27475 and "Density" <=43222] (for the Index 5 (Very high))->Ok->Right click on ‘CVI_Pop_Dens'-> Calculator-> Assign the value '5'->Ok. As a result, all-district municipalities with a density of 27475 and 43222 will be highlighted in blue. The same procedure was done for Index 1, 2, 3 and 4.

I.4.7 General Socio-economic vulnerability index calculation

To compute the general socio-economic vulnerability index, the following procedure was used: Right click on ‘District municipalities’->Open Attribute table->Table option->Add Field->In Name, CVI is set->In Type, Double is selected. The expression (‘‘Sqr (([CVI_Pop_Dens] * [CVI_Depend] * [CVI_Gender] * [CVI_Educ] / 4)) was employed. The socio-economic vulnerability index is computed by pressing Ok. To visualize the CVI in a map, the following procedure was employed: Double click on ‘District municipalities’->Symbology->Quantities->Graduate colours ->In Value, CVI is set, and in Normalization, none->In Classes, 5 is set for representing the expression (Very Low, Low, Medium, High, Very High)->the Color Ramp should be from Green to Red->Ok.

I.5 Evaluation of the economic impact of coastal erosion in Dakar region

We start from the idea that in the event of a shock the decrease in the economic value of the littoral in 2030 and 2040 is a clear sign of the vulnerability of the coast and its need for coastal protective infrastructures (because coastal areas which do not record erosion do not need protection). This study considers the shock caused by the decrease in littoral price generated by physical and socio-economic parameters. Multi-linear regression in R software is employed.

I.5.1 Data source

This study uses two categories of data: physical and socio-economic data.

The table 14 presents the study area, data and methods, and assigned code for localities and variables. Where: NC means Northern coast; WC is the Western Coast, and SC is the Southern Coast and their numberings.

Table 14: Localities, data and methods used in this study

Localities	Code	Variables	Code	Sources and materials
Bambilor	NC 1	Littoral Price/m^2 (FCFA)	**LP**	https://www.fao.org
Tivaouane	NC 2			
Malika	NC 3	Lost Areas (m^2)	**LA**	Satellite images/ArcGIS/DSAS
Yeumbeul	NC 4			
Wakhinane	NC 5	Coastal Length (m)	**CL**	Satellite images/ArcGIS
Ndiareme	NC 6			
Sam	NC 7	Dynamic Rate (m/year)	**DR**	Satellite images/ArcGIS/DSAS
Golf Sud	NC 8			
Camberene	NC 9	Littoral Areas (m^2)	**LA_s**	Satellite images/ArcGIS
Parcelles	NC 10			
Yoff	NC 11	Built Areas (m^2)	**BA**	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Ngor	WC 1			
Ouakam	WC 2	Proximity to town (m)	**PR**	Satellite images/ArcGIS
Mermoz	WC 3			
Fann	WC 4	CVI	**CVI**	Satellite images/ Hydrodynamic data/ArcGIS
Gueule Tapee	WC 5	Littoral Width (m)	**LW**	Satellite images/ArcGIS/GPS Visualizer
Medina	WC 6			
Plateau	WC 7	Number of Buildings	**NB**	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Hann	SC 1			
Dalifor	SC 2	Number Hotels	**NH**	

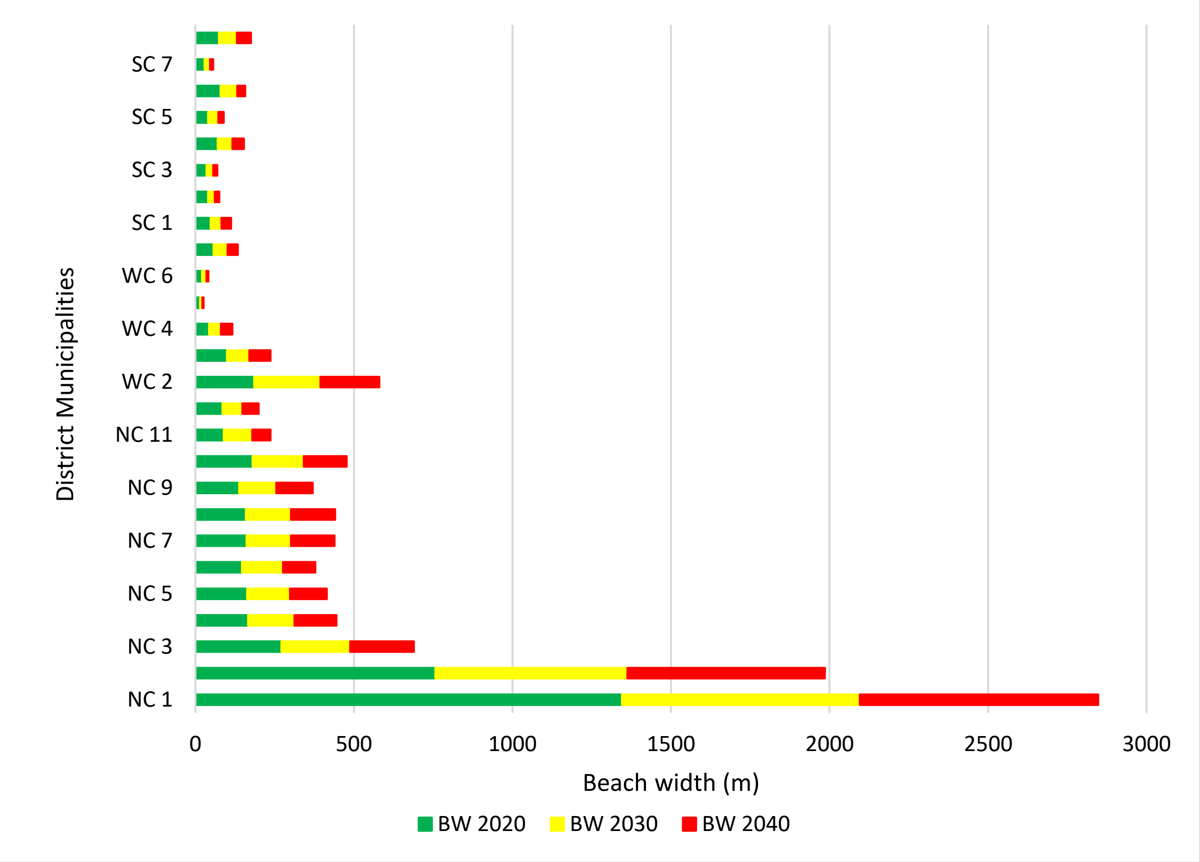
Thiaroye	SC 3			https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Diamageune	SC 4	Number of Industries	**NI**	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Mbao	SC 5			
Rufisque Ouest	SC 6	Number Fishing Points	**NFP**	Google Earth Pro
Rufisque Est	SC 7			
Yenn	SC 8	Road Length (m)	**RL**	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip

Source: Personal work

I.5.2 Littoral width estimation

The distance between the settlement and the sea is considered as littoral width. It is valuable in assessing economic littoral value. It is one of the indicators which informs about the level of exposure of local communities to coastal erosion. It provides information regarding the number of square meters of the coast of each district municipality. It was determined using satellite images, Google earth, GPS visualizer, and ArcGIS. The high urban population growth in Dakar is the consequence of the rapid occupation of the coast, which reflects the importance of the settlement's proximity to the sea. The coastal occupation dynamic shows two types of evolution: The advance of the dwellings toward the sea and, on the other hand the advance of the sea towards the dwellings.

The figure 22 represents each district municipality's littoral width in 2020, 2030, and 2040.



Source: Personal work

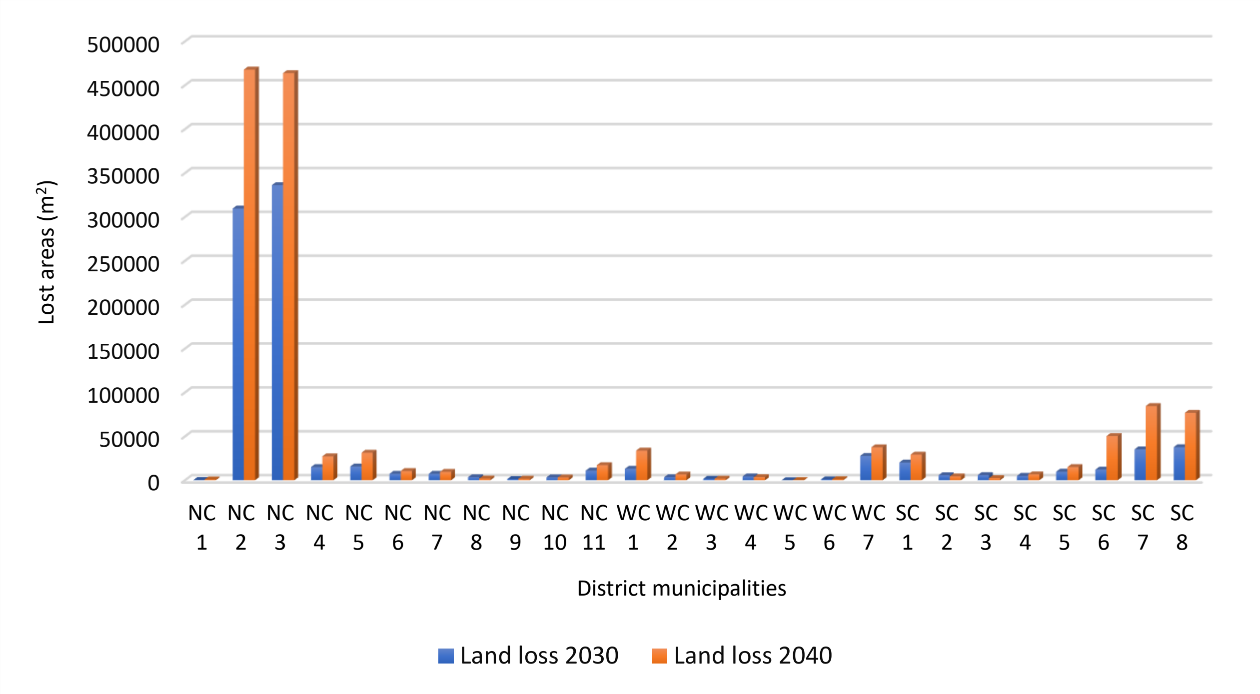
Figure 22: Beach width in districts municipalities in Dakar region in 2020, 2030 and 2040

The total littoral width in district municipalities in 2020, 2030, and 2040 is estimated respectively at 4496, 3364, and 3085 m. However, due to erosion, the littoral width will be generally reduced from 2020 to 2040 (Figure 22).

I.5.3 Lost Areas

Lost areas are estimated using the coastline of 2020 and the one of 2030 and 2040. It indicates on dynamic coastline rate and the level of risk.

The figure 23 is about land loss in each district municipality in Dakar region in 2030 and 2040. To note that the land lost depends on the dynamic of the coast.



Source: Personal work

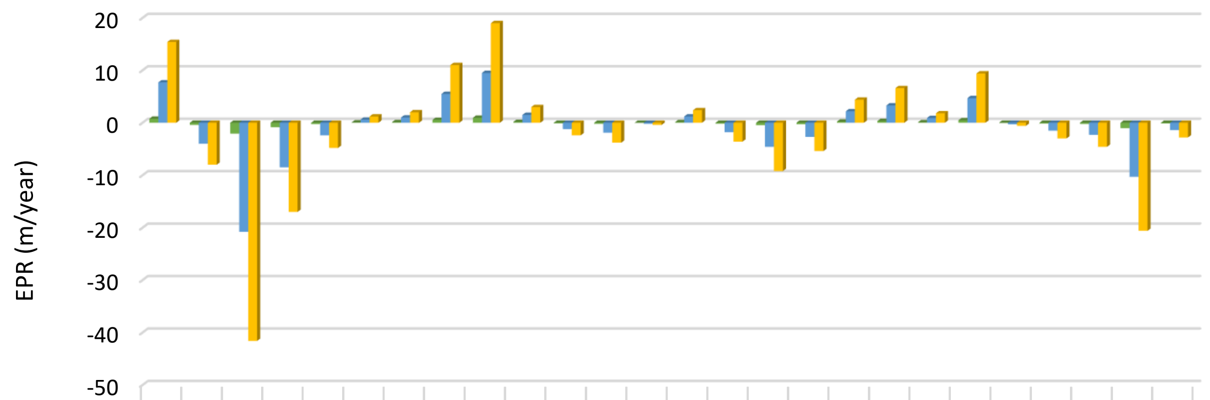
Figure 23: Land loss in districts municipalities in Dakar region in 2030 and 2040

Malika records the highest rates of beach loss, 309,561 m^2 in 2030 and 467,882 m^2 in 2040. In Tivaouvane Peul, there is estimated to be a loss of area of about 336160 and 463,823 m^2, respectively, in 2030 and 2040 (Figure 23).

I.5.4 Shoreline retreat in each district municipality

The shoreline velocity between 1990 and 2020 is evaluated. For that, the distance of shoreline movement is divided by the time elapsed between the oldest and the youngest shorelines using the Digital Shoreline Analysis System (DSAS) software which is an extension of Arc GIS 10.7. The advantage of this statistical method is that the dynamic rate is computed easily through the End Point Rate (EPR) (Himmelstoss et al. 2018).

The figure 24 is about the coastline dynamic rate in districts municipalities in Dakar in 2020, 2030 and 2040.



	NC 1	NC 2	NC 3	NC 4	NC 5	NC 6	NC 7	NC 8	NC 9	NC 10	NC 11	W C 1	W C 2	W C 3	W C 4	W C 5	W C 6	W C 7	SC 1	SC 2	SC 3	SC 4	SC 5	SC 6	SC 7	SC 8
EPR 2020	0.8	-0	-2	-1	-0	0.1	0.1	0.6	1	0.2	-0	-0	-0	0.1	-0	-0	-0	0.2	0.3	0.1	0.5	-0	-0	-0	-1	-0
EPR 2030	7.7	-4	-21	-9	-2	0.6	1	5.5	9.5	1.5	-1	-2	-0	1.2	-2	-5	-3	2.2	3.3	0.9	4.7	-0	-2	-2	-10	-1
EPR 2040	15	-8	-42	-17	-5	1.2	2	11	19	3	-2	-4	-0	2.4	-4	-9	-5	4.4	6.6	1.8	9.4	-1	-3	-5	-21	-3

Source: Personal work

Figure 24: Coastline dynamic rate (EPR) in districts municipalities in Dakar in 2020, 2030 and 2040

The analysis of the coastline dynamics in district municipalities shows two principal trends: erosion and accretion. Since the hydrodynamic, geologic, geomorphologic, and topographic conditions are not the same on the northern, western, and southern coasts, it is evident that the localities do not record the same rate (Pouye et al. 2022). Therefore, 15 out of 26 district municipalities recorded negative dynamic rates in 2020, 2030, and 2040. Malika has the highest rate of -2, -21, and -42 m/year in 2020, 2030, and 2040 respectively (Figure 24). These rates are accentuated by sand mining activities that have been exploited over the years.

I.5.5 Coastal Length

The coastal length for each district municipality is determined using satellite images and measurement tools in ArcGIS.

I.5.6 Proximity to town

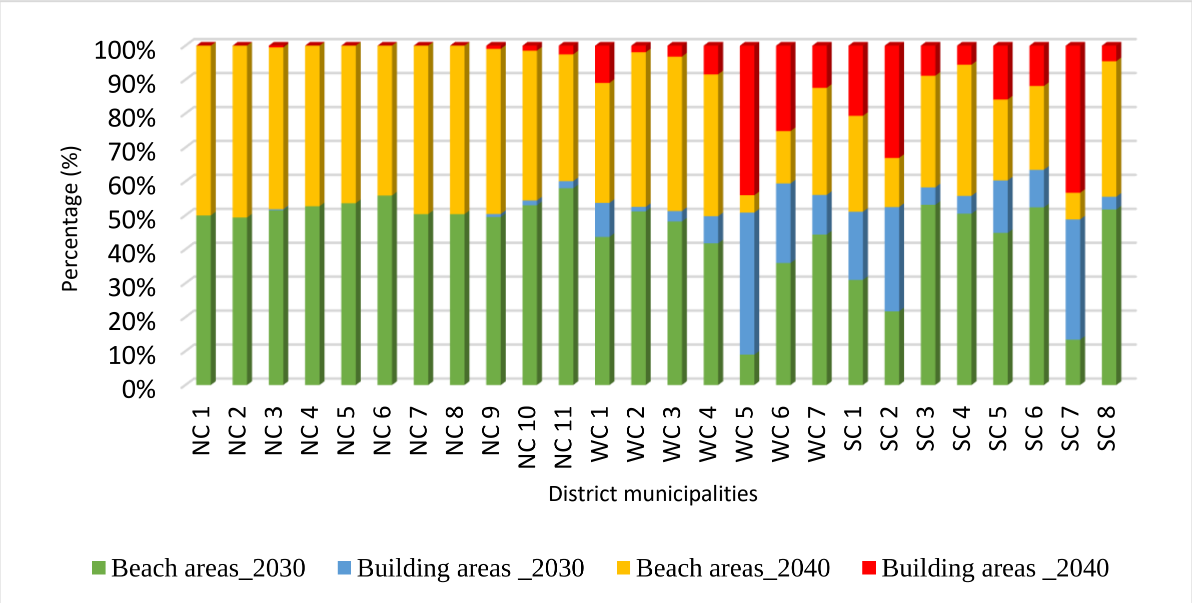
The proximity of a location to the city is a valuable variable for its economic value. In most cases, the closer a settlement is to the city, the higher its economic value. The proximity of settlements to the city is determined using the ArcGIS analysis tool.

I.5.7 Littoral pricing per m²

The prices of the littoral used in this study are based on those defined by Decree No. 2010-400 of 23 March 2010 on the scale of rental prices for the occupation of the State's private real estate domain. Indeed, the occupation of the State's private real estate domain gives rise to the payment of an annual fee proportional to the property's market value. However, a scale fixing the price of these outbuildings has yet to be established beforehand. To fill this gap, the text of Decree No. 88-074 of 18 January 1988 fixing the price scale for bare land and built-up land, applicable for determining the rent of premises for residential use and for calculating compensation for expropriation in the public interest, has always served as a reference scale. However, apart from the fact that it was not designed for this purpose, the said scale has needed more revaluation since its adoption in 1988, despite the increased value acquired by the land in the various areas of the national territory. In order to correct this situation, it was, therefore, necessary to establish a scale for setting the fee for occupying the State's private real estate domain (FAO 2010).

I.5.8 Littoral and building areas

Superficies occupied by littoral and building were estimated using shapefiles of settlements along the coast. A buffer of 200 m from the coastline was considered. The figure 25 shows the percentage of areas occupied by coastline and buildings in 2030 and 2040.



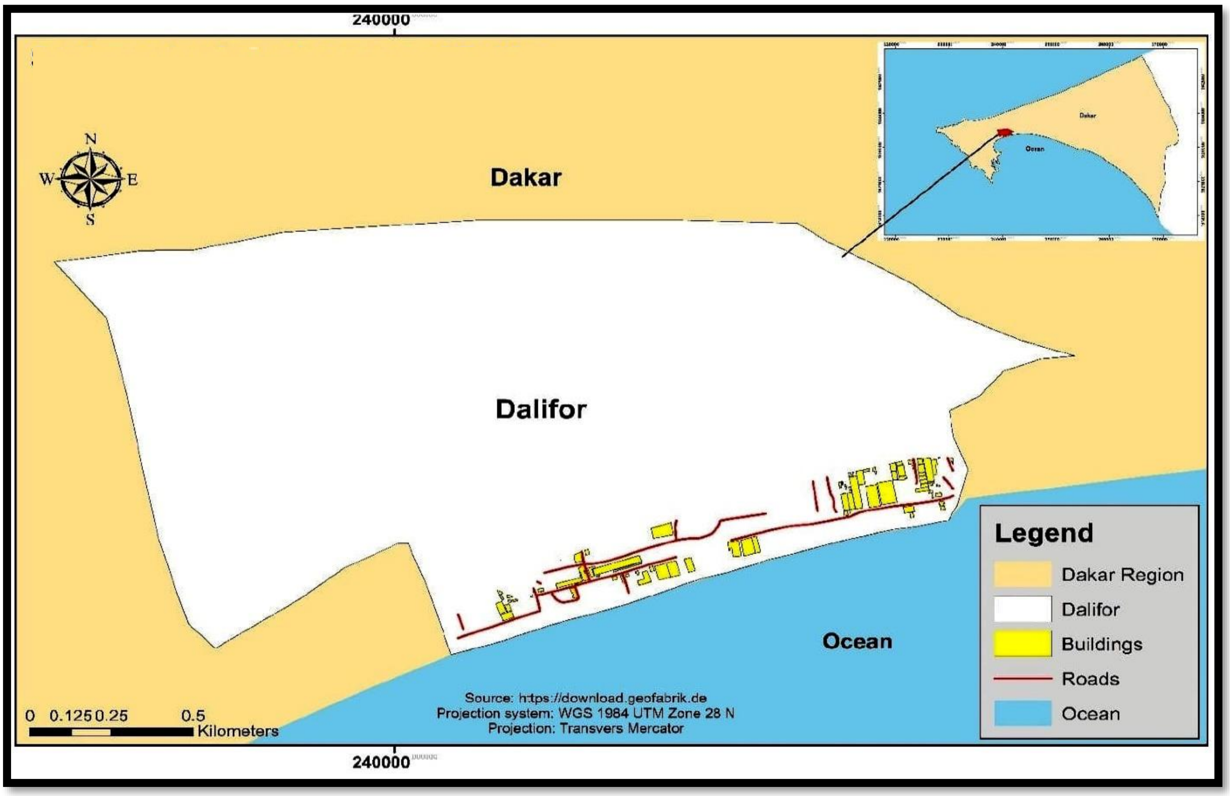
Source: Personal work

Figure 25: Percentage of beach and building areas along the coast of Dakar in 2030 and 2040

The surface area of buildings in 2030 is estimated at 803,119 m^2, whereas in 2040, it is expected to be 911,783 m^2. Regarding the coastal surface area in 2030, the number of 16,433,400 m^2 is estimated instead of 15,481,413 m^2 in 2040, with a difference of 951,987 m^2 which is the expected loss of surface area between 2030 and 2040 (Figure 25).

I.5.9 Number of buildings, hotels, industries, fishing points and road length

The buildings, hotels, industries, fishing points, and road lengths located in the buffer zones of the coastline are counted for each district municipality (Figure 26). The counting was done using the Open Street Map shapefile data in ArcGIS. These variables help to determine the economic value of a coastal zone. The following map is an example of infrastructures settled in the district municipality of Dalifor.



Source: https://download.geofabrik.de

Figure 26: Settlements along the coast of Dalifor

I.5.10 Variables used

Dependent variable, variable of interest and independent variables or control variables are used.

- **Dependent variable**

The dependent variable is each district municipality's respective share of economic littoral value. It is the variable that expresses the economic value of the coast regarding physical and socio-economic parameters.

- **Variable of interest**

The variable of interest is the Littoral Price.

- **Control variables**

Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to town, CVI, Building Price, Number of Buildings, Number of Hotels, Number of Industries, Number of Fishing Points, and Road Length are our variables of control. The linear model used is expressed as follows:

Formula 12: Multilinear regression model

$$\boldsymbol{y = \alpha + \beta choc + \lambda X} + \mathcal{E}$$

Where: $\boldsymbol{y}$ = The share of economic littoral value for each district municipality;

$\boldsymbol{choc}$ = decrease or increase of the variable of interest (Littoral Price);

$\boldsymbol{X}$ = a set of control variables (Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to town, CVI, Number of Buildings, Number Hotels, Number of Industries, Number Fishing Points and Road Length);

$\boldsymbol{\mathcal{E}}$ = the error term ; $\boldsymbol{\alpha, \beta}$ and $\boldsymbol{\lambda}$ = the model parameters.

I.5.11 Multicollinearity test

In a study, Oke et al. (2022) stated that 'multicollinearity is a statistical phenomenon in which a solid or perfect relationship exists between the predictor variables. The presence of multicollinearity can cause severe problems with the estimation and interpretation. Therefore, the much higher correlation between the explanatory variables means more risk in the statistical inference about the significance of the regression coefficients. Various tests and diagnostic measures of multicollinearity have been proposed in the econometric literature. Some measures are available for diagnosing multicollinearity, such as the Variance Inflation Factor (**VIF**), Condition Number (**CN**), Condition Index (**CI**), and Variance Decomposition (**VD**) (Belsley et al. 1980); Chi-square test statistic (Farrar and Glauber 1967, Haitovsky 1969); and an F-test by regressing each of the independent variables on the remaining independent variables. The VIF, a well-known measure of multicollinearity, is defined as

Formula 11: Variation Inflation Factor

$$VIF_i = \left(1 - R_i^2\right)^{-1}$$

Where R_i^2: is the coefficient of determination of the regression of the i-th column of **X** on the remaining columns of **X**: Based on the VIF diagnostic measure, multicollinearity is severe whenever the **VIF** is more than **10**. Therefore, there is no logical reasoning behind the value **10**. (Mohammadi 2020). In this study, multicollinearity was done to point out the dependence among independent variables. The table 15 shows the results of the multicollinearity test of the variables used.

Table 15: The variance inflation factor of independents variables in 2030 and 2040

Square root of Variation Inflation Factor (VIF)					
2030	**2040**	**2030**	**2040**	**2030**	**2040**
Littoral width (LW)		**Lost Areas**		**Coastal Length**	
2.67	2.73	2.06	2.41	2.46	2.81
Littoral areas		**Dynamic Rate (DR)**		**Building areas**	
2.44	2.74	1.63	1.85	2.69	2.87
Hotels		**Industries**		**Fishing points**	
1.24	1.26	1.19	1.37	1.39	1.39
Road Length		**Number of Buildings**		**Proximity to town**	
2.45	3.31	2.78	2.75	2.37	2.39
Coastal Vulnerability Index (CVI)					
1.58	1.61				

Source: Personal work

The results from the multicollinearity test show no collinearity among independent variables because the square roots of the VIF are lower than 5.

I.5.12 Specification of the model

AIC, BIC, and R^2 are employed to select the model used in this study. In a study, Romero

(2007) stated that it is usual practice in econometrics to employ R^2 in model selection. This goodness of fit measurement, along with others like the unadjusted R squared, the Akaike Information Criterion, and the Bayesian Information Criterion, are almost always available to researchers using econometric software. Therefore, the Akaike Information Criterion (AIC) is a prominent approach for selecting models. It is widely employed at parameter space singularities and borders to violate regularity conditions (Mitchell, et al. 2022). At the same time, the Bayesian Information Criterion is a helpful metric for comparing multilevel models. The BIC has several benefits over conventional hypothesis-testing techniques. (Lorah and Womack 2019). According to Yulistiani and Suliadi (2019), the good criteria for model selection can use the Bayesian Information Criterion (BIC). For model selection in linear mixed models, one may use Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). Distinct random effect specifications result in different covariance structures of observation because linear mixed models might provide the specific dependency structure among responses (Lee 2015).

The table 16 is about Specification of the model using AIC, R^2 and BIC test for 2030 and 2040.

Table 16: Specification of the model using AIC, R^2 and BIC test for 2030 and 2040

Test / Model	AIC		R^2		BIC	
	2030	**2040**	**2030**	**2040**	**2030**	**2040**
M_0	1476	1464	0.93	0.93	1497	1486
M_1	1334	1405	0.98	0.95	1354	1426

Source: Personal work

Where: M_0 = Model without diagnostic; M_1 = Model neither outlier nor influencer

The lower the **AIC**, the better the model. The higher the $\mathbf{R^2}$, the better the model. The lower the **BIC**, the better the model. Based on these later statements, model $\mathbf{M_1}$ was chosen.

For more details about the methodology, see the annex 28, 29, 30 and 31.

1.3.4. Questionnaires and interview guides

Questionnaires and interview guides were addressed to economic actors and local communities living along the coast of the Dakar region. These questionnaires and interview guides were helpful to get information about the awareness and perception of communities about coastal erosion and management options and to analyze the coastal erosion impacts on economic activities. The meeting environment experts help to get more suggestions about adaptation strategies.

The table 17 presents the data, its availability, source, analysis tools and the purposes for which it is used.

Table 17: Data collection and analysis tools

Data	Availability	Source	Analysis tools	Purpose
Climatological data	Yes	ANACIM	Excel	Climate variability trend
Hydrodynamic data	Yes	CROD-T, ANACIM, (Uhslc.soest.hawaii.edu/data/ n.d.) (www.psmsl.org/data/ 2021)	Excel	Wind, wave, tide dynamics
Geomorphological and geological data	Yes	USAID Project/RSI N 685 - 0233) Centre de Suivi Ecologique of Dakar	R	analyze the contribution of slope, coastal topography, and elevation to coastal erosion
Historical Maps	Yes	(Glovis.usgs.gov/ n.d.)	ArcGIS, DSAS, GPS	Coastline dynamic Depiction
Economic data	Yes	Field survey, Ministry of Tourism, Ministry of fishery	Sphinx, R	Social impacts of coastal erosion
Social data	Yes	Field survey	Sphinx, R	Economic impacts of coastal erosion; perception of community about

				coastal erosion and management options
coastal infrastructures and settlements data	Yes	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip	ArcGIS, Google Earth	Identification of elements at risk

Source: personal work

Legend:

ANACIM: Agence Nationale de la Météorologie et de l'Aviation Civile

CROD-T: Centre de Recherche Océanographique Dakar-Thiaroye

DSAS: Digital Shoreline Analysis System

GPS: Global Position System

Partial conclusion

The methodology used in this thesis can be resumed by three points: Documentary research, data collection and analysis. The documentation is started at the University of Cape Coast in Ghana. Other libraries were visited, such as the University of Lomé, the University Cheikh Anta Diop of Dakar, the "Centre de Suivi Ecologique of Dakar (CSE)", the Ministry of the Environment, ENDA Third World, the Institute of Earth Sciences, the National Agency for Statistics and Demography of Senegal and the Oceanographic Research Centre. Some articles from scientific journals were also consulted. Quantitative and qualitative data from surveys or institutions such as agencies or ministries are used. These data allow to achieve the aim of this study through the analysis of climate parameters trends, coastline dynamic depiction based on GIS tools, assessment of physical and socioeconomic vulnerability of Dakar to coastal erosion through the Coastal Vulnerability Index (CVI), and economic evaluation of coastal erosion impacts through an econometric model. The following chapter addresses the key drive parameters of coastal erosion in Dakar region.

PART II: RESULTS AND DISCUSSION

Chapter 5: Key drive parameters of coastal erosion or processes

Introduction

Coastal erosion, as its name indicates, can be defined by the alteration, or change in coastal morphology, which is generated by several parameters: the increase in temperature, rising in sea level, hydrodynamic agent effects on the coast, sediment budget deficit, abnormal settlements, sand mining, pollution, etc. In the context of climate change, the global trend of temperatures in the world has shown an increase during the last decades. Consequently, the effects of global warming on the hydrosphere and cryosphere cause an ice melting and dilatation of seawater, leading some coastal regions to a coastline retreat through the sea-level rise. The effects of this rising sea level combined with the change in the normal functioning of hydrodynamic agents, human activities such as sand mining and abnormal settlement lead to coastal erosion (Pouye 2022). Being the most advanced area in the sea in West Africa, the Dakar region is among the most coastal cities threatened by coastal erosion, which challenges communities and socio-economic activities. In this chapter, all processes that intervene in coastal erosion in Dakar are analyzed.

II. Sea level

Sea level is one of the most critical parameters in climate change research and can be used in operational oceanography applications. It is very useful in harbor operation and coastal engineering. It may also help understand complex coastal processes, such as sedimentation and erosion (Woodworth et al. 2007).

II.1 Mean Sea level

According to Ostanciaux (2012), the mean sea level at quiescence corresponds to the intersection between the geoid and solid Earth. It is the average sea level over a period, considering periodic changes due to tides and other fluctuations (such as wind waves). Its spatio-temporal fluctuation depends on eustatic variations but also the lithospheric vertical movements. (www.Marine-Conservation.Org.Uk, n.d.).

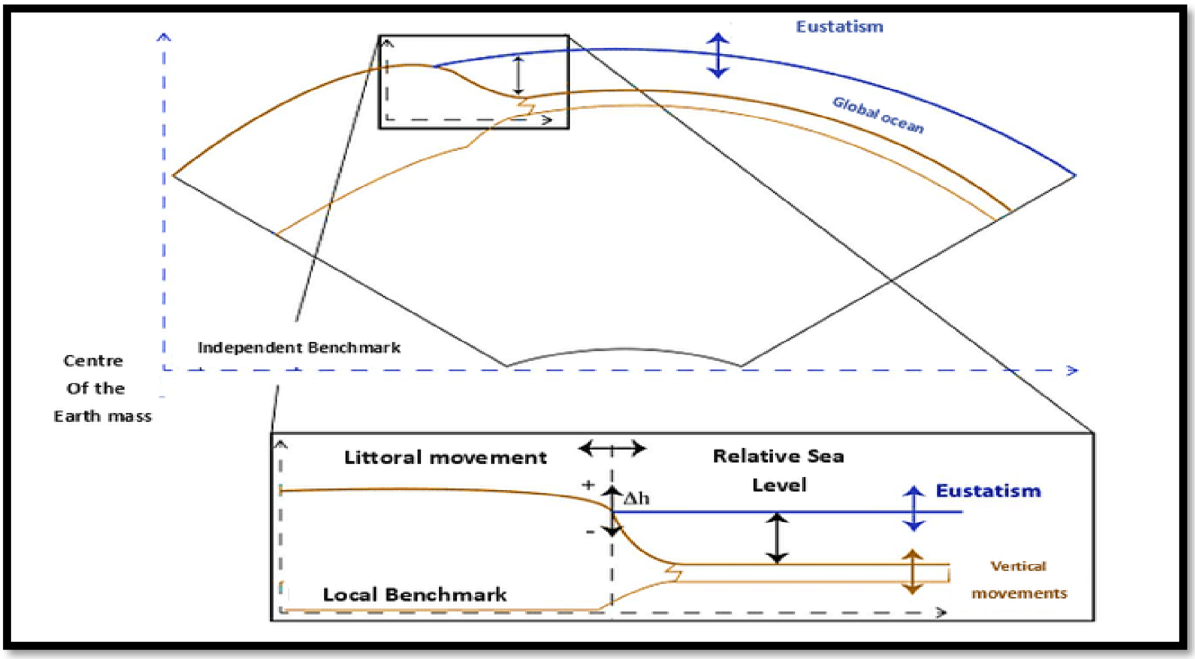
II.2 Relative Sea level and eustatism

The changes in relative sea level at a point on the coast are due to two leading causes:

- The tectonic changes in relative land elevation which are originated from plate tectonic, isostasy, deformation of the geoid and compaction of sediment.

- Eustatic changes in relative ocean elevation are caused by the growth and decay of ice sheets, changes in the volume of ocean basins, and changes in geoid and dynamic controls such as atmospheric pressure, wind and ocean currents (Davidson-Arnott et al. 2019).

The eustatism is a global variation of the sea level either by modifying the volume of oceanic waters or by modifying the basin of oceanic forms (Figure 27). Regarding the glacial-eustatism, when the water is retained on the continents in the form of ice; and of thermo-eustatism, when the modification of the volume of oceanic waters is due to a change in their temperature, and of halo-eustatism, when it is due to changes in their salinity. The terms diastrophic eustatism or tectonic-eustatism are used when the shape of oceanic basins is modified by tectonics (Paskoff 2001 in Pouye 2016). The figure 20 shows the differences between relative sea level and eustatism. Δh represents the variations in relative sea level



Source: Ostanciaux, 2012

Figure 27: Relative Sea level and eustatism representation

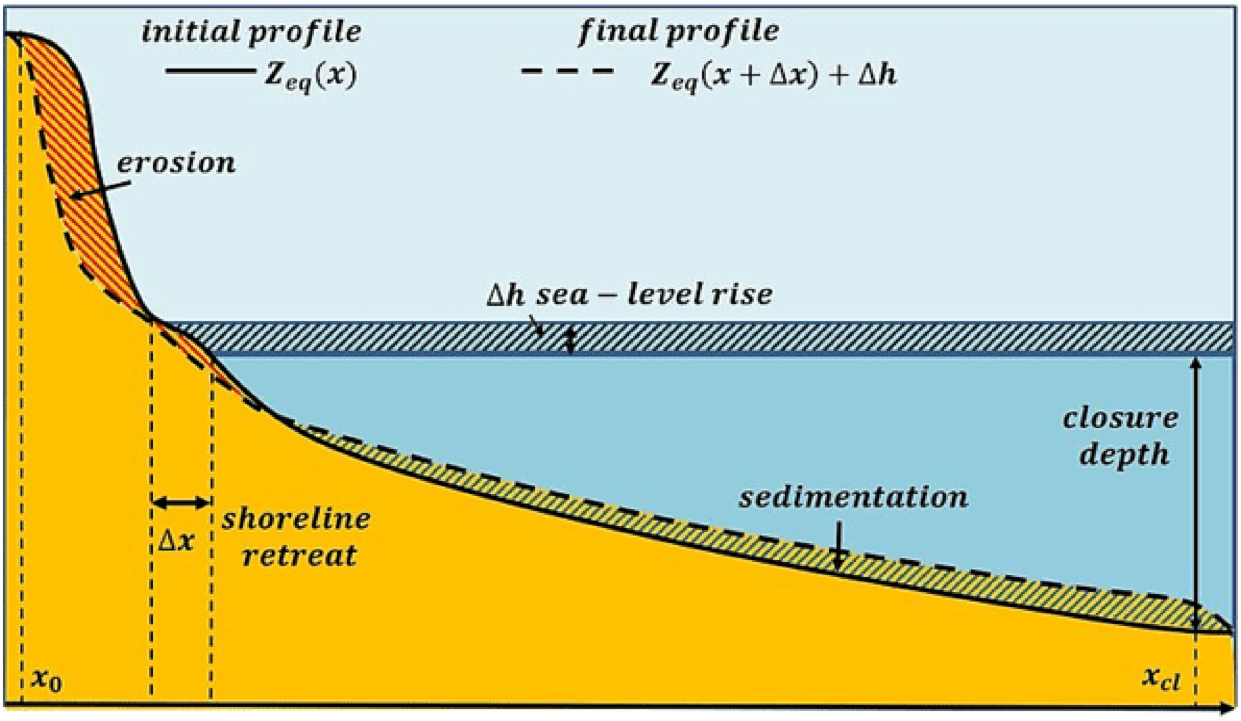
II.3 Sea Level Rise

According to Duxbury et al. (2002), the sea level has risen about 15 cm during the past century. Still, the rising rate has recently increased, and it is thought that the sea level may gain another 30 cm in the next fifty years because of the melting land ice and warming ocean water. This increasing rate of sea-level has been primarily blamed on the greenhouse effect. If the amount of CO_2 in the atmosphere doubles during the next 100 years, there are estimates that the ocean surface will warm an additional 2 to 4^o C. In addition, the expansion of warming water will also affect the sea level by raising it an additional 60 cm for each degree of increase in the average ocean temperature. As a result, the coast's edge will move inland from hundreds to thousands of meters along low-lying coasts, and coastal erosion will be accelerated. However, the rate of sea level is not the same all around the world. In the tropic, sea temperatures are rarely constants, so changes attributable to thermal expansion are small. Still, the seasonal oscillation of the meteorological equator between approximately 0 and 10N causes sea level to vary in response to atmospheric pressure changes in sea surface temperature associated with El Nino affecting sea level. In the north Atlantic and north Pacific, the annual seasonal shift from height to low-pressure cells over the oceans causes a relative change in sea level (Rising with low atmospheric pressure and falling with high pressure). Onshore winds elevate, and offshore winds depress coastal water levels. Ocean currents influenced by the Coriolis effect create a sea surface topography that varies by as much as a meter. Any climate-generated changes in speed or location of winds or currents alter sea level. Climate change associated with atmospheric warming can be expected to alter the winds, the currents and the atmospheric pressure distributions, and the thermal expansion of seawater (Sverdrup and Kudela 2014).

II.3.1 The Bruun rule

Nearshore processes influence the morphology of the coast and vis versa (Bird 2008). Based on the Bruun rule, these two profiles will translate upward and landward, maintaining their shore-normal geometry when they are subjected to sea-level rise. Consequently, the shoreline retreat can be predicted through a known amount of a rising sea level and a shape of an original offshore profile (Figure 21) (Cooper and Pilkey 2004). In a study (Bruun 1962), it is stated that the rule of shoreface adaptation to sea-level rise refers to the concept of equilibrium profile. The shaded eroded and deposited volumes are equal. The vertical/horizontal scale ratio is greatly exaggerated. Sand supply from the inland coastal profile implies shoreline retreat (designated Δx) and a corresponding landward shift of the equilibrium shoreface profile. The new translated equilibrium profile **Z new eq(x)** is then equal to the old equilibrium profile **Zeq(x)** with an upward shift equal to the sea-level rise **Δh** and a landward shift **Δx** (www.coastalwiki.org).

The figure 28 is about the Bruun rule processes and their principal components.



Source : www.coastalwiki.org, n.d.

Figure 28: Schematic representation of the shoreface shift in response to sea-level rise

Formula 1: Bruun rule

$$\mathbf{Z\ new\ eq(x)\ =\ Z\ eq\ (x + \Delta x)\ + \Delta h}$$

Where:

Z new eq(x) = New translated equilibrium profile

Z eq(x) = Old equilibrium profile

Δx = Landward shift

Δh = An upward shift equal to the sea-level rise

The principle of this Bruun rule is that when coastal sediments are eroded and moved toward the nearshore due to wave actions, the level of the initial profile growth causes a rising in sea level. Consequently, the coastline moves backwards. Even if this Bruun Rule is one of the central themes in coastal geology and sedimentation (Swift and Palmer 1978 in Williams et al. 2009), it presents some insufficiencies in terms of its applicability in the field. Despite it provided an advanced understanding of the coastal system since 1954, several specific problems were however pointed out by Cooper and Pilkey (2004): For example, the disprove of the Bruun Rule in the field; lack of revisiting post-1960 shoreface theory causing a scarceness of historical knowledge of the shoreface; its unsuitability for a complex sedimentary environment such as the nearshore zone with significant spatial and temporal variations in sediment supplies; wave conditions and coastal retreat rates in variable geological frameworks. In addition, Cooper and Pilkey (2004) stipulated that the Bruun rule does not work because of three reasons:

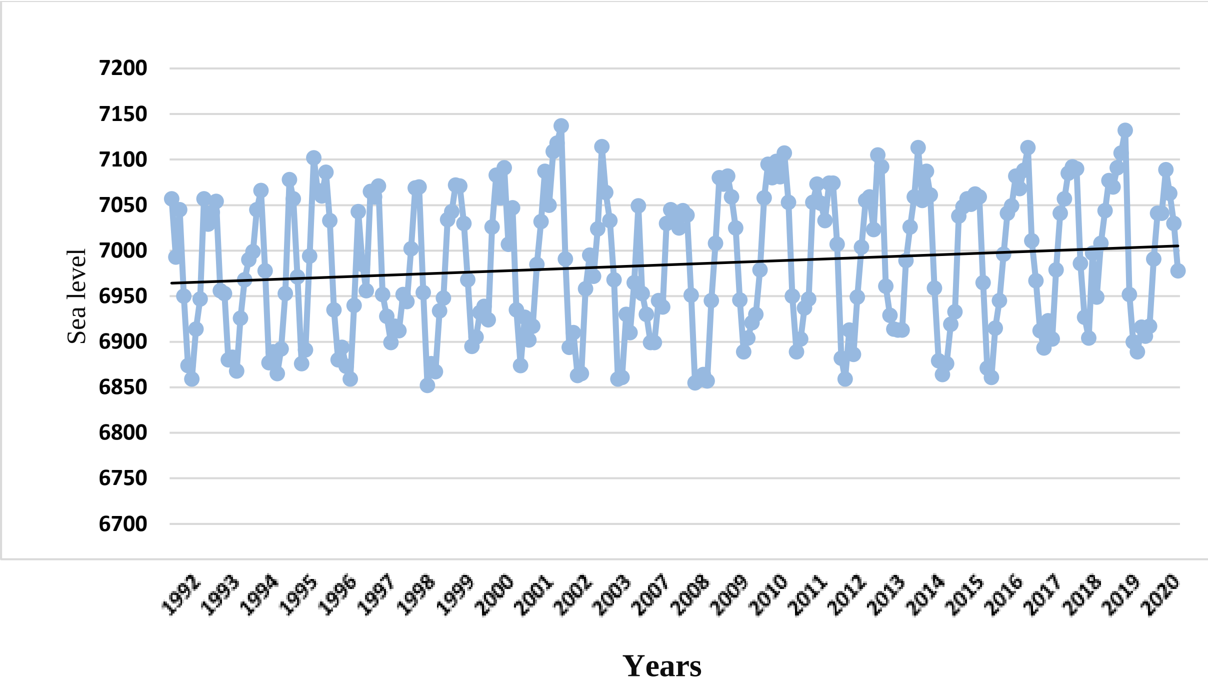
- The first one is that the assumptions behind it are so restrictive that they probably do not exist in nature. The Bruun rule supposes that the shoreline retreat is always due to the rising relative sea level. It does not have an accretionary component. Many surfaces have been known in nature to accrete even under rapid sea-level rise, meaning that the Bruun rule applies only to a small number of coasts.
- The second reason is the attribution only to wave action as responsible for sediment transport and the omission of many important variables such as rip currents, storm surge ebb currents, wind-driven up and downwelling, tidal currents; wind amplified longshore currents and the non-effect of surface slope in the coastline retreat in certain coasts.
- The third reason is the dependence of the Bruun rule on outdated and erroneous relationships. For example, implicit in the shoreface profile of equilibrium concept is the hypothesis that underlying geology has no effect or control on the translation of the profile. It is known that the geology underlying the shoreface frequently plays a role in shoreline behavior (Riggs et al. 1995; Cowell et al. 1995 in Cooper and Pilkey 2004).

II.3.2 Sea Level Rise in Dakar

Since 1982, the sea level of Dakar has been recorded through tides gauges. These sea-level data records were not regular because of the temporal breaking down of the tide gauges and other inconveniences. For example, data about 2004, 2005 and 2006 were not recorded.

The following figure is about the monthly average sea level recorded in Dakar region from 1992 to 2018. It shows a noticeable sea level increase trend from 1992 to 2020. This increase in sea-level rise can lead to coastline retreat, reduction of coastal areas, submersion, salinization of agricultural land and freshwater etc. (UEMOA 2010).

The figure 29 is about the monthly sea level average trend of Dakar from 1992 to 2018, considering the missing data for the years 2004, 2005 and 2006.

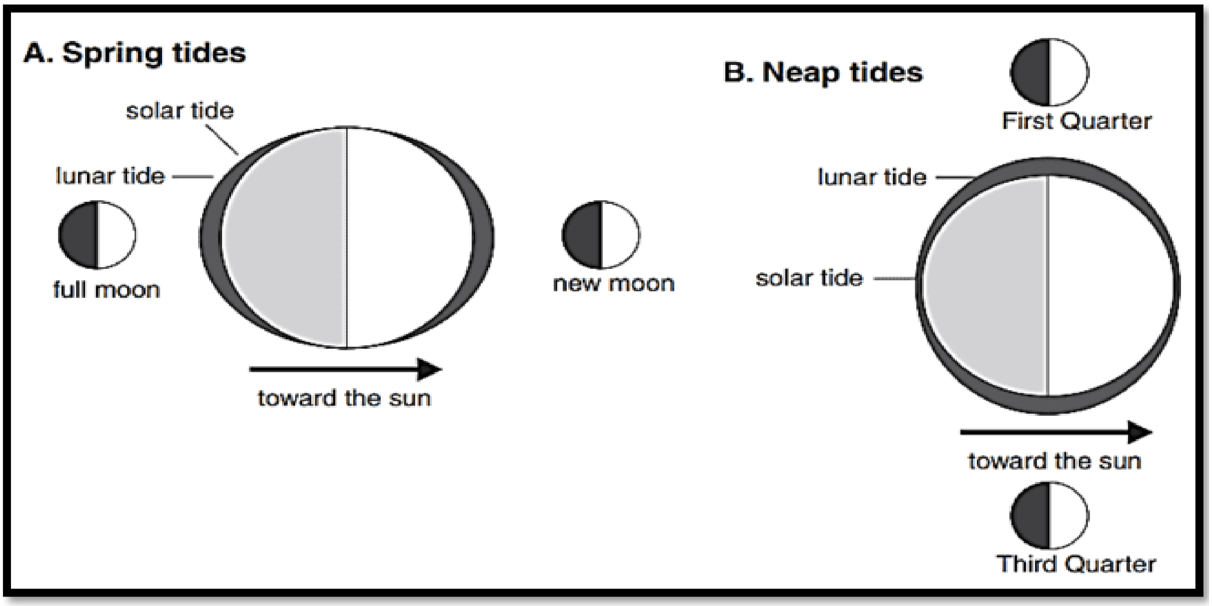


Source: ANACIM, 2021

Figure 29: Monthly Sea level average trend of Dakar from 1992 to 2018, considering the missing data for the years 2004, 2005 and 2006

III. Tide

The figure 30 is about the relative position of the Earth, sun and moon during spring and neap tide.

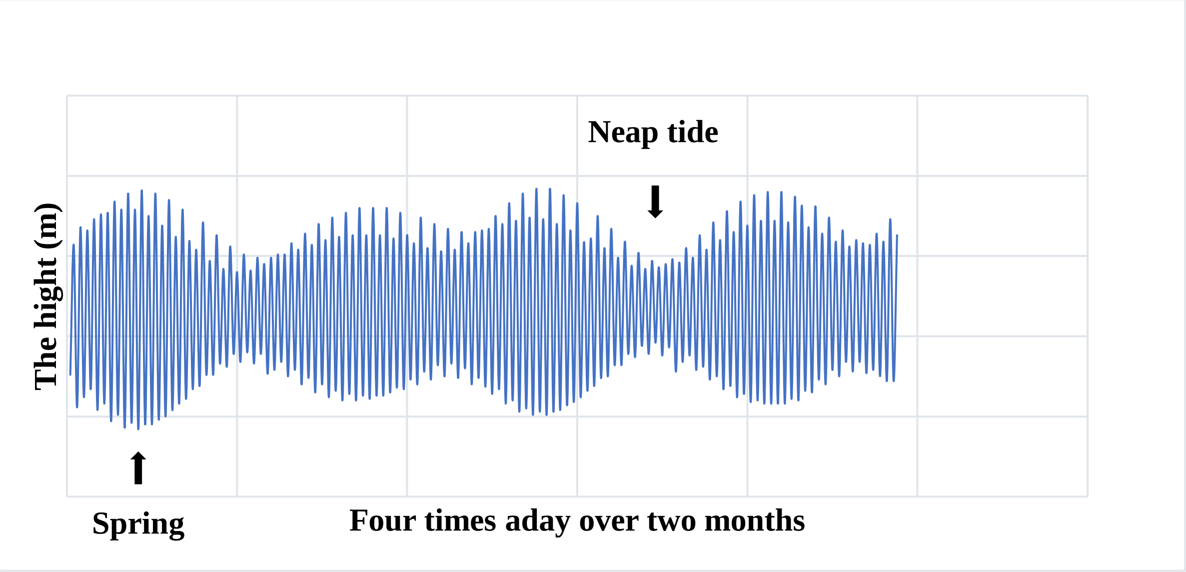


Source: Davidson-Arnott et al. 2019

Figure 30: Relative position of the Earth, sun and moon during spring and neap tide

Tides along the ocean coasts generate the regular daily rise and fall of sea level. These fluctuations are called astronomical tides since they are caused by the gravitational influence of the moon and sun and distinguish them from short-term changes in sea level produced by strong winds or barometric pressure, which are called meteorological tides. All the tidal curves show a distinct variation in the amplitude of the tidal fluctuation that occurs throughout a fortnight (two weeks). This is related to the relative positions of the two tide-generating forces of the sun and the moon (Davidson-Arnott et al. 2019).

The figure 31 is about height tide fluctuations showing the Dakar region's spring and neap tides over the months of Jun and July.



Source: ANACIM, 2021

Figure 31: Spring and nep tides graphics over two months (Jun/July 2016) of Dakar region

The tide regime of the Dakar region is characterized by the semidiurnal mixed tide (height water-low water twice a day). The moon and the sun each produce two tidal waves. When the sun and the moon are aligned in a straight line at the full and new moons, these two waves are in phase and reinforced, producing higher high tides and lower low tides. When the sun and moon are aligned at right angles, as in the first and third quarter, the tidal waves are out of phase and tend to cancel each other (Figure 30). Because the solar component is much smaller than the lunar component, it does not entirely cancel it, leaving a diminished lunar tide. Tides with the most extensive range, which occur at the full and new moons, are termed spring tides, while those with a lower range associated with the first and third quarters of the moon are termed neap tides (Figure 31). On average, the neap tidal range is about 40% lower than the spring tide (Davidson-Arnott et al. 2019). Tidal fluctuations are significant in all aspects of the coastal zone, and they affect physical processes such as the shoreward extent of wave action and the flushing of waters in estuaries, lagoons, and bays; biological activities such as the zonation of plants and the feeding activities of birds, fish, and other marine organisms; and chemical processes such as those associated with the wetting and drying of intertidal rock surfaces. The tidal range significantly affects the form and width of sandy beaches and thus the source area for coastal dunes. The difference between the elevation of high and low tide is the tidal range, which controls the excursion of the water level on the coastline (Davidson-Arnott et al. 2019).

IV. Wave and Swell

In specific literature, the wave is assimilated to swell both generated by wind on the local surface. It is described as wind waves or swells, created when the waves increase out of a storm area. They occupy a smaller piece of the spectrum. By and large, wind waves have periods from 1 to 15 seconds and swell, from 12 to 25 seconds, albeit this definition isn't elite. Wave amplitudes outside this scope of periods are few (Ioc 2006). Toffoli and Bitner-Gregersen (2017) definite waves as oscillations or disturbances of water surface that can be observed in any water basin, for example, rivers, seas, lakes, and oceans. The initial equilibrium state, its disturbance and compensation by a restoring force are the conditions for a wave to exist. Local wind, seismic oscillations of the Earth during earthquakes, atmospheric pressure gradients, and gravitational attraction between the Earth, Moon, and Sun.

Far from being among the most contributor hydrodynamic agents in coastal morphology, waves play an important role in coastal erosion. Its action on the beach depends on the nature of the wave and the coastal sediment where it breaks (Reeve et al. 2018). In a study, Strahler (2013) stipulated that the breaking of waves against a shoreline yields a variety of distinctive features. If the coast is made up of weak or soft materials (various kinds of regolith, such as alluvium), the force of the forward-moving water alone easily cuts into the coastline. Here, erosion is rapid, and the shoreline may recede rapidly. Under these conditions, a steep bank, or marine scarp, will form and steadily erode as storm waves attack it. Whereas, where resistant rocks meet the waves, sea cliffs often occur. A notch is carved essentially by physical weathering at the base of a sea cliff. Constant splashing by waves followed by evaporation causes salt crystals to grow in tiny crevices and fissures of the rock, breaking it apart, grain by grain. Hydraulic pressure of waves, and abrasion by rock fragments thrust against the cliff, also chisel the notch.

Undercut by the notch; blocks fall from the cliff face into the surf zone. As the cliff erodes, the shoreline gradually retreats shoreward. Sea cliff erosion results in various erosional landforms, including sea caves, arches, and stacks (Strahler 2013).

V. Current

In the Marine Glossary, sea current is defined as a movement of ocean water characterized by regularity, either cyclic nature or, more commonly, as a continuous stream flowing along a definable path. Three general classes, by cause, may be distinguished:

- currents related to seawater density gradients, comprising the various types of gradient current;
- Wind-driven currents are those directly produced by the stress exerted by the wind upon the ocean surface; long-wave motions produce currents.
- The latter are principally tidal currents but may include currents associated with internal waves, tsunamis, and seiches. The major ocean currents are of continuous, stream-flow character and are of first-order importance in maintaining the Earth's thermodynamic balance (www.Marine-Conservation.Org.Uk, n.d.).

The sea currents play an essential role in the sedimentation process. They influence the temperature distribution in the marine basins and the distribution of the plankton and benthos that contribute to the formation of deposits in seas and oceans (Soumare 1996).

VI. Wind

Wind performs two kinds of erosional work: deflation and abrasion. Deflation is the removal of particles, largely silt and clay, from the ground by the wind. It acts on loose soil or sediment. Dry river courses, beaches, farmlands, and areas of recently formed glacial deposits are especially susceptible to deflation. In dry climates, much of the ground surface can be deflated because the vegetation cannot hold the soil or sediment in place (Wind Action, n.d.). The capability of the wind to remove particles by deflation depends on their size. Given a mixture of particles of different sizes on the ground, deflation, combined with splash erosion and overland flow, will remove the fine particles, and leave the coarser particles behind. As a result, rock fragments ranging in size from pebbles to small boulders become concentrated into a surface layer known as desert pavement. The large fragments become closely fitted together, sheltering the smaller particles (grains of sand, silt, and clay) that remain beneath. The pavement acts as an armor that protects the remaining fine particles from rapid removal by deflation or overland flow. However, this pavement is easily disturbed by wheeled or tracked vehicles, which expose the finer particles underneath, leading to renewed deflation and water erosion. In drier plains regions, deflation can scoop out a shallow basin called a blowout, especially where the grass cover has been broken or disturbed by grazing animals, for example. The size of the depression may range from a few meters (10 to 20 feet) to a kilometer (0.6 miles) or more in diameter, although it is usually only a few meters deep. A blowout can also form in a shallow depression in a plain where rains have filled the depression and created a shallow pond or lake. As the water evaporates, the mud bottom dries out and cracks, leaving small scales or pellets of dried mud. The wind then lifts these particles out. The second process of wind erosion is abrasion. It drives sand-sized particles against an exposed rock or soil surface, wearing down the surface by the impact of the particles. Wind abrasion is most active in a layer of about 10 to 40 cm (4 to 16 in.) above the surface. The weight of the sand grains prevents them from being lifted much higher into the air. Wooden utility poles on windswept (Strahler 2013).

The wind is an essential key parameter in hydrodynamic conditions and generates swell, wave, and sea current. However, its disturbance can lead to increased storm surge frequency, coastal flooding, dune retreats or disappearances, etc.

VII. Anthropogenic contribution to coastal erosion

The impacts of human activities along the coast can be harmful since they contribute to the disequilibrium of dynamic coastal processes through sand mining, haphazard settlement, and pollution. This situation leads to the disturbance of socio-economic activities such as fishery, agriculture, and tourism. The most threaten facts which accentuate coastal erosion in Dakar can be resumed by sand mining, haphazard settlements, and pollution.

VII.1 Sand mining

For the most part, coarse sand, rock, and other bigger particles are kept close to the foundation of the eroding surfaces; the better silt is stored in the floodplain, bays, or lagoons, and at the littoral as delta deposits. The extremely fine residue and clay fractions that generally make up a significant portion of the dissolved material move seaward, where it, in the end, settles. The sand portions stored at the shoreline are slowly moved along the coast by waves and currents, giving sustenance to sea shores. In the end, a significant extent of this littoral material is frequently lost to seaward regions. The sediment yield from upstream stretches increments with expansion with the help of the drainage basin however diminishes with size, which clarifies the significance of the little streams in beachfront residue transport (Padmalal and Maya 2014). Despite the critical role in the sediments exchange along the coast in equilibrium processes, over-exploitation is noted due to the exponential population growth and the need to establish in coastal areas. The impacts of urbanization and concentration of industrial and commercial activities along the coasts have resulted from an over-exploitation of coastal sediments, mangrove forests, estuaries, and seagrass beds. The results are coastal erosion, forest loss and pollution from municipal, industrial and agricultural waste (Mensah 1997).

In Senegal, particularly in the Dakar region, the demand for sand used in construction has increased the demand for beach sand which is an indispensable material for most constructors. Human activities are also an important cause of disturbance to marine and coastal ecosystems. The exposure to coastal hazards is associated with various types of degradation. One of the most insidious factors that inexorably erodes sandy beaches is the extraction of sea sand used in large amounts for construction. This activity is very common in the neighborhoods of Parcelles Assainies, Golf, Mbao, Cambérène II, etc. The negative consequences on the coasts and buildings constitute a real public problem for Senegal (IAGU 2007). In addition, there are also seashell mining operations by local communities that are also used for construction (Figure 32 A). These materials are primarily taken from the beaches. However, when these withdrawals become too important (more significant than the sediment supply), this situation leads to a disequilibrium of the beaches, causing beach erosion. This is particularly noticeable in areas with longshore drift, which is the case on the southern coast of the Dakar region (MEPN 2010 in Pouye 2016).

On the northern coast of the Dakar region, in the extension of the Mbeubeuss dump (Malika district municipality), there are sand extraction activities for the construction sector. At least 100 tip trucks per day, i.e., about 5 million cubic meters per year, are extracted (Figure 32 B). Such volumes of withdrawals have severe impacts on sediment dynamics. Some consequences are noted: harmful effects on the shoreline and fishery activities in Yoff (Quensière et al. 2013).

The figures 32 A and B show the sediment extraction activities along the coasts of Dakar region.

Source: Pouye, 2021 and https://www.callsenegal.info/

Figure 32: Sediment exploitation activities in Petit Mbao and Malika (Northern and Southern coast of Dakar)

VII.2 Haphazard settlements

Migration from the country's interior to the capital and fishing centers, in other words, to the ocean coast, will form an adjustment variable to alleviate the pressure in rural areas. (Mbow et al. 2008 in Weissenberger et al. 2016). In Senegal, the coastal zone has become a beautiful area regarding economic, demographic, and social conditions in the last few decades. This phenomenon is strongly linked to the various ecological and economic crises that the country has experienced from the 1960s to the current period. First, a significant rainfall deficit hit West Africa in the 1970s and 1980s. The droughts significantly impacted agriculture in Senegal, which at the time was mainly based on groundnut cultivation. In addition, the country was experiencing rapid population growth. The government became less involved in the agricultural sector; an attitude reinforced and extended to all spheres of the economy in the 1980s with the implementation of Structural Adjustment Programmes (SAPs) imposed by the International Monetary Fund (IMF) and the World Bank. The rural exodus was a response to the deterioration of living conditions in rural areas, further weakened in the 1990s by another consequence of the Structural Adjustment Programmes: the devaluation of the Franc CFA (Communautés Financières d'Afrique) (Mbow et al. 2008). Consequently, this situation leads to illegal occupation of coastal areas more frequent in Senegal, particularly in the Dakar region. These abnormal settlements contribute to coastal erosion by the troubles of natural sediment exchange between land and sea.

VII.3 Pollution

The dumping of waste water causes eutrophication in the marine environment. Marine coastal eutrophication refers to the syndrome of ecosystem responses to the increase in supply of organic matter. This term includes all potential causes for such supply, such as changes in water turbidity, residence time, circulation, stratification, or mixing, as well as increased algal growth following the addition of inorganic fertilisers or organic material (Nixon 1995; Cloern 2001in Cosme and Hauschild 2017). Any of these can be impacted by human activity, either directly or indirectly, but one obvious connection between human activity and ecological consequences has been found to be the increasing flow of inorganic nutrients from anthropogenic sources to coastal waterways. (Smith et al. 1999; Gray et al. 2002; Rabalais 2002 in Cosme and Hauschild 2017). It is also noted that plastic debris contribute to marine pollution. Waves and tides can carry trash that have entered the ocean onto beaches. Plastic waste buildup on beaches can influence sediment dynamics, which can change erosion patterns. Plastics can also harm and choke coastal vegetation, which reduces their capacity to stabilise sediments. Marine pollution can significantly contribute to coastal erosion through various mechanisms that alter coastal ecosystems, disrupt natural sediment processes, and weaken the stability of coastal landforms. The impact of marine pollution on coastal erosion is a complex and multi-faceted issue, with different types of pollutants having distinct effects. In addition, dangerous chemicals and toxins are introduced into the marine environment through industrial and agricultural runoff, sewage discharge, and oil spills. Coral reefs and seagrass beds are two coastal ecosystems that these pollutants have the potential to directly damage, resulting in the loss of these habitats. The habitat's ability to prevent erosion decreases when it is compromised or destroyed, making the shoreline more susceptible to wave action and storm surges (Derraik 2002).

Marine pollution is among the most significant threat that coastal areas in the world, particularly coastal cities, face. Therefore, it is due to the population growth and lack of waste management policies, particularly in developing countries. With the economic growth, the discharge of wastewater from factories and treatment plants along the Dakar region's coast has been more frequent during the last decade. Consequently, the concentration of hydrocarbons in the Mbao sea, Hann, Cambérène and Soumbédioune are following a growing trend. In addition, local communities also pour out their wastewater into the sea. Such a situation is observed in certain localities on the northern coast of the Dakar (Yoff and Cambérène, Hann, etc.) (Figure 33).

The figure 33 is about waste water discharge in sea at Yoff and Cambérène Southern coast of Dakar)

Source: Pouye, 2016

Figure 33: Discharge of wastewater into the sea at Yoff

This situation leads to the migration of some aquatic species, such as the Epinephelus, marine turtles, etc. and a decrease in fishery incomes. At the SHS city, a pumping station was created in 2011 that collects 800 cubic meters of wastewater per day. Another sewage treatment plant was created in 2007 with a capacity of 8 500 Equivalent/inhabitants, i.e., 595 cubic meters of water per day. However, because of its low capacity of treatment, the remaining wastewater is transferred to the Cambérène station, which transfers and purifies them before discharging into the sea of Cambérène. The Cambérène station has a capacity of 200,000 Equivalent/inhabitants, a daily flow of 19,200 cubic meters and an outfall in the Cambérène Sea. It has a purification degree of 30 mg/l and a peak flow of 1400 cubic meters per Hour. Its wastewater discharges at sea or on the coast constitute one of the main factors of marine pollution on the coast of Dakar (Pouye 2016).

Partial conclusion

In conclusion, global warming can be seen as an increase in temperature patterns that were observed a few decades ago. As a result, the hydrosphere and cryosphere's ice melting is also observed. Due to the dilatation of seawater driven by global warming, most coastal regions will see a shoreline retreat as a result of increasing sea levels. Coastal erosion is caused by sea level rise, as well as the effects of hydrodynamic agents like the tide, wave, swell, current, wind, etc. and their irregularity. Coastal erosion is, aside from flooding, the most dangerous disaster that confronts local communities living along the shore in the Dakar region because of its geographic location in the sea and low-lying areas. Additionally, the trend of observed data concerning sea level, which is evident in the rising tide swell, indicates coastal erosion in the Dakar region. Even though there are two aspects to the causes of coastal erosion: the natural coastal erosion caused by hydrodynamic agents operating normally and the one that is accentuated by their dysfunction. Human conditions such as haphazard settlement, pollution, sand mining, etc. accentuate this erosion. The following chapter addresses the coastal dynamic analysis in Dakar region.

Chapter 6: Coastal dynamic analysis in Dakar region using GIS approach

Introduction

Like most of the world's capitals, the Dakar region is not safe from the impacts of coastal erosion because of its geographical position and low-lying areas. The advanced sea resulting from sea-level rise combined with the effects of climate change affects the coastal morphology of the Dakar region. This situation is accentuated by the disturbance of hydrodynamic agents such as waves, tide, wind, etc. Consequently, this reduces coastal areas, and causes human displacement toward inland, disruption of economic activities such as fishery, hostelry, industry, etc. Human activities accentuate these threats through sand mining, pollution, and illegal settlements along the coasts. The study of shoreline dynamics is generally conducted in coastal countries. Therefore, since it is an essential parameter in studying the impacts of climate change in coastal areas, scientists are more interested in littoral studies seeking deep existential knowledge. This chapter aims to depict the coastal dynamics in the Dakar region from 1990 to 2040. It can play an essential role in addressing the issue of coastal erosion in Dakar.

I. Results

I.1 Coastline dynamic analysis in short and long terms of Dakar

The analysis of the coastline dynamic in the Dakar region is conducted in the short (1990-2000; 2000-2010 and 2010-2020) (Annex: Table 1), (Annex: Figure 1, 2, 3, 4, 5, 6, 7, 8, 9) and long term (1990-2020) (Figure 37).

The table 18 shows the statistics related to the coastline dynamic in short and long periods in the northern, western and southern coasts of Dakar region..

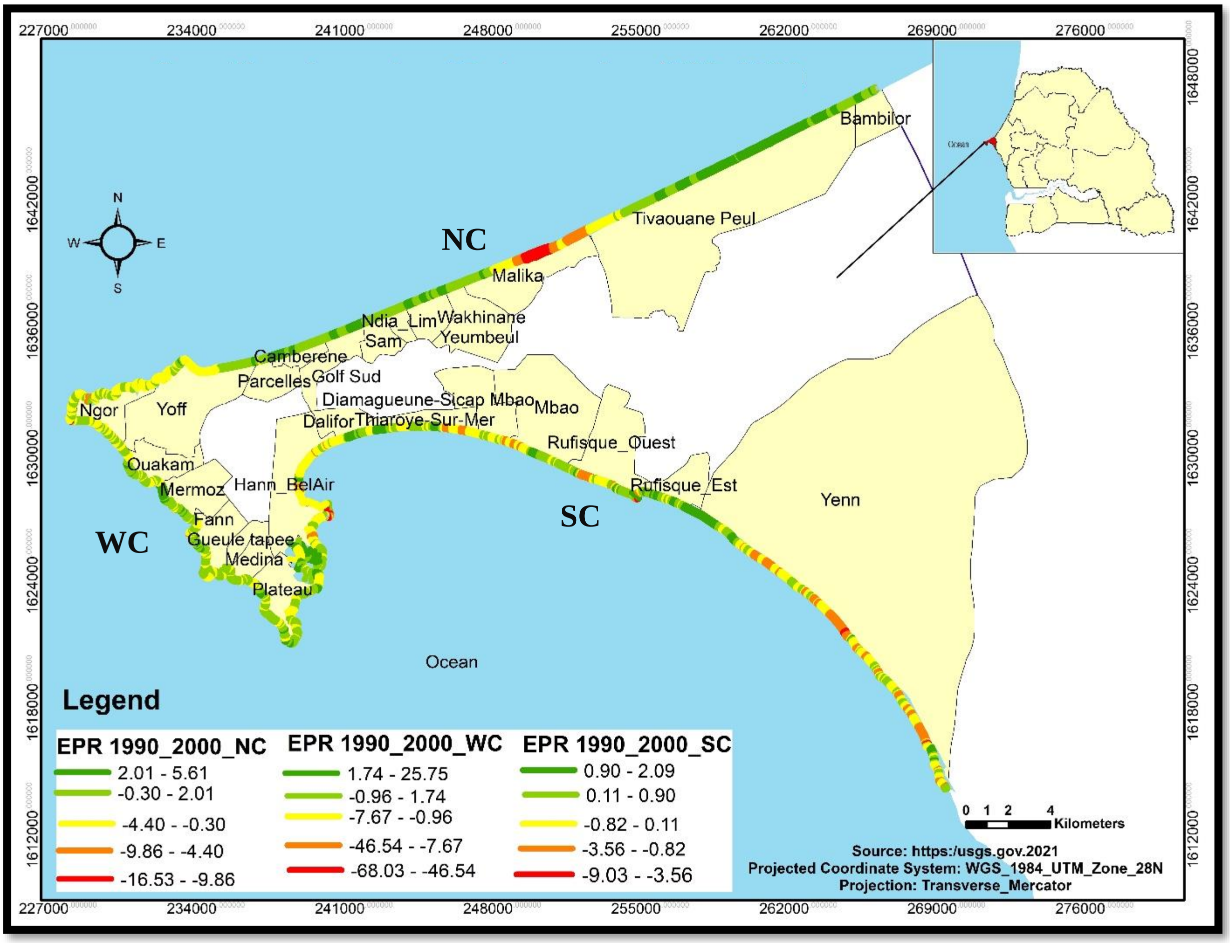
Table 18: Average rates with reduced uncertainty of the coastline dynamic of Dakar from 1990 to 2020

Shoreline changes using the (EPR) (m/year)				
Coasts	**1990-2000**	**2000-2010**	**2010-2020**	**1990-2020**
Northern coast	0.45	-4.12	-2.57	-0.44
Southern coast	-0.08	-0.13	0.29	-0.11
Western coast	-0.81	0.71	0.20	0.21

Source: Personal work

I.1.1 Coastline dynamic analysis of Dakar region from 1990 to 2000

The figure 34 is about the coastline dynamic of Dakar region from 1990 to 2000. It shows two principal trends: erosion and accretion.



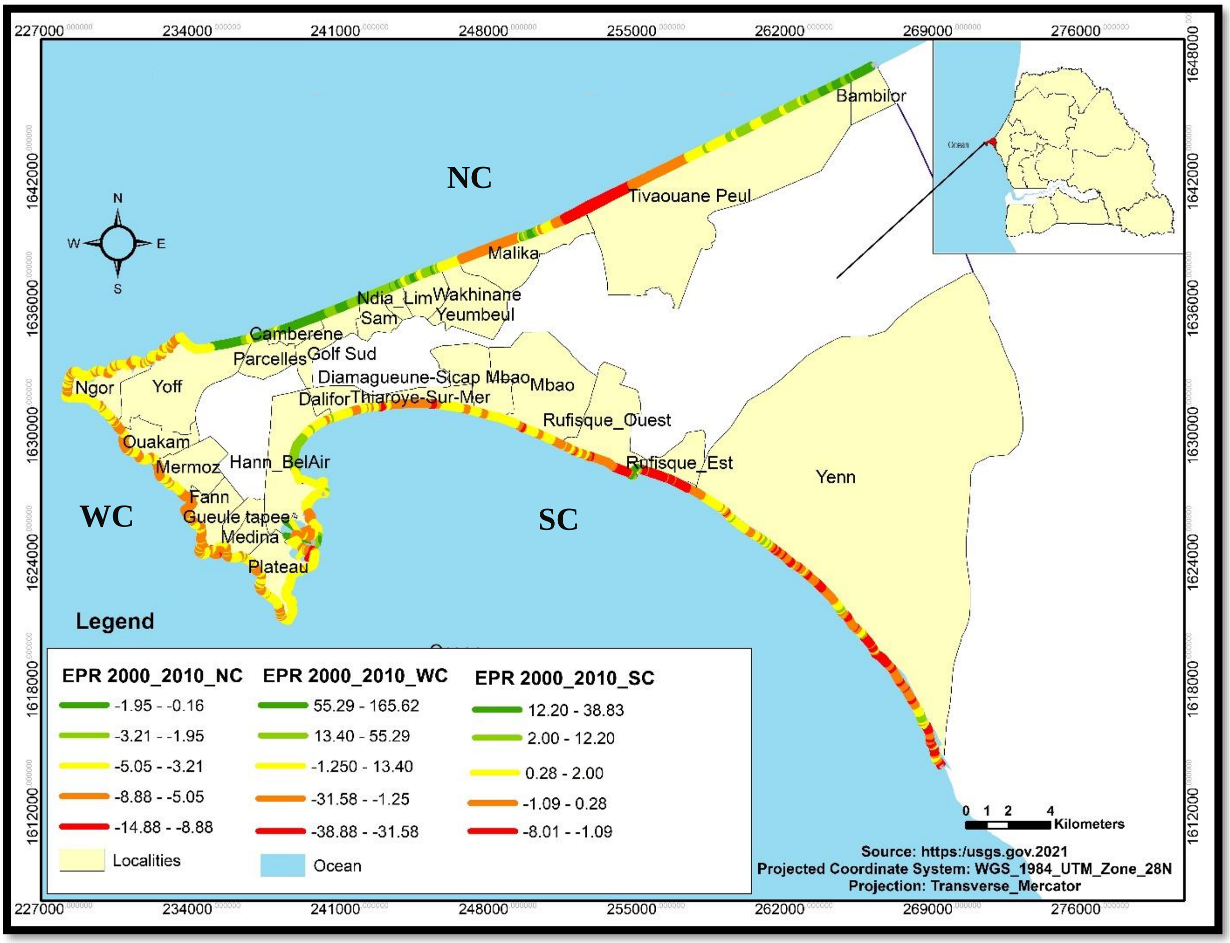
Source: Personal work

Figure 34: Coastline dynamic of Dakar region from 1990 to 2000

The analysis of the evolution of the coastlines in the Dakar region from 1990 to 2000 shows two principal trends: erosion and accretion. From 1990 to 2000, the northern coast from Bambilor to Yoff is globally marked by accretion. The average rate of the dynamic is estimated at 0.45 m/year. The district municipality of Malika records the highest erosion rates (-16.5 m/year). The western coast of Dakar is characterized by erosion with an average of about -0.81 m/year. The higher erosion rate is recorded at the harbor of Dakar and is estimated at -68.09 m/year (Figure 34). The southern coast of Dakar is globally marked by erosion (-0.08 m/year). The district municipality of Rufisque records a higher erosion rate of about -9.03 m/year.

I.1.2 Coastline dynamic analysis of Dakar region from 2000 to 2010

The figure 35 is about evolution of the coastlines in the Dakar region from 2000 to 2010.



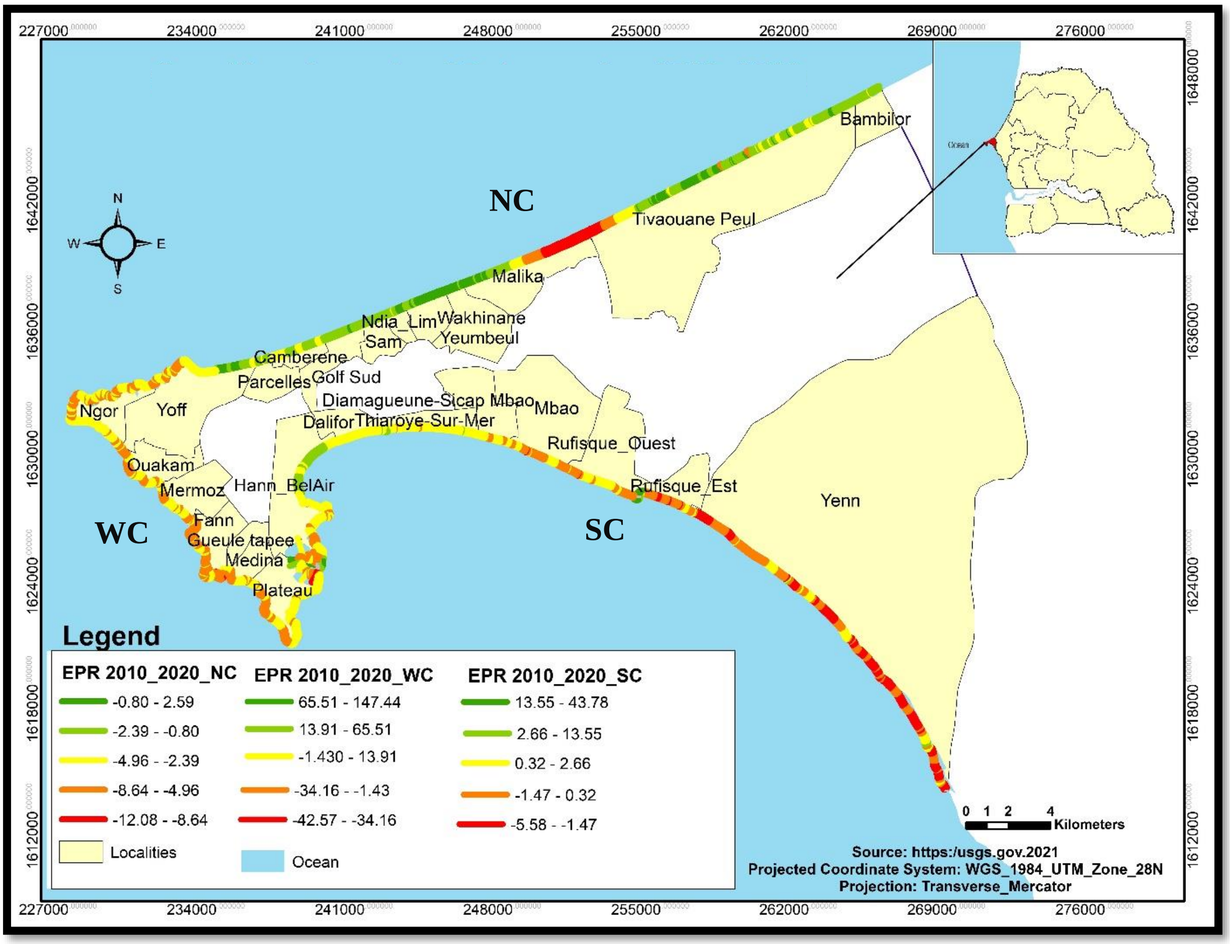
Source: Personal work

Figure 35: Coastline dynamic of Dakar region from 2000 to 2010

From 2000 to 2010, the northern coast is characterized by erosion. The average rate of the dynamic is estimated at -4.12 m/year. The district municipalities of Malika and Tivaouane Peul record the highest erosion rates. The western coast of Dakar is characterized by accretion with an average of about 0.71 m/year. The higher erosion rate is recorded at the Dakar harbor and estimated. about -38.88 m/year (Figure 35). The southern coast of Dakar is globally marked by erosion (-0.13 m/year). The district municipality of Rufisque Est records a higher erosion rate of about -8.01 m/year.

I.1.3 Coastline dynamic analysis of Dakar region from 2010 to 2020

Two main tendencies can be seen in the analysis of the dynamic of the coastlines in the Dakar region between 2010 and 2020: erosion and accretion. Erosion is noted along the northern coast from 2010 to 2020. The average rate of the dynamic is estimated at -2.57 m/year. The highest rates of erosion are found in Tivaouane Peul and Malika, district municipalities. Accumulation occurs on Dakar's western coast on average at a rate of roughly 0.20 meters each year. The harbor in Dakar, Senegal, has the greatest erosion rate, which is estimated to be -42.57 m/year (Figure 36).



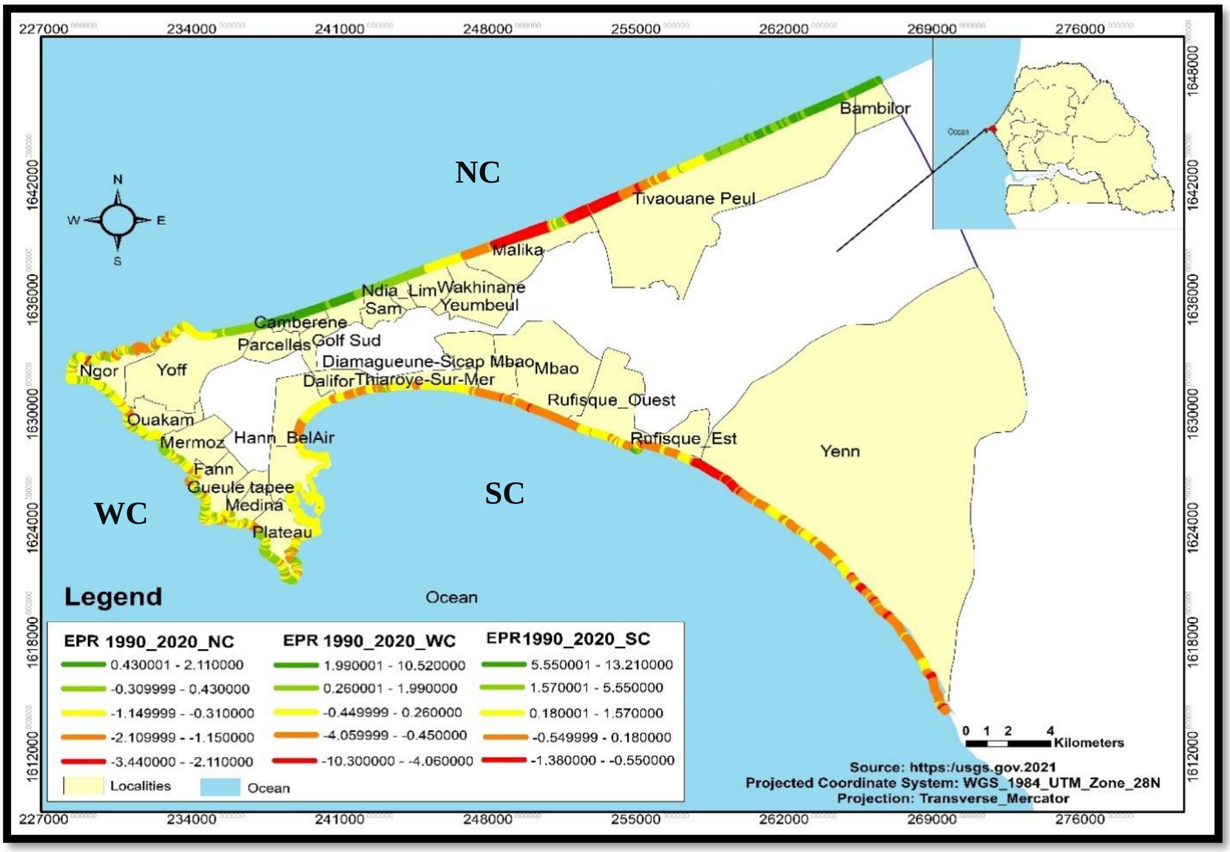
Source: Personal work

Figure 36: Coastline dynamic of Dakar region from 2010 to 2020

The southern coast of Dakar is globally marked by accretion (0.29 m/year). The district municipality of Rufisque Est records a higher erosion rate of about -5.58 m/year.

I.1.4 Coastline dynamic analysis of Dakar region from 1990 to 2020

Over the entire period 1990-2020, the north coast shows an average erosion rate of -0.44 m/year. The northern coast records an average of all erosional rates of about -1.4 m/year and an average of all accumulation rate of about 0.56 m/year. The district musicality of Malika, records the higher erosion rate (-3.44 m/year). The south coast has a low overall erosion rate of -0.11 m/year. The average of all erosional rates is about -0.35 m/year, whereas all accretional rates are about 0.50 m/year. The west coast has a low overall accretion rate of 0.21 m/year.



Source: Personal work

Figure 37: Coastline dynamic of Dakar region from 1990 to 2020

I.2 The prediction of future coastline positions and estimated lost area in the Dakar region in 2030 and 2040

The table 19 is about the prediction of the future coastline positions and lost areas in 2030 and 2040.

Table 19: Future coastline positions and forecasted lost areas in the Dakar region

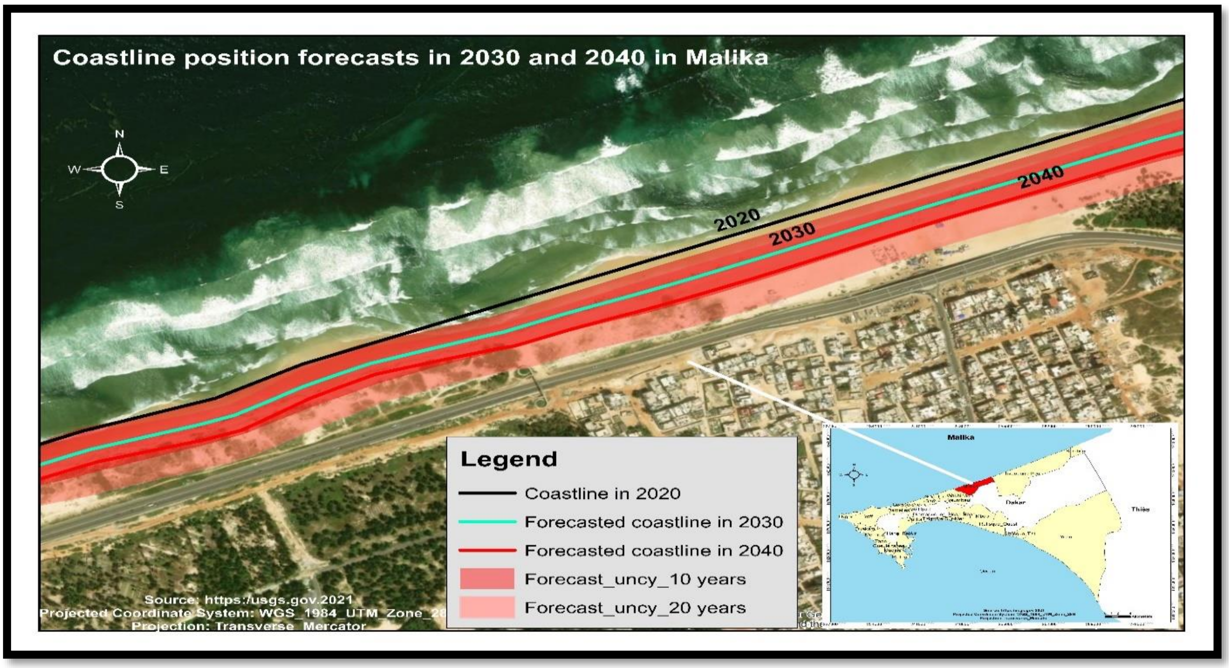
Localities	Prediction (m/year)		Forecasted lost areas (m^2)		Forecasted lost areas with uncertainty (m^2)	
	2020-2030	2020-2040	2020-2030	2020-2040	2020-2030	2020-2040
Northern coast	-4.4	-8.8	706883	1025472	2246362	3016912

Western coast	2.1	4.2	52995	89372	1317391	1829435
Southern coast	-1.1	-2.2	101395	141649	1356488	1918778

Source: Personal work

From 2020 to 2040, there is expected to be substantial erosion along Dakar's northern coast. From 2020 to 2030, the erosion rate is anticipated to be -4.4 m/year, and from 2030 to 2040, it will be considerably more severe, at -8.8 m/year. The predicted lost areas as a result of this erosion are sizable. It is predicted that the northern coast will lose 706,883 m^2 (or around 0.71 Km^2) of land between 2020 and 2030. Between 2030 and 2040, the number dramatically rises to 1,025,472 m^2 (or almost 1.03 Km^2). The infrastructure and coastal populations in this area are seriously threatened by these lost lands. The uncertainty estimations are interesting as well because they point to a variety of possible lost areas. The estimated loss area uncertainty is roughly 2.25 Km^2 (2,246,362 m^2) unclear from 2020 to 2030, and 3.02 Km^2 (3,016,912 m^2) uncertain from 2030 to 2040.

The following map is about the future coastline positions and lost areas in 2030 and 2040 in the district municipality of Malika (Figure 38).

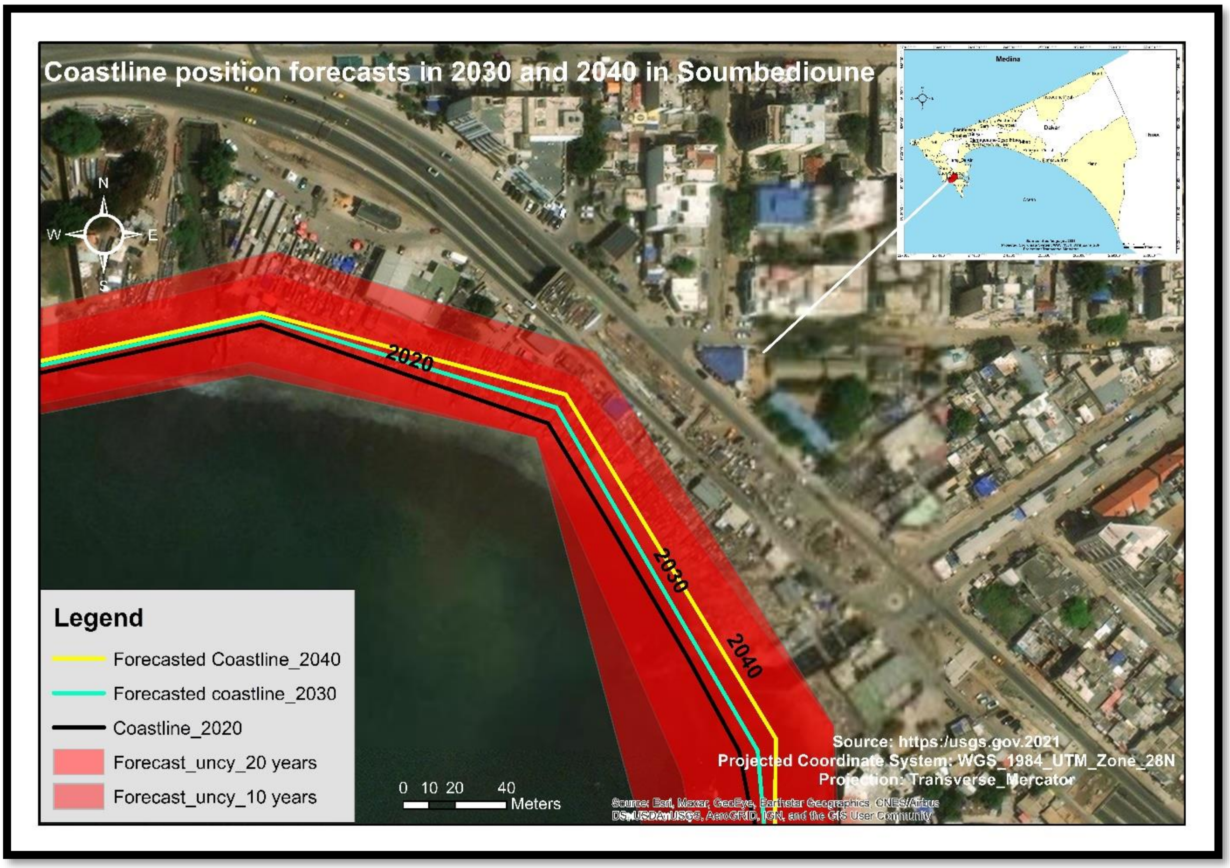


Source: Personal work

Figure 38: Future coastline positions and lost areas in 2030 and 2040 in Malika (Northern coast of Dakar).

The western coast of Dakar is projected to suffer accretion or coastal advance in contrast to the northern coast. According to the forecasts, erosion will increase from 2020 to 2030 at a positive pace of 2.1 m/year and from 2030 to 2040 at a slightly higher rate of 4.2 m/year. In comparison to the northern coast, the predicted lost areas as a result of this accretion are quite small. The western coast is expected to gain 52,995 m^2 (or roughly 0.05 Km^2) of land between 2020 and 2030. Between 2030 and 2040, this figure rises to 89,372 m^2 (or almost 0.09 Km^2). In this coastal area, these sites indicate prospective land gains. The range of potential gain regions is also provided by the uncertainty estimations. Approximately 1,317,391 m^2 (or 1.32 Km^2) of uncertainty in the predicted gained areas exists between 2020 and 2030, and it rises to 1,829,435 m^2 (or 1.83 Km^2) between 2030 and 2040.

The following map is about the future coastline positions and lost areas in 2030 and 2040 in Soumbédioune (Figure 39).

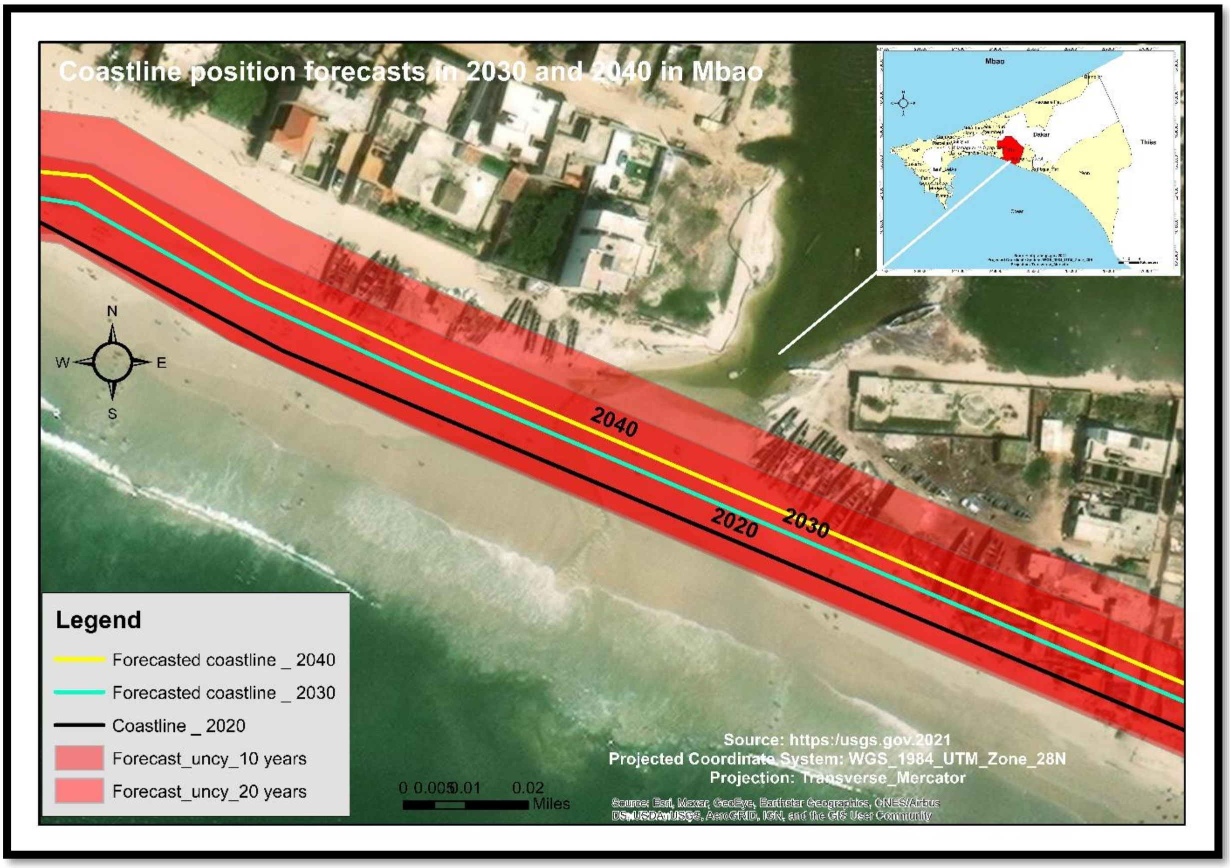


Source: Personal work

Figure 39: Future coastline positions and lost areas in 2030 and 2040 in Soumbédioune village (Western coast of Dakar)

Although at a less rapid rate than the northern coast, erosion along Dakar's southern coast is predicted. According to the forecasts, erosion will occur at a rate of -1.1 m/year between 2020 and 2030 and -2.2 m/year between 2030 and 2040. The predicted lost areas as a result of this erosion are significant. The southern coast will lose 101,395 m^2 (or around 0.10 Km^2) of land between 2020 and 2030, according to estimates. From 2030 to 2040, this figure rises to 141,649 m^2 (or almost 0.14 Km^2). This coastal location has been significantly impacted by these lost areas. The range of potential lost areas is also provided by the uncertainty estimations. The expected loss areas have an uncertainty of about 1,356,488 m^2 (or 1.36 Km^2) from 2020 to 2030, and it rises to 1,918,778 m^2 (or 1.92 Km^2) from 2030 to 2040.

The following map is about the future coastline positions and lost areas in 2030 and 2040 in the district municipality of Mbao (Figure 40).



Source: Personal work

Figure 40: Future coastline positions and lost areas in 2030 and 2040 in Mbao (Southern coast of Dakar)

I.3 Estimation of uncertainty

Table 20: Uncertainty of short- and long-term shoreline change from 1990 to 2020

Periods	Annual error (m/year)
1990-2000	± 1.41
2000-2010	± 1.36
2010-2020	± 1.46
1990-2020	± 0.47

Source: Personal work

The table details the uncertainty relating to measurements of both short-term and long-term shoreline change in the Dakar region from 1990 to 2020, expressed as annual errors in m/year. The anticipated yearly error in assessing shoreline change over the ten years from 1990 to 2000 is 1.41 m/year. This indicates that there is an uncertainty of plus or minus 1.41 m/year in the shoreline change measurements made during this time. In other words, the actual coastline change throughout this period of time could vary by up to 1.41 metres from the stated amount for any given year.

Similar to the previous decade, from 2000 to 2010, the annual inaccuracy is 1.36 m/year. This suggests a marginally reduced uncertainty compared to the previous ten years, suggesting that the observations of shoreline change during this time were significantly more accurate. The measurement error for shoreline change from 2010 to 2020 is 1.46 m/year. This indicates that the accuracy of shoreline change measurements may have somewhat reduced during this time, as there is a little increase in uncertainty compared to the previous decade. The average yearly error in shoreline change measurements throughout the three-decade period from 1990 to 2020 is 0.47 m/year. The fact that this decade's period-specific uncertainty value is the lowest among the others shows that, on average, monitoring shoreline change accurately over the long term is significantly more difficult.

Depending on the particular time period under consideration, there are different levels of uncertainty in shoreline change measurements. The annual errors vary for each decade from

1990 to 2010, but they always fall within a range of roughly 1.36 to 1.46 m/year. The annual error, however, drops to an average of 0.47 m/year when looking at the entire three-decade period from 1990 to 2020, indicating that long-term observations of shoreline change are typically more accurate than short-term studies.

II. Discussion

Erosion and accretion are the two primary tendencies identified by the analysis of the shoreline dynamics in the Dakar region from 1990 to 2020 (Figure 37). The dynamics are different since the hydrodynamic, geological, geomorphological, and topographical conditions on the north, west, and south coasts are not the same.

Dakar's northern coast has a very high risk of coastal erosion. With a modest retreat of 0.45 m/year from 1990 to 2000, the rate of erosion was rather low. However, it experienced substantial erosion between 2000 and 2010, with a rate of -4.12 m/year, showing that the shoreline was retreating at an alarming rate. Rising sea levels, a rise in storm activity, and perhaps human activities like building and infrastructure development close to the coast are some of the causes of this time of significant erosion. Although the rate of erosion decreased significantly between 2010 and 2020, it was still negative at -2.57 m/year, indicating that the northern coast was still facing serious erosion issues. The northern coast showed an average erosion rate of -0.44 m/year throughout the entire three decades, demonstrating an ongoing trend of coastline retreat.

This dynamic is justified by the fact that the northern coast is under the predominant influence of the Northwest swells, which induce a coastal drift directed towards the South (Pinson-Mouillot, 1980; Barusseau, 1980; Sall, 1982; Pedersen and Tarbotton, 1985 in Niang-Diop, 1996). In addition, the northern coast records powerful waves generated by winds. These waves play an essential role in this dynamic since the coast is built by soft materials (mainly composed of sandy coastal dunes and marine beaches - Raw mineral soils); the wave force breaks on the coast bringing materials offshore. The wave force breaks on the coast accumulating the materials onshore, generating dune retreats inland estimated by Niang-Diop (1996) as about 200,000 and 1 500,000 cubic meters per year. Due to this wave, swell conditions and sand mining activities, the northern coast records an average of all erosional rates of about -1.4 m/year and an average of all accumulation rate of about 0.56 m/year. The district musicality of Malika, records the higher erosion rate (-3.44 m/year) (Figure 37). It is the most truncated area on the northern coast of Dakar from 1990 to 2020 because it lodges the extension of Mbeubeuss dump, where sand mining activities are operated (at least 100 tip trucks per day, i.e., about 5 million cubic meters per year are extracted). This causes problems in sediment dynamics (Quensière et al. 2013) (Figure 25 B). Despite the high dynamic, this northern coast is less vulnerable than the southern coast to coastal erosion due to the powerful dunes system, which can be considered as a barrier between the sea and coastal infrastructures.

Whether the northern and southern coasts are all sandy, the western coast is characterized by cliffs. It experienced considerable erosion at a rate of -0.81 m/year from 1990 to 2000. However, there was a noticeable change between 2000 and 2010, with a positive erosion rate of 0.71 m/year, indicating a net gain in the shoreline. From 2010 through 2020, this tendency persisted, although at a lower rate of 0.20 m/year. The western coast showed a minor overall accretion rate of 0.21 m/year for the entire 30-year period, indicating that, generally, the shoreline in this area has been reasonably stable or seeing minor advance. The average of all erosional rates is about -0.35 m/year, whereas all accretional rates are about 0.50 m/year. Geologic, hydrodynamic, and topographic conditions justify this dynamic. Due to its geologic structure, which is marked by volcanic rock such as basaltic, tuffaceous and sedimentary rocks (Sane and Yamagishi 2004), the substratum of the western coast is not porous and do not allow significant erosion dynamic rates. According to Strahler (2013), when the waves meet resistant rocks, the result is sea cliffs which, on the hydraulic pressure of waves and the abrasion by rock fragments, trust against the cliffs and sculpt the scarf. Consequently, the cliff's block rocks fall into the surf zone, and the coastline retreats gradually. In addition, this western coast is less exposed to coastal erosion because it lodges the plateau of Dakar, where the latitude is above 50 meters (Sane and Yamagishi 2004). Globally, moderate accretion characterizes the western part of the coast of the Dakar region because a cliff of volcanic rock backs the beach (Figure 37).

In contrast to the north and west coast, the southern coast remains more vulnerable to erosion due to its high population and industrial and touristic infrastructures. The southern coast of Dakar, in contrast to the northern coast, showed a more stable coastline from 1990 to 2000, with a small erosion rate of -0.08 m/year. This implies that there was some retreat, but it happened gradually. In the decade that followed (2000-2010), the trend persisted, with an erosion rate of -0.13 m/year. Even though erosion continued, it maintained to be minimal. Notably, there were significant modifications in the trend from 2010 to 2020, with a positive erosion rate of 0.29 m/year, showing that the southern coast in fact gained beach during this time. This might be explained by sediment accretion, which supported the observed upward tendency. The southern shore had a low total erosion rate of -0.11 m/year for the whole 30-year period, indicating relative stability with slight variations. An average rate of retreat with the uncertainty of about -0.11 +/- 0.47 m/year has been recorded, with the highest retreat (-1.38 m/year) noted on the coast of Rufisque east. This southern coast is segmented in a succession of capes and bays whose arrangement is controlled by tectonics. It is characterized by sandy beaches backed by a shallow barrier beach. This coast is subject to a northwest swell whose energy is reduced due to refraction and diffraction around the Cape-Verde peninsula. Although a south-eastward littoral drift is present and the estimates of sediment transport indicate that the provision is much less critical than along the northern coast, 10,500 to 300,000 cubic meters per year (Barusseau, 1980; Sall, 1982, in Niang-Diop, 1996) (Figure 37).

This dynamic can also be justified by the fact that in the department of Rufisque, the limestone plateau of the Bargny-Rufisque district, whose substratum is part of limestone and Marl of Eocene age. In addition, in the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion (Sane and Yamagishi 2004).

In 2030 and 2040, the average rate of retreat on the northern coast is estimated at -4.4 and -8.8 m/year. The forecasted lost areas are estimated respectively in 2030 and 2040, about 706,883 and 1,025,472 m^2 causing a loss of coastal areas and infrastructures. For example, in the district municipality of Malika (which is the most at risk), the VDN highway will be affected, disrupting the urban traffic and economic activities such as fishery activities in Yoff and Cambérène. This situation is accentuated by the woodcutting activities for settlement habitat implantation in this locality (Malika). Dune retreats in these localities along the northern coast will be more intensified (Figure 38). On the western coast, the coastline dynamics are estimated in 2030 and 2040, respectively, at about 2.1 and 4.2 m/year. These dynamic rates will generate a loss of coastal areas, estimated at 52,995 m^2 in 2030 and 89,372 m^2 in 2040. Even if the western coast is less exposed to erosion due to its geologic and swell conditions, some coastal areas are subjected to erosion, such as the Soumbédioune village, which is among the most crucial fishing points in Senegal (Figure 39). Being the most exposed to erosion due to its population, geologic and topographic conditions, the coastline dynamics are estimated in 2030 and 2040, respectively, to be about -1.1 and -2.2 m/year on the southern coast of Dakar (Figure 40).

Partial conclusion

The shoreline dynamic is generated by hydrodynamic, climatic, geologic, geomorphologic and pedologic conditions. It is essential to analyze the climate change impacts on the coastal area. Dakar region is among the most vulnerable cities in the world to coastal erosion due to its geographical position and low-lying area. The shoreline dynamic depiction is performed through the DSAS tool using four Landsat images (1990, 2000, 2010, and 2020). The results have shown that the region records the respective average rate retreats about -0.44 m/year, 0.21 m/year, and -0.11 m/year at the northern, western, and southern coasts. These dynamic rates are expected to be about -4.4 m/year (for the north coast), 2.1 m/year (for the west coast) and -1.1 m/year by 2030. (South coast). By 2040, they are estimated to be around -8.8 m/year (north coast), 4.2 m/year (west coast) and -2.2 m/year (south coast). These predicted dynamic rates will result in a loss of coastal areas, estimated at 861273 m^2 in 2030 and 1256493 m^2 in 2040. These dynamic rates depend on the behavior of hydrodynamic agents and coastal characteristics. They also provide information on the level of vulnerability of Dakar to erosion. The chapter 7 addresses the physical coastal vulnerability assessment in Dakar region.

Chapter 7: Physical coastal vulnerability assessment in Dakar region

Introduction

Most of the Dakar region's coasts are challenged by climate change's impacts, such as the advanced sea resulting from the rising sea level, coastal erosion, and coastal flood. In addition, the disturbance of the normal functioning of hydrodynamic factors increases the frequency of storm surges and coastal temporal floods. Therefore, this situation is aggravated by human activities along the coast through sand mining, haphazard settlement, and pollution. Consequently, the coastal areas are reduced, causing several damages to socio-economic activities and settlements along the coasts of the Dakar region.

I. Results

The table 21 shows the level of vulnerability from 1 (low vulnerability) to 5 (high vulnerability) according to each variable (slope, geomorphology, geology, existing protective infrastructure, relative sea level, movement of the coastline, tidal range, wave height and distance between the settlement and the sea) for the district municipalities along the Dakar coast. Vulnerability linked to the geomorphology or natural physical characteristics of the coastal zone takes into account factors such as the shape of the coastline, the presence of protective features (e.g. dunes) and susceptibility to erosion. Geology assesses vulnerability according to the geological characteristics of the area, including the type of coastal relief. Most of the municipalities along the west coast have a low level of vulnerability, not exceeding 1. On the north and south coasts, most district municipalities have a level of around 5, which means that they are highly vulnerable from a geomorphological and geological conditions. In terms of vulnerability based on existing infrastructure, district municipalities with protective infrastructure or a rocky coastline are less vulnerable than those with no protective infrastructure. Vulnerability linked to relative changes in sea level takes into account the rate of rise in sea level and its impact on the coastal zone. All the coastal district municipalities in the Dakar region have an index of around 1, as the average sea level recorded from 1990 to 2020 in the region is around 1.14 mm. The annual daily tidal averages recorded in Dakar show that the tidal trend line has increased from 1992 to 2020, with an average daily tide of 10.55 cm. As a result, the district municipalities record an index of around 2, which means that the level of vulnerability based on the tide is low. In the Dakar region, swell heights from 1991 to 2018 did not exceed 2 metres. The district municipalities have an index of around 1, meaning that the level of vulnerability based on swell is very low.

Table 21: Coastal Vulnerability Index for each variables the district municipalities

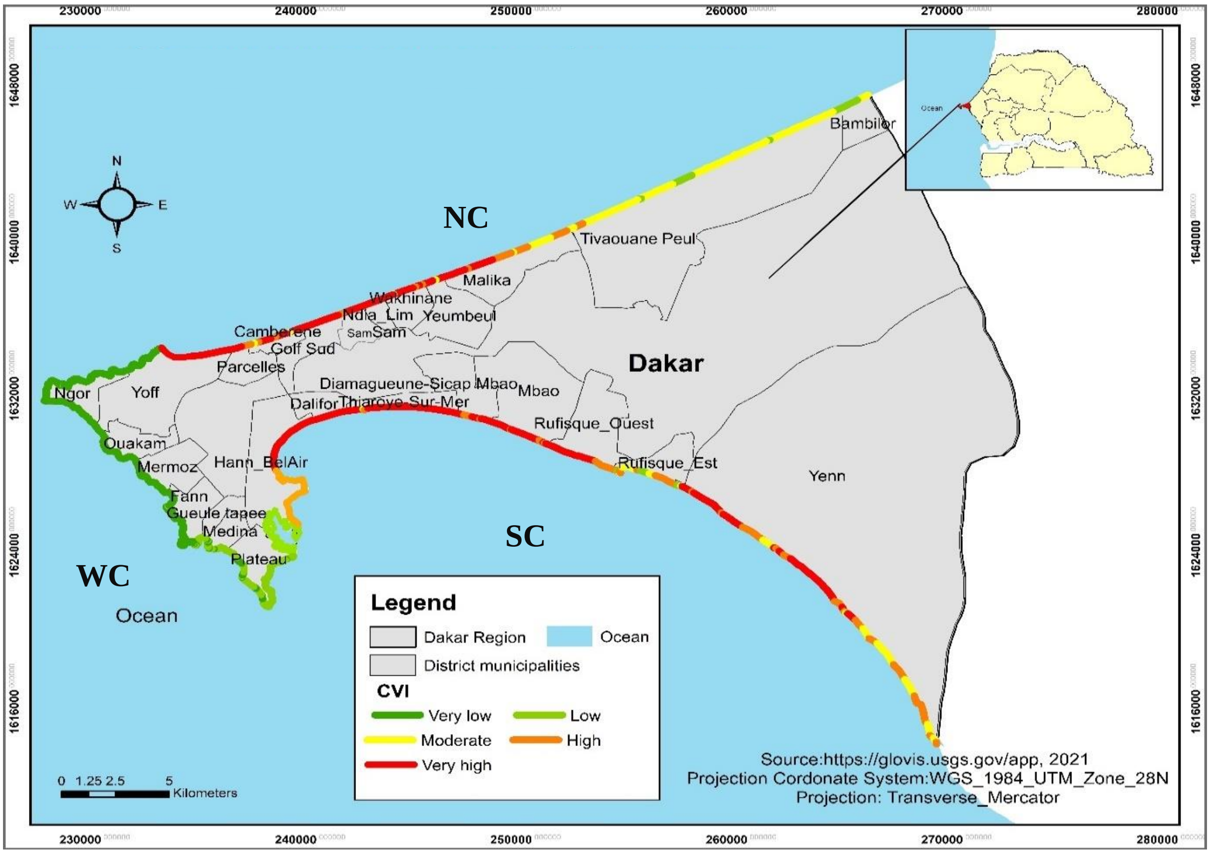
District municipalities	CVI_Geom	CVI_Geol	CVI_Infras	CVI_RSLC	CVI_Tide	CVI_Wave	CVI_Swell	CVI_EPR	CVI_Dist	CVI_Slope
Mermoz/ Sacré-Coeur	1	1	1	1	2	5	1	2.92	4.58	3.41
Ngor	1	1	1	1	2	5	1	3.11	4.56	3.62
Ouakam	1	1	1	1	2	5	1	3.07	3.57	3.77
Yoff	1.25	1.25	1.25	1	2	5	1	3	4.63	3.6
Fann/Point E/ Amitie	1	1.33	1	1	2	5	1	3	4.89	3.72
Gueule Tapée/Colobane/Fass	1	3	1	1	2	5	1	3	5	3.8
Médina	1	3	1	1	2	5	1	3	5	3.77
Plateau	1	3	1	1	2	5	1	2.96	4.86	4.31
Hann/ Bel Air	5	5	5	1	2	5	1	3	5	3.5
Cambérène	5	5	5	1	2	5	1	2.69	4	1
Parcelles Assainies	5	5	5	1	2	5	1	2.66	1	1
Golf Sud	5	5	5	1	2	5	1	3	1	1
Ndiaréme Limamoulaye	5	5	5	1	2	5	1	3	1	1
Sam Notaire	5	5	5	1	2	5	1	3	1	1
Wakhinane Nimzatt	5	5	5	1	2	5	1	3	1	1
Malika	5	5	2.33	1	2	5	1	4.41	1	1
Yeumbeul Nord	5	5	5	1	2	5	1	3.57	1	1
Daliford	5	5	5	1	2	5	1	3	5	1
Diamaguene Sicap Mbao	5	5	4.88	1	2	5	1	3	4.84	1
Thiaroye Mer	5	5	4.5	1	2	5	1	2.83	5	1
Bambilor	5	5	1	1	2	5	1	2.66	1.33	1
Tivaouane Peulh-Niagha	5	5	1	1	2	5	1	3	2	1
Yéne	3	4.56	4.83	1	2	5	1	3	4.7	2.5
Rufisque Est	4	3	2.64	1	2	5	1	2.71	5	1
Rufisque Ouest	5	5	4	1	2	5	1	3	4.76	1

Source: Personal work

The Dakar region has an average wave height of around 1.75 m, making all the arrondissement municipalities in the Dakar region vulnerable. They all have an index of around 5 (very high vulnerability). With regard to the level of vulnerability based on slope, the district municipalities on the west coast and part of the south coast (Yéne) are vulnerable, with an index of over 2. On the north coast, from Yoff to Malika, the slope is less than 1%, while from Tivaouane Peuhl to Mbambilor, it does not exceed 4%. On the south coast, from Hann Bel-air to Rufisque, the gradient is less than 1%, while on the coast of the district of Yéne the gradient is between 0 and 39%. The slope of the west coast (from Ngor to Plateau) is between 3 and 41.9%.

II. Discussion

The physical vulnerability assessment of the Dakar region to coastal erosion was done using the Coastal Vulnerability Index (CVI). The results of this study show that the values of the CVI on the northern, Western, and southern coasts are respectively estimated at (94, 10 and 23).



Source: Personal work

Figure 41: Physical coastal vulnerability map of the Dakar region

The difference in terms of Slope, Geomorphology, Geology, Existing Protective Infrastructures, Sea-level Change, Coastline dynamic (EPR), Mean Tidal Range, Swell Range, Mean Wave Height and Distance between settlement and sea explains these levels of vulnerability. These results are comparable to those from a study (Bakhoum et al. 2018) where seven variables were used (Geomorphology, Slope, Mean Sea Level, Shoreline displacement, Tide range, Swell range and Pedology). It was found that in the northern, western, and southern coast, the CVI were respectively estimated at 20, 5 and 17. The northern coast is highly vulnerable to coastal erosion and the level of vulnerability is not uniform. Certain localities are more vulnerable than others. Yoff village, being among the most vulnerable, records an average CVI of about 92. In Cambérène, a CVI of about 74 is recorded. Malika, where the higher coastline dynamic rate is recorded (-3.44 m/year) on the northern coast, records a CVI of about 60. It is the most truncated area on the north coast of Dakar from 1990 to 2020 because it lodges the extension of the Mbeubeuss dump, where sand mining activities also are operated (at least 100 tip trucks per day, i.e., about 5 million cubic meters per year are extracted). This causes problems in sediment dynamics (Quensière et al. 2013). In addition, the low-lying area with (a slope less than 1%) (see Figure 11 in annex), and sandy coast with fine unconsolidated sediments (that allow erosion due to their porosity and high infiltration capacity) favor an average of coastline dynamic rates about -0.44 m/year from 1990 to 2020 (Figure 41). This vulnerability is accentuated by the predominant influence of the Northwest swells, which induce a coastal drift towards the South (Niang-Diop 1996). Powerful waves (1.75m) and swell (1.65m) are recorded and play an important role in this erosion since the coast is built by soft materials. Wave force breaks on the coast bringing materials offshore and accumulating the materials onshore, generating dune retreats inland which is estimated by Niang-Diop (1996) about 200,000 and 1.5 million cubic meters per year. The increasing trend of mean sea level with an average about 1.14 mm and tide level (1.65m) recorded during three decades in the past, accentuate also the vulnerability and lead to coastline retreat, reduction of coastal areas, submersion, salinization of agricultural land and freshwater (UEMOA 2010). An existing protective infrastructure is noted in the northern coast. It is the planting filaos (Casuarina equisetifolia). In fact, planted in 1948 on the northern coast of Senegal, the filao is a shrub of the Fabaceae family originating from the Pacific. This nitrogen fixer can be used as a windbreak and firewood and is very effective in retaining even sandy and degraded soils (PRL 2001).

The western coast is characterized by cliff records with a dynamic rate of about 0.21 m/year. It is less exposed to erosion than the northern and southern coasts. The average of all erosional rates is about -0.35 m/year, whereas the average of accretional rates is about 0.50 m/year. Like the northern coast, the western coast is also under the predominant Northwest swells, which induce a coastal drift towards the South. From Ngor to Plateau, the geomorphology is characterized by volcanic rocks such as basaltic, tuffaceous, and sedimentary rocks. The substratum of the western coast is not porous and does not allow critical erosion due to its impermeability and solidity. The average slope on the west coast is estimated at 21% (25% from Ngor to Gueule Tapée and 11% from Gueule Tapée to Plateau). The western coast is less vulnerable compared to the northern coast, with an average CVI of about 10. From Ngor to Fann, the average CVI is about 7, whereas, from Fann to Plateau, the CVI is about 11. Certain localities on the west coast are more vulnerable than others to coastal erosion. The Eastern Corniche is most exposed to erosion compared to the Mamelles but is still vulnerable to coastal erosion with a CVI of 13 with a geomorphological structure composed of sedimentary rock. Les Almadies, the most westerly locality in Africa, has an estimated CVI of about 6. It is the most advanced in the Atlantic Ocean. From the Pointe des Mamelles to Fann, there is a marked retreat of the coastline, which is justified by the solid northwest swells, or even exceptionally from the west, but also by the variations in the geological and sediment nature of the coastal zone. In some places on the corniche, the retreat of the coastline is such that gabions and cliff consolidation structures have had to be constructed, as is the case, for example, in front of Cheikh Anta Diop University to protect the corniche and the promenade that runs alongside it (Quensière et al. 2013). In terms of the Distance between settlements and sea, the Western coast is generally vulnerable (See Figure 23 in Annex).

The southern coast of the Dakar region (from Hann to Yéne) is composed of a succession of capes and bays whose arrangement is controlled by tectonics. A shallow barrier beach backs the sandy beaches. This coast is subject to a northwest swell whose energy is reduced due to refraction and diffraction around the Cape-vert peninsula. This swell corresponds, at a depth of 13 m, to directions from the South (N150° to 210°E). These changes in the orientation of the swell planes are accompanied by a dispersion of energy in the Bay of Gorée, which is already fluctuating according to the importance of the refraction phenomena (especially on the shoal zone between Mbao and Bargny). Originating in the South Atlantic, the southwest swell is most noticeable during the rainy season. Offshore, its energy is lower than the northwest swell (Nardari 1993 in Guerin 2003). They reach a depth of 13 m with a minimum direction of N200°. Due to its low occurrence and low offshore energy, the importance of this type of swell could be minimized. However, it generates energetic and moderate (1.75 m) or (2.75 m to 3.75

m). Although a south-eastward littoral drift is present and the estimates of sediment transport indicate that the provision is much less critical than along the northern coast, 10,500 to 300,000 cubic meters per year (Niang-Diop 1996). In contrast to the north and west coast, the southern coast remains vulnerable to erosion due not only to its high population but also to the industrial and touristic infrastructures. An average rate of retreat of the coastline of about -0.11 m/year has been recorded, with the highest retreat (-1.38 m/year) noted on the coast of Rufisque east. The geomorphologic condition plays an essential role in the coastline dynamic and is the primary driver of the vulnerability of Dakar to coastal erosion. It is composed of the limestone plateau of the Bargny-Rufisque district, whose substratum is part of limestone and Marl of the Eocene age. In addition, in the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials (Sane and Yamagishi 2004). In Rufisque East and West, the geomorphologic conditions in this locality are characterized by lithosols, and regosols dismantled on sandstone non or slightly leached ferruginous soils on colluvium, which have high porosity and water infiltration and are generally subjected to erosion. In the Sendou littoral cells, the geomorphology is marked by holomorphic and hydromorphic soils on clayey material poorly developed on sands and vertic and hydromorphic soils on marly-limestone clay material, which is less exposed to erosion due to its less porous characteristic and high compacity of soil. The geomorphology in the Toubab Dialaw littoral cell is almost the same as in the Sendou littoral cell (Holomorphic and hydromorphic soils on clayey material poorly developed on sands). Sandy coast (from Hann Bel-Air to Rufisque Ouest), Medium cliff and Cobble beach (Rufisque Est to Yéne) are noted. The average CVI is about 23. From Hann Bel-Air to Rufisque west, the CVI is estimated at 93. This vulnerability is explained by the fact that slope is less than 1 % (see Figure 11 in annex), and geomorphology is characterized by fine unconsolidated sediments which allow erosion. From Rufisque west to Yéne the CVI is about 64. These localities are mainly characterized by cobble beaches and a slope of about 11 %. Hann Bay (Hann Bel-Air) has a CVI of 96 and this vulnerability is accentuated by severe pollution and nuisances. The causes of this critical ecological situation are known, linked to the proximity of the industrial zone and its untreated and uncontrolled effluent discharges and the massive eutrophication caused by urban effluents. The various forms of pollution, such as the abundance of decomposing green algae, remain the most obvious sign, in addition to the fact that the bay is also the scene of coastal erosion resulting from a reverse transit compared to the previous zone. Due to the dominant angles of the northwest swell on the littoral, the current develops from East to west from the divergence zone of Mbao. These numerous attacks on the environment are the sources of the high vulnerability of these zones to coastal erosion resulting from climate change. From Mbao to Bargny, the CVI is estimated at 60 due to a sedimentary dynamic with progradation zones. Human activities accentuate this dynamic through sand mining and seashell exploitation activities. Nevertheless, some actions in parallel intended to curb a retreat of the coastline are noted near densely inhabited places by riprap, protective walls and gravel.

Partial conclusion

The vulnerability assessment is evidence-gathering activity to assess who or what is vulnerable, to what, and under what circumstances. The impacts of climate change in coastal countries make the population living along the coasts vulnerable to coastal erosion. Therefore, most of the coastal erosion studies during the last decades are meanly focused on coastal vulnerability assessment using the CVI. The coast of Dakar region is physically vulnerable to coastal erosion because of climate change such as the disturbance of climatic and hydrodynamic parameters combine to geomorphologic and geologic conditions. This vulnerability is accentuated by the haphazard settlements along the coasts and the lack of protectives infrastructures. The coastal Vulnerability Index is used to show the level of vulnerability. This study used ten variables: slope, geomorphology, geology, existing protective infrastructures, relative sea level, shoreline displacement, tidal range, swell range, wave height and distance between settlement and the sea. The results show that the values of the CVI vary on the northern, western, and southern coasts. The difference explains this variety in terms of variables used. Different levels of vulnerability on the northern (94), western (10) and southern coasts (23) are noted. Even if Dakar region is physically vulnerable to coastal erosion, it would be important to note that this vulnerability is accentuated by human activities. That is why, socio-economic vulnerability assessment should also be considered in coastal management in the Dakar region. The chapter 8 addresses the socio-economic vulnerability assessment.

Chapter 8: Socio-economic vulnerability assessment

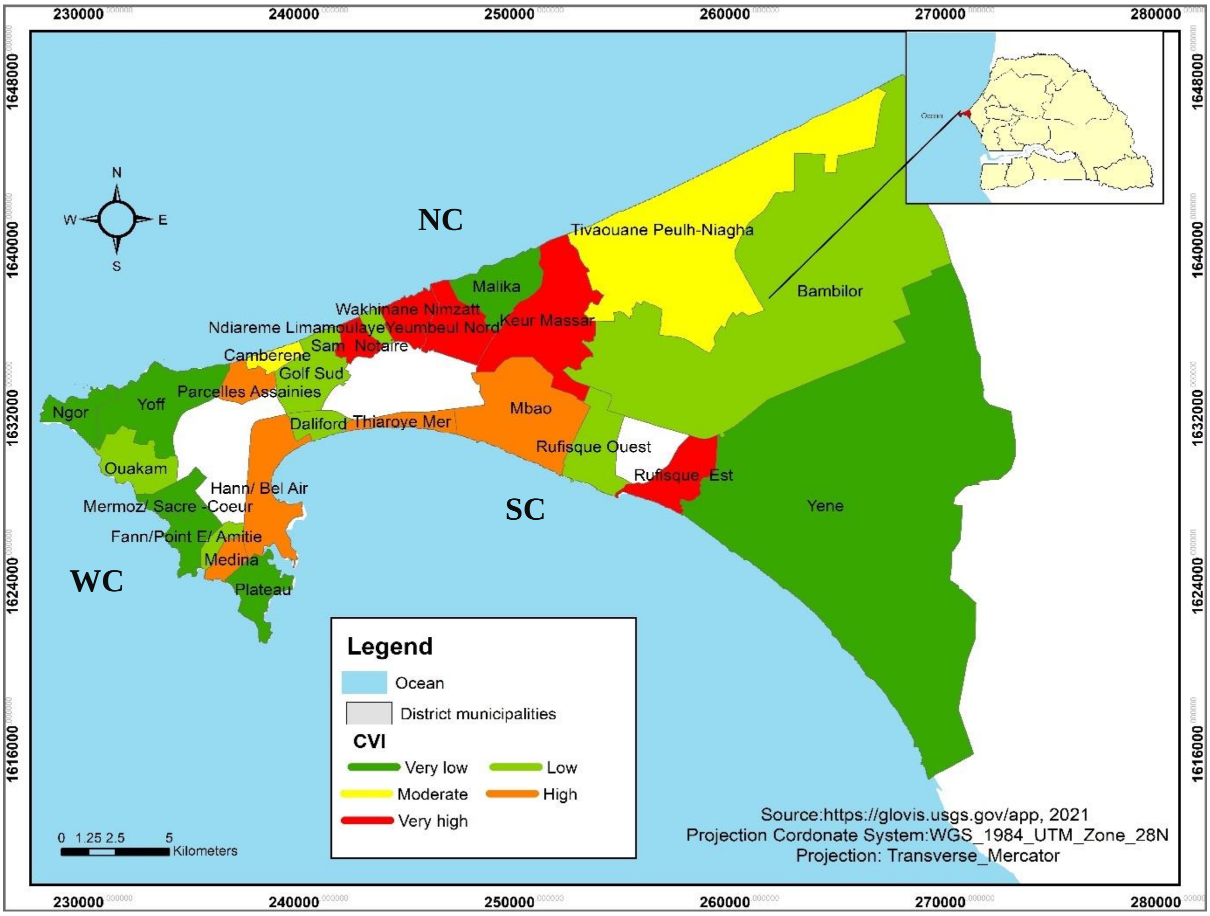
Introduction

According to Rahadiati et al. (2019), vulnerability is a low resistance of a community facing threats that influence the disaster risk level. It can be considered from the economic, environmental, and socio-cultural factors and social conditions such as poverty, social pressure, and a less than strategic environment, which may decrease the community's resistance to facing threats. Coastal vulnerability assessment focuses on how climate change will impact coastal communities and the ecosystem service they provide. These services may incorporate natural resources and infrastructures (Oloyede et al. 2022). Primarily, coastal vulnerability induced by climate change was based on natural processes and less on socio-economic aspects (Giorgos Alexandrakis et al. 2014). This study assessed socio-economic vulnerability of the coasts of Dakar region to erosion using indicators such as population density, dependency ratio, gender ratio and education level.

I. Results

The socio-economic vulnerability assessment has been done by merging the four variables (population density, dependency ratio, gender ratio and education level). The indices are scaling from 0 to 10. The results show that, in total, five district municipalities are very highly vulnerable (Sam Notaire (5.4), Wakhinane Nimzatt (6), Yeumbeul Nord (6.7), Keur Massar (5.8) and Rufisque Est (6)) (Figure 42). The district municipalities of Mbao, Thiaroye Sur Mer, Bel-Air, Medina and Parcelles Assainies are highly vulnerable with the respective indices 4.8, 4.2, 4.2, 5 and 4.3. The high dependency ratio and density justify the socio-economic vulnerability in these district municipalities. The level of education in these localities is lower than in others, with the alphabetic rate, which does not exceed 75%. The district municipalities of Tivaouane-Peuhl (3.8) and Cambérène (3.4) present moderate vulnerability indices. The district municipalities of Ouakam, Gueule Tapée, Dalifor, Rufisque Ouest, Bambilor, Ndiaréme Lilmamoulaye and Golf Sud present low vulnerability indexes whereas, the district municipalities of Yoff, Ngor, Malika, Mermoz, Fann, Plateau and Yéne present very low indexes.

The figure 42 is about the socio-economic vulnerability level of the district municipalities of Dakar region.



Source: Personal work

Figure 42: Socio-economic vulnerability Index map of district municipalities

II. Discussion

Socio-economic components used in this study (population density, gender and dependency ratio and education level) play an important role in the definition of coastal socio-economic vulnerability by determining the level of vulnerability and adaptative capacities to coastal erosion impacts on local communities. These variables vary in the different district municipalities along the coasts. For example, the population density in the department of Guédiawaye, representing the minor department in the region with an area of 13 km^2, still has the highest density as in previous years (30,168 inhabitants/km^2 in 2019). This department is almost twice as dense as Pikine and Dakar's departments and 20 times as dense as the department of Rufisque. The average socio-economic vulnerability index in this department is 4. The higher socio-economic vulnerability index was recorded in the district municipality of Wakhinane Nimzatt, with a vulnerability index about 6. In 2019, the department of Dakar, with eleven district municipalities along the coast, had a density of 17,707 inhabitants/km^2. The average socio-economic vulnerability index in this department is 2.5. The higher index was recorded in the district municipality of Medina (5). The department of Pikine, with five district municipalities, has a density of 16,010 inhabitants/km^2. The average socio-economic vulnerability index in this department is 4.3. Yeumbeul (6.7) and Keur Massar (5.8) record the higher indices (Figure 42). The department of Rufisque, which is the largest in terms of surface area (372 km^2 or 68% of the region's surface area), has the lowest density, with 1,569 inhabitants per km^2 (ANSD 2021). The average socio-economic vulnerability index in this department is 3.3. The higher index was recorded in the district municipality of Rufisque Est (6). The socio-economic vulnerability indexes of district municipalities such as Sam Notaire (5.4), Wakhinane Nimzatt (6), Yeumbeul Nord (6.7), Keur Massar (5.8), Rufisque Est (6), Mbao (4.8), Thiaroye Sur Mer (4.2), Bel-Air (4.2), Medina (5) and Parcelles Assainies (4.3) is justified by the fact that dependency ratio and density are high in these localities. The population structure allows for a better appreciation of the demographic dependency ratios (Annex: Table 3). The "demographic dependency ratio" is the ratio of the combined population of young (0 - 14 years) and old (65 years or older) to the working-age population (15 - 64 years). In the Dakar region, the proportion of young people under working age is relatively high (33%). In contrast, the proportion of older people remains relatively low (3%). The dependency ratio of the Dakar region is 56%. The gender ratio within its departments is: Dakar 100%, Pikine 102%, Guédiawaye 102% and Rufisque 99.6% (see Figure 25 in annex).. Education is marked by increased school infrastructure, staff, enrolment and performance. Nevertheless, access to education declined in 2019 at the pre-school, elementary and middle-secondary levels, particularly for boys. A drop in the success rate was noted in 2018 and 2019 for the Brevet de Fin d' Etude Moyenne (BFEM) and the Baccalaureate, rarely reaching 50%. Moreover, there is a clear dominance of private institutions in the higher cycle, although there is a plurality of fields of study (ANSD 2021).

Partial conclusion

In summary, the socio-economic vulnerability assessment of the district municipalities along the coast of the Dakar region was assessed using four parameters (population density, dependency ratio, gender ratio and education level). The index of each variable was determined. The population of the Dakar region is unequally distributed in the different departments such as Dakar, Pikine, Guédiawaye and Rufisque. This concentration of the population is becoming denser and denser, increasing the need for urbanization and allotments.

Despite this importance, the Dakar region faces challenges such as unemployment, traffic jams, insecurity, infectious and respiratory diseases, etc. The allotment and allocation of land plots remain more focused on the department of Rufisque, which still has unused land. Nevertheless, building permits continue to be issued throughout the Dakar region. The concentration of the main economic activities, industries and administrative services in Dakar explains its importance compared to other regions. Its population mainly comprises working-age people (61% aged between 15 and 64) and women (50.43%). The number of jobs declared in 2018 at the Employment and Social Security Inspectorate level is more significant than that created in 2019. The dependency ratio of the Dakar region is 56%.

As far as education is concerned, the school system is marked by its dynamism with developments in all the indicators studied, namely infrastructure, staffing, enrolment and performance at school level. However, the indicators on access fell in 2019 at the pre-school, elementary and middle-secondary levels declined particularly for males. Thus, much effort is still required to improve access and quality of education. Also, a drop in the success rate for the Brevet de Fin d' Etude Moyenne (BFEM) was noted from 2018 to 2019, and overall, the success rates for the BFEM and Baccalaureate rarely reach 50%. Moreover, there is a clear dominance of private institutions in the higher cycle, although there is a plurality of fields of study (ANSD 2021). The socio-economic vulnerability index averages in the Dakar region's different departments are Guédiawaye 4, Dakar 2.5, Pikine 4.3 and Rufisque 3.3. The highest indexes were recorded in the district municipalities of Sam Notaire (5.4), Wakhinane Nimzatt (6), Yeumbeul Nord (6.7), Keur Massar (5.8), Rufisque Est (6), Mbao (4.8), Thiaroye Sur Mer (4.2), Bel-Air (4.2), Medina (5). This is because of the high dependency ratio and density in these localities. The chapter 9 addresses the evaluation of economic impacts.

Chapter 9: Evaluation of the economic impact of coastal erosion

Introduction

Besides the environmental impacts, climate change negatively affects the economic value of coastal zones. Coastal erosion, which is one of its impacts, causes damage to people living along the coast. The narrowing of the beach due to erosion causes socio-economic damage by reducing the areas where economic activities are carried out. Consequently, livelihood, settlements, and economic activities such as fishing, tourism, and industry are disturbing. Knowing the factors generating coastal erosion in the Dakar region, dynamic coastline speed, and level of physical and socio-environmental vulnerability, evaluating the economic impacts of coastal erosion is timely and relevant. This chapter aims to economically investigate the most affected coastal areas in Dakar region in 2030 and 2040 in terms of land value to prevent economic loss generated by coastal erosion with protective infrastructures. The assessment is done by estimating the economic value of the beach using multi-linear regression, an econometric forecasting model. Software such as R, Excel, ArcGIS, and DSAS was used in this study.

I. Results

The table 22 presents the results of the linear model of the study. Model 1 was chosen due to its lower AIC, BIC, and higher R^2. Multilinear regression, which is an econometric forecasting model, was used. The model performed well, with 11 out of 13 variables significant at 10%, and the R^2 is estimated at 0.986 for the year 2030. Almost the same case is noted for 2040, with 9 out of 13 variables significant at 10% and an R^2 of 0.9123. The more confident we are in the coefficient's ability to predict, the higher the t-value. Low t-values signify that the coefficient's predictive capacity could be more reliable (AllBusiness.com n.d.). Therefore, 9 out of 13 have positive t values for 2030, whereas 7 out of 13 have positive t values in 2040. The relationship between littoral price and variables is significant since the p-value is less than 0.05. It is estimated at 1.206e-12 for 2030 and 1.343e-07 for 2040. That means that the independent variables (Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to town, CVI, Number of Buildings, Number of Hotels, Number of Industries, Number Fishing Points, and Road Length) affect the dependent variable (Economic littoral value). The table 22 is about the statistics from the linear regression model for 2030 and 2040.

Table 22: Linear model results for 2030 and 2040

Variables	Code	Model 1 (2030)				Model 1 (2040)			
		Estimate	Std.Error	t value	Pr(>|t|)	Estimate	Std.Error	t value	Pr(>|t|)
	(Intercept)	-5822000000	4.49E+09	-1.296	0.21594	-20840000000	7.28E+09	-2.863	0.01185*
Littoral Width	**LW**	74080000	4.48E+07	1.653	0.120663	-104900000	2.45E+07	-4.278	0.00066***
Lost Areas	**LA**	186100	3.32E+04	5.615	0.0000638***	137900	4.07E+04	3.39	0.00404**
Coastal Length	**CL**	1790000	8.66E+05	2.066	0.0578.	3131000	1.47E+06	2.132	0.04995*
Littoral Areas	**LA_s**	-11400	3.26E+03	-3.493	0.003587**	-3187	3.33E+03	-0.959	0.3529
Dynamic Rate	**DR**	1361000000	3.10E+08	4.397	0.000608***	791400000	2.61E+08	3.028	0.00848**
Built Areas	**BA**	281200	6.42E+04	4.38	0.000628***	280800	1.33E+05	2.109	0.05218.
Number Hotels	**NH**	23850000000	1.50E+09	15.881	0.000000000239***	4502000000	6.96E+09	0.647	0.52736
Number of Industries	**NI**	471400000	4.21E+09	0.112	0.912426	-634500000	5.94E+09	-0.107	0.91635
Number Fishing Points	**NFP**	-11060000000	4.40E+09	-2.517	0.024655*	-4989000000	5.12E+09	-0.974	0.34542
Road Length	**RL**	1091000	3.73E+05	2.924	0.011113*	1194000	6.63E+05	1.8	0.09197.
Number of Buildings	**NB**	-32040000	8.97E+06	-3.573	0.00306**	-48100000	1.65E+07	-2.919	0.01058*
Proximity to town	**PR**	1174000	3.51E+05	3.347	0.004795**	2635000	4.87E+05	5.412	0.000072***
Costal Vulnerability Index	**CVI**	-203900000	4.94E+07	-4.127	0.001026**	-93700000	6.08E+07	-1.541	0.14408

Signification of codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Source: Personal work

Model 1 (2030) = Residual standard error: 4.468e+09 on 14 degrees of freedom

Multiple R-squared: 0.9927, Adjusted R-squared: 0.986

F-statistic: 147.3 on 13 and 14 DF, p-value: 1.206e-12

Model 1 (2040) = Residual standard error: 6.756e+09 on 15 degrees of freedom

Multiple R-squared: 0.953, Adjusted R-squared: 0.9123

F-statistic: 23.39 on 13 and 15 DF, p-value: 1.343e-07

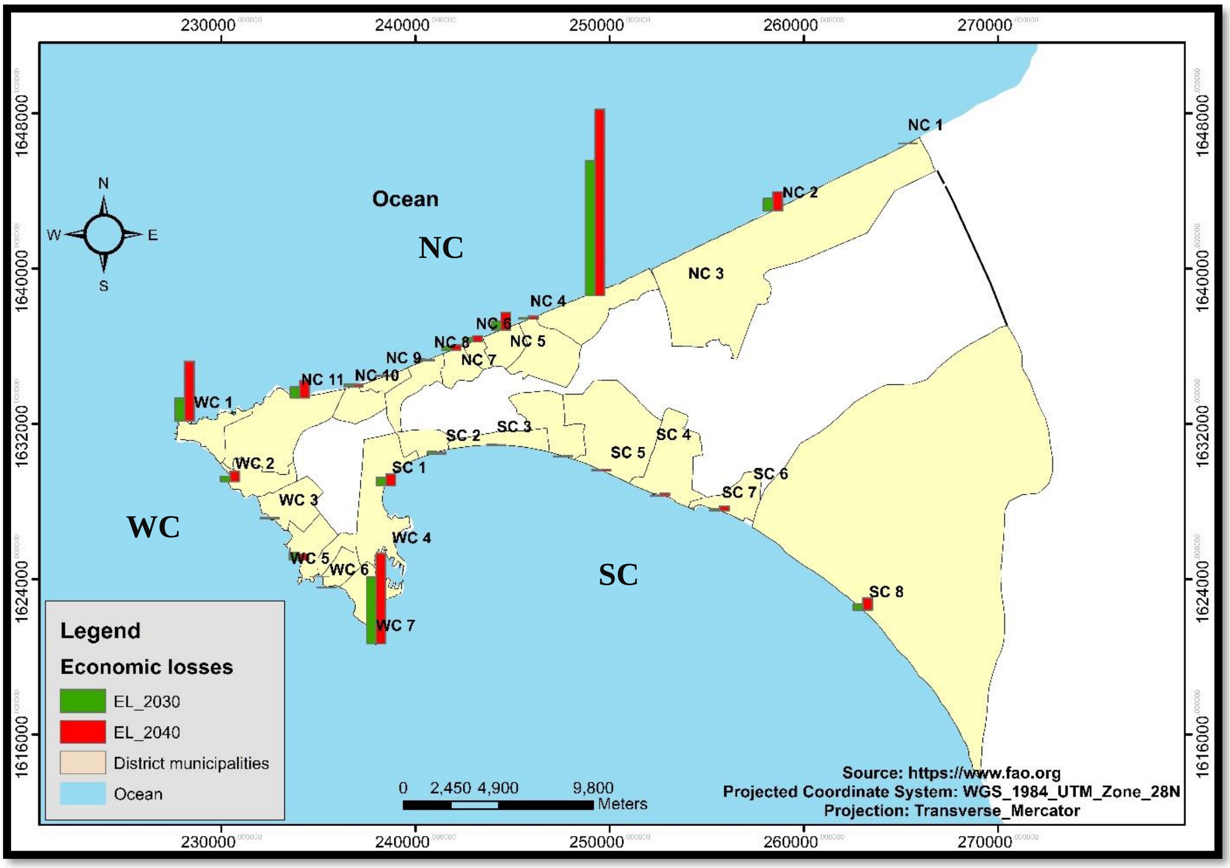
The results show that if the littoral width, coastal length, dynamic rate, proximity to a town, and road length change by one meter, it is expect that the littoral value gets respectively 74,080,000 ; 1,790,000 ; 1,361,000,000 ; 1,174,000, and 1,091,000 FCFA in 2030. If the lost areas, littoral, and building areas change by one square meter, the littoral value is expected, respectively, 186,100, -11,400, and 281,200 FCFA. If the coast vulnerability index, number of buildings, hotels, industries, and fishing points change by one unit, the littoral value will get respectively -203,900,000, -32,040,000, 23,850,000,000, 471,400,000, and -11,060,000,000 FCFA.

In 2040, if the littoral width, coastal length, dynamic rate, proximity to a town, and road length change by one meter, we expect that the littoral value gets respectively -104,900,000 ; 3,131,000 ; 791,400,000 ; 2,635,000 and 1,194,000 FCFA. If the lost areas, littoral, and building areas change by one square meter, the littoral value is expected, respectively, 137900 ; -3,187, and 280,800 FCFA. If the coast vulnerability index, number of buildings, hotels, industries, and fishing points change by one unit, the littoral value will get respectively -93,700,000, -48,100,000 ; 4,502,000,000, and -634,500,000 FCFA.

I.1 Economic lost estimation based on littoral price

The following figure estimates the coast's lost economic value between 2030 and 2040 based on the littoral price per square meter. In all district municipalities, economic loss is estimated based on littoral price and lost areas in 2030 and 2040. The district municipality of Malika recorded the highest loss, with a loss estimated at 16,808,000,000 FCFA in 2030 and 23,191,150,000 FCFA in 2040. Plateau records a loss of about 8,300,100,000 FCFA 2030 and 11,259,000,000 FCFA 2040. In Ngor, the economic loss is estimated at 2,869,900,000 FCFA 2030 and 7,421,260,000 FCFA 2040. The overall economic loss based on littoral price and lost areas in all district municipalities along the coast is estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040 (Figure 43).

The figure 43 is about the economic losses based on the littoral land value in 2030 and 2040 for each district municipalities.



Source: https://www.fao.org

Figure 43: Economic losses in 2030 and 2040 based on littoral price

II. Discussion

Covering more than 71% of the Earth's surface, the oceans are the most heavily trafficked areas because of their usefulness for the economy, transport and biodiversity. More than 600 million people live in coastal areas, representing 10% of the world's population (Gou and Tourian 2021). Due to its geographic location and low-lying sections, the Dakar region, like the majority of the world's capitals, is vulnerable to the effects of coastal erosion. The Dakar region's coastal morphology is impacted by the advanced sea brought on by sea level rise and climate change. The disruption of hydrodynamic agents like waves, tide, wind, etc. accentuates this phenomenon. As a result, there is a reduction in coastal regions, a shift of people inland, and a disturbance of various economic activities like fishing, lodging, and industry. Sand mining, pollution, and unauthorized settlements along the coasts are examples of human activities that exacerbate these problems (Pouye et al. 2023).

The coasts of the Dakar region have significant economic value for the Senegalese economy.

However, climate change and the advancing sea cause the losses of coastal areas by reducing their economic values which vary from one locality to another. These economic values depend on several factors such as the proximity to the town, economic activities (fishing, tourism, and industry), infrastructures (Roads, hospitals, stadiums, and university), and other socio-economic parameters (allotment, sanitation, accessibility). Therefore, estimating the economic value of the beach based on physical and socio-economic parameters takes much work. Nevertheless, econometric models make it easier than a few decades ago. It helps decision-makers understand the economic situation of the coasts in the future to determine whether there is a need for protection to prevent eventual coastal erosion damages. Most of the coasts of Dakar region are highly vulnerable to erosion. For instance, the Dakar region's northern and southern coasts record an average coastal vulnerability index (CVI) of about 94 and 23 respectively. In contrast, the western coast, which is less vulnerable, records an average of about 10. This vulnerability is justified by the dynamic rates of the coastline, which are estimated at -0.44 m/year, 0.21 m/year, and -0.11 m/year, respectively, on the northern, western, and southern coasts (Pouye et al. 2022). Based on the results of this study, one can note that if the CVI changes by one unit, the littoral value will change by -203,900,000 and -93,700,000 FCFA, respectively, in 2030 and 2040. In addition, the change by one unit of the dynamic rate will cause a change of 1,361,000,000 FCFA in 2030 and 791,400,000 FCFA in littoral value. Since the dynamic of the coast leads to erosion or accretion, in addition to the socio-economic activities, it characterizes the width of the beach, which is among the key parameters used by researchers in beach value estimation through the Hedonic pricing model (Landry and Hindsley 2011; Gopalakrishnan et al. 2011; Alexandrakis et al. 2015; Catma 2020).

In coastal zones where erosion is noted, the width of the littoral is reduced, causing a loss of areas. Sometimes, this situation leads to the disruption of economic activities along the coast. The economic impacts of beach width change and land loss due to erosion in Dakar are estimated. If the beach width changes by one meter, it is expected that the littoral value will change by 74,080,000 FCFA in 2030 and -104,900,000 FCFA in 2040. In all district municipalities, economic loss is estimated based on littoral price and lost areas in 2030 and 2040. The highest loss is recorded in the district municipality of Malika, with a loss estimated at 16,808,000,000 FCFA in 2030 and 23,191,150,000 FCFA in 2040. Plateau records a loss of about 8,300,100,000 FCFA 2030 and 11,259,000,000 FCFA 2040. In Ngor, the economic loss is estimated at 2,869,900,000 FCFA 2030 and 7,421,260,000 FCFA 2040. The overall economic loss based on littoral price and lost areas in all district municipalities along the coast is estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040.

Coastal areas in Dakar are the most strategic areas for industry, tourism, transport and fishing activities. However, these activities are confronted with coastal erosion through the reduction of exploitation areas and income. In the Dakar region, socio-economic sectors such as fishing, recreational activities and human settlements along the coast are affected by coastal erosion. Fishing is an activity that depends on the biological production of marine and coastal ecosystems and plays a considerable socio-economic role in Senegal, particularly in the Dakar region. This situation is exacerbated by the rapid retreat of the coastline observed in some coastal areas, resulting in the reduction of secure storage areas for their fishing boats, the destruction of fishing docks and markets. The main fishing points (Yoff, Soumbédioune, Hann, Thiaroye and Rufisque) are exposed to the impacts of climate change and coastal erosion. In addition, marine pollution from sewage, chemicals, solid waste, etc., increases erosion, leading to disruption of marine and coastal biodiversity and exposing local communities to infectious diseases, reduced fish species, reduced income, etc. Recreational facilities such as hotels, hostels, restaurants, etc. along the coast of the Dakar region are weakened by the retreat of the coastline. From Yoff to Cité Djily Mbaye, there are large huts with hotels and hostels that represent a large part of the working population. The advancing sea destroys the huts, especially during the marshy period (wintering) from November to January, putting many beach workers out of work. It should be noted that in winter, these beach activities are less lucrative because of the cold, and the clientele is less frequent than in summer. This study demonstrates that if the number of hotels, industries, and fishing points changes by one unit, the littoral value will get 23,850,000,000, 471,400,000, and -11,060,000,000 FCFA in 2030. In 2040, if the number of hotels, industries, and fishing points changes by one unit, the littoral value will get respectively -48,100,000, 4,502,000,000, and -634,500,000 FCFA. Usually, economic activities and infrastructures are highly correlated to land value.

In a study, it is stated that the value of land increases as the areas' buildings grow with economic activities (Nakagawa et al. 2007 in Saputra et al. 2021). In 2030 and 2040, if the number of buildings changes by one unit, the littoral value will get respectively -32,040,000 and -48,100,000 FCFA. Far from being neglected, the proximity of the land to the town affects its value. Land value decreases with distance from the Central Business District, according to the urban economic theory built on a monocentric city (O'Sullivan 2007 in Han et al. 2020). If the proximity to the town changes by one meter, it is expected that the littoral value will get

1,174,000 CFA in 2030 and 2,635,000 FCFA in 2040. The dynamics of the coastline from 1990 to 2020 shows that the region records average retreats of about -0.44 m/year, 0.21 m/year and -0.11 m/year respectively on the northern, western and southern coasts. These dynamic rates are expected to be about -4.4 m/year (for the north coast), 2.1 m/year (for the west coast) and -1.1 m/year by 2030. (south coast). By 2040, they are estimated to be around -8.8 m/year (north coast), 4.2 m/year (west coast) and -2.2 m/year (south coast). These dynamic rates will cause the losses of area which is estimated at 861,273 m^2 in 2030 and 1,256,493 m^2 in 2040 (Pouye et al. 2022). In this study, it is estimated that if it changes by one square meter, the littoral value is expected to change by 186,100 FCFA in 2030 and 137,900 FCFA in 2040.

Partial conclusion

In summary, climate change has detrimental effects on the economic value of coastal zones and its adverse effects on the ecosystem. Coastal communities suffer from several harms one of its effects, coastal erosion. Consequently, these effects affect economically the coastal areas. The results of this study showed that the littoral width, eroded areas, length of the coast, dynamic rate of the coastline, surface of the littoral, built areas, proximity to town, CVI, number of buildings, hotels, industries and fishing points and the length of the roads play an essential role on littoral value. The estimation of economic loss based on littoral price and lost areas showed that the district municipalities along the coast of Dakar recorded a loss estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040. These losses are shared unequally in coastal areas in Dakar. The most exposed in terms of economic loss are Malika, Plateau, and Ngor. Whether the coast of Dakar region is challenged economically by coastal erosion, abnormal settlements, pollution sand mining aggravates the economic loss. It should be essential to note that the application of law n°76-66 of 2 July 1976 defines the natural public domain with the shores of the sea, and the artificial public domain with the numerous urban infrastructures built or planned. The law Nº 83-05 of 28 January 1983 of the Environmental Code specifies that settlements along the coast must neither be a source of erosion nor degradation of the site. Unfortunately, this law is not respected by most of economic actors. The chapter 10 addresses the coastal erosion impacts in the Dakar region.

Chapter 10: Coastal erosion impacts in the Dakar region

Introduction

In Senegal, a large part of the population who live in coastal areas is threatened by the rising sea level (Diop 2007). It causes an aggravation of temporary submersion, extension of permanent submersion on low-lying areas, lagoon shores, maritime marshes, coral reefs, reinforcement of erosion actions on cliffs and beaches, increased salinization of estuaries, and reduction in the volume of freshwater aquifers. (Bird 1993; Paskoff 1998). The consequences of such a natural phenomenon affect the economy through the reduction of agricultural productivity and marine biodiversity, risk of flooding of port and road infrastructures, and destruction of tourism facilities. (DEEC 2001).

Being the most threatening natural disaster apart from flood, coastal erosion challenges the population of the Dakar region, disrupting economic activities such as fishing and tourism. It reduces the coastal areas. According to Guerin (2003), coastal erosion will substantially reduce beaches, mainly in the Dakar region. The southern coast is much more vulnerable, particularly the coastal segment from Hann to Thiaroye, where there is a deficit of sedimentary supply from hydrodynamic factors. This chapter enumerates the Dakar region's environmental and socio-economic impacts of coastal erosion.

I. Morphologic features of the coastal environment in the Dakar region

Due to climatic and hydrodynamics factors such as wave, wind, drift, tide etc., coastal areas are the most dynamic zones in the world. Depending on the degree of porosity and nature of sediment that composes the coast, they are subjected to changes. The drive factors of these changes are the geologic, geomorphologic, hydrodynamic, biologic, climatic and anthropogenic conditions. Geologic conditions, characterized by the sediment structures' type, arrangement and resistance and isostasy, are the basis of morphological processes and the development of coastal relief. In contrast, geomorphologic conditions are determined by climatic factors such as precipitation, rainfall, and wind. These geologic and geomorphologic conditions are the generator of the forms of typical relief and sediment supply (Łabuz 2015). Hydrodynamic factors such as waves and wind play an important role in coastal environmental change. According to Strahler (2013), if a wave breaks into weak or soft materials, the forward-moving water's force easily cuts into the littoral. It causes erosion, and the retreat of the shoreline is rapid. If the wave breaks into resistant rocks, the result is sea cliffs. A notch is formed at the base of sea cliffs due to physical disintegration. Wave activities combined with evaporation generate salt crystals to grow in the tiny fissure of the rock, breaking it apart grain by grain. The force of waves and abrasion by rock fragments pushed against the cliff and carved the notch. Consequently, blocs of rock fall from the surf zone cliffs due to the notch's effect. As the cliff erodes, the shoreline gradually retreats toward the shore. The erosion of sea cliffs generates a variety of landforms such as sea arches, sea caves and sea stacks.

Wind performs two kinds of erosional work: deflation and abrasion. Deflation is the removal of particles, largely silt and clay, from the ground by the wind. It acts on loose soil or sediment. Dry river courses, beaches, farmlands, and areas of recently formed glacial deposits are especially susceptible to deflation. In dry climates, much of the ground surface can be deflated because the vegetation cannot hold the soil or sediment in place. The capability of the wind to remove particles by deflation depends on their size. Given a mixture of particles of different sizes on the ground, deflation, combined with splash erosion and overland flow, will remove the fine particles, and leave the coarser particles behind. As a result, rock fragments ranging in size from pebbles to small boulders become concentrated into a surface layer known as desert pavement. The large fragments become closely fitted together, sheltering the smaller particles (grains of sand, silt, and clay) that remain beneath. The pavement acts as an armor that protects the remaining fine particles from rapid removal by deflation or overland flow. However, this pavement is easily disturbed by wheeled or tracked vehicles, which expose the finer particles underneath, leading to renewed deflation and water erosion. In drier plains regions, deflation can scoop out a shallow basin called a blowout, especially where the grass cover has been broken or disturbed by grazing animals, for example. The size of the depression may range from a few meters (10 to 20 feet) to a kilometer (0.6 miles) or more in diameter, although it is usually only a few meters deep. A blowout can also form in a shallow depression in a plain where rains have filled the depression and created a shallow pond or lake. As the water evaporates, the mud bottom dries out and cracks, leaving small scales or pellets of dried mud. The wind then lifts these particles out. The second process of wind erosion, abrasion, drives sand-sized particles against an exposed rock or soil surface, wearing down the surface by the impact of the particles. Wind abrasion is most active in a layer about 10 to 40 cm above the surface. The weight of the sand grains prevents them from being lifted much higher into the air. Wooden utility poles on windswept (Strahler 2013).

The coasts of the Dakar region are subjected to the effects of climatic, hydrodynamic agents, which shape coastal morphology. The geologic and geomorphologic conditions play an essential role in this dynamic. In addition, anthropic activities along the coast play an important role in the dynamic coastal morphology through settlements and sand mining. The length of the coasts of the Dakar region is estimated to be about (133,69 kilometers), i.e., 18,91% of the total coast of Senegal (Bakhoum et al. 2018). Its delimitation is based on the different types of coasts: the sandy coast in the northern and southern part and the western coast, which is composed of cliffs.

The northern coast is a sandy coast characterized by fine unconsolidated sediments composed of raw mineral soil supply (Figure 44). Due to the effects of hydrodynamic agents such as wave, wind, swell tide, drift etc., the sediments from the northern coast of Senegal are deposed and accumulated along the north coast of Dakar, predominantly influenced by north-westerly swells, which induce littoral drift, directed towards the South (Bakhoum et al. 2018).

The figure 44 is about the morphology of the northern coast of Dakar region which is a sand coast.

Source: Google Earth

Figure 44: Northern coast of Dakar region

The shapes of these different coasts are linked to geology, hydrodynamic, climatic, and morpho-pedological conditions. According to Adjoussi (2001), three different activities determine the geologic history of the Dakar region: volcanic activities, marine transgressions, and regressions observed from the pre-quaternary period up to the quaternary period in the Dakar region. Significant faults mark this geology. The morphology of these two horsts is accentuated by the occurrence of recent volcanic cones composed of both volcanic ash and basaltic lavas. In addition, in a study, Sane & Yamagishi (2004) stated that "These faults formed two horsts: The Dakar and Ndias horst. Dakar plateau 50 m high above sea level consists mainly of Tertiary volcanic such as basaltic, tuffaceous, and sedimentary rocks. The Ndias horst reaches a height of 105 m and is formed of quaternary volcanic deposits. The morphology of the two horsts is accentuated by the occurrence of recent volcanic cones composed of both volcanic ash and basaltic lavas.

The figure 45 is about the morphology of the western coast of Dakar region which is a cliffy coast.

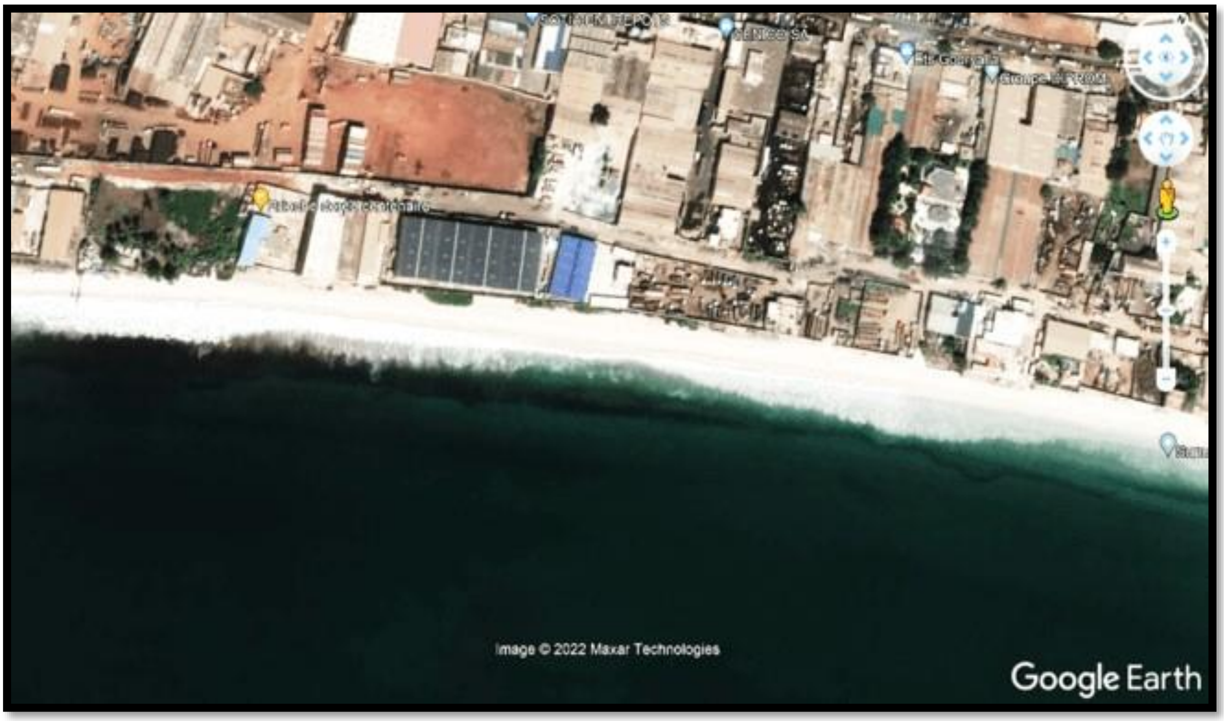
Source: Google Earth

Figure 45: Western coast of Dakar region

The horsts develop indented, cliffy shorelines that preserve a less degraded structure (Figure 45). On such shorelines, waves' direct impact is reduced and slows erosion. Five formations characterize the morpho-pedological conditions of the Dakar region: Recent volcanic formation, formation on Maastrichtian sandstone (Cretaceous), and formation on marl-limestone rocks (Paleocene-Eocene), recent Ergs and littoral formations. These morpho-pedological conditions are among the most vital factors shaping the coast. In addition, far from being negligible, climate conditions play an essential role in the coastal dynamic. The climate of the Dakar region can be determined by airline conditions which are the trade wind maritime, harmattan and the monsoon. In the coastal area, the wind is among the critical factor in the coastal system generating swell, sea currents and waves and plays a vital role in coastal sediment transport.

The Southern Coast or Petite Côte is a coastline segmented into a succession of capes and bays whose layout is controlled by tectonics. This coast is also subject to a north-westerly swell whose energy is reduced by refraction and diffraction around the Cape-Vert peninsula. Although a south-eastward longshore drift is present, sediment transport estimates indicate that the supply is much less critical than along the northern coast (Figure 46).

The figure 46 is about the morphology of the southern coast of Dakar region which is also a sand coast.



Source: Google Earth

Figure 46: Southern coast of Dakar region

II. Socio-economic impacts of coastal erosion

Covering more than 71% of the Earth's surface, oceans are the most convoyed zones due to their utilities in the economy, transport, and biodiversity. More than 600 million people live in coastal areas, e.g., 10 per cent of the world population. In addition, coastal zones constitute the most strategic areas for industry, tourism, transport, and fishery activities. However, these activities are challenged by coastal erosion through the reduction of operational areas and incomes. In the Dakar region, socio-economic sectors such as fishing, recreative activities, and human settlements along the coast are affected by coastal erosion.

II.1 Impacts on fishing activities

Fishing is an activity depending on the biological production of marine and coastal ecosystems and plays a considerable socio-economic role in Senegal, particularly in the Dakar region. Climate change affects these ecosystems, phytoplankton, and fish (biogeography and species phenology). It modifies the dominance and distribution of many species (e.g., small aquatic) and the functioning and diversity of marine ecosystems. As a result, fisheries resources are scarce, impacting food security (USAID 2018). This situation is accentuated by the rapid coastline retreat observed in certain coastal zones causing the reduction of secure storage areas (Figure 38) for their fishing boats, destruction of fishing quays and markets. The key fishing points (Yoff, Soumbédioune, Hann, Thiaroye and Rufisque) are exposed to the impacts of climate change and coastal erosion. In addition, marine pollution through wastewater, chemical product, solid waste discharges, etc., accentuate the erosion leading to the disturbance of marine and coastal biodiversity and exposing local communities living along the coast to infectious diseases, the rarity of halieutic species, low-income, etc.

The table 23 is about the perceptions of fishermen about the impacts of coastal erosion on fishing activities in our study area. Five fishing points along the Dakar coast were chosen (Yoff, Soumbédioune, Hann, Thiaroye and Rufisque). From each fishing point, 10 respondents were selected.

Table 23: Impacts of coastal erosion based on the fishermen perception

Impacts on fishery activities	Number of citations	Frequency (%)
No response	1	0.735294118
Migration of aquatic species elsewhere	39	28.67647059
Rarity of fishing products	37	27.20588235
Increase of infectious disease frequency	25	18.38235294
Low incomes	20	14.70588235
Reconversion of fishermen to other activities	7	5.147058824
Illegal migration of fishermen elsewhere	3	2.205882353

Fishermen family's dislocation	2	1.470588235
Reduction of hope	2	1.470588235
Other	0	0
Total citation	**136**	**100**

Source: Field survey

The viewpoint of fisherman regarding the effects of coastal erosion is covered in this table. It demonstrates that 39 of the 136 statements believe that coastal erosion is the cause of the spread of aquatic species to other locations. This implies that aquatic species may be harmed and that fishermen may need to modify their fishing techniques. As a result of coastal erosion, the supply of fish is disrupted, resulting in a decrease in catches and perhaps having an influence on fishermen's livelihoods, according to the respondents. According to 18.38% of respondents, coastal erosion has led to a rise in the prevalence of infectious diseases. This shows that changes in the aquatic environment brought about by erosion may have affected water quality and increased the prevalence of diseases that can affect both fish and fisherman. 14.71% of the respondents claimed their income has been impacted by coastal erosion. This shows that erosion has impacted fishing activities' profitability, maybe as a result of lower catches or altered market dynamics brought on by the effects. The coastline erosion, according to about 5.15% of respondents, had caused fishermen to switch to other occupations. This could mean that some fishermen have had to look for alternate sources of income due to erosion's detrimental effects on their fishing activities.

II.2 Impacts on tourism

Infrastructures for recreational activities, such as hotels, hostels, restaurants, etc., are noted along the coast of the Dakar region. There are large huts with hotels and hostels, which account for a large part of the active population. However, climate change and the advancing sea are the main constraints on beach activities. The advancing sea destroys the huts, especially during the marsh period (winter) from November to January, putting several beach workers out of work. It should be noted that during the winter, these beach activities are less lucrative because of the cold, and the clientele is less important compared to the summer.

The table 24 is about the perceptions of fishermen about the impacts of coastal erosion on fishing activities in our study area.

Table 24: Impacts of coastal erosion based on the hotelkeeper's perceptions

Impacts on fishery activities	Number of citations	Frequency (%)
Low incomes	42	44.68085106
Touristic infrastructures damage	13	13.82978723
Reconversion of hotelkeepers to other activities	13	13.82978723
Illegal migration of hotelkeepers elsewhere	10	10.63829787
Hotelkeeper’s family’s dislocation	9	9.574468085
Reduction of operational areas for hostelry	6	6.382978723
Other	1	1.063829787
Total citation	**94**	**100**

Source: Field survey

Low revenue was the effect that respondents (44.68%) noted the most. This suggests that the financial sustainability of hotels in the area has been negatively impacted by coastal erosion. This implies that decreasing hotel revenues are the result of fewer tourists visiting the area or changes brought on by deterioration in the local ecosystem. Infrastructural damage to the tourism industry was noted by 13.83% of respondents as a result of coastal erosion. This means that physical damage from erosion has occurred to the buildings and infrastructure that support the tourism industry, which may impede the functioning of hotels and other tourism-related services. As a result of coastal erosion, 13 out of the 94 respondents mentioned that hoteliers had switched to other professions. This suggests that because of the damaging impacts of erosion on the hotel industry in the Dakar region, some hoteliers have been obliged to look for new sources of income. As a result of coastline erosion, 10.64% of respondents highlighted the illegal migration of hoteliers to other countries. This shows that due to the detrimental impacts of erosion on the tourism industry in Dakar, some hoteliers may have made the decision to relocate to other areas or nations in pursuit of better economic prospects. The impact of coastal erosion on the hotel business was mentioned by approximately 6.38% of respondents. This means that erosion may have led to the loss or diminution of land usage or coastal regions where hotels operate, restricting their ability to operate and maybe causing a loss of revenue.

II.3 Impacts on human settlement

Most of the district municipalies are exposed to advanced sea in our study area. Some of them have been victims of heavy extraction of marine sand over the last ten years. This is what most favors the advance of the sea in these localities. In addition to the threat posed by the advancing sea, there are also sea breeze effects on the houses. The sea breeze, with its chemical components, negatively impacts buildings and household appliances. It damages household appliances (television, refrigerator, cooker, water heater, iron, etc.) and reduces their life span. Indeed, these localities of the northern coast are crossed by the high-frequency wind according to the marine currents. Under the salt, the breeze attacks the walls and roofs of the concessions, creating cracks that accelerate the iron's corrosion in a short period. As a result, these leases tend to collapse, posing enormous dangers to the population. A significant proportion of abandoned houses in an advanced state of disrepair are noted along the northern coast of the Dakar region (Figure 47).

Source: Author’s field visit, 2021

Figure 47: The destruction of human settlements and reduction of coastal area in Petit Mbao (Southern coast of Dakar region)

III. The questionnaire addressed local communities

The questionnaire for the field survey was addressed to local communities living along the coast of the Dakar region. It was separated into four principal sections. The first is identifying our respondents through their name, sex, age, profession, and education level. The second section is about local communities' perception of coastal erosion through the definition, cause, and effects of coastal erosion on habitat. The third one is the economic cost of home equipment maintenance. The last section was focused on adaptation measures through the different approved adaptation strategies; efficacity of dune covered by plants against erosion, dyke construction and its effects on the beach, challenges of coastal erosion management in the Dakar region, stakeholder of coastal erosion management and participation of local communities, the role of local and regional authorities, existing protective infrastructures and its effectiveness and displacement of affected people.

III.1 Identification of respondents

This step was crucial for starting the survey. First, A sampling technique was employed to select respondents in different districts and municipalities along the coast of the Dakar region. Accordingly, a quota method was used. For this method, the number of people living in these district municipalities is determined. The quota of each district municipality for the total sample was estimated at 700 people.

The table 25 is about the distribution of the respondents by age and gender.

Table 25: Distribution of the respondents by age and gender

Age range	No response	Male	Female	Total
No response	13	128	69	210
Under 10	0	1	0	1
10 – 20	0	22	10	32
20 - 30	1	60	41	102
30 - 40	1	170	92	263
40 - 50	1	46	12	59
50 - 60	0	11	2	13
60 and more	0	13	7	20
Total	**16**	**451**	**233**	**700**

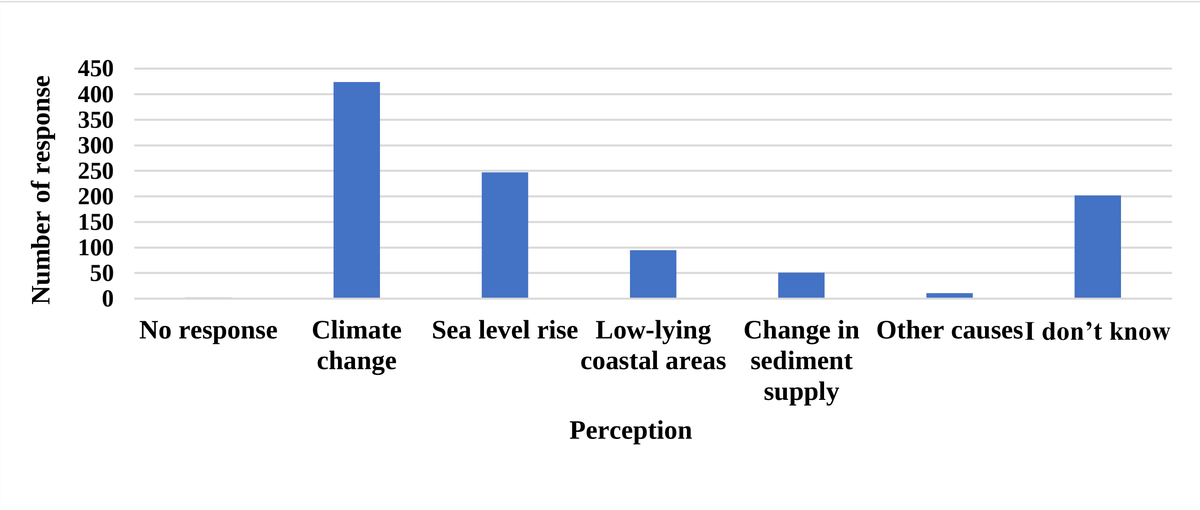
Source: Field survey

The designation of respondents in terms of age or sex was randomly determined. The dominant age range of respondents is from 30 to 40 years old. In the total of 700 respondents, 451 men and 233 women were investigated. 79% of respondents have received an education, and 2.4% are jobless. These indicators give us an idea about the adaptative capacity to cope with the impacts of climate change in these localities and the level of vulnerability analyzed in the following chapter.

III.2 Local communities' perception of coastal erosion

To get the perception of local communities about coastal erosion, its definition, cause and effects on habitat, their agreement or disagreement about the following statements: Inappropriate development of coastal areas can expose houses to coastal erosion; We must accept that erosion is a natural process; There is a range of methods to stop erosion permanently; The width of the dune changes over the years; Once a dune is destroyed, there is no way to restore it; I don't know. The following figure is about the causes of coastal erosion according to the local communities. 424 responses out of 1032 argued that the cause of coastal erosion is climate change; 247 thought that sea-level rise is the generator of coastal erosion. 202 respondents did not know (e.g., 19.57% of the total response). 95 responses, e.g., 9.21 %, argued that it is due to low-lying areas that the coast is eroded. According to 385 respondents (e.g., 55% of the total sample (700)), coastal erosion damages houses. Mostly, they live on the northern coast, where the hydrodynamic agents such as wave action and drift are more active. A significant proportion of abandoned houses in an advanced state of deterioration are noted along the northern coast of the Dakar region, which is subjected to high-frequency winds due to the sea currents (Figure 48).

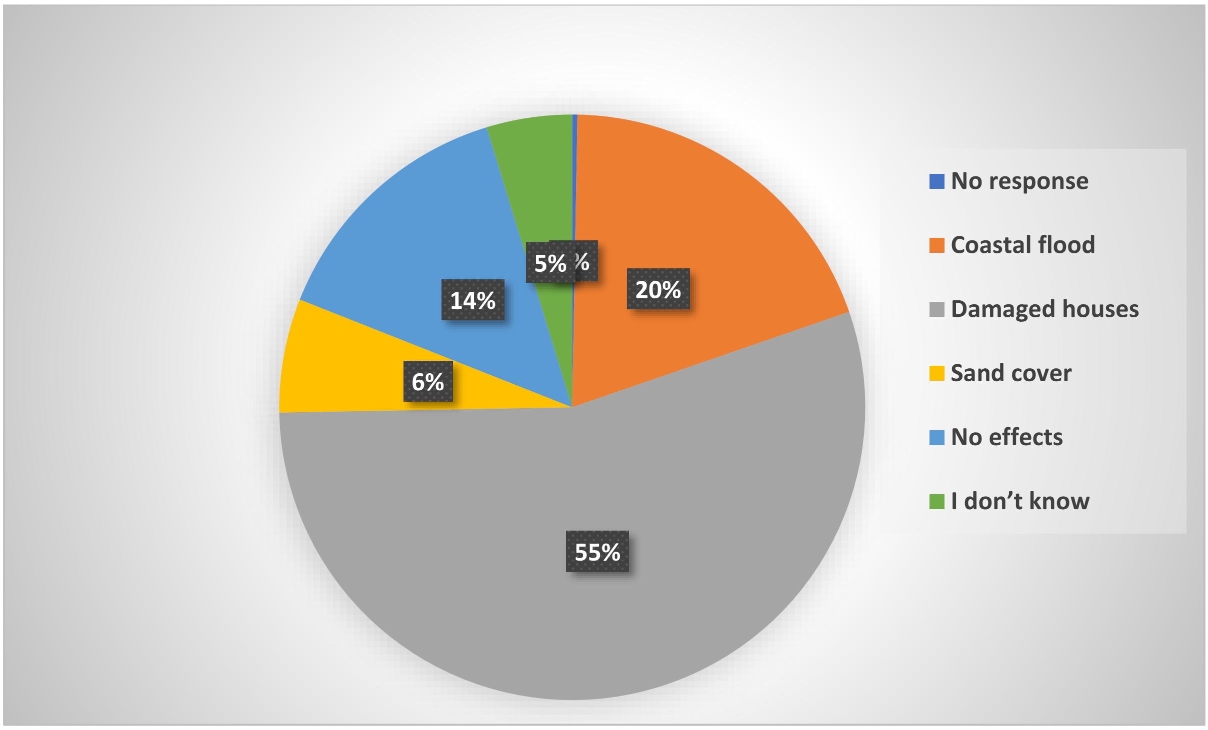
The figure 48 is about the perception of local communities about the causes of coastal erosion.



Source: Field survey

Figure 48: Cause of coastal erosion according to the local communities

As a result, these concessions tend to collapse, causing considerable risks to the population. Under the influence of salt, wind attacks the walls and roofs of the buildings, creating fissures that accelerate the corrosion of the iron in a short period. The sea breeze negatively impacts household equipment (television, fridge, cooker, water heater, iron, etc.) and reduces their uptimes due to its chemical components.



Source: Field survey

Figure 49: Effects of coastal erosion on human habitat in Dakar region

Whether the northern coast is challenged by the effects of wind and sea breeze on houses, the southern coast is affected by coastal floods during storm surge periods. 409 respondents out of 700 stated that there are deserted houses. 136 respondents, e.g., 20%, argued that the impact of coastal erosion in their localities is a coastal flood. In the traditional villages (Yoff, Rufisque and Bargny), a loss of beaches is noted due to the deficit of sediment budget generated by sea currents (Figure 49). This situation is accentuated by the amplification of swell, causing recurrent marine floods with disastrous consequences such as the destruction of houses and fishing equipment (Weissenberger et al. 2016). Consequently, maintaining local communities' home equipment and house maintenance is the main challenge in certain localities, particularly the northern coast of Dakar, causing crucial economic losses.

Partial conclusion

In conclusion, coastal erosion and floods that are driven by sea-level rise, as well as an increase in temperature, are all effects of climate change. Therefore, coastal areas are the most dynamic zones in the world and are vulnerable to some changes because of hydrodynamic agents such as waves, wind, drift, tides, etc. Geologic and geomorphological, hydrodynamic, biological, climatic, and anthropogenic circumstances are the driving forces behind these changes. The coasts of the Dakar region are composed of the northern, western, and southern coasts. These various coasts' morphologies are influenced by geological, hydrodynamic, climatic, and morpho-pedological factors. The geology is characterized by large faults. The presence of recent volcanic cones made of both volcanic ash and basaltic lavas highlights the morphology of the two horsts. These coasts are subject to the effects of climatic and hydrodynamic agents, which are responsible for the dynamic morphology of the coasts.

Being the most threatening natural disaster apart from flood, coastal erosion challenges the population of the Dakar region, disrupting activities such as fishing and tourism, the reduction of coastal areas and flooding. Climate change affects these ecosystems, phytoplankton, and fish (biogeography and species phenology). It modifies the dominance and distribution of many species and marine ecosystem's structure, functioning and diversity. It also affects touristic activities. Infrastructures for recreational activities are noted along the coast of the Dakar region. The impacts of the sea breeze on the dwellings are another factor, particularly along the northern coast. Buildings and home appliances are negatively impacted by the sea breeze's chemical components. It harms home appliances, resulting in lots of financial losses. The chapter 11 addresses the adaptation measures against coastal erosion in Dakar region and perspective of the study.

PART III: ADAPTATION STRATEGIES, AND RECOMMENDATION

Chapter 11: Adaptation measures and recommendation

Introduction

Since a long time ago, human beings have been challenged sometimes by the inconveniences of nature (floods, volcanic eruptions, earthquakes, storm surges, drought). However, they have always found ways to adapt to these obstacles to survive and improve their living conditions. Therefore, to protect against coastal erosion, several means are used: protective walls, groin fields, reforestation, dykes, riprap, beach nourishment, dune restoration, beach draining systems, and breakwaters. Among these means, some are more effective depending on their quality, their resistance duration against hydrodynamic conditions (swell, winds, sea currents, waves), and the type of coast where they are installed. However, despite the advantages that these infrastructures provide to communities in terms of the preservation of coastal ecosystems, it should be noted that they can be a hindrance to the exchange of sediments between continents and oceans.

In addition, some of these protective infrastructures are very expensive. Consequently, in some coastal regions doing nothing is the easiest coastal management option. This situation is generally the case in areas with no people, so nothing economical or institutional value should be protected. Today there is a practice of non-intervention/no action in West Africa, but this is not an act of addressing coastal problems in a planned manner. Many sections of the West African coast are under natural and manmade threats without any coastal management plan in place. This is not what the "do nothing" approach preaches: dealing with natural phenomena, possibly losing land to the sea, but without loss of infrastructure or even lives. While this is the cheapest and most environmentally friendly option for many parts of developing regions such as West Africa, one must weigh the costs (for people, tourism, industries, infrastructure) against the benefits (the advantages of letting the area return to its natural processes). If the costs greatly outweigh the benefits, for example, by relocating people or losing valuable facilities, other options must be considered. This situation is not practiced in West Africa. Not all problems have been addressed because governments have no financial resources to conduct detailed research. Otherwise, they would surely do something. It is therefore advisable to consider this practice. Do due diligence and do nothing (Alves et al. 2020).

In Senegal, particularly in the Dakar region, several adaptation measures have been experienced in adapting to coastal erosion. Nevertheless, the coastline is still retreating.

I. Different adaptation measures against coastal erosion

I.1 Riprap

Ripraps are transverse structures (Figure 50). These structures, known as groins, are solid or perforated and perpendicular or parallel to the coastline. They use various materials, the most common being riprap or masonry, although wooden groins are also used. The most recent techniques use geotextiles as an envelope to compose defense works. These protective infrastructures form a dam to retain the sediments transported by the littoral drift. Groynes have the advantage of slowing down the erosion of a sandy coastline or protecting against cliff erosion by trapping sediments that protect against wave attacks. In addition, they can be locally effective in stopping the movement of tidal channels and reducing coastal erosion and the amount of sand to be recharged locally. It should also be noted that rockfill groins have the advantage of being based on simple construction methods. As a result, they have long-term durability while absorbing wave energy due to their semi-permeable nature. On the other hand, wooden groins are less durable and tend to reflect energy rather than absorb it (Niang et al. 2012). The figure 50 is about the riprap along the coast of Ndéppé (Southern coast of Rufisque department).

Source: Author’s field visit, 2021

Figure 50: Riprap along the Ndéppé’s coast (Southern coast of Rufisque department)

I.2 Protective wall

Breakwaters are free-standing protective structures placed between the top of the beach and the infrastructure immediately behind it. They are erected parallel to the coastline, primarily protecting the facilities behind them from the risk of flooding by seawater. Their function is to limit the damage caused by powerful swells and are structures capable to protect tidal inflows, rivers, and estuaries from intermittent storm surge occurrences (Appelquist, Balstrøm, and Halsnæs 2016). The main demerit of the storm surge barrier is that it is capital-intensive with high maintenance costs, as this coastal management solution involves high capital costs for implementation and maintenance. Therefore, it is only well suited to the general situation in West Africa if it can be considered in the future for particular areas (Alves et al. 2020). They do not protect the beaches at the ends of the walls and do not combat the causes of erosion (Isabelle Niang et al. 2012). These walls also have disadvantages: ineffectiveness if erosion is dominated by transport in the profile; only local protection; unattractive structures; negative environmental aspects (limitation of natural pathways, lower water quality, and visual impact); high costs (MEEDM 2009).

In the Department of Rufisque located on the southern coast of the Dakar region, protective walls were built in Keuri Kad and Keuri Souf between 1983 and 1990 by a group of Netherlands consultants, they are trapezoidal dams with a width of 5 m at the top and 12 m at the base. Its length is about 3.5 km. The top of the dikes is over 5 m above the water level. The slopes are 45°, and a geotextile filter supports the structure. The structure's body is made of limestone rubble weighing 3 to 5 kg and is protected on the seaward side by basalt blocks weighing 1 to 2 tonnes. Another wall was built by the Direction des Travaux Publics. They were built in Diokoul between 1990 and 1992. They are concrete walls supported by gabions filled with rocks. These walls are currently undergoing collapse or overturning. A new vertical concrete wall was built before the first collapsed wall in August 2004 (Isabelle Niang et al. 2012). According to the Senegalese coastal vulnerability study, costs have been estimated at between US$4.6 and 5.33 million per km of sea wall (based on US$1 for 600 FCFA). Moreover, sea walls seem to lead to the disappearance of beaches in front of them due to wave reflection phenomena.

I.3 Protective dykes

According to the LAROUSSE dictionary, a dyke can be defined as a causeway to contain water.

Dikes are protective structures against the advancing sea. There are different types of dykes, which can be classified into five categories, each of which is specific in nature, design, and size: embankment dykes (or rockfill dykes), vertical dykes with a solid face (or solid caissons), caisson dykes with perforated walls, partial dykes and articulated dykes.
The tragedy of 2007 caused several damages along the southern coast of Rufisque, such as the collapse of the cemetery Thiawlene's wall. As a result, an idea to build a new dyke in the Rufisque-Est coastal zone occurred. The dyke is implemented by the West Africa Monetary Union with an amount of about 6.5 million $. It is a length of about 730 m and a width of 23 m. It was inaugurated on July 2013 (Koulibaly and Ayoade 2021).

I.4 Reforestation

Reforestation is defined in the LAROUSSE dictionary as the re-planting of trees on deforested land. It can be a means of fixing the coastal dunes and protecting against the advancing sea. The degradation of the forest cover in the Dakar region, particularly the northern coast, was already a problem in coastal management. It is linked to many factors, including encroachments for the construction of new housing estates or the extension of market gardening activities; the anarchic removal of sand from the filao strip (Casuarina equisetifolia), causing trees and shrubs to fall over; illegal cutting and the roaming of animals within this perimeter; dumping of rubbish within this strip of filao in Guédiawaye; ageing of the strip of filao and salt intrusion. (CSE 2010). In addition, the extension of the VDN causing deforestation accentuates the problem.

Several projects of dune fixation by planting filaos were undertaken in the past to halt the decline of dunes. Planted in 1948 on the northern coast of Senegal, the filao is a shrub of the Fabaceae family originating from the Pacific. This nitrogen fixer can be used as a windbreak and firewood and is very effective in retaining even sandy and degraded soils. However, particularly adapted to the climatic conditions of the Niayes, it produces a critical litter that is very sensitive to fire. These plantations are being deforested in the Dakar region because of the high land ownership and demography pressure. This risk leads to a vulnerability for existing land assets and the agricultural economy, which depends on this area and the unique ecosystem that represents the Niayes. Therefore, several development projects aimed to improve its management. In the recent past, efforts have been undertaken by the Senegalese government with the support of UNDP-UNSO, Canadian and American cooperation to fix the dunes along the northern coast of Dakar by reforesting 12.000 ha between 1974 and 1990.

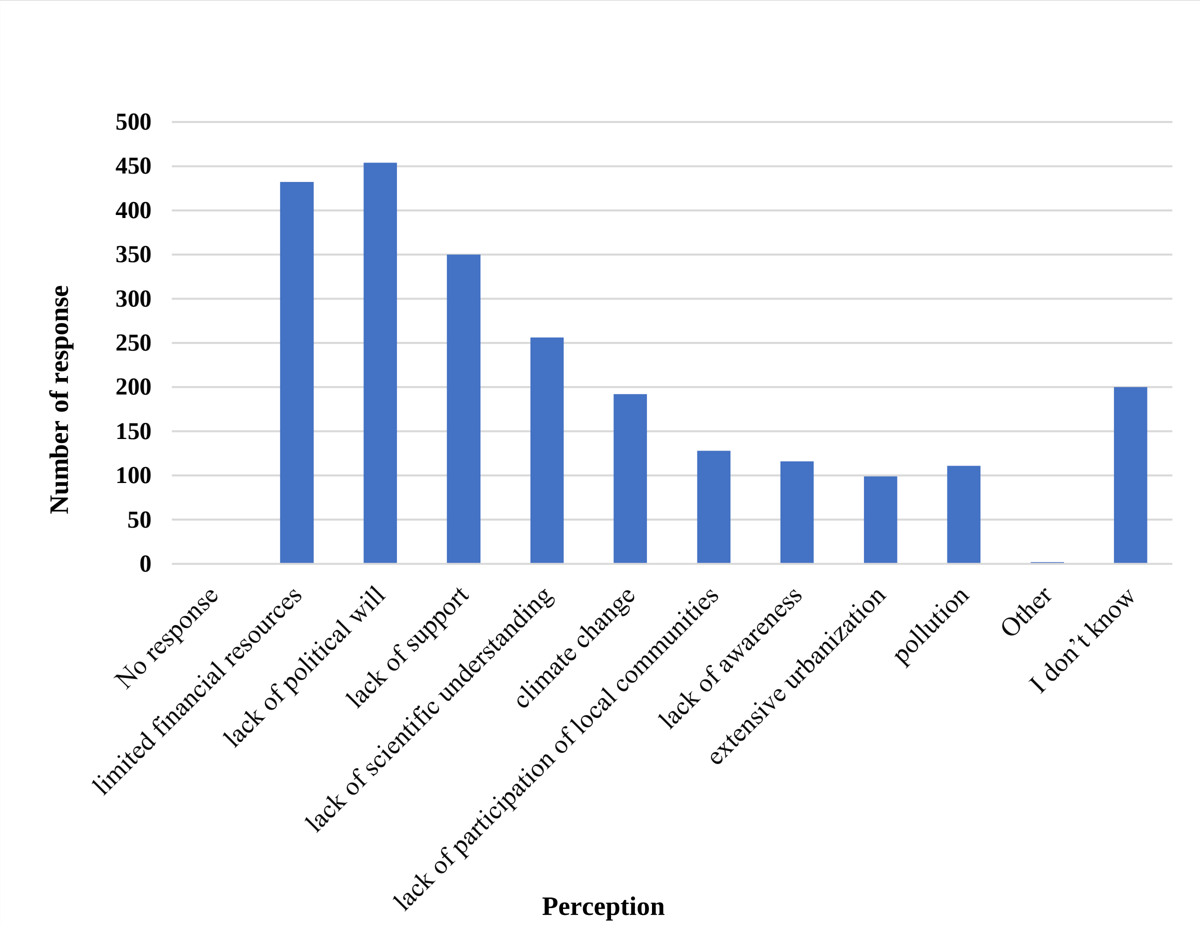
Within the "Plan d'Action Forestier au Sénégal" drawn up in 1992, the Senegalese government designed a project to preserve the Niayes area and fix the dunes around it. In this context, the Senegalese government requested, in August 1998, non-reimbursable financial assistance from the Japanese government for the supply of equipment and the installation of facilities necessary for the reafforestation project. In response to this request, the Japanese government, through JICA (Japan International Cooperation Agency), conducted from April to November 2000, the basic plan studies and planned its cooperation for the establishment of plantations fixing the 16 dunes of 2.037 ha in the regions of Thiès and Louga (MEDD 2001). In 2006, SOS Sahel launched a project to plant one million trees against desertification in the regions of Louga and Thiès. The objective was to renew the aging filaos that protect the agricultural basin and fragile ecosystem of the Niayes. The result in 2009 is the maintenance of 8 ha of dunes stabilized by the reforestation of 8.330 filaos. Reforestation continues through an integrated reforestation program. In 2011, in the Thiès region, ISRA was working with local people on a forest regeneration project to broaden the genetic basis of the filaos. In the Dakar region, there was a virtual absence of reforestation between 1986 and 2010 (Ndoa, 2012; Quensière et al. 2013).

1.5 Adaptation measures base on communities' perception

To get the point of view of respondents about the adaptation measures. 661 out of 700 respondents argued that plant-covered dunes prevent beach erosion because their roots hold the sand that is washed away by storms and help build up sand reserves. 341 out of 700 respondents argue that dyke construction offers limited protection to constructions along the coast and may increase the effects of coastal erosion elsewhere. For more details on the questionnaire addressed to local communities (see the annex).

Being among the developing countries, Senegal has not enough meant to fight against coastal erosion. Therefore, the Dakar region is challenged by coastal erosion management because of its expensiveness. According to the local communities, the biggest challenges facing coastal erosion management are limited financial resources; lack of political will; lack of support; lack of scientific understanding; climate change; lack of participation of local communities; lack of awareness; extensive urbanization and pollution (Figure 51). Respondents have seen the government of Senegal as the main one responsible for managing coastal erosion, and the participation of local authorities and communities is crucial.

The figure 51 is about the challenges of coastal erosion management in the Dakar region according to local communities.



Source: Field survey

Figure 51: Challenges of coastal erosion management in the Dakar region according to local communities

II. Institutional, Political, legislative and law framework in climate change and coastal erosion management in Senegal

II.1 The institutional framework of climate change in Senegal

Institutionally, the issue of climate change is managed in Senegal by the Ministère de l'Environnement et du Développement Durable (MEDD). Previously called the Ministère de l'Environnement et de la Protection de la Nature (MEPN), the mandate and competencies of this ministry have remained relatively stable since the early 1990s. Its mandate is to implement the government's policy on ecology, environmental monitoring and protection, fauna, and flora, as well as in the field of retention basins and aquaculture. Within this framework, it is in charge of pollution and waste management, national parks, and other protected areas. It prepares and applies legislation and regulations on hunting. It ensures aquaculture development in conjunction with the Ministries of Fisheries and Agriculture. It works on the development of eco-tourism. It is in charge of the fight against desertification and the development of environmental education. It manages the mechanism for monitoring climate change and environmental trends. Finally, it represents Senegal in international meetings on environmental protection, sustainable development, climate, and biodiversity.

Recognizing the multi-sectoral dimension of the climate problem, the Senegalese government launched the idea of a coordinating body in 1994 by creating the Comité National sur les Changements Climatiques (COMNACC). It was set up in 2003 following a decree by the Ministère de l'Environnement et de la Protection de la Nature. However, it was not until the decree of 2011 (Decree n°2011-1689 of 3 October 2011) that a fundamental institutional framework for this committee appeared. Placed under the authority of MEPN, the COMNACC's mission is to coordinate, consult, train, raise awareness and monitor the various activities identified in the framework of the implementation of the United Nations Framework Convention on Climate Change (UNFCCC). It brings together representatives of all State ministries, sectors of activity, universities and research centers, associations, and local elected representatives. It comprises three thematic sub-groups: mitigation, adaptation, and financing.

Among the stakeholders of the COMNACC, the National Platform for Science-Policy Dialogue for the Adaptation of Agriculture and Food Security to Climate Change should be highlighted. This platform is responsible for the synergy of actions between the key national actors involved in the orientation and the necessary political decision-making for climate change plans and strategies.

In addition, the Ministry of Environment and Sustainable Development created a Climate Change Division in the 2000s within the Direction de l'Environnement et des Établissements Classés (DEEC). This division, consisting of a team of about ten people, is divided between the adaptation and mitigation aspects of climate action. It should be noted that the DEEC is the Designated National Authority (DNA) for the Clean Development Mechanism (CDM), the Adaptation Fund (AF), and the Green Climate Fund (GCF). Within the MEDD, another structure should be considered, namely the Centre de Suivi Ecologique (CSE). The CEM is a public utility association under the supervision of the MEDD. In addition to its competencies in environmental monitoring, it plays a fundamental role in access to climate finance by being the national implementing entity of the Adaptation Fund (AF) and the Green Climate Fund (GCF) for micro-projects only.

Finally, the National Agency for Civil Aviation and Meteorology (ANACIM) completes the picture of institutional actors. On the one hand, ANACIM is the focal point of the Intergovernmental Panel on Climate Change (IPCC). However, on the other hand, it is in charge of producing climate information: weather forecasts and medium and long-term climate projections. Consequently, it is a critical player in climate action in Senegal.

Created in 2002, the Centre National de Données et d’Informations Océanographiques du Sénégal (CNDOSN) is a tool for decision support and service to research, teaching and development and sustainable management of the marine and coastal area and resources of Senegal. It is supported by the Direction des Pêches Maritimes (DPM) and the Oceanographic Research Centre of Dakar-Thiaroye. (Centre National De Donnees Oceanographiques du Senegal - Centre National de Données Océanographiques n.d.).

II.2 Political framework for climate change and coastal erosion management in Senegal

With an economy strongly threatened by crisis, dependence on natural resources, and the impacts of climate change, Senegal has necessarily felt the need to engage in international climate policies to find appropriate solutions. In June 1992, it signed the United Nations Framework Convention on Climate Change (UNFCCC), ratified on 17 October 1994. The UNFCCC entered into force in January 1995. The first inventory of greenhouse gas emissions (GGE) was carried out in 1994 by the Ministry of the Environment. In 1997, the government of Senegal submitted its first national communication to the UNFCCC secretariat, entitled Senegal's Initial Communication under the UNFCCC. The communication highlighted the efforts the country intended to make in the context of the mitigation component and presented an initial vulnerability diagnosis. Following this communication, the Senegalese Ministry of the Environment voluntarily developed the National Implementation Strategy (NIS) of the UNFCCC in 1999 with the support of the Global Environment Facility (GEF) and the Netherlands Cooperation. The document shows the international community how Senegal intends to integrate the climate change dimension into its economic and social development policy. In 2006, Senegal produced its National Action Plan for Adaptation to Climate Change (NAPA) with technical support from the United Nations Environment Programme (UNEP) and financial support from the GEF. When the Adaptation Fund became operational in 2010, it was the first country to receive funding. It was also among the first African countries to file its second national communication with the UNFCCC Secretariat in 2010. In 2015, before COP 21 in Paris, Senegal submitted its Intended Nationally Determined Contribution (INDC) and its Third National Communication. Sectoral Nationally Determined Contributions (NDCs) were also developed to contribute to the national NDC.

Similarly, since 2015, the Senegalese government has developed its National Adaptation Plan (NAP) by developing a roadmap for its national process based on a sectoral approach. Thus, in 2016 the NAP for the fisheries sector was developed. A project to support the NAP is being implemented with German cooperation (Noblet et al. 2018).

The Senegalese government has started to consider climate change as a risk in its medium- and long-term development strategies and plans and in its sectoral plans. It has set up climate change coordination committees at national and regional levels (Zamudio and Terton 2016). Regarding climate policy documents, the analysis goes back to 1999 and the National Implementation Strategy (NIS), the first national climate strategy document. This document also marks the beginning of assessing the vulnerability to climate change of crucial sectors of the Senegalese economy. All documents produced following the NIS were then analyzed, including planning documents such as the National Action Plan for Adaptation to Climate Change (NAPA), national communications to the UNFCCC, and the most recent document to date, the Nationally Determined Expected Contribution (NDEC), as well as the sectoral Expected Contributions (EC). These reports have also contributed to coastal erosion management (Noblet et al. 2018).

Senegal's initial national communication updated an inventory from 1994 national data by Article 12 of the Convention on Climate Change, which is to provide a national inventory of anthropogenic emissions by sources and removals by sinks of all GHG. The communication also examines the problems related to the vulnerability of Senegal's coastal zones to climate change and its impacts on bio-geophysical and socio-economic systems. It shows that the Senegalese coastal zone is a vulnerable environment subject to various aggressions (erosion and drying of the coasts, salinization of waters, degradation of mangroves. The consequences of global warming, which would accelerate the rise in sea level, are likely to exacerbate the stresses on coastal areas. Moreover, as a place of high human and economic concentration, the coastal zone represents a strategic space. Hence the importance of conducting further in-depth studies and implementing a policy to mitigate possible impacts (MPN/DE 1997).

The National Implementation Strategy (NIS) of the United Nations Framework Convention on Climate Change (UNFCCC) is a document that allows member countries of the convention to show the international community how it intends to integrate the climate change dimension into its economic and social development policy. Unlike the National Communication (NC), the NIS is not an obligation to the UNFCCC but simply a tool for the country concerned to carry out international discussions on significant development issues. Therefore, the proposed framework includes action items, an implementation plan, a list of projects that would promote development in the face of climate change, and a forecast for monitoring the implementation of this NIS. The measures to promote sound economic and social development have been proposed for each sector. At the level of the coastal zone (fisheries and tourism), the significant measures to be taken concern the protection of the coast through reforestation and diking measures; the diversification of the tourism product by promoting eco-tourism and cultural tourism; the rehousing of populations in coastal areas whose coastline is affected by erosion; the development of aquaculture in the shallows and continental valleys to satisfy the demand for fish resources of populations not bordering the coast; the strategic dialogue with the private sector and the integrated management of the coast (CCNUCC 1999).

The National Action Plan for Adaptation to Climate Change has been implemented in a context where Senegal is a developing country and wants to face the impacts of climate change. In this context, there is a need to understand climate change better to develop measures to adapt to this vulnerability. It is in this context that Senegal, following the example of the international community, has developed its National Action Plan for Adaptation (NAPA), the objective of which is to carry out a participatory and integrated study and analysis of the vulnerability of the various regions to the negative impacts of climate change on critical sectors of the economy, namely water resources, agriculture, and coastal areas. Adaptation options were proposed for coastal protection. Among these options, we can note

- The development of the coastline towards the level of the Langue de Barbarie (Ghoxou mbath, Guet Ndar, Saint Louis hydrobase). The technical work of the "groin field" type: 2,800,000 FCFA/linear meter, coupled with a plantation of filaos for more durability, was recommended at this level.

- The exploitation of the sand of the continental shelf (0 to 200 m depth from the sea). This sand could be used for construction purposes and the artificial nourishment of beaches, particularly for tourism. Therefore, potential extraction areas and the modalities of sand extraction should be studied, particularly for the sand at sea.

- Reduction of erosion at the level of the Sangomar spit: a plantation of filaos on the barrier beach, over a length of 10 km (between Djifère and Palmarin) and an average width of 100 m; development works accompanying this filao wall. The feasibility studies have to be carried out to determine the structures' sedimentary flows and currents and the design parameters.

- A method for fixing the dunes in the Niayes area has been proposed and aims to stabilize the coastal dunes to preserve a sedimentary stock that can be mobilized in the event of coastal erosion. There are various methods, including the use of either wooden panels or vegetation, both of which aim to fix the sand.

- The restoration of mangroves has been proposed for the Petite Côte on an area of 500 ha of mangrove per year for five (5) years and the promotion of energy-saving wood techniques.

- An awareness and information campaign on the problems caused by the uncontrolled extraction of marine sand and on the possibility of using other types of sand, notably continental sand, as an alternative in construction; a support fund for the reconversion of fraudulent beach sand extractors and the monitoring of fraudulent exploitation of marine sand (MEPN 2006).

A management scheme has been implemented that meets the management needs of West African coastal areas in general and Senegal in particular. The set of strategic orientations and recommendations resulting from this plan constitutes a platform for adaptation to the effects of climate change in coastal areas. For coastal risk reduction, four main points have been proposed: governance of coastal risks through protection and impact mitigation; the watch and vigilance program with knowledge of hazards, vulnerability, and coastal risk assessment; communication, capacity building, and preparation of populations and decision makers (UEMOA 2010).

The Second National Communication defines a national adaptation strategy for the coastal zone. This strategy is based on fundamental principles and must be consistent with the country's current strategic policies (Poverty Reduction, Accelerated Growth Strategy, Disaster Risk Reduction, and National Action Plan for Adaptation). It must also be in harmony with the sectoral policies of the various institutional structures that share the coastline management. Furthermore, it must be in line with the development plans of coastal communities. Furthermore, the expectations of coastal populations regarding socio-economic development must inspire it. Finally, it must be validated regarding technical standards and environmental approaches. The overall objective of the strategy is the integration of the various aspects of sustainable management of the coastal Environment in a development plan that respects both the analytical data and the concerns of perspective development and prevention of coastal erosion. The specific objectives are the implementation of a master plan for coastal development; the adoption of a law on the coastline; the assurance of institutional coherence in coastal management; the control of the phenomenon of coastal erosion through research/development activities; the establishment of a coastal observatory; the construction of diversified works adapted to the local context; the strengthening of capacities for monitoring works. The accompanying measures to be implemented are to find and promote alternatives to sea sand in construction, with the exploitation of dune sand, recycling of demolition rubble, and pumping of sea sand; Develop a capacity building plan on coastal erosion; Develop an advocacy and communication plan on coastal erosion (MEPN/DEEC 2010).

The 2013-2017 Strategy advocates sustainable development that integrates the management of natural resources. The aim is to preserve and maintain them while guaranteeing equitable access for the population. The increasing air and water pollution in cities is a sign that what is often perceived as progress can be a source of deterioration in the quality of life, particularly for vulnerable groups. Integrating the issue of sustainable development calls for prioritizing environmental impact at all local and sectoral planning levels. To this end, the Environment and natural resources sub-sector are pursuing policies and strategies to be implemented through the following strategic objectives.

- Mitigate the effects of climate change on ecosystems through the promotion of the preservation and management of natural resources by local communities, the development of community forests and the rational management of forest resources, the fight against bushfires, deforestation, and land degradation, the ecological management of chemical products and waste, the fight against coastal erosion and the systematization of prior environmental assessments;
- Strengthen environmental and natural resource management capacities with the promotion of environmental education, the production and dissemination of information on the state of

the Environment and natural resources, and capacity building for environmental actors;

- Promote the green economy and the creation of green jobs;
- Making rural ecosystems less vulnerable to the effects of climate change through the development of agro-silvopastoral activities, the promotion of private investment, and the fight against air and water pollution (Ipar 2012).

The project's main objective, "Establishment of an integrated coastal zone management plan in Senegal (ICZM)," is to support the Government of Senegal in preparing an integrated coastal zone management plan that considers the challenges posed by coastal erosion and adaptation to climate change. With a provision of 4 million euros (2.6 billion CFA francs), the project also includes a provision for pilot actions that, on the one hand, initiated the implementation of activities retained in the ICZM plans and, on the other hand, contribute to consolidating the institutional consultation mechanisms, which are the only way to ensure the long-term sustainability of the management of the coastal territory and its resources. The results produced are the setting up of a coastal monitoring tool (Geographic Information System - GIS) allowing the coastline to be mapped, its evolution to be monitored, and which can be used as a basis for the constitution of an alert tool, including the production of 5 cartographic atlases; the analysis of the legal and institutional framework in the perspective of integrated coastal management; the national strategy for integrated coastal zone management for Senegal, together with four integrated management plans for the pilot sites: Saint Louis, Dakar, Mbour and Diogué (MEDD 2013).

Following a request from the Senegalese government through the Ministry of the Environment for an economic and spatial study of the vulnerability and adaptation of coastal zones to climate change, a study was carried out with the support of the Municipalities of the pilot sites (Saint Louis, Rufisque-Bargny and Saly), a technical committee (administrations and agencies concerned with coastal development monitored and guided the elaboration of the study) and the Centre de Suivi Ecologique (CSE). The study comprises four phases: methodology development; spatial vulnerability analysis; economic modeling and analysis of adaptation options; consolidated recommendations to inform the development of an integrated coastal zone management plan. The recommendations include the following:

- ➢ Streamlining of natural risk management procedures (substantial simplification of procedures and reduction in the number of institutional interlocutors;
- ➢ Reframing and implementation of reference texts: Coastal Law, National Programme

against Coastal Erosion, and NAPA;

- Establish or strengthen monitoring and early warning systems through a set of structural actions, to help improve preparedness and response potential at the national level;
- Establish a budgetary policy for adaptation to climate change, including new funding streams, additional economic and financial analysis, and production and operating account for each project;
- Monitor the evolution of the position of the Senegal River mouth with a view to a possible decision to recreate an artificial breach;
- Delimiting the Public Maritime Domain, to make the Coastal Law applicable;
- Reduce the vulnerability of buildings, equipment, and infrastructures in Saint-Louis: establish diagnoses, and make expensive equipment (individual and collective) watertight;
- Liberate certain low-lying areas of Saint-Louis that are illegally occupied with associated rehousing programs;
- Protection of the Langue de Barbarie against coastal erosion and marine submersion (groins, recharging, and reprofiling of the beach);
- Protection of Saly against coastal erosion and marine submersion (creation of artificial beaches);
- Reinforcement of existing coastal protection on Rufisque-Bargny and strategic retreat of the most exposed sectors (Egis International 2013).

With a growth rate close to that of the population, a weak private sector, limited access to social services, failure to achieve the Millennium Development Goals (MDGs), an inappropriate development policy, low GDP growth, and a sluggish economy, Senegal needs to find a new development model to accelerate its progress towards emergence. This strategy is the Plan Sénégal Émergent (PSE), the benchmark for economic and social policy in the medium and long term. Furthermore, to manage the adverse effects of climate change, particularly coastal erosion, Senegal intends to pursue the following strategic objectives: prevent and reduce significant disaster risks and improve natural disaster management. In the environmental sector, Senegal is committed to integrating the principles of sustainable development into national policies and reversing the trend of wasting environmental resources. In particular, it is pursuing the objective of reducing biodiversity loss. To this purpose, Senegal intended to pursue the following strategic sectoral objectives.

- Improve the knowledge base of the Environment and natural resources;

- Intensify the fight against the degradation of the Environment and natural resources in compliance with the relevant conventions;

- Strengthen the institutional and technical capacities of actors in the implementation of environmental and natural resource conservation actions;

- Encourage the development of natural resources following the example of the initiatives underway in the Bandia reserve in Mbour and Fatala in Saloum; and

- Preserve biosphere reserves (parks, nature reserves), promote a green economy, and capture funding for green jobs (Republique du Senegal 2014).

This advocacy helped to update the characteristics of the coastal dynamics on the Senegalese coast between Malika and Djiffère. The studies confirm the regressive trend of the different coastlines, already noted in previous studies. They also highlight the strong dynamics of the Senegalese coastline and its vulnerability to poorly controlled risks due to a lack of knowledge or, at least, imperfectly known and controlled. This technical report presents the state of vulnerability of the Senegalese coastline and proposes adaptation measures to address the risks and vulnerabilities. The proposals made in this report take into account the results of previous studies, in particular, the "Economic and spatial study of the vulnerability and adaptation of coastal zones to climate change in Senegal: main lessons learned" and those carried out as part of the project "Establishment of an integrated coastal zone management plan in Senegal." Measures to prevent coastline retreat and marine submersion have been proposed. They aim to: improve knowledge of the phenomenon, the hazard, and issues related to erosion or marine submersion, monitor, prevent and alert, educate and inform, take risks into account in planning and urban development, reduce vulnerability at the level of the issues at stake, set up collective protection systems, prepare for crises (SenGEO, 2015).

The objectives of the third communication are: to strengthen the capacities of local actors to better take into account climate change in local planning; to analyze the evolution of eco-geographic zones (strongly impacted by climate change); to strengthen the climate observation system; to take into account climate change in public procurement, and to strengthen the implementation of emission trading mechanisms. It is based on data and results produced by the National Agency for Statistics and Demography (ANSD), ANACIM, the Africa Rice Center, and the Senegalese Institute for Agricultural Research (ISRA) and derived from the

Stratégie Nationale de Développement Economique et Social (SNDES). It also used the results of the study by Gaye and Sylla (2008) to assess the status of future climate trends. For the coastal zone, only one new reference appears: the coastline monitoring study carried out by the Mission d'Observation du Littoral Ouest Africain (MOLOA) in 2010. However, this study mainly takes stock of the coastline but needs to consider the future impact of climate change on the Senegalese coastline. Three sites considered highly vulnerable were targeted for this study. Saint Louis, Rufisque-Bargny, and Saly Portudal sites have recently been the subject of interventions to combat coastal erosion. The objective of this choice is to report on the implementation of the policy of adaptation of the coastal zone to climate change since the last national communication. The third communication should have resorted to scientific publications in A-ranked journals, as did the NAPA. The second communication presented the vulnerability and impacts of climate change but relied mainly on existing scientific productions (MEDD, DEEC, 2015).

Senegal's Nationally Determined Expected Contribution is part of its development strategy, the Plan Sénégal Émergent (PSE), and its sectoral programs for the sustainable management of its natural and environmental resources. A team of local consultants developed it under the supervision of the Directorate of Environment and Classified Establishments (DEEC) and the Ministry of Environment and Sustainable Development in collaboration with the National Committee on Climate Change (COMNACC) based on a participatory and inclusive process. Adaptation to climate change, beyond the development of the CPDN, is a national concern. Senegal's ambition is to integrate adaptation to climate change in the formulation and programming of development policies to ensure a controlled trajectory of growth objectives. For the adaptation options, sectoral objectives for Senegal for the period 2016-2035 have been defined. For the management of the coastal zone, we can note the following:

- The establishment and support of a coastal observatory;

- The protection of vulnerable areas and the relocation of vulnerable populations;

- Scientific and technical studies on restoring threatened coastal ecosystems (MEDD, 2015).

Reducing the degradation of the Environment and natural resources, the adverse effects of climate change and the loss of biodiversity is the first specific objective of the Environment and Sustainable Development sector policy letter and contributes to reversing the trend of degradation of natural resources and the Environment to provide multiple services and benefits including the conservation of biodiversity, the fight against coastal erosion and the invasion of aquatic plants, the promotion of more intensive and sustainable agro-silvopastoral production, the sustainable exploitation of natural resources including biomass and ligneous and non-ligneous products, the promotion of actions to fight against the adverse effects of climate change and the reinforcement of environmental education actions.

To achieve this objective, three programs have been implemented:

- Combating deforestation and land degradation to ensure the restoration and sustainable management of land; promotion of land rehabilitation initiatives in areas subject to migration; implementation of a reforestation and revegetation program for degraded areas; reduction in the frequency and extent of bushfires; reduction in the degradation of forest resources; promotion of forest management; development of value chains for non-timber forest products.

- Biodiversity conservation and management of protected areas to improve the state of conservation of marine, coastal and terrestrial ecosystems; slow down the erosion of biological diversity; improve the implementation of the land-use policy; update the legal and institutional framework for biosafety; improve the management of wetlands, particularly by combating the invasion of water bodies by aquatic plants.

- Fight against pollution, nuisances, and the harmful effects of climate change to fight against coastal and river erosion; improve the management of chemicals such as mercury and hazardous waste; significantly strengthen actions for assessment, environmental education, and monitoring of air and water quality. Moreover, implement measures for adaptation and mitigation of the harmful effects of climate change. (MEDD 2016).

The coastal zone NDCs is based on future climate trends on the work conducted by ANACIM in the Contribution Prévue Déterminée Nationale (CPDN) framework. Sea level rise projections refer to the 4^{th} IPCC report (2007). The NDC also used the work mobilized in the NAPA and the Second Communication and published in the A-ranked journals (e.g., Emery and Aubrey, 1991; Dennis et al. 1995). To characterize the evolution of the coastline, the paper draws on a large body of scientific work (some of which has been published in scientific journals) carried out in the sub-region between 1985 and 2010, including the recent work of MOLOA, which has already been used in the CPDN. In addition, to characterize the swells and winds, the NDC mobilizes various works (internship report, doctoral thesis, laboratory report, and scientific publications) carried out between 1968 and 2007. The results of some doctoral and master's level research were also used. Overall, the NDC presents a characterization of the Senegalese coasts and the meteorological and oceanic parameters and is, therefore, mainly a presentation of the current vulnerability of the Senegalese coastal zone. Future climate trends and future projections of sea level rise are considered, including some indications of increased extreme events and impacts in terms of marine submersion (Noblet et al. 2018).

Among the objectives of Senegal's nationally determined contribution, increasing the resilience of ecosystems and populations to the impacts of climate variability and change figures prominently. Priority adaptation measures in coastal areas have been proposed according to the impacts of current (2°C scenarios) and future (4°C scenarios). The priority adaptation measures according to current impacts (2°C scenarios) are summarized as follows:

- Integrated Coastal Zone Management (implementation of a coastal monitoring system, identification of forcing factors and physical processes that govern the functioning and dynamics of the coastline, updating of the legal and institutional framework of the coastline, morpho dynamic modeling of the coastal zone, identification of the main coastal risks and risk areas, and planning of coastal occupation.)
- Protection and development of risk areas and restoration of degraded coastal ecosystems
- Identification of adaptation issues
- Regulation of coastal occupation.

For the priority adaptation measures according to current impacts (2°C scenarios), we can note

- Knowledge of the swell climate and its modeling;
- Identification of areas at risk in the event of a rise in sea level;
- Analysis of coastal risks and the vulnerability of infrastructures and populations;
- Regulation of coastal occupation (République du Sénégal 2020).

II.3 Legislative framework for coastal and marine environment management

Senegal has ratified several international conventions to provide a solid basis for its coastal and marine environment management and protection policy. Among these conventions, we can note the following:

Being aware of their fundamental ecological functions, resources of great economic, cultural, scientific, and recreational value, and the desire to curb their progressive encroachment, states are convinced that the protection of these areas would be of capital importance for the economy and the Environment, hence the creation of the Ramsar Convention on 2 February 1971, which came into force on 21 December 1975. The convention defines wetlands in its article 1 as areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters. Each Contracting Party shall designate suitable wetlands in its territory for inclusion in the List of Wetlands of International Importance. Furthermore, the Contracting Parties shall formulate and implement their planning to promote the conservation of the listed wetlands and, as far as possible, the wise use of wetlands in their territory (UN, 1976). Consequently, as early as the 1970s, Senegal began to protect its wetlands by establishing protected areas (Djoudj National Bird Park in 1971, the Saloum Delta National Parks in 1976, the Madeleines island and the Langue de Barbarie) (Wetlands 1998). It should be noted that this convention applies to all marine shores (UEMOA 2010).

The United Nations General Assembly resolution 2997 of 15 December 1972 (on institutional and financial arrangements for international cooperation in the field of the environment) (UN 2013) with the creation of the Governing Council of the United Nations Environment Programme, which convened in Abidjan from 26 to 23 March 1981 a conference of plenipotentiaries on cooperation in the protection and enhancement of the marine environment and coastal zones in West and Central Africa as well as two legal instruments: The Convention on Cooperation in the Protection and Development of the Marine Environment and Coastal Areas; the Protocol concerning Cooperation in Combating Pollution in Cases of Emergency. The Convention is an agreement that aims to protect and manage the signatory countries' coastal zone and marine environments. It is the primary text for protecting the marine environment in West Africa. It lists the sources of pollution that must be controlled and define the aspects of environmental management: coastal erosion, pollution control, and environmental impact assessment (PNUE 1981). Senegal ratified the Abidjan Convention and the Protocol concerning cooperation in combating marine pollution on 5 June 1984. To implement this Convention, Senegal has developed the National Plan for the Fight against Marine Pollution (POLMAR) and periodic reports on the state of the marine and coastal environment (UEMOA 2010).

After the Law of the Sea conferences of 1959 and 1960 in Geneva, the signatory states felt the need to establish a legal order for the seas and oceans. This order facilitates international communication and promotes the peaceful use of the seas and oceans efficiently and equitably as well as their resources, the conservation of the marine environment with a new Convention on the Law of the Sea concluded in Montego Bay on 10 December 1982 and entered into force on 16 November 1994. This Convention, which defines the competencies of the State of Senegal in its territorial sea, continental shelf, and contiguous zone, was ratified on 25 October 1984 by the State of Senegal (UN, 1994).

With the adverse effects of climate change on the planet, the United Nations established a United Nations Convention on Climate Change in 1992. For the proper management of coastal issues, provisions were made in General Assembly resolution 44/206 of 22 December 1989 on the possible adverse effects of sea-level rise on islands and coastal areas, particularly low-lying coastal areas (UN, 1992). All parties shall cooperatively prepare for adaptation to the impact of climate change and develop appropriate and integrated plans for coastal zone management (UN, 1992). Senegal ratified the Convention in May 1994. For the Implementation of the Convention, projects are likely to promote development in the perspective of climate change through the National Implementation Strategy (NIS) and the National Action Plan for Adaptation (NAPA) to climate change in several sectors, including the coastal zone (UEMOA, 2010).

Environmental issues have always been an important issue in international debates. In this section, an attempt has been made to see what the different millennium and sustainable development goals have been that concern coastal erosion management and the efforts that the government of Senegal has made to achieve these goals.

In September 2000, the Heads of State and Governments of 191 countries, as well as the significant international cooperation institutions, adopted the "Millennium Declaration," which emphasizes an international partnership driven by a shared vision of sustainable human development. The goals were:

1- Eradicate poverty and hunger;

2- Achieving universal primary education;

3- Promotion of gender equality and empowerment of women

4- Reducing child mortality;

5- Improving maternal health;

6- Combating HIV/AIDS, malaria, and other diseases;

7- Ensuring environmental sustainability;

8- Developing a global partnership for development.

In the context of coastal erosion management, Goal 7, which focuses on ensuring environmental sustainability through the restoration of natural resources, combines actions of land reclamation, mass planting, and forest management. These actions have made it possible to improve the level of reforestation, which has been increasing since 2001. Indeed, the reforested areas have increased from 14.533 ha in 2001 to an average of nearly 30.000 ha per year since 2006 (MEF, 2010). In 2006, SOS Sahel launched a project to plant one million trees against desertification in the regions of Louga and Thiès. The objective was to renew the aging filaos that protect the agricultural basin and fragile ecosystem of the Niayes. The result in 2009 is the maintenance of 8 ha of dunes stabilized by the reforestation of 8.330 filaos. Reforestation continues through an integrated reforestation program. In 2011, in the Thiès region, ISRA was working with local people on a forest regeneration project to broaden the genetic basis of the filaos. In the Dakar region, there was a virtual absence of reforestation between 1986 and 2010 (Ndoa, 2012; Quensière et al. 2013).

At the third United Nations Conference on Financing for Development, held in July 2015 in Addis Ababa, the international community committed itself, in a new agenda setting out the Sustainable Development Goals (SDGs), to achieving the international development goals by 2030. The UN adopted the agenda in September 2015. To achieve these goals, an organizational framework and reforms at the national and international levels must be put in place to promote accelerated growth, improve equity and equality of opportunity and determine environmental sustainability. The seventeen (17) SDGs and their one hundred and sixty-nine (169) targets or sub-goals and nearly two hundred and forty (240) indicators form the core of the 2030 Agenda. These goals are:

1- Eradicate poverty in all its forms everywhere in the world.

2- Eradicate hunger, ensure food security, improve nutrition and promote sustainable agriculture.

3- Achieve health for all and promote well-being for all ages.

4- Ensure equitable, inclusive, quality education and lifelong learning opportunities.

5- Achieve gender equality and empower all women and girls.

6- Ensure access for all to sustainably managed water and sanitation services.

7- Ensure access to reliable, sustainable, and modern energy services at an affordable cost.

8- Promote sustained, shared, and sustainable economic growth, full and productive employment, and decent work.

9- Build resilient infrastructure, promote sustainable industrialization that benefits all, and encourages innovation.

10- Reduce inequalities within and between countries.

11- Make cities and human settlements inclusive, safe, resilient, and sustainable.

12- Establish sustainable consumption and production patterns.

13- Take urgent action to address climate change and its impacts.

14- Conserve and sustainably use the oceans and seas.

15- Preserve and restore terrestrial ecosystems and halt ozone depletion.

16- Promote peaceful and inclusive societies for sustainable development, ensure access to justice for all, and build effective, accountable, inclusive institutions at all levels.

17- Strengthen the means to implement the Global Partnership for Sustainable Development and revitalize it.

For the Sustainable Development Goals, two objectives 13 and 14 concerned the management of coastal erosion in Senegal. The Ministry of Environment and Sustainable Development (MEDD) is responsible for defining and implementing the targets at the national level. Taking into account the orientations of the PES and sectoral policies, the table 26 shows how targets 13 and 14 of the SDGs will be domesticated in Senegal (MEFP 2018).

Table 26: Senegal's targets for SDGs 13 and 14

SDGs		**NATIONAL TARGET**
N° SDGs	**N° TARGET**	**NATIONAL GOAL**

GOAL 13	**T13.1.**	Between 2016 and 2030, ensure the implementation of national and local strategies for disaster risk reduction.
	T13.2.	Between 2016 and 2030, systematize the integration of climate change measures into public policies, projects and programmes.
	T13.3.	Between 2016 and 2030, integrate climate change adaptation issues into their curricula and through awareness raising.
	T13. a.	Between 2016 and 2030, increase the volume of green finance, relative to the COP 21 Green Fund.
GOAL 14	**T14.1**	Sustainably manage and protect marine and coastal ecosystems, including by enhancing their resilience.
	T14.4.	Effectively regulate fisheries and put an end to overfishing and illegal fishing.
	T14.5.	Increase the preservation of marine and coastal areas.
	T14. b.	Guarantee access to marine resources and markets for small-scale fishermen.

Source: MEFP, 2018

To take urgent measures to combat climate change and its repercussions, sub-Saharan countries in general and Senegal, in particular, are subject to severe environmental constraints (global warming, desertification, degradation of plant cover, marine pollution, poor urban waste treatment, and coastal erosion). To address this worrying situation, the government has adopted a Letter of Policy for the Environment and Sustainable Development Sector (LPSEDD 2016-2020) and various implementation instruments to ensure that the sector contributes effectively to the fight against poverty and the improvement of the quality of life of the population. In 2003, the Senegalese government also set up a National Committee on Climate Change (NACOMCC), which brings together various structures (state and private). It serves as a framework for harmonizing the country's internal positions with its African peers during the various COPs on climate. In addition, Senegal ratified the Kyoto Protocol in 2001 and set up a Designated National Authority (DNA) for projects subscribed to the international carbon market. Furthermore, measures to reduce vulnerability have been taken in the wake of a national climate change policy, which is the reference framework for the various interventions. This political will is expressed through implementing climate change mitigation and adaptation instruments. These instruments include the National Sustainable Development Policy (NSDP) or National Climate Change Policy (NCCP), which aims to contribute to sustainable development and the fight against poverty through climate change adaptation and mitigation measures, and which aims to address urgent climate risks in three key sectors of the national economy that are vulnerable to climate change: agriculture, water resources, and coastal zones. This plan integrates both mitigation and adaptation activities. Mitigation involves contributing to the reduction of greenhouse gases through the promotion of low-carbon projects. Furthermore, for adaptation to the adverse effects of climate change in coastal areas, we can cite the Implementation of the NAPA programs and priority projects such as the Adaptation to Climate Change in Coastal Areas in West Africa (ACCC) program, which aims to develop replicable tools for the adaptation of coastal communities to climate change; the Integrated Coastal Zone Management Project: Study of Coastal Zones: In-depth Study and Practical Actions to Combat and Adapt to Climate Change; the Project on Adaptation to Coastal Erosion in Vulnerable Areas (MEFP, 2018).

For the conservation and sustainable use of the oceans and seas to prevent pollution and increase economic benefits for small island states and developing countries. The targets of SDG 14 are in line with the orientations set out in the Environment and Fisheries sector policy letters. These sector policy letters focus on biodiversity conservation, protected area management, and combating pollution, nuisance, and the adverse effects of climate change. The national objectives of Goal 14 include the sustainable management and protection of marine and coastal ecosystems, in particular by strengthening their resilience, avoiding the severe consequences of their degradation, and taking measures for their restoration to restore the health and productivity of the oceans. In addition, the State of Senegal is pursuing the Integrated Coastal Zone Management (ICZM) program and is seeking to expand and consolidate it. The various activities, such as the monitoring and mapping of mangrove and filao plantations in the ICZM project pilot sites (Saint-Louis, Petite Côte, Casamance); the development of the Thiawlène dyke promenade to consolidate it; the study of the morpho-sedimentary evolution of the Pilot

Barre beach and the Langue de Barbarie; the extension of ICZM to the Saloum islands with the development of two local plans; the consolidation of the GIS unit to ensure information sharing with all coastal stakeholders; the marking of the Saly breakwaters to secure navigability (MEFP, 2018). To achieve this target, additional efforts are needed, especially with the difficulties related to the advancing sea. In a report, the World Bank concluded that 25% of the coastline is at high risk of coastal erosion due to rising sea levels and flooding caused by marine storms. It also warns that uncontrolled urbanization and sand extraction would increase this rate to 75% by 2080. Thus, the cost of rising sea levels and coastal erosion in the targeted sites (Saint-Louis, Rufisque-Bargny, and Saly, Mbour) is estimated at 1.500 billion FCFA francs. The cost of coastal erosion and marine submersion is estimated at 344 billion FCFA francs. The cost of coastal flooding beyond Saint-Louis, mainly due to flooding, is estimated at 389 billion FCFA francs. In addition, the net present cost of flooding in this city is 818 billion FCFA and represents more than half of the total estimated damage (MEFP, 2018).

Nevertheless, major coherence problems in marine and coastal conservation policy are also noted (Bonnin et al. 2016). On the one hand, these problems are linked to the conflicts of competence noted between the MEDD and the MPEM on the mechanisms and strategies for conserving marine and coastal ecosystems and the sustainable management of fisheries resources. On the other hand, a lack of financial and technical resources is an obstacle to achieving target 14.5 on preserving at least 10% of marine and coastal areas by national and international Law and considering the best available scientific information. As planned in the PES, the synergy of action in public policies for sustainable development must be perceptible (Nassirou 2018).

II.4 Law framework in coastal erosion management in Senegal

Senegal, like all countries, is governed by laws, especially about protecting and managing the environment and natural resources. Regarding coastal erosion management, repressive and preventive laws are designed to counter abuses and damage to the coastal environment. These laws are:

- **Public and maritime domains regulation**

- Law n°76-66 of 2 July 1976 defines the natural public domain with the shores of the sea and the artificial public domain with the numerous urban infrastructures built or planned. This Law is completed by the Merchant Navy Code (Law n°2002-22 of 16 August 2002), which defines the maritime public domain. Nevertheless, this text suffers from ambiguities concerning the determination of the physical limits of the maritime public domain with the imprecision in the definition of the level of the highest tides and the modalities of occupation and exploitation of this zone which are defined by the state but with the possibility of declassifying portions of the maritime public domain. Indeed, the public maritime domain is declassified to accommodate housing estates or buildings intended for economic activities such as tourism. Thus, in a large part of the Dakar region and the Petite Côte, the public maritime domain has been reduced to 30 meters wide from the limit reached by the highest tides instead of the 100 meters defined by the Law (UEMOA, 2010). No one can therefore acquire land on these lands. In theory, only temporary occupation with simple and dismantled installations can be permitted, for which Law N° 83-05 of 28 January 1983 of the Environmental Code specifies that they must 'neither be a source of erosion nor degradation of the site .'This Law is, however, poorly respected in practice, particularly by touristic complexes. This can also be explained by the importance of the tourism sector, which is Senegal's second largest source of income after fishing. Some parliamentarians and associations such as SOS Littoral have called for the demolition of these private (often foreign) establishments authorized by the abusive use of Law No. 19 of the State Property Code, which allows to declassify land from the public domain (Weissenberger et al. 2016).

- **Marine and coastal environmental protection**

- The provisions of Law N°2001-01 of 15 January 2001 on the Environment Code and its implementing Decree N°2001-282 of 12 April 2001 constitute the fundamental legislative and regulatory framework governing activities with environmental impacts. On 4 November 2004, marine protected areas were created by Decree N° 2004-1408 following the recommendation of the Durban Congress on National Parks held in September 2003. It was noted that most of the protection efforts carried out until then concerned continental ecosystems. In this context, states focused on protecting at least 5% of their coastal and marine areas to strengthen integrated marine and coastal area management regimes. Then, the marine protected areas of Saint Louis, Kayar, Joal-Fadiouth, Abene, and Bamboung were created (Bonnin et al. 2016).

- **Mining underground resources regulation**

- Law n° 88-06 of 26 August 1988 on the Mining Code stipulates in Article 3 that ‘all useful mineral substances contained in the subsoil of the Republic of Senegal are the property of the

State' and Law nº 98-03 of 8 January 1998 and Decree Nº 98-164 of 20 February 1998 regulate mining, including sand extraction. Decree nº 89-907 of 5 August 1989, setting out the modalities for its application, was replaced by Law Nº 2003-36 of 24 November 2003 on this Mining Code. However, criminal sanctions are foreseen for all those who do not respect them. For example, for the extraction of marine sand, fines are foreseen: 75.000 FCFA for carts and 150.000 FCFA for vehicles to 15 days in prison (Adjoussi, 2001).

- **Coastal and marine pollution regulation**

In 2001, a standard was defined for wastewater management and the regulation of discharge conditions. Water pollution is defined as any discharge, flow, direct or indirect deposit of water or materials, and generally, any act that may alter the quality of surface, ground, or marine waters. The standard applies to wastewater discharges within the country's territorial limits to receiving environments such as surface, ground, or marine waters. Any discharge of liquid effluents causing stagnation, inconvenience to the neighborhood, pollution of surface, ground, or marine waters, and discharges of hydrocarbons or other toxic chemicals from ships or other means of transport and through pipelines is prohibited throughout the country. Special protection zones, such as the Bay of Hann and certain enclosed seas where discharge levels are restrictive, are subject to special protection and discharges if not prohibited. These zones are subject to a memorandum of understanding between the operator of the facility generating the discharge according to Article 2 of the standard. The standard also provides for sanctions according to Article 7, which stipulates that 'all violations of the normative provisions contained in standard NS 05-061, cited above, are subject to sanctions defined in Articles L96, L97, L98, L100 of Law No. 2001-01 of 15 January 2001, on the Environmental Code referred to above and in Article L51 of Decree No. 2001-282 on the application of the Environmental Code' (DEEC 2001). As far as the police force on seawater pollution is concerned, it is governed by Book II of Law Nº 2002-22 of 16 August 2002 on the Merchant Navy Code. The purpose of these various provisions is to protect seawater against any pollution, and to satisfy or reconcile, during the various uses, activities, or works, the requirements of health, public health, civil security, fisheries, marine cultures, industry, transport, tourism, leisure and water sports as well as all other human activities legally carried out. The introduction into the marine environment of substances or energies defined in Article 1 of this Code is prohibited by Article 577 of the Merchant Shipping Code (Bonnin et al. 2016). As regards the deposit of waste on beaches, the hygiene code stipulates in article L.20 that it is forbidden to deposit on the public highway, to throw into ponds, rivers, lakes, seas, or on the shores, to bury in a general way at less than 35 m from the perimeter of protection of springs, as well as water catchment and supply works, animal corpses, and household waste. The hygiene code has defined beach hygiene rules. Article L.27 underlines that are abandoning any object likely to alter the place's cleanliness on the beaches is forbidden, notably cans, fish, or rubbish. Article L.28 prohibits access to dogs, even if they are on a lead, to cattle and all other animals. Article L.29 prohibits the circulation of animals, animal-drawn vehicles, automobiles, moto bikes, and bicycles on the beach (*1-Loi N° 83.71 Du 05 Juillet 1983 Portant Code de l'hygiène | Ministère de la Santé et de l'Action Sociale*, n.d.). Concerning pollution by incineration at sea, Article 594 defines incineration in the marine environment as any deliberate combustion of waste, substances, products, or materials shipped for disposal from a ship or a fixed artificial structure. Incineration is prohibited at sea by Article 595 ("Law Nº 2002-22 of 16 August 2002 on the Merchant Navy Code" n.d.).

III. Recommendations for adaptation strategies to coastal erosion

Despite the Senegalese government's efforts to fight against coastal erosion, the coastline is still retreating. Therefore, in this study, some recommendations to empower adaptation strategies for better resilience were pointed out: Empowerment of capacity building of institutions, Empowerment of existing early warning systems, Local communities' involvement in coastal management, empowering economic actors by funding and equipment supply, Implementation of new relocation policies for affected communities and raising public awareness about climate change and coastal erosion impacts.

III.1 Empowerment of capacity building of institutions

In a study, Flaspohler et al. (2008) defined capacity building as an enhancement of an organization's infrastructure, skills, and motivation. General capacity building may take place in conjunction with support for the Implementation of a specific innovation, or as a separate activity not associated with dissemination activities. It involves the transfer of competencies necessary for community groups or individuals to identify their issues and address their concerns (Suarez-Balcazar et al. 2008). The institution which is in charge of coastal management in Senegal is the Division de l'Environnement des Etablissements Classés. It is under the supervision of the Ministère de l'Evironement et du Développement Durable. It is responsible for implementing the government's environmental policy, including protecting nature and people against pollution and nuisances. This institution's empowerment in the capacity building would be helpful in coastal erosion management. It can be effective with the enhancement of both infrastructures and knowledge. To enhance coastal management skills, the Senegalese government should encourage education in the areas such as Oceanography and coastal engineering. In addition, the Senegalese government should increase the budget of the ministry of environment. It should also encourage international organizations and NGOs to support the environmental policies of Senegal.

III.2 Empowerment of existing early warning systems

In terms of early warning systems, the Senegalese government makes several efforts through the Agence National de l'Aviation Civile et de la Météorologie (ANACIM). It provides information on daily tide levels and prevents fishermen from eventual perturbation of the sea, such as storm surges. Nevertheless, this is not enough. Early warning systems should be effective by installing equipment such as tide and wind gauges along the Senegalese coasts. In addition, public information programs should be developed through the frequency of weather forecasts and information for local communities about probable damages, such as storm surges and the perturbation of hydrodynamic agents.

III.3 Local communities' involvement in coastal management

The involvement of local communities in coastal management should be beneficial for coastal management. Teams of managers for coastal cleanliness and word-of-mouth communication on the dangers of coastal erosion should be set up in each district municipality. A specific budget for coastal management in district municipalities should be the plan. Focus group discussions about how economic actors such as fishermen and hotel keepers should participate in coastal management, should be organized frequently.

III.4 Empowering economic actors by funding and equipment supply

Empowering economic actors by funding equipment supply will be helpful for economic actors such as fishermen and hotel keepers. It allows them to strengthen their adaptative capacity to the impacts of coastal erosion on fishery and recreational activities (rarity of fishing products, destruction of fishing and tourism infrastructures, low incomes, reconversion of fishermen and hotel keepers to other economic activities).

III.5 Implementation of new relocation policies for affected communities

The Implementation of new relocation policies will be helpful for affected people. It can allow new planning and installation of new amenities, which will be more resistant to the effects of hydrodynamic agents.

III.6 Raising public awareness about climate change and coastal erosion impacts

In coping with the impacts of climate change on the coast, specific parameters must be taken into account: the installation of protective structures if necessary; raising people's awareness of climate change, its causes, and impacts on the environment (variations in rainfall cycles, their duration, and intensity, the advance of the sea with marine invasion phenomena); the development and Implementation of education, information and communication strategies; the strengthening of technical and scientific meetings and reflections on specific sectors, in particular, the agriculture, water, fisheries, tourism and health sectors; the adaptation of the scientific information provided by the Intergovernmental Panel on Climate Change to the context of the actors concerned; the integration of an adaptation strategy to climate change in Senegal's sectoral development policies (MEPN 2006). In addition, local communities along the coast should be aware of the impacts of coastal erosion and marine pollution. Team managers for coastal cleanliness and word-of-mouth communication on the dangers of coastal erosion should be set up in each district municipality.

Partial conclusion

To sum up, in terms of coastal erosion management, the protection against coastal erosion of the Senegalese coasts is materialized by several means: protective walls, groin fields, reforestation, dykes, riprap, and breakwaters. In addition, the Senegalese government has ratified some international conventions for providing coastal and marine environment management and protection policies. Among these conventions, we can note: the Ramsar Convention, Abidjan Convention, United Nations Convention on the Law of the Sea, United Nations Framework Convention on Climate Change, Millennium Development Goals, and Sustainable Development Goals. Laws for protecting and managing the environment and natural resources were defined to counter abuses and damage to the coastal environment. These laws are public and maritime domain regulation, marine and coastal environmental protection, mining underground resources regulation, and coastal marine pollution regulation. However, despite the Senegalese government's efforts to fight against coastal erosion, the coastline is still retreating. Therefore, some recommendations to empower adaptation strategies for better resilience were pointed out: Empowerment of capacity building of institutions, Empowerment of existing early warning systems, Local communities' involvement in coastal management, empowering economic actors by funding and equipment supply, Implementation of new relocation policies for affected communities and raising public awareness about climate change and coastal erosion impacts.

GENERAL CONCLUSION

In summary, the growth of temperature cause by global warming cause the ice melting from the hydrosphere and cryosphere. It also causes the dilatation of seawater, leading most coastal areas to a coastline retreat through the rising sea level. This sea-level rise, combined with the climate characteristics and effects of hydrodynamic agents such as tide, wave, swell, the current, wind, and their irregularity, generates coastal erosion. This erosion is accentuated by geological, geomorphological, biological, climatic, and anthropogenic conditions.

The coasts of the Dakar region are composed of the northern, western, and southern coasts. The shapes of these different coasts are linked to geology, hydrodynamic, climatic, and morpho-pedological conditions. Three different activities determine the geologic history of the Dakar region: volcanic activities, marine transgressions, and regressions observed from the pre-quaternary period up to the quaternary period in the Dakar region. Significant faults mark this geology. The region has a Canarian climate influenced by geographical and atmospheric conditions. It is crossed by the maritime trade winds from the Azores anticyclone from the North to North-East sector. It is a fresh, moist wind which explains its stability. The harmattan also is noted. The trade wind's trajectory is entirely continental and comes from the Maghrebian anticyclone. It warms up and dries out as it crosses the Sahara zone to reach Senegal. These two flows from the northern hemisphere are opposed to the monsoon flow from the Saint Helena anticyclone, which takes over Cape Verde from July to September. When it is continental, the monsoon is generally accompanied by abundant rainfall. As a result, Senegal, particularly the Dakar region, is experiencing two seasons. The dry and wet seasons. The geomorphological condition of the Dakar region is composed of the massive Ndias in the southern part, which corresponds to the Maastrichtian horst. It is a relief of hills and trays often cuirassed, covered with lithosols and ferruginous. Along the coast, red sandstone mounds are bordered by cliffs. In the Rufisque-Bargny area, low plateaus extend over a surface that overlaps the limestone and marl Eocene. Most of Dakar is occupied by fixed continental dunes. Since the climatic, geologic, and geomorphologic conditions play an essential role in coastal dynamics in the Dakar region, the hydrodynamic agents are the key generators of these dynamics.

The dynamic of the shoreline shows that the region records the respective average rate retreats of about -0.44 m/year, 0.21 m/year, and -0.11 m/year at the northern, western, and southern coasts. These dynamic rates are expected to be about -4.4 m/year (for the north coast), 2.1

m/year (for the west coast) and -1.1 m/year by 2030. (south coast). By 2040, they are estimated to be around -8.8 m/year (north coast), 4.2 m/year (west coast) and -2.2 m/year (south coast). These predicted dynamic rates will result in a loss of coastal areas, estimated at 861273 m^2 in 2030 and 1256493 m^2 in 2040. These forecasts depend on the behavior of hydrodynamic agents and coastal characteristics. They also provide information on the level of vulnerability. Even if coastal erosion is generated by natural factors such as hydrodynamic agents, climate parameters, and geologic and geomorphologic conditions, it would be accurate to say that human conditions contribute to this erosion through abnormal settlement, pollution, and sand mining.

This contribution of human can be explained by the fact that Dakar region has a population of 3.835.019 inhabitants, an exceptional density of 6972 inhabitants/km^2, and the average density of the country is 85 inhabitants/km^2. Its rapid population growth characterizes it. Consequently, this concentration of people led to a construction boom and then excessive sand extraction from beaches and dunes. As a result, a deficit in terms of sediment budget is noted along the coasts. In addition, pollution is among the most critical environmental challenge in the Dakar region. This situation accentuates the Dakar region's physical and socio-economic vulnerability to coastal erosion. The Coastal Vulnerability Index is used to assess the level of vulnerability. Ten variables: slope, geomorphology, geology, existing protective infrastructures, relative sea level, shoreline displacement, tidal range, swell range, wave height, and distance between settlement and the sea are employed. The results show that the values of the CVI vary on the northern, western, and southern coasts. Different levels of vulnerability on the northern (94), western (10), and southern coasts (23) are noted. This difference is explained by the different variables used. The socio-economic vulnerability of coastal district communities in the Dakar region were therefore assessed using four variables (population density, dependency ratio, gender ratio, and level of education). The average values of the socio-economic vulnerability index in different sectors of the Dakar region are Guédiawaye 4, Dakar 2.5, Pikine 4.3, and Rufisque 3.3. The highest indices were found in the district municipalities of Sam Notaire (5.4), Wakhinane Nimzatt (6), Yeumbeul North (6.7), Keur Massar (5.8), Rufisque Est (6), Mbao (4.8) and Thiaroye Sur Mer (4.2), Bel Air (4.2) and Medina (5). This is due to the high dependency ratio and density of these locations.

The estimation of economic loss based on littoral price and lost areas due to erosion was also conducted. It is showed that the district municipalities along the coast of Dakar recorded a loss estimated at 38507856000 FCFA in 2030 and 57822698000 FCFA in 2040. These losses are shared unequally in coastal areas in Dakar. The most exposed in terms of economic loss are Malika, Plateau, and Ngor. Whether the coast of Dakar region is challenged economically by coastal erosion, abnormal settlements, pollution sand mining aggravates the economic loss. It should be essential to note that the application of law n°76-66 of 2 July 1976, which defines the natural public domain with the shores of the sea, and the artificial public domain with the numerous urban infrastructures built or planned and law Nº 83-05 of 28 January 1983 of the Environmental Code which specifies that settlements along the coast must neither be a source of erosion nor degradation of the site. Unfortunately, this law is not respected by most economic actors.

To combat coastal erosion, the Senegalese government has always found ways to adapt to erosion. Therefore, several measures include protective barriers, ledge fields, reforestation, embankments, ripraps, dune restoration, beach drainage systems, and breakwaters. Some of these means are more effective depending on their quality, resistance to hydrodynamic conditions (swells, winds, currents, and waves.), and the type of beach they are installed. In addition, the Senegalese government has ratified many international conventions on managing and protecting the coastal and marine environment. For example, we can note the Ramsar and Abidjan convention, the United Nations on the Law of the Sea convention, the United Nations Framework Convention on Climate Change, and the Millennium and Sustainable Development Goals. Regarding coastal erosion management, laws are defined to protect and manage the marine environment and natural resources to combat abuse and damage. These laws are public and maritime domain regulation, Marine and coastal environmental protection, Mining underground resources regulation, and coastal and marine pollution regulation. However, despite the efforts made by the Senegalese government to combat coastal erosion, the coast is still receding. Several recommendations were therefore identified for enhancing adaptative strategies to increase resilience, strengthening institutional capacity building, strengthening existing early warning systems, engaging local communities in coastal management, empowering economic actors by providing funding and equipment, developing new resettlement policies for affected communities, Implementation, raising public awareness of the impacts of climate change and coastal erosion.

Perspectives

This study examines the dynamics of the coastline from 1990 to 2040 and finds that the northern, western, and southern coasts all experience average retreats of roughly -0.44 m/year, 0.21 m/year, and -0.11 m/year, respectively. By 2030, it is projected that these dynamic rates will be around -4.4 m/year (for the northern coast), 2.1 m/year (for the western coast), and -1.1 m/year (for the southern coast). The north's coast rate is predicted to be -8.8 m/year, the west coast's rate will be 4.2 m/year, and the south coast's rate will be -2.2 m/year by 2040. These predicted dynamic rates will cause a loss of coastal areas projected at 861273 m^2 in 2030 and 1256493 m^2 in 2040. These predicted rates are based on coastal characteristics and how hydrodynamic agents behave. Additionally, the Dakar region's socioeconomic and physical vulnerability was investigated. The northern (94), western (10), and southern (23) coasts were revealed to have various vulnerability indices. The Dakar region is physically vulnerable to coastal erosion, but it is important to highlight that human activities have made it even more vulnerable form a socioeconomic standpoint. The economic value of the coast will be significantly impacted in 2030 and 2040 due to this physical and socioeconomic vulnerability. According to the assessment of economic loss, a loss of 38507856000 FCFA in 2030 and 57822698000 FCFA in 2040 is predicted to occur along the Dakar coastline. These predictions would enable the potential installation of protective infrastructures in the most exposed locations, thereby preventing the effects of coastal erosion.

Previous studies on coastal dynamics have been conducted. Diallo (1982) found that the rate of coastline evolution was -1.29 m/year. Sall (1982) found -1.3 m/year of coastline erosion, while Niang Diop (1996) found -1.2 m/year of coastal change. According to Dieye (2000), the coastline between Bel Air and Rufisque is showing annual erosion at a rate of -0.6 m/year. Guerin (2003) found a 0.77 percent annual erosion of the shoreline. Ndour (2015) noted an approximate dynamic rate of 1.6 m/year. Therefore, the originality of this study is in the assessment of the coastline dynamics and the predictions made for the future coastline position and loss areas due to erosion in 2030 and 2040. In addition, the physical vulnerability assessment, taking into account the distance between sea and settlements and the existing protective infrastructures, and the socioeconomic vulnerability assessment, using population density, dependency ratio, gender ratio, and education level, as well as the economic impacts assessment of coastal erosion using an econometric model, are also innovative aspects of this study. Practically, this study provides new insights such as the use of GIS techniques for predicting the loss areas in 2030 and 2040, the determination of topographic value for transects, the delineation for existing protective infrastructures, and the computation of the distance between sea and settlements in the physical vulnerability assessment. The economic evaluation of the impacts of coastal erosion based on the littoral price is an important technique that allow to determine the economic land value that will be lost in 2030 and 2040 due to erosion. Theoretically, this thesis provides knowledge about the key driving parameters of coastal erosion in Dakar, the level of vulnerability both physically and socioeconomically, and the economic evaluation of the impact of coastal erosion. These practical and theoretical insights can be helpful for researcher in general and particularly for GIS experts, geomaticians, environmental economists, and policymakers. Overall, this study provides a clear overview of coastal erosion, its impacts in Dakar, Senegal, and all different processes that mediate coastal erosion. It can serve as evidence to enable economic actors and populations to make decisions about the impacts of coastal erosion on their activities, and provides knowledge on sustainable adaptation and mitigation strategies. It also provides essential information to relevant institutions in Senegal, such as the Ministry of Tourism, Ministry of fishery, Ministry of Higher Education, and the Direction de l'Environnement et des Etablissements Classés (DEEC), as well as Non-Governmental Organization (NGOs) working in this area. Additionally, it contributes to the literature on coastal erosion in Dakar, Senegal, and opens up a new pathway for future research. One limitation of this study is the assessment of the economic impacts of coastal erosion on economic activities such as fishery and tourism. Future research could expand on this by examining these economic sectors that may be affected by coastal erosion.

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Annex

Table 1: Shoreline changes (EPR)/ average of all erosional and accretional rates (m/year)

Coasts	Averages	1990-2000	2000-2010	2010-2020	1990-2020
Northern coast	Average of all erosional rates	-5.3	-4.12	-2.86	-1.4
	Average of all accretional rates	1.99	0	0.73	0.56
Southern coast	Average of all erosional rates	-0.78	-1.07	-1.37	-0.35
	Average of all accretional rates	0.68	1.45	2.03	0.50
Western coast	Average of all erosional rates	-2.33	-3.06	-3.13	-0.63
	Average of all accretional rates	1.41	5.16	5.89	0.44

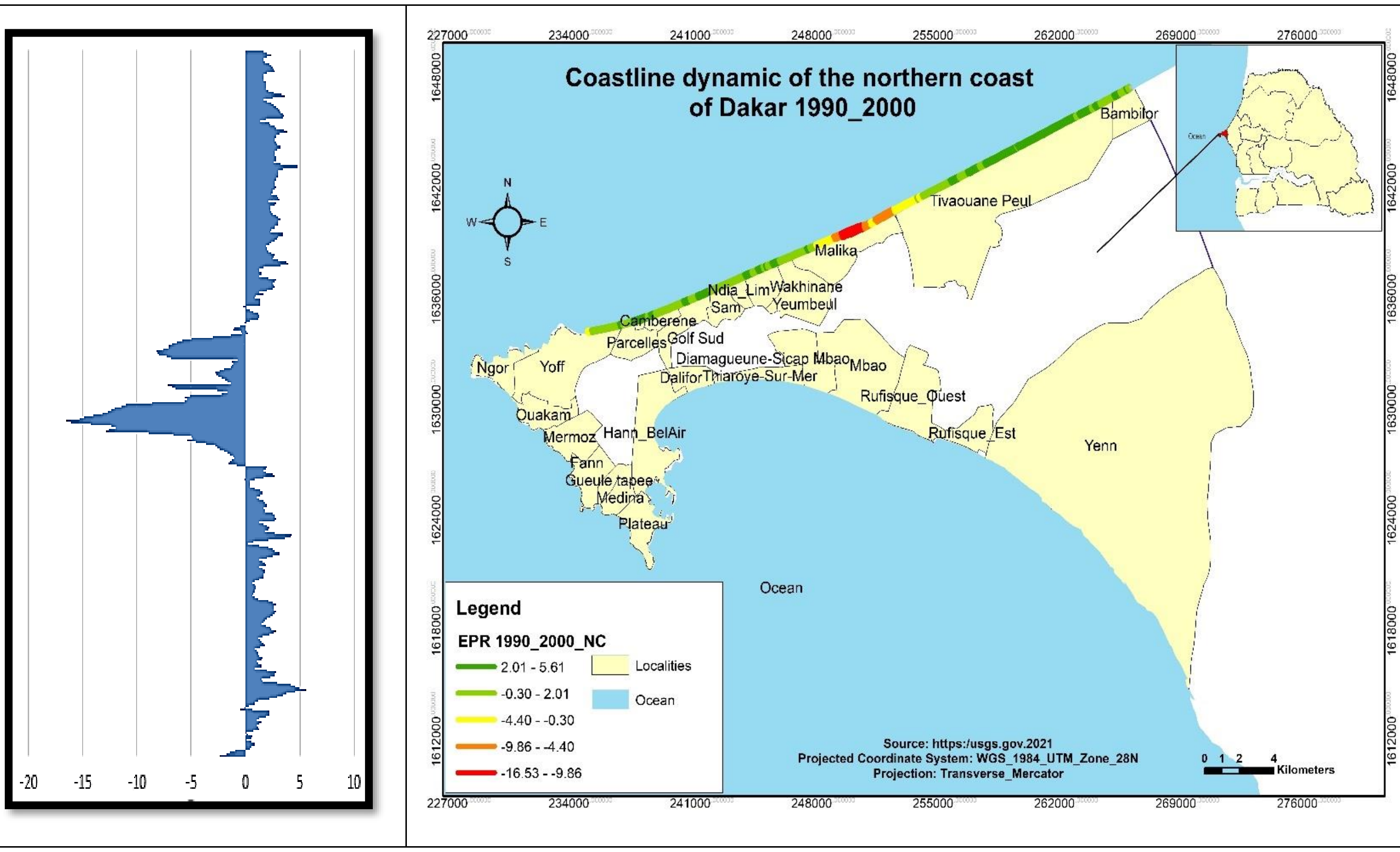


Figure 1: Coastline dynamic of the northern coast of Dakar 1990_2000

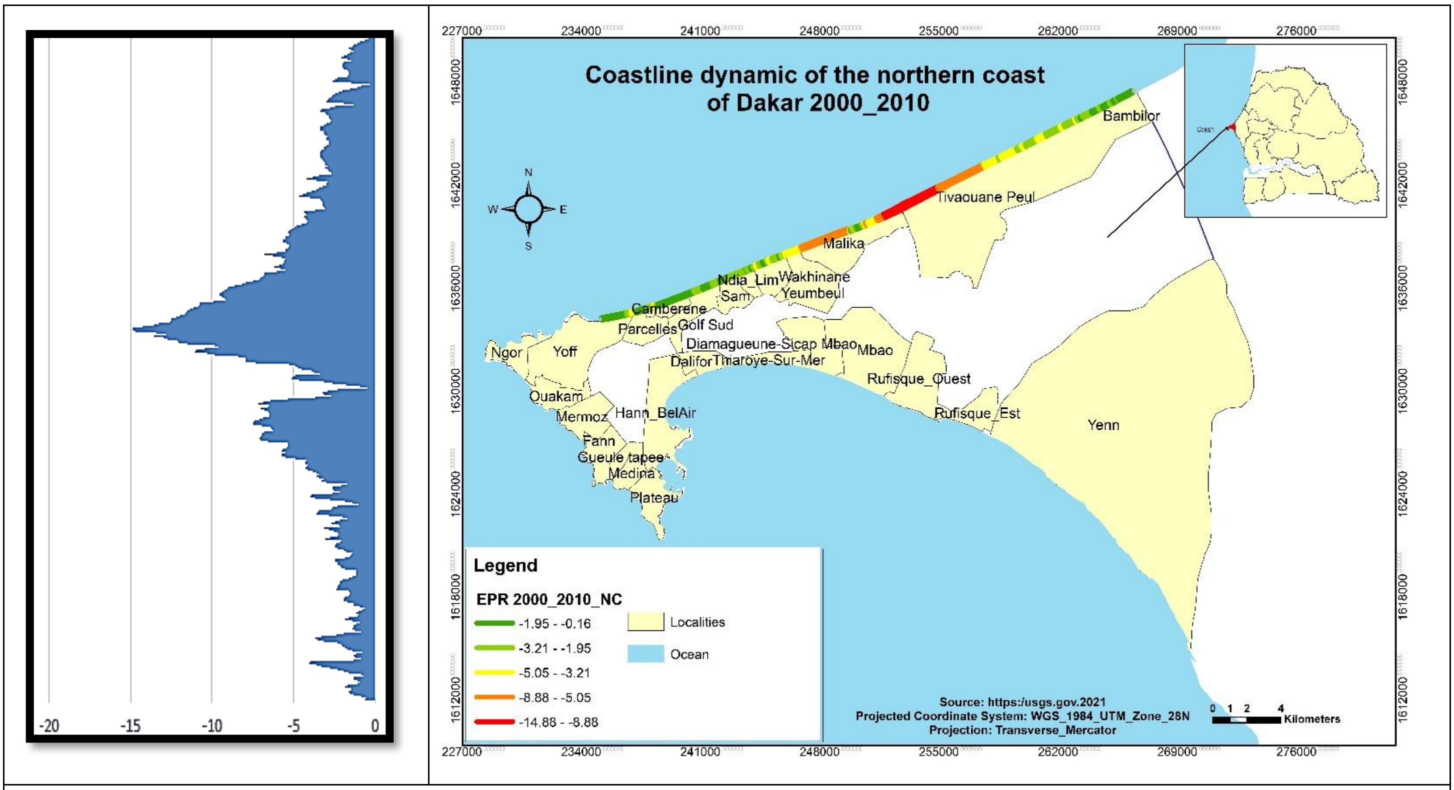


Figure 2: Coastline dynamic of the northern coast of Dakar 2000_2010

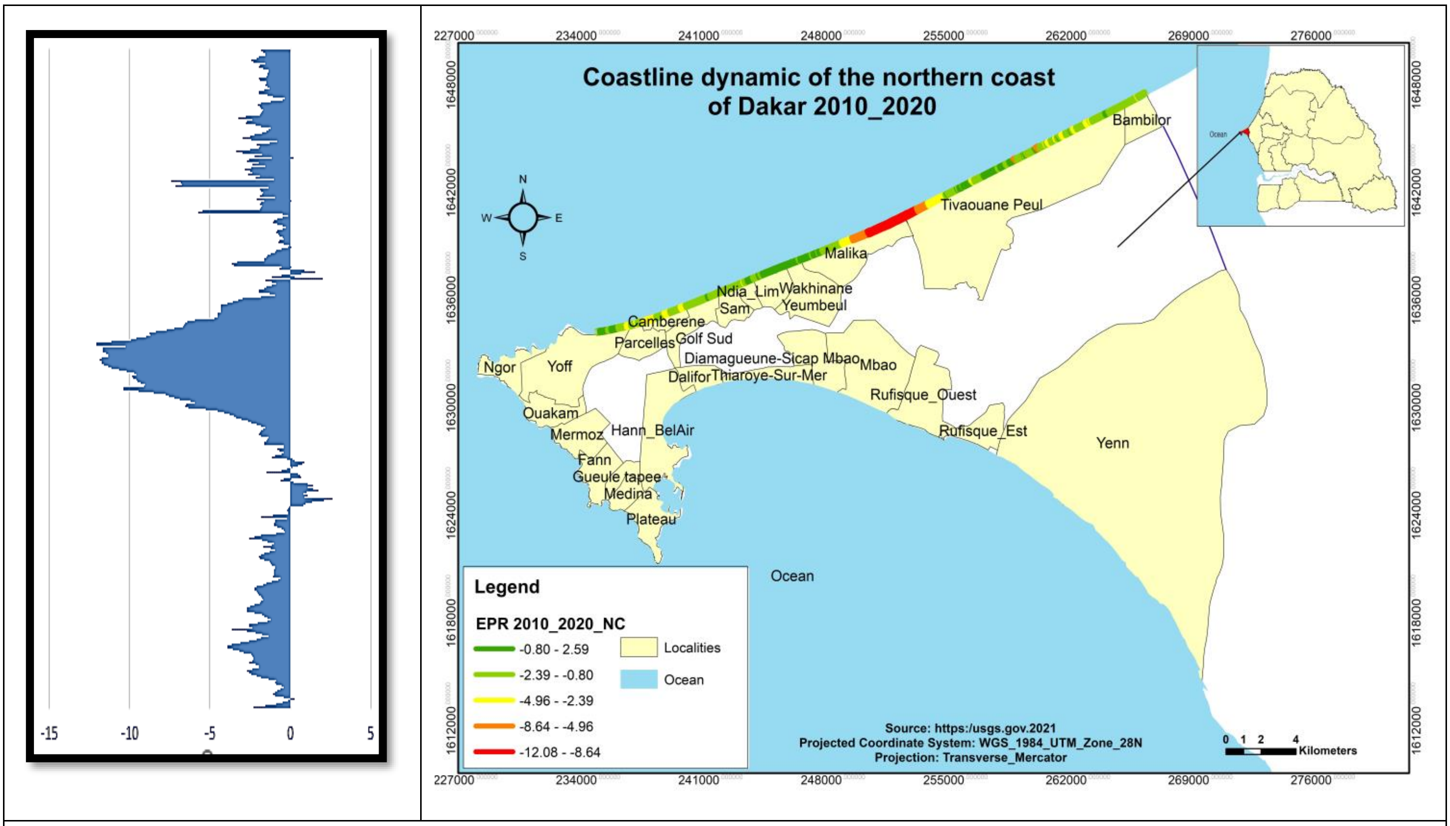


Figure 3: Coastline dynamic of the northern coast of Dakar 2010_2020

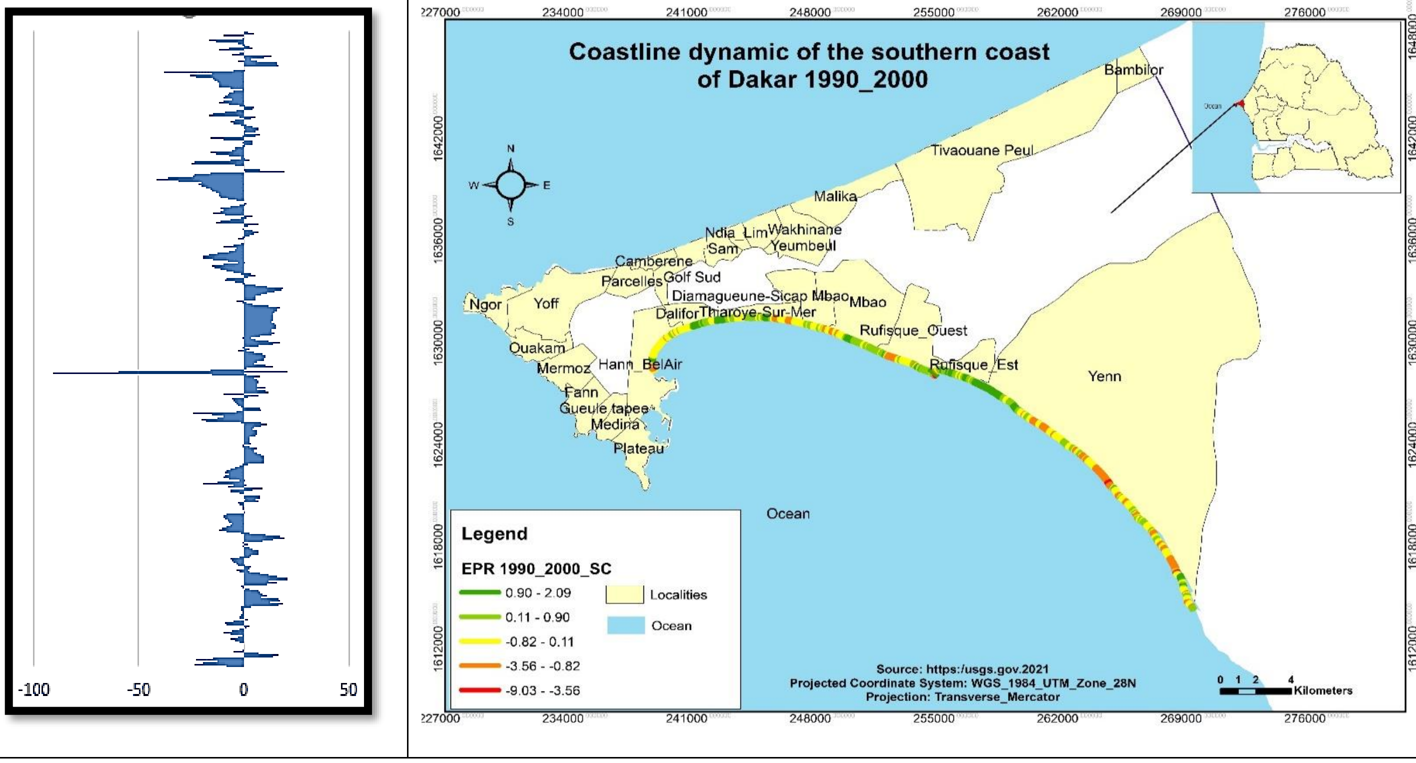


Figure 4: Coastline dynamic of the southern coast of Dakar 1990_2000

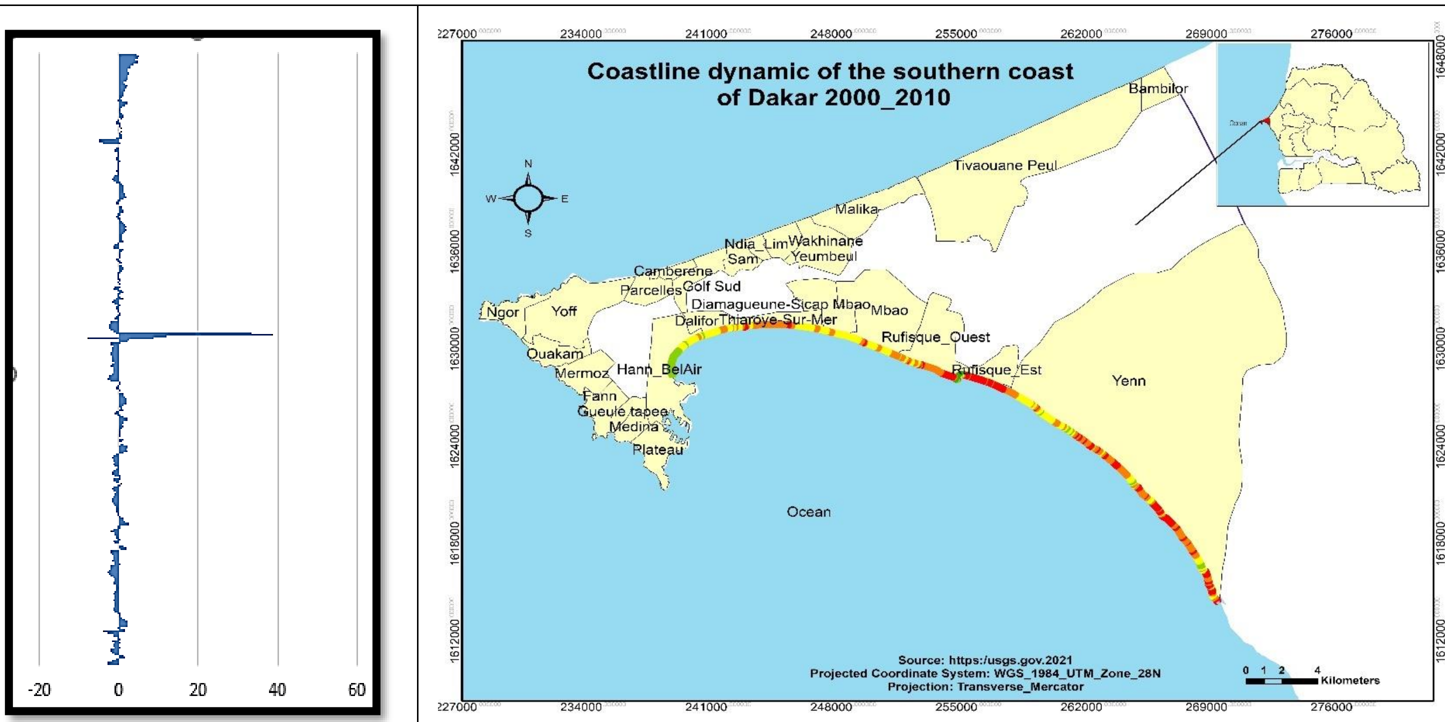


Figure 5: Coastline dynamic of the southern coast of Dakar 2000_2010

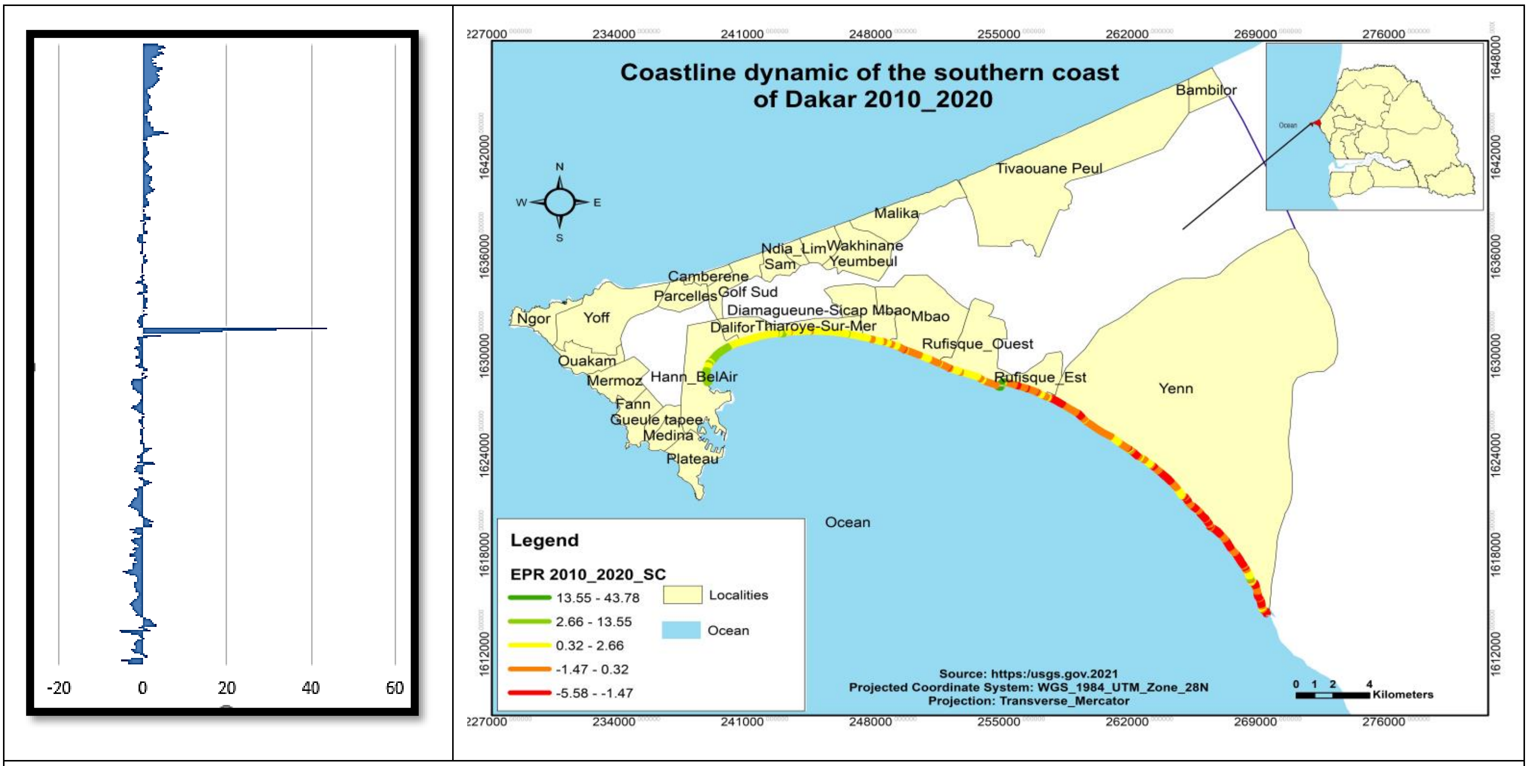


Figure 6: Coastline dynamic of the southern coast of Dakar 2010_2020

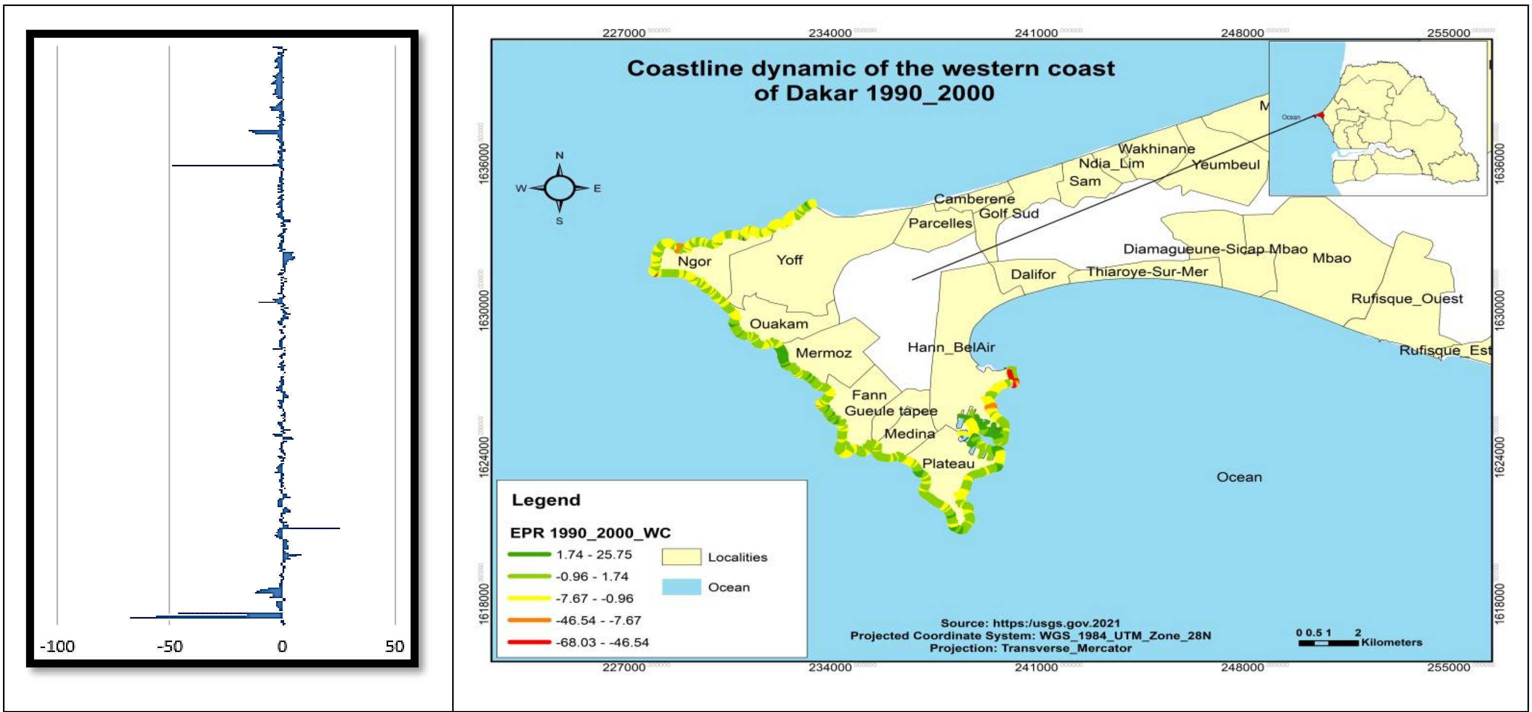


Figure 7: Coastline dynamic of the western coast of Dakar 1990_2020

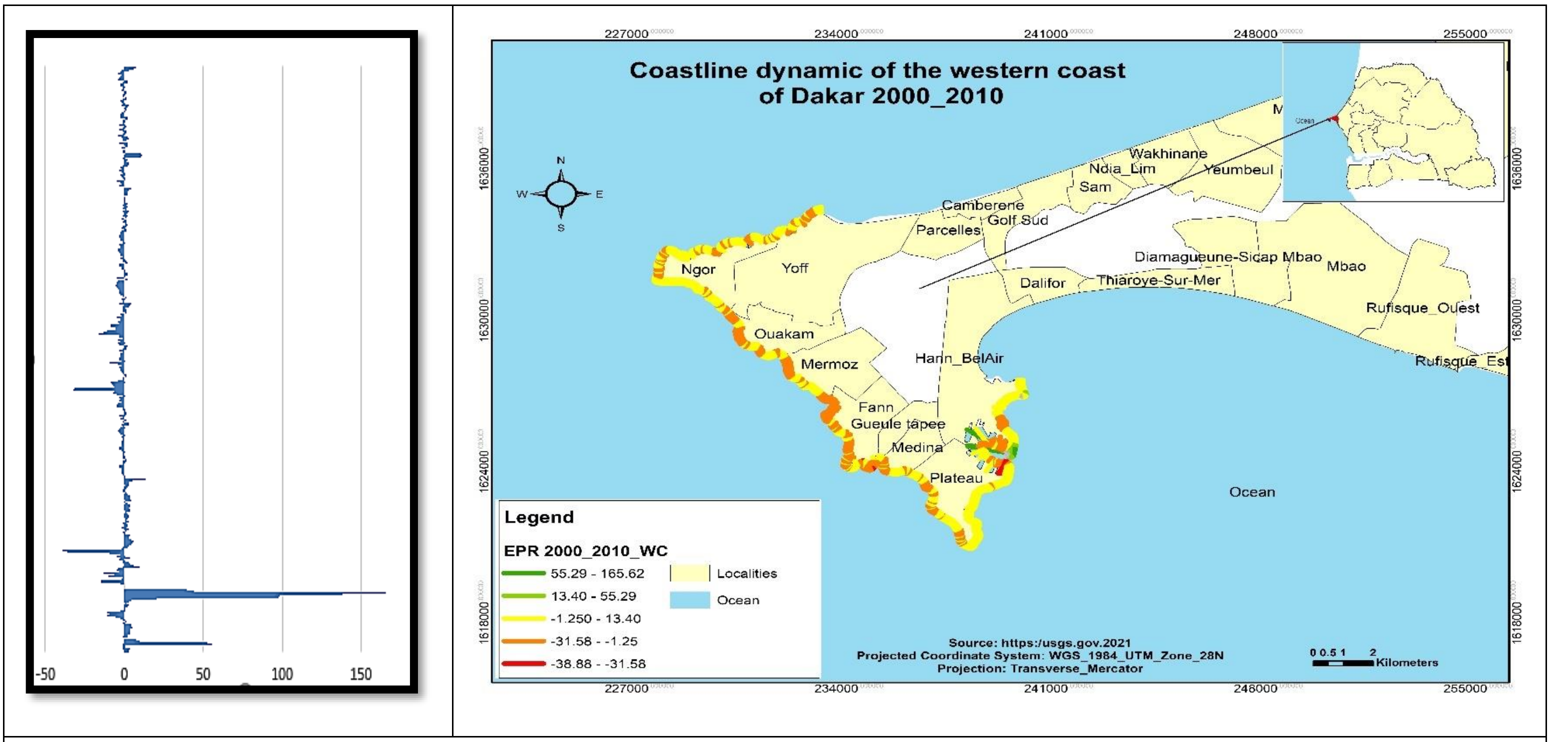


Figure 8: Coastline dynamic of the western coast of Dakar 2000_2010

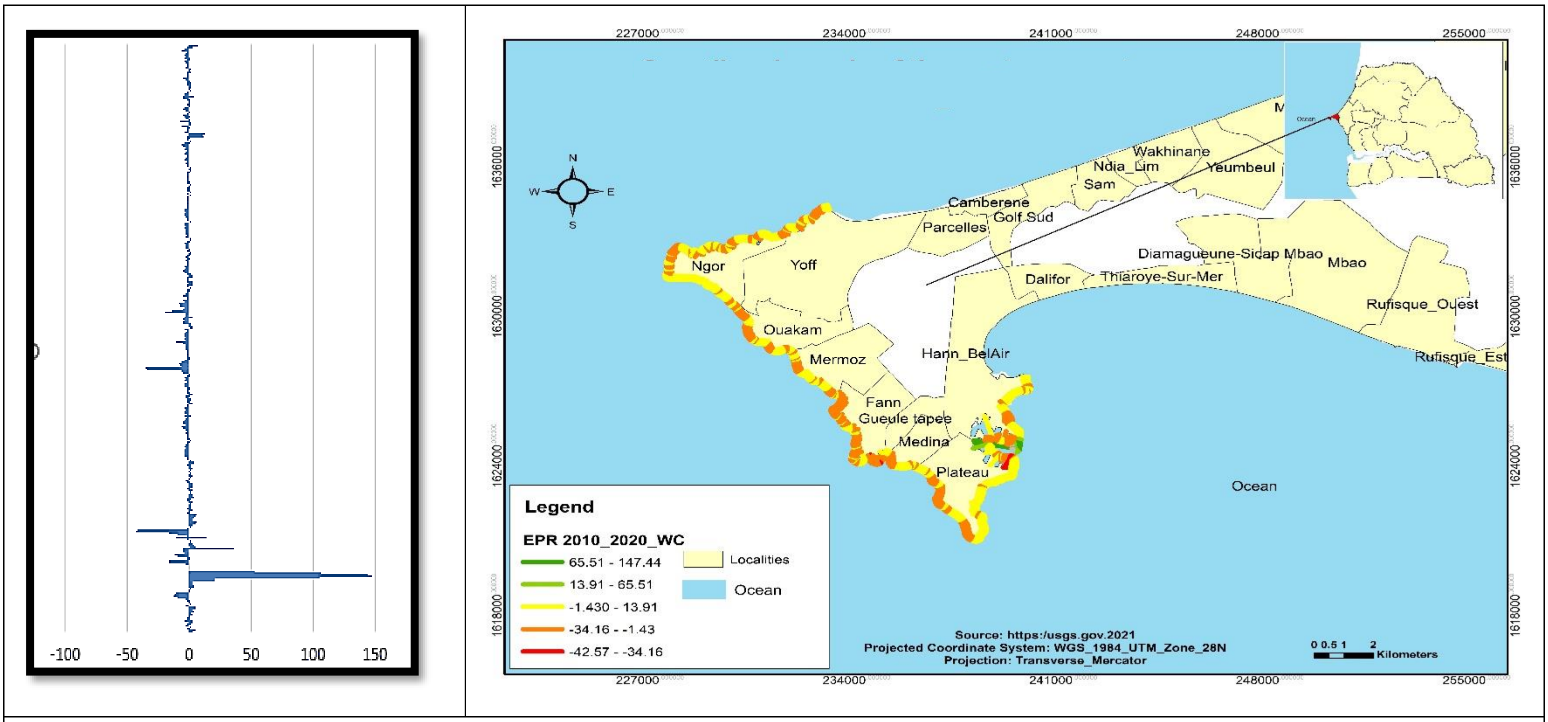
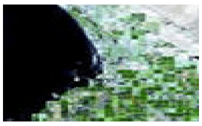
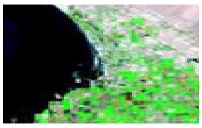


Figure 9: Coastline dynamic of the western coast of Dakar 2010_2020

Common Landsat Band RGB Composites

Table 2: Common Landsat Band RGB Composites

Common Landsat Band RGB Composites			
Images	**Color characteristics**	**Landsat 4-5 TM, Landsat 7**	**Landsat 8**
	Color Infrared	4, 3, 2	5, 4, 3
	Natural Color	3, 2, 1	4, 3, 2
	False Color	5, 4, 3	6, 5, 4
	False Color	7, 5, 3	7, 6, 4
	False Color	7, 4, 2	7, 5, 3

Source: (USGS n.d.)

The table above resumed the possible band combinations of Landsat 4-5 TM (Thematic Mapper), 7, and 8. For natural images, the combination of the bands 3, 2, and 1 for Landsat 4-5 TM and 7 is correct and the bands 4, 3, and 2 for Landsat 8. For infrared images, the combination of the bands 4, 3, and 2 for Landsat 4-5 TM and 7 is adequate and the bands 5, 4, and 3 for Landsat 8. All other combinations lead to false color. Therefore, in coastal studies, some combinations are more suitable to better distinguish the limit between the sea and continent. In some literature cited by Guariglia et al. (2006), it is stated that TM channel 7 is more useful to control the change of the coastline position whereas the TM channel 5 is suitable in clear water conditions.

Table 3: Age distribution in different departments of Dakar region

Departments	0 - 14	Freq	15 - 64	Freq	>64	Freq
Dakar	316033	30.72482	790461	39.32076	39558	40.05143
Pikine	417882	40.6266	720449	35.83808	32462	32.86692
Rufisque	186840	18.16464	287833	14.31799	16022	16.22185
Guediawaye	107837	10.48394	211546	10.52316	10726	10.85979
Total	1028592	100	2010289	100	98768	100

Source: (ANSD 2014)

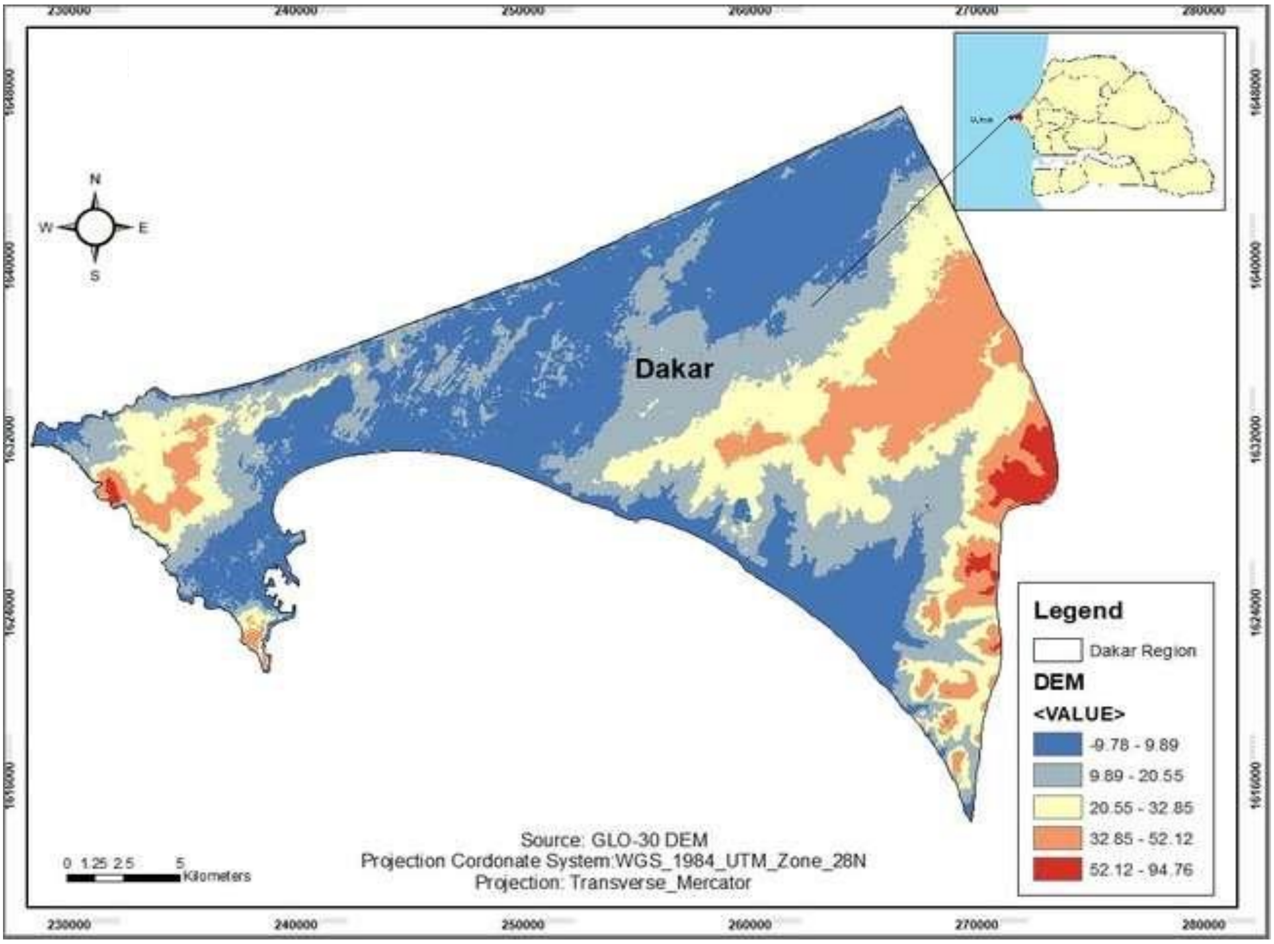


Figure 10: Digital Elevation Model of Dakar region (GLO_30 DEM)

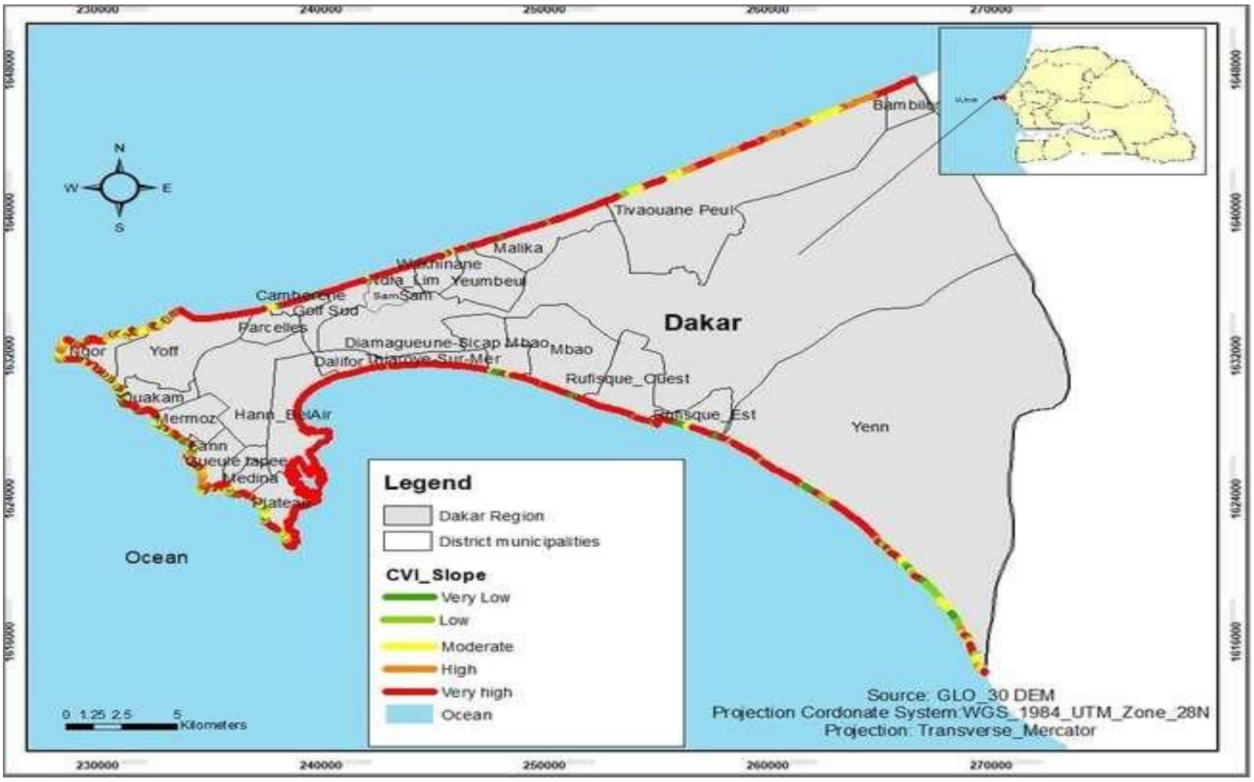


Figure 11: CVI of Dakar region based on Slope (GLO_30 DEM)

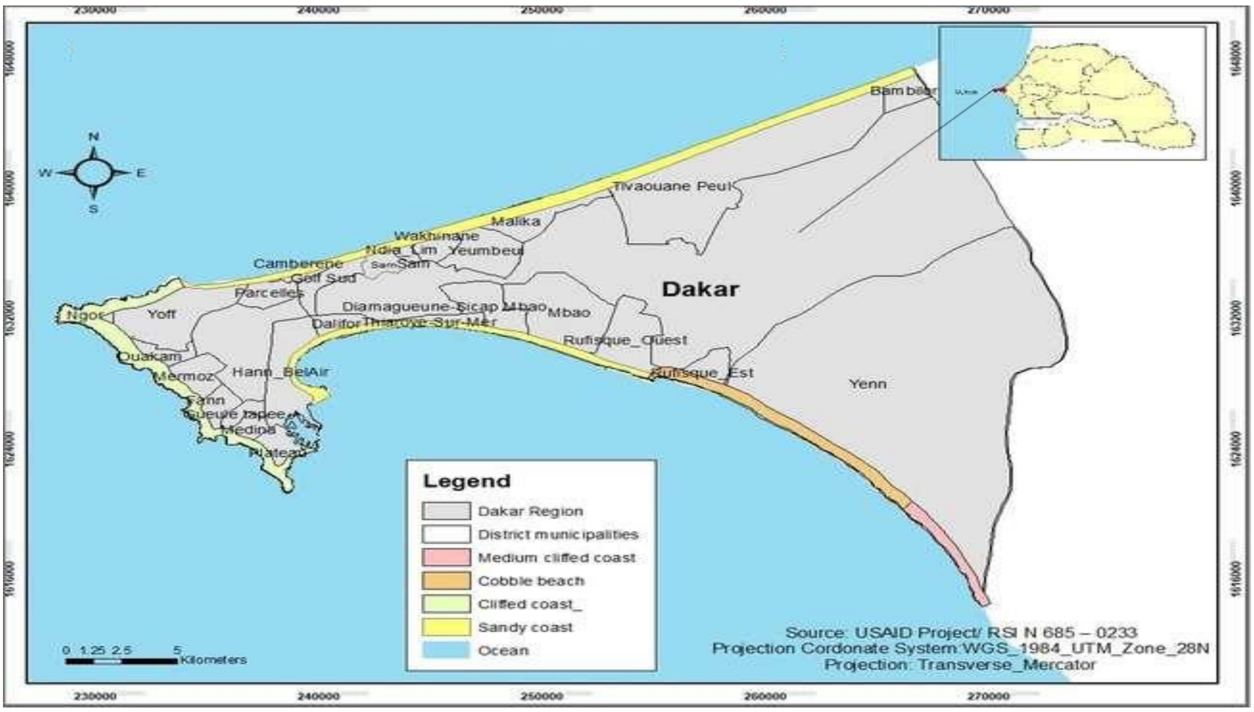


Figure 12: Geomorphology of the coasts of Dakar (USAID Project/RSI N 685 - 0233)

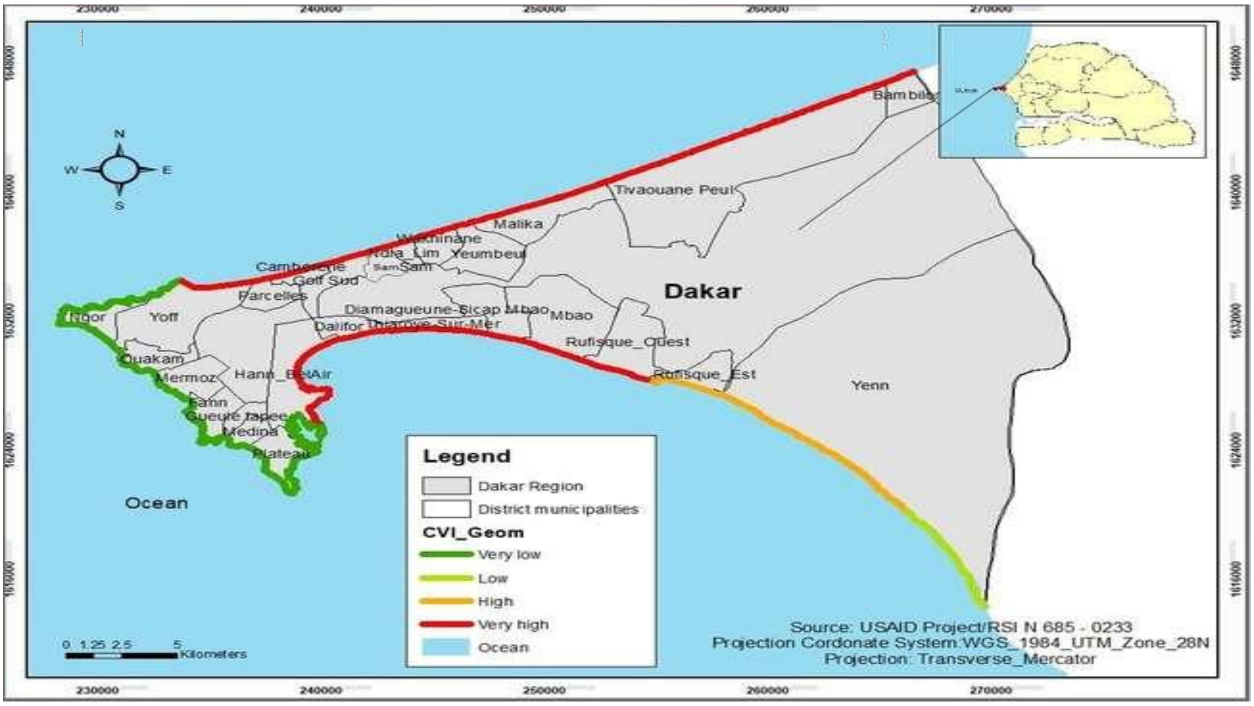


Figure 13: CVI of Dakar region based on coastal geomorphology of Dakar (USAID Project/RSI N 685 - 0233)

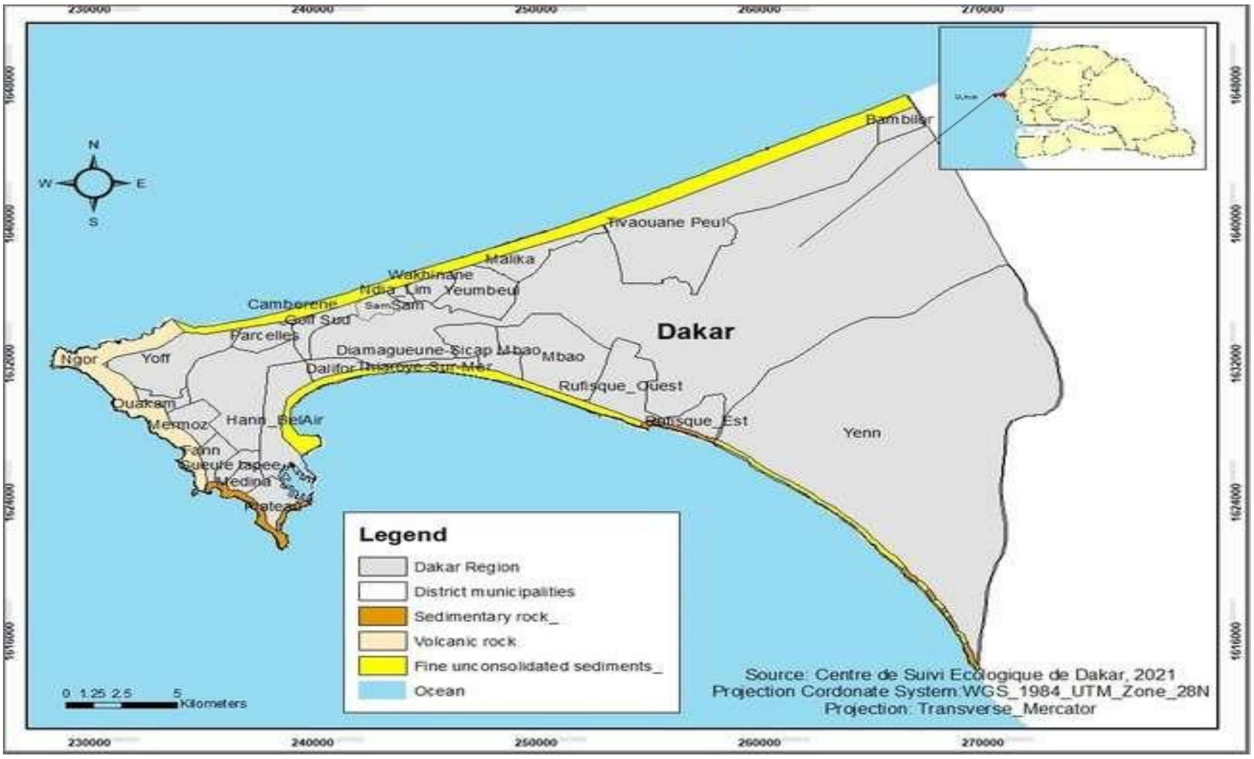


Figure 14: Geology of the coasts of Dakar (Centre de Suivi Ecologique of Dakar)

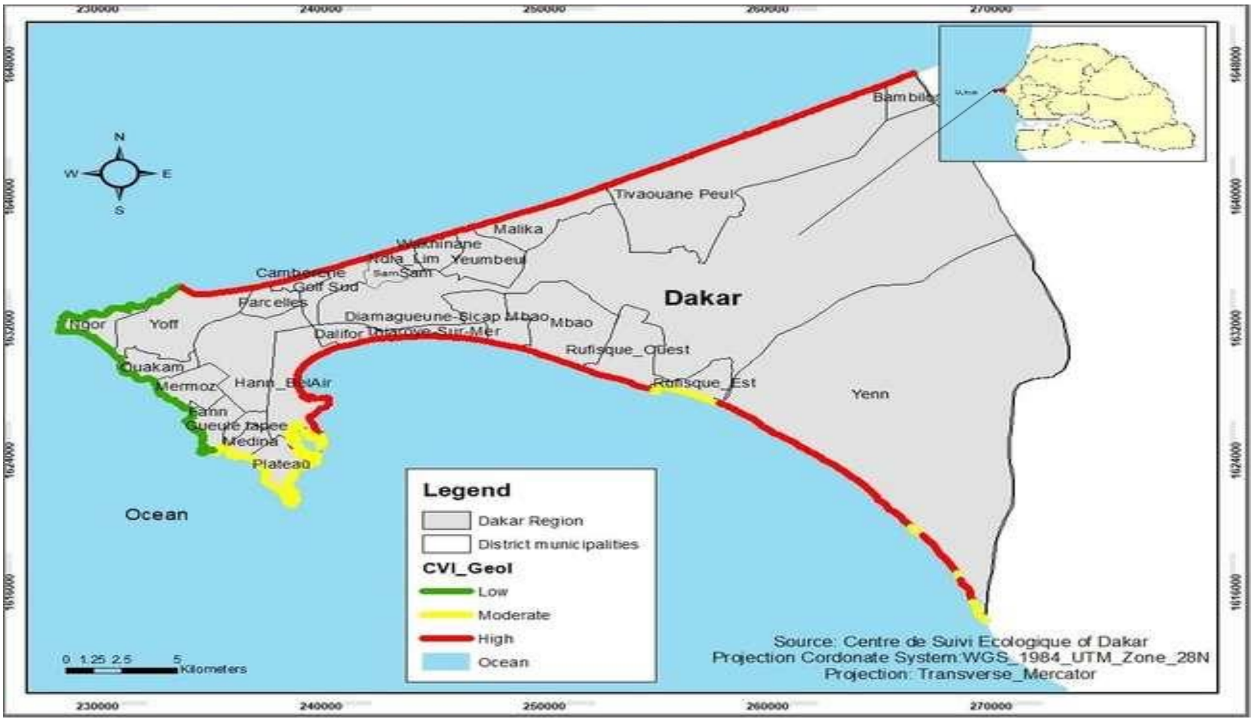


Figure 15: CVI of Dakar region based on coastal geology of Dakar (Centre de Suivi Ecologique of Dakar)

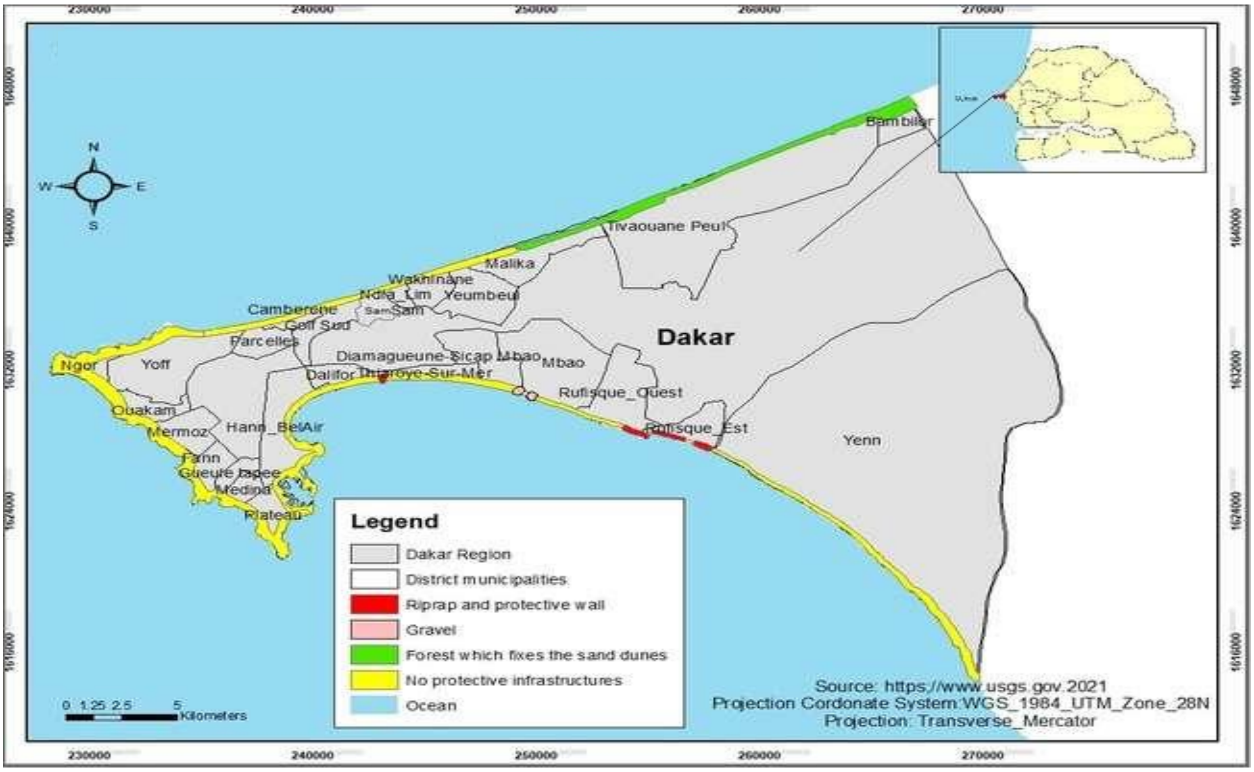


Figure 16: Existing or no existing protective infrastructures (Field survey/ Google Earth)

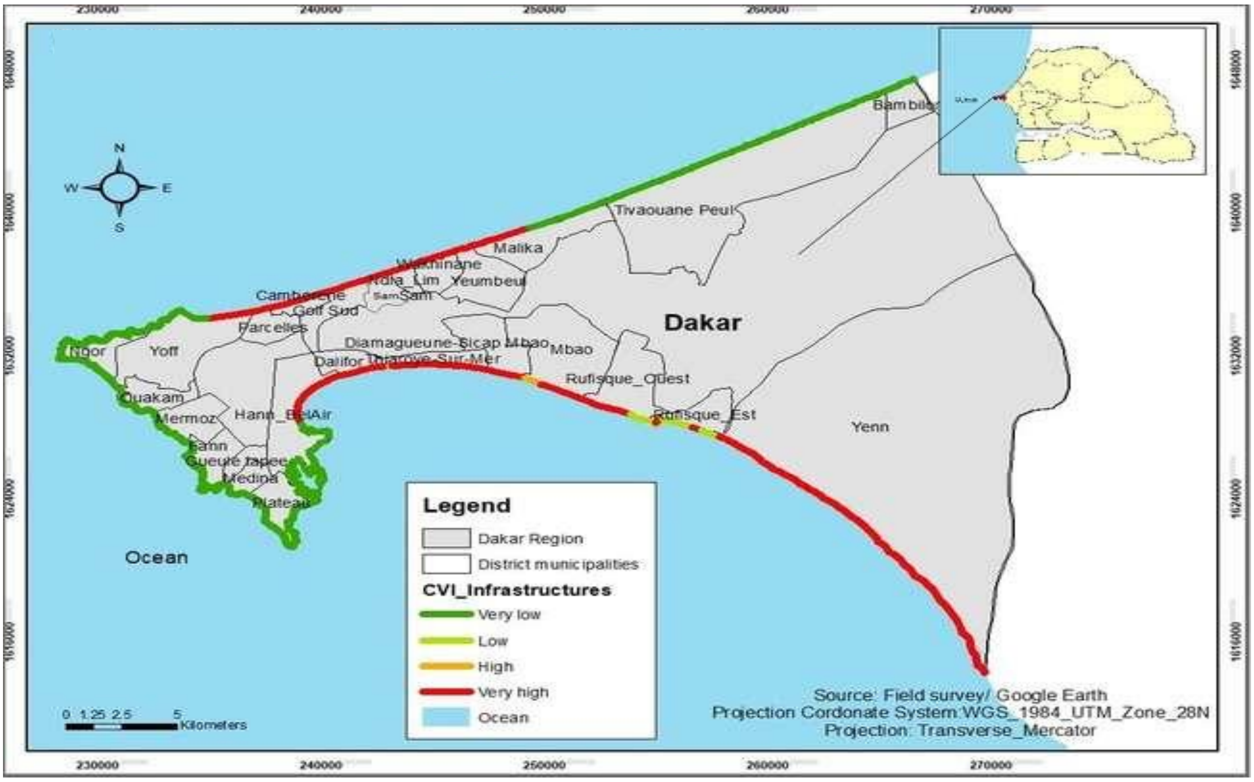


Figure 17: Coastal Vulnerability map based on Existing or no existing protective infrastructures (Field survey/ Google Earth)

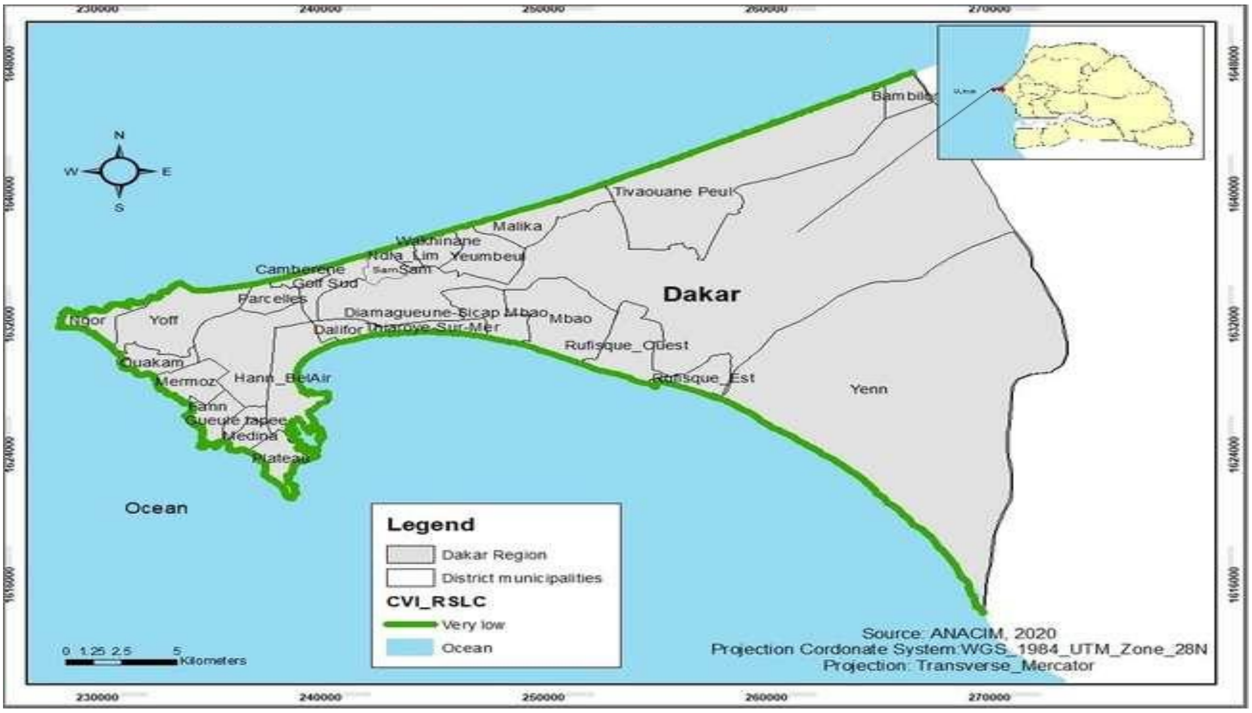


Figure 18: Coastal Vulnerability map based on Sea Level of Dakar region (ANACIM 2020)

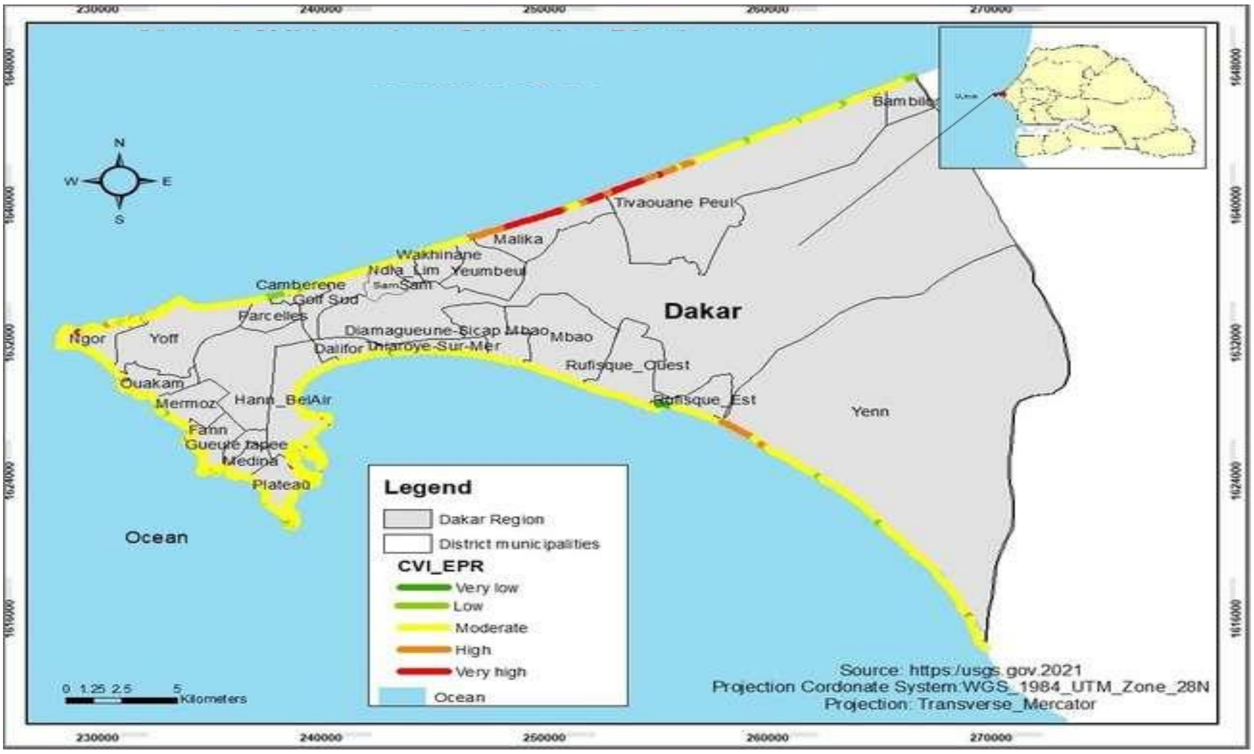


Figure 19: Coastal Vulnerability map based on the shoreline displacement of Dakar region from 1990 to 2020 (https:/usgs.gov.2021)

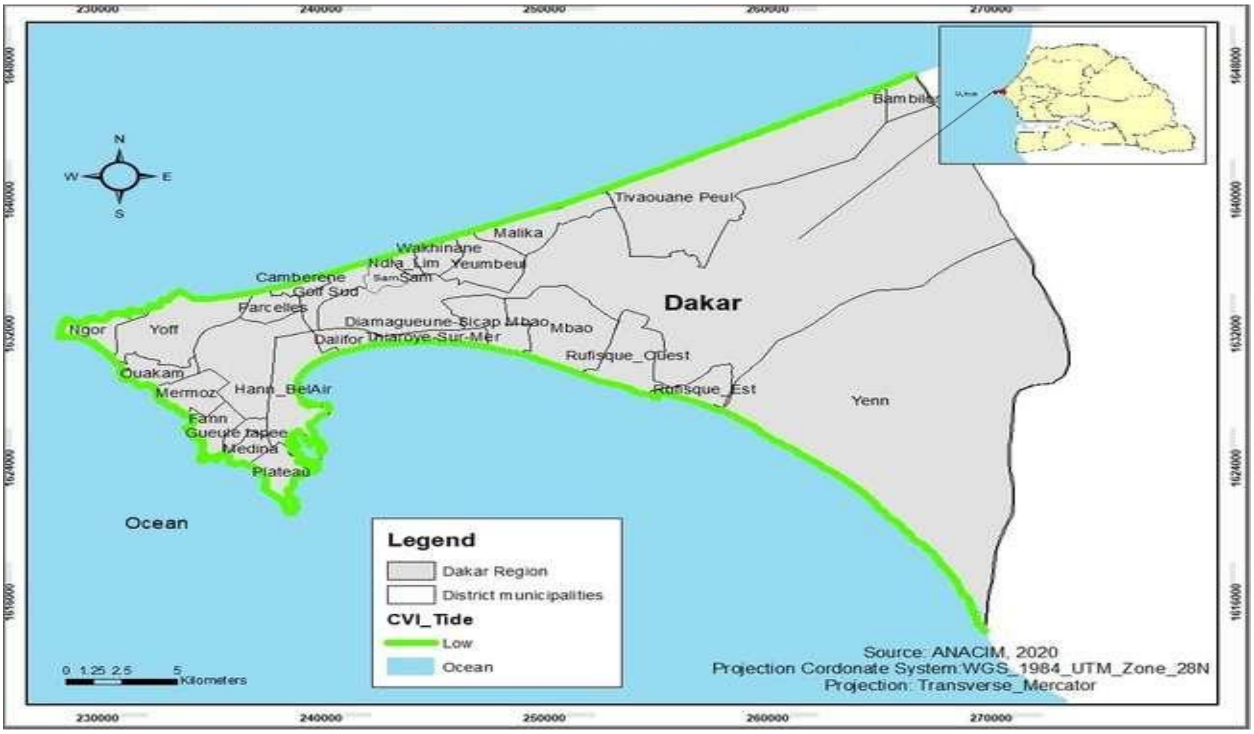


Figure 20: Coastal Vulnerability map based on tidal range of Dakar region (ANACIM 2020)

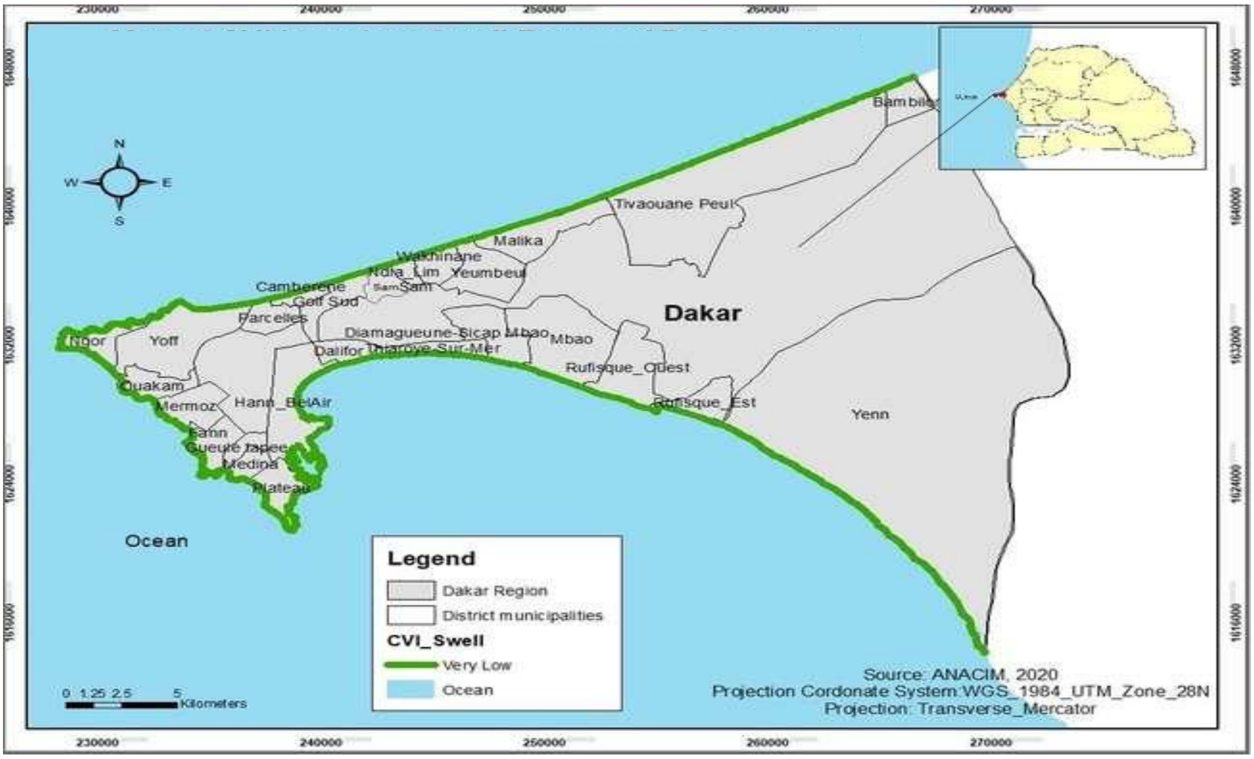


Figure 21: Coastal Vulnerability map based on swell Range of Dakar region (ANACIM 2020)

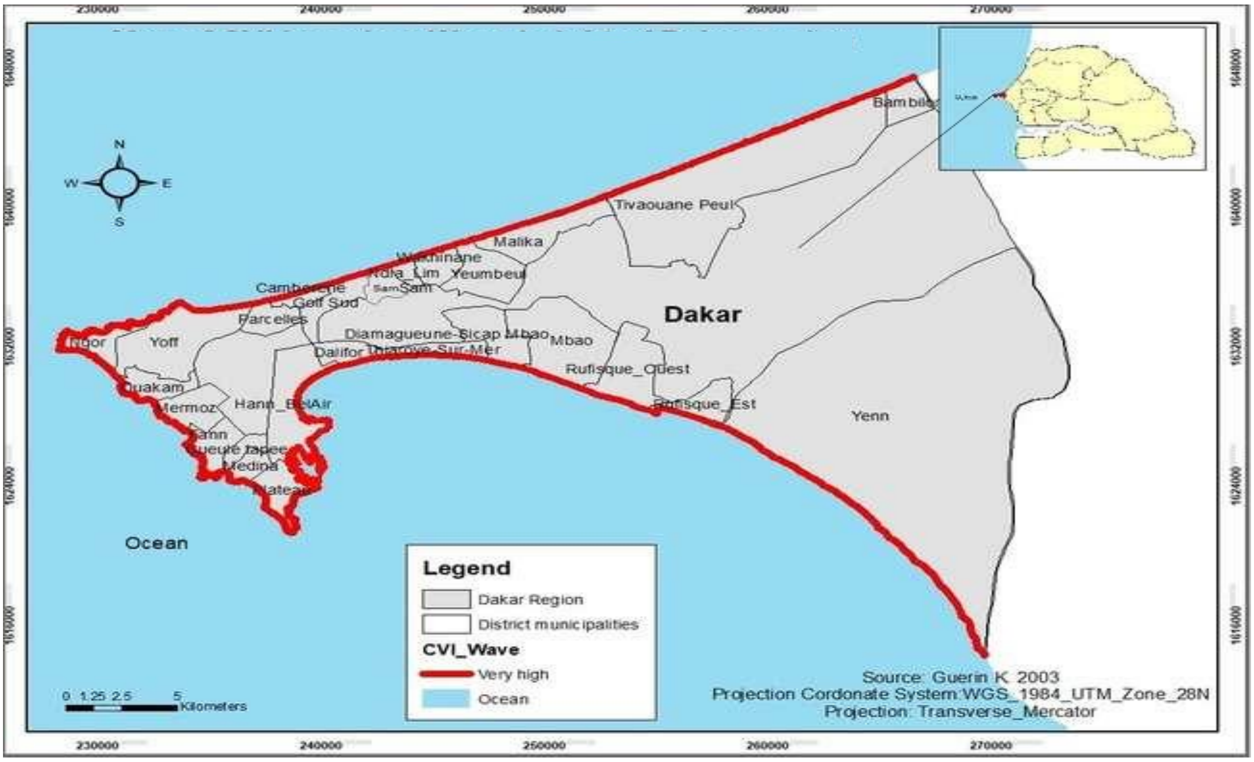


Figure 22: Coastal Vulnerability map based on the Wave height (Guerin 2003)

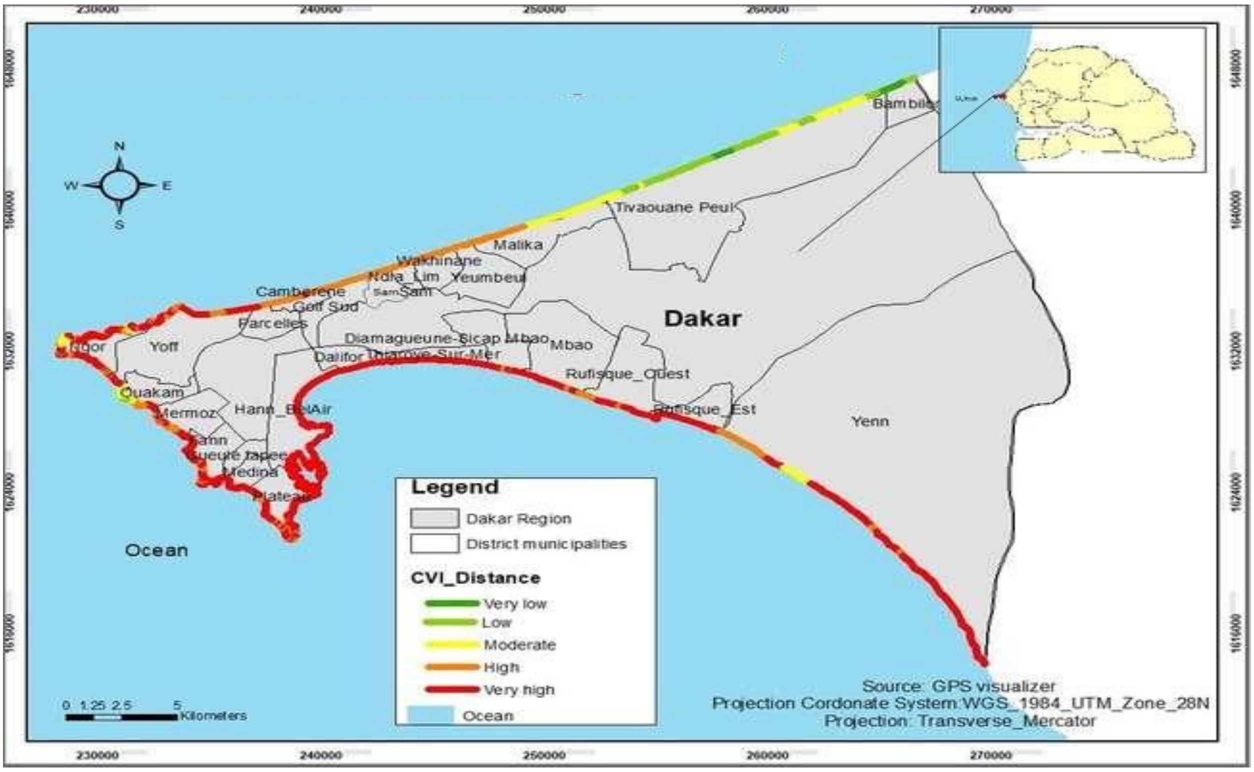


Figure 23: Coastal Vulnerability map based on the Distance between settlements and the sea (GPS visualizer)

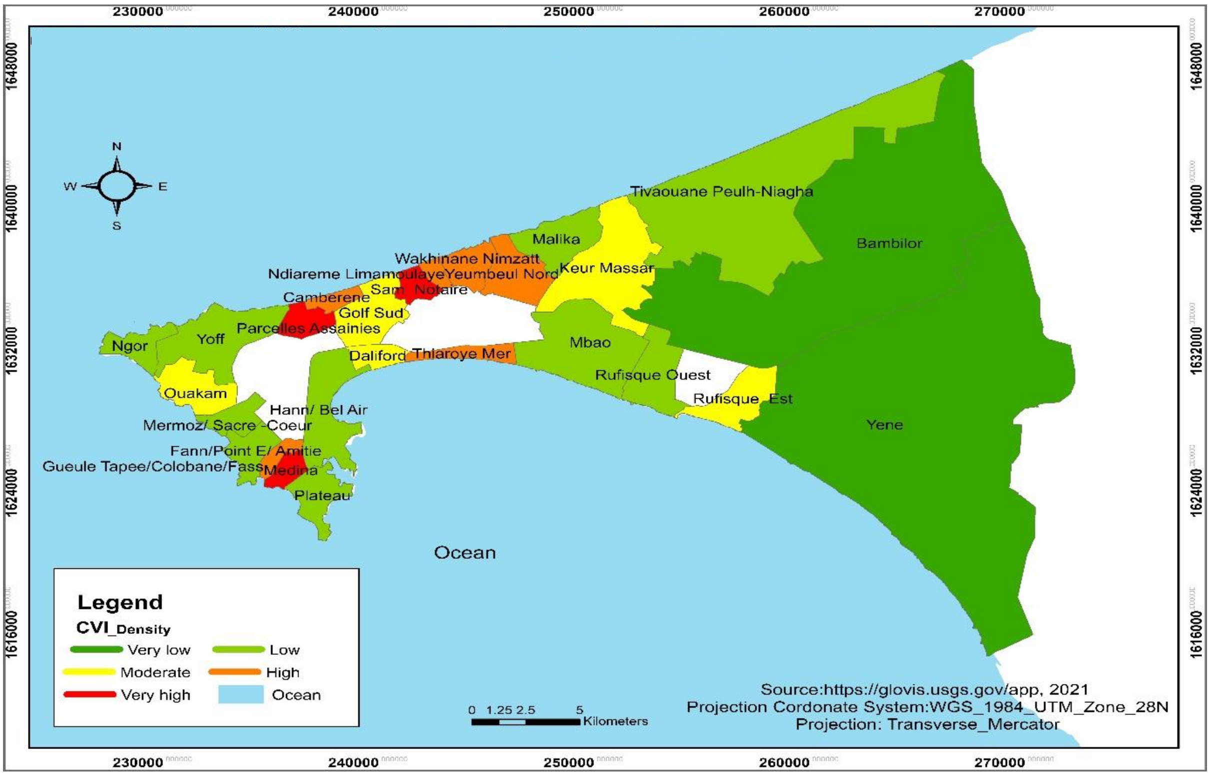


Figure 24: Coastal Vulnerability map based on **c**oastal population density map of Dakar region

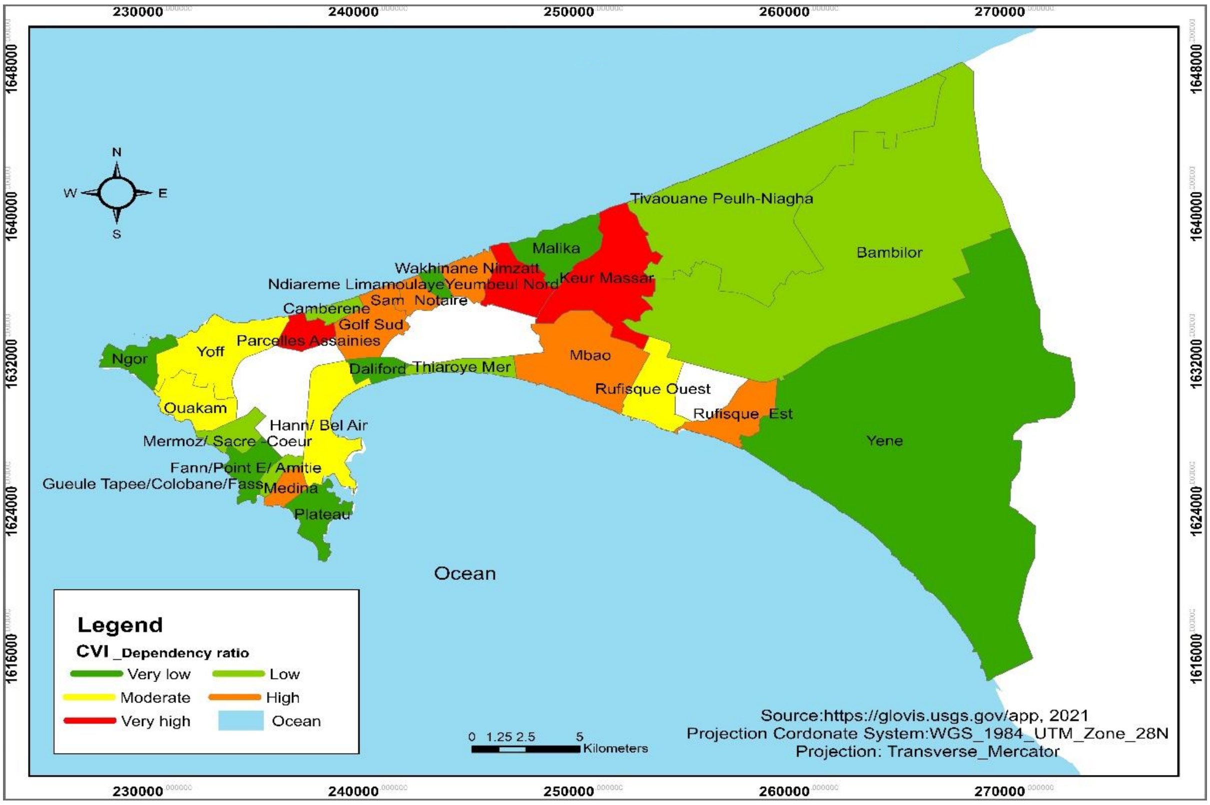


Figure 25: Coastal vulnerability map based on the percentage of population under 14 and over 65 years old of Dakar region

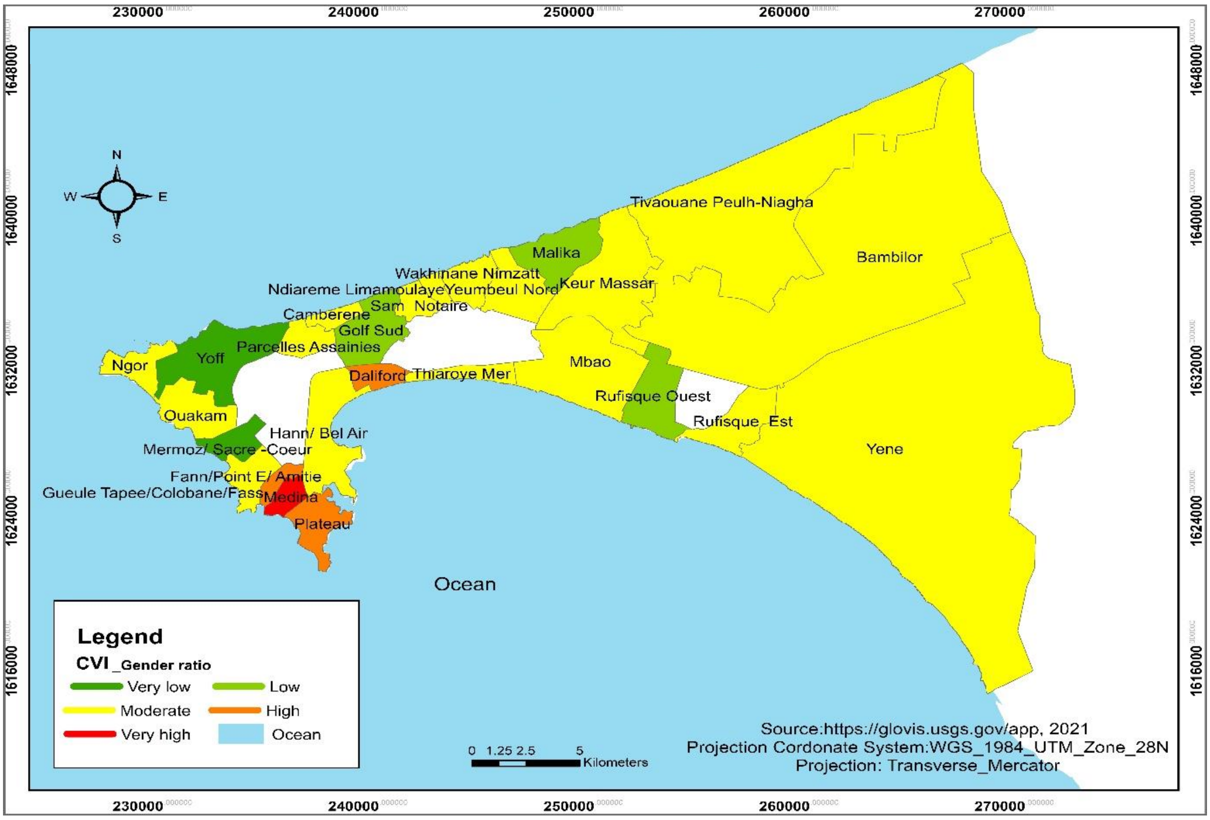


Figure 26: Coastal vulnerability map based on the gender ratio in Dakar region

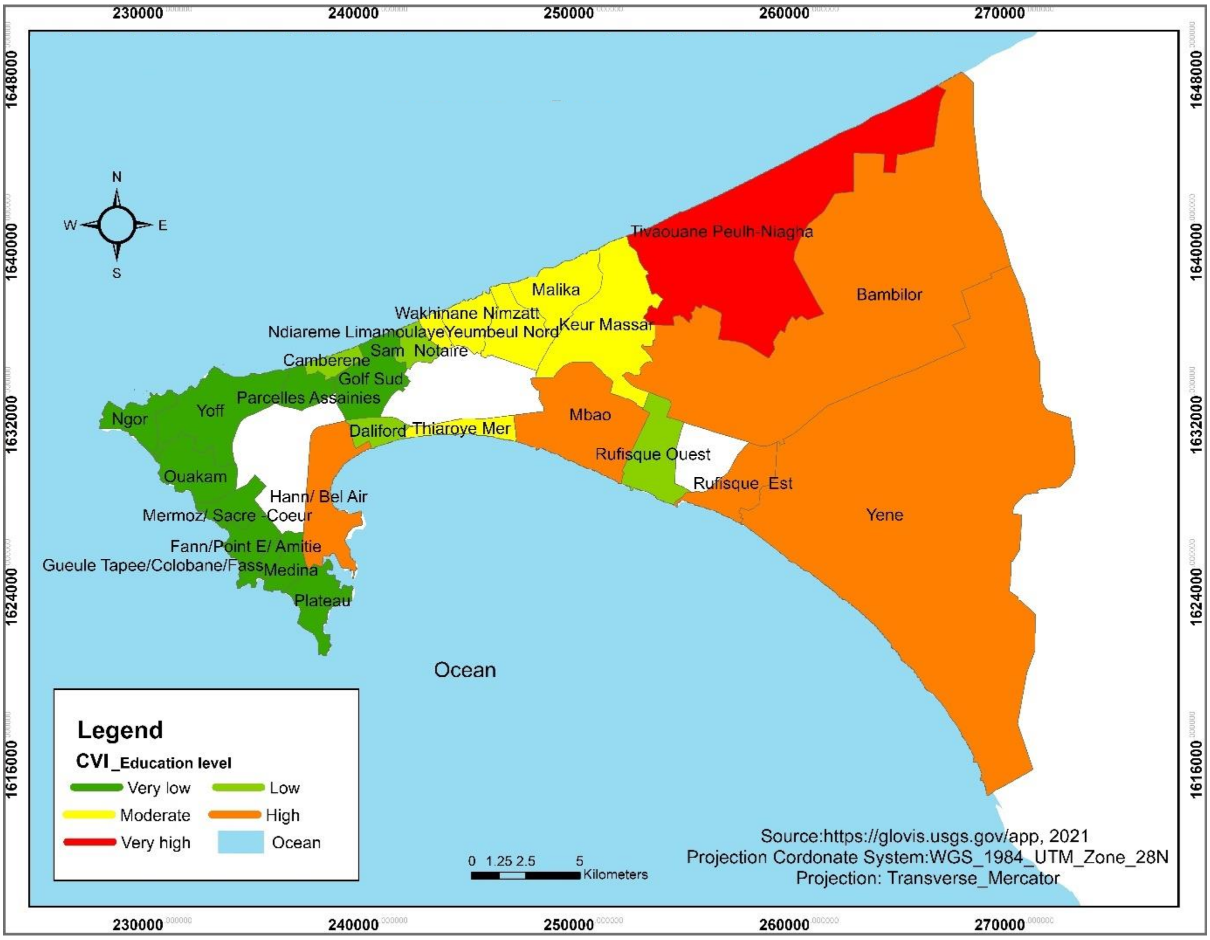


Figure 27: Coastal vulnerability map based on the education level of Dakar region

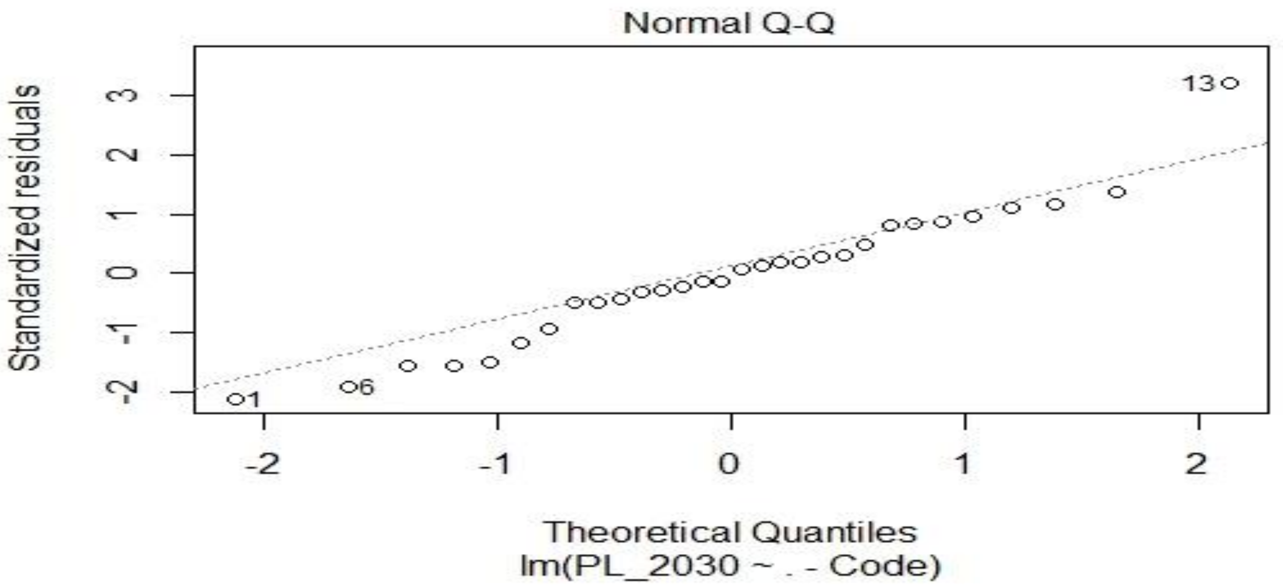


Figure 28: Simple linear regression model without diagnostics for 2030

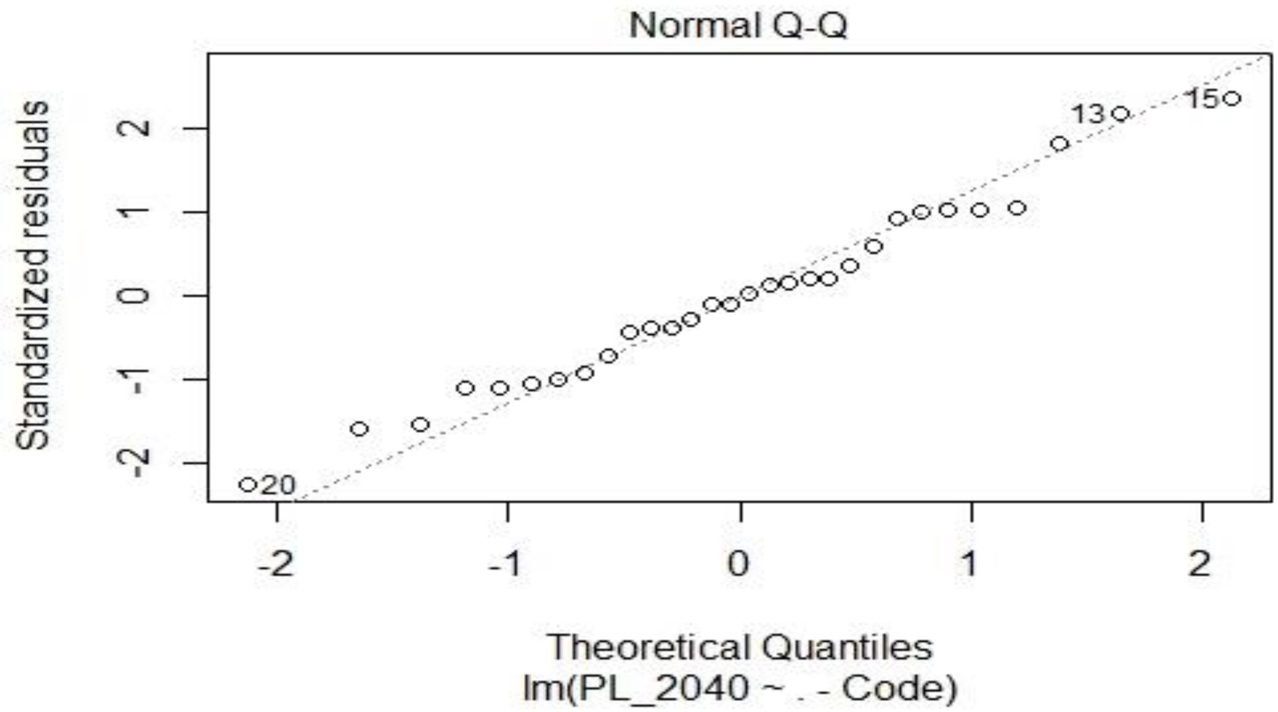


Figure 29: Simple linear regression model without diagnostics for 2040

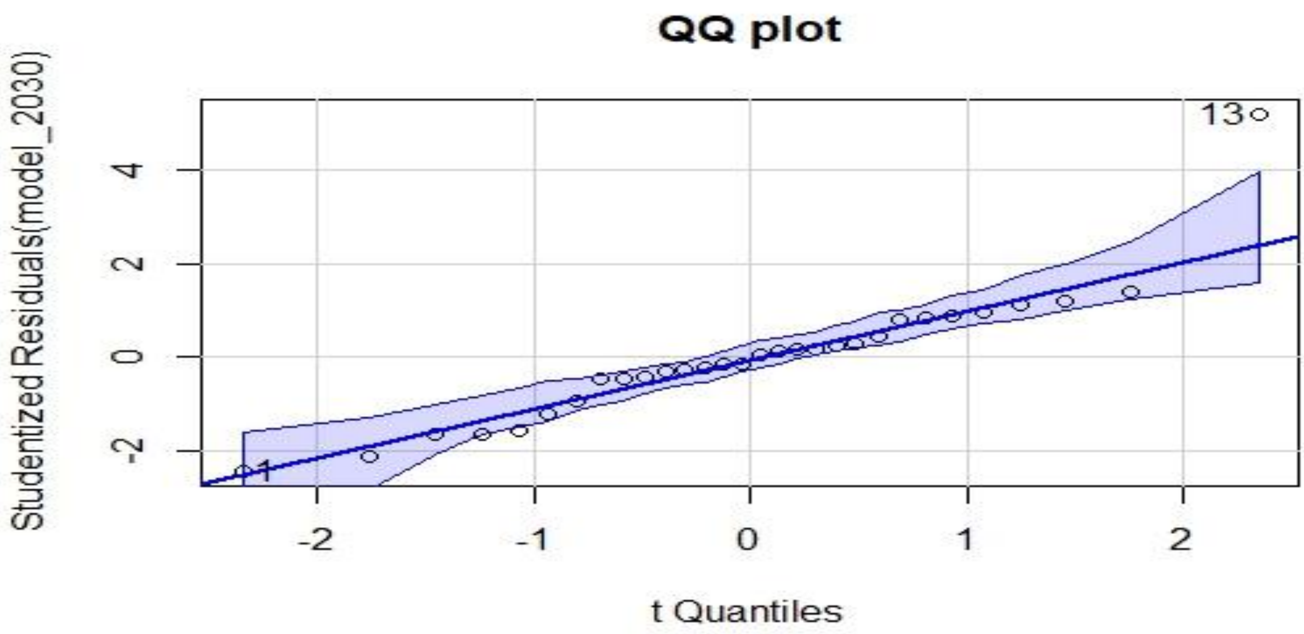


Figure 30: Outlier cheeking for 2030

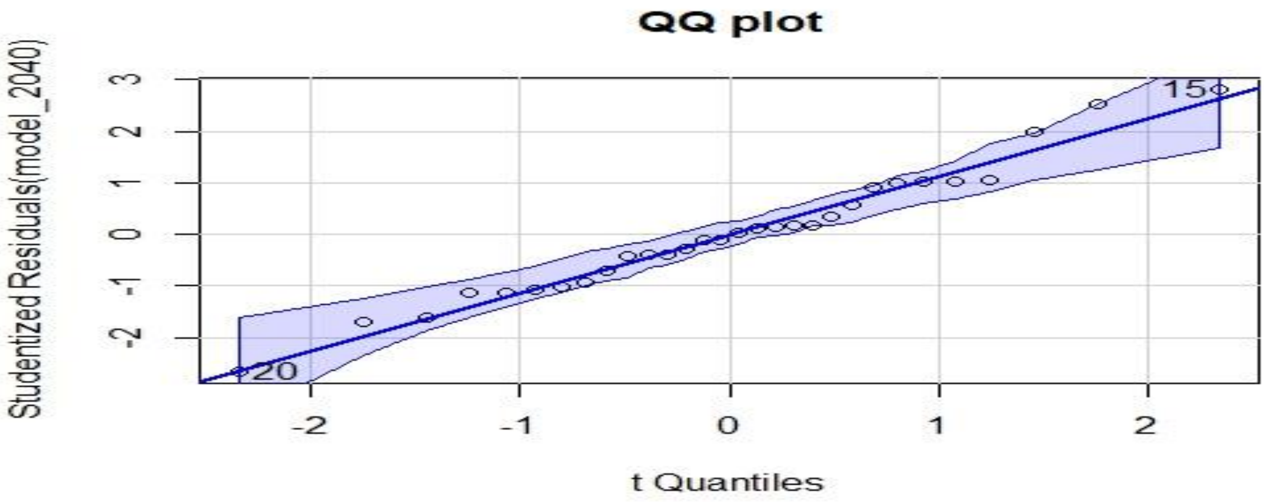


Figure 31: Outlier checking for 2040

QUESTIONNAIRE FOR LOCAL COMMUNITIES LIVING ALONG THE COAST OF DAKAR

2020-2023 - WASCAL

This survey is realized in the context of the thesis about past, present and future coastal erosion dynamics of Dakar, Senegal: climatological and socio environmental approaches. The aim of this survey is to depict coastal erosion issues on community, their perception about coastal erosion and some adequate measures about its effects.

I-Identification

1. What is your name?

2. What is your sex?

- O 1. Male
- O 2. Female

3. What is your occupation

4. What is your level of education

5. How old are you?

II-Community perception of coastal erosion

6. What is coastal erosion?

7. What do you think is the main cause of coastal erosion?

- O 1. Changes in sand supply to the beach Storms
- O 2. Sea level rise
- O 3. Low lying coastal areas
- O 4. Other causes
- O 5. Don't know

8. What do you think is the effects of coastal erosion on your habitations

- O 1. Sea spray affects houses materials
- O 2. Coastal flooding
- O 3. Covered houses in sand
- O 4. No effects
- O 5. I don't know

9. For each of the following statements do you agree or disagree?

- O 1. Inappropriate development in coastal areas can put houses at risk from erosion
- O 2. We must accept that erosion is a natural process at the coast
- O 3. There are a range of methods available to stop coastal erosion indefinitely
- O 4. The width of the dune changes during the years
- O 5. Once a dune is destroyed there is no way to bring it back

III-Economic cost of coastal erosion on community settlement

10. Did your household lose any of the following household appliances because of the water inundation, height wave or sea spray?

- O 1. Refrigerator
- O 2. Fan
- O 3. Radio
- O 4. Air conditioner
- O 5. Television
- O 6. Wall
- O 7. Door
- O 8. Window
- O 9. Roof
- O 10. Lock
- O 11. Tap
- O 12. Other (Describe)

11. How often do you change these lost household appliances?

12. What is the cost of these changes?

13. Are there abandoned houses in your locality due to coastal erosion?

- O 1. Yes
- O 2. No

14. Do you apply any kind of protection measures to prevent the effects of coastal erosion on your house?

- O 1. Yes
- O 2. No

15. If yes, describe the protection measures?

16. What is its cost?

Coastal erosion management

17. What do you think is the biggest challenges facing coastal management in Dakar?

- O 1. Limited resources
- O 2. Lack of political will
- O 3. Lack of political support
- O 4. Lack of scientific understanding
- O 5. Climate change
- O 6. Lack of public involvement
- O 7. Lack of public awareness
- O 8. Urbanization
- O 9. Pollution
- O 10. Other
- O 11. I don't know

18. Is adaptive management generally used in coastal management?

O 1. Yes O 2. No O 3. I don't know

19. If No, why? (Please specify)

20. What do you think about stakeholder participation is?

- O 1. Vital for sustainable coastal management
- O 2. Useful, but takes too much time and resources
- O 3. Is a waste of time and money
- O 4. Other
- O 5. I don't know

21. What do you think about public participation is?

- O 1. Vital for sustainable coastal management
- O 2. Useful, but takes too much time and resources
- O 3. Is a waste of time and money
- O 4. Other
- O 5. I don't know

22. Are there any protection measures to present or remediate coastal erosion in your locality?

O 1. Yes O 2. No

23. If yes describe it and tell us its efficiency?

24. Which forms of coastal management do you approve of? (Tick all that apply)

- O 1. Dune planting (To restore or maintain an adequate buffer zone)
- O 2. Construction of seawalls and rock walls
- O 3. Beach nourishment (adding extra sand)
- O 4. Moving of buildings back from the beachfront (managed retreat)
- O 5. Doing nothing (i. e. letting the sea dictate)
- O 6. Other options (please describe)

25. A good cover of plants on dunes... (tick one option only)

- O 1. Stops the beach eroding because their roots keep the sand from being washed away in storms
- O 2. Helps build up sand reserves by stopping it from blowing away, making a store of sand
- O 3. Won't help with beach erosion as the dunes come and go with the tides and winds
- O 4. Protects buildings built on dunes from erosion
- O 5. Unsure

26. Building a seawall on a sandy beach... (tick one option only)

- O 1. Protects beach-front properties from erosion indefinitely
- O 2. Only provides limited protection to the properties behind it
- O 3. Provides protection for properties immediately to the sides of the seawall
- O 4. Protects properties behind it from storm events of any size
- O 5. Unsure

27. The effect a seawall has on the natural behavior of a sandy beach... (tick one option)

- O 1. Is limited to the beach in front of the seawall
- O 2. Doesn't change the width of the beach
- O 3. Doesn't increase the effects of coastal erosion along other parts of the beach
- O 4. Can increase the effects of coastal erosion along other parts of the beach
- O 5. Unsure

28. In general, who do you think should fund coastal erosion control measures where private property is at risk? (tick all that apply)

- O 1. Private owners whose property is at risk
- O 2. Local communities or towns
- O 3. District community (e.g. via District Council rates)
- O 4. Regional community (e.g. via Regional Council rates)
- O 5. Government (via taxes)
- O 6. Other (please describe)

Interview guide to fishermen

2020-2023 - WASCAL

This interview guide is addressed to fishermen

Identification

1. What is your name?

2. How old are you?

3. What is your sexe?
○ 1. Male ○ 2. Female

4. What is your level of education?

Awareness

5. Do you know marine pollution?
○ 1. Yes ○ 2. No

6. If yes, what do you know about marine pollution?

7. What do you think are the causes of marine pollution?
- ☐ 1. Lack of sanitation
- ☐ 2. Lack of solid and liquid waste management
- ☐ 3. Lack of awareness
- ☐ 4. Other

Vous pouvez cocher plusieurs cases.

8. Is the area prone to marine pollution?
○ 1. Yes ○ 2. No

9. If yes, which kind of pollution exist in your locality?
- ☐ 1. Solid waste from household
- ☐ 2. Liquid waste from sewage
- ☐ 3. Liquid waste from industry
- ☐ 4. Other

Vous pouvez cocher plusieurs cases.

Effects of marine pollution on fishing activities/Exposure

10. What are the direct effects of marine pollution in fishing activities?
- ☐ 1. Migration of aquatic species elsewhere
- ☐ 2. Rarity of fishing products
- ☐ 3. Increase of infectious disease frequency
- ☐ 4. Other

Vous pouvez cocher plusieurs cases.

11. What are the indirect effects of marine pollution in fishing activities?
- ☐ 1. Low incomes
- ☐ 2. Reconversion of fishermen to other activities
- ☐ 3. Illegal migration of fishermen elsewhere
- ☐ 4. Fishermen families dislocation
- ☐ 5. reduction of ope
- ☐ 6. Other

Vous pouvez cocher plusieurs cases.

Perception on coastal erosion and its impacts on fishery activities

12. Do you kwnow coastal erosion?
○ 1. Yes ○ 2. No

13. What doyou think is the main causes of coastal erosion?
- ☐ 1. Changes in sand supply to the beach
- ☐ 2. Storms
- ☐ 3. Sea level rise
- ☐ 4. Low lying coastal areas
- ☐ 5. Other causes
- ☐ 6. Don't know

Vous pouvez cocher plusieurs cases.

14. What are the most challenged impact of coastal erosion on fishing activities?

- ☐ 1. Migration of aquatic species elsewhere
- ☐ 2. Rarity of fishing products
- ☐ 3. Increase of infectious disease frequency
- ☐ 4. Low incomes
- ☐ 5. Reconversion of fishermen to other activities
- ☐ 6. Illegal migration of fishermen elsewhere
- ☐ 7. Fishermen families dislocation
- ☐ 8. Reduction of ope
- ☐ 9. Other

Vous pouvez cocher plusieurs cases.

15. What is monthly income? [ ]

Susceptibility/Adaptive capacity/Resilience

16. Among this fishing infrastructures, which one do you dispose in your locality?

☐ 1. Fishing pier ☐ 2. Fish market ☐ 3. Fuel station
☐ 4. Fishing factories ☐ 5. Other

Vous pouvez cocher plusieurs cases.

17. Do you have health insurance for fishermen?

○ 1. Yes ○ 2. No

18. Do you have mutual credit for fishermen?

○ 1. Yes ○ 2. No

19. Do you have solid waste management structure?

○ 1. Yes ○ 2. No

20. If yes, in what frequence it works?

○ 1. One a month ○ 2. Twice a month
○ 3. Three times per month ○ 4. Other

21. If no, how do you manage your solid waste?

○ 1. Incinerarion ○ 2. Throw away trash in the sea
○ 3. Waste inhumation ○ 4. Other

22. Do you have sanitation for your liquid waste?

○ 1. Yes ○ 2. No

23. If no, how do you manage your liquid waste?

○ 1. Dumping toward the sea ○ 2. Other

24. Do you have any assistance from the authorities?

○ 1. Yes ○ 2. No

25. If yes, which kind of support?

- ○ 1. Modern facilities for fishermen
- ○ 2. Financial support
- ○ 3. Fishing license cost reduction
- ○ 4. awareness about the effects of marine pollution
- ○ 5. Other

26. What is your average income per month? [ ]

27. Is fishing your only source of income?

○ 1. Yes ○ 2. No

28. If yes, what is your other income source?

[ ]

INTERVIEW GUIDE ADDRESSED TO HOTELKEEPER

2020-2023 - WASCAL

This interview guide is addressed to hotelkeepers

I-Identification

1. What is your name?

2. What is your sex?
- ○ 1. Male ○ 2. Female

3. What is your level of education?

4. How old are you?

5. What is your monthly income?

II-Hotelkeeper perception of coastal erosion and its impacts on tourism activities

6. Do you kwnow coastal erosion?
- ○ 1. Yes ○ 2. No

7. What do you think is the main cause of coastal erosion?
- ○ 1. Changes in sand supply to the beach
- ○ 2. Storms
- ○ 3. Sea level rise
- ○ 4. Low lying coastal areas
- ○ 5. Other causes
- ○ 6. Don't know

8. For each of the following statements do you agree or disagree?
- ☐ 1. Inappropriate development in coastal areas can put hotel activities at risk from erosion
- ☐ 2. We must accept that erosion is a natural process at the coast
- ☐ 3. There are a range of methods available to stop coastal erosion indefinitely
- ☐ 4. The width of the dune changes during the years
- ☐ 5. Once a dune is destroyed there is no way to bring it back

Vous pouvez cocher plusieurs cases.

9. What are the most challenged impacts of coastal erosion on tourism activities?
- ☐ 1. Low incomes
- ☐ 2. Touristic infrastructures damage
- ☐ 3. Reconversion of hotelkeepers to other activities
- ☐ 4. Illegal migration of hotelkeeper elsewhere
- ☐ 5. Hotelkeeper's families dislocation
- ☐ 6. Reduction of operational area for hostelry
- ☐ 7. Other

Vous pouvez cocher plusieurs cases.

IV-Coastal erosion management regarding hostelry activity

10. Do you have a protective infrastructue?
- ○ 1. Yes ○ 2. No

11. If yes, Which kind of protective infrastructure do you have?
- ☐ 1. Gravel ☐ 2. protective wall ☐ 3. Vegetation
- ☐ 4. Other

Vous pouvez cocher plusieurs cases.

12. In general, which forms of coastal erosion management do you approve of for some sustainable hostelry activities?
- ☐ 1. Dune planting (To restore or maintain an adequate buffer zone)
- ☐ 2. Construction of seawalls and rock walls
- ☐ 3. Beach nourishment (adding extra sand)
- ☐ 4. Moving of hostelry infrastructures back from the beachfront
- ☐ 5. Doing nothing
- ☐ 6. Other options (please describe)

Vous pouvez cocher plusieurs cases.

13. A good cover of plants on dunes... (tick one option only)

- O 1. Stops the beach eroding because their roots keep the sand from being washed away in storms
- O 2. Helps build up sand reserves by stopping it from blowing away, making a store of sand
- O 3. Won't help with beach erosion as the dunes come and go with the tides and winds
- O 4. Protects buildings built on dunes from erosion
- O 5. Unsure

14. Building a seawall on a sandy beach... (tick one option only)

- O 1. Protects beach-front properties from erosion indefinitely
- O 2. Only provides limited protection to the properties behind it
- O 3. Provides protection for properties immediately to the sides of the seawall
- O 4. Protects properties behind it from storm events of any size
- O 5. Unsure

15. The effect a seawall has on the natural behavior of a sandy beach... (tick one option)

- O 1. Is limited to the beach in front of the seawall
- O 2. Doesn't change the width of the beach
- O 3. Doesn't increase the effects of coastal erosion along other parts of the beach
- O 4. Can increase the effects of coastal erosion along other parts of the beach
- O 5. Unsure

16. New adequate hostelry infrastructures ....

- ☐ 1. Reduce the effects of coastal erosion on hostelry activities
- ☐ 2. Doesn't have any effects to reduce the effects of coastal erosion on hostelry
- ☐ 3. Increase the incomes
- ☐ 4. Increase the incomes_
- ☐ 5. Unsure

Vous pouvez cocher plusieurs cases.

American Journal of Climate Change, 2022, 11, 23-36
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Coastline Dynamics Analysis in Dakar Region, Senegal from 1990 to 2040

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How to cite this paper: Pouye, I., Adjoussi, D. P., Ndione, J. A., Sall, A., Adjaho, K. D., & Gomez, M. L. A. (2021). Coastline Dynamics Analysis in Dakar Region, Senegal from 1990 to 2040. *American Journal of Climate Change, 11,* 23-36.
https://doi.org/10.4236/ajcc.2022.112002

Received: October 29, 2021
Accepted: May 6, 2022
Published: May 9, 2022

Abstract

In the context of climate change, the study of shoreline dynamics is a critical issue concerning economic losses in coastal countries. Therefore, since it is an important parameter to study the impacts of climate change in coastal areas, scientists are more interested in littoral studies seeking deep existential knowledge. This study aims to depict separately the coastal dynamics from 1990 to 2020 in Dakar region. The difference in terms of geologic, geomorphologic and hydrodynamic conditions within the three different coasts of Dakar and the prediction until 2040 have been taken into account in comparison to the previous studies. To achieve this purpose, the Geographic Information System (GIS) approach which is among the most current methods to determine the coastline dynamics is used. Historical Landsat images from the USGS, QGIS 3.12.0, Arc GIS 10.4 and DSAS software have been used for the Landsat images pre-processing and coastline dynamic computation. After obtaining the coastline velocity rate, some predictions of future coastline position have been estimated using the formula of velocity. The results showed that the Dakar region is characterized by an average rate of retreat about −0.44 m/year on the northern coast. The western and southern coasts record respectively a rate of about 0.21 and −0.11 m/year. In 2030, the average rates of retreat of −4.4, 2.1 and −1.1 m/year were estimated respectively in the northern, western and southern coasts.

Keywords

Coastline Dynamics, DSAS, Erosion, Accretion, Dakar Region

1. Background

The coastline is sometimes assimilated to the shoreline. However, there are some nuances and complexity both in terms of practice and semantics (Faye, 2010). Chand and Acharya (2010), state that "the shoreline is the boundary between land and water body. The term is considered synonymous with coastline but it considers different so the precise definition of shoreline is considered as the line contacting between the mean high-water line and the shore". According to Bird (2008), "the coastline is defined as the edge of the land at the limit of normal high spring tides; the subaerial land margin, often marked by the seaward boundary of terrestrial vegetation. On cliff coasts, it is taken as the cliff foot at high spring tide level. The shoreline is the water's edge, moving to and fro as the tides rise and fall so that there is a low-tide shoreline, a mid-tide shoreline, and a high-tide shoreline. Shorelines thus move to and fro as the tide rises and falls, whereas coastlines are submerged only in exceptional circumstances (e.g., during storm surges)." In this study, the shoreline is considered as the limit between the continent and the sea. Due to the frequency of extreme events such as storm surge, flooding, etc. particularly in coastal areas in a few decades in the past, scientists are more and more interested in the coastline dynamic study.

In fact, in the context of climate change, the recorded temperatures in the world show an increase in the global trend. Consequently, global warming is noted. The effects of this global warming on the hydrosphere and cryosphere cause an ice melting and dilatation of seawater leading in most coastal areas in the world a coastline retreat resulting in sea-level rise. The effects of this rising sea level combined with human activities such as sand mining and abnormal settlement lead to coastal erosion which is accentuated by the effects of hydrodynamic agents. Therefore, this situation leads to the reduction of coastal areas; human displacement toward inland; disruption of economic activities such as fishing, recreational, hotel and industrial activities. These threats are accentuated by humankind through sand mining, pollution and illegal settlements (Pouye, 2016). Dakar region, like most of the world's capitals, is not safe from the impacts of climate change and coastal erosion because of its geographical position and low-lying areas. Advanced sea resulting from the rise in sea level is affecting the coasts. Some studies have been focused on coastal erosion in Senegal particularly in the Dakar region (Niang-Diop, 1996; Faye, 2010; Weissenberger et al., 2016; Pouye, 2016; Bakhoum et al., 2018b).

2. Materials and Method

2.1. Study Area

The Dakar region is located in West Africa between 17˚10 and 17˚32 West long and 14˚53 and 14˚35 North latitude. It covers an area of 550 km^2 or 0.28% of the national territory. It is bordered to the east by the Thiès region and by the Atlantic Ocean in the northern, western, and southern parts (Pouye, 2016). Our study areas are all coastal zones in the Dakar region (133.69 kilometers) (Bakhoum et al., 2018a) i.e., 18.91% of the total coast of Senegal. Its delimitation is based on the different types of coasts: the sandy coast in the northern and southern part and the western coast which is composed of cliffs. The shapes of these different coasts are linked to geology, hydrodynamic, climatic, and morpho-pedological conditions. According to Adjoussi (2001), three different activities determine the geologic history of the Dakar region: volcanic activities, marine transgressions, and regressions which were observed from the pre-quaternary period up to the quaternary period in the Dakar region. This geology is marked by significant faults. The morphology of the two horsts is accentuated by the occurrence of recent volcanic cones composed of both volcanic ash and basaltic lavas. The horsts develop indented and cliffy shorelines that have preserved a less degraded structure. On such shorelines, the direct impact of waves is consequently reduced and slows erosion. The morpho-pedological conditions of the Dakar region are characterized by five formations: recent volcanic formation, formation on Maastrichtian sandstone (Cretaceous), formation on marl-limestone rocks (Paleocene-Eocene), recent Ergs and littoral formations. These morpho-pedological conditions are among the most key important factors that shape the coast. In addition, climate conditions far from being negligible play an important role in the coastal dynamic. The climate of the Dakar region can be determined by airline conditions which are the trade wind maritime, harmattan and the monsoon. In the coastal area, the wind is among the key factor in the coastal system generating swell, sea currents and waves and plays an important role in coastal sediment transport. However, the perturbation of these airline conditions in coastal zones accentuates coastal erosion through an increase in storm surge frequency, coastal flooding, dune retreats, dune disappearances, etc. At a global level, an increase in temperature leads to a rise in sea level. As a result, the coastline moves backwards causing a disturbance in coastal zones. By the presence of a seafront surrounding almost the whole of the Dakar region, it is characterized, during the year by a microclimate marked by the influence of the sea trade winds; hence the existence of a fresh and a quasi-permanent and relatively high humidity of around 25%. However, the harmattan, Saharan continental trade wind, is felt weakly in the dry season further away from the coast. The minimum temperature varies between 17˚C and 25˚C from December to April and from 27˚C to 30 C from May to November (ANSD, 2007).

The following **Figure 1** is about the location map of the coast of the Dakar region.

2.2. Data

The data used in this study are four different Landsat images from 1990, 2000, 2010, and 2020 which are Multi-Resolution Satellite Data (Landsat MSS, TM, ETM+, and OL_TIRS). These images are characterized by the provided satellite, sensor, path and row, the number of bands, and the acquisition date (**Table 1**).

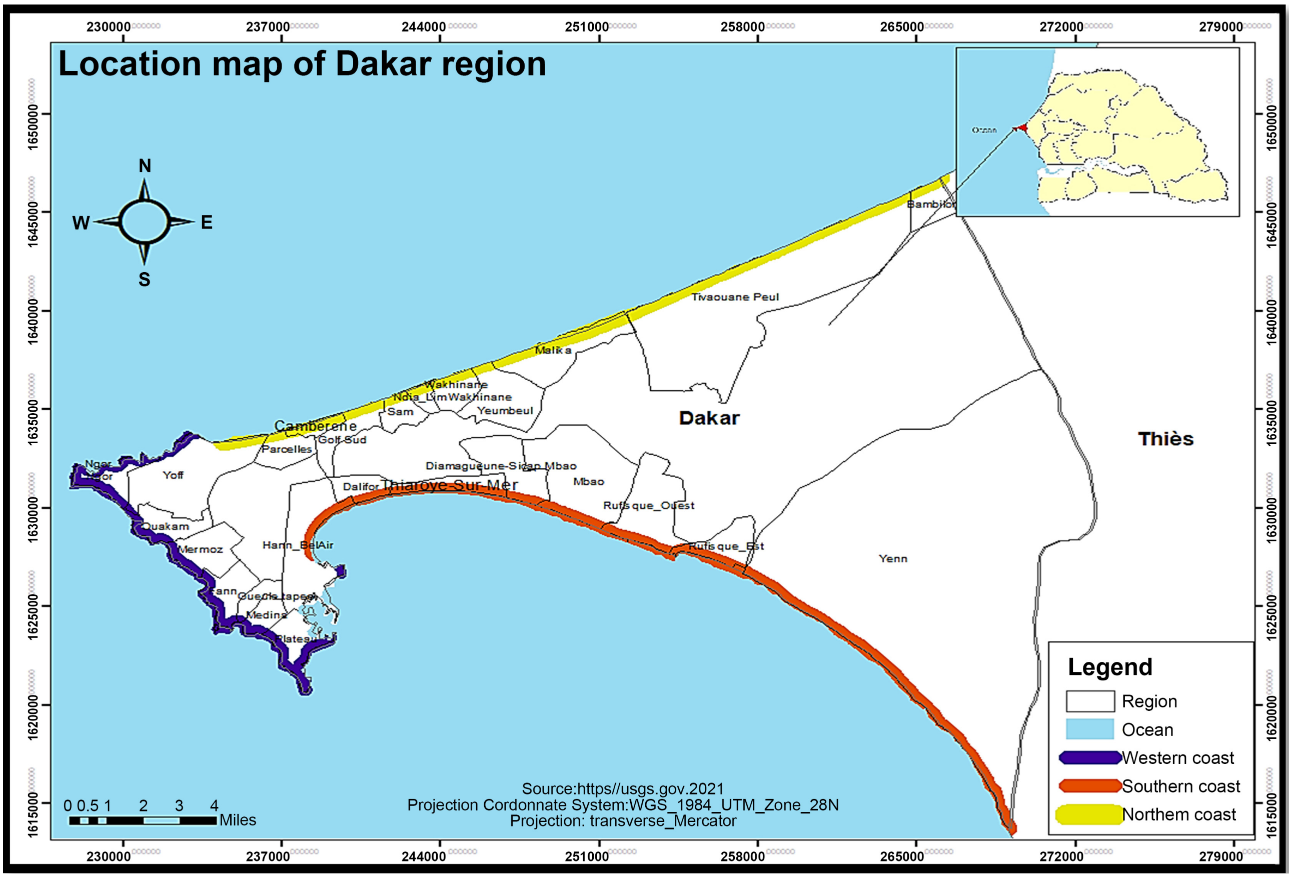

Figure 1. Location map of the coast of Dakar region. Source: glovis.usgs.gov.

Table 1. Landsat images' information (1990, 2000, 2010, and 2020) of Dakar region Senegal.

Satellite	Sensor	Path/Row	Band number	Resolution	Acquisition date
Landsat 5	TM	205/50	7	30 m	05/12/1990
Landsat 7	ETM	205/50	9	30 m	05/30/2000
Landsat 5	TM	205/50	7	30 m	10/25/2010
Landsat 8	OLI_TIRS	205/50	11	30 m	07/02/2020

Source: glovis.usgs.gov.

These maps were downloaded from USGS Global Visualization Viewer (GloVis) (glovis.usgs.gov).

2.3. Methods (Figure 2)

In this study, the Geographic Information System (GIS) approach is used to determine the shoreline dynamic in the Dakar region through the QGIS 3.12.0 and DSAS software which is an extension within the System Research Institute (ESRI) (Thieler et al., 2009). It is very useful to calculate, quantify, measure, and monitor the shoreline rate-of-change statistics from multiple historic shoreline positions and sources. The application of DSAS is in the use of polyline layers as

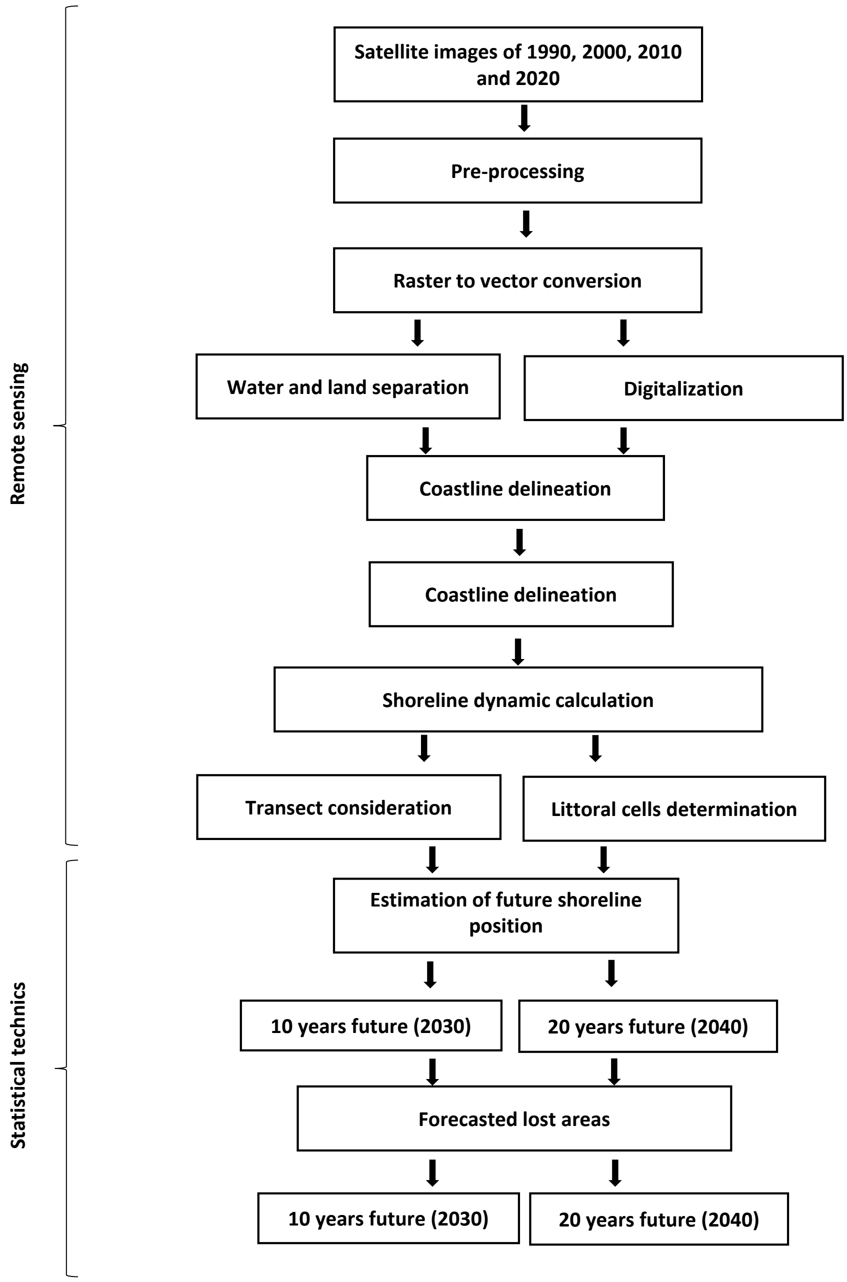

Figure 2. Flow chart showing the methodology adopted in this study inspired from Kumar, Narayana, & Jayappa (2010).

a representation of a specific shoreline feature at a particular point in time. A range of statistical change measures is divided within DSAS, based on the comparison of shoreline position through time. These include the Net Shoreline Movement (NSM), Shoreline Change Envelop (SCE), End Point Rate (EPR), Linear Regression Rate, and the Weighted Linear Regression (WLR) (Oyedotun, 2014).

2.3.1. Images Processing and Coastline Delineations

Landsat images for the years 1990, 2000, 2010, and 2020 were pre-processed in

QGIS 3.12.0. For that, the plugin SCP is installed. The following procedure was employed: go to Manager and install plugins and choose semi-automatic classification plugins and get the plugin SCP. In the SCP, go to Pre-processing and choose Landsat. In the section Directory Containing Landsat bands, load the Landsat images, and then for the section Selecting MTL file an MTL file would be loaded, and click on Run. As result, RT images which are undergone atmospheric correction with a resolution of about 30 meters and PAN Sharpening images done after atmospheric correction with a resolution of about 10 meters are observed. To have an image with high quality in terms of visibility and clarity, the loaded images must be merged. For the merging, go to Raster, and in this Raster section, click on Miscellaneous and Merge. The purpose of this pre-processing is to get high-quality images for better differentiation of the land and sea and accurate results.

The following Figure 3 is about the pre-processed images for the years 1990, 2000, 2010 and 2020.

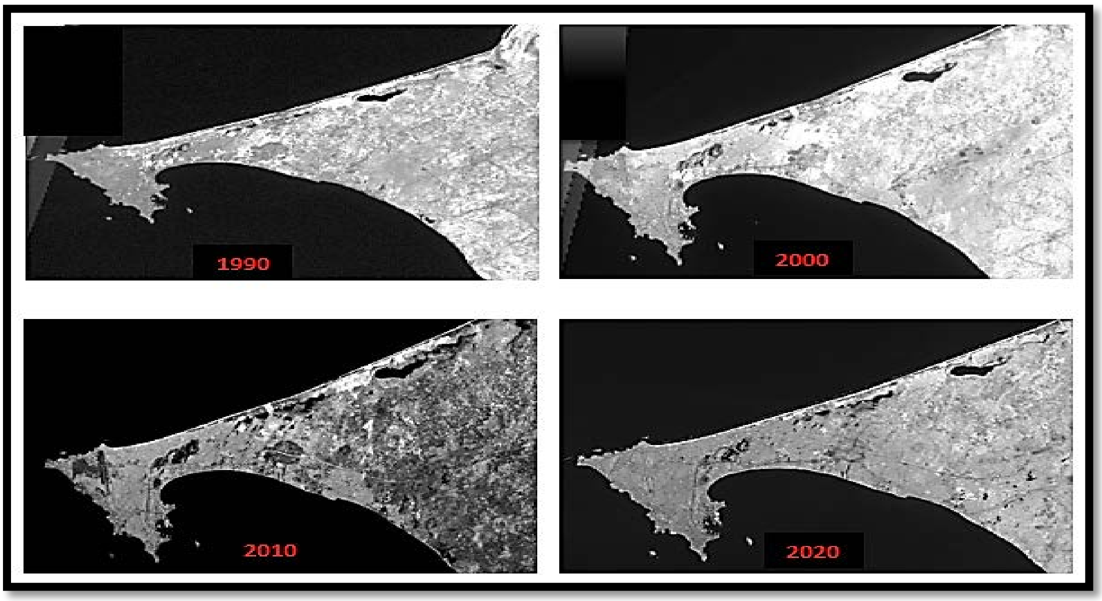

Figure 3. Four pre-processed Landsat images of the Dakar region (1990, 2000, 2010, and 2020). Source: glovis.usgs.gov.

After the processing of Landsat images, digitalization was performed to delineate the coastlines for the years 1990, 2000, 2010 and 2021.

2.3.2. Coastline Dynamic Calculation

The analysis of the coastline dynamics of the Dakar region from 1990 to 2020 is performed in the DSAS software which is an extension of ArcGIS. It is based on four different parameters: The Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), Linear Regression Rate (LRR).

❖ The Net Shoreline Movement is the distance between the most recent shorelines and the oldest shorelines for each transect and is measured in meters (m).

- The shoreline change Envelope (SCE) reports a distance (in meters), not a rate. The SCE value represents the greatest distance among the shorelines that intersect a given transect. As the total distance between two shorelines has no sign, the value for SCE is always positive. The transect rate file may be clipped to this span for display purposes (Himmelstoss et al., 2018).
- The End Point Rate (EPR) statistical method is computed by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and the youngest shorelines.
- The linear regression rate-of-change statistic can be determined by fitting a least-squares regression line to all shoreline points for a transect. The regression line is placed so that the sum of the squared residuals is minimized. It is the slope of the line. The method of linear regression includes these features: all data are used, regardless of changes in trend or accuracy, the method is purely computational, the calculation is based on accepted statistical concepts and the method is easy to employ (Dolan et al., 1991; Crowell et al., 1997 in Himmelstoss et al., 2018).

The coastline dynamic is an important parameter to study the evolution of the coast. It is not static whatever the type of coast and is very difficult to apprehend. According to Guariglia et al. (2006), due to specific events, the coastline position can be cyclical, long-term, or random. The cyclical changes of the coastline are linked to seasonality or tidal conditions. The long-term variations are due to the rising sea level or sand storing along the coast. The random variations are due to wave conditions, storms, or floods. In this random variation, the coastline can change in a very short period. To perform a study of the shoreline dynamics of the Dakar region using a GIS approach, a database is composed of different Landsat images from 1990, 2000, 2010, and 2020.

These images were pre-processed before depicting the coastlines. This pre-processing of images allows not only to make them more readable but also to enhance their quality. After the processing, images are digitalized to delineate the coastlines. Therefore, based on these coastlines, the shoreline velocity is evaluated between two dates for example 1990 and 2020. For that, the statistical method is computed by dividing the distance of shoreline movement by the time elapsed between the oldest and the youngest shorelines using the Digital Shoreline Analysis System (DSAS version 5) software which is an extension in Arc GIS 10.4. The advantage of this statistical method is that it is computed easily and does only require two shoreline dates through the shoreline through the Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR) and Linear Regression Rate (LRR) (Himmelstoss et al., 2018).

2.3.3. Prediction

In this study, predictions of the future shoreline positions and lost areas in 2030 and 2040 have been made. For that, a simulation is automatically performed using the Buffer tool based on the current velocity rate. For the prediction of the shoreline position, the formula of velocity V = Distance/Elapsed time between

2020, 2030 and 2040. If the year 2020 is taken as the origin, with a rate of change in the retreat of the coastline equal to X meters, it will emerge that assuming this average constant rate of change at that date, the coastline will retreat to a distance of Y meters in 2030 depending on its current position. For the predictions of the lost areas, the coastlines of the years 2020, 2030 and 2040 were merged. After that, the conversion of the merged shapefile to the polygon is performed from which the lost or gained area along the coast were determined.

2.3.4. Estimation of Uncertainty

All measurements are subject to error which analysis is an important part of any scientific experiment. The analysis of error is the evaluation of uncertainties which allow scientists to estimate the accuracy of their results and reduce uncertainties if necessary (Taylor, 1997). In this study, the estimation of the shoreline uncertainty using the End Point Rate of two shoreline positions (1990-2000) is computed by adding their square. The square root of the summation of squares is divided by the number of the year (10 years) between the two shorelines to determine the uncertainty of the End Point Rate (EPRunc) (Himmelstoss et al., 2018) (**Table 2**).

2.3.5. Limits of the Method

Despite the advantages of this statistical method (the easy computation of the shoreline dynamic through almost two shorelines), some limits are noted: in the Digital Shoreline Analysis System (DSAS) version 5.0 user guides: U.S. Geological Survey Open-File Report, it is stated that if there are more than two shorelines, certain additional information provided by shorelines are omitted. Some gap is also noted for example the changes in sign, magnitude, or cyclical trends (Himmelstoss et al., 2018) and the inability of the DSAS software to determine the forcing of morph dynamics (Oyedotun, 2014). In this study, four Landsat images (1990, 2000, 2010, and 2020) were used to analyze the coastline dynamic from 1990 to 2020. Therefore, it is better to work with more than two shorelines otherwise the LRR does not appear. In certain cases, one can work with only two coastlines for more accurate results but the LRR can be omitted. The tide aspect was not taken into account in this study.

3. Results

The following **Table 2** is about the Shoreline Change Envelope, Net Shoreline

Table 2. Uncertainty of short- and long-term shoreline change from 1990 to 2020.

Periods	Annual error (m/year)
1990-2000	±1.41
2000-2010	±1.36
2010-2020	±1.46
1990-2020	±0.47

Movement End Point Rate, and Linear Regression Rate of the Dakar region from 1990 to 2020.

The coastline dynamics analysis of the Dakar region from 1990 to 2020 shows two principal trends: erosion and accretion (**Table 3**).

Table 3. Shoreline dynamic statistics of Dakar region from 1990 to 2020.

Coasts	EPR (m/year)				Prediction of the coastline (m/year)		Forecasted lost areas (m^2)	
	1990-2000	2000-2010	2010-2020	1990-2020	2020-2030	2020-2040	2020-2030	2020-2040
Northern coast	0.45	−4.12	−2.57	−0.44	−4.4	−8.8	706,883	1,025,472
Western coast	−0.81	0.71	0.20	0.21	2.1	4.2	52,995	89,372
Southern coast	−0.08	0.13	0.29	−0.11	−1.1	−2.2	101,395	141,649

Source: Personal work.

4. Discussion

The analysis of the coastline dynamics in the Dakar region from 1990 to 2020 shows two principal trends: erosion and accretion. Since the hydrodynamic, geologic, geomorphologic, topographic conditions are not the same in the northern, western and southern coasts, it is obvious that the dynamic is different.

- **Northern coast**

Generally speaking, the coastline's trend of the northern coast of the Dakar region is mainly characterized by a high erosion (−0.44 m/year). This dynamic is justified by: the fact that the northern coast is under the predominant influence of the North-West swells which induce a coastal drift, directed towards the South (Pinson-Mouillot, 1980; Barusseau, 1980; Sall, 1982; Pedersen and Tarbotton, 1985 in Niang-Diop, 1996). In addition, the northern coast records powerful waves generated by winds. These waves play an important role in this dynamic since the coast is built by soft materials (mainly composed of sandy coastal dunes and marine beaches—Raw mineral soils), the wave force breaks on the coast bringing materials offshore. The wave force breaks on the coast accumulating the materials onshore generating dune retreats inland which is estimated by Niang-Diop (1996) about 200,000 and 1500,000 cubic meters per year. Due to this wave, swell conditions and sand mining activities, the northern coast records an average of all erosional rates about −1.4 m/year and an average of all accumulation rate of about 0.56 m/year. The district musicality of Malika where the higher erosion is recorded (−3.44 m/year) is the most truncated area in the northern coast of Dakar from 1990 to 2020 because it lodges the extension of the Mbeubeuss dump where sand mining activities also are operated (at least 100 tip trucks per day, i.e., about 5 million cubic meters per year are extracted) (**Figure 4**). This causes problems in sediment dynamics (Quensière et al., 2013). Despite the high dynamic, this northern coast is less vulnerable to coastal erosion due to the powerful dunes system which can be considered as a barrier between the sea and coastal infrastructures.

The following map is about the ERP of the northern coast of the Dakar region from 1990 to 2020.

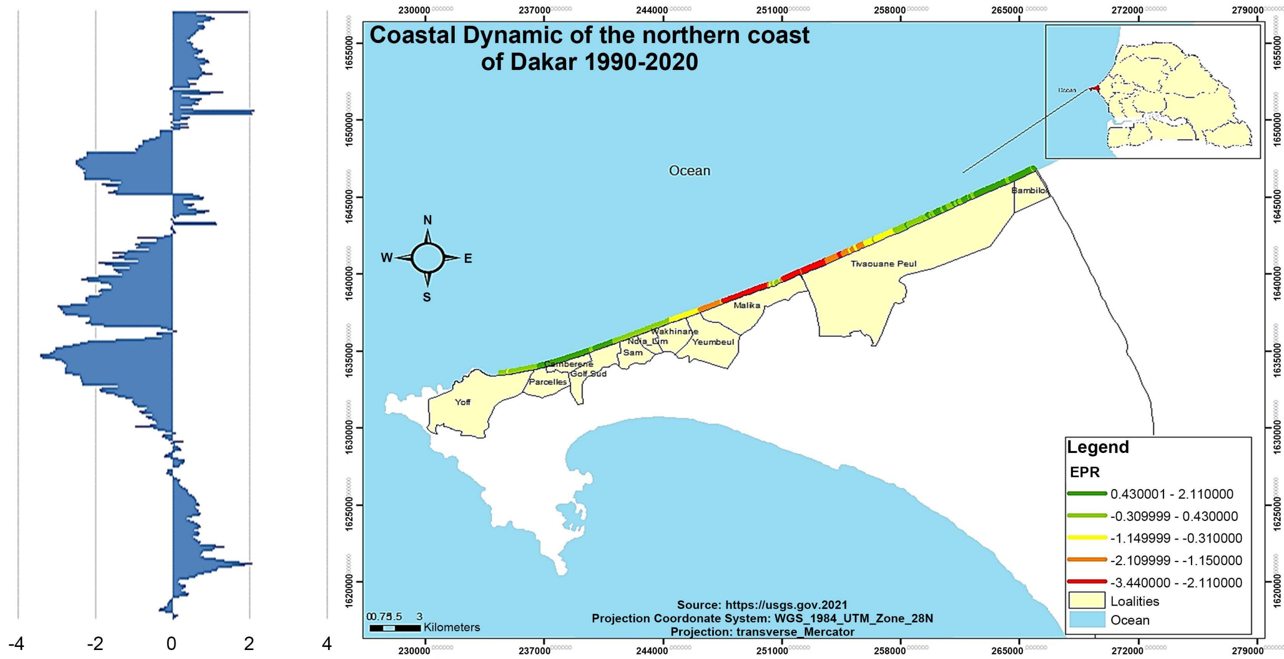

Figure 4. ERP of the northern coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

In 2030 and 2040, on the northern coast, an average rate of retreat of −4.4 and −8.8 m/year is estimated. The forecasted lost areas are estimated respectively in 2030 and 2040 about 706,883 and 1,025,472 m^2 causing a loss of coastal areas and infrastructures. For example, in the district municipality of Malika (which is the most locality at risk), the VDN highway will be affected disrupting the urban traffic and economic activities such as fishery activities in Yoff and Camberene. This situation is accentuated by the woodcutting activities for settlement habitat implantation in this locality (Malika). Dune retreats in these localities along the northern coast will be more intensified.

- **Western coast**

Whether the northern and southern coasts are all sandy, the western coast is characterized by cliff records with a dynamic rate of about 0.21 m/year (**Figure 5**). It is less exposed to erosion than the northern and southern coasts. The average of all erosional rates is about −0.35 m/year whereas the average of all accretional rates is about 0.50 m/year. This dynamic is justified by the nature of geologic, hydrodynamic and topographic conditions. Due to its geologic structure which is marked by volcanic rock such as basaltic, tuffaceous and sedimentary rocks generated (Sane & Yamagishi, 2004), the substratum of the western coast is not porous and do not allow important erosion dynamic rates. According to Strahler (2013), when the waves meet resistant rocks, the result is sea cliffs which on the hydraulic pressure of waves and the abrasion by rock fragments trust against the cliffs and sculpt the scarf. Consequently, the block rocks from cliffs fall in the surf zone and the coastline retreats gradually. In addition, this western coast is also less exposed to coastal erosion because it lodges the plateau of Dakar which where the latitude is above 50 meters (Sane & Yamagishi, 2004).

The following map is about the ERP of the western coast of the Dakar region from 1990 to 2020.

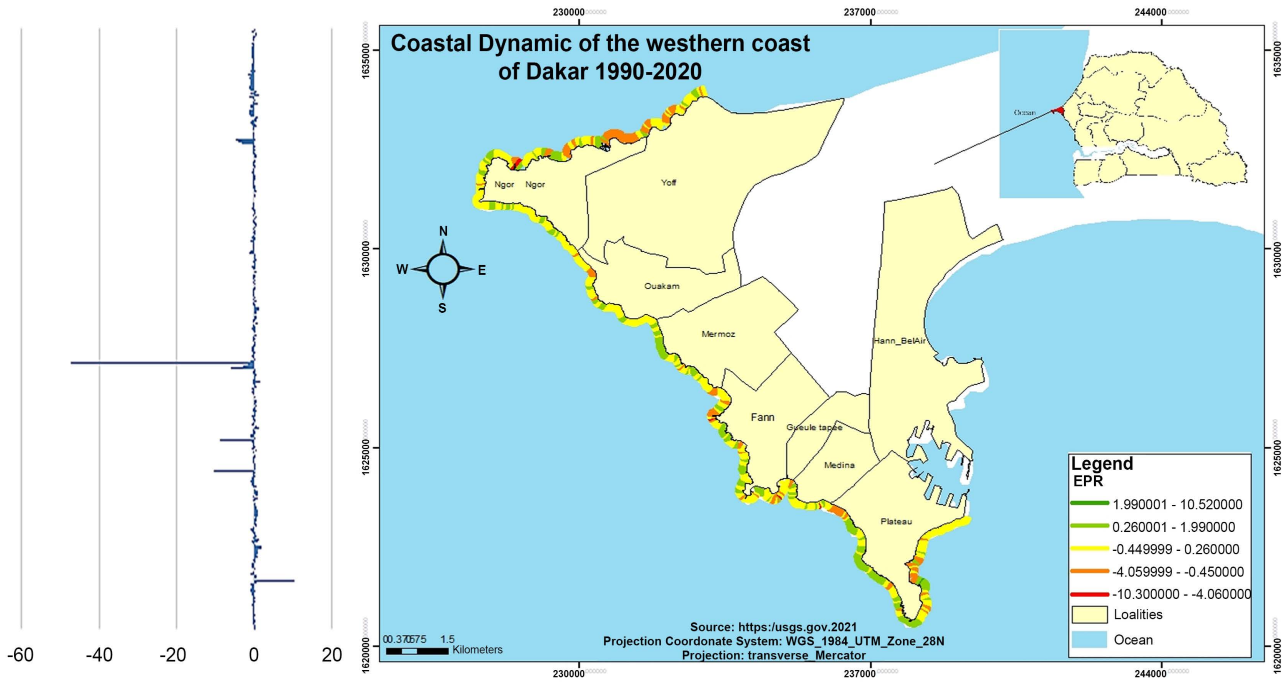

Figure 5. ERP of the western coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

On the western coast, the coastline dynamics are estimated in 2030 and 2040 respectively about 2.1 and 4.2 m/year. This loss of coastal areas is estimated at 52,995 m^2 in 2030 and 89,372 m^2 in 2040. Even if the western coast is globally less exposed to erosion due to its geologic and swell conditions, some coastal areas are subjected to erosion such as the Soumbedioune village which is among the most important fishing point in Senegal.

- **Southern coast**

The southern coast (from Hann to Djiffere) is segmented in a succession of capes and bays whose arrangement is controlled by tectonics. The sandy beaches are backed by a shallow barrier beach. This coast is subject to a northwest swell whose energy is reduced due to refraction and diffraction around the Cape-vert peninsula. Although a south-eastward coastal drift is present and the estimates of sediment transport indicate that the provision is much less important than along the northern coast, 10,500 to 300,000 cubic meters per year (Niang-Diop, 1996). In contrast to the north and west coast, the southern coast remains more vulnerable to erosion due not only to its high population but also the industrial and touristic infrastructures along the coast. An average rate of retreat with an uncertainty of about −0.11 +/− 0.47 m/year have been recorded, with the highest retreat (−1.38 m/year) noted on the coast of Rufisque east. This dynamic is also justified by the limestone plateau of the Bargny-Rufisque district, whose substratum is part of limestone and Marl of Eocene age. In addition, in the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion (Sane & Yamagishi, 2004).

The following map is about the ERP of the southern coast of the Dakar region from 1990 to 2020.

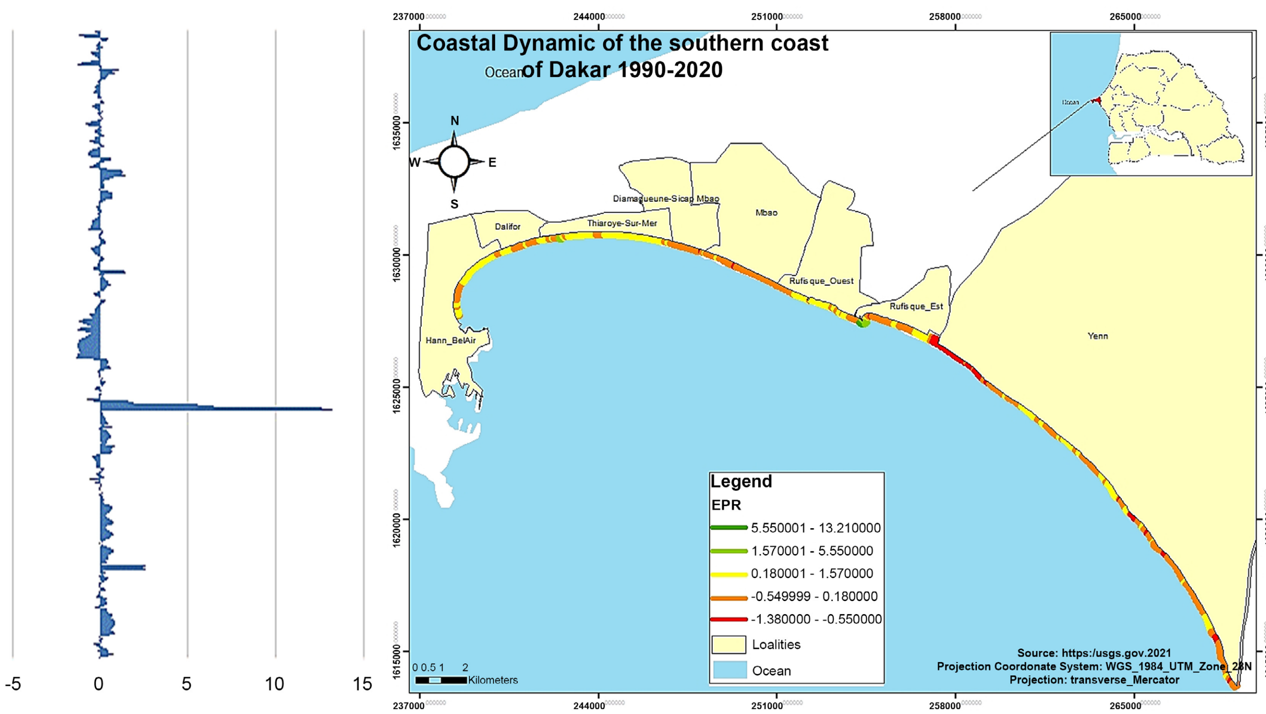

Figure 6. ERP of the southern coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

Being the most exposed to erosion due to its population and geologic and topographic conditions, the coastline dynamics are estimated in 2030 and 2040 respectively about −1.1 and −2.2 m/year in the southern coast of Dakar. These dynamic rates will generate a loss of coastal areas which is estimated at 101,395 m^2 in 2030 and 141,649 m^2 in 2040 (Figure 6).

5. Conclusion

In summary, the shoreline dynamic is generated by hydrodynamic, climatic, geologic, and morpho-pedologic conditions. It is an important parameter to analyze the climate change impacts in the coastal area. Dakar is among the most vulnerable regions in the world to coastal erosion due to its geographical position and low-lying area. In this study, the shoreline dynamic depiction is performed through the GIS approach using the DSAS tool which is an extension of ArcGIS software using four Landsat images (1990, 2000, 2010, and 2020). The results show that the region records the respective average rate retreats about −0.44 m/year, 0.21 m/year, and −0.11 m/year at the northern, western, and southern coasts. These rates are linked not only to the nature of the coasts but also to hydrodynamic agents' behaviors. Even if the hydrodynamic, geologic, climatic, and morpho-pedological conditions play an important role in the morphology of the littoral, human activities through the abnormal settlement and sand mining accentuate this erosion.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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coasts

Article

Topography, Slope and Geomorphology's Influences on Shoreline Dynamics along Dakar's Southern Coast, Senegal

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Abstract: Among the impacts of climate change in West Africa, coastal erosion is the most threatening disaster apart from floods and the increase in temperatures. The southern coast of the Dakar region, as part of the most threatened coastal zones in West Africa, records the most current coastal damages in Dakar due to its coastline dynamics and low-lying area. This paper investigates the influences of the topography and slope of the beach on shoreline dynamics using remote sensing, cartographic tools and statistical methods such as linear regression. It also states the important role of geomorphologic structures in shoreline dynamics. It was conducted in three littoral cells (Mbao, Bargny and Toubab Dialaw) along the southern coast of Dakar. It helps to understand better the role that topography, slope and geomorphology play in coastal dynamics. The Modified Normalized Difference Water Index (MNDWI) was employed to delineate the coastlines before computing the dynamic rate of the coastline using Digital Shoreline Analysis System (DSAS) software. After that, the topography and slope were determined using a digital elevation model (DEM). Then, the correlation between the coastline dynamic, topography and slope was analyzed using the coefficient of correlation and linear regression model. In the Mbao and Bargny littoral cells where the geomorphology is mostly dominated by soils little or not evolved in situ, there is a significant relationship between the coast line dynamic, topography and slope with a coefficient of correlation of about 0.63 and 0.87, respectively. The relationship is not significant in Toubab Dialaw, where the topography and slope are high, and the geomorphology is mainly characterized by a category of sandstone, with a coefficient of 0.15. We conclude that topography, slope and geomorphology play an important role in the shoreline dynamics in the study area.

Keywords: shoreline change; geomorphology; topography; correlation coefficient

Citation: Pouye, I.; Adjoussi, D.P.; Ndione, J.A.; Sall, A. Topography, Slope and Geomorphology's Influences on Shoreline Dynamics along Dakar's Southern Coast, Senegal. *Coasts* **2023**, *3*, 93–112. https://doi.org/10.3390/coasts3010006

Academic Editor: Enzo Pranzini

Received: 13 January 2023
Revised: 2 March 2023
Accepted: 7 March 2023
Published: 16 March 2023

1. Introduction

Due to climatic and hydrodynamics factors such as waves, wind, drift, tides, etc., coastal areas are the most dynamic zones in the world. Depending on the degree of porosity and the nature of sediment that composes the coast, they are subjected to changes. The drive factors for these changes are the geological and geomorphological, hydrodynamic, biological, climatic and anthropogenic conditions. Geologic conditions, characterized by the sediment structure type, arrangement, resistance and isostasy, are the basis of morphological processes and the development of coastal relief. In contrast, geomorphologic conditions are determined by climatic factors such as precipitation, rainfall and wind. These geologic and geomorphologic conditions are the generator of the forms of typical relief and sediment supply [1]. In addition, hydrodynamic factors such as waves and wind play an important role in coastal environmental change. If a wave breaks into weak or soft materials, the forward-moving water's force easily cuts into the littoral. It causes erosion, and the retreat of the shoreline is rapid. Wind is an essential key para- meter in hydrodynamic conditions and generates swell, waves and sea currents. It contributes to this erosion and performs two kinds of erosional work: deflation and abrasion. Deflation is the removal of particles, largely silt and clay, from the ground by the wind. It acts on loose soil or sediment. The second process of wind erosion, abrasion, drives sand-sized particles against an exposed rock or soil surface, wearing down the surface by the impact of the particles [2].

However, the normal functioning of these key generators of erosion is disturbed by climate change. This is a meaningful phenomenon which challenges the economic development and prowess of our environment. It is severe in many parts of the world. Most areas in the world are vulnerable to the impacts of climate change, such as advancing seas, coastal erosion, decreasing biodiversity, land salinity, the disappearance of human establishments, ocean acidification, fishing reduction and an unbalance between water supply and water demand, etc. The long-term and immediate impacts of climate change include its massive global effects and implications for small changes in the earth's orbit. Human actions have an effect on the atmosphere, ecology and seas, which results in a warming of the planet and an increase in air and marine temperatures. Extreme weather, heat waves, storms and flooding, forest fires, reduced safety, economic troubles, long-term effects on human health and the ecosystem, risks to water and food resources, and altitudinal and tree line shifts are all effects of climate change that we are currently experiencing [3]. Furthermore, climate change will accelerate the loss of biodiversity and dwindling freshwater and land resources and increase societal vulnerabilities, particularly in areas where the economies are highly dependent on natural resources [4]. West Africa makes a very small contribution to global climate change, but because of its position and poor capacity for adaptation, it is extremely sensitive to the consequences of climate variability and change. As they rely on rain-fed agriculture and ecosystem services, inhabitants in the dry parts of West Africa, in particular, suffer unfavorable effects from rising temperatures and fluctuating rainfall patterns. In various West African nations, flooding is another typical ha- zard brought on by the environment [5].

In this context, one of the most important effects of climate change on the coastal areas of many countries is sea-level rise. An increase in temperatures is anticipated in addition to the increasing sea levels (between 0.09 and 0.88 m by 2100). The sea level has risen by around 15 cm over the previous century, but due to melting land ice and warming ocean waters, the rate of rise has recently accelerated, and it is anticipated that the sea level will rise by another 30 cm over the next 50 years. The greenhouse effect has primarily been held responsible for this accelerating rate of sea-level rise. The ocean surface is predicted to warm by an extra 2 to 4 °C if atmospheric CO2 doubles during the next 100 years [6]. The rising sea level causes an aggravation of temporary submersion; extension of permanent submersion on low-lying areas; lagoon shores; maritime marshes; coral reefs; reinforcement of erosion actions on cliffs and beaches; increased salinization of estuaries; and reduction in the volume of freshwater aquifers [7]. The consequences of such a natural phenomenon affect the economy through the reduction of agricultural productivity and marine biodiversity, the risk of flooding of port and road infrastructure and the destruction of tourism facilities [8].

One of the effects of sea-level rise is coastal erosion. It is the most threatening disaster in Senegal apart from flooding. Therefore, the Dakar region, like most coastal cities in the world, is not safe from the impacts of coastal erosion. The advance of the sea resulting from the rise in sea level affects the coasts of Dakar [9]. Most tourist facilities are endangered, and up to 180,000 people could lose their homes [10]. Such impacts suggest that vulnerability to sea-level rises will increase substantially over the next few decades. At the local level, the coastal dynamics of the Dakar region show that there is indeed an advance in the sea, which is probably due to variations in oceanic waters aggravated by the effects of hydrodynamic agents, such as wave, tide, wind, geomorphologic and topographic conditions. Therefore, a reduction of coastal areas, human displacement toward inland and the disruption of economic activities (fishing, recreation and hotel and industrial activities) are noted. These threats are accentuated by humankind through sand mi- ning, pollution and illegal settlements along the coast [9].

When combined with the coast's low-lying nature and low socioeconomic and institutional development, these parameters would suggest that West Africa is vulnerable to sea-level rises. Large areas of land could be lost, and most of the threatened land is wetland areas within deltas or around estuaries and lagoons [10]. Therefore, to protect against coastal erosion, several means are used: protective walls, groin fields, reforestation, dikes, riprap, beach nourishment, dune restoration, beach draining systems and breakwaters. Among these means, some are more effective depending on their quality, their resistance duration against hydrodynamic conditions (swell, winds, sea currents and waves) and the type of coast where they are installed. According to Stewart et al. (2011), long-term coast management is an important and challenging task. Some challenges coastal managers face include maintaining and protecting public access and natural cha- racter, protecting people and property from natural hazards and sustainable planning and use of natural and physical resources [11]. Despite all the endeavors of West African countries against coastal erosion, the coasts are still challenged by this phenomenon. Nevertheless, it is important to note that the impacts of possible responses to sea-level rises vary at the local and regional scales.

This study aims to investigate the contribution of the topography, slope and geomorphological conditions in shoreline dynamics through the use of remote sensing, cartographic tools and statistical methods. The Modified Normalized Difference Water Index (MNDWI) was employed to delineate the coastlines before computing the dynamic rate of the coastline using Digital Shoreline Analysis System (DSAS) software. After that, the topography and slope were determined using a digital elevation model (DEM). Then, the correlation between the coastline dynamic, topography and slope was analyzed through the coefficient of correlation and multiple linear regression model.

2. Study Area

The southern coast of Dakar region is located between 14°43′ north latitude and 17°16′ west longitude. Its coastal length is estimated at 41 km. This study was conducted in three littoral cells (Mbao (3.9 km), Bargny (5.5 km) and Toubab Dialaw (4.9 km)) on the southern coast of the Dakar region (Figure 1). Approximately 500,000, or 17% of the regional population, live in the department of Rufisque [12]. It has infrastructures for industrial, artisanal and industrial fishing. It remains the most vulnerable to erosion due to its high population and the industrial and tourist infrastructures along the coast. The southern coast comprises two maritime facades to the north and south. Its climate is determined by airline conditions. Geographical and atmospheric conditions strongly influence the climate. Three types of wind are noted: the trade wind maritime, harmattan and monsoon. The wind is among the critical factors in the coastal systems generating swell, sea currents and waves and plays an important role in coastal sediment transport. However, the perturbation of these airline conditions in coastal zones accentuates coastal erosion through an increase in storm surge frequency, coastal flooding, dune retreats, dune disappearances, etc. [9]. The southern coast is subjected to a northwest swell whose energy is reduced due to refraction and diffraction around the Cap-Vert Peninsula and the southwest swell, which is more noticeable during the rainy season. Offshore, its energy is lower than the northwest swell (11 $kW.m^{-1}$ vs. 18 $kW.m^{-1}$) [13–15]. The northwest swell reaches a depth of 13 m with a minimum direction of N200°. Due to its low occurrence and low offshore energy, the importance of this type of swell could be minimized [16,17].

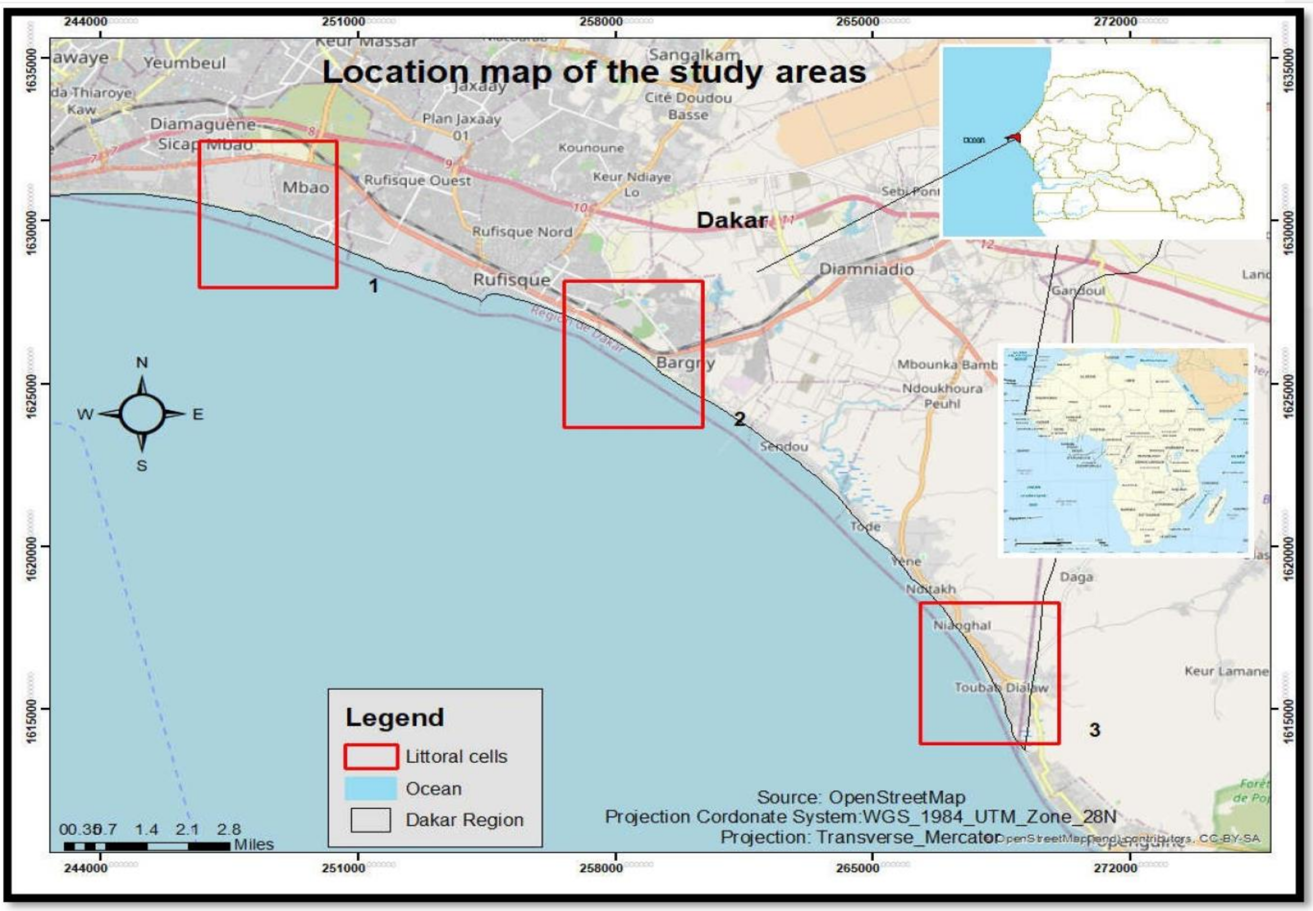

Figure 1. Location map of the study areas. Source: OpenStreetMap.

The lithology of the southern coast from Mbao to Bargny is marked by outcrops of Lower Eocene (Ypresian) formations with white marl and grey marl and Middle Eocene or Lutetian formations characterized by Bargny limestone, Thiore and Dakh-Abdak marl and limestone. There are also volcanic formations of the Miocene age. The Quaternary is represented by four main types of formations, namely the beach sandstones or beach rocks with an altitude of 1 to 2 m above sea level, the Ogolian dunes of the erg of Pikine with a height of 3 to 7 m and the Nouakchottennes, which are sandy–clay stretches with an a-verage altitude of 2 m above sea level. These formations, from the Ypresian to the Lutetian, are organized in a monoclinal series with a dip of 6 to 12° [15].

The geomorphologic and morpho-pedologic conditions are essential in the morphology and natural coastal erosion dynamic. The limestone plateau of the Bargny–Rufisque district, whose substratum is part limestone and marl from the Eocene age, is found. Geomorphological units are portrayed by low topography, high porousness and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion [18]. These characteristics are marked by five for mations: recent volcanic formation, formation on Maastrichtian sandstone (Cretaceous), formation on marl–limestone rocks (Paleocene–Eocene), recent Ergs and littoral formations. The Cap-Vert Peninsula in Senegal has been the site of si-gnificant magmatic activity. The recent volcanic formation is composed of a Basaltic spread, a low-leaching tropical ferruginous soil on complex material in the head of the Dakar region. These volcanic rocks are scattered over 7000 km^2 from Dakar to the east of Thiès [19]. The formation of Maastrichtian sandstone (Cretaceous) can be found in trays and small valley zones and is composed of two types of sediment, lithosols and regosols, on cuirass dismantled on sandstone, which can be found in the tray zones at the center of Dakar and the north close to the coastal dunes and tropical ferruginous soils with little or no leaching and on colluviums, which appear in small valley zones. (Regosols in the World Reference Base for Soil Resources (WRB) are very weakly developed mineral soils in unconsolidated materials. Regosols are extensively eroded lands, particularly in arid and semi-arid areas and mountain regions [20]). The formation of marl–limestone rocks (Paleocene–Eocene) can be found in trays, alluvial plains, cliff zones and the edges of pla-teaus and are composed successively by vertic hydromorphic soils on clayey marly–limestone material, which is strongly tirsified; deep hydromorphic soils on sandy–clayey alluviums; hydromorphic soils on various materials; erosion Rendzina on marl–limestone rocks; and hydromorphic soils on limestone colluvium. (Rendzina soils typically develop from solid or unconsolidated rocky material that is carbonate- or sulphate-rich. Limestone is the most common, but others include dolomite, gypsum, marble, chalk and marlstone [21]). The recent Ergs are composed of inland dunes and coastal dunes: hydromorphic soils in the Niayes area and low-leaching tropical ferruginous soils. Three sediments characterize the littoral formations: sharp coastal dunes and marine beaches—raw mineral soils; semi-fixed coastal dunes—raw mineral soils and holomorphic soils on clayey material; and slightly evolved soils on exuding sands [22]. (The pedogenic process of salinization forms holomorphic soils. The areas where silts and clays make up a large proportion of the soil body are called holomorphic soil [23]).

In our study areas, the composition of the geomorphologic conditions is different regarding the nature of rocks and sediment, their permeability and porousness. Therefore, Mbao littoral cell's geomorphology is characterized by soils that have little or not evolved in situ (wind soils); soils more or less developed in situ after significant mechanical action; sands; a group of erosion Rendzinas with Rendzine on marly limestone; and the category of sandy–clay colluvium and alluvium. (Colluvium can be defined as being produced by mass–gravity-driven transport on steep slopes, and alluvium is produced by water-driven transport on floodplains and wind soil [24]). Alluvium is loose clay, silt, sand or gravel deposited by running water in a stream bed, on a floodplain, in an alluvial fan or beach or similar settings [24]). In Bargny, the following geomorphologic features are distinctive: soils that have little or not evolved in situ (wind soils); the category of sandy–clay alluvium; and soils more or less developed in situ after significant mechanical action. Depleted sandstone; eolian soil; Dior soils on sandy–clay colluvium; and soils that have little or not evolved in situ are the defining features of Toubab Dialaw (Figure 2). (Dior soils constitute the wealth of Senegal; the dunes they form are highly favorable to peanut cultivation, whereas the soils between the dunes are suitable for other food crops, such as sorghum [25]).

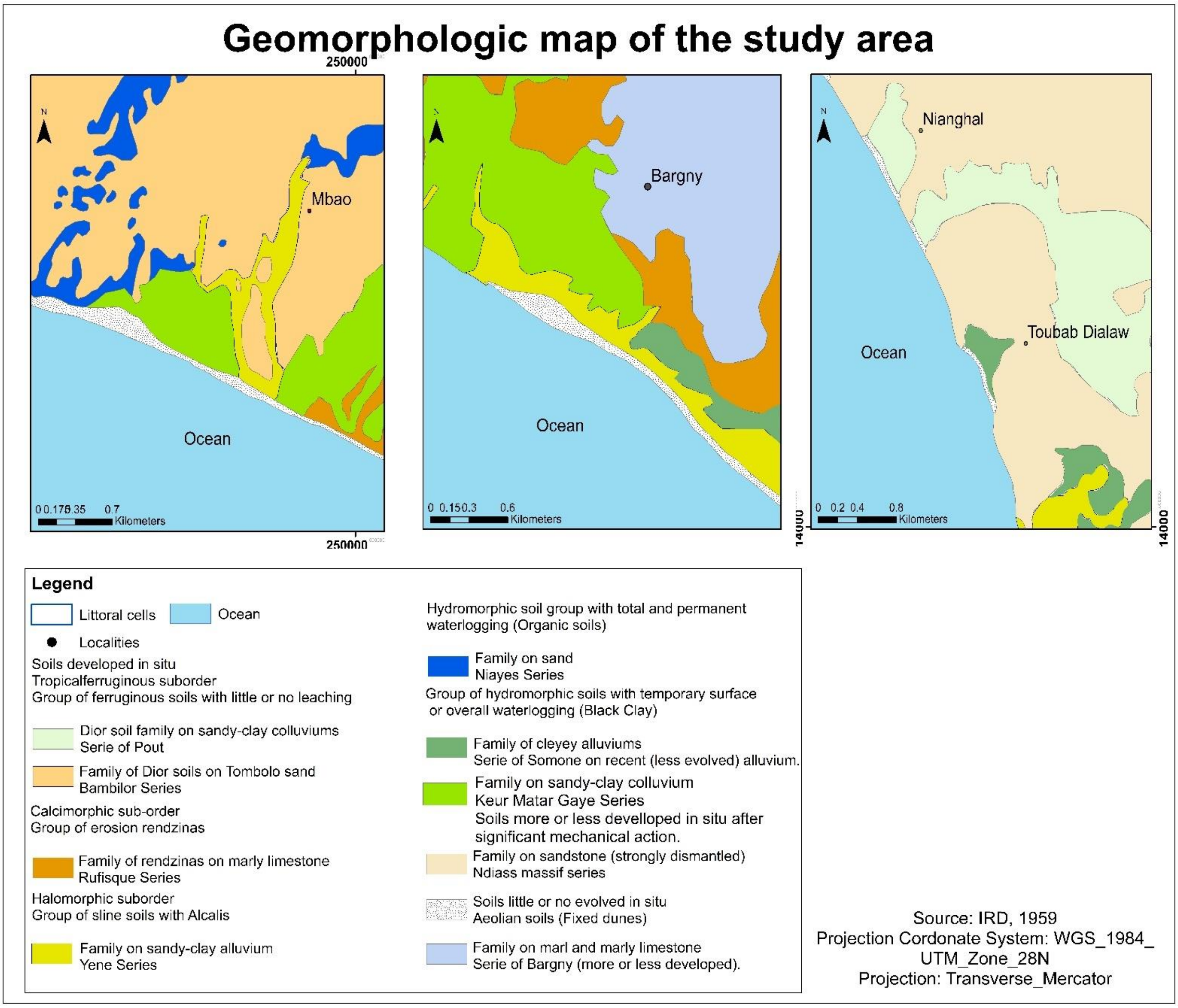

Figure 2. Geomorphologic conditions of the Mbao, Bargny and Toubab Dialaw littoral cells. Source: IRD, 1959.

3. Materials and Methods

In this study, remote sensing and statistical techniques were used to analyze the relationship between coastline dynamics and topography and slope conditions. Using the historical Landsat images, the Modified Normalized Difference Water Index (MNDWI) was employed to delineate the coastlines before computing their evolution rate. After that, the relationship between the coastline dynamic rate, topographic and slope conditions was analyzed through the correlation coefficient and linear regression model. The following flow chart summarizes the methodology employed in this study (Figure 3).

3.1. Data Source

The data used in this study are five different Landsat images from 1980, 1990, 2000, 2010 and 2020. These images are characterized by the provided satellite, sensor, path and row, the number of bands and the acquisition date. Topographic data from GLO-30 DEM and geomorphologic data from the website (http://sphaera.cartographie.ird.fr/ (accessed on 7 May 2022)) were also employed.

The following table summarizes all helpful information related to the different Landsat images (Table 1).

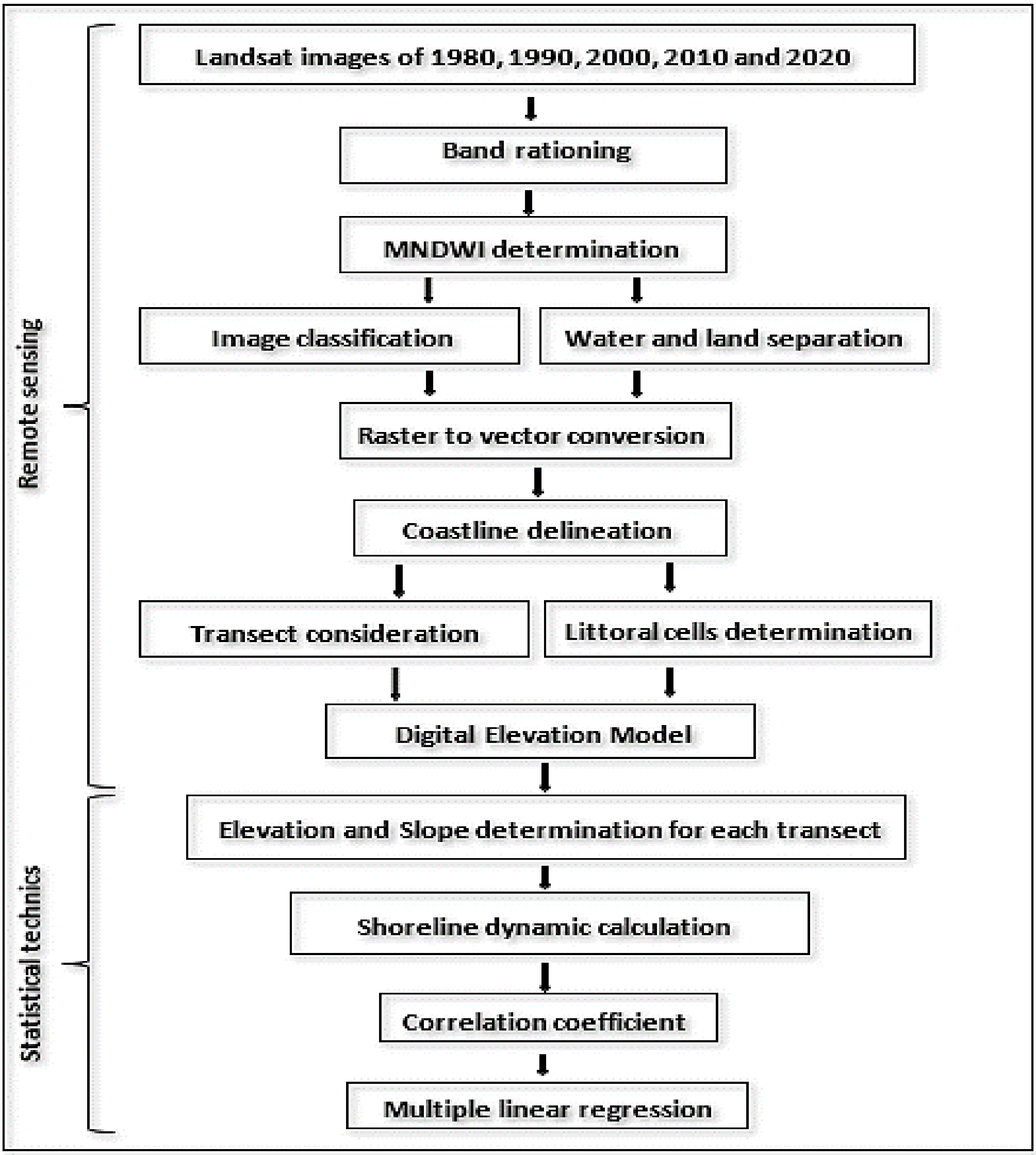

Figure 3. Flow chart summarizing the methodology adopted in this study [26] accessed on 9 July 2021.

These Landsat images were processed using the QGIS software's semi-automatic classification plugin. According to Congedo (2021), a semi-automatic classification plugin was created in Python to make land cover monitoring easier. By simplifying and automating the land cover classification phases, from downloading remote sensing data to analysis, it offers a set of interconnected tools and a user interface. It enables image processing with tools for classifying or analyzing land cover. Additionally, it permits post-processing using instruments to enhance and assess the classification's accuracy or incorporate additional data [27]. After processing of the images, the Modified Normalized Difference Water Index (MNDWI) is used for the coastline delineations.

Table 1. Landsat image information (1980, 1990, 2000, 2010 and 2020) for Dakar region, Senegal.

Satellite	Sensor	Path/Row	Number of Bands	Resolution	Acquisition Date
Landsat 3	MSS	221/50	4	60 m	12 June 1980
Landsat 5	TM	205/50	7	30 m	12 May 1990
Landsat 7	ETM+	205/50	9	30 m	30 May 2000
Landsat 5	TM	205/50	7	30 m	25 October 2010
Landsat 8	OLI_TIRS	205/50	11	30 m	2 July 2020

Source: glovis.usgs.gov.

3.2. The Use of the Modified Normalized Difference Water Index (MNDWI)

To better dissociate the land surface and sea, the Modified Normalized Difference Water Index (MNDWI) was used in this study (Figure 4). For that, the band rationing technique was employed using near infrared (NIR) and short-wave infrared (SWIR) [28]. The bands 2 and 5 for Landsat 5 TM and Landsat 7 were used. For Landsat 8, bands 3 and 6 were used. In MNDWI, the highest value is +1, and the lowest is −1. The threshold value for classification is 0.

$$MNDWI = (GREEN) - (SWIR)/(GREEN) + (SWIR) \quad (1)$$

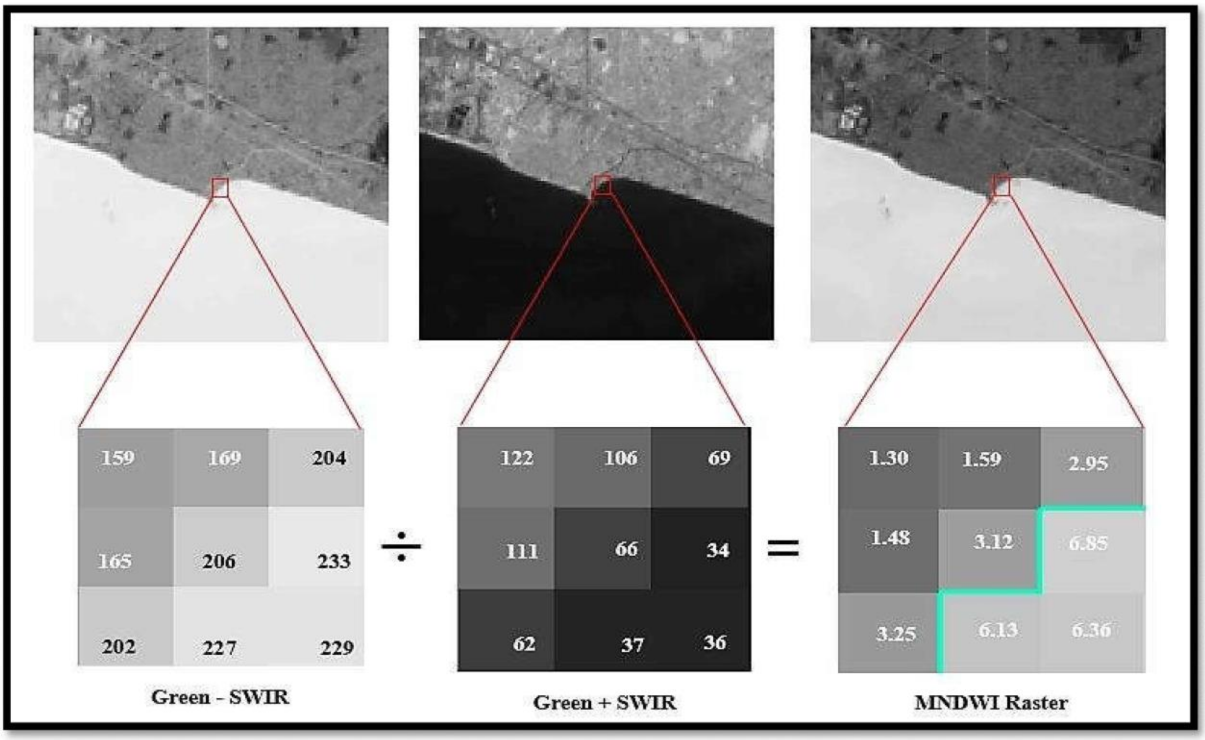

Figure 4. Band rationing of Landsat-OLI imagery of the southern coast for delineating the shoreline. Source: glovis.usgs.gov.

The Modified Normalized Difference Water Index (MNDWI) originates from the Normalized Difference Water Index (NDWI), which is calculated using two near-infrared channels. These two indices are enhancement techniques using band rationing. According to Gao (1996), the NDWI is used for remote sensing vegetation liquid water interacting with solar radiation [29]. In a study, McFeeters (1996) stated that this NDWI takes benefits from the condition where the presence of features that show higher near-infrared reflectance and lower red light reflectance (e.g., terrestrial vegetation) will be enhanced, while those with low red light reflectance and very low NIR reflectance (e.g., water) will be suppressed or eliminated [30]. This NDWI is modified by substituting a middle infrared band, such as Landsat TM band 5, for the near-infrared band used in the NDWI. To enhance and extract water information in the water regions where the background is dominated by built-up land areas, the MNDWI is more suitable than the NDWI because it reduces or even removes built-up land and vegetation noise [31] (Figure 4).

3.3. Classification, Digitalization and Coastline Delineations

Landsat images for each year (1980, 1990, 2000, 2010 and 2020) from the MNDWI calculation were used to analyze the coastline dynamics. The MNDWI images were classified to distinguish the land and sea boundary. Note the threshold value for classification is 0. Next, these classified raster images were converted to vector layers from which the coastline was delineated using the editing tool in arcGIS (Figure 5).

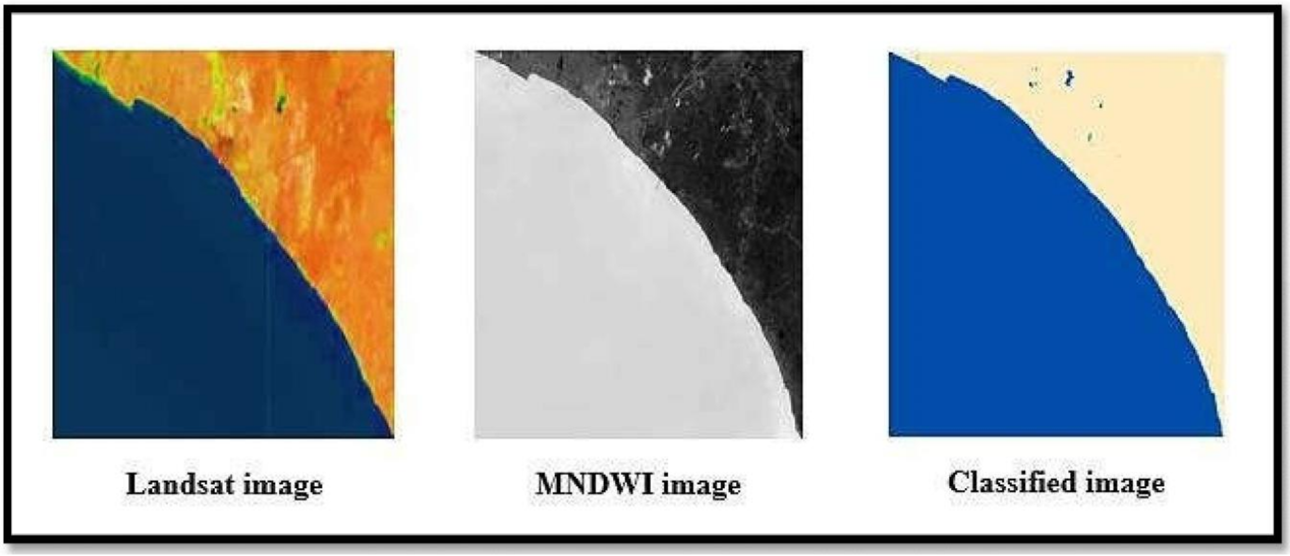

Figure 5. The classified image based on the MNDWI of the southern coast of Dakar.

3.4. Shoreline Dynamic Calculation

Two methods were used to analyze the shoreline retreat in Senegal over time. The first one was primarily concerned with interpreting old geological maps in relation to sea levels. The second method involved analyzing modern geospatial tools that included ae-rial photos and cadastral maps. Nonetheless, the accessibility of satellite pictures and various computerized geospatial analytic techniques has benefited the monitoring of coastal erosion [32]. In this study, satellite images and Digital Shoreline Analysis System (DSAS) software, which is an extension in Arc GIS 10.7, are used for the shoreline velocity between 1980 and 2020. For that, the distance of shoreline movement is divided by the time elapsed between the oldest and the youngest shorelines. The advantage of this statistical method is that the dynamic rate is computed easily through the end point rate (EPR) [33]:

$$EPR = NSM/TE \tag{2}$$

where:

- EPR = end point rate (EPR) statistical method is computed by dividing the net shoreline movement (NSM) by the time elapsed between the oldest and the youngest shorelines;
- NSM = net shoreline movement is the distance between the most recent shorelines and the oldest shorelines for each transect and is measured in meters (m);
- ET = elapsed time between 1980 and 2020 [33–39].

3.5. Littoral Cells and Transect Determinations

According to Inman (2005), a littoral cell is a coastal compartment containing a complete sedimentation cycle, including sources, transport paths and sinks. The cell boundaries delineate the geographical area within which the sediment budget is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. The sediment sources are commonly streams, sea cliff erosion, onshore migration of sandbanks and material of biological origin such as shells, coral fragments and skeletons of tiny marine organisms. The usual transport path is along the coast by waves and currents (longshore transport, longshore drift or littoral drift). Cross-shore (on/offshore) paths may include windblown sand, overwash and ice-push. The sediment sinks are usually offshore losses at submarine canyons and shoals or onshore dune migration, rollover and deposition in bays and estuaries [34]. This study has considered three littoral cells: Mbao, Bargny and Toubab Dialaw on the southern coast of Dakar. In each littoral cell, over 80 transects were taken into account, and the distance between two transects is estimated at 50 m (Figure 6). For each transect, the coastline dynamic rate, average topographic values of 5 intersects (1980, 1990, 2000, 2010 and 2020) (Figure 7) and slope value was employed to a-nalyze their relationship.

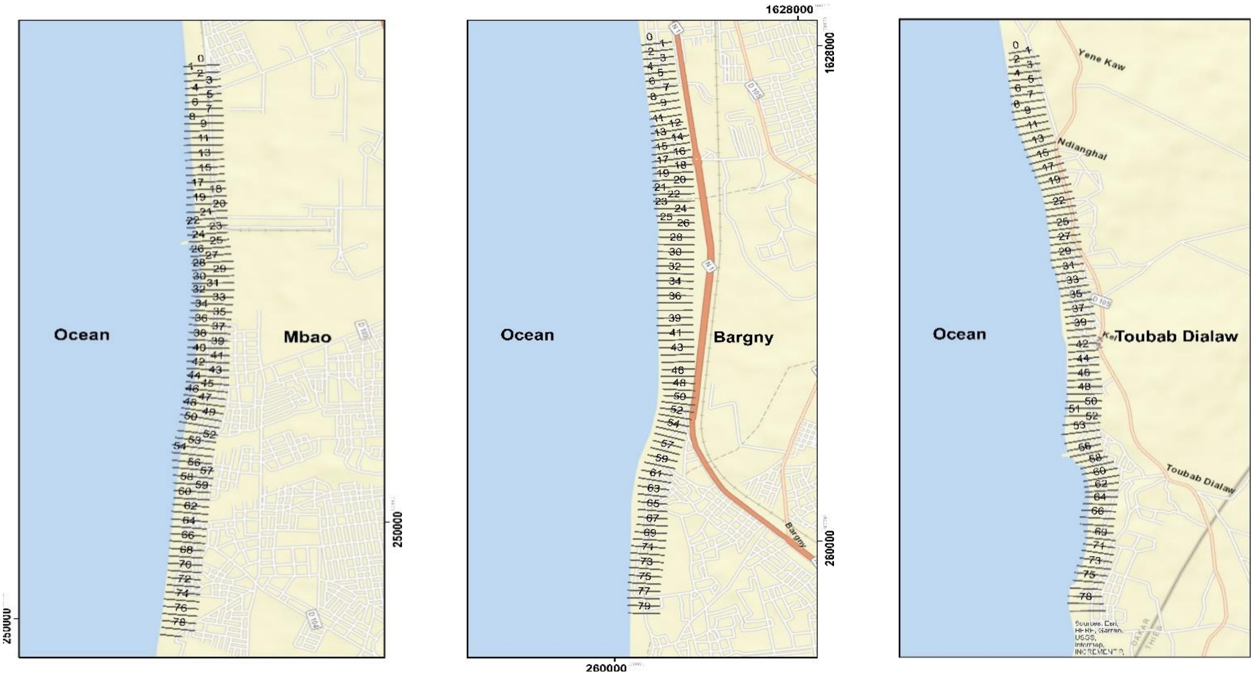

Figure 6. Transect considerations in Mbao, Bargny and Toubab Dialaw littoral cells.

3.6. Determination of Elevation Value for Each Transect Using a DEM Copernicus Raster

In this study, elevation is defined as the height of a topographic point (intersect). Its value is measured by extracting the corresponding topographic value of each intersect using X and Y coordinate intersect points and a digital elevation model. The average elevation value of the years 1980, 1990, 2000, 2010 and 2020 for each transect is considered. It was determined in Mbao, Bargny and Toubab Dialaw littoral cells (Figure 7).

3.7. Slope Determination

Coastal areas are the most dynamic part of the terrestrial sphere. Several factors and processes lead to this dynamism. Far from being negligible, slope plays an essential role in shoreline dynamics. Most often, the lower it is, the faster the shoreline retreat. Low-lying areas are more exposed to submersion than coastal areas with high topographic values. In this study, the slope is included in the relationship between the topography and shoreline dynamic to power the linear regression prediction. It was determined using a digital elevation model Copernicus raster and the spatial analysis tool in ArcGIS (Figure 8).

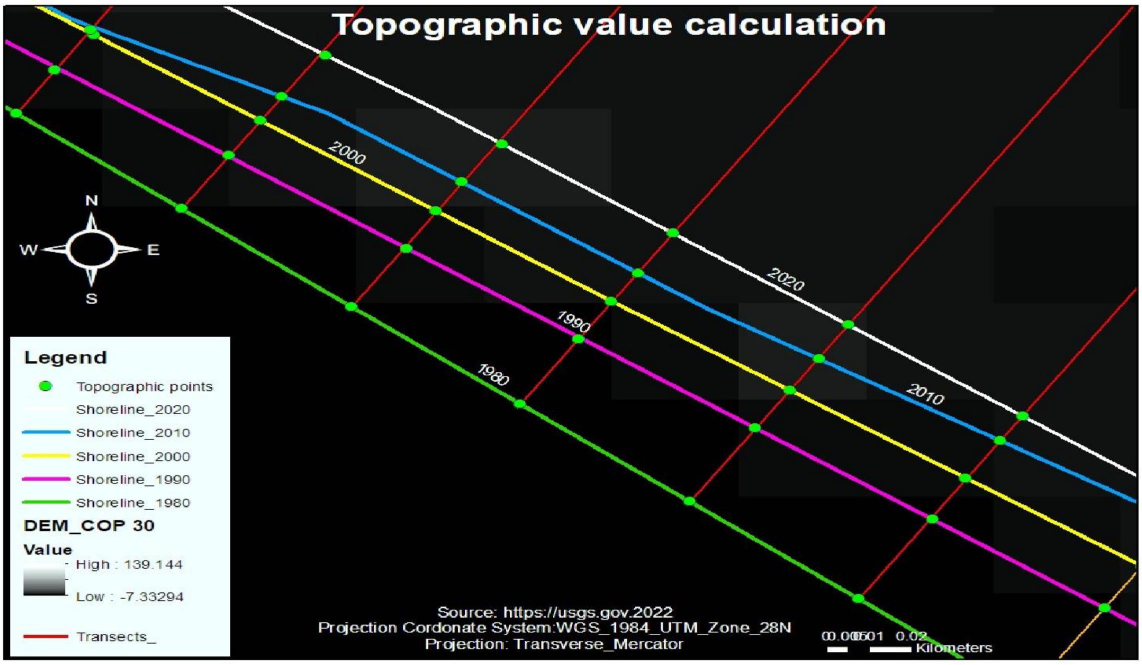

Figure 7. Determination of the topographic values in the study area. Source: GLO-30 DEM.

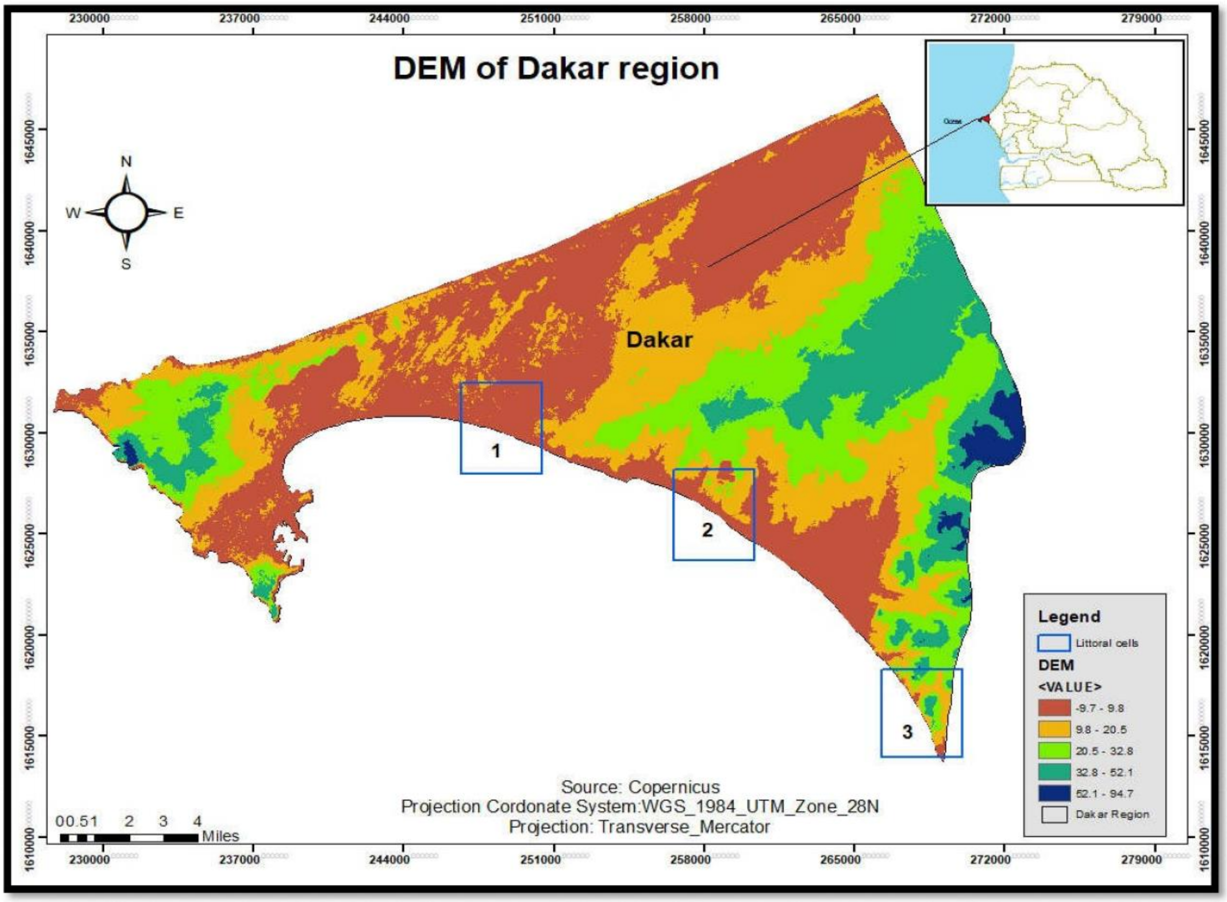

Figure 8. Determination of the slope values in the study area. Source: GLO-30 DEM.

3.8. Linear Regression between Coastline Dynamic, Slope and Topography

In a study, Uyanık and Güler (2013) state that 'regression analysis is a statistical technique for estimating the relationship among variables which have reason and result relation. The mean focus of univariate regression is to analyze the relationship between a dependent and one independent variable and formulates the linear relationship equation between the dependent and independent variable' [35]. The following formula is used to point out the correlation between the coastline dynamic, slope and topography:

$$Y = \beta_1 X_{i,1} + \beta_2 X_{i,2} + \beta_3 X_{i,3} + \varepsilon \tag{3}$$

where:

Y = predicted variable.
$X_{i,1}$ = EPR; $X_{i,2}$ = slope; $X_{i,3}$ = topography.
$\beta_{i\,(1,2,3)}$ = parameters to be estimated or model parameters.
ε = the error term.

3.9. Multicollinearity Test

In a study, Oke et al. (2022) stated that 'Multicollinearity is a statistical phenomenon in which there exists a strong or perfect relationship between the predictor variables. The presence of multicollinearity can cause serious problems with the estimation of and the interpretation' [36]. Therefore, a much higher correlation between the explanatory variables means more risk in the statistical inference about the significance of the regression coefficients. Various tests and diagnostic measures of multicollinearity have been proposed in the econometric literature. Some measures are available for diagnosing multicollinearity, such as the variance inflation factor (VIF), condition number (CN), condition index (CI) and variance decomposition [37]; chi-square test statistic [38,39]; and an F-test by regressing each of the independent variables on the remaining independent variables. The VIF, a well-known meas ure of multicollinearity, is defined as:

$$VIF_i = \left(1 - R_i^2\right)^{-1} \tag{4}$$

where R_i^2 is the coefficient of determination of the regression of the i-th column of X on the remaining columns of X. Based on the VIF diagnostic measure, multicollinearity is severe whenever the VIF is more than 10. There is no logical reasoning behind the value 10 [40]. In this study, a multicollinearity was performed to point out the dependence among independent variables (Table 2).

Table 2. The variance inflation factor of independents variables (topography and slope).

Square Root of VIF	
Topo	**Slope**
1.33	1.33

The results from the multicollinearity test show that there is no collinearity among independents variables because the square roots of the VIF are lower than 5.

3.10. Specification of the Model

Akaike information cri terion (AIC), Bayesian information criterion (BIC) and R^2 are employed. In a study, Romero (2007) stated that it is usual practice in econometrics to employ R^2 in model selection. This goodness-of-fit measurement, along with others, such as unadjusted R squared, Akaike Information Criterion and Bayesian Information Criterion, are almost always available to researchers using econometric software [41].

Therefore, a prominent approach for selecting models is the Akaike Information Criterion (AIC). It is widely employed at parameter space singularities and borders to violate regularity conditions [42], whereas a helpful metric for comparing multilevel models is the Bayesian Information Criterion. The BIC has a number of benefits over conventional hypothesis-testing techniques [43]. According to Yulistiani and Suliadi (2019), good criteria for model selection can use Bayesian Information Criterion (BIC) [44]. For model selection in linear mixed models, one may use Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). Distinct random effect specifications result in different covariance structures of observation because linear mixed models might provide a specific structure of dependency among responses [45] (Table 3).

Table 3. Specification of the model using AIC, R^2 and BIC tests.

Model/Test	AIC	R^2	BIC
M0	671	0.52	685
M1	637	0.54	652

M0 = model without diagnostic; M1 = model that is neither outlier nor influencer.

The lower the AIC, the better the model is. The higher the R^2 is, the better the model is. The lower the BIC is, the better the model is.

The AIC of the M1 model (637) is lower than the one in M0 (671). The higher R^2 is recorded in the M1 model (0.54) and the lower in M0 (0.52). For the BIC, the lower is re-corded in M1 and the higher in M0 (685). Based on these results, model M1 was chosen.

4. Results

The average coastal dynamics from 1980 to 2020 in Mbao, Bargny and Toubab Dialaw were estimated at −1.04, −1.17 and −0.06 m/year, respectively. The average dynamics in all littoral cells is about −0.75 m/year. High topographic values were recorded at Toubab Dialaw with an average of 5.27 m, while low topographic values were noted in Mbao (1.85 m) and Bargny (1.37 m). With regard to slope, Toubab Dialaw recorded an average of 17.92°, while Mbao and Bargny recorded 4.98 and 3.45°, respectively. In terms of geomorphology, the Mbao coast is characterized by soils little or not evolved in situ (wind siols), soils more or less developed in situ after significant mechanical action, sands, group of erosion renzinas with rendzine on marly limestone and category of sandy clay alluvium and colluvium. In Bargny, the geomorphology is marked by soils little or not evolved in situ (wind soils), category of sandy-clay alluvium and soils more or less developed in situ after significant mechanical action. Toubab Dialaw is characterized by depleted sandstone, eolian soil, Dior soil on sandy-clay colluvium and soils little or not evolved in situ (wind soils). A positive correlation between coastline dynamics, topography (elevation) and slope is noted at Mbao (0.63) and Bargny (0.87). However, in Toubab Dialaw, the correlation coefficient is not significant (0.15) (Table 4).

Table 4. Littoral cells, transect considerations and statistic values.

Littoral Cells	Net Shoreline Movement (m)	Average of Shoreline Dynamic from 1980 to 2020 (m/Year)	Average of Topographic Value (m)	Average of Slope (Degree)	Correlation Coefficient of the Shoreline Change Rate, Topography and Slope	Geomorphologic Characteristics
Mbao	−41.3	−1.04	1.85	4.98	0.63	Soils little or not evolved in situ (wind soils); soils more or less developed in situ after significant mechanical action; sands; group of erosion Rendzinas with Rendzine on marly limestone; and category of sandy–clay alluvium and colluvium.
Bargny	−46.9	−1.17	1.37	3.45	0.87	Soils little or not evolved in situ (wind soils); category of sandy–clay alluvium; and soils more or less developed in situ after significant mechanical action.

Table 4. *Cont.*

Littoral Cells	Net Shoreline Movement (m)	Average of Shoreline Dynamic from 1980 to 2020 (m/Year)	Average of Topographic Value (m)	Average of Slope (Degree)	Correlation Coefficient of the Shoreline Change Rate, Topography and Slope	Geomorphologic Characteristics
Toubab Dialaw	−3.8	−0.06	5.27	17.92	0.15	Depleted sandstone, eolian soil, Dior soil on sandy–clay colluvium and soils little or not evolved in situ (wind soils)
General	−30.6	−0.75	2.86	8.78	0.55	Soils little or not evolved in situ (wind soils); soils more or less developed in situ after significant mechanical action; sands; group of erosion Rendzinas with Rendzine on marly limestone; category of sandy–clay alluvium and colluvium; depleted sandstone; and Dior soils on sandy–clay colluvium.

Linear Regression between Coastline Dynamic, Topography and Slope

The following figures show the linear regression of the topography (elevation) and dynamic shoreline rate (EPR) in different littoral cells of the study area (Figure 9).

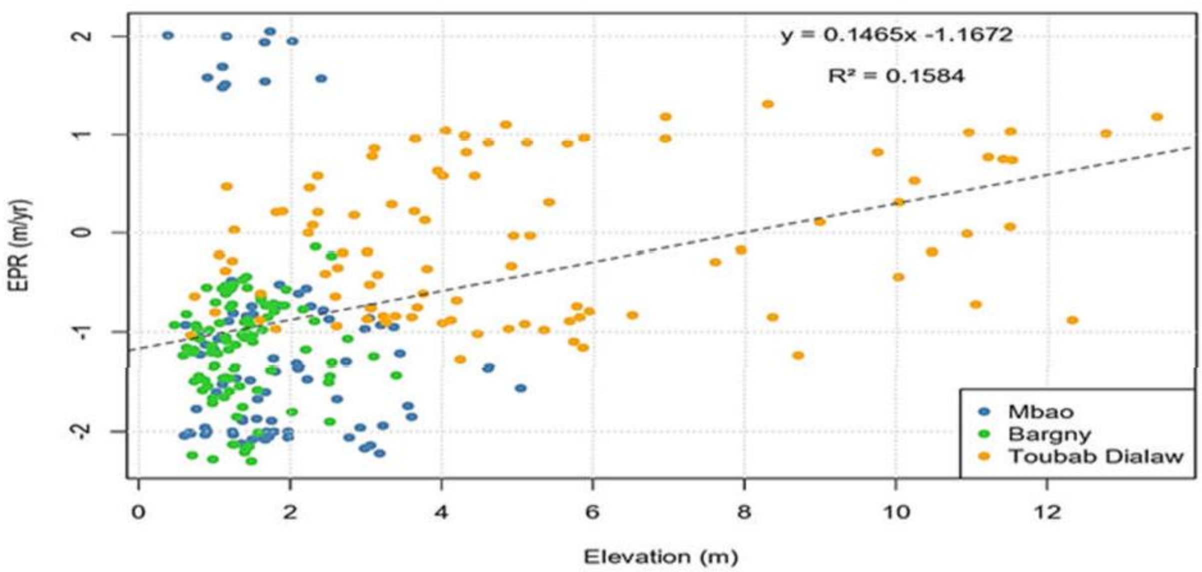

Figure 9. Cross plot of the shoreline change rate (EPR) and topography in the three littoral cells.

The coefficient of correlation between the coastline dynamic and slope is estimated at 0.56 in Mbao and 0.87 in Bargny, whereas in the littoral cell of Toubab Dialaw, the coefficient is lower than those recorded in Mbao and Bargny (0.06) because of high slope values with an average of about 17.92° and a low dynamic rate of −0.06 m/year (Figure 10).

The following figure is the box plot of the topography, slope and coastline dynamic rate (EPR) in the three littoral cells. It helps to understand the distributional characteristics of the topography, slope and coastline dynamic value in each littoral cell. For the topography, the upper quartiles in Mbao and Bargny are lower than 2.5 m, whereas in Toubab Dialaw, 50% of the observed values exceed 4 m. In terms of slope, all quartiles are lower than 10.5°. In Toubab Dialaw, 75% of observations are higher than 10°. In Mbao and Bargny, 75% of quartiles regarding the coastline dynamic rate are lower than 0.8 m/year, whereas, in Toubab Dialaw, 75% of quartiles are higher than 0.8 m/year (Figure 11).

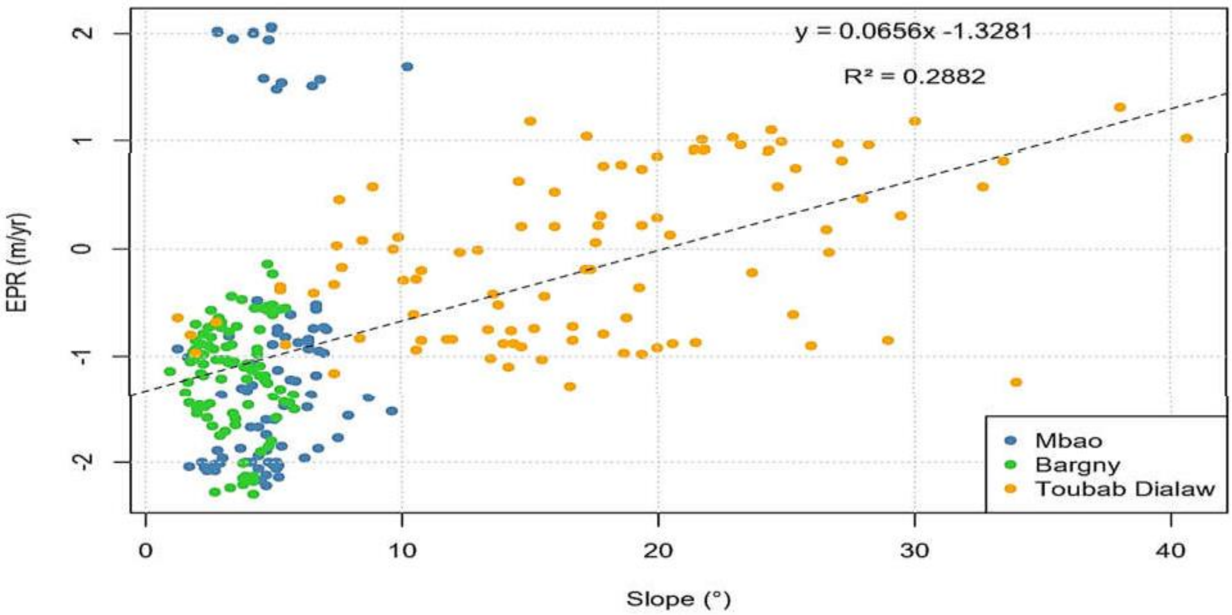

Figure 10. Cross plot of the shoreline change rate and slope in the three littoral cells.

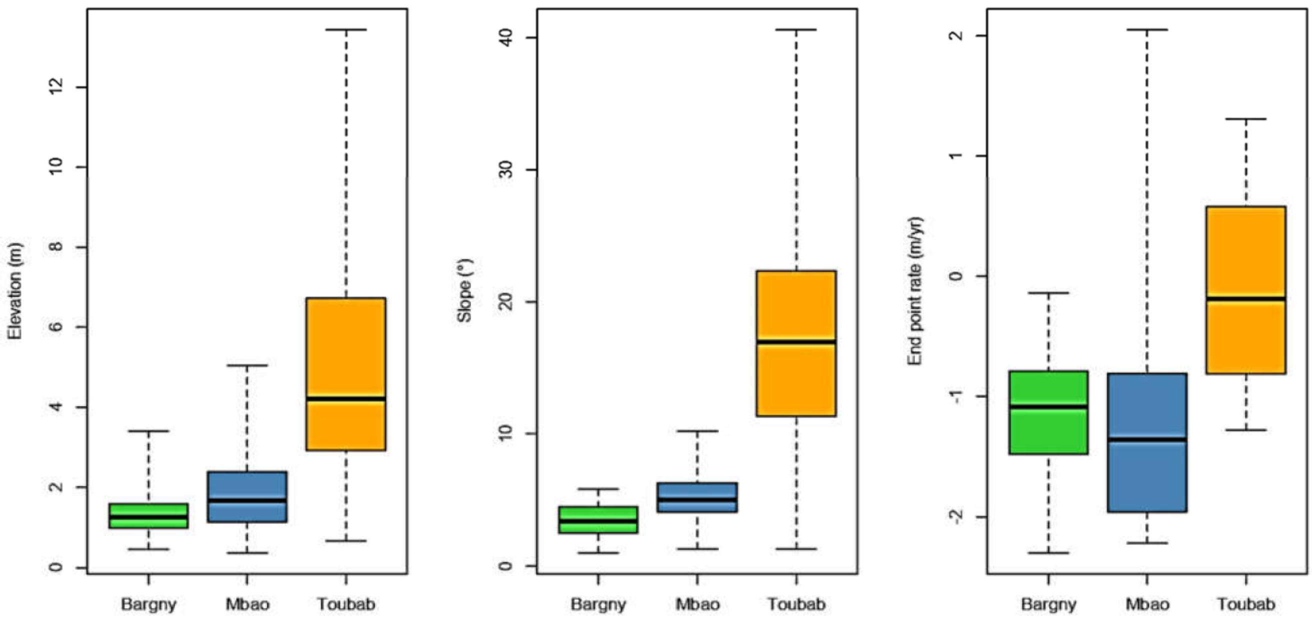

Figure 11. Box plot of the topography (elevation), slope and EPR in the three littoral cells.

5. Discussion

In the context of climate change, the recorded temperatures in the world show an increase in the global trend. Consequently, global warming is noted. The effects of this global warming on the hydrosphere and cryosphere cause ice melting and dilating seawater, leading in most coastal areas in the world to a coastline retreat resulting from sea-level rises. The effects of this rising sea level combined with human activities, such as sand mining and abnormal settlement, lead to coastal erosion, which is accentuated by the effects of hydrodynamic agents [46]. In addition, geologic and geomorphologic conditions along the coasts play an important role in this coastline dynamic. According to Adjoussi (2001), three different activities determine the geological history of the Dakar region: vo-lcanic activities, marine transgressions and regressions, which were observed from the pre-Quaternary period up to the Quaternary period in the Dakar region, and the geomorphological structure is the result of the evolutionary dynamics of these geological formations [47].

The coastal shapes observed in the Dakar region evidence that there is a difference in terms of the geomorphologic composition and topographic and slope conditions. Therefore, due to its geographical position in the sea and low-lying areas, the Dakar region is vulnerable to coastal erosion, the most threatening disaster that challenges coastal communities. In this study, the average shoreline dynamic in Mbao, Bargny and Toubab Dialaw littoral cells from 1980 to 2020 are estimated, respectively, at −1.04, −1.17 and −0.06 m/year. In all littoral cells, the average dynamics is roughly −0.75 m/year. These dynamic rates are similar to those found in some studies about coastline dynamic assessment. Diallo (1982) found that the rate of shoreline evolution was −1.29 m per year. Sall (1982) found −1.3 m/year of coastline erosion in the same location, while Niang Diop (1996) found −1.2 m/year of coastal change. According to Dieye (2000), the coastline between Bel Air and Rufisque is showing annual erosion at a rate of 0.6 meters per year. Guerin (2003) found a 0.77 percent annual erosion of the shoreline. Ndour (2015) noted an approximate dynamic rate of −1.6 m/year [14,15,17,48–50]. These dynamic rates are similar to those observed in other West African countries. For example, the dynamics of the coastline on a portion of the West Cameroon Coast from Batoke to Seme Beach was estimated at −1.09 m/year between 1979 and 2018 by Arnaud in 2019 [51]. In Ghana, Jonah estimates the average dynamic rates at −1.24 and −0.85 m/year in the medium and short term periods, respectively [52]. In Côte d'Ivoire, it was estimated at −1.40 m/year in the report on coastal management practices in West Africa in 2019 [53].

While climatic and hydrodynamic conditions contribute to coastal erosion, it should be noted that topography and slope play an important role in this erosion. The morphology of the Rufisque department shows high topographic levels forming two plateaus in the northwest (Cap des Biches) and the southeast (Kolobane, Arafat), separated by a depression in the center (Keury Souf) [54]. Therefore, in the littoral cell of Toubab Dialaw, high topographic values were observed with an average of 5.27 m, whereas low topographic values were observed in Mbao (1.85 m) and Bargny (1.37 m). In terms of slope, Mbao and Bargny registered 4.98 and 3.45°, respectively, while Toubab Dialaw recorded an average of 17.92°.

Even though topography and slope are two of the most essential factors determining how vulnerable coastal zones are to erosion, geomorphologic characteristics along the beaches are crucial to this shoreline dynamic. In a study, Bird (2008) stipulated that the feature of a coastline may vary due to large-scale geology factors, surface processes and the effects of recent changes in the relative level of the sea and land [55]. The geomorphology of the Mbao shore is characterized by soils little or not evolved in situ (wind soils); soils more or less developed in situ after significant mechanical action; sands; group of erosion Rendzinas with Rendzine on marly limestone; and the category of sandy–clay alluvium and colluvium. In Bargny, the following geomorphologic features are distinctive: soils little or not evolved in situ (wind soils); the category of sandy–clay alluvium; and soils more or less developed in situ after significant mechanical action. Depleted sandstone; eolian soil; Dior soils on sandy–clay colluvium and soils little or not evolved in situ are the defining features of Toubab Dialaw.

The results of this study show that the geomorphologic conditions intervene in the relationship between the coastline dynamic rate, topography and slope. For example, in the Mbao and Bargny littoral cells, there is a significant relationship between the topographic and slope conditions and coastline dynamic with a coefficient of correlation of about 0.63 and 0.87, respectively. The geomorphology in these coasts is most characterized by soils little or not evolved in situ (wind soils), with high porosity and water infiltration and is generally subjected to erosion. Contrary to the Toubab Dialaw littoral cell where the geomorphology is marked by a category of sandstone (strongly dismantled), it is less exposed to erosion due to its less porous characteristic and the high compacity of soil. Sandstone is a sedimentary rock made of sand-sized grains of mineral, rock or organic material bonded together over time by natural processes. Strongly disassembled sandstone has suffered extensive physical weathering, such as by the action of wind, water or ice, which has caused it to disintegrate into smaller pieces. According to Boggs (2012), 20 to 25 % of all sedimentary rocks are sandstones, which can include different levels of se-diment [56]. Sandstone and other siliciclastic sedimentary rocks undergo a significant dia- genetic process known as sedimentation. It significantly contributes to decreasing the porosity of sedimentary rocks and may have an impact on sediment compaction [57]. The relationship in Toubab Dialaw is not significant, with a correlation coefficient of about 0.15, assuming that the average of the topography (5.27 m) and slope (17.92°) do not favor high shoreline dynamic rates, and the geomorphologic conditions do not allow rapid erosion because of its compacity and impermeability of geomorphological structures.

Some efforts were made in order to fight against coastal erosion in Senegal, particularly on the southern coast of Dakar region. In a study, it is stated that faced with this coastal erosion, the Senegalese government adopted some adaptation measures depen-ding on the means at its disposal: protective walls, reforestation, protective dikes, rock fills, dune replenishment, beach drainage systems, breakwaters, etc. Among these protective measures, some are more effective depending on their quality, their duration of resistance against hydrodynamic parameters and the type of coastline where they are installed [46]. However, it should be noted that these protective infrastructures constitute a significant constraint on sedimentary exchanges between continents and oceans. To better manage coastal erosion and pollution, 26 additional development and preservation projects have been inventoried for an estimated budget of more than XOF 30 billion [58]. Despite all the endeavor that the Senegalese government made, coastal erosion still remains a challenge for communities living along the coasts.

6. Conclusions

In summary, this study was undertaken to investigate if there is a relationship between the coastline dynamic, topographic and slope and the contribution of the geomorphology along the southern coast of Dakar. It provides a better understanding of the roles of topography, slope and geomorphology in coastal dynamics using remote sensing, cartographic tools and statistical methods. It also allows for more knowledge about the most vulnerable coastal areas in terms of topography, slope and geomorphology. In the littoral cells of Mbao and Bargny where the topography and slope are low, the average shoreline dynamics are estimated, respectively, at −1.04 and −1.17 m/year. In contrast to the littoral cell of Toubab Dialaw where the topography and slope are more important, the average shoreline dynamic rate is about −0.06 m/year. Therefore, the geomorphologic structure plays an essential role in the relationship between the topography, slope and shoreline dynamic. For example, in the Mbao littoral cell, where porous and erodible structures characterize the geomorphologic condition, there is a positive relationship between the topography, slope and coastline dynamic (0.63). In the littoral cell of Bargny, the relationship between the topography, slope and coastline dynamic is positive with a coefficient of about 0.87, whereas, in the Toubab Dialaw littoral cell, the coefficient of correlation (0.15) is not significant. This is because of the domination of compact and impermeable structures in this coastal zone. Even though topography, slope and geomorphology play a vital role in the shoreline dynamic, it should be important to search for an answer to the following question: what about the contribution of the population to the shoreline dynamic?

Author Contributions: Conceptualization, I.P., D.P.A., J.A.N. and A.S.; methodology, I.P.; software, I.P.; validation, I.P., D.P.A., J.A.N. and A.S.; formal analysis, I.P.; investigation, I.P.; resources, I.P.; data curation, I.P.; writing—original draft preparation, I.P.; writing—review and editing, I.P.; visualization, I.P.; supervision., D.P.A., J.A.N. and A.S.; project administration, I.P.; funding acquisition, I.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: EPR, topography and slope datasets are available upon a request at pouye.i@edu.wascal.org. Geomorphologic dataset are avialable at http://sphaera.cartographie.ird.fr.

Acknowledgments: I appreciate the opportunity to conduct a study at the Institute of Environmental Social Sciences and Geography at the Albert Ludwig University in Freiburg, Germany and the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). Support was offered in the form of funding, remote sensing, charting and statistical technics.

Conflicts of Interest: The authors declare no conflict of interest.

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Journal of Coastal Research	00	0	000–000	Charlotte, North Carolina	Month 0000

Evaluation of the Economic Impact of Coastal Erosion in Dakar Region

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ABSTRACT

Pouye, I.; Adjoussi, D.P.; Ndione, J.A., and Sall, A., 0000. Evaluation of the economic impact of coastal erosion in Dakar region. *Journal of Coastal Research,* 00(0), 000–000. Charlotte (North Carolina), ISSN 0749-0208.

Besides the environmental impacts, climate change negatively affects the economic value of coastal zones. Coastal erosion, which is one of its impacts, causes damage to people living along the coast. The narrowing of the beach due to erosion leads to socio-economic damage by reducing the areas where economic activities are carried out. As a result, livelihoods, human settlements, and economic activities such as fishing, tourism, and industry are disrupted. The evaluation of the economic impacts of coastal erosion is timely and relevant. This study aims to economically investigate the most affected coastal areas in Dakar region in 2030 and 2040. It also allows for the identification of localities that need protective infrastructure to prevent economic losses from coastal erosion. The assessment is done by estimating the economic value of the beach using multilinear regression, an econometric forecasting model. Software such as R, Excel, ArcGIS, and Digital Shoreline Analysis System were used in this study. The results show that, due to coastal erosion, the district municipalities along the coast of Dakar will record a loss estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040. The results of this study suggest that the parameters such as Beach Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, Coastal Vulnerability Index, Number of Buildings, Number of Hotels, Number of Industries, Number of Fishing Points, and Road Length play an important role on littoral value. Coastal erosion will be among the most threatening disasters in the Dakar region if the “do nothing” option is adopted as an adaptation measure.

ADDITIONAL INDEX WORDS: *Economic activities, vulnerability, coastal management.*

INTRODUCTION

Dakar region, like most of the world’s capitals, is not safe from the impacts of climate change and coastal erosion because of its geographical position and its low-lying (Pouye *et al.*, 2022). Advanced sea resulting from the rise in sea level is affecting the coasts. Dakar's current and expected coastal dynamic shows that there is indeed an advanced sea due to variations in oceanic waters aggravated by the effects of hydrodynamic agents such as waves, tides, and wind. Therefore, this situation reduces coastal areas; human displacement toward inland; disruption of economic activities such as fishing, recreation, hotel, and industry activities. Man accentuates these threats through sand mining, pollution, and illegal settlements (Pouye, 2016). According to Niang *et al.* (2012), scenario-based studies have predicted land losses in Dakar by 2050. These losses will be estimated at 0.21 to 1.79 km^2, *i.e.* 3.8 to 28.5% of the total beach area. By 2100, they will be between 0.77 and 3.95 km^2, *i.e.* 12.2 to 62.8% of the total beach area.

This coastal erosion causes significant economic losses, the estimation of which is complex. Knowledge of the economic value of the beach was minimal, beyond that suggested by property values. There needs to be more scientific information on the economic value of the beach to assess the effectiveness of investing exorbitant amounts of money in beach erosion management (Edwards and Gable, 1991). So far, this economic value of beach erosion was sometimes assessed by the cost of protective infrastructures without considering income losses (Alexandrakis, Manasakis, and Kampanis, 2015). Therefore, with the use of econometric models, this challenge is resolved. This evaluation is no longer linked to the protection infrastructures but to the revenues generated by economic activity such as tourism and the economic value of coastal properties. In a study, Alexandrakis, Manasakis, and Kampanis (2015) estimated the value of eroded beaches through the hedonic pricing model, where the beach value is determined by its width and tourism business. Some studies argued that the value of the properties is relative to beach width. Brown and Polakowski (1977), in a study, indicate that the value of a

DOI: 10.2112/JCOASTRES-D-23-00018.1 received 13 March 2023; accepted in revision 11 June 2023; corrected proofs received 31 July 2023; published pre-print online 12 September 2023.
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Table 1. *Localities, data, and methods used in this study.*

Localities	Code	Variables	Code	Methods
Bambilor	NC 1	Littoral Price (LP)/m^2 (FCFA)	LP	https://www.fao.org
Tivaouane	NC 2			
Malika	NC 3	Lost Areas (LA) (m^2)	LA	Satellite images/ArcGIS/DSAS
Yeumbeul	NC 4			
Wakhinane	NC 5	Coastal Length (CL) (m)	CL	Satellite images/ArcGIS
Ndiareme	NC 6			
Sam	NC 7	Dynamic Rate (DR) (m/year)	DR	Satellite images/ArcGIS/DSAS
Golf Sud	NC 8			
Camberene	NC 9	Littoral Areas (LA) (m^2)	LA_s	Satellite images/ArcGIS
Parcelles	NC 10			
Yoff	NC 11	Built Areas (BA) (m^2)	BA	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Ngor	WC 1			
Ouakam	WC 2	Proximity to Town (PR) (m)	PR	Satellite images/ArcGIS
Mermoz	WC 3			
Fann	WC 4	CVI	CVI	Satellite images/ Hydrodynamic data/ArcGIS
Gueule Tapee	WC 5	Littoral Width (LW) (m)	LW	Satellite images/ArcGIS/GPS Visualizer
Medina	WC 6			
Plateau	WC 7	Number of Buildings (NB)	NB	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Hann	SC 1			
Dalifor	SC 2	Number of Hotels (NH)	NH	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Thiaroye	SC 3			
Diamageun	SC 4	Number of Industries (NI)	NI	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip
Mbao	SC 5			
Rufisque Ouest	SC 6	Number Fishing Points (NFP)	NFP	Google Earth Pro
Rufisque Est	SC 7			
Yenn	SC 8	Road Length (RL) (m)	RL	https://download.geofabrik.de/africa/senegal-and-gambia-latest-free.shp.zip

CVI = Coastal Vulnerability Index; DSAS = Digital Shoreline Analysis System

property decreases with distance from the water. The effect of beach quality, as determined by beach width, on property values in two South Carolina coastal towns is investigated by Pompe and Rinehart (1995). In addition, in a study, Landry, Keeler, and Kriesel (2003) emphasized the complexity of the relationship between property value, the erosion rate, and distance from erosion reference. Property owners appreciate shorter distances to the reference erosion feature for recreational and amenity reasons. They also value the protection against storm surges and the risk of erosion, fostered by a larger beach width, a more considerable distance to the reference erosion feature, and a decreased erosion rate.

The importance of assessing the economic value of beaches is to evaluate coastal management policies and projects (Lew and Larson, 2008). It may identify coastal areas needing protective infrastructure based on physical and socio-environmental vulnerability, coastal dynamism rate, and beach width reduction. Further, this study uses an econometric model (multilinear regression) which points out the impacts of Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, Coastal Vulnerability Index (CVI), Number of Buildings, Number of Hotels, Number of Industries, Number Fishing Points, and Road Length on beach value along the coast of Dakar region (Table 1). Geographic Information System techniques were used to determine independent variables through spatial data.

Study Area

The study area is the district municipalities along the coast of Dakar region (Figure 1), which is located in west Africa between 17° 10 and 17° 32 west longitude and 14° 53 and 14° 35 north latitude. It covers an area of about 550 km^2, *e.g.*, 0.28% of the national territory. It is bordered to the east by the Thiès region and to the north, west, and south by the Atlantic Ocean (Pouye, 2016). As the capital of Senegal, Dakar region hosts about 3,938,358 inhabitants, *e.g.*, 22.8% of the total population (ANSD, 2020). Dakar region hosts over 50% of economic activities and most of the administrative infrastructures.

Consequently, the concentration of the population is becoming denser and denser, increasing the need for urbanization and land allotments (ANSD, 2021). This concentration of population causes problems in the marine environment. The urbanization of the coastline has become a thoughtless phenomenon that reflects the importance of the proximity of water. The dynamics of coastal occupation show two types of evolution: on the one hand, the advance of dwellings towards the sea, and on the other hand, the advance of the sea towards the dwellings. In addition, several economic activities, such as fishing, tourism, and industry, are carried out along the coast of Dakar, which gives the beach an increasing economic value (Pouye, 2016). According to Amuzu *et al*. (2018), several people live along the coast, contributing to the Gross Domestic Product (GDP) through economic activities such as tourism and fishing. In West Africa, the contribution of fishing to the GDP in Senegal decreased from 1.7% in 2012 to 1.4% in 2015. In Dakar region, the Bay of Hann, Rufisque, Soumbedioune, Thiaroye, and Yoff is the prominent localities where fishing activities represent an essential part of economic income. Nevertheless, because of over-exploitation of marine resources, pollution, and environmental degradation, weakness of the institutional framework managing the sector, insufficient human resources, lack of adequate financing, inadequate fiscal environment,

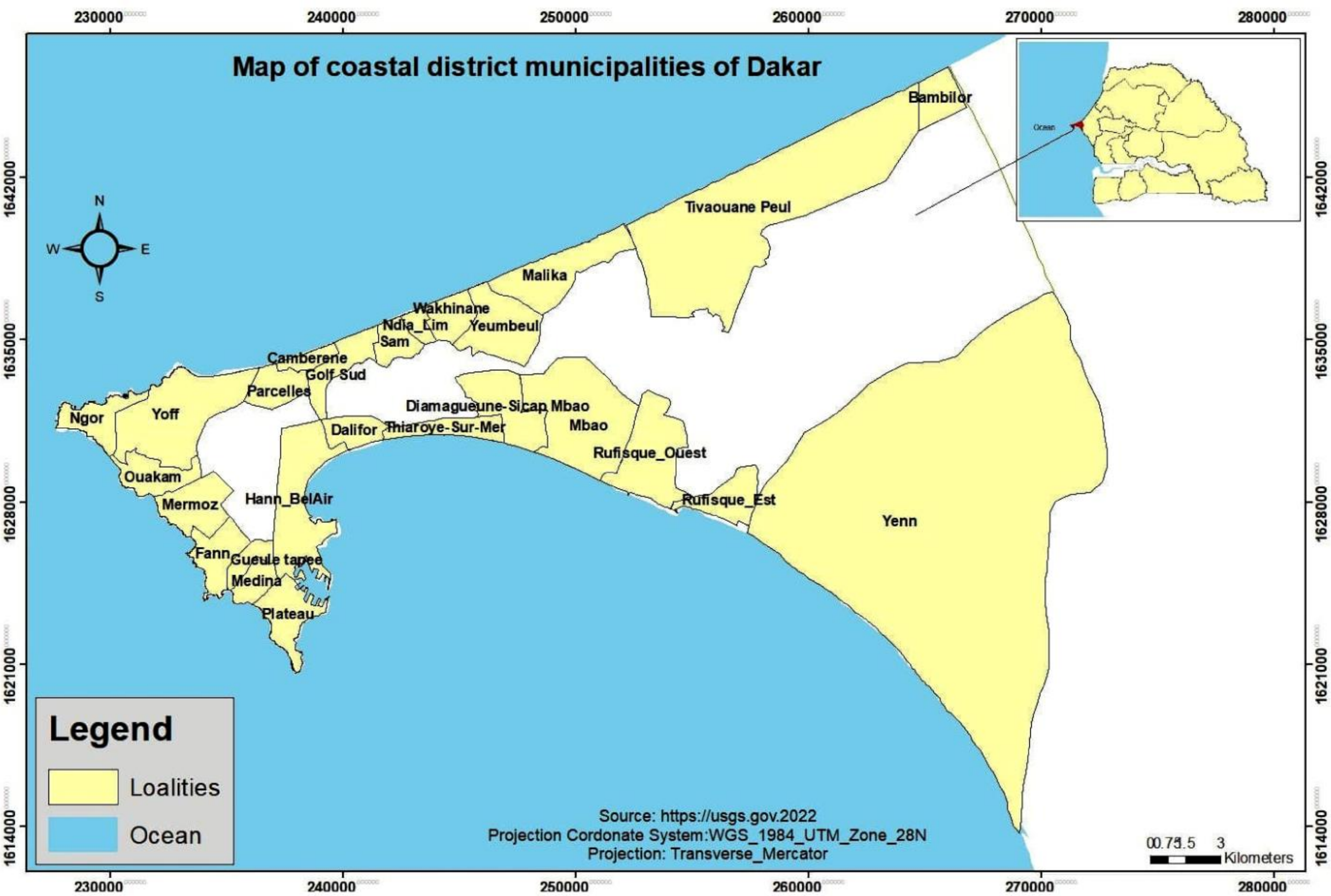


Figure 1. Location map of the district municipalities along the coast of Dakar region.

weakness of information system and research capacities, sustainable fishing is not guaranteed (ANSD, 2018). Far from being negligible, industries along the coast also play an essential role in the national economy. Tourism is among the most important economic activities which generate income in the national economy. In a report (ANSD, 2021), it is stated that tourism is the second largest provider of income. Due to its geoclimatic situation, Dakar region occupies a central place in tourism activities and the hotel sector. In addition, Dakar is a platform linking Europe, Africa, and America, which gives it a prime position in business tourism in West Africa. Since coastal zones constitute the most strategic areas for industry, tourism, transport, and fishery, the high profitability of these economic activities is challenged by erosion through the reduction of littoral zones and incomes.

Data Source

This study uses two categories of data: physical and socio-economic data. The following table presents the study area, data, and methods, and assigned code for localities and variables, where NC means northern coast, WC is the western coast, and SC is the southern coast.

Beach Width Estimation

The distance between the settlement and the sea is considered as beach width. It is valuable in assessing economic littoral value. It is one of the indicators which informs about the level of exposure of local communities to coastal erosion. It provides information regarding the number of square meters of the coast of each district municipality. It was determined using satellite images, Google Earth, GPS visualizer, and ArcGIS. The high urban population growth in Dakar is the consequence of the rapid occupation of the coast, which reflects the importance of the settlement's proximity to the sea. The coastal occupation dynamic shows two types of evolution: the advance of the dwellings toward the sea and, on the other hand, the advance of the sea towards the dwellings. The total beach width in district municipalities in 2020, 2030, and 2040 is estimated respectively at 4496, 3364, and 3085 m (Figure 2). However, due to erosion, the beach width is generally reduced.

Lost Areas

Lost areas are estimated using the coastline of 2020 and the one of 2030 and 2040. It indicates that on dynamic coastline rate and the level of risk. Malika records the highest rates of beach loss, 309,561 m^2 in 2030 and 467,882 m^2 in 2040. In

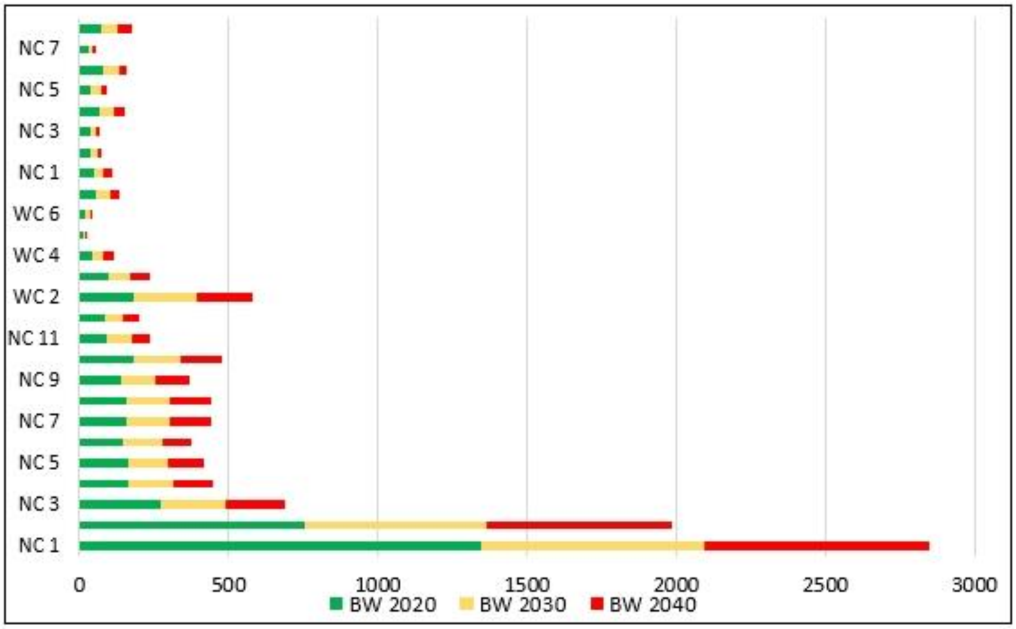


Figure 2. Beach width in the district municipalities in Dakar region in 2020, 2030, and 2040 showing the reduction of the beach width due to coastal occupation.

Tivaouvane Peul, there is estimated to be a loss of area of about 336,160 and 463,823 m^2, respectively, in 2030 and 2040 (Figure 3).

Shoreline Retreat in Each District Municipality

The rate of shoreline retreat between 1990 and 2020 is evaluated. For that, the distance of shoreline movement is divided by the time elapsed between the oldest and the youngest shorelines using the Digital Shoreline Analysis System (DSAS) software which is an extension of ArcGIS 10.7. The advantage of this statistical method is that the dynamic rate is computed easily through the end point rate (EPR) (Himmelstoss *et al.*, 2018):

$$EPR = \mathrm{NSM} / \mathrm{ET} \quad (1)$$

where

- EPR = End point rate statistical method is computed by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and the youngest shorelines.

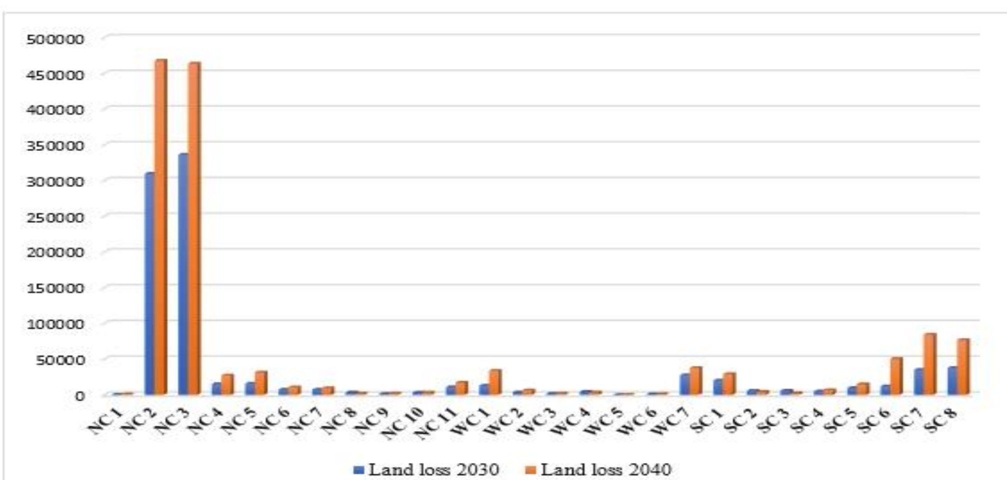
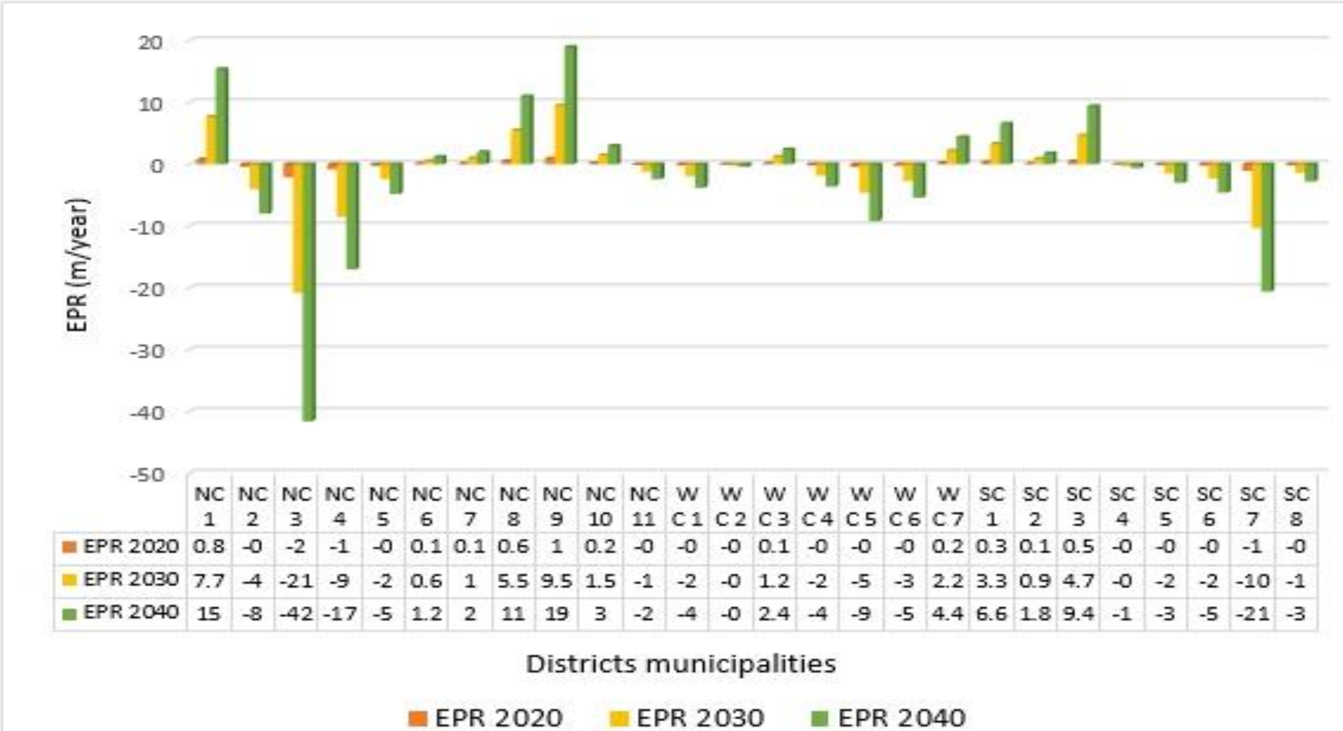


Figure 3. Estimated areas lost in the district municipalities of the Dakar region in 2030 and 2040 due to coastal erosion.



	NC 1	NC 2	NC 3	NC 4	NC 5	NC 6	NC 7	NC 8	NC 9	NC 10	NC 11	W C 1	W C 2	W C 3	W C 4	W C 5	W C 6	W C 7	SC 1	SC 2	SC 3	SC 4	SC 5	SC 6	SC 7	SC 8
EPR 2020	0.8	-0	-2	-1	-0	0.1	0.1	0.6	1	0.2	-0	-0	-0	0.1	-0	-0	-0	0.2	0.3	0.1	0.5	-0	-0	-0	-1	-0
EPR 2030	7.7	-4	-21	-9	-2	0.6	1	5.5	9.5	1.5	-1	-2	-0	1.2	-2	-5	-3	2.2	3.3	0.9	4.7	-0	-2	-2	-10	-1
EPR 2040	15	-8	-42	-17	-5	1.2	2	11	19	3	-2	-4	-0	2.4	-4	-9	-5	4.4	6.6	1.8	9.4	-1	-3	-5	-21	-3

Figure 4. Evolution of accreting or eroding coastlines in district municipalities in Dakar region in 2020, 2030, and 2040.

- NSM = Net Shoreline Movement is the distance between the most recent shorelines and the oldest shorelines for each transect and is measured in meters (m).
- ET = Elapsed time between 1990 and 2020 (Himmelstoss *et al*., 2018 and Pouye *et al*., 2022).

The analysis of the coastline dynamics in district municipalities shows two principal trends: erosion and accretion. Since the hydrodynamic, geologic, geomorphologic, and topographic conditions are not the same on the northern, western, and southern coasts, it is evident that the localities do not record the same rate (Pouye *et al*., 2022). Therefore, 15 out of 26 district municipalities recorded negative dynamic rates in 2020, 2030, and 2040. Malika has the highest rate of 22 m/year, 221 m/year, and 242 m/year in 2020, 2030, and 2040, respectively. These rates have been exacerbated by the sand mining activities that have taken place over the years (Figure 4).

Coastal Length

The coastal length for each district municipality is determined using satellite images and measurement tools in ArcGIS.

Proximity to Town

The proximity of a location to the city is a valuable variable for its economic value. In most cases, the closer a settlement is to the city, the higher its economic value. The proximity of settlements to the city is determined using the ArcGIS analysis tool.

Littoral Pricing per m^2

The prices of the littoral used in this study are based on those defined by Decree No. 2010-400 of 23 March 2010 on the scale of rental prices for the occupation of the state's private real estate domain. Indeed, the occupation of the state's private real estate domain gives rise to the payment of an annual fee proportional to the property's market value. However, a scale fixing the price of these outbuildings has yet to be established beforehand. To fill this gap, the text of Decree No. 88-074 of 18 January 1988 fixing the price scale for bare land and built-up land, applicable for determining the rent of premises for residential use and for calculating compensation for expropriation in the public interest, has always served as a reference scale. However, apart from the fact that it was not designed for this purpose, the said scale has needed more revaluation since its adoption in 1988, despite the increased value acquired by the land in the various areas of the national territory. In order to correct this situation, it was, therefore, necessary to establish a scale for setting the fee for occupying the state's private real estate domain (FAO, 2010).

Littoral and Building Areas

Superficies occupied by littoral and building were estimated using shapefiles of settlements along the coast. A buffer of 200 m from the coastline was considered. The surface area of buildings in 2030 is estimated at 803,119 m^2, whereas in 2040, it is expected to be 911,783 m^2. Regarding the coastal surface area in 2030, the number of 16,433,400 m^2 is

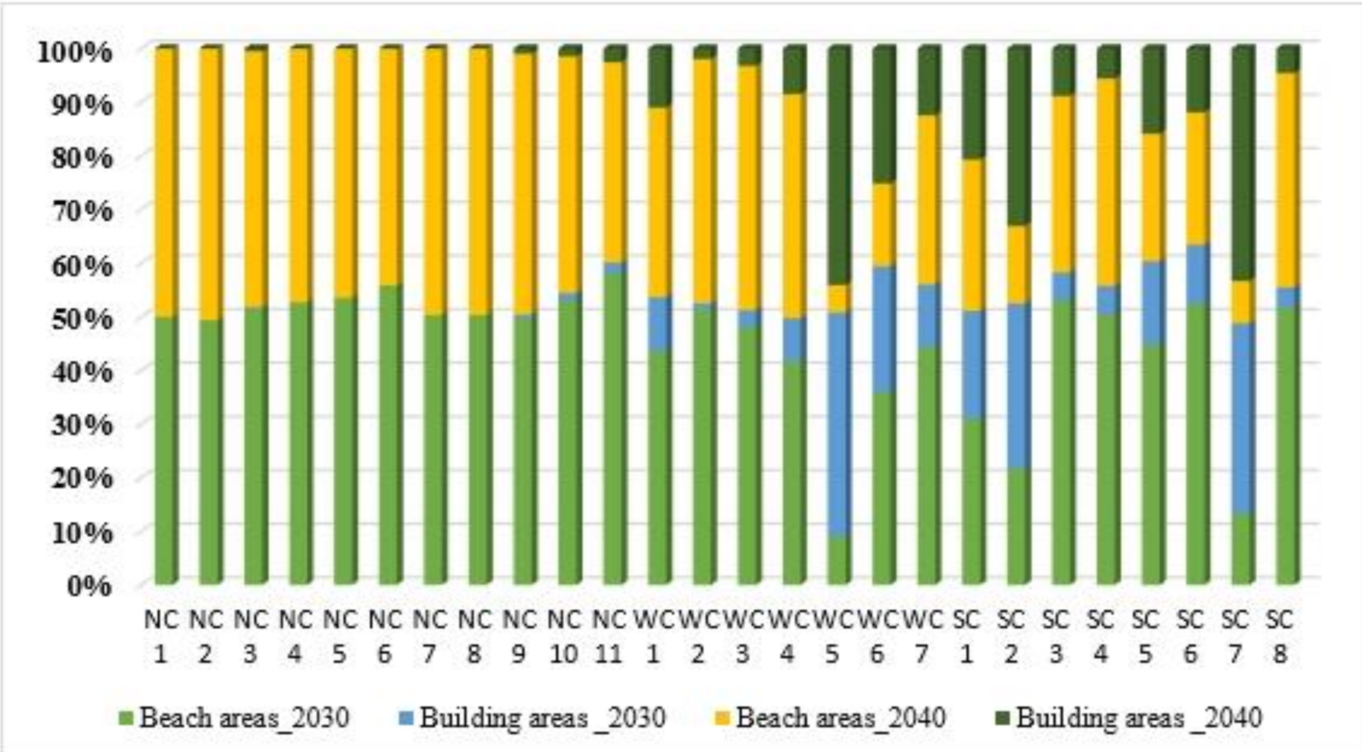


Figure 5. Beach reduction due to construction along the Dakar coast in 2030 and 2040.

estimated instead of 15,481,413 m^2 in 2040, with a difference of 951,987 m^2 which is the expected loss of surface area between 2030 and 2040 (Figure 5).

Number of Buildings, Hotels, Industries, Fishing Points, and Road Length

The buildings, hotels, industries, fishing points, and road lengths located in the buffer zones of the coastline are counted for each district municipality. The counting was done using the Open Street Map shapefile data in ArcGIS (Figure 6). These variables help determine the economic value of a coastal zone.

Coastal Vulnerability Index

The CVI is calculated using the square root of the product of variables (slope, geomorphology, geology, existing protective infrastructures, sea level change, shoreline displacement, mean tidal range, swell range, mean wave height, and distance between settlement and sea) divided by the total number of variables. Then, variables are ranked from 1 to 5 and divided by the total number of variables. These variables are the key driving factors of the physical coastal vulnerability and are quantitative and qualitative. Variables have different units. The CVI of each district municipality is determined and used as an independent variable to highlight its importance in the economic values of coastal width:

$$\mathbf{CVI} = \sqrt{\frac{(\mathbf{a} * \mathbf{b} * \mathbf{c} * \mathbf{d} * \mathbf{e} * \mathbf{f} * \mathbf{g} * \mathbf{h} * \mathbf{i} * \mathbf{j})}{\mathbf{10}}} \quad (2)$$

where a = slope; b = geomorphology; c = geology; d = existing protective infrastructures; e = sea level change; f = shoreline displacement; g = mean tidal range; h = swell range; i = mean wave height; j = distance between settlement and sea.

Variable Used for the CVI Computation

This study uses ten variables: slope, geomorphology, geology, existing protective infrastructures, relative sea level, shoreline displacement, tidal range, swell range, wave height and distance between the settlement and sea.

Slope

The susceptibility of the coast to immersion by flood and the quickness of shoreline retreat are influenced by the area's relief. This was changed later by the coastal slope (Kotinas *et al*., 2016). In this study, data about the slope of the Dakar region were obtained by downloading the Digital Elevation Model (DEM) through the Copernicus website (GLO_30 DEM) and using ArcGIS software. The slope is calculated by measuring the distance from each shoreline segment to the points with a contour over 4 m. The slope is obtained by dividing the rise by distance and multiplying by 100 (Equation (3); Kotinas *et al*., 2016). Three steps were performed for calculating coastal slope: a selection of coastal areas over 4 m altitude, segmentation of shoreline in small parts and distance from each part of the shoreline to the nearest points with an elevation of 4 m:

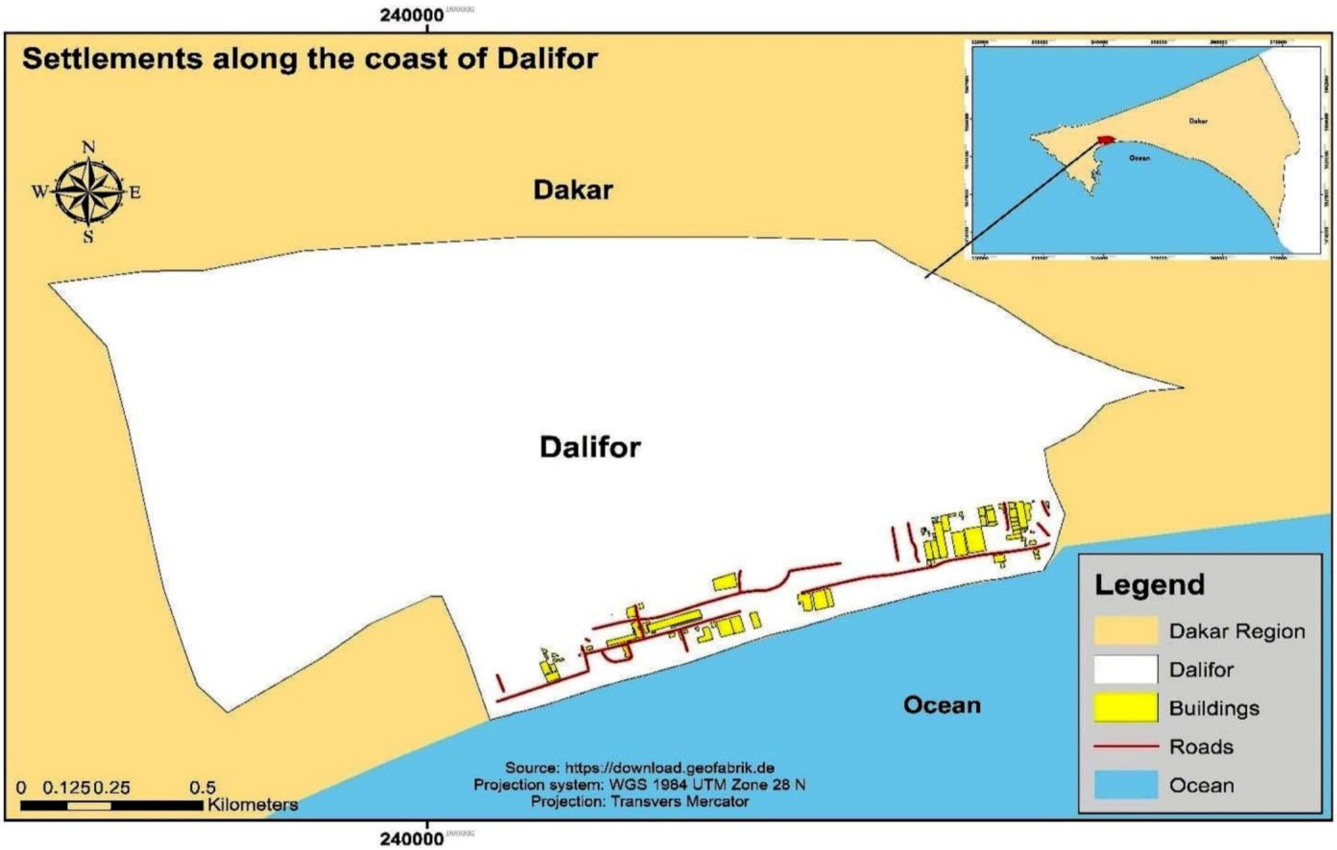


Figure 6. Identification of buildings, hotels, industries, fishing points, and the length of roads in the district municipalities of the Dakar region (case of Dalifor).

$$\textbf{Slope} = 4 / \textbf{Distance} * 100 \quad (3)$$

The coastal slope of the Dakar region is used to determine the level of exposure of the coast to inundation. The coastal slope of the Dakar region can be divided into three sections. On the northern coast, from Yoff to Malika, the slope is lower than 1%, whereas from Tivaouane Peuhl to Mbambilor, it does not exceed 4%. On the southern coast from Hann Bel-air to Rufisque, the slope is lower than 1%, whereas on the coast of the district municipality of Yene slope is comprised of between 0 to 39%. The slope of the western coast (from Ngor to Plateau) is between 3 to 41.9%. To integrate slope in coastal vulnerability assessment, a selection of coastal areas over 4 m altitude, segmentation of shoreline in small parts, and distance calculation were done using ArcGIS (Figure 7).

Geomorphology

According to Sane and Yamagishi (2004), the accompanying geomorphological units are recognized in the graben. Coastal dunes arranged along the northern coast include two influential groups: the live coastal dunes spread out at the rear of the high seashore, and the youth dunes stand out behind the live coastal dunes. These are set up by N-S-oriented littoral drift. The Ogolian Erg is situated in the focal and northern parts of the Dakar region. It incorporates longitudinal dunes running in the NE-SW direction, isolated by dame interdune corridors. The substratum of the limestone plateau of the Bargny-Rufisque district is made out of limestone and marl of the Eocene age. In the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion. The coastal geomorphology of the Dakar region is one of the conditions determining its susceptibility to erosion. It is characterized by sand on the whole north and south coast from Hann Bel-Air to Rufisque Ouest. Cobble beach and medium cliff coast describe the coast from Rufisque Est to Yene. The western coast is characterized by a cliff. Data about the geomorphology of the coast of the Dakar region have been collected through the USAID Project/RSI N 685–0233 (USAID, 1983). Many types of sediment have been identified: sandy beach, cobble beach, cliff, and medium cliff coast. These geomorphologic conditions have different resistivity to erosion. The geomorphologic data of the coasts of the Dakar region was integrated to the workspace. Each shoreline part is attributed to a geomorphologic feature by joining the information of the two layers (Split_Shore and Geomorphology.Shp) through the Spatial Join Tools (Figure 8).

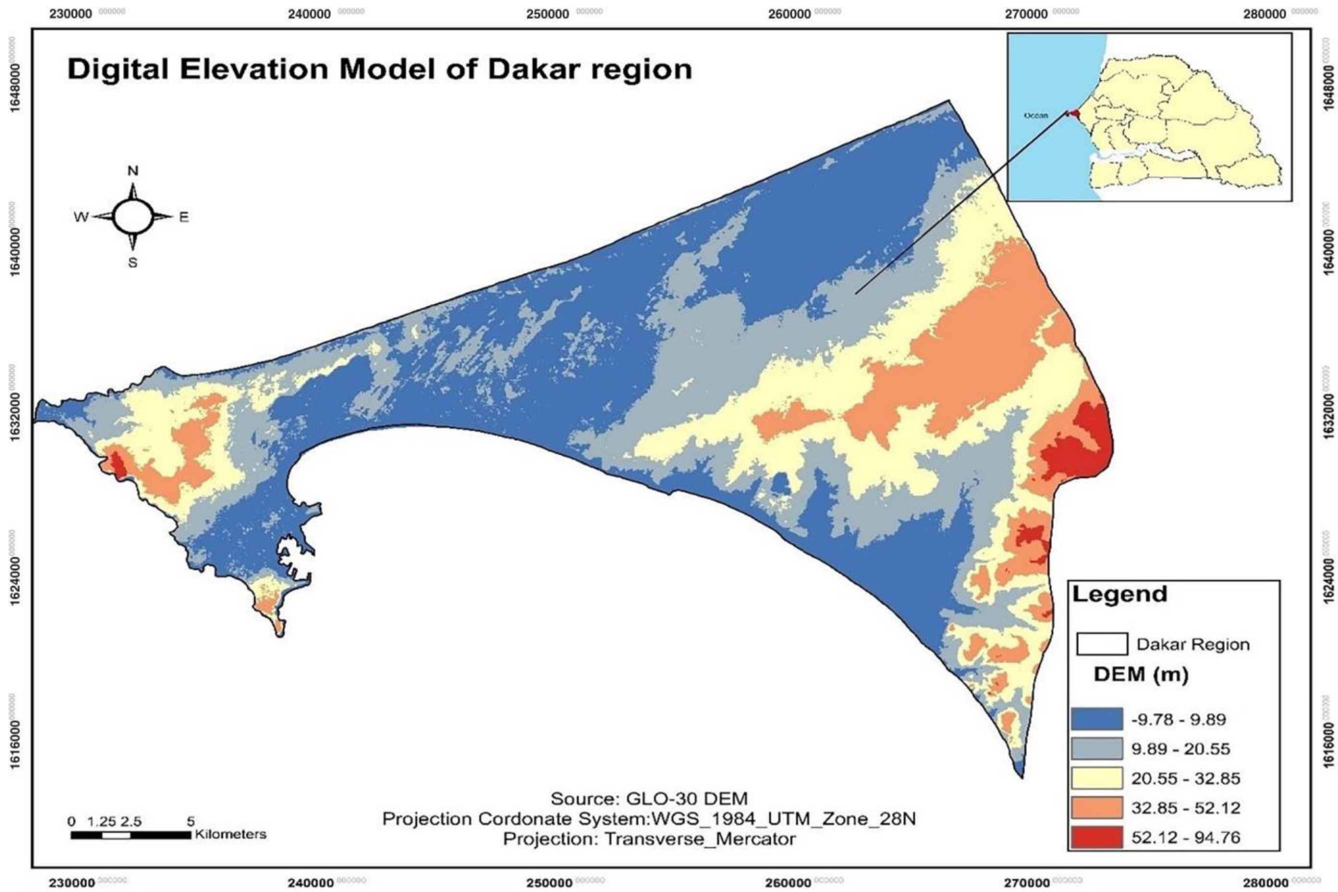


Figure 7. Digital elevation model of Dakar region used to determine the contribution of coastal slope in the Coastal Vulnerability Index (CVI).

Geology

Three different activities determine the geologic history of the Dakar region: volcanic actions, marine transgressions, and regressions, which are observed from the prequaternary period up to the quaternary period and mark traces are still visible. They are made up of mainly Nouakchott deposits (5500 years BP). These deposits are sands or grey marl rich in coastal fauna with limestone bets of an average thickness of 100 m. The brown marl deposits are also visible in the northern part of Dakar. As a result, the limestone and limestone soils are currently the framework and substratum of Dakar (Adjoussi, 2001). Geologically, from the Mesozoic to the Quaternary age, the overall advancement of western Senegal is portrayed by significant faulting framed two horsts (in Dakar's surrounding region). In Dakar city, the southern horst shapes the Dakar plateau 50 m high above the ocean level. It comprises essentially tertiary volcanic, for example, basaltic, doleritic, and tuffaceous rocks, and sedimentary rocks. The Ndiass horst arrives at a tallness of 105 m and is framed by Quaternary volcanic deposits. The morphology of the two horsts is emphasized by the occurrence of recent volcanic cones made out of both volcanic debris and basaltic magmas. The horsts create intended, cliffy shorelines that safeguard a less corrupted structure. On such shorelines, the wave's immediate effect is reduced, which slows erosion. Between the two horsts is an enormous graben overwhelmed by Quaternary residue, which shows the lowest topographic point since altitudes rarely rise 5 m above sea level. Long after the tertiary volcanism, severe disintegration of the horsts happened during the early Quaternary. Mechanical change of the igneous rocks happened by common enduring of the dolerite facies and separation of the stone along joints, causing the formation of erratic blocks. Chemical modifications started with the decay of individual grains. This phenomenon is notable in tropical areas (Sane and Yamagishi, 2004). The geology of the study area is meanly characterized by fine unconsolidated sediments, volcanic, and sedimentary rocks. Information concerning the geology of Dakar region were added to the workspace by making the layers Geology.Shp. Each shoreline part is attributed to a geologic feature by joining the information of the two layers (Split_shore_geom and Geology.Shp) through the Spatial Join Tools (Figure 9).

Existing Protective Infrastructures

The protective infrastructures against coastal erosion are installed along the coast of the Dakar region. Plantations that fix the dunes, riprap, defensive walls, and breakwater and

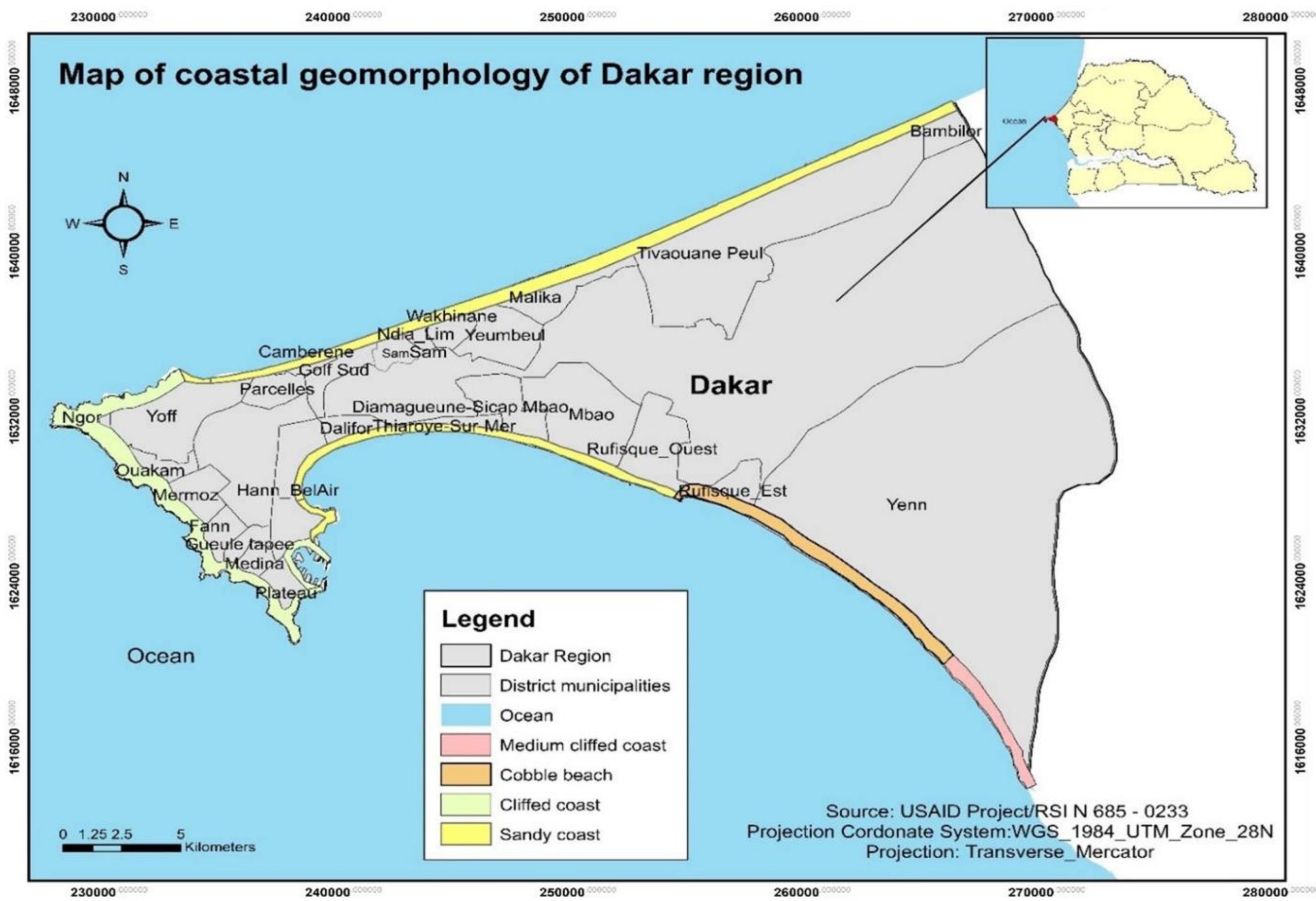


Figure 8. Different coastal geomorphological structures in the district municipalities of the Dakar region.

gravel are noted in some coastal segments in the Dakar region. The existing or no existing protective infrastructures is a helpful variable to determine the level of vulnerability and adaptative capacity of local communities to cope with coastal erosion. For the incorporation of the existing protective infrastructures in the CVI assessment, each shoreline part was assigned to "existing protective infrastructure" or to "not existing protective infrastructure." For that, the coastal areas that have a protective infrastructure or not were inventoried. The vector layers (polygon) for protective infrastructures were created. After that, the information was joined to the layer.

Relative Sea Level

Since 1982, the sea level of Dakar has been recorded through tides gauges. These sea-level data records were not regular because of the temporal breaking down of the tide gauges and other inconveniences. For example, data about 2004, 2005, and 2006 were not recorded. Therefore, the mean sea level (MSL) trend at Dakar 2, Senegal, is +1.14 mm/year with a 95% confidence interval of ±0.61 mm/year, based on monthly mean sea level data from 1992–1999 to 2018–2012. The plot shows the monthly mean sea level without regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. By default, the long-term linear trend is also shown, in red, along with its 95% confidence interval. The plotted values are relative to the most recent MSL datum established by the National Oceanic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS). To account for sea-level change, data should be added to the layer's attribute table. For that, a new file is created by selecting Table Option and Add Field and then creating the new field named "RSL." Each transect is attributed to a value of 1.14 mm.

Shoreline Displacement

The shoreline displacement is an indicator that informs on the vulnerability to coastal erosion and is determined by the End Point Rate, which is computed by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and the youngest shorelines (Equation (1)) through the use of the DSAS tool, which is an extension of ArcGIS software (Himmelstoss *et al.*, 2018). The NSM distance between the most recent shorelines and the oldest shorelines for each transect, and is measured in meters (m) (Pouye *et al.*, 2022).

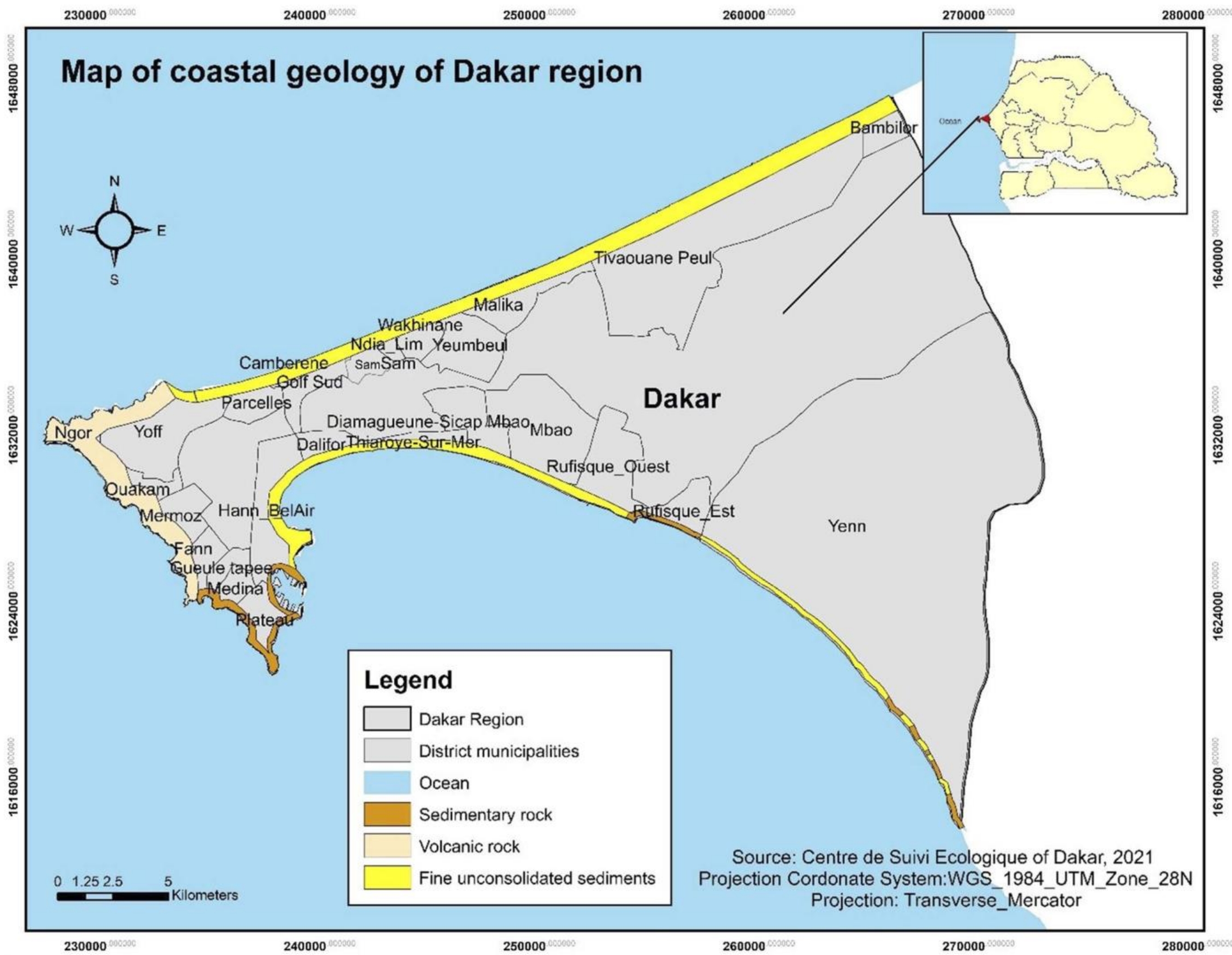


Figure 9. Different coastal geological structures in the district municipalities of the Dakar region.

Tidal Range

Tides are linked with both permanent and episodic inundation events. An extensive tidal range determines the spatial extent of the coast. Areas with large tidal waves have broad, near-zero relief intertidal zones and are susceptible to permanent inundation following sea-level rise. Besides, they are exposed to episodic flooding associated with storm surges, particularly if these coincide with high tide. The annual daily averages of tide recorded in Dakar show that the trend line of tide increased from 1992 to 2020 with a mean daily tide of 10.55 cm (ANACIM, 2020). To consider tide, data should be added to the layer's attribute table. For that, a new file is created by selecting Table Option and Add Field and then creating the new field named "Tide." Each transect is attributed to the value of 10.55 cm.

Swell Range

Generated by wind and currents, swell is one of the most important forces that influence and determine the dynamic behavior of beaches. In the Dakar region from 1991 to 2018, the height of the swell does not exceed 2 m. The highest height swell was about 1.74 m, recorded in 1995. Guerin (2003) states that the swells of the Cape Verde peninsula are short (less than 7.5 seconds). The swell data were acquired from the Agence National de l'Aviation Civile et de la Meteorologie (ANACIM). Furthermore, the mean high swell from 1991 to 2018 is about 1.65 m. The swell data were added to the layer's attribute table. For that, a new file is created by selecting Table Option and Add Field and then creating the new field named "Swell Range" and each transect is attributed to a value of 1.65 m.

Mean Wave Height

Toffoli and Bitner-Gregersen (2017) define waves as oscillations or disturbances of water surface that can be observed in any water basin; for example, rivers, seas, lakes, and oceans. The initial equilibrium state, its disturbance, and compensation by a restoring force are the conditions for a wave to exist. Local wind, seismic oscillations of the Earth during earthquakes, atmospheric pressure gradients, and gravitational attraction between the Earth, Moon, and Sun. Data about the average wave height is from Guerin (2003). It plays an important role in coastal erosion. Its action on the beach depends on the nature of the wave and the coastal sediment where it breaks (Reeve, Chadwick, and Lleming, 2018). In a study, Strahler (2013) stipulated that the breaking of waves against a shoreline yields a variety of distinctive features. If the coast is made up of weak or soft materials (various kinds of regolith, such as alluvium), the force of the forward-moving water alone easily cuts into the coastline. Here, erosion is rapid, and the shoreline may recede rapidly. Under these conditions, a steep bank, or marine scarp, will form and steadily erode as storm waves attack it, whereas, where resistant rocks meet the waves, sea cliffs often occur. A notch is carved essentially by physical weathering at the base of a sea cliff. Constant splashing by waves followed by evaporation causes salt crystals to grow in tiny crevices and fissures of the rock, breaking it apart, grain by grain. Hydraulic pressure of waves, and abrasion by rock fragments thrust against the cliff, also chisel the notch. Undercut by the notch, blocks fall from the cliff face into the surf zone. As the cliff erodes, the shoreline gradually retreats shoreward. Sea cliff erosion results in various erosional landforms, including sea caves, arches, and stacks (Strahler, 2013). To account for Mean Wave Hight (MWH), data should be added to the layer's attribute table. For that, a new file is created by selecting Table Option and Add Field and then creating the new field named "MWH" and each transect is attributed to a value of 1.75 m.

Distance between Settlements and the Sea

The distance between the settlement and the sea is a useful variable in assessing vulnerability. It is one of the indicators which informs about the level of exposure of local communities to coastal erosion. The distance between the settlement and sea for each transect was determined using Google Earth, GPS visualizer, and ArcGIS. The urban population growth in Dakar is the consequence of the rapid occupation of the coast, reflecting the importance of the settlement's proximity to the sea. The coastal occupation dynamic shows two types of evolution: The advance of the dwellings toward the sea and, on the other hand, the advance of the sea towards the houses. In addition, there has been a reduction or disappearance of vegetation cover in the Dakar region in favour of the settlement. For instance, the retreat of the filao on the northern coast, particularly in the department of Guédiawaye, is less exposed compared to the southern coast, which is more vulnerable based on the distance between the houses and the sea, which does not exceed 100 meters (Pouye, 2016). The corresponding "distance between settlement and sea" was attributed to each transect in the attribute table by joining the information of the layer and "distance between settlement and sea" based on their spatial information through the Spatial Join Tools.

Ranking Values for CVI Calculation

The ranking values for CVI are made based on the different variables. The scale is from 1 to 5, indicating each variable's vulnerability level (Table 2; Figure 10). The ranking values were done first by creating a new field for each variable in the layer and then the ranking value.

Table 2. *Coastal Vulnerability Index (CVI) variables (personal work inspired by Thieler and Hammar-Klose [1999] in Kotinas et al. [2016]).*

	CVI				
Variable	Very Low, 1	Low, 2	Moderate, 3	High, 4	Very High, 5
Coastal slope (%)	> 32	16–32	8–16	4–8	0–4
Geomorphology	Rocky, cliffed coasts, artificial constructions	Medium cliffs, indented coasts	Low cliffs, alluvial plains, beach rocks, dunes (mixed material)	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marsh, mudflats, deltas, mangrove, coral reefs
Geology	Plutonic volcanic high-medium grade metamorphic	Low grade metamorphic sandstones and conglomerates	Most sedimentary rocks	Coarse, poorly sorted unconsolidated sediments	Fine unconsolidated sediments volcanic ash
Existing protective infrastructures	The forest which fixes the sand dunes	Riprap	Protective walls andbreakwater	Gravel	No protective infrastructure
Relative level sea change (mm/year)	< 1.8	1.8–2.5	2.5–3.0	3.0–3.2	> 3.2
Shoreline displacement (m/yr.)	> 2.0	1.0–2.0	-1.0–+1.0	-1.1–2.0	<-2.0
Mean tide range (m)	> 6.0	4.1–6.0	2.0–4.0	1.0–1.9	<1.0
Mean swell range (m)	< 2.0	2.5–3.0	3.0–3.5	3.5–4.0	> 4
Mean wave height (m)	< 0.55	0.55–0.85	0.85–1.05	1.05–1.25	> 1.25
Distance between settlements and sea (m)	1149–2053	589–1149	267–589	96–267	0.72–96

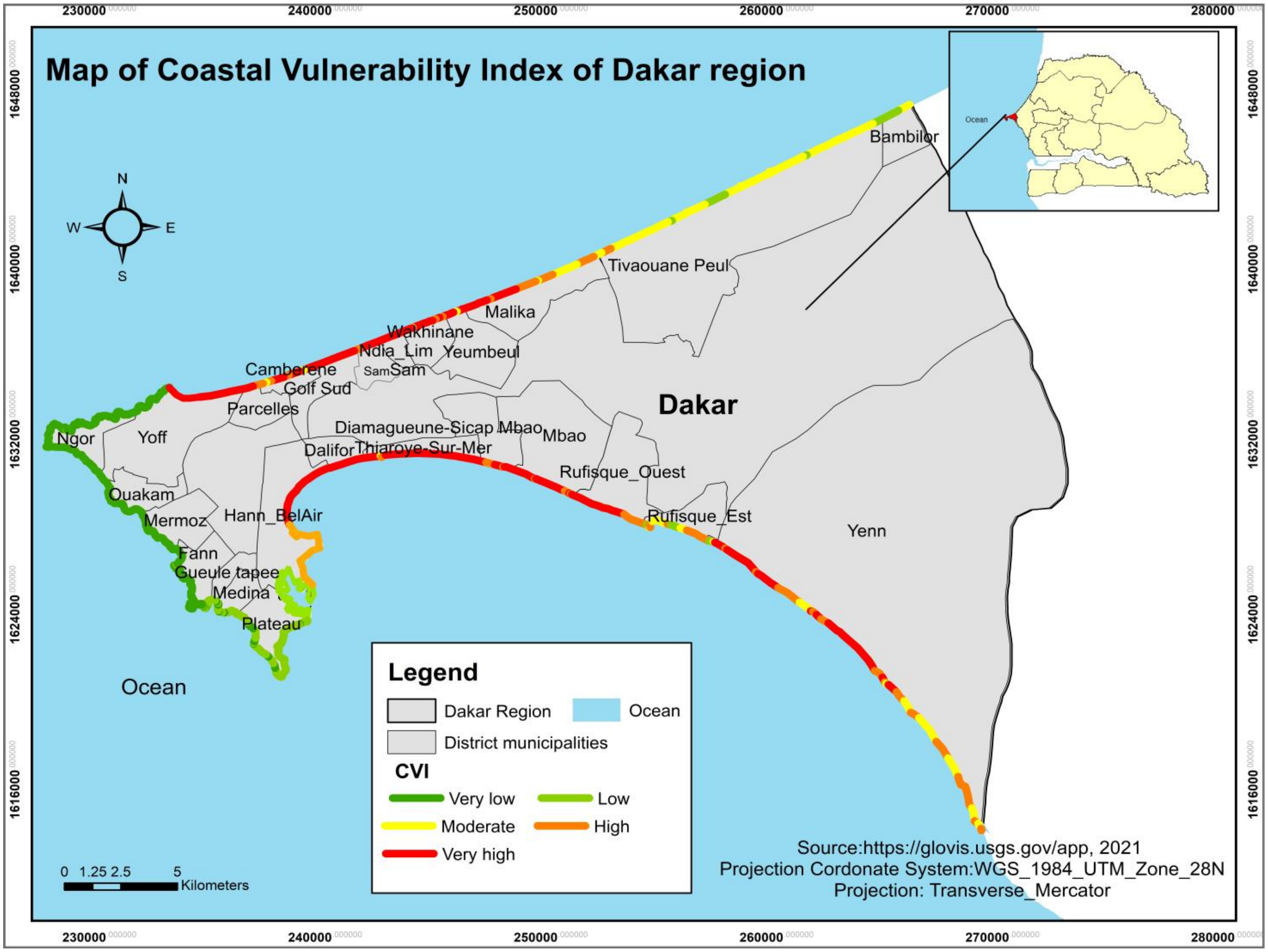


Figure 10. Physical coastal vulnerability map of the Dakar region showing the level of vulnerability in each district municipality.

The fields were created by selecting Table Option and Add Field. In Name, CVI_ plus the name or abbreviation of the variables is set and Type set as "integer." These names should be CVI_Slope, CVI_Geom, CVI_Geol, CVI_EPI, CVI_SLR, CVI_EPR, CVI_Tide, CVI_Swell, CVI_MWH, and CVI_Dist.

To rank the values of a variable for example Slope, the following procedure was used: Selection Menu > Select by Attributes> in Layer option, the file Split_shore_FINAL has to be set > Double click on Slope > Set the expression Slope > 32 (for the Index 1, Very low) > Ok > Right click on CVI_Slope > Calculator > Assign the value 1 > Ok. As a result, all coastal areas with a slope over 32 will be highlighted in blue. The sameprocedure was done for Indexes 2, 3, 4, and 5.

METHODS

Starting from the idea that, in the event of a shock the decrease in the economic value of the littoral in 2030 and 2040 is a clear sign of the vulnerability of the coast and its need for coastal protective infrastructures (because coastal areas which do not record erosion do not need protection). This study considers the shock caused by the decrease in littoral price generated by physical and socio-economic parameters. Multi-linear regression in R software is used.

Variables Used

Dependent variables or variables of interest and independent variables or control variables are used as follows:

- Dependent variable: The dependent variable is each district municipality's respective share of economic littoral value. It is the variable that expresses the economic value of the coast regarding physical and socio-economic parameters.
- Variables of interest: The variable of interest is the Littoral Price.
- Control variables: Beach Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, CVI, Building Price, Number of Buildings, Number of

Table 3. *The variance inflation factor of independents variables in 2030 and 2040.*

Variable	Square Root of VIF	
	2030	2040
Littoral Width	2.67	2.73
Lost Areas	2.06	2.41
Coastal Length	2.46	2.81
Littoral Areas	2.44	2.74
Dynamic Rate	1.63	1.85
Building Areas	2.69	2.87
Hotels	1.24	1.26
Industries	1.19	1.37
Fishing Points	1.39	1.39
Road Length	2.45	3.31
Number of Buildings	2.78	2.75
Proximity to Town	2.37	2.39
CVI	1.58	1.61

VIF = Variance Inflation Factor; CVI = Coastal Vulnerability Index

Hotels, Number of Industries, Number of Fishing Points, and Road Length are the variables of control. The linear model used is expressed as follows:

$$\boldsymbol{y = \alpha + \beta choc + \lambda X + \varepsilon} \qquad (4)$$

where y = The share of economic littoral value for each district municipality; choc = decrease of littoral price X = a set of control variables (Littoral Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, CVI, Number of Buildings, Number of Hotels, Number of Industries, Number Fishing Points and Road Length); choc = the decrease or increase of the variable interest (littoral price); ε = the error term; α, β, and λ = the model parameters.

Multicollinearity Test

In a study, Oke, Akinkunmi, and Etebefia (2022) stated that "multicollinearity is a statistical phenomenon in which a solid or perfect relationship exists between the predictor variables. The presence of multicollinearity can cause severe problems with the estimation and interpretation." Therefore, the much higher correlation between the explanatory variables means more risk in the statistical inference about the significance of the regression coefficients. Various tests and diagnostic measures of multicollinearity have been proposed in the econometric literature. Some measures are available for diagnosing multicollinearity, such as the variance inflation factor (VIF), condition number (CN), condition index (CI), and variance decomposition (Belsley, Kuh, and Welsch, 1980); Chi-square test statistic (Farrar and Glauber, 1967; Haitovsky, 1969); and an F-test by regressing each of the independent variables on the remaining independent variables. The VIF, a well-known measure of multicollinearity, is defined as:

$$\boldsymbol{VIF_i = \left(1 - R_i^2\right)^{-1}} \qquad (5)$$

where R_i^2: is the coefficient of determination of the regression of the ith column of X on the remaining columns of X. Based on the VIF diagnostic measure, multicollinearity is severe whenever the VIF is more than 10. There is no logical reasoning behind the value 10. Therefore, there is no logical reasoning behind the value 10 (Mohammadi, 2020). In this study, multicollinearity was done to point out the dependence among independent variables. The results from the multicollinearity test show no collinearity among independent variables because the square roots of the VIF are lower than 5 (Table 3).

Specification of the Model

Akaike information criterion (AIC), Bayesian Information Criterion (BIC), and R^2 are used to select the model used in this study (Table 4). In a study, Romero (2007) stated that it is usual practice in econometrics to use R^2 in model selection. This goodness of fit measurement, along with others like the unadjusted R^2, the AIC, and the BIC, are almost always available to researchers using econometric software. Therefore, the AIC is a prominent approach for selecting models. It is widely used for parameter space singularities and borders to infringe upon regularity conditions (Mitchell, Allman, and Rhodes, 2022). At the same time, the Bayesian information criterion is a helpful metric for comparing multilevel models. The BIC has several benefits over conventional hypothesis-testing techniques (Lorah and Womack, 2019). According to Yulistiani and Suliadi (2019), the good criteria for model selection can use the BIC. For model selection in linear mixed models, one may use AIC or BIC. Distinct random effect specifications result in different covariance structures of observation because linear mixed models might provide the specific dependency structure among responses (Lee, 2015).

RESULTS

Multilinear regression, which is an econometric forecasting model, was used. The model performed well, with 11 out of 13 variables significant at 10%, and the R^2 is estimated at 0.986 for the year 2030. Almost the same case is noted for 2040, with 9 out of 13 variables significant at 10% and an R^2 of 0.9123. The

Table 4. *Specification of the model using Akaike Information Criterion (AIC), R^2, and Bayesian Information Criterion (BIC) test for 2030 and 2040.*

	Test					
	AIC		R^2		BIC	
Model	2030	2040	2030	2040	2030	2040
M_0	1476	1464	0.93	0.93	1497	1486
M_1	1334	1405	0.98	0.95	1354	1426

M_0 = model without diagnostic; M_1 = model neither outlier nor influencer
The lower the AIC, the better the model. The higher the R^2, the better the model. The lower the BIC, the better the model. Based on these later statements, model M_1 *was chosen.*

Table 5. *Linear model results for 2030 and 2040.*

Variables	Code	Model 1 (2030)† Estimate	Std. Error	t value	Pr(>ltl)§	Model 1 (2040)‡ Estimate	Std. Error	t value	Pr(>ltl)§
	(Intercept)	-5,822,000,000	4.49E + 09	-1.296	0.21594[e]	-20,840,000,000	7.28E + 09	-2.863	0.01185[c]
Littoral Width	LW	74,080,000	4.48E + 07	1.653	0.120663[e]	-104,900,000	2.45E + 07	-4.278	0.00066[a]
Lost Areas	LA	186,100	3.32E + 04	5.615	0.0000638[a]	137,900	4.07E + 04	3.39	0.00404[b]
Coastal Length	CL	1,790,000	8.66E + 05	2.066	0.0578[d]	3,131,000	1.47E + 06	2.132	0.04995[c]
Littoral Areas	LA_s	-11,400	3.26E + 03	-3.493	0.003587[b]	-3187	3.33E + 03	-0.959	0.3529[e]
Dynamic Rate	DR	1,361,000,000	3.10E + 08	4.397	0.000608[a]	791,400,000	2.61E + 08	3.028	0.00848[b]
Built Areas	BA	281,200	6.42E + 04	4.38	0.000628[a]	280,800	1.33E + 05	2.109	0.05218[d]
Number of Hotels	NH	23,850,000,000	1.50E + 09	15.881	0.000000000239[a]	4,502,000,000	6.96E + 09	0.647	0.52736[e]
Number of Industries	NI	471,400,000	4.21E + 09	0.112	0.912426[e]	-634,500,000	5.94E + 09	-0.107	0.91635[e]
Number Fishing Points	NFP	-11,060,000,000	4.40E + 09	-2.517	0.024655[c]	-4,989,000,000	5.12E + 09	-0.974	0.34542[e]
Road Length	RL	1,091,000	3.73E + 05	2.924	0.011113[c]	1,194,000	6.63E + 05	1.8	0.09197[d]
Number of Buildings	NB	-32,040,000	8.97E + 06	-3.573	0.00306[b]	-48,100,000	1.65E + 07	-2.919	0.01058[c]
Proximity to Town	PR	1,174,000	3.51E + 05	3.347	0.004795[b]	2,635,000	4.87E + 05	5.412	0.000072[a]
Costal Vulnerability Index	CVI	-203,900,000	4.94E + 07	-4.127	0.001026[b]	-93,700,000	6.08E + 07	-1.541	0.14408[e]

†*Model 1 (2030): Residual standard error = 4.468E + 09 on 14 df; multiple R^2 = 0.9927; adjusted R^2 = 0.986; F statistic = 147.3 on 13 and 14 df; p ¼ 1.206E-12*
‡*Model 1 (2040): Residual standard error = 6.756E + 09 on 15 df; multiple R^2 = 0.953; adjusted R^2 = 0.9123; F statistic = 23.39 on 13 and 15 df; p ¼ 1.343E-07*
§*Signification of codes: a = 0; b = 0.001; c = 0.01; d = 0.05; e = 1*

more confident the coefficient's ability to predict, the higher the *t*-value. Low *t*-values signify that the coefficient's predictive capacity could be more reliable (AllBusiness.com, 2023). Therefore, 9 out of 13 have positive t values for 2030, whereas 7 out of 13 have positive t values in 2040. The relationship between littoral price and variables is significant since the p-value is less than 0.05. It is estimated at 1.206e-12 for 2030 and 1.343e-07 for 2040. That means that the independent variables (Beach Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, CVI, Number of Buildings, Number of Hotels, Number of Industries, Number Fishing Points, and Road Length) affect the dependent variable (economic littoral value).

The results show that if the beach width, coastal length, dynamic rate, proximity to a town, and road length change by one meter, it is expected that the littoral value gets, respectively, 74,080,000, 1,790,000, 1,361,000,000, 1,174,000, and 1,091,000 FCFA in 2030. If the lost, littoral, and building areas change by one square meter, the littoral value is expected, respectively, 186,100, -11,400, and 281,200 FCFA. If the coast vulnerability index, number of buildings, hotels, industries, and fishing points change by one unit, the littoral value will get respectively -203,900,000, -32,040,000, 23,850,000,000, 471,400,000, and -11,060,000,000 FCFA.

In 2040, if the beach width, coastal length, dynamic rate, proximity to a town, and road length change by one meter, it is expected that the littoral value gets respectively -104,900,000, 3,131,000, 791,400,000, 2,635,000, and 1,194,000 FCFA. If the lost, littoral, and building areas change by one square meter, the littoral value is expected, respectively, 137,900, -3187, and 280,800 FCFA. If the coast vulnerability index, number of buildings, hotels, industries, and fishing points change by one unit, the littoral value will get respectively -93,700,000, -48,100,000, 4,502,000,000, and -634,500,000 FCFA (Table 5).

Economic Lost Estimation Based on Littoral Price

In all district municipalities, economic loss is estimated based on littoral price and lost areas in 2030 and 2040. The district municipality of Malika recorded the highest loss, with a loss estimated at 16,808,000,000 FCFA in 2030 and 23,191,150,000 FCFA in 2040. Plateau records a loss of about 830,010,0000 FCFA 2030 and 11,259,000,000 FCFA 2040. In Ngor, the economic loss is estimated at 2,869,900,000 FCFA 2030 and 7,421,260,000 FCFA 2040. The overall economic loss based on littoral price and lost areas in all district municipalities along the coast is estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040 (Figure 11).

DISCUSSION

Covering more than 71% of the Earth's surface, the oceans are the most heavily trafficked areas because of their usefulness for the economy, transport, and biodiversity. More than 600 million people live in coastal areas, representing 10% of the world's population (Gou and Tourian, 2021). Due to its geographic location and low-lying sections, the Dakar region, like the majority of the world's capitals, is vulnerable to the effects of coastal erosion. The Dakar region's coastal morphology is affected by the advanced sea brought on by sea level rise and climate change. The disruption of hydrodynamic agents like waves, tide, wind, *etc*. accentuates this scenario. As a result, there is a reduction in coastal regions, a shift of people inland, and a disturbance of various economic activities like fishing, lodging, and industry. Sand mining, pollution, and unauthorised settlements along the coasts are examples of human activities that exacerbate these problems (Pouye *et al*., 2023).

The coasts of the Dakar region have significant economic value for the Senegalese economy. However, climate change and the advancing sea cause the losses of coastal areas by reducing their economic values which vary from one locality to another. These economic values depend on several factors such as the proximity to the town, economic activities (fishing, tourism, and industry), infrastructures (roads, hospitals, stadiums, and university), and other socio-economic parameters (allotment, sanitation, accessibility). Therefore, estimating the economic value of the beach based on physical and

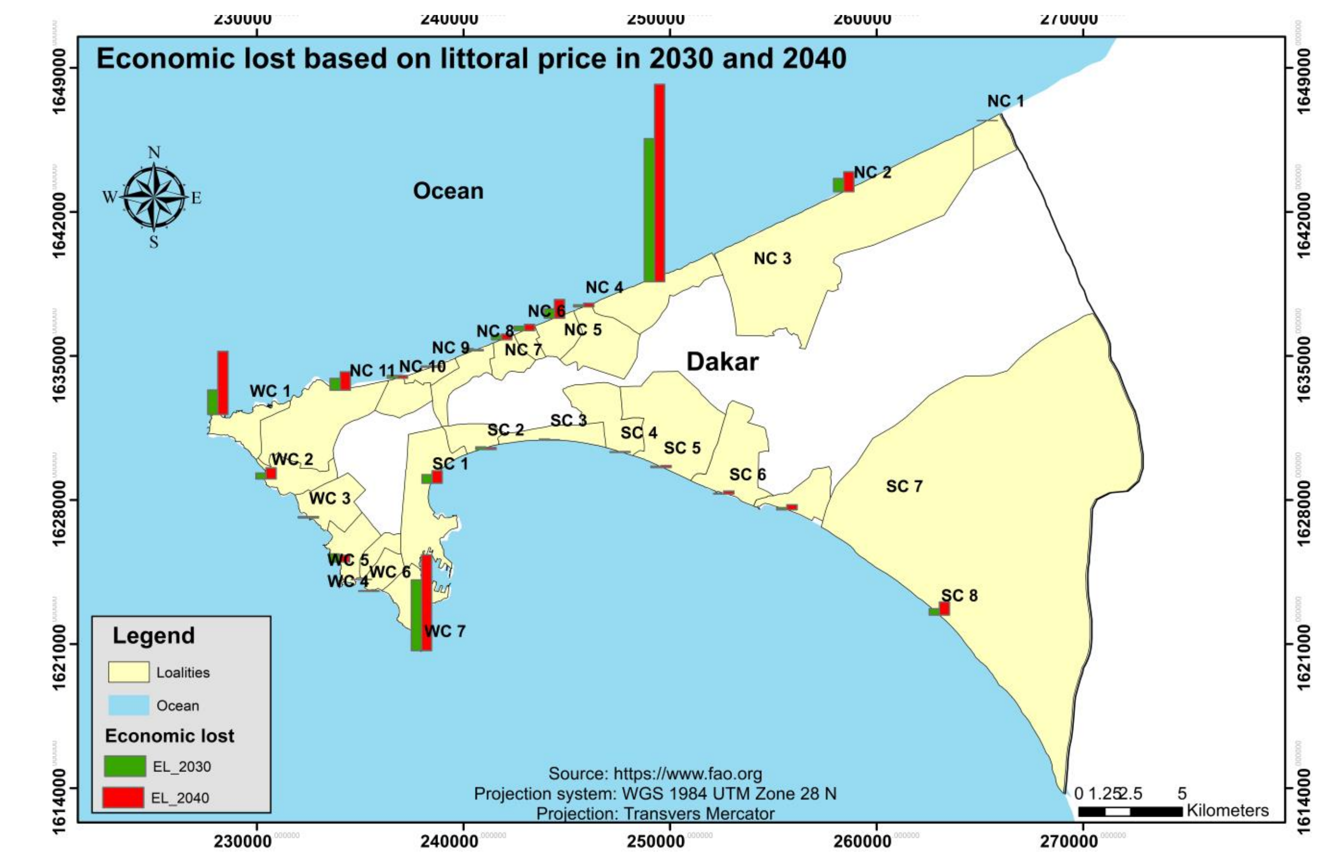


Figure 11. Economic lost estimations in 2030 and 2040 due to coastal erosion in each district municipality.

socio-economic parameters takes much work. Nevertheless, econometric models make it easier than a few decades ago. It helps decision makers understand the economic situation of the coasts in the future to determine whether there is a need for protection to prevent eventual coastal erosion damages. Most of the coasts of Dakar region are highly vulnerable to erosion. For instance, the Dakar region's northern and southern coasts record an average coastal vulnerability index (CVI) of about 94 and 23. In contrast, the western coast, which is less vulnerable, records an average of about 10. This vulnerability is justified by the dynamic rates of the coastline, which are estimated at -0.44 m/year, 0.21 m/year, and -0.11 m/year, respectively, on the northern, western, and southern coasts (Pouye *et al*. 2022). Based on the results of this study, one can note that if the CVI changes by one unit, the littoral value will change by -203,900,000 and -93,700,000 FCFA, respectively, in 2030 and 2040. In addition, the change by one unit of the dynamic rate will cause a change of 1,361,000,000 FCFA in 2030 and 791,400,000 FCFA in littoral value. Since the dynamic coastal lead to erosion or accretion, in addition to the socio-economic activities, it characterizes the width of the beach, which is among the key parameters used by researchers in beach value estimation through the Hedonic pricing model (Alexandrakis, Manasakis, and Kampanis, 2015; Catma, 2020; Gopalakrishnan *et al*., 2011; Landry and Hindsley, 2011).

In coastal zones where erosion is noted, the width of the littoral is reduced, causing a loss of areas. Sometimes, this situation leads to the disruption of economic activities along the coast. The economic impacts of beach width change and land loss due to erosion in Dakar are estimated. If the beach width changes by one meter, it is expected that the littoral value will change by 74,080,000 FCFA in 2030 and -104,900,000 FCFA in 2040. In all district municipalities, economic loss is estimated based on littoral price and lost areas in 2030 and 2040. The highest loss is recorded in the district municipality of Malika, with a loss estimated at 16,808,000,000 FCFA in 2030 and 23,191,150,000 FCFA in 2040. Plateau records a loss of about 8,300,100,000 FCFA 2030 and 11,259,000,000 FCFA 2040. In Ngor, the economic loss is estimated at 2,869,900,000 FCFA 2030 and 7,421,260,000 FCFA 2040. The overall economic loss based on littoral price and lost areas in all district municipalities along the coast is estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040.

Coastal areas in Dakar are the most strategic areas for industry, tourism, transport and fishing activities. However, these activities are confronted with coastal erosion through the reduction of exploitation areas and income. In the Dakar region, socio-economic sectors such as fishing, recreational activities and human settlements along the coast are affected by coastal erosion. Fishing is an activity that depends on the biological production of marine and coastal ecosystems and plays a considerable socio-economic role in Senegal, particularly in the Dakar region. This situation is exacerbated by the rapid retreat of the coastline observed in some coastal areas, resulting in the reduction of secure storage areas for their fishing boats, the destruction of fishing docks and markets. The main fishing points (Yoff, Soumbedioune, Hann, Thiaroye, and Rufisque) are exposed to the impacts of climate change and coastal erosion. In addition, marine pollution from sewage, chemicals, solid waste, *etc*. increases erosion, leading to disruption of marine and coastal biodiversity and exposing local communities to infectious diseases, reduced fish species, reduced income, *etc*. Recreational facilities such as hotels, hostels, restaurants, *etc*. along the coast of the Dakar region are weakened by the retreat of the coastline. From Yoff to Cité Djily Mbaye, there are large huts with hotels and hostels that represent a large part of the working population. The advancing sea destroys the huts, especially during the marshy period (wintering) from November to January, putting many beach workers out of work. It should be noted that in winter, these beach activities are less lucrative because of the cold, and the clientele is less frequent than in summer. This study demonstrates that if the number of hotels, industries, and fishing points changes by one unit, the littoral value will get 23,850,000,000, 471,400,000, and -11,060,000,000 FCFA in 2030. In 2040, if the number of hotels, industries, and fishing points changes by one unit, the littoral value will get respectively -48,100,000, 4,502,000,000, and -634,500,000 FCFA. Usually, economic activities and infrastructures are highly correlated to land value.

In a study, it is stated that the value of land increases as the areas' buildings grow with economic activities (Nakagawa, Saito, and Yamaga, 2007; Saputra *et al*., 2021). In 2030 and 2040, if the number of buildings changes by one unit, the littoral value will become, respectively, -32,040,000 and -48,100,000 FCFA. Far from being neglected, the proximity of the land to the town affects its value. Land value decreases with distance from the Central Business District, according to the urban economic theory built on a monocentric city (Han, Zhang, and Zheng, 2020; O'Sullivan, 2007). If the proximity to the town changes by one meter, it is expected that the littoral value will reach 1,174,000 CFA in 2030 and 2,635,000 FCFA in 2040. The dynamics of the coastline from 1990 to 2040 shows that the region records average retreats of about -0.44 m/year, 0.21 m/year and -0.11 m/year respectively on the northern, western and southern coasts. These dynamic rates are expected to be about -4.4 m/year (for the north coast), 2.1 m/year (for the west coast), and -1.1 m/year by 2030 (south coast). By 2040, they are estimated to be around 28.8 m/year (north coast), 4.2 m/year (west coast), and -2.2 m/year (south coast). These dynamic rates will cause the losses of area which is estimated at 861,273 m^2 in 2030 and 1,256,493 m^2 in 2040 (Pouye *et al*., 2022). In this study, it is estimated that if it changes by one square meter, the littoral value is expected to change by 186,100 FCFA in 2030 and 137,900 FCFA in 2040.

CONCLUSION

In summary, climate change has detrimental effects on the economic value of coastal zones and its adverse effects on the ecosystem. People who live by the coast suffer several harms as a result of one of its effects, coastal erosion. Consequently, these effects affect economically the coastal areas. The results of this study showed that the parameters such as Beach Width, Lost Areas, Coastal Length, Dynamic Rate, Littoral Areas, Built Areas, Proximity to Town, CVI, Number of Buildings, Number of Hotels, Number of Industries, Number of Fishing Points, and Road Length play an essential role on littoral value. The estimation of economic loss based on littoral price and lost areas showed that the district municipalities along the coast of Dakar recorded a loss estimated at 38,507,856,000 FCFA in 2030 and 57,822,698,000 FCFA in 2040. These losses are shared unequally in coastal areas in Dakar. The most exposed in terms of economic loss are Malika, Plateau, and Ngor. Whether the coast of Dakar region is challenged economically by coastal erosion, abnormal settlements, pollution sand mining aggravates the economic loss. It should be essential to note that the application of law no. 76–66 of 2 July 1976, which defines the natural public domain with the shores of the sea, and the artificial public domain with the numerous urban infrastructures built or planned (Quensière *et al*., 2013) and law no. 83–05 of 28 January 1983 of the Environmental Code which specifies that settlements along the coast must "neither be a source of erosion nor degradation of the site" (FAO, 2010). Unfortunately, this law is not respected by most people making economic decisions.

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