# CLIMATE CHANGE INDUCED SEA LEVEL RISE ALONG THE COASTLAND OF TOGO

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**A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILMENT OF REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (PhD) IN CLIMATE CHANGE AND HUMAN HABITAT**

**JUNE, 2024**

## DECLARATION

I hereby declare that this thesis titled: **"Climate change induced sea level rise along the coastland of Togo"** is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

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Signature & Date

## CERTIFICATION

The thesis titled "**Climate Change Induced Sea Level Rise along the Coastland of Togo**" by: KONKO, Yawo (PhD/SPS/FT/2019/11130) meets the regulations governing the awards of the degree of PhD of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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## ABSTRACT

Global warming is a worldwide phenomenon with disastrous implications ranging from ocean warming and glacier melting to sea level rise (SLR) and coastal damage. In recent decades, the majority of the world's coastal countries have seen tremendous population growth in their coastal districts. Coastal erosion is growing increasingly common as global temperatures rise, displacing coastal inhabitants and damaging towns and socioeconomic infrastructure, making sustainable management of coastal areas extremely difficult. One means for sustainable management and decision-making is to have information on the trend of climatic parameters at the local scale, the settlement pattern, the spatial distribution and dynamics of coastal peoples, the coastal erosion kinematics, the coastal erosion hotspots, the coastal vulnerability to SLR and inundation. This research contributes to the understanding of the range of climatic characteristics, spatial distribution and dynamics of coastal peoples, coastal erosion kinematics, and coastal sensitivity to SLR and inundation in Togo, West Africa. Images from satellites (Landsat and Sentinel-2), population data, field data, geographical data, and ground truth climatic data, specifically precipitation, temperature, wind speed, sunshine, and tidal gauge, were used from 1988 to 2020. The Mann-Kendall test and Sen's slope test were used to analyse the climate trends, while the Object-Based Image Analysis (OBIA) method was used to map settlement areas. The Support Vector Machine (SVM) method was used to extract the shoreline, and the kinematics were evaluated using the statistical linear regression method (LRR).The Integrated Valuation of Environmental Services and Tradeoffs (InVEST) for coastal vulnerability model was used to assess coastal vulnerability to SLR and inundation. Based on the findings, the temperature trend is significant at $\alpha = 0.001$, while the SLR exhibits a substantial annual trend at $\alpha = 0.05$.The temperature analysis showed an increase of trend of 0. 038 °C per year while the tidal gauge data analysis showed an increase of trend of 13.75 millimeters per year. The annual sunshine, annual wind speed and annual cumulative precipitation trend record variability which are not significant. However, the analysis of monthly sunshine identified significant trends at $\alpha = 0.1$ in April and September.According to statistical analysis of settlement dynamics, Togo's Maritime region, which had a population of 1,042,385 people in 1980, experienced population increase ranging from 2.06 per cent to 11.85 per cent between 1988 and 2020. The equivalent yearly expansion rate is 6.15 hectare per year from 1988 to 2000, 23.41 hectare per year from 2000 to 2015, and 40.16 hectare per year from 2015 to 2020. In 2022, the Maritime region has reached a population of 3,534,991 people. In addition, near the sea, the pattern of settlement areas is compacted with high density of peoples. In the inland this pattern is dispersed. In terms of shoreline kinematics, the Togolese coast has an average erosion rate ranging from 1.66 to 5.25 metre per year. Four high coastal erosion zones have been reported in the Alogavi, Devi-Kinme, Agbavi, and Baguida sectors. One high accretion zone was detected in the port region, near Adawlato sector. For coastal vulnerability model, high vulnerability is observed on the Baguida-Agbodrafo section, moderate vulnerability is observed in the Adawlato area and Agbodrafo-Aneho section, the low vulnerability is located in the port area. According to the findings, land in Togo's coastal zone is in great demand, the rate of settlement is increasing, and the temperature and sea level are rising. Taking this information into account can help to determine the extent of climate change phenomena and draw up suitable coastal management and adaptation plans at the country scale.

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# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background to the Study

Global warming causes oceans to warm, glaciers to melt, sea levels to rise (SLR), and coastal human homes to collapse, becoming symptomatic of humanity's ubiquitous and escalating effect on our oceans, coastlines, and landscapes (Jackson *et al.,* 2001; Pew Oceans Commission, 2003, Worm *et al.*, 2009). Among these growing impacts, there is coastal erosion phenomenon mainly caused by SLR (Intergovernmental Panel on Climate Change (IPCC), 2014). Some of the consequences of coastal erosion are coastal area inundation, damage on human habitat and people’s displacement (Adjoussi, 2015). According to Zhang *et al.* (2004), coastal erosion is still a major concern because half of the world's population lives within 100 kilometres of a coastline, and more than 100 million people live in coastal areas less than a metre above sea level. It is estimated that 20 million people (or 36% of the entire population of the nations involved) live on the West African coast, which covers over 3,400 kilometres (Regional Partnership for the Conservation of the Coastal and Marine Area (RPCM), 2018).

Climate change is one of the most critical concerns confronting humanity, with the potential to damage every natural and human system on the planet (IPCC, 2007; Stocker *et al.,* 2013). Changes in the Earth's energy balance induced by an increase in the amount of heat retained by the Earth's atmosphere create climate change (Climate Change, 2014). Rising greenhouse gas emissions in the atmosphere are disrupting the climate system's balance and causing global warming, which raises surface temperatures. The global warming have several impacts: In agriculture, an increase in the mean seasonal temperature can decrease the growing season of many crops, resulting in lower final yield (Mahato, 2014). In hot regions, the lethal temperature of crops could be reached with an immediate impact on yields (IPCC, 2014). Overall, agricultural productivity worldwide is expected to fall by 3 to 16 per cent by 2080 (Mahato, 2014). Climate change will affect all forms of natural resources. Plant and animal ranges will continue to shift as rising temperatures disturb ecosystems and intensify current environmental difficulties (Konko *et al.,* 2021), and will vary widely depending on the species and other factors (Grossi *et al.,* 2019). For coastal areas, there is coastal erosion phenomenon caused by SLR. Globally, coastal erosion affects more than 24 per cent of the world's sandy beaches, with rates of erosion exceeding 0.5 metres per year (Luijendijk *et al.,* 2018).

West Africa has been identified as a regional hotspot for climate change (Müller *et al.,* 2014). Average rates of coastal erosion along Africa's west coast range between one and two metres per year. However, more serious rates of up to hundreds of metres per year have been seen locally, particularly when the process is caused by human activity (Pacifici *et al.*, 2018). Coastal erosion has disastrous consequences, including the loss of infrastructure such as roadways. It also concerns communities who can no longer live along the coast, and it is anticipated to worsen as a result of climate change and SLR (IPCC, 2014). This will result in additional issues such as salinization of water and soils, ecosystem deterioration, and flooding. These forecasts were reaffirmed in the fourth report of the IPCC (2007).

In 2014, according to the IPCC, global sea levels will increase by 19 to 59 centimetres by 2100. SLR and coastal erosion will have a greater influence on all continents, albeit their severity will vary geographically (Yang *et al.,* 2012; Bayram *et al.,* 2013). According to Zhang *et al.* (2004), coastal erosion is still a serious concern because half of the world's population lives within 100 kilometres of a coastline and around 100 million peoples live in coastal areas that are less than a metre above sea level. It is projected that 20 million peoples (or 36 per cent of the total population of the countries involved) live on West Africa's 3,400-kilometre-long coast (RPCM, 2018).

At the global scale, future SLR-induced erosion and land-cover changes have the potential to enhance coastal flooding and influence tidal dynamics (Resio and Irish, 2015). For example, historical SLR of around 0.75 metres in the New Orleans (United States) area since 1900 increased hurricane and flood levels by about 1.3 metres (twice the SLR amount), owing primarily to SLR-induced loss of wetlands in the area (Irish *et al.,* 2014). SLR is one of the most serious difficulties that Portugal (Europa) and its coastal lowland regions face. To fight against this phenomenon, some scientific work has been done. Ceia *et al.* (2010) analysed the coastal vulnerability of Ria Formosa (southern mainland Portugal) by examining the evolution of the Ria Formosa barrier island system (from 1940 to 2008) and identifying vulnerable locations. The study identified various soft stabilisation solutions that would be required to protect these regions. Soft stabilisation procedures include beach nourishment, dune building (including replanting native flora), beach bulldozing (beach scraping), restoration, sand bypassing, inlet relocation (then following natural evolution), ecological dredging operations, and reshaping (Griggs, 1999).

Coastal erosion is occurring in various regions on a regional scale. Many West African countries have used various techniques to counteract coastal erosion. Jetties, seawalls, groynes, and breakwaters are all examples of coastal protection systems (Angnuureng *et al.,* 2013; Laïbi *et al.,* 2014), can be found on the coastlines of Benin, Ivory Coast, Togo, Gambia, and Senegal (Ndour *et al.,* 2018, Konko *et al.,* 2018a).

With a population estimated at more than 20 million of people on the West African coast (RPCM, 2018), the effectiveness of the structures of protection against the phenomenon of coastal erosion is a major necessity. Specifically, in Benin Republic, Makponse and Hounsou (2017) carried out research to assess the effectiveness of coastal protection structures and their impacts. The methodology based on topographic surveys combined with direct observations and aerial photographs was used. The results showed that the implementation of groynes along the Beninese coasts reduces the advance of the sea with a persistence of risks and threats. Despite all the interventions carried out, the rates of Beninese coastal erosion continue to rise with significant damage on human activities, socio-economic infrastructure and human habitats (Makponse and Hounsou, 2017) which includes rural and urban settlements.

At country scale, especially in republic of Togo, the maritime Region dominated by the Ewe, Mina, Ouatchi and Guin peoples (Ministry of environment and forest resources (MERF), 2011) is affected by Coastal erosion. With 3,534,991 inhabitants in 2022, the phenomenon of coastal erosion in this Region is a particular form of soil degradation which has been the subject of scientific observations since 1964 (Adjoussi, 2015). It manifests itself by an advance of the sea on the continent which results over the years in a dynamic modification of the coastal area accompanied by destruction of human habitats (Plate I) and socio-economic infrastructures.

**Plate I: Damage on Coastal Settlements in Togolese Coast**
**Source**: Author's field work (2023)

### 1.2 Statement of the Research Problem

Generally coastlands comprise of a variety of landforms created through erosion or deposition and range from gentle sloping sandy beaches to dangerous high cliffs. Coastal areas have always attracted people because of their resources, in particular their provision of subsistence resources; for logistical reasons, as they offer access points to shops and transport; for recreational, cultural, scientific and economic services; or simply because of their special sense of belonging at the interface between land and sea (Bruce *et al.*, 2015). For this reason, coastal areas are regarded as special and coveted for their well-being. Coastal development and use have risen dramatically in recent decades, and the coasts are undergoing huge socioeconomic and environmental changes, a trend that is expected to continue in the future (Neumann *et al.*, 2015).

Human habitats in coastal regions around the world are primarily dynamic in character, changing quickly in response to natural processes and human activity. The utilisation of beaches as residential areas is crucial, with 70 per cent of coastal areas worldwide experiencing population expansion (Faye, 2010; Semedi *et al.,* 2016). The bulk of the world's megacities are located near the sea at low elevations, with many of them nestled in enormous deltas (Hens *et al.,* 2018).

Today, the increasing level of human activities are rising the greenhouse emissions in the atmosphere and changing the climate system balance and resulting to global warming which increases the surface temperature (Climate Change, 2014). The temperature rising leads to oceans warming, glaciers melting and SLR. According to IPCC (2014) all the continents over the world will be more affected by seas level rising phenomena induced by global warming. Many African coastal countries are vulnerable to sea-level rise, particularly in areas where large expanding cities with high population density are located (Nicholls *et al.,* 2008; United Nations Human Settlements Programme (UN-HABITAT), 2008). Most African coastal countries are undergoing rapid population increase, urbanisation, coastward migration, and associated socioeconomic growth, which is causing severe coastal change (Stanley and Warne, 1993; Boko *et al.,* 2007). This entails a quick increase in the vulnerability of people and assets to sea-level unpredictability, as well as long-term rising sea levels (Zinyowera *et al.,* 1998; Nicholls *et al.,* 2008). Local factors, such as natural and man-made ground subsidence, may aggravate the condition, especially in deltaic areas (Syvitski and Milliman, 2007).

West African coastal settlements also grow rapidly and, at the same time, are severely affected by coastal erosion phenomena (Djagoua *et al.,* 2016; Semedi *et al.,* 2016).

In most West African countries, some scientific study is done to provide support tools for coastal area management. In Ivory Coast, Djagoua *et al.* (2016) used Landsat images to analyze the dynamic of shoreline from 1998 to 2014. Dossou and Glehouenou-Dossou (2007) released a paper in Benin on Cotonou's vulnerability to climate change: the rise in sea level. In Ghana, Evadzi *et al.* (2017) used analogue photogrammetric method to analyse the erosion trend and detect hotspot. In the Republic of Togo, Blivi and Adjoussi (2004) used Landsat image analysis and showed a regression of the shoreline ranging from 5 to 10 metres per year.

The recent research of Konko *et al.* (2018) using Landsat and Sentinel-2 images in the Eastern part coast of Togo showed that, the coastal erosion is advanced and coastal human settlement and peoples are endangered. In addition, the area of urban structures increased and the average annual expansion is 7.84 hectares per years. Predictions based on those averages rate showed that the barrier beach with its residential areas which the local population estimated at 2.5 million inhabitants (National Institute of Statistics, Economic and Demographic Studies (INSEED), 2010) are exposed to a continual risk of inundation by shoreline regression which may affect more than seven per cent of its surface area by 2070. All these studies cited used various methods but the spatial multi source modelling approach is lacking. This approach is also very important because it takes into consideration of several factors (variety multisource data) to model and identify the settlements, building area and coastal area that are in risk zones of coastal erosion (Konko *et al.,* 2018b) and inundation.

This research, which is based on spatial multi source modelling approach, is a major contribution to the Togolese Coastland's vulnerability assessment in climate change studies. The peculiarity of this study is that it take into consideration the Climate trend, coastal urban growth model, shoreline dynamics and high coastal erosion zones with a focus on the human habitat.

The research questions are stated below:

i. How has climate change affected Togo?

ii. What is the pattern and settlement dynamics from 1988 to 2020 within the coastal part of Togo?

iii. Which part of the Togolese coastline has receded the most between 1988-2020?

iv. How is the Togolese Coastland's Vulnerability model to SLR and inundation?

v. What are the contribution of the results of this study to existing strategic focus of the master plan for coastal management resilient to climate risks in Togo?

### 1.3 Aim and Objectives

The aim of this research is to assess the extent of climate change and the coastal area's vulnerability to SLR at a local scale in order to provide helpful informations for decision making. The study's specific objectives are to:

**i.** Examine the extent of change in the Climate of Togo;

**ii.** Examine the pattern and settlement dynamics from 1988 to 2020 within the coastal part of Togo;

**iii.** Evaluate the dynamics of the Togolese coastline from 1988 to 2020;

**iv.** Generate the Togolese Coastland's Vulnerability model due to SLR and inundation;

**v.** Identify the contribution of the results of this study to existing strategic focus of the master plan for coastal management resilient to climate risks in Togo.

## 1.4 Justification for the Study

Coastal areas have always lured people owing to their resources, notably their availability of subsistence supplies and logistical reasons, since they give access points to stores and transit, as well as recreational, cultural, scientific, and commercial activities (Bruce *et al.*, 2015). For this reason, coastal areas are regarded as special and most desired because of their natural attributes. Today, most of the coastal areas are exposed to a continual risk of inundation by shoreline regression due to SLR phenomena induced by global warming.

Therefore, this study provides decision-support tools needed for the adaptive management of the coastal human habitats. Furthermore, the findings of this study will aid the government in policy development. The policy on adaptation and practice measures will directly be beneficial to the coastal people living along the Togolese coastland communities. Another category of potential beneficiaries are groups, organizations, governmental and non-governmental organization that may apply the results of the study to improve operational performance and project elaboration.

Additionally, students and researchers are another set of potential beneficiaries to this study. Students and researchers in University of Lome, University of Kara, other universities and research institutes may find the result of this coastal study useful for further studies. Researchers and students at the international and regional level are also another set of potential beneficiaries of this study. The result of the study can be useful in revising, refining and extending the frontiers of knowledge.

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 Conceptual Framework

This research focuses on coastal erosion caused by climate change. Human activities contribute to climate change through increasing greenhouse gas emissions into the atmosphere, resulting in global warming. Glaciers melt and sea levels rise as a result of global warming (Beck and Mahony, 2017). Coastal erosion is one of the consequences of SLR, and it is responsible for coastal erosion. The conceptual framework and the relationship between all variables (independents and dependents) are represented in Figure 2.1. Climate change and SLR are independent variables, while coastal erosion is dependent. Some of their relevant variable for this study are explicated below.

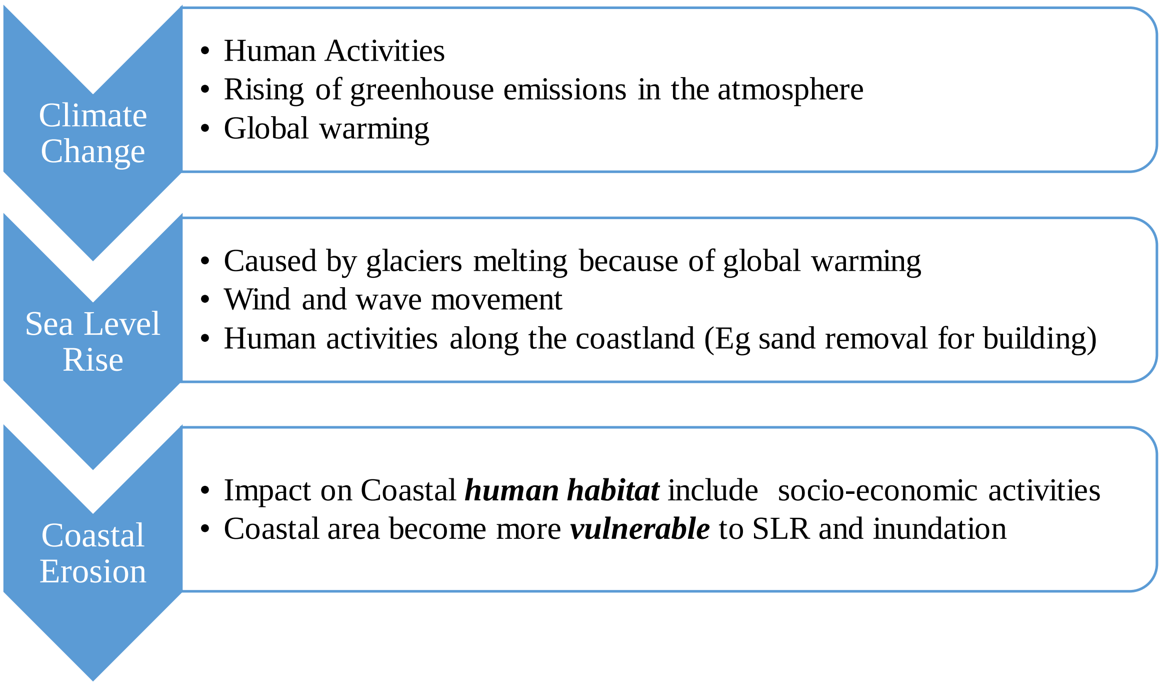



**Figure 2.1. Scheme of Conceptual Framework**
**Source:** Author's field work (2023)

### 2.1.1 Climate

Climate is a measure of the average weather pattern or circumstances in a certain place over a lengthy period of time, up to 30 years (Climate Change, 2014). Temperature, humidity, air pressure, wind, precipitation, atmospheric particle count are examples of these conditions. As a result, climate is naturally changeable, as evidenced by the lack of consistency in the seasons from year to year (Madsen *et al.*, 2018).

### 2.1.2 Climate change

Climate change is defined as a significant and long-term shift in the statistical distribution of weather patterns that spans decades to millions of years (Veenema *et al.*, 2017). It could be a shift in average weather conditions or a shift in the distribution of weather around typical circumstances (i.e., more or fewer extreme weather events). This means that as climate changes, the frequencies of different weather events, particularly extremes, will change. It is these changes in extreme conditions that are most likely to be noticed (Beck and Mahony, 2017).

According to the United Nations Environment Programme (UNEP) (2021), anthropogenic global warming has led to shifts in climatic zones, mainly due to an expansion of areas of arid climates and a contraction of areas of polar climates. Further warming is predicted to result in climates without precedents in the tropics. Because to global warming, the frequency and intensity of certain extreme weather and climate events have grown and will continue to increase under scenarios with moderate and high emissions. This is true for recent heat waves in most terrestrial locations, as well as droughts in the majority of African countries. These tendencies are likely to continue as the world average temperature rises. Droughts are projected to become more frequent and intense in southern Africa, in particular.

Face to the increasingly capricious climate that affects food security, West African countries are working to develop expertise in the field of climate science and are benefiting from the support of the International community. The Economic Community of West African States (ECOWAS) and the German government have worked together to construct more than ten West African Science Service Centres on Climate Change and Adapted Land Use, which include a climate research programme, a graduate programme, and observation networks.

### 2.1.3 Sea level rise

Rising sea levels are one of the most serious consequences of climate change, and they might affect hundreds of millions of people worldwide. Melting ice sheets and glaciers have accounted for more than half of the total observed current rise in recent decades (Climate Change, 2014), a number that is anticipated to increase with sustained global warming. According to the Intergovernmental Panel on Climate Change, global sea levels will increase by 19 to 59 centimetres by 2100 (IPCC, 2014).

Togo is concerned about SLR and its consequences. This phenomena, caused by glacier melting and ocean thermal expansion, is currently a major worry for the international community, particularly for developing countries where the majority of the population lives near the sea (in the littoral zone). The phenomena of coastal erosion, which is the first source of marine flooding and displacement of coastal communities, is exacerbated by sea-level rise.

Indeed, Togo, like the majority of West African coastal countries, is affected by the phenomenon of coastal erosion, the consequences of which include the complete disappearance of certain human settlements (coastal villages), losses of land, plantations, and seaside infrastructure (roads, houses, hotels), and ongoing threats to socio-economic infrastructure and disruption of economic activities.

We also observe in the littoral zone, the phenomenon of salinization, consequence of the rise in sea level, which increasingly rises in the rivers flowing into the sea. This salinization has impacts on freshwater ecosystems which are invaded by brackish water leading to the disappearance of most freshwater species. Also does SLR cause groundwater tables to rise, increasing thus the risks of flooding of communities living in the coastal zone.

### 2.1.4 Human habitats

The environment in which something lives is referred to as its habitat. The places where people live are thus referred to as the human habitat, and this includes the environment in which they sleep, eat, and frequently work. People do not normally live alongside wild animals in nature; instead, they create their own ecosystem that is tailored to their requirements, and they so have control over the good or terrible environment. Most people live with other people, whether as a single family in the countryside, in a village or tribe, or in a bigger town or city. A human habitat can range in size from a farm with a family of four to a city of 10 million or more people, but the fact that people live together brings unique environmental challenges. These issues frequently worsen as the population grows in size and harsh weather patterns change (Kowalewski, 2008).

### 2.1.5 Vulnerability

According to the IPCC (2014) definition, vulnerability is an integrated measure of the expected extent of detrimental impacts on a system produced by a given level of specific external stressors. This term represents a third school of thinking, which is most prevalent in global change and climate change research. According to this school, vulnerability encompasses an external dimension, which is represented here by a system's 'exposure' to climate changes, as well as an internal dimension, which includes its 'sensitivity' and 'adaptive capability' to these stressors (a stressor is an activity or phenomenon that induces an adverse effect and therefore degrades the condition and viability of a natural system (IPCC, 2014). Exposure refers to the inventory of elements in an area in which hazard events may occur (Sharma and Patwardhan, 2008).

The sensitivity in climate change adaptation is the physical predisposition of human beings, infrastructure, and environment to be affected by a dangerous phenomenon due to lack of resistance and predisposition of society and ecosystems to suffer harm as a consequence of intrinsic and context conditions making it plausible that such systems once impacted will collapse or experience major harm and damage due to the influence of a hazard event (Sharma and Patwardhan, 2008). Adaptive capability refers to the positive features of people's characteristics that may reduce the risk posed by a certain hazard. Improving capacity is often identified as the target of policies and projects, based on the notion that strengthening capacity will eventually lead to reduced risk. Capability clearly also matters for reducing the impact of climate change (Sharma and Patwardhan, 2008).

Another popular example of an integrated (or 'synthetic') framework is the 'hazards of location' model, which tries to incorporate biophysical and social factors of vulnerability (climate change, 2014). Hazard refers to the possible, future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements (Sharma and Patwardhan, 2008). Although hazard has often been used interchangeably with risk, it is now commonly recognised that it is a component of risk rather than risk itself.

## 2.2 Theoretical Framework

### 2.2.1 Climate change theories

#### *2.2.1.1 Geological theory*

At the beginning of creation, the earth consists of just one continent. It was then called a Pangea. But because of changes in the climatic conditions from one location to another, the earth was further subdivided into several continents. These broad climatic changes had significant impact on the energy content of each location, leading to different climatic regions (Climate Change, 2014).

#### *2.2.1.2 Astronomical theory*

Changes in the position of the sun's orbit cause climate change. Remember that the earth moves around the sun on its orbit, causing seasonal fluctuations. However, the Earth's orbit might vary or move at any time. As a result, the rotating location of the solar radiation received by the earth's surface shifts (Climate Change, 2014).

#### *2.2.1.3 Carbon dioxide ($CO_2$) theory*

Climate change is caused by growing levels of carbon dioxide ($CO_2$) in the atmosphere, which is one example of a greenhouse gas. The growing concentration of carbon dioxide in the atmosphere raises the temperature of the earth's surface by lowering the amount of radiation that escapes back into space. This concept describes the extent of the study. Indeed, human activities cause carbon dioxide emissions into the atmosphere, which raises surface temperatures, causes glaciers to melt, and causes coastal erosion (Beck and Mahony, 2017).

### 2.2.2 Settlement growth theories

Wegener (1994) define numerical models as mathematical abstractions of the real world that can recreate a prior (or current) state and anticipate future possibilities. An urban growth model is a form of numeric model that investigates the mechanisms of urban evolution and feedback in the urban system using economics, geography, sociology, and statistics. Urban models are associated with a wide range of activities (or contents), including land use, housing, population, travel, networks, transportation, employment, and workplaces (Wegener, 1994). An urban model cannot adequately imitate all urban activities in interdisciplinary urban studies or complex urban systems (Batty, 2008). They can, however, be explored separately and then combined into a systematic model. As a result, several distinct urban growth models have been established based on specific urban theories during the course of their protracted evolution since the 1920s (Batty, 2008). Using a literature study, we will present and discuss three types of urban growth models: concentric zone theory (Burgess, 1925), sector theory (Hoyt, 1939), and multi-nuclei theory (Harris and Ullman 1945).

#### *2.2.2.1 The concentric zone theory*

The concentric zone theory is developed by Burgess (1925). According to Burgess (1925), urban land use around the Central Business District (CBD) occurs in concentric rings. Burgess's theory was established on the base of Chicago' city observations in the early 1980s. The CBD (Zone I) represents the heart of the city and is the most accessible area. It contains offices, shops, restaurants, hotels and banks. The zone II represents the transition zone that surrounds the CBD. This area is characterized by trade and light industry. Zone III surrounds Zone II and is inhabited by civil servants working in industries and who wish to live close to their workplace. The Zone IV is located after zone III. It is occupied by high class apartments buildings located in exclusive areas reserved for single family housing. Beyond Zone IV are suburban areas or satellite towns (Zone V) located within a 30 to 60 minutes from CBD. The process of spatial land use change of residential areas can be described as a succession of the process of "invasion" and "succession". The enlargement of the CBD would exerts an immediate pressure on the transition area. The expansion of the CBD causes the invasion and displacement of neighboring residential neighborhoods to the outside. The process of expansion is progressive and continues from one zone to another.

According to Burgess (1925), housing in the city centre is occupied largely by foreigners and immigrants with low socio-economic income. As the city become larger and the CBD expands outward, low-income residents move to neighboring neighborhoods while high-income residents move away from the CBD. A correlation exists between income status and place of residence. In other words, low-income residents live close to the CBD while high-income residents live far from CBD.

#### *2.2.2.2 The sector theory*

The sector theory is proposed by Hoyt (1939). It makes a modification to the theory of concentric zones and mainly describes the structure of residential zones. Hoyt (1939), studied the model of 25 American cities and concluded that the expansion of cities follows a model of sectors and not of concentric circles. According to Hoyt, the expansion of cities follows the development of road infrastructure (highways and railways). The model proposed by Hoyt (1939), shows that the commercial functions are implanted in the CBD while the manufacturing trades are located along the road infrastructures. In addition, middle-income and high-income households are located far from factories, while low-income households are located near factories. In conclusion, the different compartments of the cities develop in an irregular way with a varied rhythm. Unlike the Burgess model, Hoyt added the directional element following road infrastructure for city development.

#### *2.2.2.3 Multi-nuclei theory*

Harris and Ullman (1945) proposed the multi-nuclei theory. According to them, cities did not develop only around a CBD but rather through the continuous integration of several centres or cores. The CBD are shopping centres but the activities develop according to the specific requirements. (Harris and Ullman, 1945) defined four factors responsible to the development of the sub-centres: (a) The correlation between the activity and the location according to the geographical proximity; (b) the need for regrouping to increase the profitability of activities; (c) the incompatibility of several zones with the requirements of the activities and finally the high price of housing which affects the nucleation process. In addition, accessibility, topography and hydrography and historical influences have impacts on the spatial distribution of urban land uses. According to Harris and Ullman (1945), cities develop in a polycentric manner unlike the monocentric models of the theory of concentric zones which could not explain the pattern of urban land use in several cities. In addition, unlike the two previous theories, the multi-nuclei theory gives a description of urban land use at a given time.

## 2.3 Review of Related Studies

Several papers on coastal areas have been written all around the world. Using Landsat data from 1986 to 2015, Xu (2018) assessed coastline change in Texas (USA). From 1986 through 2015, Landsat data (TM: Thematic Mapper, ETM+: Enhanced Thematic Mapper Plus, and OLI: Operational Land Imager) were used. The annual land usage maps were created using satellite photos. In their study, the shoreline was represented by the border between land and water. The annual land area was then calculated to characterise the shoreline dynamic, and the change rate was estimated using a linear regression model. The issue is the lack of a validation strategy.

Manaf *et al.* (2017) provided a viable approach for validating Assessment of Shoreline Extraction on Medium Resolution Satellite Images. The researchers validated the results of 11 classifiers' extracted shorelines with a reference shoreline provided by the local government in the study. The validation assessment was specifically undertaken to investigate the discrepancy between the extracted shorelines and the reference shorelines. Unfortunately, the technique did not provide a comprehensive description of the reference data. According to the research findings, the Support Vector Machine Linear method was the most effective image classification technique, as indicated by the shortest mean distance between the extracted and reference shorelines. The data also revealed that the accuracy of the derived shoreline was not directly proportional to the accuracy of the picture categorization.

Burningham and French (2017) presented another approach for coastal area monitoring. Based on digital orthophoto images, the study compared two simplification methods for shoreline extraction. A regional-scale case study of the Suffolk coast in eastern United Kingdom was used to demonstrate cluster-based segmentation of shoreline dynamics. To investigate intra-decadal scale change in coastline location, an extraordinarily complete suite of shoreline datasets encompassing the period 1881 to 2015 was used. Analysis of variations in shoreline location at 100 metres intervals along 74 kilometres of coastline revealed a variety of unique tendencies. The set of behaviour varies depending on the timescale of analysis. There is minimal evidence of consistent regional coastline alteration. The studies show a complex relationship between met-ocean forcing, inherited geology and geomorphological restrictions, and evolving anthropogenic involvement that causes shifting erosion.

Konko *et al.* (2018a) used satellite imagery to monitor coastline erosion in Togo. The study included data from optical satellite images (Landsat TM, ETM+; Sentinel-2A MSI) and radars (Sentinel-1A).The chosen technology is based on a mix of optical and radar remote sensing pictures. Support Vector Machine Supervised classification was used to extract the shoreline. The statistical linear regression approach (LRR) was used to estimate the rates of change of the shoreline. As a result, the annual rate of coastline regression ranged from 1.66 to 5.25 metres. Blivi and Adjoussi (2004) employed Landsat images (MSS and TM) for coastline monitoring in another investigation in Togo. This study also employed field data and found a regression of the shoreline of 5 to 10 metres per year.

The disparity between Blivi and Adjoussi (2004) and Konko *et al.* (2018a) research could be explained by differences in methodological approach. In fact, Konko *et al.* (2018a) used supervised classification of satellite images (Landsat TM, ETM+, and Sentinel-2A MSI) to extract the shoreline, and the kinematics were analysed using the statistical linear regression approach (LRR). Blivi and Adjoussi (2004), on the other hand, used Landsat image analysis (MSS and TM), and the methods of shoreline extraction and kinematics computation were not explicitly specified. Divergences are also related to the government's installation of protection infrastructure (jetties, seawalls, and breakwaters) along some areas of the coastline over the last decade to prevent coastal erosion. Indeed, security systems have a good impact and are highly recommended. All these studies cited used different methods but the spatial modelling approach was lacking. This approach is also very important because it allowed the use of many multisource data and to identify the settlements and building area that are in climate risk zones of coastal erosion and inundation (Konko *et al.,* 2020).

This research, which is based on spatial modelling approach, is a contribution for Togolese Coastland's vulnerability assessment to climate change in Togo. The uniqueness of this study takes into account of a variety of parameters like coastal urban growth model, shoreline dynamic, Coastland's Vulnerability Index and with a focus on human habitat.

### 2.4 Examples from Other Regions/Countries

The aim of the study in Nouakchott (Hachemi *et al.,* 2014) was to quantify the evolution of the coastline using a multi-temporal Synthetic Aperture Radar (SAR) satellite images from the Environmental Satellite (Envisat) satellite. A total of nine amplitude satellite images for different dates (2004, 2005, 2008, 2009, and 2010) calibrated and georeferenced (UTM, WGS 84) at 20 metres spatial resolution were used for analysis. The authors used maps, charts and tables to illustrate the results. The results show an average accumulation of about 100 metres at the north of the port and an average erosion of about 140 metres in the south for a period of six years (From January 2004 to October 2010). During a year, the average rate of accumulation and advance of sand was estimated at more than 14 metres per year while the average rate of erosion was estimated at more than 20 metres per year. In addition, it was observed that the rate of sandy accumulation on the coast in the north decreased between 2004 and 2010. On the other hand, the rate of coastal erosion at the south seems to remain constant.

This study is relevant and it's innovative because it employed the use of radar satellite data for the monitoring of the coastline in Mauritania. The radar system is robust and operates independently of cloudy weather conditions while the optics system is limited by the presence of clouds in the sky. However, one of the disadvantages of the radar system is that the line of the sea and land interface is not clear enough and the images are very heavy in downloading and processing (Konko *et al.* 2018b).

The shortcomings of Hachemi *et al.* (2014) is the methodological approach which does not clearly describe the method of the coastline extraction from satellite images and the kinematics calculation. In addition, the vulnerability of coastal area has not been assessed. Furthermore, many expected components of the current investigation were not attempted in the original work. In fact, the current work will extract shoreline utilising optical satellite pictures (Landsat TM, ETM+, and Sentinel-2A MSI) via supervised classification. In addition, the kinematics will be evaluate using the statistical linear regression method (LRR). More so, the coastal human habitat vulnerability will be assessed and the adequate strategy for coastal management will be made up.

Another regional example is the research work of Degbe *et al.* (2017) in Benin republic, Coastal neighboring country of Togo. This study aimed at assessing the morphology and evolution of the coastline in order to better understand the phenomenon of coastal erosion in Benin. The methodological approach is based on the direct method based on measurements from topographic surveys carried out from 2011 to 2014 in sensitive areas of the Benin coast. The findings were presented in the form of images, graphs, maps, and tables. The acquired data reveal vertical and horizontal mobility of the beach profiles, allowing us to distinguish between times of major erosion from May to September and periods of dominant accretion from November to April. The profiles tend to vary from convex to concave during the first period, then from concave to convex during the second period. The coastal sectors most threatened by coastal retreat are located to the east of Cotonou, with an average speed of retreat of the coastline of about -9 metres per year at Donatin and about -30 metres per year at Djondji, with -2 metres per year at Hillacondji and -5 metres per year at Agoue. The authors conclude that the shoreline of the Beninese littoral has a seasonal evolution.

The study of Degbe *et al.* (2017) used a direct method based on measurements from topography of the field. It showed the possibility of using a direct method for coastal erosion monitoring. The difference between Degbe *et al.* (2017) study and the present study is the methodological approach. In fact, Degbe *et al.* (2017) used the direct method based on measurements from topography of the field while this study's methodology will use multi-temporal satellite images analyses in combination to field work activities. One of the disadvantage of direct method is the fact that the measurement is located on small area. The satellite images have the advantage to cover a large area and are available during the past and the present periods (Konko *et al.*, 2018b). The using of satellite images offer the possibility to cover the whole of the coastal area during a same period in order to perform the results of coastal monitoring. The current study has the advantage of focusing on the Coastland's Vulnerability Index to SLR, which will highlight the locations that are more sensitive to SLR and coastal erosion based on satellite photos.

## 2.5 The Overview and Key Issues of the Study

The phenomenon of climate change is a major concern on a global scale. It is mainly caused by the increasing in greenhouse gas emissions into the atmosphere which leads to global warming (IPCC, 2007). Oceans are warming, glaciers are melting, and sea levels are increasing as a result of global warming (Worm *et al.*, 2009). The phenomenon of coastal erosion is one of the consequences of rising sea levels (IPCC, 2007). Coastal erosion is a significant phenomenon in terms of its repercussions. It is to blame for coastal flooding, socioeconomic infrastructure damage, human habitat destruction, and population displacement (Adjoussi, 2015). According to the IPCC (2007), global sea levels would rise by 19 to 59 centimetres by 2100. Furthermore, coastal erosion threatens half of the world's population since they live within 100 kilometres of a coastline, and around 100 million people live in coastal areas that are less than one metre above sea level (RPCM, 2018). SLR and coastal erosion will have a greater influence on all continents, including Africa, however the specific local impacts and levels may vary.

Various ways of combating coastal erosion have been explored in numerous West African countries. Several coastal defence systems, such as jetties, dykes, and breakwaters (Angnuureng *et al.*, 2013; Laïbi *et al.*, 2014), may be found along the Gulf of Benin's coastline, as well as the coasts of Ivory, Togo, Gambia, and Senegal (Ndour *et al.*, 2018, Konko *et al.*, 2018a). Although the infrastructures of coastal protection have a positive effect, the rates of coastal erosion in several West African countries continue to increase with significant damage to human activity, socio-economic infrastructures and habitats humans (Yang e*t al.*, 2012; Bayram *et al.*, 2013).

In Togo, although the protective groynes are installed on the coast, the maritime region dominated by the Ewe, Mina, Ouatchi and Guin peoples (MERF, 2011) continues to be affected by coastal erosion. With 2,599,955 inhabitants in 2010, the phenomenon of coastal erosion in this Region is a particular form of soil degradation that has been the subject of scientific observations since 1964 (Adjoussi, 2015). It is manifested by an advance of the sea on the continent which over the years results in a dynamic modification of the coastal zone accompanied by the destruction of human habitats and socio-economic infrastructures.

To protect the coast and its ecosystems in Togo, an integrated coastal zone management plan has been drawn up which is part of the overall framework of environmental programmes established by the Ministry of the Environment and Forest Resources. Similarly, the National Action Plan for the Environment (PNAE-Togo) has included in its work components the coastline as a threatened and risky ecosystem, under the effect of various anthropogenic, industrial and natural pressures. For the legislative and regulatory aspect, the Togolese government has drawn up several regulations relating to the management of the environment, marine and coastal environment. Among these regulations, there is the Law n ° 88-14 of November 3, 1988 establishing the Code of Environment; the Law 96-004 / PR of February 26, 1996 on the mining code of the Togolese Republic; and the Law 98-012 of 11 June 1998 on the Regulation of Fishing in Togo.

A variety of public entities are active in the battle against coastal and littoral degradation at the institutional level. The following ministries are involved in this area: the Ministry of Maritime Economy, Fisheries, and Coastal Protection; the MERF; the National Agency for State Action at Sea; the Maritime Prefecture; the Ministry of Agriculture, Livestock, and Rural Development; the Ministry of Mines and Energies; the Ministry of Water and Village Hydraulics; the Ministry of Security and Civil Protection; and the National Agency for Civil Protection. Togo has ratified or acceded to various treaties or agreements dealing to the management, conservation, or preservation of the maritime and coastal environment and the natural resources living there (MERF, 2022). As such, the Convention on International Trade in Endangered Species of Wild Fauna and Flora

(CITES), signed on 3rd March, 1973 in Washington and ratified by Togo on 23rd October, 1978, might be cited. The Abidjan Convention on the Regional Sea in West and Central Africa on Cooperation in the Protection and Development of the Marine Environment and Coastal Areas of the West and Centre African Region ratified by law n ° 83-17 of 20th June, 1984, published by Decree n ° 84-9 of 2nd January, 1985; the United Nations Convention on the Law of the Sea ratified by Ordinance n ° 85-4 of February. Togo signed the treaty on 21st November, 1973, however it has yet to be approved. Although Togo has established an institutional, legal, and regulatory framework, it is facing some problems in the areas of financing, logistics, and competent employees, preventing it from being completely implemented.

## CHAPTER THREE

## 3.0 MATERIALS AND METHODS

### 3.1 Description of the Study Area

#### 3.1.1 Location and map of study area

The research area is in Togo's coastline region known as the Maritime Region. Ghana borders this region on the west, the Plateau Region on the north, Benin on the east, and the Atlantic Ocean on the south (Nimon *et al.*, 2020). It is bounded between the latitudes 6°00’ and 6°50’ North and the longitudes 0°25’ and 2°00’East. The Figure 3.1 shows the map of the study area with Digital Elevation Model (DEM).

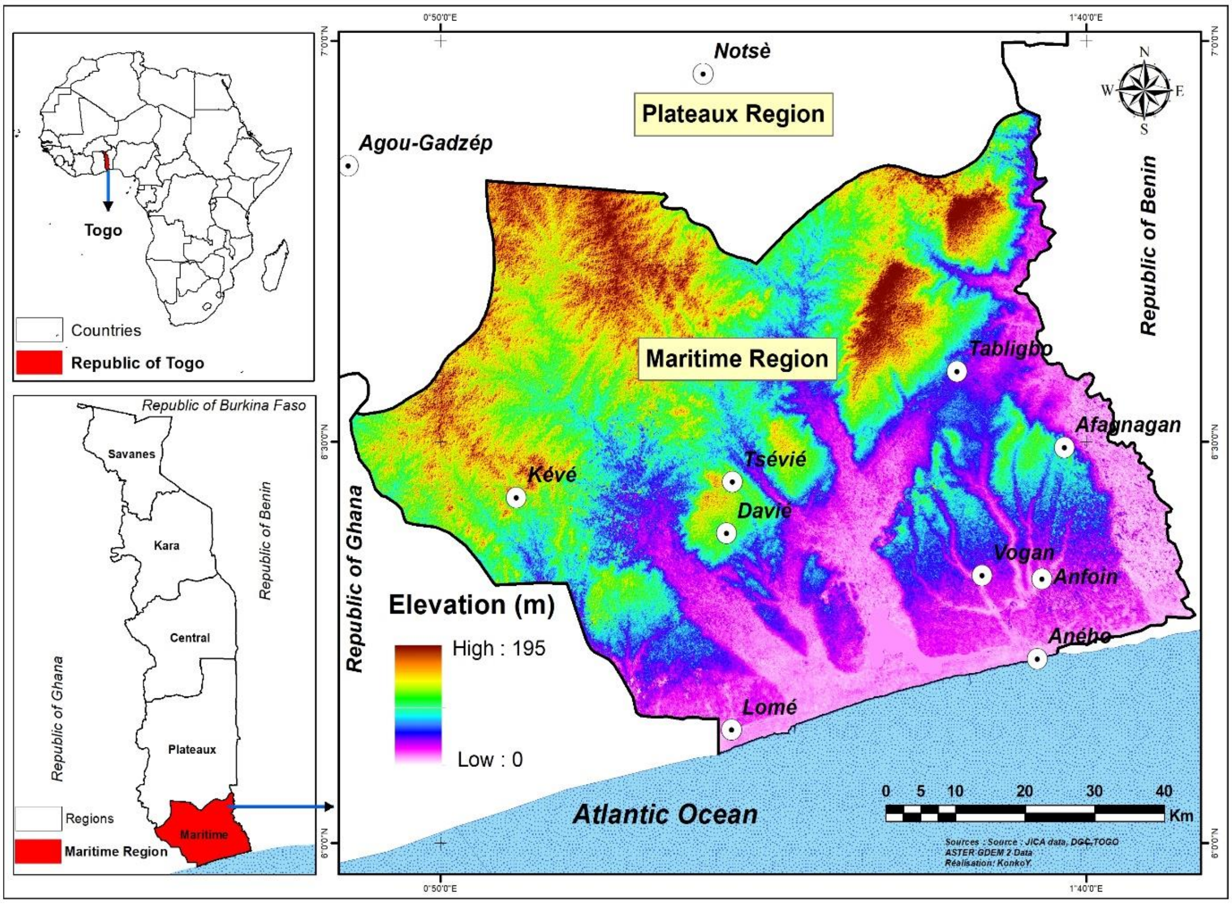



**Figure 3.1. Area of Study Showing the Maritime Region with Digital Elevation Model in Togo**

**Source:** Author’s field work (2023)

### 3.1.2 Climate

The study area has a Guinean subequatorial climate. This regime is characteristic of an equatorial transitional climate resulting from the movement of two types of high pressure air masses. These are continental air masses (coming from the northeast and characterised by the harmattan, a dry and hot wind) and maritime air masses (coming from the southwest and characterised by the monsoon, a humid and hot breeze) (Nimon *et al.*, 2020). This climate is distinguished by an alternation of two rainy seasons and two dry seasons of unequal durations: a large rainy season occurs from March to July, a small dry season occurs from July to September, a small rainy season occurs from September to October, and finally a large dry season occurs from November to February (Blivi and Adjoussi, 2004). The annual rainfall is ranging from 1000 to 1400 millimeter per year.

The average temperature is roughly 27 degrees Celsius (MERF, 2011). On the coastal area, the thermal amplitude is higher in the dry season, especially in January (9.2 degrees celsius), February (8.3 degrees Celsius) and March (8 degrees Celsius). It is during this season that the extent of the monthly average temperature distribution is very large, while it is low in the rainy season for the months of June (4.8 degrees Celsius), July (4.3 degrees Celsius) and September (5.6 degrees Celsius) (Adjoussi, 2000). Relative humidity on the Coastal area is constantly high with a monthly average of over 80 per cent. Its seasonal evolution is closely linked to precipitation and evaporation. It is especially in the rainy season that we observe the highest maxima reaching 98 per cent in June and September. On the other hand, the lowest minima are recorded during periods with high evaporation, mainly the months of January (55.6 per cent) and February (59.4 per cent) (Adjoussi, 2000).

For sunstroke on the Togolese coastal area, it is largely dependent of the seasons. According to Adjoussi (2000), observation of the rate of sunstroke reveals long average monthly durations during the period from October to May. This is the period during which rainfall activities are low and therefore the sky is less cloudy. The monthly average of hours is beyond the seven hours with an annual average of 78.5 hours. The wet season is less sunny, the monthly average is around 4.5 hours, which is explained by the importance of the cloud in the sky during this season. On the Togolese coastal area, the wind blows during a year, in all seasons at an average monthly speed of 2 to 4 metres per second in the South-Southwest (SSW) and Southwest (SW) directions, parallel to the coast (Avumadi, 2019).

### 3.1.3 Vegetation, soil and drainage

Ern (1979) classified terrestrial and marine habitats in Togo into five ecological zones: northern plains zone (Zone I), northern mountain zone (Zone II), central plains zone (Zone III), southern zone of the Togo Mountains (Zone IV), and southern coastline zone (Zone V). The vegetation of the maritime region is characteristic of zone V according to the ecological classification from Ern (1979). This zone corresponds to the coast and presents degraded plant formations. In some places, there is a mosaic of disparate forest islets with species such as *Milicia excelsa, Antiaris africana,* and relics of gallery forests with *Cynometra megalophylla, Pterocarpus santalinoides, Cola gigantea*.

There are also coastal thickets, halophilic or marshy meadows, plantations, mangroves, fallows, crops and vast highly anthropized flood savannas with *Mitragyna inermis, Andropon spp, Hyparhenia spp* (MERF, 2011). Furth more, the Maritime Region contains different types of fauna. There is among others *Tragelaphus spekei*, *Tragelaphus scriptus*, *Sylvicapra grimmia, Potamochoerus porcus, Cephalophinae, Dasyprotidae, Canidae, Sciuridae, Ceratogymna elata, Tokus fasciatus, Bucorvus abyssinicus* (MERF, 2011).

Concerning the soils, there are several types of soil founded in Maritime Region. They belong to three classes of soils according to the French pedological classification of the Research Institute for Development (IRD) (Food and Agriculture Organization (FAO), 1997). Firstly the poorly evolved soils subdivided into two types: erosion soils and contribution soils. For the erosion soils, there are lithosols on gneiss and granito-gneiss with quartz veins. They are mostly found near rocky outcrops, on steep slopes and hilltops. They are shallow and stony. The soils are poorly developed. For the Contribution soils, modal on fluvial alluvium located along the Mono river and rivers, they are of alluvial and colluvial origin. They exhibit good fertility but rather slow drainage, responsible for temporary hydromorphy. Secondly, there are vertisols made up of swelling clay rich in mineral salts (Faure and Pennanaech, 1981) and finally there are Soils containing iron sesquioxides.

The hydrographic network is made up of a lagoon system, the Mono River, the Zio and Haho rivers which feed the littoral drift. The waters of the lagoon system are brackish (MERF, 2011), as they are influenced by the intrusion of oceanic waters. This salinity increases during the low flow period and is not without effect on the waters of shallow aquifers, especially those of the terminal continental, quaternary sands, but also on the Eocene aquifer around Lake Togo. The Mono river take its source in the mountain area at the Aledjo mountains (Avumadi, 2019). It has a length of 560 kilometres, a watershed of 21,300 square kilometres with a single high water season centered on the month of September (MERF, 2011). It is a low-sloping lowland river with large overflow areas. The Zio river has a length of 176 kilometres and a watershed of 2,800 Square kilometres.

It is essentially characterized by the relative importance of its flow and the permanence of its flow. The Haho river is 140 kilometres long, developing a small flood plain not far from its mouth in Lake Togo (MERF, 2011). It originates in the dry region and is therefore characterized by the seasonal intermittence of its flow. The length of the period without flowing varies from 30 days to almost 130 days. As for groundwater, it is due to the infiltration of rainwater and runoff. The rate of infiltration depends on the slope and the nature of the soil and rocks. Geological formations have a very great influence on the conditions of existence of these groundwater and on its depth.

### 3.1.4 Topography and geology

The topography of the Maritime Region consists of large plains and minor hills (Figure 3.1). The Maritime Region inland is characterized by cities, villages, crops, vegetation, lake, river, ocean, Barrier Beaches (MERF, 2011). The research area is in southern Togo's coastal sedimentary basin, which is transgression over the crystalline basement of the Dahomeyides range. The rock is made up of migmatites, orthogneiss with biotite, granites, and calcoalkaline granodiorites (Johnson, 1987; Akouvi *et al.,* 2008). The basin has been heavily influenced by tectonics and so compartmentalised. Because of tectonic influences, the basin has been compartmentalised.

The longitudinal faults' throw can approach 100 metres at times, and the bedrock dips from northeast to southwest. The morphology of the sedimentary strata follows the tectonics of the basin (Johnson *et al.,* 2000).Two distinct series lie on top of the crystalline basement. A Maastrichtian/Eocene marine sequence of sand, marly limestone, marl, and clay sinks south first. Second, the marine series is supported horizontally and discordantly by a continental and coastal Quaternary series. It is made up of sand, gravel, and clay, with various lateral facies alterations.

### 3.1.5 Demography and socio-economy

The Maritime region is more populated than the other regions of the country. According to the general population census in 2010, the population of the Maritime region is characterized by strong growth (3.16 per cent). According to the last general population census in 2022, the population of the Maritime region is characterised by strong growth. With a population of 3,534,991 people for an area of 6,395 square kilometres, it recorded a density of 553 people per kilometre square in 2022, compared with 407 people per kilometre square in 2010, and 163 people per square kilometres in 1981 (INSEED, 2022). The population has quintupled in 50 years, going from 474,133 inhabitants in 1960 to 2,599,955 in 2010 and to 3,534,991 in 2022. The region concentrates nearly half (42 per cent) of the national population, which stands at 8,095,498 inhabitants (INSEED, 2022). This rapid population change is explained in particular by the massive rural exodus of people from localities in the interior of the country to Lome and its outskirts. The urban architecture of the Maritime Region is dominated by the large metropolitan area of the capital Lome, which has a population of 2,188, 376 (INSEED, 2022). Six out of ten city dwellers live in this agglomeration.

The Maritime region is dominated by the female gender, which represents approximately 52 per cent or 1,831,611 women against 1,703,380 men (INSEED, 2022). Although the Ewe ethnic are in the majority, the population of the Maritime region remains very diverse and includes all the ethnic groups (43) of Togo, the main ones being: Adja, Mina, Ouatchi, Kabyè, Losso, Lamba, Tchokossi, Tem, Natchaba, Dyé , Tamberma, Bassar, Tchamba and Moba, Akposso, Akébou, Ana-Ifé. To these ethnic groups are added other African and non-African languages (INSEED, 2022). Due to its size, the Maritime region appears to be the smallest in the country. Nevertheless, it is the most populous and remains the best endowed with public services, equipment, employment and socio-economic activities. The macrocephaly in the Maritime region compared to the country as a whole is explained by several factors. To begin with, the location of the country's capital in the region has favoured the concentration of major services, specifically the seats of government and the National Assembly, the Presidency of the Republic, large commercial and financial establishments, industries, deep-water port, international airport, public and private universities, and so on. Then, this area offers a climate and fertile land suitable for agricultural and mining activities, thus attracting populations from the north, the centre of the country and some neighboring countries. Finally, in addition to its fine sand beach, the region is home to several tourist sites and historic localities such as Togoville on the shores of Lake Togo, the Sacred Forest of Glidji, Agbodrafo and Aneho, which also attract populations from other places (Konko *et al.* 2018a) regions and neighboring countries.

The Maritime region, sheltering the coastline of Togo, offers the country a strategic position in the region. Indeed, the Autonomous Port of Lome, installed over more than 900 ha (MERF, 2011), constitutes a commercial and industrial centre of attraction thanks to a vast industrial free zone where several dozen companies and industrial production units are located. The only deep-water port on the West African coast (16.60 metres) (MERF, 2011) that can accommodate 3$^{rd}$ generation ships, it is a real hub of development on the West African coast, but also an international crossroads of trade . It is also the only port through which one can reach several capitals in one day in the region. Thus, thanks to its strategic geographical position and its connectivity, the Port of Lome constitutes the arm of the sea for the countries of the Sahel. The new Lome airport, with its capacity to accommodate over 2.5 million passengers and 50,000 tonnes of freight per year, has made Lome a regional hub for air transport. The presence of the University of Lome and prestigious higher education schools, make the coastal area of the country an intellectual and cultural melting pot (MERF, 2011).

## 3.2 Data Collection

### 3.2.1 Description of materials

The informatics materials used are computer with high performance, external hard drive, Global Positioning System (GPS), digital camera, pen drive, Microsoft office, Remote sensing software (Environment for Visualizing Images (ENVI), Sentinel Application Platform (SNAP)), Geographic Information Systems (GIS) software (Quantum GIS (QGIS)), Coastal vulnerability modelling software (Integrated Valuation of Environmental Services and Tradeoffs (InVEST Coastal Vulnerability) Tools).

The computer used is high performance to allow data processing and data storage. The external hard drive is for data backup. The GPS is used to mark waypoint (geographical coordinate). The digital camera is for photo or field pictures. The Microsoft office software is for reports, data analysis. The remote sensing software (ENVI, SNAP) are used for satellite images analysis. GIS software is for GIS analysis. The INVEST Tools is used for coastal vulnerability modelling. Other materials like scientist articles, books and internet links are used for literature review.

### 3.2.2 Description of methods of data collection

For this investigation, two types of data were used: satellite images and climate data. The satellite image data were obtained from the dedicated websites of Landsat (https://landsat.usgs.gov/) and Sentinel (https://sentinel.esa.int/). The photos are derived from various sensors, including Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) for Landsat satellites, and Multi Spectral Instrument (MSI) for Sentinel-2 satellites. In terms of satellite images availability, the years 1988, 2000, 2015, and 2020 were chosen during the lengthy dry season in order to use images free of clouds.

The Landsat images were chosen for historical data from 1988 to 2000 and Sentinel-2 images for the period from 2015 to 2020. Sentinel-2 data were chosen from 2015 because it was on this date that the Sentinel 2 A satellite was launched by the European Space Agency (ESA). TM and ETM+ images have a spatial resolution of 30 m, but MSI images have a spatial resolution ranging from 10 to 60 m. The satellite data used is broken out in Table 3.1.

**Table 3.1: Characteristics of Satellite Images Used**

| Satellites | Sensor | Sensing date (Day-month-year) | Spatial resolution | Tile number or Path/Row |
|---|---|---|---|---|
| Sentinel-2A | MSI | 29th January, 2020 | 10 (10 - 60) | T31NCH |
| Sentinel-2A | MSI | 08th February, 2020 | 10 (10 - 60) | T31NBH |
| Sentinel-2A | MSI | 29th March, 2020 | 10 (10 - 60) | T31NBG |
| Sentinel-2A | MSI | 28th April, 2020 | 10 (10 - 60) | T31NCG |
| Sentinel-2A | MSI | 24th December, 2015 | 10 (10 - 60) | T31NCH |
| Sentinel-2A | MSI | 24th December, 2015 | 10 (10 - 60) | T31NBH |
| Sentinel-2A | MSI | 24th December, 2015 | 10 (10 - 60) | T31NBG |
| Sentinel-2A | MSI | 24th December, 2015 | 10 (10 - 60) | T31NCG |
| Landsat 7 | ETM+ | 14 th December, 2000 | 30 (15 - 30) | 192/055 |
| Landsat 7 | ETM+ | 14 th December, 2000 | 30 (15 - 30) | 192/056 |
| Landsat 7 | ETM+ | 14 th December, 2000 | 30 (15 - 30) | 193/055 |
| Landsat 4 | TM | 12th February, 1988 | 30 (30) | 192/055 |
| Landsat 4 | TM | 12th February, 1988 | 30 (30) | 192/056 |
| Landsat 4 | TM | 12th February, 1988 | 30 (30) | 193/055 |

**Source:** https://www.esa.int/ (2021)

The field work was done in 2020 in order to allow geometric correction of satellite images of 2020. For the years of 1988, 2000 and 2015, the Google Earth images in very high spatial resolution were used for geometric correction. The climate parameters like precipitation, temperature, wind speed and sunshine for Lome city were obtained for the period from 1989 to 2019 from meteorological agency in Togo according to their availability. The appendices A, B, C and D show an overview of the annual climatic data acquired. Tidal gauge data for the study area was unavailable, so the data available for the closest station, Takoradi (Ghana) was used for the period of 1983-2012 after downloaded them from the website of the sea level centre of university of Hawaii (http://uhslc.soest.hawaii.edu/data/?rq). For this station, only the data for 12 years were available on the website for this period. According to the research work of Young *et al.* (2003), proximity tidal gauge data can be used in the absence of data from the area of interest.

All of these climatic parameters were chosen based on the relevance of their impacts on the marine and coastal environment. As example, rising temperatures are causing glaciers melting, sea levels rise and extreme heat waves on populations (IPCC, 2014). An abundance of precipitation leads to flooding while a precipitation deficit increases the salinity of coastal surface waters (Sagna *et al.*, 2021). For sunshine, prolonged sunshine and drought allow water evaporation and reduce the supply of fresh water to lagoons, rivers and coastal rivers thus increasing the risk of water salinity and disruption of coastal ecosystem functionality (Lare *et al.*, 2021). Sunshine is also a factor that promotes significant temperature variations between day and night. Regarding the parameter of winds speed, storm surges inundate low-lying areas, disrupt transportation systems, damage property, destroy human habitats, and threaten human health and safety on coastal area (Lu *et al.*, 2018). The variation in wind speed is also a factor that could provide a beneficial cooling effect on coastal areas, influencing wave height and swell (Balaka and Egbendewe, 2021).The field work was another way for data collection. On the field, the focus group with the local population allows to get useful information on coastal people security, climate change impacts, coastal erosion impact, and SLR. In addition, the GPS was used on the field to collect waypoint. These data on waypoint were used to calibrate the satellite images and for modelling.

### 3.2.3 Scope and limitations

The area of Maritime Region in Togo is covered in this study. Ghana borders the study area on the west, Plateau Region on the north, Benin on the east, and the Atlantic Ocean on the south (Nimon *et al.*, 2020). The Maritime region with a population of 3,534,991 people in 2022, is chosen because it is the coastal area and is very affected by coastal erosion phenomenon. The study cover 50 km of the coastal maritime region and cover a period of 1988-2020. The reason for chosen this period is linked to the availability of the data. Specifically, the study, firstly, focused on climate trend. Taking this information into account can help to determine the extent of climate change phenomena and draw up suitable coastal management and adaptation plans at the country scale. Secondly, the study focused on the pattern and settlement dynamics. This could help to draw the policies for coastal area management and coastal risk management. Thirty, the study focused on the dynamics of the Togolese coastline from the past to the present. The shoreline dynamic is important to know the place that is at risk. Finally the study focused on the Togolese Coastland's Vulnerability to SLR and to inundation. The Togolese Coastland's Vulnerability model reveal the place that is more vulnerable to SLR and inundation. Some of the limitations of this study experienced includes the fact that COVID 19 has prevented close interaction with respondents during field data collection because their health status is unknown. Other limitations include the unavailability of current satellite images without cloud on Togolese coastal area.

### 3.2.4 Description of methods of data analysis

The methodological approach was carefully designed in order to achieve the specific objectives. It was based on existing methods through the literature (Djagoua, 2016; Thieler, 2017; Konko *et al.*, 2018a; He *et al.*, 2019) that offers perspectives for achieving our specific objectives. The figure 3.2 is the flow chart of the study.

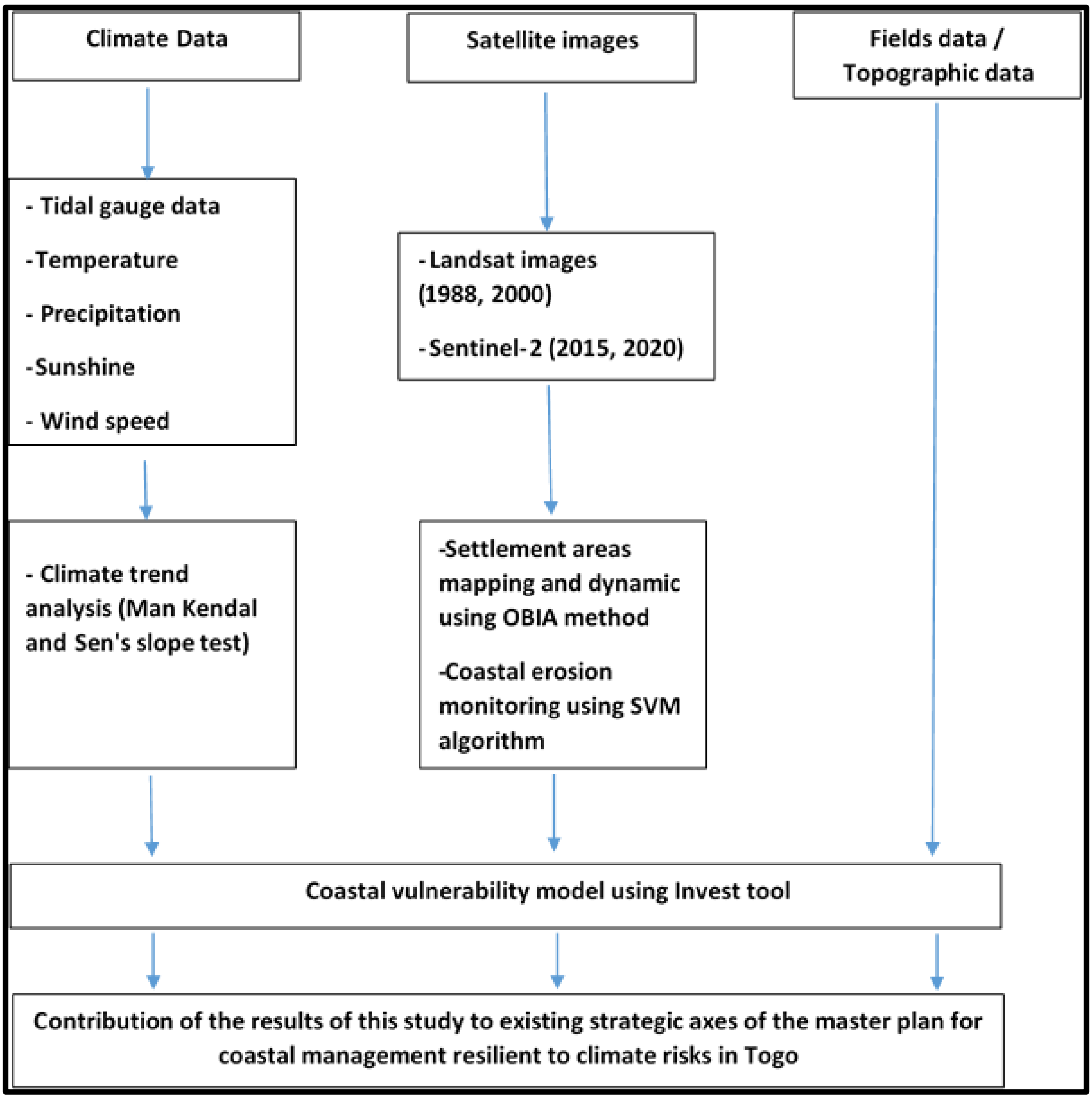



**Figure 3.2: Flow Chart of the Study**
**Source:** Author's field work (2023)

### 3.2.5 Examination of the extent of change in the climate of togo

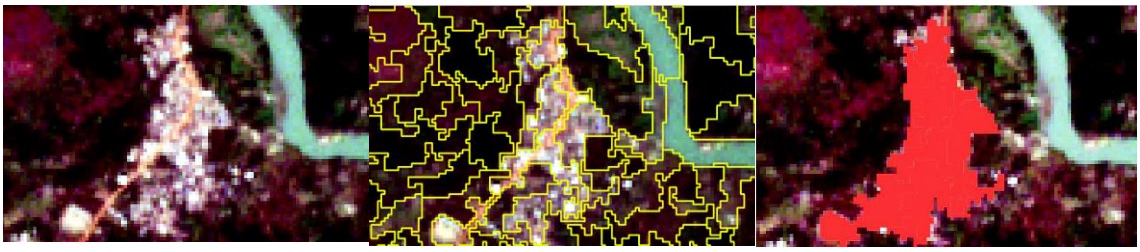
The first goal is to use available data to describe the extent of change in Togo's climate. Sen's slope test (Sen, 1968), Mann-Kendall test (Mann, 1945; Kendall, 1975), linear regression trend tests (Haan, 1977), and other approaches have been developed and used to monitor the trend of climatic parameters. This study used the Mann-Kendall test and Sen's slope test to investigate the temporal trend in annual and monthly cumulative precipitation, annual and monthly mean temperature, yearly and monthly mean wind speed, annual and monthly mean sunlight, and annual mean of tidal gauge data. Both tests were chosen due to their popularity, robustness, ease of execution, complementarity, and performance in similar studies in West Africa (Yue and Wang, 2004; Mavromatis and Stathis, 2011; Caloiero *et al.,* 2011; Tabari *et al.,* 2013; Koffi and Komla, 2015; Güçlü, 2020). The Mann Kendall test can detect expanding or diminishing significant patterns when there is no serial correlation in the data. This non-parametric test does not require a normal data distribution and is only moderately sensitive to abrupt discontinuities caused by non-homogeneous time series (Koffi and Komla, 2015). Sen's slope test is also a non-parametric one. It's used to figure out how big a trend is (Sen, 1968). This test is unaffected by substantial data errors and outliers (Malik and Kumar, 2020).

### 3.2.6 Settlement pattern and dynamics analysis

Settlement patterns and dynamics are used to analyze settlement conditions to establish related effects from climate change, policies and management. In general, there are several methods for extracting settlement areas from satellite images. These methods are classified into two main categories. The first one is Pixel-based methods including unsupervised classification (Grinias *et al.,* 2016), supervised classification (Forget *et al.,* 2018), deep learning classification (Misra *et al.,* 2020), Urban Index (Piyoosh and Ghosh, 2018), Normalised Difference Built-Up Index (Zha *et al.,* 2003), Index-based Built-Up Index (Xu, 2008), Improved built-up and bareness indexes (As-syakur *et al.,* 2012). The second category is Object-Based Image Analysis (OBIA) method (Samal and Gedam, 2015). For this study, OBIA method was chosen. This method is used for medium and high satellite images resolution and have the advantage to resolve the problem of artificial square cells in Pixel-based method (Blaschke, 2010). The OBIA method have the particularity to use the object as the smallest spatial unit in the image instead of individual pixels (Hossain and Chen, 2019). The OBIA method require a segmentation of images. Apart from these two main categories methods for settlement areas extracting, there are the global products of the Global Human Settlement Layer (GHSL) for the dates 1975, 1990, 2000, 2015 and 2018. The GHSL products are interesting, and take into account the data of the population and settlements but do not fully take into account the dates retained within the framework of our study (1988, 2000, 2015, and 2020). In addition, information related to data accuracy and commission/omission errors at the local level (country scale) are not clearly defined.

In this study, the OBIA method was used. The Landsat and sentinel-2 images in natural colour (Figure 3.3a) underwent the segmentation operation (Figure 3.3b) using mean-shift algorithm (Fukunaga and Hostetler, 1975). This algorithm is popular and widely exploited as a robust method of image segmentation (Demirović, 2019; Xiao *et al.,* 2019). The segmentation consists of subdivision of satellite images into meaningful image-objects through the creation of segments (Hay and Castilla, 2006). Subsequently, the classification was carried out by assigning the segments resulting from the segmentation operation to the class of settlement areas (Figure 3.3c). At the end of this operation, the settlements areas for each date, cover percentage and annual rate of expansion were calculated. The appendices E, F, G and H show an overview of the Attribute Tables generated for the calculation of settlement areas. The settlements areas were calculated by summing all the settlement areas segments of the study area for each date. The settlement cover percentage is the ratio of settlements areas for a year and maritime region area. The Annual Rate of Expansion (ARE) is calculated by Equation (1). Ay1 represent the settlements area for the first year (y1) while Ay2 represent the settlements areas for the second year (y2).

$$ARE = \frac{\mathrm{Ay2} - \mathrm{Ay1}}{\mathrm{y2} - \mathrm{y1}} \qquad \text{Equation (1)}$$



(a) (b) (c)

**Figure 3.3: Overview of Methodological Approach for Settlement Area Mapping. (a) Composite Image of Sentinel-2 Showing Settlements Area; (b) Image Segmented; (c) Settlements Area Classified**
**Source:** Author's data analysis (2023)

Ground examinations were used to validate the results of satellite image processing. For each date, a total of 100 points were preserved for ground checks. To avoid any correlation, the distribution of points was made at random with a distance limitation of 100 m between neighbouring spots (Congalton, 1991). The total accuracy was calculated after the field checks. It represents the percentage of correctly classified points in relation to the total number of control points. The overall precision is calculated by dividing the total number of correct points by the total number of points tested (Rwanga and Ndambuki, 2017).

### 3.2.7 Evaluation of the dynamics of the togolese shoreline from 1988 to 2018

A coastline is the point at which land meets the sea (Stanchev *et al.*, 2013). The study of the situation of coastal erosion and the dynamics of the coastline concerns the entire Togolese coastline subdivided into two segments from an environmental point of view: a first segment from Aneho to Agbata located on the coastal facade of the reserve of mono biosphere (RBM) (Appendix I) and a second segment from Agbata to Aflao that is not part of the RBM (Appendix J) (Konko *et al.*, 2018a). In order to allow a better visualization of the evolution over time, the 50 kilometres long coast has been subdivided into several rectangular sectors of about three kilometres in length. Indeed, it is easier to indicate where changes have taken place and where actions need to be taken thanks to these sectors. The time scale of the study is between 1988 and 2020 in accordance with the documentation consulted.

#### *3.2.7.1 Images pre-processing*

All the satellite images have been pre-processed under the ENVI software. Firstly, the images were geo-referenced from GPS field surveys, aerial photograph and JICA topographic data, under the projection World Geodetic System (WGS) 84, Universal Transverse Mercator (UTM) 31 North. Subsequently, pretreatments focused on radiometric correction, resampling and geometric correction operations. The radiometric correction operation allowed to reduce the atmospheric effects: The FLAASH model was used to transform the at-sensor radiance (digital number, ND) values to surface reflectance (Wang et al., 2017). The Near Infrared (NIR) band and the Green band of TM/ETM+ and MSI images from 1988, 2000, and 2018 were resampled to 15 m by the nearest neighbourhood resampling method to unify the spatial resolution of Landsat and Sentinel-2A images. Geometric correction is used to remove geometric distortion: the image-to-image registration method in ENVI software was used to rectify the Landsat and Sentinel-2A images. The other images were created using the Sentinel-2A MSI image from 2018.

#### *3.2.7.2 Water index calculation*

Various water index methods for improve the discrimination of aquatic and terrestrial areas from satellite imagery have been developed: Normalized difference water index (Mcfeeters, 1996), modified normalized difference water index (Wang *et al.,* 2017). In this study, the spectral water indice based on normalized difference water index, namely, NDWI (Mcfeeters, 1996) has used because of his efficiency and convenience (Wang *et al.,* 2017). NDWI is computed according to the Equation 3.1 where NIR refers to the Near infrared band (for the MSI images, NIR corresponds to Band 8 while for TM and ETM + images, NIR corresponds to Band 4) and Green to the Green band (for the MSI images, Green corresponds to Band 3 while for TM images and ETM +, Green corresponds to Band 2). NDWI tries to maximise the reflectance of water utilising green wave-lengths, minimise the poor reflectance of NIR by water features, and finally, take advantage of the high reflectance of NIR by both vegetation and soil. As a result, water usually has a positive value, but soil and vegetation have either a nil or a negative value.

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad 3.1$$

#### *3.2.7.3 Shoreline extraction methods*

Stanchev (2013) defines the shoreline as the point where land meets the sea. Several approaches for extracting shorelines and detecting changes from satellite data have been developed. Manual methods, image enhancement, write function memory insertion, density slice using single or multiple bands and multi-spectral classification, multi-date data classification and comparison of two independent land cover classifications, image digitization, both supervised and unsupervised, are the most commonly used change detection techniques (Mas, 1999; Frazier and Page, 2000; Burningham and French, 2017; Stanchev *et al.,* 2017; Konko *et al.,* 2018a). Several image processing algorithms, including pre-segmentation, segmentation, and post-segmentation, have also been used for autonomous coastline extraction from satellite data (Liu and Jezek, 2004).

The exploratory analysis of the performances of three distinct commonly used methods on the NDWI indices was performed in this study in order to define the most suitable method for extracting the shoreline in Togo coast in tropical context: Otsu threshold segmentation method, Iso Cluster Unsupervised Classification method, and SVM supervised Classification method. National topographic data from 2013 provided by the Japanese International Cooperation Agency (JICA) at a scale of 1/50 000 (Sheet NB-31-XIV-1b Baguida; Sheet NB-31-XIV-1a Lome), aerial photograph acquired in January 2018, and field data were used as reference data for validation and comparison of tree method results.

The Otsu's approach (Otsu, 1975) is a dynamic method that has successfully partitioned the input raster picture into homogenous land and water regions by reducing intra-class variation (Li *et al.,* 2013; Du *et al.,* 2014; Du *et al.,* 2016). The Otsu threshold segmentation approach is effective, with dynamic and variable thresholds based on different regions and sectors (Li *et al.,* 2013). It is still one of the most widely used thresholding techniques (Sezgin *et al.,* 2004; Kuleli *et al.,* 2011). To establish a good separation between land and sea water, the thresholding approach automatically sets the threshold value based on local features. It is based on discriminating analysis and computes the thresholding level using the zeroth and first-order cumulative moments of the histogram.

The iso Cluster Unsupervised Classification method uses the Iso Cluster and Maximum Likelihood Classification tools to perform unsupervised classification on a sequence of input raster bands. The Iso Cluster tool employs the migrating means technique, which is a modified iterative optimisation clustering procedure. In the multidimensional space of the input bands, the algorithm divides all cells into the user-specified number of unique unimodal groups. This technique is typically used to prepare for unsupervised categorization (Ball and Hall, 1965; Venkateswarlu and Raju, 1992). The Maximum Likelihood Classification tool's algorithm is founded on two principles: the cells in each class sample in the multidimensional space being regularly distributed, and Bayes' decision-making theorem. When allocating each cell to one of the classes contained in the signature file, the tool takes into account both the variances and covariances of the class signatures.

The SVM Supervised Classification method has been successfully used to separate terrestrial and aquatic environments (Konko *et al.,* 2018b). SVM is a non-parametric statistical learning technique that is supervised. In general, it is based on the search for a hyperplane making it possible to separate observations while maximizing the margin (the distance from the point closest to the hyperplane) (Mantero *et al.,* 2005). Vapnik (1982) created the first formulation of the algorithm. This approach can produce high classification results even when the quantity of training samples for the region of interest (ROI) is limited, which is a common constraint in remote sensing applications. SVM Supervised Classification also has the ability to minimize the risk of classification error even without prior knowledge on data distribution. Its pixel separation performance is frequently superior to that of other standard classifiers such as the maximum likelihood approach (Mantero *et al.,* 2005).

Ground checks were used to validate the results of three independent methods of coastline extraction. For each date and procedure, a total of 100 points were retained for ground checks. To avoid any correlation, the distribution of points was made at random with a distance limitation of 100 metres between neighbouring spots (Congalton, 1991). The total accuracy was calculated after the field checks. It represents the percentage of correctly classified points in relation to the total number of control points. The overall precision is calculated by dividing the total number of correct points by the total number of points tested (Rwanga and Ndambuki, 2017).

#### *3.2.7.4 Shoreline kinematics*

The specific Digital Shoreline Analysis System (DSAS) module of ArcGIS is used to examine shoreline kinematics (Himmelstoss *et al.,* 2018). DSAS extension requires the integration of shoreline shapefile within a geodatabase and the digitization of an imaginary baseline from which DSAS creates perpendicular transects to the lines to be compared. A conventional step of 50 metres measurements is used between 500 metres long transects.

The estimation of the rates of variation of the shoreline is performed following the linear regression (LRR) method. This method was used when data are multiple. A LRR method of change statistic is calculated by fitting a least-squares regression line to all shoreline points along a specific transect. It allows highlighting the evolutionary trend over time (Crowell *et al.*, 1997; Thieler *et al.*, 2017; Konko *et al.*, 2018a; Himmelstoss *et al.*, 2018).

### 3.2.8 Generation of the togolese coastland's vulnerability model to sea level rise and inundation

#### *3.2.8.1 InVEST coastal vulnerability model*

The method used is on the base of the InVEST Coastal Vulnerability model (Thieler, 2017). The InVEST Coastal Vulnerability model is a tool that gives an exposure index ranking on all sections of the coast. Exposure refers to the inventory of elements in an area in which hazard events may occur (Sharma and Patwardhan, 2008). This index has the advantage of representing the vulnerability of the coast to SLR and inundation. The vulnerability model encompasses an external dimension, which is represented here by a system's 'exposure' to climate changes, as well as an internal dimension, which includes its 'sensitivity' and 'adaptive capability' to these stressors (a stressor is an activity or phenomenon that induces an adverse effect and therefore degrades the condition and viability of a natural system (IPCC, 2014)). The sensitivity in climate change adaptation is the physical predisposition of human beings, infrastructure, and environment to be affected by a dangerous phenomenon due to lack of resistance and predisposition of society and ecosystems to suffer harm as a consequence of intrinsic and context conditions making it plausible that such systems once impacted will collapse or experience major harm and damage due to the influence of a hazard event (Sharma and Patwardhan, 2008). Adaptive capability refers to the positive features of people's characteristics that may reduce the risk posed by a certain hazard. Improving capacity is often identified as the target of policies and projects, based on the notion that strengthening capacity will eventually lead to reduced risk (Sharma and Patwardhan, 2008).Capability clearly also matters for reducing the impact of climate change. Generally, the exposure index is constructed on the basis of approximately seven biogeophysical variables organized in two groups: the exposure variables and the sensitivity variables. The exposure variables include SLR, wave exposure, wind exposure and surge potential while the sensitivity variables include geomorphology, relief and natural habitat.

Relative to all other shoreline segments, the index assesses the exposure of each segment. Depending on the scale, the extent, the resolution of the input data, the results of the model are potentially relevant. The InVEST Coastal Vulnerability model is a robust tool that works on sheltered, uniform, heterogeneous or complex coastlines. The model also has the advantage of incorporating the density of coastal populations that can be used to create maps of the relative vulnerability of populations to coastal storms. The appendix K show the interface of Invest tools for coastal vulnerability assessment.

#### *3.2.8.2 Coastal exposure index*

To calculate the Coastal Exposure Index (EI), the InVEST Coastal Vulnerability model can use up to seven physical and biological variables on all segments of the coastline. The degree of exposure can vary from very low (rank = 1) to very high (rank = 5) depending on the variables used by the operator. This ranking system is based on the methods proposed by Gornitz *et al.* (1991) as shown in Table 3.2.

**Table 3.2: Ranking Table Factors**

| Rank | 1 (very low) | 2 (low) | 3 (moderate) | 4 (high) | 5 (very high) |
|---|---|---|---|---|---|
| Geomorphology (Variable of sensitivity) | Rocky; high cliffs; fjord; fiard; seawalls | Medium cliff; indented coast; bulkheads and small seawalls | Low cliff; glacial drift; alluvial plain; revetments; rip-rap walls | Cobble beach; estuary; lagoon; bluff | Barrier beach; sand beach; mud flat; delta |
| Natural Habitats (Variable of sensitivity) | Coral reef; mangrove; coastal forest | High dune; marsh | Low dune | Seagrass; kelp | No habitat |
| Slop (Variable of sensitivity) | 81 to 100 Percentile | 61 to 80 Percentile | 41 to 60 Percentile | 21 to 40 Percentile | 0 to 20 Percentile |
| Sea Level Change (Variable of exposure) | 0 to 20 Percentile | 21 to 40 Percentile | 41 to 60 Percentile | 61 to 80 Percentile | 81 to 100 Percentile |
| Wave Exposure (Variable of exposure) | 0 to 20 Percentile | 21 to 40 Percentile | 41 to 60 Percentile | 61 to 80 Percentile | 81 to 100 Percentile |
| Wind Exposure (Variable of exposure) | 0 to 20 Percentile | 21 to 40 Percentile | 41 to 60 Percentile | 61 to 80 Percentile | 81 to 100 Percentile |
| Surge Potential (Variable of exposure) | 0 to 20 Percentile | 21 to 40 Percentile | 41 to 60 Percentile | 61 to 80 Percentile | 81 to 100 Percentile |

**Source :** https://geomodeling.njnu.edu.cn/

The model calculates the exposure index (Equation 3.2) for each shoreline point as the geometric mean of all the variable ranks:

$$EI = (R_{Geom} * R_{Slop} * R_{Habitats} * R_{SLR} * R_{Wind\ Exposure} * R_{Wave\ Exposure} * R_{Surge})^{1/7} \quad (3.2)$$

### 3.2.9 Identification of the contribution of the results of this study to the master plan for coastal management resilient to climate risks in Togo

This objective is to contribute to the existing strategies focus to minimize Togo's coastland's vulnerability to SLR and inundation. The methodological approach is based initially on a summary presentation of the 2021 Content of the existing strategic axes of the master plan for coastal management resilient to climate risks in Togo. Then a contribution is made on the basis of our results.

### 3.2.10 Description of data presentation methods

For the first objective, the extent of change in climate is presented in graph form, numeric format. For the second objective, the maps of settlement pattern, the maps of settlement dynamic from the past to the present, the graph and table are presented in numeric format. On the third objective, the maps of shoreline dynamic from the past to the present, the statistic of kinematic of shoreline, graph and table are presented in numeric format.

The fourth objective show the Coastal Vulnerability to coastal erosion and inundation and is presented in table and spatial map in numeric format.

### 3.2.11 The Output of the study

The first objective provide the extent of change in climate. This objective is necessary to understand the trend of climate parameter in Togo. The study also provide Coastal settlement pattern and dynamics from 1988 to 2020. This information is useful to draw the policies for coastal area management. Furthermore, the dynamics of the Togolese shoreline from 1988 to 2020 are allow to ascertain the place that is more at risk. In addition, the Togolese Coastland's Vulnerability model outputs can be used to protect services offered by natural habitats and coastal populations. This information can help coastal managers, planners, landowners and other stakeholders identify regions of greater risk to coastal hazards, which can in turn better inform development strategies and permitting.

# CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSIONS

### 4.1 Presentation and Analyses of Results

### 4.1.1 Extent of change in the climate

#### *4.1.1.1 Annual tidal gauge trend*

The temporal trend of annual tidal gauge data mean is shown in Table 4.1. The tidal gauge data analysis showed an increasing trend (Figure 4.1) of 13. 75 millimetre per year. The trend has been significant at $\alpha = 0.05$.

**Table 4.1: Trend Statistics of Tidal Gauge Data in Takoradi Station (Ghana)**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| Annual tidal gauge data mean (millimetre) | 1983-2012 | 12 | 2.13 | * | 13.75 |

* Significant at $\alpha = 0.05$

(Source: Author's data analysis (2023))

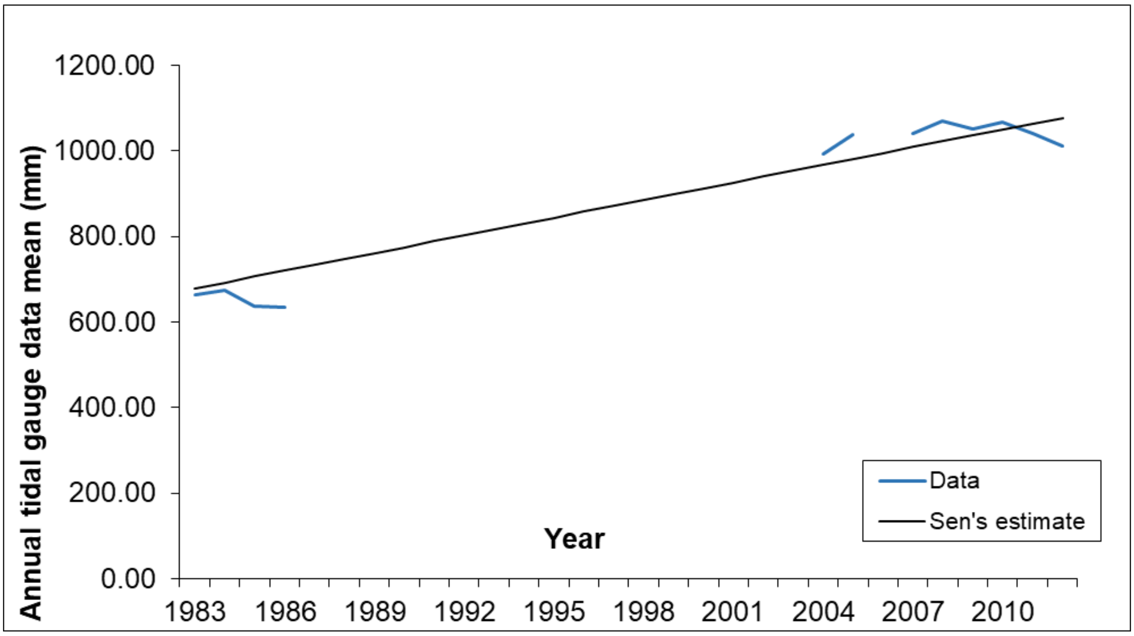



**Figure 4.1: See Level Rise Trend (Annual Means of Tidal Gauge Data) from 1983-2012 over Takoradi City in Ghana as Shown by Observation Dataset**

### *4.1.1.2 Annual and monthly temperature trend*

The temporal trend in annual mean temperature is shown in Table 4.2. The temperature analysis showed an increasing trend (Figure 4.2) of 0.038 °C per year over that period. The trend has been significant at $\alpha = 0.001$.

**Table 4.2: Trend Statistics of Temperature Data in Lome City (Togo)**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| Annual mean temperature (°C) | 1989 - 2019 | 31 | 5.27 | *** | 0.038 |

*** Significant at $\alpha = 0.001$

**Source:** Author's data analysis (2023)

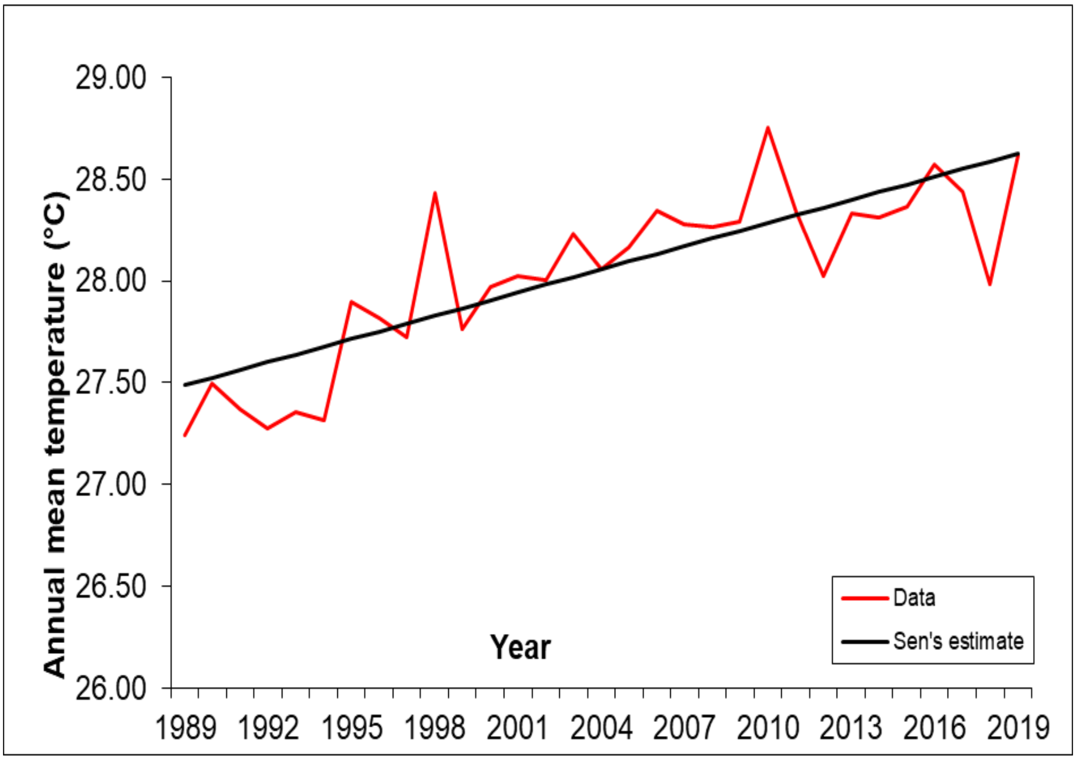



**Figure 4.2: Trend of Temperature (Annual Mean) from 1989-2019 over Lome City as Shown by Observation Dataset.**

The temporal trend in monthly mean temperature is shown in Table 4.3. The monthly mean temperature analysis showed an increasing trend. The trend has been significant at $\alpha = 0.01$ for March, May, June, August months and at $\alpha = 0.001$ for January, February, April, July, September, October, November, December months.

**Table 4.3. Monthly Temperature Trend in Lome City**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| JANUARY | 1989-2019 | 31 | 3.98 | *** | 0.059 |
| FEBRUARY | 1989-2019 | 31 | 3.62 | *** | 0.040 |
| MARCH | 1989-2019 | 31 | 2.89 | ** | 0.037 |
| APRIL | 1989-2019 | 31 | 3.81 | *** | 0.045 |
| MAY | 1989-2019 | 31 | 3.26 | ** | 0.034 |
| JUNE | 1989-2019 | 31 | 2.58 | ** | 0.021 |
| JULY | 1989-2019 | 31 | 4.42 | *** | 0.039 |
| AUGUST | 1989-2019 | 31 | 2.75 | ** | 0.027 |
| SEPTEMBER | 1989-2019 | 31 | 3.59 | *** | 0.034 |
| OCTOBER | 1989-2019 | 31 | 4.59 | *** | 0.042 |
| NOVEMBER | 1989-2019 | 31 | 4.93 | *** | 0.038 |
| DECEMBER | 1989-2019 | 31 | 5.10 | *** | 0.058 |

** Significant at $\alpha = 0.01$; *** Significant at $\alpha = 0.001$

**Source:** Author's data analysis (2023)

### *4.1.1.3 Annual and monthly precipitation trend*

The temporal trend in annual cumulative precipitation is shown in Table 4.4. The analysis of precipitation data exhibited no significative trend. However only variability was shown in the precipitation data over Lome during that period (Figure 4.3).

**Table 4.4: Trend Statistics of Precipitation Data in Lome City (Togo)**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| Annual cumulative precipitation (millimetre) | 1989-2019 | 31 | 0.85 | N/A | 4.291 |

**Source:** Author's data analysis (2023)

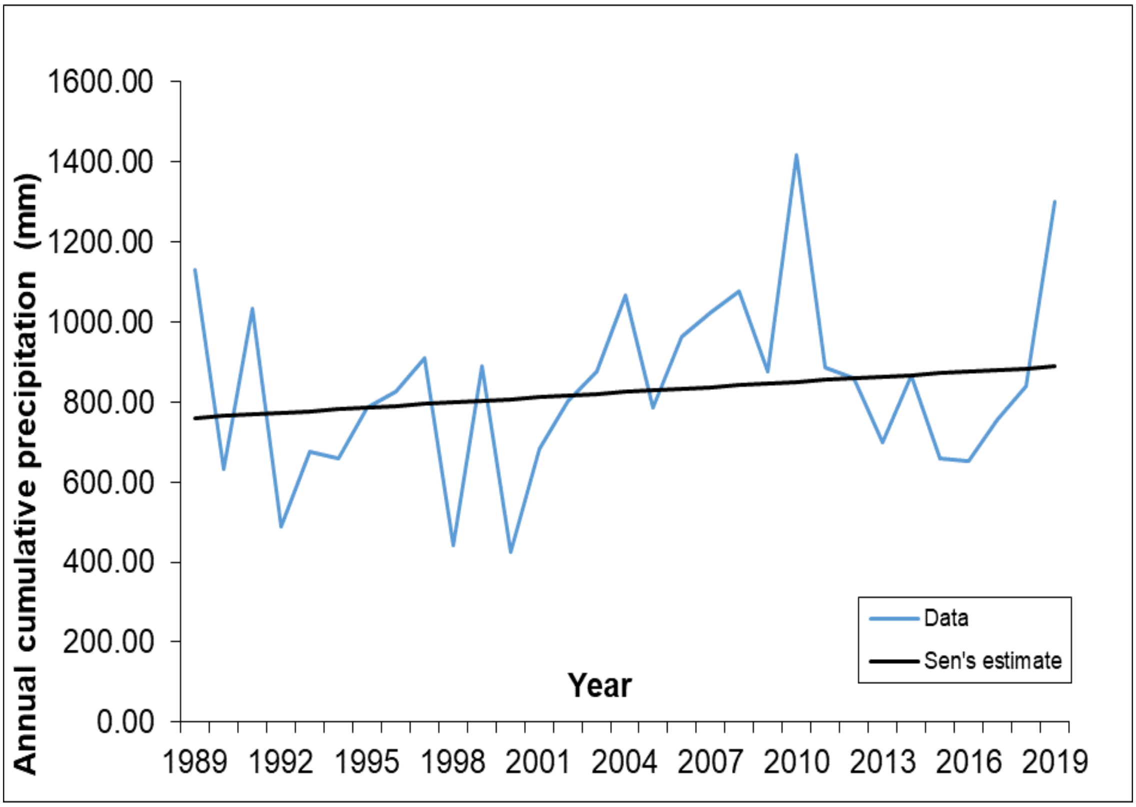



**Figure 4.3: Trend of Precipitation (Annual Cumulative) from 1989-2019 over Lome City as Shown by Observation Dataset.**

The temporal trend in monthly cumulative precipitation is shown in Table 4.5. The monthly cumulative precipitation trend is not significant but exhibited some variation. Indeed during the dry season period (December, January, February), no variation is observed while for the other months of the year the variation is slightly increasing excepted the month of April where it is decreasing.

**Table 4.5: Monthly Precipitation Trend in Lome City**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| JANUARY | 1989-2019 | 31 | 0.86 | N/S | 0.000 |
| FEBRUARY | 1989-2019 | 31 | 0.68 | N/S | 0.000 |
| MARCH | 1989-2019 | 31 | 0.92 | N/S | 0.856 |
| APRIL | 1989-2019 | 31 | -1.26 | N/S | -1.292 |
| MAY | 1989-2019 | 31 | 0.10 | N/S | 0.081 |
| JUNE | 1989-2019 | 31 | 1.02 | N/S | 1.315 |
| JULY | 1989-2019 | 31 | 0.41 | N/S | 0.350 |
| AUGUST | 1989-2019 | 31 | 0.85 | N/S | 0.371 |
| SEPTEMBER | 1989-2019 | 31 | 1.22 | N/S | 1.240 |
| OCTOBER | 1989-2019 | 31 | 1.09 | N/S | 1.300 |
| NOVEMBER | 1989-2019 | 31 | 0.09 | N/S | 0.025 |
| DECEMBER | 1989-2019 | 31 | -1.00 | N/S | 0.000 |

N/S = Not Significant

**Source:** Author's data analysis (2023)

#### *4.1.1.4 Annual and monthly winds speed trend*

The temporal trend in annual mean winds speed is shown in Table 4.6. For the annual mean wind speed analysis, the trend is not significant but the variation is increasing (Figure 4.4). The temporal trend in monthly mean winds speed is shown in Table 4.7. For the monthly mean wind speed analysis, the trend is not significant and show few variation.

**Table 4.6: Trend Statistics of Winds Speed Data in Lome City (Togo)**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| Annual mean wind speed (metre per second) | 1989-2019 | 31 | 1.16 | N/A | 0.008 |

N/S = Not Significant
**Source:** Author's data analysis (2023)

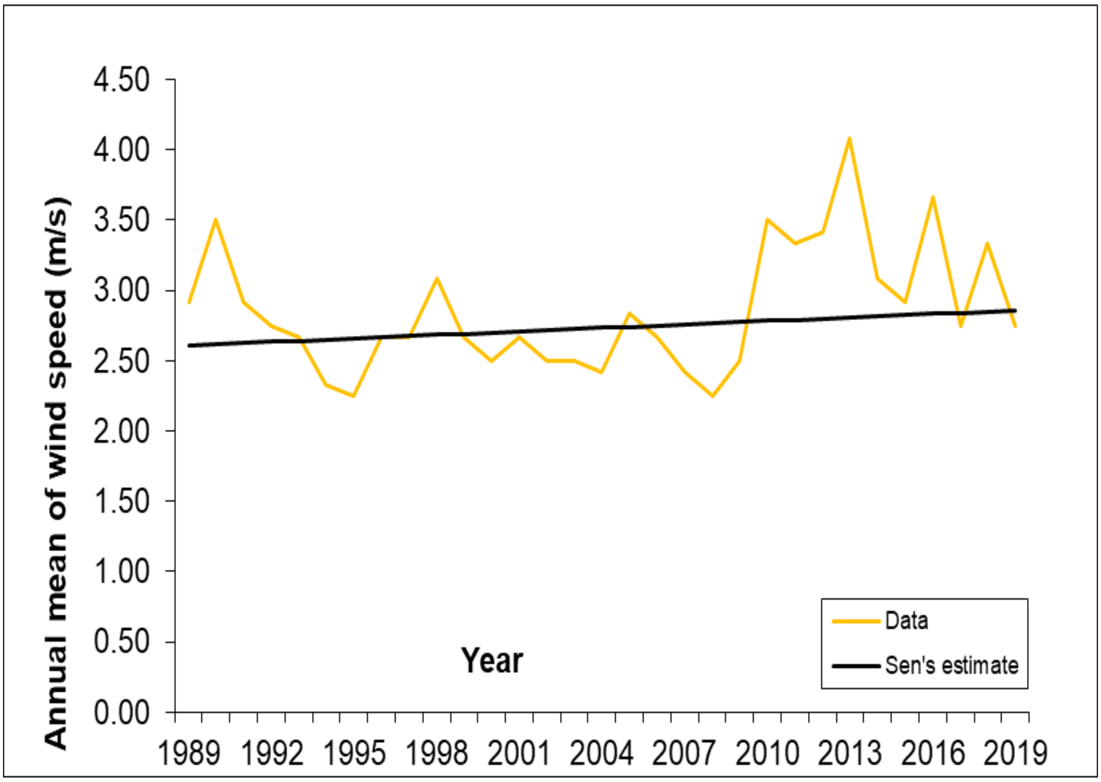



**Figure 4.4: Trend of Wind Speed from 1989-2019 over Lome City as Shown by Observation Dataset.**

**Table 4.7: Monthly Wind Speed Trend in Lome City**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| JANUARY | 1989-2019 | 31 | 1.41 | N/S | 0.002 |
| FEBRUARY | 1989-2019 | 31 | 1.40 | N/S | 0.001 |
| MARCH | 1989-2019 | 31 | 2.30 | N/S | 0.003 |
| APRIL | 1989-2019 | 31 | 0.27 | N/S | 0.002 |
| MAY | 1989-2019 | 31 | -0.59 | N/S | -0.001 |
| JUNE | 1989-2019 | 31 | 2.04 | N/S | 0.001 |
| JULY | 1989-2019 | 31 | -0.50 | N/S | -0.003 |
| AUGUST | 1989-2019 | 31 | 0.96 | N/S | 0.002 |
| SEPTEMBER | 1989-2019 | 31 | 1.26 | N/S | 0.000 |
| OCTOBER | 1989-2019 | 31 | 0.23 | N/S | 0.002 |
| NOVEMBER | 1989-2019 | 31 | 0.77 | N/S | 0.005 |
| DECEMBER | 1989-2019 | 31 | 1.41 | N/S | 0.000 |

N/S = Not Significant

**Source:** Author's data analysis (2023)

#### *4.1.1.5 Annual and monthly sunshine trend*

The temporal trend in annual mean sunshine is shown in Table 4.8. The annual mean sunshine analysis shown decreasing variation with not significant analysis (Figure 4.5)

**Table 4.8: Annual Trend Statistics of Sunshine Data in Lome City (Togo)**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| Annual mean sunshine (hours and tenths*)* | 1989-2019 | 31 | -1.31 | N/A | -0.01 |

N/S = Not Significant

**Source:** Author's data analysis (2023)

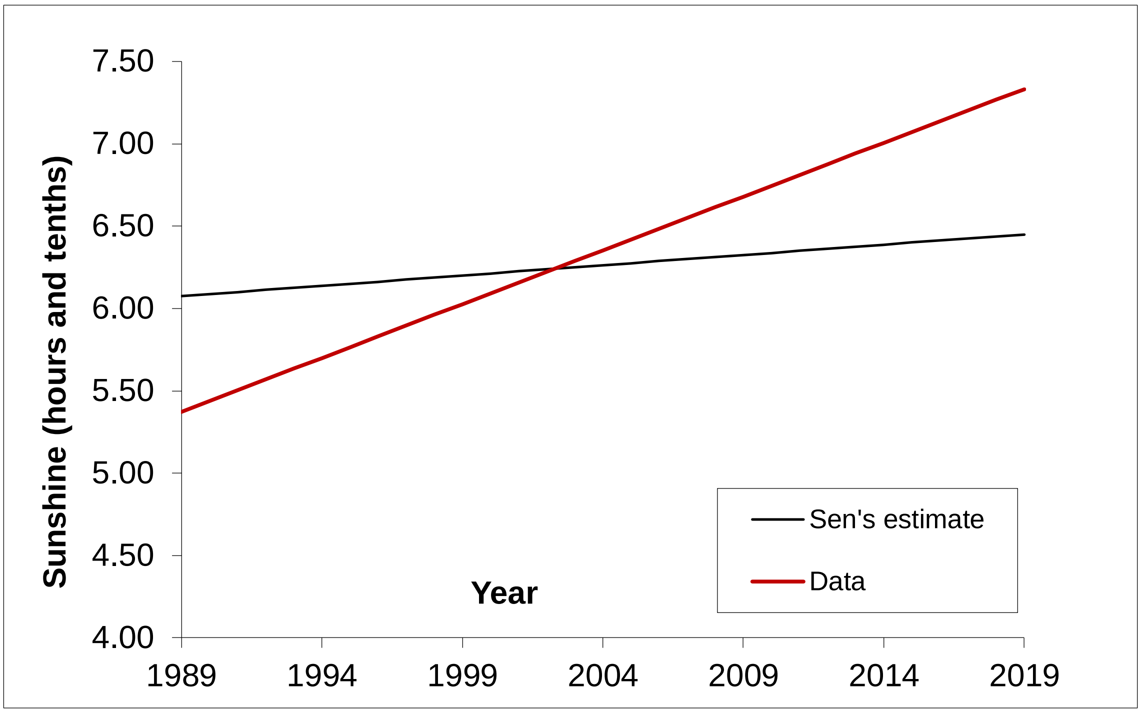



**Figure 4.5: Annual Trend of Sunshine from 1989-2019 over Lome City as Shown by Observation Dataset.**

The temporal trend in monthly mean sunshine is shown in Table 4.9. The monthly mean sunshine analysis showed significant trend at $\alpha = 0.1$ for April and September months. For the others months of the year, the trend is not significant but exhibited variability.

**Table 4.9: Monthly Sunshine Trend in Lome City**

| Time series | Period | n | Test Z | Significant | Slope |
|---|---|---|---|---|---|
| JANUARY | 1989-2019 | 31 | 0.68 | N/S | 0.013 |
| FEBRUARY | 1989-2019 | 31 | 0.95 | N/S | 0.014 |
| MARCH | 1989-2019 | 31 | -0.09 | N/S | 0.000 |
| APRIL | 1989-2019 | 31 | 1.84 | + | 0.025 |
| MAY | 1989-2019 | 31 | -0.39 | N/S | -0.007 |
| JUNE | 1989-2019 | 31 | -0.56 | N/S | -0.011 |
| JULY | 1989-2019 | 31 | 1.16 | N/S | 0.033 |
| AUGUST | 1989-2019 | 31 | 0.97 | N/S | 0.013 |
| SEPTEMBER | 1989-2019 | 31 | 1.86 | + | 0.028 |
| OCTOBER | 1989-2019 | 31 | 0.22 | N/S | 0.000 |
| NOVEMBER | 1989-2019 | 31 | 0.70 | N/S | 0.005 |
| DECEMBER | 1989-2019 | 31 | -0.32 | N/S | -0.005 |

+ Significant at 0.1; N/S = Not Significant

**Source:** Author's data analysis (2023)

### 4.1.2 Settlement pattern and dynamics from 1988 to 2020

#### *4.1.2.1 Settlement area mapping accuracy*

The processing of satellite data has enabled the mapping of settlements dynamics. The overall precisions of the results obtained are 88.91 per cent; 89.14 per cent; 96.08 per cent; 97.25 per cent respectively for the years 1988, 2000, 2015, 2020. Mapping of settlements dynamics using Landsat data at 30 metres spatial resolution is less accurate than sentinel-2 data at 10 metres resolution. For all the dates, it was observed that, the overall precision is greater than 80 per cent, indicating a strong link between the values of the map and the values of the ground. According to the results of this study, the settlements mapping using OBIA method is more effective on Sentinel-2 images than Landsat images and the results are reliable.

*4.1.2.2 Settlement pattern and dynamics from 1988 to 2020*

Analysis of settlements dynamics from 1988 to 2020 shows an evolving dynamics of settlements areas (Figure 4.6a, Figure 4.6b, Figure 4.6c, and Figure 4.6d). Near the sea, it observed a strong concentration and dynamics of settlement areas. Surrounding of Lake Togo, the dynamics of settlements areas are weak.The expansion of settlements is observed throughout the maritime region with strong changes in the city of Lome, the capital.

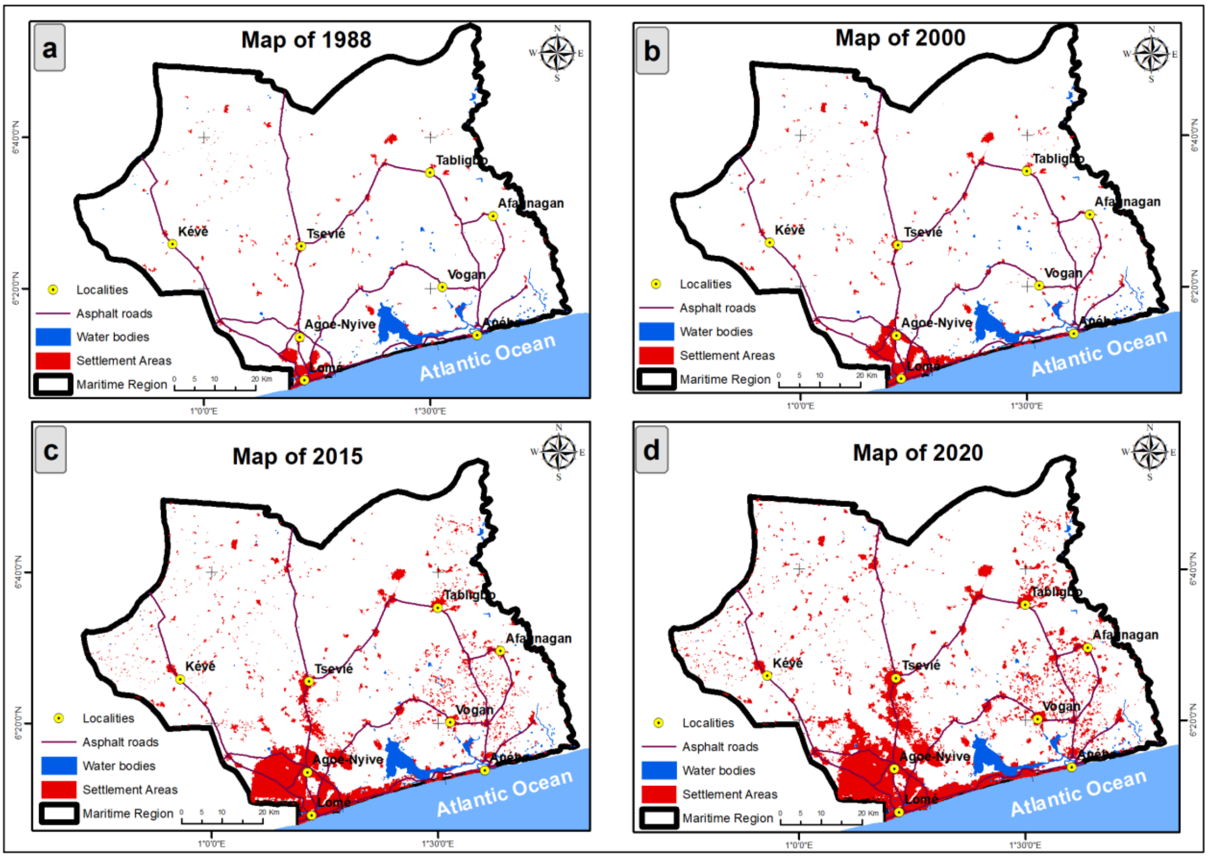



**Figure 4.6: Spatio-Temporal Trend of Settlements Areas During the Period 1988-2020. Settlement Areas Dynamics in the Following Years (a) 1988; (b) 2000; (c) 2015; (d) 2020**

The analysis of the changes that have taken place in the city of Lome (capital) and the peripheral zone shows a rapid evolution of settlements over the period 1988-2020 (Figure 4.7a, Figure 4.7b). In fact, in 1988 the capital was located in Lome near the sea, but in

2000 it expanded to Agoe-Nyive city and from 2000 to 2020 settlement areas continue to grow towards the direction of Tsevie and Keve cities.

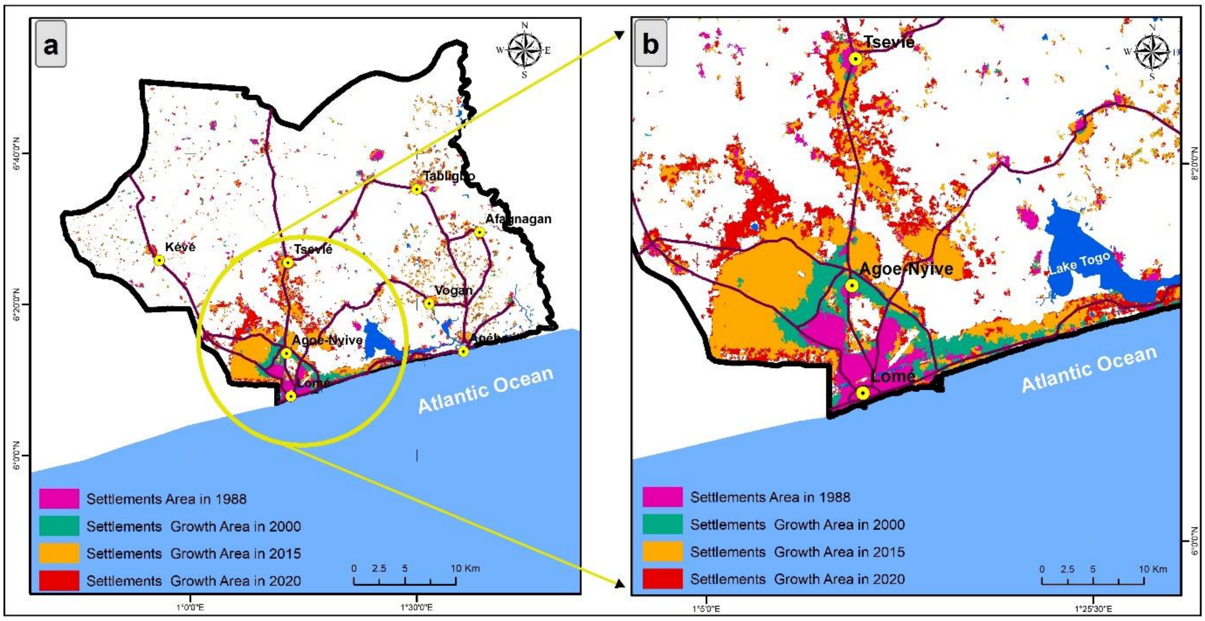



**Figure 4.7: Spatio-Temporal Dynamics of Settlement Areas in Lome. (a) Settlements Growth Area; (b) Dynamics of Settlements Area in the City of Lome and Surrounding.**

Statistical analysis of settlements dynamics shows that settlement areas have expanded from 2.06 per cent to 11.85 per cent in maritime region between 1988 and 2020 (Table 4.10). The corresponding annual expansion rate is 6.15 hectares per year for the period 1988-2000, 23.41 hectares per year for the period 2000 to 2015 and 40.16 hectares per year for the period 2015- 2020 (Table 4.11).

**Table 4.10: Changes of Settlements Areas from 1988 to 2020**

| Year | 1988 | 2000 | 2015 | 2020 |
|---|---|---|---|---|
| Settlements areas (Ha) | 13174 | 20556 | 55679 | 75761 |
| Settlements cover percentage (%) | 2.06 | 3.21 | 8.71 | 11.85 |

**Source:** Author's data analysis (2023)

**Table 4.11: Annual Rate of Settlements Areas Expansion**

| Period | 1988-2000 | 2000-2015 | 2015-2020 |
|---|---|---|---|
| Annual rate of expansion (Ha/year) | 6.15 | 23.41 | 40.16 |

**Source:** Author's data analysis (2023)

### 4.1.3 Dynamics of the togolese shoreline

#### *4.1.3.1 Comparison of the performance of the three methods on linear surfaces*

The performances of Otsu threshold segmentation method, Iso Cluster Unsupervised Classification method and SVM Supervised Classification method for the extraction of the shoreline from the NDWI indices are shown in Figure 4.8 As shown on the NDWI indices of the MSI images, the three methods show good performance for the extraction of the shoreline (Figure 4.8b; Figure 4.8c and Figure 4.8d). The global accuracies are more than 90 per cent. On the other hand on the NDWI indices of the ETM + images, Otsu threshold segmentation shows better performances (Global accuracy = 93 per cent) followed by SVM Supervised Classification (Global accuracy = 92 per cent) and Iso Cluster Unsupervised Classification (Global accuracy = 90 per cent) (Figure 4.8f; Figure 4.8g and Figure 4.8h). For the NDWI indices of TM images, although Otsu threshold segmentation (Global accuracy = 92 per cent) and SVM Supervised Classification (Global accuracy = 92 per cent) show better performance, Iso Cluster Unsupervised Classification has a tendency which is substantially the same (Global accuracy = 91 per cent) (Figure 4.8j; Figure 4.8k and Figure 4.8l.).

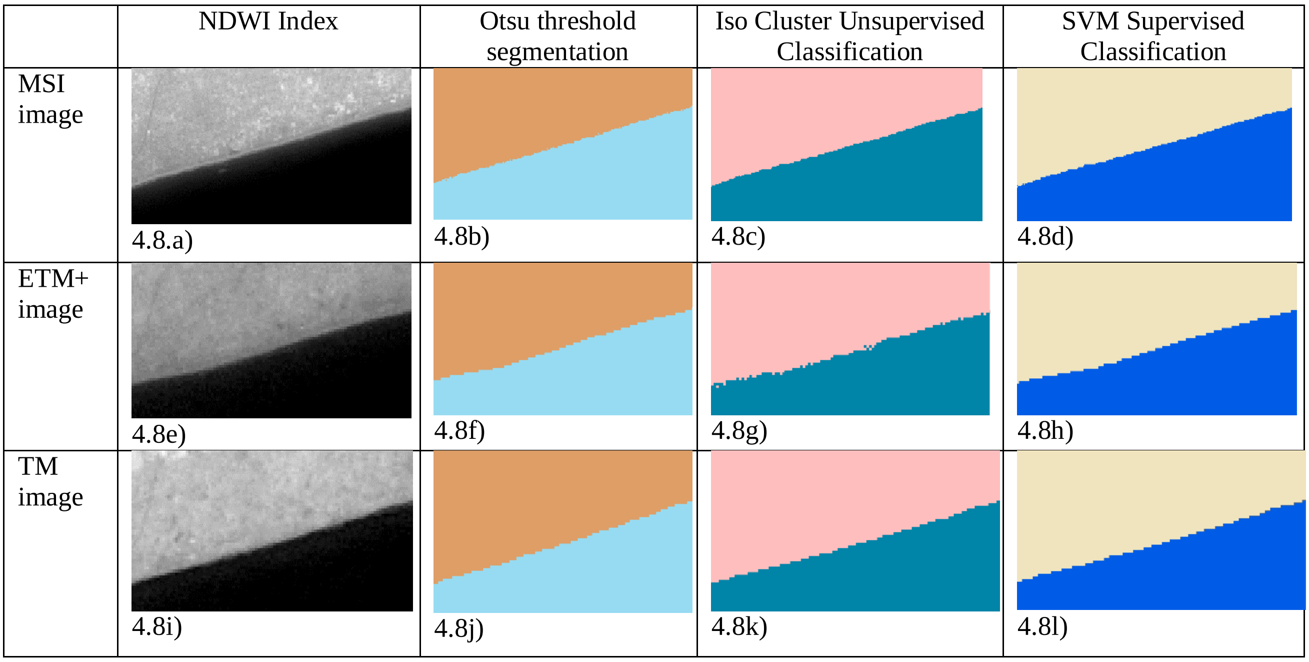



**Figure 4.8: Overview of the Performance of the Three Methods for Shoreline Extraction on Linear Coastal Surface.**

#### *4.1.3.2 Comparison of the performance of the three methods on non-linear surfaces*

The performances of Otsu threshold segmentation, Iso Cluster Unsupervised Classification and SVM Supervised Classification methods for the extraction of the shoreline on non-linear surfaces from NDWI indices are represented in Figure 4.9. It can be observed on the NDWI indices of the MSI images, that SVM Supervised Classification (Figure 4.9d) and Iso Cluster Unsupervised Classification (Figure 4.9c) shows good performance (Global accuracy > 92 per cent) compared to Otsu threshold segmentation (Global accuracy = 90 per cent) (Figure 4.9b).

The same observations were experienced on the NDWI indices of the ETM + and TM images (Figure 4.9f; Figure 4.9g; Figure 4.9h; Figure 4.9j; Figure 4.9k; Figure 4.9l). However, with regards to the comparison of SVM Supervised Classification and Iso Cluster Unsupervised Classification methods, the interpretation does not allow any conclusion. Additional statistical analyzes could help to judge the performance of these two algorithms on non-linear surfaces.

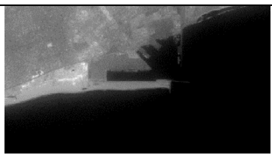
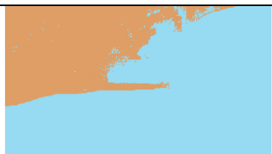
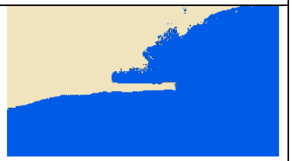
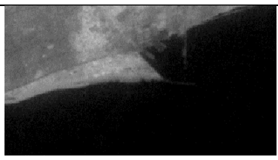
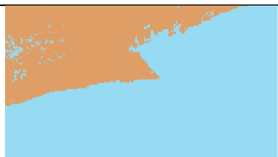
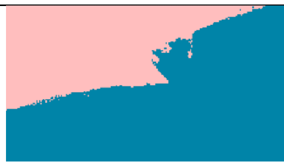
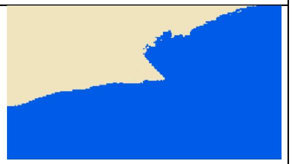
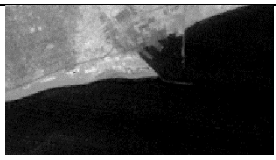
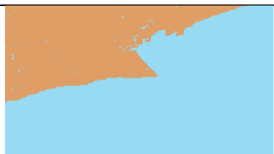
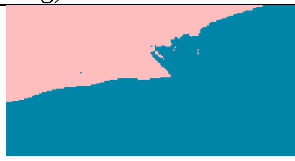
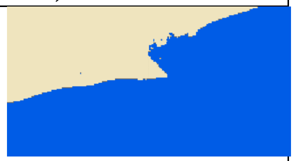
| | NDWI Index | Otsu threshold segmentation | Iso Cluster Unsupervised Classification | SVM supervised Classification |
|---|---|---|---|---|
| MSI image |  4.9a) |  4.9b) |  4.9c) |  4.9d) |
| ETM + image |  4.9e) |  4.9f) |  4.9g) |  4.9h) |
| TM image |  4.9i) |  4.9j) |  4.9k) |  4.9l) |

**Figure 4.9: Overview of the Performance of the Three Methods for Shoreline Extraction on Non-Linear Coastal Surface**

### *4.1.3.3. Method selected for shoreline extraction*

In the extraction of the shoreline from the NDWI indices of the MSI images which have good spatial resolution (10 metres), the three methods showed good results on the linear surfaces. On the other hand, on the low spatial resolution images (ETM + and TM), SVM Supervised Classification and Otsu threshold segmentation showed a good performance for the discrimination of terrestrial and aquatic surfaces compared to Iso Cluster Unsupervised Classification.

On non-linear coastal surfaces, SVM Supervised Classification and Iso Cluster Unsupervised Classification showed good performance on the NDWI indices of MSI, ETM + and TM images compared to Otsu threshold segmentation.

For this study, SVM Supervised Classification method is chosen because of its good performance on the NDWI indices of MSI, ETM + and TM images on linear and non-linear surfaces (Global accuracy > 91 per cent).

#### *4.1.3.4 Historical trend of shoreline on the aneho-agbata segment from 1988 to 2018*

The results of Shoreline dynamics from 1988 to 2018 based on satellite data (Landsat and Sentinel) revealed variable average coastal erosion ranging from 1.66 to 5.25 metres per year from Aneho to Agbata. The figure 4.10 is a Map of shoreline change from 1988 to 2018. The figure 4.11 show an overwiew of Shoreline change statistics for the period 1988 to 2018 by LRR methods. The lowest erosion rate is in Glidji (Sector 8) with a rate of 1.66 metres per year while the highest erosion rates were observed near Agbata (Sector 1), Togokomé (Sector 2) and Alogavi (Sector 3) with respective rates of 5.2 metres per year; 5.25 metres per year and 4.88 metres per year.

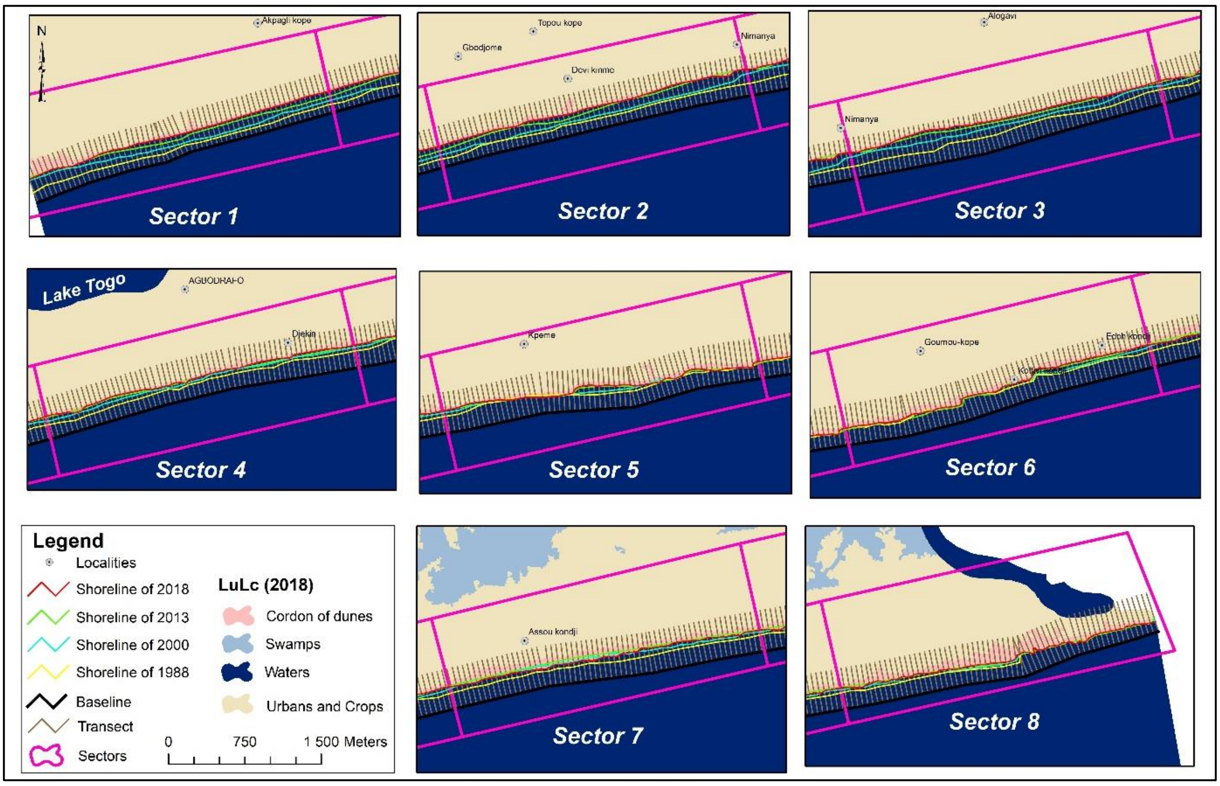



**Figure 4.10: Shoreline Change from 1988 to 2018.**

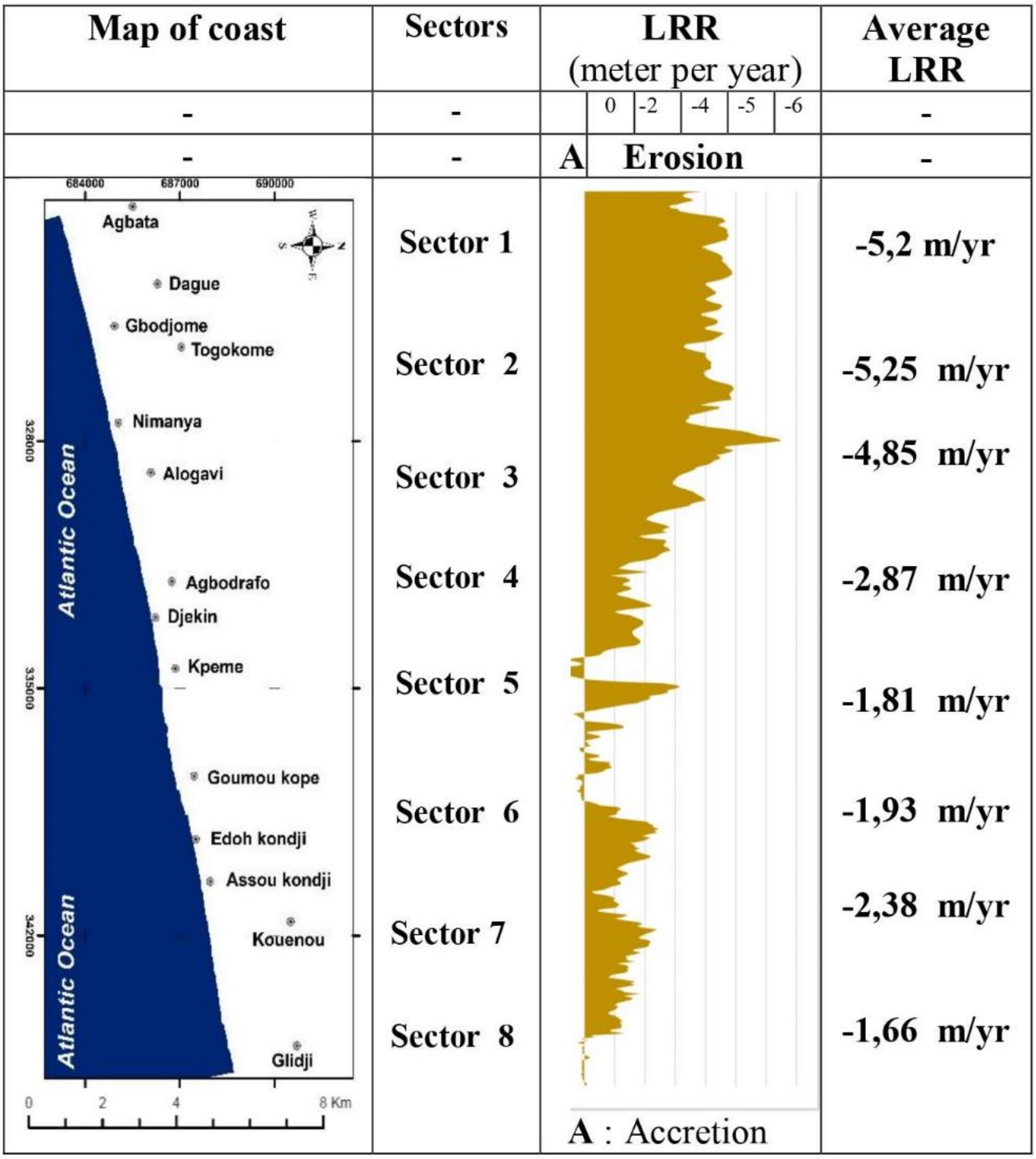



**Figure 4.11: Shoreline Change Statistics for the Period 1988 to 2018 by LRR Methods.**

#### *4.1.3.5 Historical trend of shoreline on the agbata-aflao segment from 1988 to 2018*

The analysis results based on satellite data (Landsat and Sentinel-2) and ground checks, showed that the Agbata-Aflao segment underwent profound variable changes between 1988 and 2018 depending on the sectors (Figure 4.12). These variations are reflected initially by erosion phenomena followed by accumulation or accretion phenomena. An in-depth analysis of the changes using the LRR method made it possible to draw up Table

4.12. It can be seen from Table 4.12 and Plate II that all sectors suffered erosion except sectors C and D which have experienced accumulation phenomena. The erosion rate varies from 2.49 to 5.07 metres per year. The lowest rate is observed around Kodjoviakopé (sector A) while the highest rate is observed around Kpogan (sector H). Although the lowest erosion rate is observed in sector A, the erosion process is very advanced in this sector and the sea is close to the asphalt road. Appropriate measures must be taken in this sector to avoid the immersion of the road by the sea.

Sectors E, F and G show an average erosion rate of 3.00 metres per year; 4.15 metres per year and 4.13 metres per year respectively. Sector B (towards Adawlato) presents a particular case. It records both erosion and accumulation phenomena. Photo 16 is an aerial photograph from 2018 showing this area. Sectors C and D record accumulation phenomena. Sector D is a port area while sector C is an area near the port.

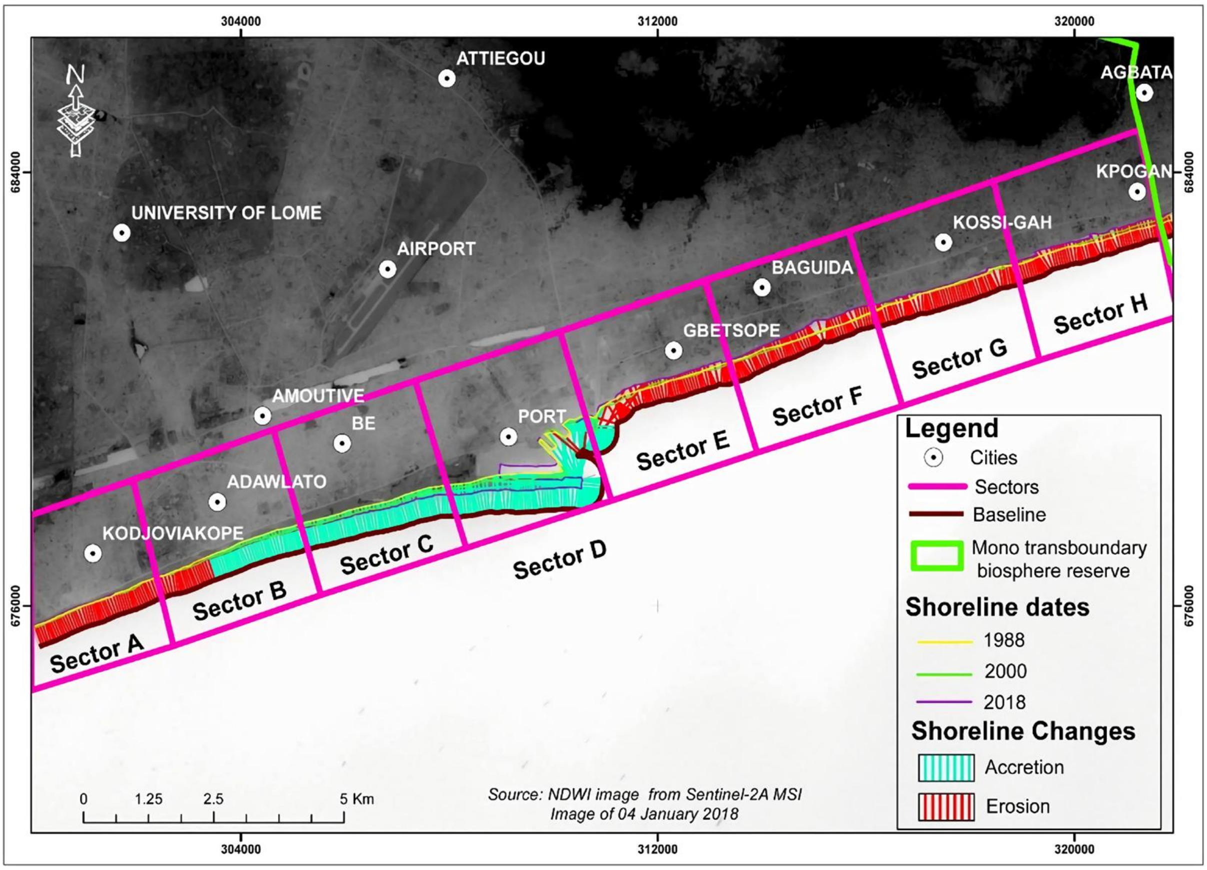



**Figure 4.12: Evolution of the Coastline on the Agbata-Aflao Segment from 1988 to 2018**

**Table 4.12: Coastline Evolution Statistics on the agbata-aflao Segment from 1988 to 2018**

| | Sector A | Sector B | | Sector C | Sector D | Sector E | Sector F | Sector G | Sector H |
|---|---|---|---|---|---|---|---|---|---|
| **Low value (metre per year)** | -3.9 | -3.5 | +1.7 | +1.9 | - | -4.2 | -6.6 | -5.5 | -6.4 |
| **High value (metre per year)** | -1.1 | -1.0 | +2.8 | +2.2 | - | -1.8 | -1.7 | -2.8 | -3.8 |
| **Average (metre per year)** | -2.5 | -2.3 | +2.3 | +2.1 | - | -3.0 | -4.2 | -4.1 | -5.1 |

**Source:** Author’s data analysis (2023)

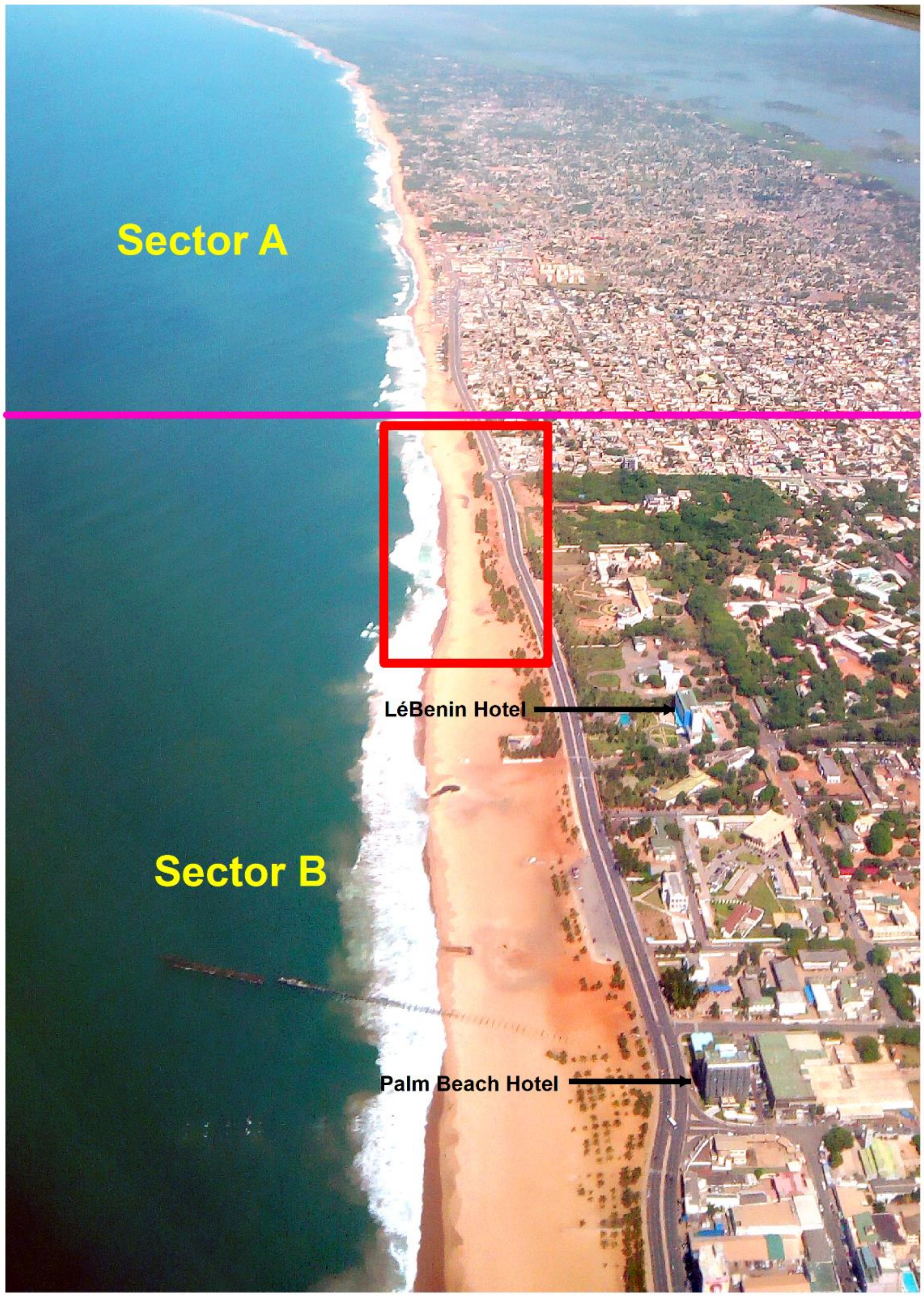



**Plate II: Overview of a Part of Coastal Area of Togo. The Sea is Very Close to the Paved Road in Sector A Because of Coastal Erosion Process. For Sector B, an Eroded Portion is Coloured in Red Showing the Sea Nearby of the Road**

#### *4.1.3.5 Shoreline dynamics on the aneho-aflao segment from 2015 to 2020*

The Togolese coast presents a major asset. It is a centre of stories and offers access points to national and international trade. It also provides subsistence resources through fishing activities, recreational, cultural, tourist, scientific and economic services. The Togolese coast is thus desired for the ecosystem services it provides for the well-being of the populations.

Today, although the coastal zone presents opportunities, it faces the phenomenon of coastal erosion which causes considerable damage to socio-economic infrastructure and profoundly modifies the provision of ecosystem services (Konko *et al.,* 2020). Despite the various government initiatives to remedy it, the phenomenon of coastal erosion remains a major concern (Konko *et al.,* 2018).

From 2015 to 2020, the Togolese coast recorded erosion and accumulation phenomena. Four (04) high coastal erosion zones were recorded respectively in the sectors of Alogavi, Devi-Kinme, Agbavi, and Baguida (Figure 4.13). The figure 4.14 is an illustration of high coastal erosion zones for the period 2015-2020. One (01) high accretion zone was also recorded in the port area from Adawlato towards Be. The rate of erosion remains variable from one area to another. It is on the order of 3 to 5 metres per year. The highest erosion rate is observed at Baguida. Apart from these zones, the phenomenon of erosion is observed at the other portions of the coast but on a low rate.

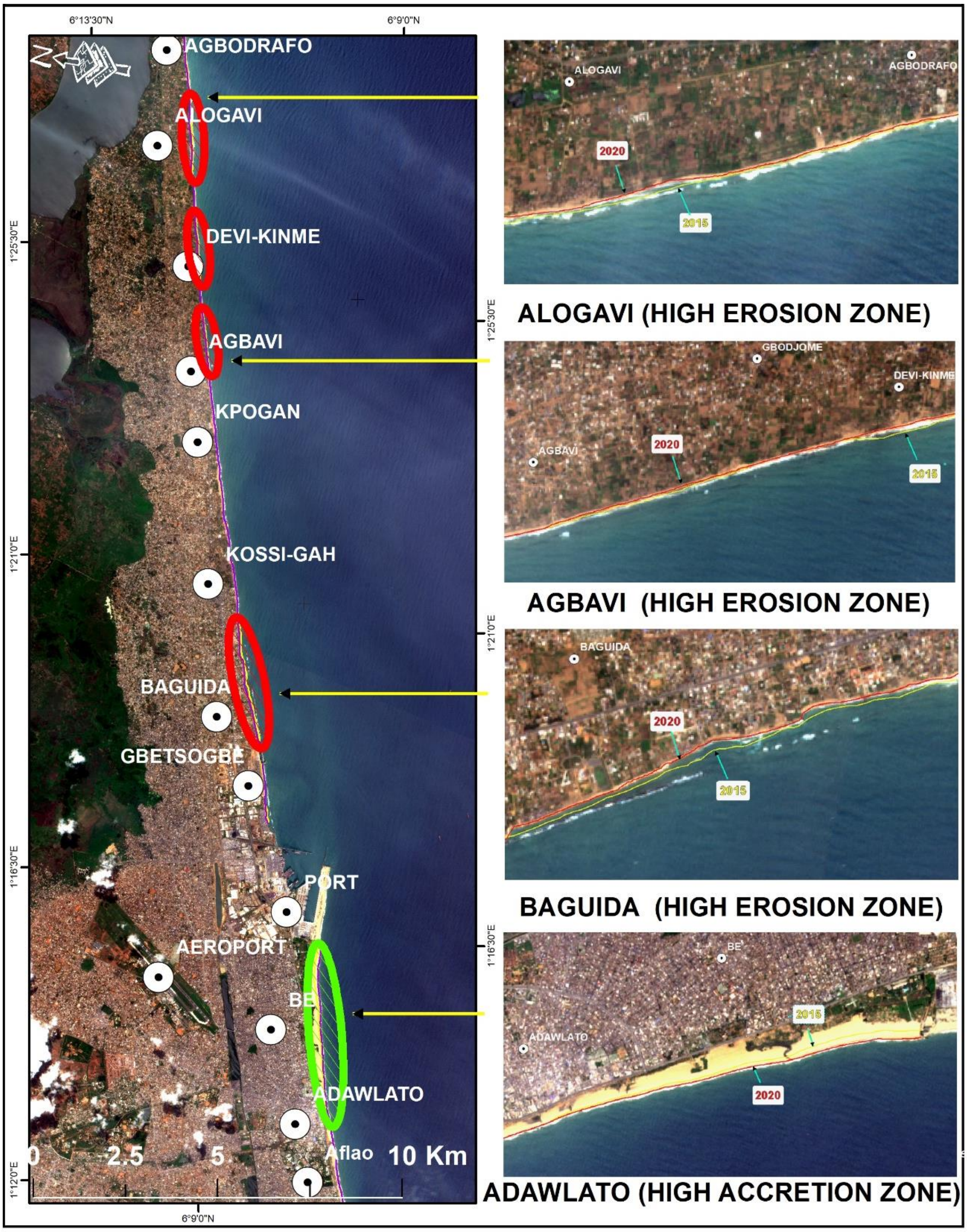



**Figure 4.13: Shoreline Dynamics on the Agbodrafo-Aflao Segment from 2015 to 2020**

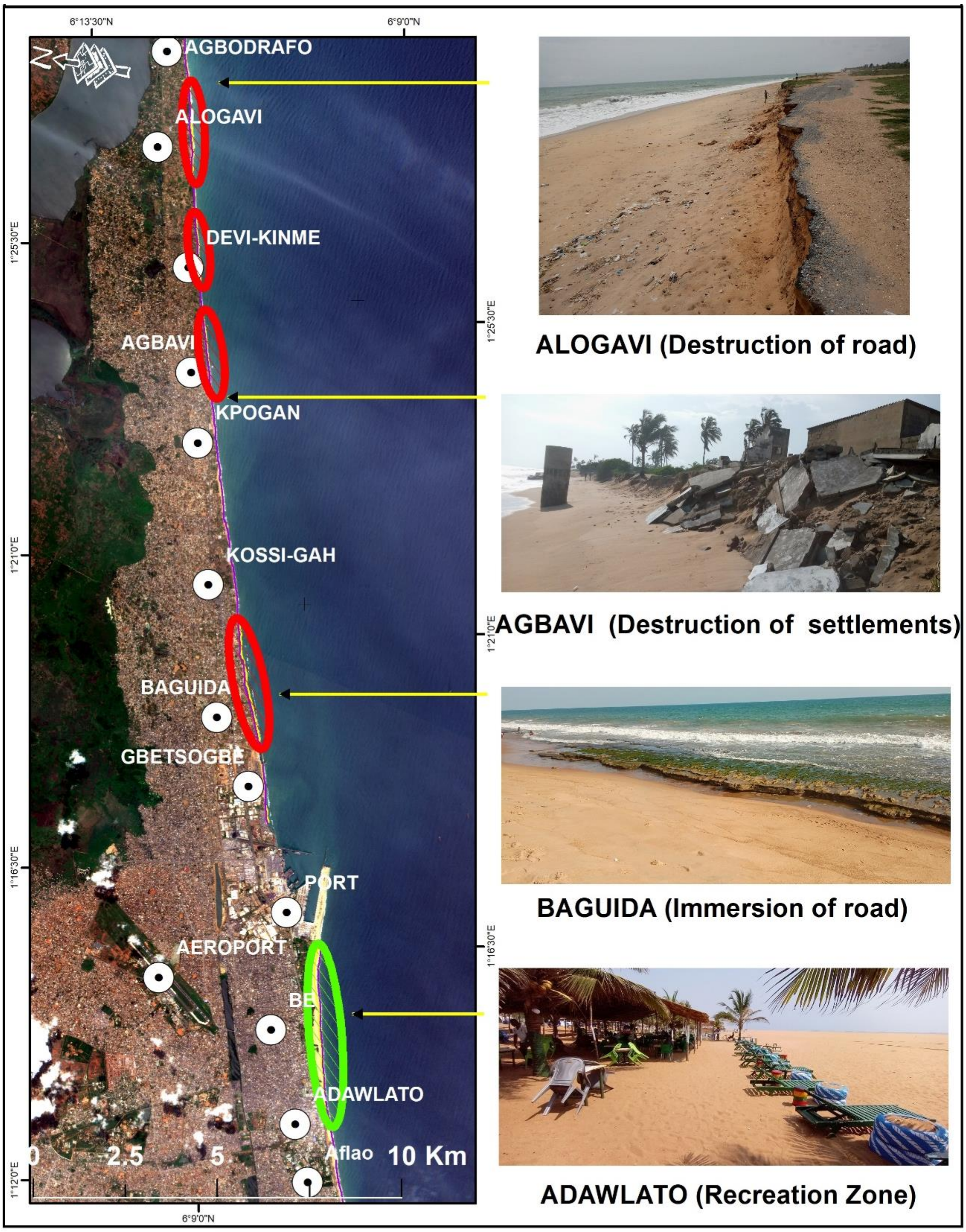



**Figure 4.14: Illustration of Shoreline Dynamics Impacts on the Agbodrafo-Aflao Segment from 2015 to 2020**

### 4.1.4 Togolese coastland's vulnerability model to sea level rise and inundation

The results of the analyses generated Coastal Exposure Index values ranging from 2 to 5 reflecting three types of coastal vulnerability to coastal erosion and inundation (Figure 4.15). High vulnerability is observed on the Baguida-Agbodrafo section, moderate vulnerability is observed in the Adawlato area and Agbodrafo-Aneho section. Finally, the low vulnerability is located in the port area. The plates III, IV and V provide overviews of the high, medium, and low vulnerability coastal zone respectively.

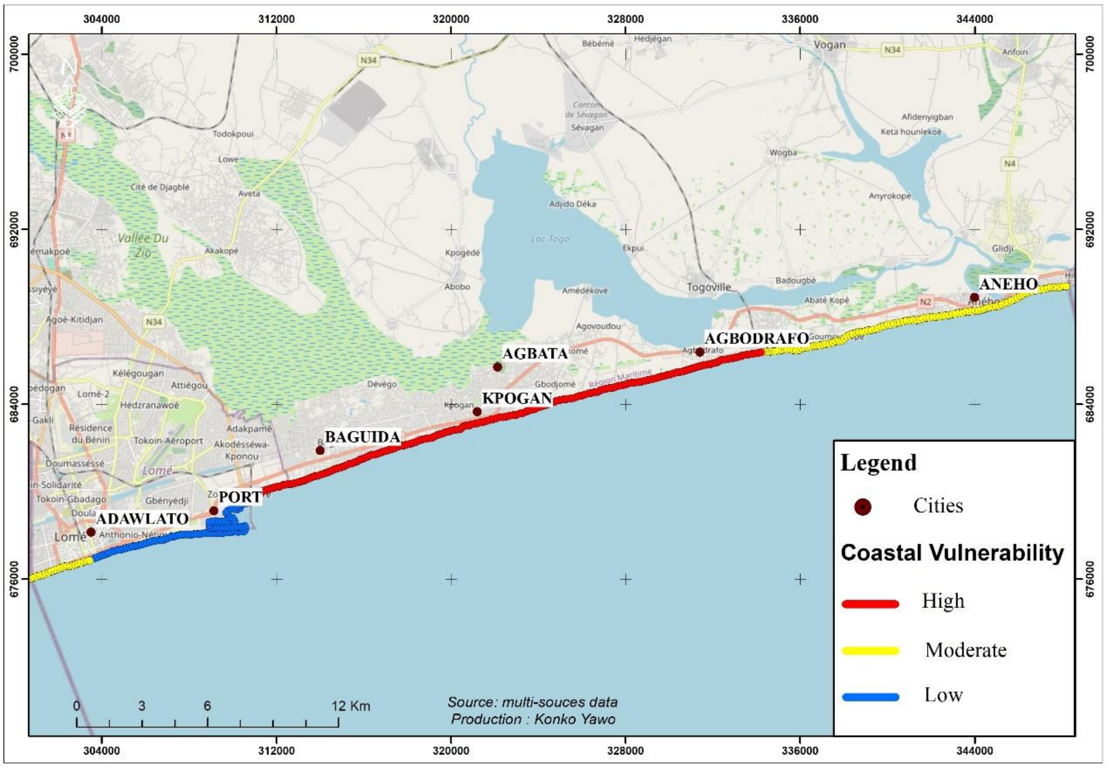



**Figure 4.15: Togolese Coastland's Vulnerability Model to Coastal Erosion and Inundation**

**Plate III: Overview of a Place in the High Coastal Vulnerability Area Around Kpogan Sector**
**Source:** Author's field work (2023)

**Plate IV: Overview of a Place in the Moderate Coastal Vulnerability Over the Section Agbodrafo-Aneho**
**Source:** Author's field work (2023)


**Plate V: Recreation Place in the Low Coastal Vulnerability Area Around a Port Sector**
**Source:** Author’s field work (2023)

According to Togo's National Climate Change Adaptation Plan, with the sensitivity of the Togolese coast, human settlements are vulnerable to the effects of climate change. As impacts, precarious housing and shelters located in low-lying areas could be largely destroyed following flooding, causing material losses and sometimes human lives. Water runoff can also strip the foundations of houses and also wash away dwellings. Floods and high tides will also have serious impacts on road infrastructure and socio-economic facilities, sometimes leading to the isolation of localities. On the other hand, with rising temperatures, living conditions will be more difficult for poor and vulnerable populations (IPCC, 2014).In the health sector, vector-borne diseases such as malaria, which affect children aged zero to five years and pregnant women much more, will be amplified by the floods (IPCC, 2014). As for diseases such as diarrheal diseases including cholera, they will be aggravated by the frequency of floods. The high temperatures will accentuate the prevalence of diseases such as meningitis, cardiovascular and cerebrovascular diseases, respiratory diseases (bronchitis, pneumonia, asthma) which will affect people of all ages (IPCC, 2014). Due to the inadequacy of the rainwater drainage system, the Littoral Zone is vulnerable to heavy rain; indeed, the soils are susceptible to waterlogging, runoff, salinization and drainage. By 2030, the rain forecasts, +10 per cent increase will lead to a situation of flooding throughout the coastal plain, violent flows transporting enough sediments from the Mono and Volta rivers to feed the coastal drift cells. The floods resulting from these rains would affect large areas, including 20 to 35 per cent of the areas usually not flooded, mainly the area of the two cordons (the lower town of Lome between the lagoon and the sea) where 40 to 50 per cent of the populations reside and 80 per cent of industrial and hotel infrastructure and equipment and would be of major magnitude. In addition, coastal erosion will mobilize volumes of sands in the cells.

The 20 kilometres stretch of coast of the Keta – Port of Lome cell will experience hydro-sedimentary activity in favor of the Lome accumulation zone. The sedimentary transit zone from the border, over three kilometres, will be marked by progressive erosion. The current coastal physical oceanographic conditions combined with probable situations (spring tides, storms, SLR) will cause on the coast, between the Port and Agbodrafo, an estimated decline at the 2030 scale of between 160 and 240 metres, and the salinization of watercourses and soils.

### 4.1.5 Strategies to minimize togo's coastland's vulnerability to inundation

#### *4.1.5.1 Content of the existing strategic focus of the master plan for coastal management resilient to climate risks in togo*

In order to improve coastal management, the Togolese government has drawn up several documents, strategies and policies. The most recent concerns the master plan for coastal management resilient to climate risks drawn up in 2021. This master plan is structured in six strategic focus.

Strategic Focus 1: Governance, institutional and legal strengthening. This strategic focus has two strategic objectives. The first objective of this strategy is to improve territorial governance. The second objective is to strengthen the institutional and legal framework. Concerning the first objective of the strategy, it is concretely a question of carrying out the delimitation and the demarcation of the local authorities, of carrying out the cadastre of the zone in the coastal municipalities to identify the plots, strengthening the capacities of the coastal municipalities in particular concerning the acquisition of tools and software for planning and managing the territory of municipalities, on the geo-representation of areas (industrial, residential). For the second objective, it will be necessary to promote a legal framework adapted to the coast, in particular through the adoption of the law relating to the development, protection and enhancement of the coast, the adoption of regulatory texts for the application of the law, to create a regional and local institutional framework for concerted and participatory collective management, to draw up and have adopted the town planning and construction code, to revise the texts of decentralization, in particular the missions of the governorate of Lame, to develop a sea and coastal policy, and finally to create a coastal development and spatial recomposition fund.

Strategic focus 2: Research, knowledge, reinforcement and awareness. Strategic focus 2 has three strategic objectives. The first objective is to support research and build knowledge, the second objective will build capacity in relation to climate change and the third is to strengthen communication around climate change. Concerning the first objective, it is mainly a question of developing academic and fundamental knowledge on the coast and climate change, carrying out additional studies on the fluvio-lagoon system of Lake Togo, carrying out additional studies on the various coastal hazards, Carry out a diagnostic study and adaptation of infrastructures to climate change, carry out a specific study of the mouth of Lake Togo to define suitable facilities to allow its navigability, study the creation of a artificial mouth before Agbodrafo, carry out an aerology study to understand the heat island phenomenon, carry out a regional sediment management plan.

For the second objective, it will be necessary to improve awareness of climate change through research and awareness, Strengthen the human capacities of actors on coastal issues and climate change, set up an information education and communication programme with the first responsible regarding health and disaster aspects, Strengthen coastal surveillance and control capacities in coastal municipalities, set up an internet platform for exchanges and sharing of actors and skills, set up public establishments for inter-municipal cooperation, promote cross-border cooperation to develop, study and develop common areas at risk, integrate the axes of the management plan for the cross-border chenal gbaga ramsar site in the mono basin. Finally, for the third objective, it is necessary to continue the actions of communication, management, and coordination of the littoral in a continuous perspective of the biodiversity and the quality of life of the territory, to reinforce the information, awareness and marine environment education, Strengthen information on risks and the culture of risk and crisis management.

Strategic Focus 3: Sustainable urban planning and development. Strategic focus 3 has four strategic objectives. The first objective is to control urbanization and improve the living environment, promote sustainable mobility, enhance the lagoon system and the seaside, combine coastal hazards with territorial development. Concerning the first objective, it will be a question of developing and implementing urban planning and management tools, making an inventory of the various planning and programming tools and documents existing in the territory, identifying the steps in progress elaboration or those to come that can assimilate the issues relating to climate change, decentralize and train the services in charge of the elaboration of planning documents in the climatic and environmental issues of the territories, set strategic orientations in terms of adaptation to climate change that can be included in planning documents, introduce concrete provisions concerning adaptation to climate change in operational documents and planning regulations, train the services in charge of examining building permits in climate and environmental issues, integrate an architect/planner consultant into the construction permit investigation team, strengthen the cadastral system and carry out addressing, clearly define the vocations of spaces in terms of agricultural spaces, wooded areas, sensitive natural spaces, and prohibit urbanization through to planning documents.

There are also restructure and regularize developed urban fabrics, reclaim urban wasteland, ensure proper management of administrative reserves, create and strengthen public structures such as public land establishments, creation of a regional agency for urban development sustainable, strengthen the means of monitoring and controlling land use, develop an urban corridor to the north of the coastal lagoon system (Vogan, Anfoin, Hahotoé, Aklakou), improve the infrastructure coverage of secondary coastal towns and develop connections, provide secondary towns with structuring equipment (universities, industries, special training centres), develop and implement a waste management plan at the scale of the maritime region, create a wastewater treatment plant, ensure the needs for urban services, socio-collective infrastructure and sanitation, in particular by strengthening major hospital facilities, promoting the installation of sanitary facilities, in particular latrines meeting the demand of the population, reducing precarious housing in coastal areas, improving the supply of decent housing through housing construction programmes, promote forms of housing that consume less space to reinforce urban intensity and the quality of the living environment of populations, develop a development plan for beaches. The second objective will make it possible to promote sustainable mobility, strengthen the road network and improve mobility, develop an urban transport plan on the scale of Lome, improve the supply of public transport, set up a river transport system lagoon area, prioritize the routes and define the associated uses, develop car parks at strategic locations, promote the emergence of a large air hub structured around the

Eyadema Gnassingbe international airport. Pursue the rehabilitation of secondary traffic routes, release interurban routes from local functions, restore and strengthen rail transport. The third objective has the activity of restoring and preserving the hydrographic network, developing and implementing specific development plans for sensitive wetlands, developing and implementing specific development plans for sensitive wetlands, sanitizing, occupying and enhance urban water bodies, initiate and develop the principle of integrated rainwater management in urban areas at different scales, initiate water urban planning projects with pilot projects, in particular for houses on stilts in flood-prone areas , carry out constructions on embankments or even super-dikes in flood-prone areas in a moderate manner, carry out a feasibility study to link the lagoons to lake Togo to facilitate the flow of water and make them navigable with a reopening of the canal at the border to reconnect those of Togo and Ghana, backfill the Zio valley to recover building land from sediments its resulting from the dredging of the old lake Boko by recreating the lake, restoring mainly flood zones their vocation as flood expansion zones, establishing and preserving a 100 m strip of coastline and areas close to the protected shore accompanied by the stabilization of beach slopes.

The fourth objective will make it possible to draw up regulatory documents for the consideration in local planning of the combination of the various land and maritime hazards, to carry out feasibility studies for relocation with communities and voluntary economic structures, to move the issues that do not require proximity to the sea, ensure the relocation of populations, activities and equipment threatened by the effects of climate change, set up a fund for relocation, develop a resettlement action plan for volunteers, identify sites of relocation, carry out environmental and social impact studies of the relocation sites.

Strategic Focus 4: Strengthening protective monitoring and adaptation measures. Strategic focus 4 has two strategic objectives. The first objective is to Continue and strengthen monitoring measures and the second objective is to continue and strengthen protection and adaptation measures. The first objective will make it possible to continue adapting and strengthening road infrastructure, coastal protection and sanitation works. Carry out the rehabilitation project of the Lome-Cotonou road and facilitate transport on the Abidjan-Lagos corridor and coastal protection, Build coastal protection structures on unprotected segments and rehabilitation of existing structures, carry out beach replenishment, particularly in cross-border areas (Ghana/Togo) and in the various compartments, build coastal protection systems to promote the development of seaside activities while protecting the coastline, create a bypass to supply sediment transit at east of the autonomous port of Lome, carry out the project to rehabilitate the Lome-Cotonou road and facilitate transport on the Abidjan-Lagos corridor and coastal protection, build coastal protection works on the unprotected segments and rehabilitation of the works existing structures, carry out beach replenishment, particularly in cross-border areas (Ghana/Togo) and in the various lockers, build coastal protection devices to promote the development of seaside activities while protecting the coastline, create a bypass to supply sediment transport to the east of the autonomous port of Lome.

In addition, build a sand motor in the area, carry out a pilot coastal promenade project combining plant engineering with coastal engineering to improve the living environment and fight against wind erosion, develop a guide on the sustainable management of beaches, use techniques that can limit the surface temperature of pavements and for buildings that can generate short-term heat island effects, develop and implement coastal risk prevention plans and flooding, develop and operationalize a marine pollution prevention plan with the involvement of all institutional actors involved in the coastal area, improve air quality and effluent discharge.

Strategic focus 5: Dynamism and economic diversification. Strategic focus 5 has height strategic objectives. The first objective is to develop employment and improve its territorial distribution. The second objective is to train in trades in the development of the sea. The third objective is to support and organize tourism and develop ecotourism. The fourth is to Structure and develop the craft. The fifth is to support fisheries and aquaculture. The sixth is to create and develop salt and seaweed farming. The seventh objective is to create and develop salt and seaweed farming, and finally the eighth is to consolidate and establish the regional dominance of the autonomous port of Lome, the flagship of the Togolese economy.

Concerning the first objective, it is mainly a question of developing the other cities of the project area and their capacity to accommodate more inhabitants with adequate services, promoting rural employment and the development of activities that do not require proximity to the city, in particular the primary functions (agriculture, poultry farming, fish farming, and fishing) and production. The second objective will make it possible to create high schools and vocational training establishments and maritime and aquaculture colleges.

The third objective will make it possible to organize and structure the existing tourist offer with: The rehabilitation and reinforcement of existing tourist sites, the creation of a museum on the coast, the development of recreational and picnic areas built with removable equipment, the construction of collective play and picnic areas on the coast for the relocation of economic structures, the promotion of light tourist facilities. It will also make it possible to affirm the tourist vocation of the coast (promote the beaches, creation of an international tourist circuit, offer of accommodation and hotels), reinforcing the economic vocation of beaches and promoting seaside tourism (consider the concession of beaches, and/or temporary occupation authorizations for collective purposes, to accommodate and develop seaside and nautical leisure activities), reinforcing the tourism potential of the coast by strengthening its sustainable dimension: initiate and promote ecotourism (Launch an ecotourism design study), develop a charter on tourism and the preservation of the environment, develop motorized and non-motorized water sports and leisure and structure the offer, inventory and promote the visit of places belonging to the cultural and historical heritage (study of rehabilitation of the landing stage of Togo , rehabilitation of the Wood house of the slaves, study of establishment of rustic dwellings and equestrian centre).

The fourth objective promotes the blue economy: develop aquaculture, organization and investment in the fisheries sector. It also makes it possible to promote and organize the development of craft activities, to develop communal activity areas at the level of the chief towns of gulf and lakes communes. The fifth objective makes it possible to create an aquaculture support fund for marine gravel extraction actors in the Gbétsogbé-Kpogan area, train candidates for aquaculture projects and support them, train in pre-salted type farming, support the structuring and diversification of fishing, set up a renewal programme for the artisanal fishing fleet, promote the production of fishery resources through aquaculture and the development of water bodies, carry out a feasibility study of aquaculture on lake Togo, in ponds and on the coast with a view to formulating aquaculture projects, rehabilitate and improve existing aquaculture projects, extend aquaculture projects to other localities (coastal localities located between Alogavi and Goumoukope), create artificial reefs and Restore fish stocks. The sixth objective makes it possible to create a special agricultural zone covering the sensitive agricultural zone between Devikinmè and Alogavi, protect peri-urban agricultural zones and establish urban agricultural zones, develop community agricultural areas on the coast in the areas of Vogan, Anfoin, Afagnan and Aklakou, develop and rehabilitate rural roads to open up agricultural production areas and promote the delivery of products from local agriculture, improve productivity and increase crop yields climate-smart agriculture, build storage, preservation and packaging equipment for horticultural products in Alogavi, support the poultry sector, rapidly complete the existing irrigation schemes nearby, in particular the djagblé plain rural development project, strengthen the irrigation schemes of the development project from the lower mono valley to Agome-Glozou. The seventh objective makes it possible to build and operate sea salt and seaweed production units in the area between Devikeme and Goumoukope.

Strategic focus 6: Preservation, management and enhancement of the environment. This strategic focus recommends the creation of an environmental and coastal police, the creation of marine and terrestrial protected areas. It has four main objectives: Conserve and develop forest potential, support the transition towards controlled and sustainable waste management, restore soils and manage water resources, improve consideration of respect for the environment in quarries and industries. Concerning the first objective, it is mainly a question of materializing the limits of the classified areas, carrying out ecological and landscape developments in the classified forests, developing and implementing forest management and development plans, planting in the areas replenishment of beaches with suitable species, restore mangrove sites by protecting the Gbaga channel, lake zalivé and the Akissa forest, restore mosaic-type mangrove sites, strengthen and promote the creation of community forests of mangroves or other woody species. The second objective makes it possible to develop and implement a territorial strategy for the organization and management of waste at the scale of the project area, improve and consolidate the integrated management system for solid waste, implement a treatment strategy, waste recovery and restoration of sites used as uncontrolled dumps, promote the development of waste recovery channels, continue and coordinate waste clean-up campaigns on the coast and at sea. The third objective makes it possible to restore the soil, promote the installation of a large seawater desalination plant combined with an electricity production plant in the Goumoukope area, deliver drinking water from external resources to the project area from Ghana as part of the cross-border project "Drinking Water Sogakope-Lome", anticipate the urbanization of coastal cities to come through sanitation master plans and urban planning rules integrating climate change in all coastal towns or groups of towns, reinforce the sewerage network of the Lome conurbation, reduce the input of chemical contaminants into the sea to maintain good overall quality of coastal water bodies. The fourth objective makes it possible to ensure and strengthen the monitoring of the implementation of the environmental and social management plans for industries and the various sand quarry operations, redefine the conditions for the operation of sand quarries, identify all existing industries likely to affect the environment or the living environment of populations and carry out environmental audits, restore the sites of former disused quarries.

#### *4.1.5.2 Contribution of the results of this study to existing strategic focus of the master plan for coastal management resilient to climate risks in togo*

The results of this study provide relevant information that can effectively contribute to the implementation of the six strategic focus of the master plan for coastal management resilient to climate risks in Togo. For the strategic focus 1, the results of our study bring new precise information for the improvement of the governance of the coastal zone. Taking into account the necessity of climate data gaps filing, the trend of climatic parameters (precipitation, temperature, wind speed, sunshine and tidal gauge), the coastal peoples dynamics, the hot spot of coastal erosion, the vulnerable areas to SLR and inundation in coastal policies like coastal management plan, coastal hazard risk management plan, coastal strategies and management plans, coastal space planning, development programmes would help the governments to develop an effective adaptation plans to climate change. The policy on adaptation and practice measures will directly be beneficial to the coastal people living along the Togolese coastland communities

Regarding strategic focus 2, the results of our study also provide useful information for research, knowledge, capacity building and awareness of coastal populations. Students and researchers are another set of potential beneficiaries to this study. Students and researchers in universities of Togo, other universities and research institutes may find the result of this coastal study useful for further studies. Researchers and students at the regional and international level are also another set of potential beneficiaries of this study. The result of the study can be useful in revising, refining and extending the frontiers of knowledge. Another category of potential beneficiaries are groups, organizations, governmental and non-governmental organization that may apply the results of the study to improve operational performance and project elaboration.

For strategic focus 3, the results of this study provide useful information for sustainable urban planning and development. Indeed, the results relating to the evolution of the climate, the dynamics of coastal human populations, coastal erosion and the identification of coastal vulnerability zones make it possible to implement the appropriate tools for planning, urban management, the management of the urban environment, the combination of coastal hazards with territorial development and also the enhancement of the lagoon system.

Regarding strategic focus 4, the results of our study also provide precise information for the strengthening of monitoring and adaptation protection measures. Finally, the results of the tide gauge data for SLR, coastal erosion hotspots, and identified areas with high coastal vulnerabilities will be able to guide the choice of construction areas for coastal protection infrastructures and sanitation. They will also enable and strengthen coastal protection and adaptation measures.

For strategic focus 5, the results of this study provide useful information for economic diversification. Indeed, the poles of high population density identified within the framework of this study could be used for the development and diversification of economic activities such as general trade, agriculture, tourism, crafts and fishing.

Regarding strategic focus 6, the results of our study also provide useful information for the preservation, management and enhancement of the environment. Indeed maps of the spatial and dynamic distribution of dwellings can be used for waste and environmental management planning. In addition, these maps will be used to define the perimeters of marine and terrestrial protected areas.

### 4.2 Discussion of Results

The analysis of annual cumulative precipitation data exhibited no significative trend. However, increasing variability was shown. A deep analysis of monthly cumulative precipitation also revealed no significant trends, but variation was observed. Indeed, during the dry season (December, January, February), no variation is observed, while for the other months of the year the variation was slightly increasing, except in the month of April, where it was decreasing. According to the first report on the state of the marine and coastal environment of Togo (MERF, 2022) the distribution of precipitation remains largely in a bimodal configuration on a time scale of 30 years from 1983 to 2013 with an average of 818 millimetres. This value is similar to the Sudano-Guinean zone where rainfall varies from 500 to 900 millimetres (Climate Change, 2014).Compared to the period from 1971 to 2000, which recorded an average precipitation of 730 millimetres, it appears that precipitation in the coastal zone has increased slightly.

The pseudo-unimodal trend only becomes apparent during years of strong climatic anomaly. In fact, although the analyses of precipitation over time show no significant trends, Lome often faces flooding phenomena caused by precipitation and a poor water drainage system. For example, in June 2010 Lome City saw massive exceptional flooding following precipitation which affected approximately 200,000 people (Emergency Health Programme Aids Flood Victims (EHPAFV), 2010). According to Bhattacharya and Lamond (2011), the flooding phenomenon in Lome is essentially linked to poor urban planning, a lack of adequate drainage infrastructure and maintenance and low levels of awareness and education around flood management.

The annual and monthly trend analysis of climatic parameters in the Maritime Region of Togo revealed a significant increase in average temperatures. The increase in temperatures observed at the country scale confirms the trend of global warming. According to the 2021 Emission Gap Report (UNEP, 2021), warming is observed in all countries in the world and will exceed 1.5°C in the next two decades. This phenomenon is mainly caused by greenhouse gas emission. In Lome, there is a high concentration of manufacturing and also a steady flow of cars and motorcycles contributing to greenhouse gases emissions. For this reason, the city of Lome is heating up (Nimon *et al.*, 2020).

For the annual mean wind speed analysis, no significant trends were found, but the variation is increasing. The monthly mean wind speed trend is not significant and shows variation. The variation in wind speed is a factor that could provide a beneficial cooling effect on coastal areas, influencing wave height and swell (Balaka *et al.*, 2021). Regarding the cooling effect of the wind on the coasts, Erhart *et al.* (2022) explain that coastal populations are becoming concentrated near the sea because of its cooling effect in a context of global warming. For wave height, there is a significant correlation between coastal wind speed and wave height (Young and Ribal, 2019). For these authors, the increase in wind speed could increase the movement of waves and lead to flooding of coastal areas. Regarding the swell, it is quite regular on the Togolese coast and is distinguished by an average height of one to 1.5 metres (MERF, 2022). The maximum wave height varies between two and three metres in July, August and September (MERF, 2022). The period of strongest swells is August to September, and the weakest swells (0.4-0.5 metres height) occur from October to November and from May to June (MERF, 2022).

The annual mean sunshine analysis showed decreasing variation with no significant trends. The monthly mean sunshine analysis showed a significant trend at $\alpha = 0.1$ for the months of April and September. For the others months of the year, the trend is not significant but exhibited variation. In the coastal area of Togo, there is a strong feeling of heat and sunshine during the months of April and September (Nimon *et al.*, 2020). During these periods, the coast receives significant daily insolation, and average irradiation reaches levels above 1,700 kilowatt-hours per square metre per year and a daily sunshine duration of 7 to 8 hours (MERF, 2022). Sunshine is also a factor that promotes significant temperature variations between day and night.

The results of the tide gauge data remain a concern. The tide gauge data from Ghana (neighbouring country) was used to illustrate the phenomenon of SLR in Togo. According to the research work of Young *et al.* (2003), proximate tidal gauge data can be used in the absence of data from the area of interest. A series of missing data was also observed for a few years and an adapted methodology (the Mann-Kendall test) for a robust analysis of data with gaps was adopted. The Mann-Kendall test, in reality, is a non-parametric test that does not require a normal distribution of data and has a low sensitivity to unexpected discontinuities caused by non-homogeneous time series.

Apart from the problems related to the use of proximate tide gauge data, the use of a series of data with gaps, and other biophysical factors such as geology, bathymetry and wave flow direction could set a limit on the reliability of the results at the level of the area of interest (Zerbini *et al.*, 2017). Within the framework of this study, Togo and Ghana share the same geomorphological and bathymetric characteristics, helping ensure the reliability of the results obtained from the proximate tidal gauge data (Adjoussi, 2010). However, it is important to fill data gaps in order to better understand climate change at the country scale and at the regional scale. In this study, analysis of the tidal gauge data showed an increasing trend of 13.75 millimetres per year for the period from 1983 to 2012. For the same station, the trend of SLR was 3.32 millimetres per year between 1929 and 1969 according to the centre for Operational Oceanographic Products and Services (https://tidesandcurrents.noaa.gov/). These trends show that SLR is increasing over time.

Coastal erosion is one of the repercussions of SLR. In Togo, research by Konko *et al.* (2020) shows an average erosion rate ranging from 2.49 to 5.07 metres per year. This average erosion rate is lower than the results of Blivi and Adjoussi (2004) in Togo who obtained a regression ranging from 5 to 10 metres per year. The difference observed is justified by a difference in methodological approach. Indeed for this study, the Shoreline was extracted from the NDWI indices of satellite images (Landsat TM, ETM+ and Sentinel-2A MSI) with the SVM algorithm and the kinematics was calculated using the DSAS tool while Blivi and Adjoussi (2004) analyzed Landsat images (MSS and TM) and the methods of calculating of the kinematics are not clearly explained.

The phenomenon of coastal erosion is observed in many West African countries. Indeed, several studies conducted in West Africa show a reduction in the coastal zone (Konko *et al.*, 2018a; Evadzi *et al.*, 2017). West Africa's coastline erosion has advanced, and coastal people are growing more exposed to SLR. According to Nyadzi *et al.* (2020), a rise in sea level of one meter could submerge 194,000 kilometre square of coastal land and displace at least 56 million people in low-income countries around the world. The observed SLR of 13.75 millimetres per year in West Africa remains very worrying and could lead to the displacement of populations as well as damage to socio-economic infrastructure and settlements. According to the IPCC (2014), climate change, SLR and coastal erosion will affect every continent on the planet.

Alongside these phenomena, land in the Togolese coastal region is in high demand and is facing a rapid and irregular expansion of settlements. In fact, near the sea, the pattern of settlement areas is compacted with high population densities. Inland, this pattern is dispersed. This could be explained by the well-being and the cooling effect offered by the sea in a context of global warming. Similarly, around Lake Togo, the rate of population growth is lower. According to Konko *et al.* (2018a) the expansion of settlement areas around Lake Togo is very difficult because of the surrounding floodplains and the spreading of the perimeter of Lake Togo at a rate of 1.55 metres per year. The current settlement patterns of Togo's coastal zone are the result of various geographical and environmental factors including hydro-geomorphological conditions.

The rate of settlement expansion in the Maritime Region was 6.15 hectares per year for the period from 1988 to 2000, 23.41 hectares per year from 2000 to 2015 and 40.16 hectares per year between 2015 and 2020. The rapid expansion of settlements could be explained by the continual population growth of the Maritime Region. In fact, this region is more populated than any other region in the country. According to the last general population census in 2022, the population of the Maritime region is characterised by strong growth. With a population of 3,534,991 people for an area of 6,395 kilometre square, it recorded a density of 553 people per kilometre square in 2022, compared with 407 people per kilometre square in 2010, 163 people per kilometre square in 1981 and 75 people per kilometre square in 1981 in 1960 (INSEED, 2022).

The region's population has quintupled in 50 years, going from 474,133 inhabitants in 1960 to 2,599,955 in 2010 and to 3,534,991 in 2022. The Maritime Region concentrates nearly half (42 per cent) of the national population, which stands at 8,095,498 people (INSEED, 2022). The extension of the region's road network in recent years has also contributed to the emergence of new peripheral towns and the development of the industrial sectors. The number of small agglomerations has multiplied and continues to increase. This rapid population growth is exacerbated by the massive rural exodus of people from neighbouring countries and inland localities to Lome for the economic opportunities provided by the presence of the Atlantic Ocean and the deep-water port.

Population growth in the Maritime Region can also be explained by the attractiveness of the coastal zone. In fact, coastal areas have always attracted people because of their resources, in particular their provision of subsistence resources; for logistical reasons, as they offer access points to shops and transport; for recreational, cultural, scientific and economic services; or simply because of their special sense of belonging at the interface between land and sea (Bruce *et al.*, 2015). For this reason, coastal areas are regarded as special and coveted for their effects on well-being. The habitation of coastal areas has increased considerably in recent decades, and the world's coasts are undergoing enormous socio-economic and environmental changes, a trend that is expected to continue (Neumann *et al.,* 2015). The human habitats of the world's coasts are highly dynamic in nature, changing rapidly in response to natural processes and human activities. Utilisation of the coasts as residential areas is vitally important, with 70 per cent of coastal areas around the world being areas of settlement growth (IPCC, 2014). Most of the world's megacities are located in the low-elevation areas near the sea, and many of them are situated in large deltas (Hens *et al.,* 2018).

The coastal zone of Togo is in high demand, seeing ever-faster population growth while at the same time facing rises in temperature, sea level and coastal erosion. This will result in a rapid increase in the vulnerability of persons and assets to coastal erosion harm. Recent research by Konko *et al.* (2018a) in Togo, shows that coastal erosion is advanced and at the same time the area of urban structures increased at an average rate of 7.84 hectare per year for the period from 1988 to 2018. These authors concluded that the barrier beach with its settlement areas and population is exposed to a continual risk of inundation due to SLR, which may affect more than 7 percent of its surface area by the 2070. Local causes, such as natural and anthropogenic ground subsidence, have the potential to exacerbate the issue (Syvitski and Milliman, 2007).

According to Moriconi-Ebrard *et al.* (2016), almost every large coastal settlement in West Africa has grown in recent years from the city of Abidjan (Ivory Coast) to Lagos (Nigeria) through the cities of Accra (Ghana), Lome (Togo) and Cotonou (Benin). In this coastal axis, the population has increased rapidly and the population density is the highest in the West African region. The coastal countries of West Africa will continue to experience settlement expansion and strong demographic growth, which will induce significant intra-regional migratory flows. Taking into account the necessity of filling gaps in climatic data, the analysis of climatic trends, coastal population dynamics, coastal erosion hotspot and coastal vulnerability to SLR and inundation in coastal policies like coastal management plans, coastal hazard risk management plans, coastal strategies and management plans, coastal space planning and development programmes will help the governments of West African coastal nations to develop effective plans to adapt to climate change.

# CHAPTER FIVE

# 5.0 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

This study contributes to the assessment of the extent of climatic characteristics, spatial distribution and dynamics of coastal peoples, coastal erosion kinematics, and coastal susceptibility to SLR and inundation in the maritime region of Togo located in West Africa. Satellite images (Landsat and Sentinel-2 images), population data, field data, geospatial data and Ground Climatic data in particular, precipitation, temperature, wind speed, sunshine, tidal gauge for the period from 1988 to 2020 were used. Climate trend analysis was performed using the Mann-Kendall test and Sen's slope test, while settlement area mapping was completed using the Object-Based Image Analysis approach.

The shoreline was extracted by Support Vector Machine algorithm on Normalized Difference Water Index generated from satellite images and the kinematics was evaluated using the statistical LRR available in the Digital Shoreline Analysis System. To assess coastal vulnerability to SLR and inundation, the InVEST Coastal vulnerability model was utilised. Temperature and SLR showed a substantial annual trend, according to the findings. The temperature analysis showed an increase of trend of 0. 038 °C per year while the tidal gauge data analysis showed an increase of trend of 13.75 millimeters per year. The other annual climatic parameters trend record variability which are not significant. However, the monthly analysis revealed the months of the year in which the trends are significant.

Statistical analysis of settlements dynamics shows that settlement areas which has a population of 2,599,955 in 2010 have changed from 2. 06 per cent to 11. 85 per cent between 1988 and 2020. The corresponding annual expansion rate is 6. 15 hectares per year for the period of 1988-2000; 23. 41 hectares per year for the period of 2000-2015 and 40.16 hectares per year for the period 2015-2020. In addition, near the sea, the pattern of settlement areas is compacted with high density of peoples. In the inland this pattern is dispersed. For the kinematics of the shoreline, the Togolese coast has an average erosion rate ranging from 1.66 to 5.25 metres per year. Four high coastal erosion zones were recorded respectively on the transect of Alogavi, Devi-Kinme, Agbavi, and Baguida. One high accretion zone was recorded in the port area towards Adawlato. For Coastal vulnerability model, High vulnerability is observed on the Baguida-Agbodrafo section, moderate vulnerability is observed in the Adawlato area and Agbodrafo-Aneho section, the low vulnerability is located in the port area.

The results allowed to conclude that the coastal areas of Togo are very coveted by peoples and registering an increasing trend of the settlement areas and people and at the same time are vulnerable and facing the rise in temperature, SLR and coastal erosion. It is recommended to use these finding at local scale in coastal policies like coastal management plan, coastal hazard risk management plan, coastal strategies and management plans, coastal space planning, development programmes to develop an effective adaptation plans to climate change at country scale.

### 5.2 Recommendations

This study provides decision-support tools needed for the adaptive management of the coastal human habitats. Furthermore, the findings of this study will aid the government in policy development. The policy on adaptation and practice measures will directly be beneficial to the coastal people living along the Togolese coastland communities. Another category of policies are coastal planning policy, state planning framework policy, environment and natural resources policy, coastal water resources policy, coastal urban growth and settlement policy, natural hazards and disasters policy that may use the results of the study to improve coastal management. Additionally, students and researchers are another set of potential beneficiaries to this study. Students and researchers in University of Lome, University of Kara, other universities and research institutes may find the result of this coastal study useful for further studies in coastal policies improvement. Researchers and students at the international and regional level are also another set of potential beneficiaries of this study. The result of the study can be useful in revising, refining and extending the frontiers of knowledge.

Based on the findings of the study and conclusion drawn, it is recommended to use the results as guidelines for strategic planning for climate risk prevention in coastal area. This will also serve as a foundation for future, more comprehensive climate studies in Togo and the West African coastal region. In addition, the finding can be used to incorporate coastal people distribution and dynamics into every planning, design, operation in coastal area. Also, it is necessary to incorporate coastal erosion hotspot and coastal vulnerability model into every planning, design, operation in coastal area. Furthmore, future research should explore the daily climate trend analysis in the Togolese coastal area to improve the climate adaptation policies. This will facilitate a robust climate risk management. It is also recommended to install tidal gauge infrastructures on Togolese coast in order to allow the availability of data for sea level rising analysis.

This study discovered that Togo's coastline zone will be vulnerable to SLR. The study's findings are likely to be used by key stakeholders to build long-term planning for the coastal management. This will restrict construction in high-risk locations, such as coastal erosion hotspots. The government must support the relocation of infrastructure and new facilities to safer places. Steps should be taken to strengthen coastal communities' physical and socioeconomic resilience in the face of rising sea levels. The Ministry of Trade and Industry should encourage the growth of sustainable industries and facilitate the transfer of firms within the country.

Furthermore, coastal populations should be encouraged to embrace nature-based solutions to counteract the effects of SLR, such as educating communities on the maintenance and restoration of natural barriers including mangrove forests, salt marshes, and dune systems. These habitats offer important protection from erosion, storm surges, and flooding.

This study focus on the extent of climate change, coastal population dynamics, coastal erosion hotspots, coastal area vulnerability to SLR and inundation. For climate trend, the study used monthly and annual data. Further studies will be important on the daily climate trend in coastal area. In addition, it is suggested further studies on environmental and socio-economic factors influencing the coastal erosion. It is also suggested the research investigation on the impact of coastal erosion on human habitats. The further research is also suggested on the relationship between coastal climate trend and coastal people dynamics. Finally, future studies are suggested to examine the potential climate risk in the future.

### 5.3 Contribution to Knowledge

Some new findings on the vulnerability of coastal areas to climate change have been added. Based on the results, the temperature trend is significant at $\alpha = 0.001$, while the SLR shows a significant annual trend at $\alpha = 0.05$.The temperature analysis showed an increase in trend of 0. 038 °C per year, while the tide gauge data analysis showed an increase in trend of 13.75 millimetres per year. The analysis of monthly sunshine showed significant trends with $\alpha = 0.1$ in April and September. According to the statistical analysis of settlement dynamics, the maritime region of Togo, which had a population of 1,042,385 in 1980, experienced a population increase between 2.06 per cent and 11.85 per cent between 1988 and 2020. The corresponding annual growth rate is 6.15 ha per year from 1988 to 2000, 23.41 ha per year from 2000 to 2015 and 40.16 ha per year from 2015 to 2020. In 2022, the maritime region will have a population of 3,534,991 people. In addition, the pattern of settlement areas near the sea is dense, with a high population density. Inland, this pattern is dispersed. In terms of coastal kinematics, the Togolese coast has an average erosion rate of between 1.66 and 5.25 metres per year. According to the findings, land in Togo's coastal zone is in great demand, the rate of settlement is increasing, and temperatures and sea levels are rising.

The key strength of this study is the use of local climate data for monthly and annual climate trend analysis in Togolese coastal area. Another strength is the use of high satellite resolution images for settlement areas mapping. Furthermore, this study has the advantage of locating coastal erosion hotspots and coastal locations that are particularly vulnerable to sea-level rise and inundation. Therefore, the research findings could be helpful for decision making and urban planning and managing capacity.

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# APPENDICES

## Appendix A: Data of Annual Cumulative Precipitation (mm)

| Year | Annual Cumulative Precipitation (mm) |
|---|---|
| 1989 | 1131.1 |
| 1990 | 630.8 |
| 1991 | 1032.3 |
| 1992 | 489 |
| 1993 | 675.7 |
| 1994 | 657.9 |
| 1995 | 786.7 |
| 1996 | 825.3 |
| 1997 | 910.5 |
| 1998 | 442.6 |
| 1999 | 889.3 |
| 2000 | 423.9 |
| 2001 | 681.3 |
| 2002 | 803.3 |
| 2003 | 876.4 |
| 2004 | 1065.8 |
| 2005 | 784.6 |
| 2006 | 962.5 |
| 2007 | 1024.8 |
| 2008 | 1075.3 |
| 2009 | 875.7 |
| 2010 | 1416.7 |
| 2011 | 888.1 |
| 2012 | 859 |
| 2013 | 700 |
| 2014 | 866.1 |
| 2015 | 658.5 |
| 2016 | 651.1 |
| 2017 | 756.6 |
| 2018 | 840.4 |
| 2019 | 1300.1 |

**Appendix B: Data of Annual Mean Temperature (°C)**

| Year | Annual Mean Temperature (°C) |
|---|---|
| 1989 | 27.24 |
| 1990 | 27.50 |
| 1991 | 27.37 |
| 1992 | 27.28 |
| 1993 | 27.35 |
| 1994 | 27.31 |
| 1995 | 27.90 |
| 1996 | 27.82 |
| 1997 | 27.72 |
| 1998 | 28.43 |
| 1999 | 27.76 |
| 2000 | 27.97 |
| 2001 | 28.03 |
| 2002 | 28.00 |
| 2003 | 28.23 |
| 2004 | 28.06 |
| 2005 | 28.16 |
| 2006 | 28.35 |
| 2007 | 28.28 |
| 2008 | 28.27 |
| 2009 | 28.29 |
| 2010 | 28.75 |
| 2011 | 28.34 |
| 2012 | 28.03 |
| 2013 | 28.33 |
| 2014 | 28.31 |
| 2015 | 28.36 |
| 2016 | 28.57 |
| 2017 | 28.44 |
| 2018 | 27.99 |
| 2019 | 28.62 |

**Appendix C: Data of Annual Wind Speed (meter per second)**

| Year | Wind Speed (meter per second) |
|---|---|
| 1989 | 2.92 |
| 1990 | 3.50 |
| 1991 | 2.92 |
| 1992 | 2.75 |
| 1993 | 2.67 |
| 1994 | 2.33 |
| 1995 | 2.25 |
| 1996 | 2.67 |
| 1997 | 2.67 |
| 1998 | 3.08 |
| 1999 | 2.67 |
| 2000 | 2.50 |
| 2001 | 2.67 |
| 2002 | 2.50 |
| 2003 | 2.50 |
| 2004 | 2.42 |
| 2005 | 2.83 |
| 2006 | 2.67 |
| 2007 | 2.42 |
| 2008 | 2.25 |
| 2009 | 2.50 |
| 2010 | 3.50 |
| 2011 | 3.33 |
| 2012 | 3.42 |
| 2013 | 4.08 |
| 2014 | 3.08 |
| 2015 | 2.92 |
| 2016 | 3.67 |
| 2017 | 2.75 |
| 2018 | 3.33 |
| 2019 | 2.75 |

**Appendix D: Data of Annual Sunshine (hours and tenths)**

| Year | Sunshine (hours and tenths) |
|---|---|
| 1989 | 6.07 |
| 1990 | 6.64 |
| 1991 | 5.94 |
| 1992 | 5.86 |
| 1993 | 6.58 |
| 1994 | 6.03 |
| 1995 | 6.59 |
| 1996 | 6.33 |
| 1997 | 6.22 |
| 1998 | 6.71 |
| 1999 | 6.34 |
| 2000 | 6.63 |
| 2001 | 6.31 |
| 2002 | 6.10 |
| 2003 | 6.38 |
| 2004 | 5.88 |
| 2005 | 6.13 |
| 2006 | 6.23 |
| 2007 | 5.73 |
| 2008 | 5.71 |
| 2009 | 6.40 |
| 2010 | 6.13 |
| 2011 | 6.51 |
| 2012 | 6.26 |
| 2013 | 5.88 |
| 2014 | 6.13 |
| 2015 | 6.23 |
| 2016 | 5.73 |
| 2017 | 5.71 |
| 2018 | 6.40 |
| 2019 | 6.13 |

**Appendix E: Overview of the Attribute Table of the Housing Map for the Year 1988**

**Year : 1988**

| FID | OBJECTID | DN | Code | Area (kilometre square) |
|---|---|---|---|---|
| 0 | 1 | 1754 | 1 | 0.11427522 |
| 1 | 2 | 1800 | 1 | 0.2033559 |
| 2 | 3 | 1815 | 1 | 0.46159991 |
| 3 | 4 | 1931 | 1 | 0.38061747 |
| 4 | 5 | 2219 | 1 | 0.11337542 |
| 5 | 6 | 2506 | 1 | 0.12237346 |
| 6 | 7 | 2693 | 1 | 0.46339952 |
| 7 | 8 | 2747 | 1 | 0.15206703 |
| 8 | 9 | 2756 | 1 | 0.0917801 |
| 9 | 10 | 2757 | 1 | 0.12057385 |
| 10 | 11 | 2770 | 1 | 0.11247561 |
| 11 | 12 | 2788 | 1 | 0.3869161 |
| 12 | 13 | 2800 | 1 | 0.14396878 |
| 13 | 14 | 2805 | 1 | 0.11607483 |
| 14 | 15 | 2826 | 1 | 0.15566624 |
| 15 | 16 | 2832 | 1 | 0.18625961 |
| 16 | 17 | 2844 | 1 | 0.11607483 |
| 17 | 18 | 2934 | 1 | 0.16736371 |
| 18 | 19 | 3027 | 1 | 0.13946976 |
| 19 | 20 | 3030 | 1 | 0.14126937 |
| 20 | 21 | 3065 | 1 | 0.11877424 |
| 21 | 22 | 3215 | 1 | 0.10167795 |

## Appendix F: Overview of the Attribute Table of the Housing Map for the Year 2000

Year : 2000

| FID | OBJECTID | DN | Code | Area (kilometre square) |
|---|---|---|---|---|
| 0 | 1 | 2210 | 1 | 0.09627913 |
| 1 | 11 | 585 | 1 | 0.21415359 |
| 2 | 19 | 1126 | 1 | 0.215953191 |
| 3 | 20 | 1280 | 1 | 0.09447952 |
| 4 | 23 | 1711 | 1 | 0.146668196 |
| 5 | 25 | 1812 | 1 | 0.179960999 |
| 6 | 26 | 1863 | 1 | 0.178161356 |
| 7 | 27 | 1873 | 1 | 0.127772282 |
| 8 | 28 | 2132 | 1 | 0.099878356 |
| 9 | 31 | 2372 | 1 | 0.102577759 |
| 10 | 34 | 2602 | 1 | 0.156566048 |
| 11 | 36 | 2627 | 1 | 0.242947311 |
| 12 | 37 | 2705 | 1 | 0.180860813 |
| 13 | 38 | 2711 | 1 | 0.362621353 |
| 14 | 40 | 2735 | 1 | 0.163764506 |
| 15 | 41 | 2738 | 1 | 0.311332471 |
| 16 | 44 | 2948 | 1 | 0.156566081 |
| 17 | 48 | 3129 | 1 | 0.222251814 |
| 18 | 51 | 3781 | 1 | 0.199756685 |
| 19 | 52 | 3792 | 1 | 0.254644764 |
| 20 | 53 | 3903 | 1 | 0.168263516 |
| 21 | 54 | 3907 | 1 | 0.220452198 |

## Appendix G: Overview of the Attribute Table of the Housing Map for the Year 2015

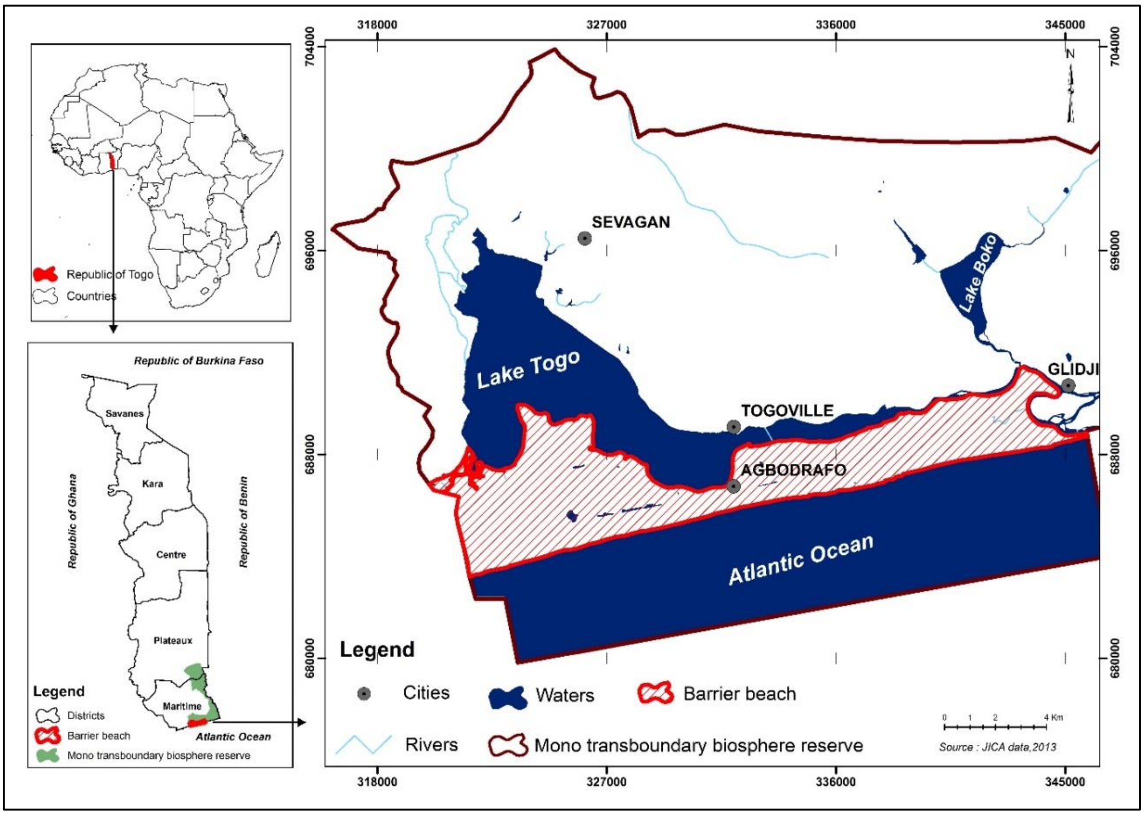
**Year : 2015**

| FID | OBJECTID | DN | Code | Area (kilometre square) |
|---|---|---|---|---|
| 0 | 1 | 4462 | 1 | 0.01899873 |
| 1 | 2 | 4488 | 1 | 0.01149923 |
| 2 | 3 | 4525 | 1 | 0.01969869 |
| 3 | 4 | 4527 | 1 | 0.03279782 |
| 4 | 5 | 6044 | 1 | 0.01089928 |
| 5 | 6 | 6508 | 1 | 0.01209919 |
| 6 | 7 | 6510 | 1 | 0.02339843 |
| 7 | 8 | 6604 | 1 | 0.02569829 |
| 8 | 9 | 6638 | 1 | 0.02199854 |
| 9 | 10 | 6648 | 1 | 0.01259916 |
| 10 | 11 | 6712 | 1 | 0.03189787 |
| 11 | 12 | 6723 | 1 | 0.03169789 |
| 12 | 13 | 6746 | 1 | 0.01869875 |
| 13 | 14 | 6758 | 1 | 0.01439903 |
| 14 | 15 | 6763 | 1 | 0.01229919 |
| 15 | 16 | 6769 | 1 | 0.02619825 |
| 16 | 17 | 6787 | 1 | 0.01169922 |
| 17 | 18 | 6801 | 1 | 0.03329778 |
| 18 | 19 | 6802 | 1 | 0.01309913 |
| 19 | 20 | 6834 | 1 | 0.01699886 |
| 20 | 21 | 6844 | 1 | 0.02179855 |
| 21 | 22 | 6849 | 1 | 0.01609893 |

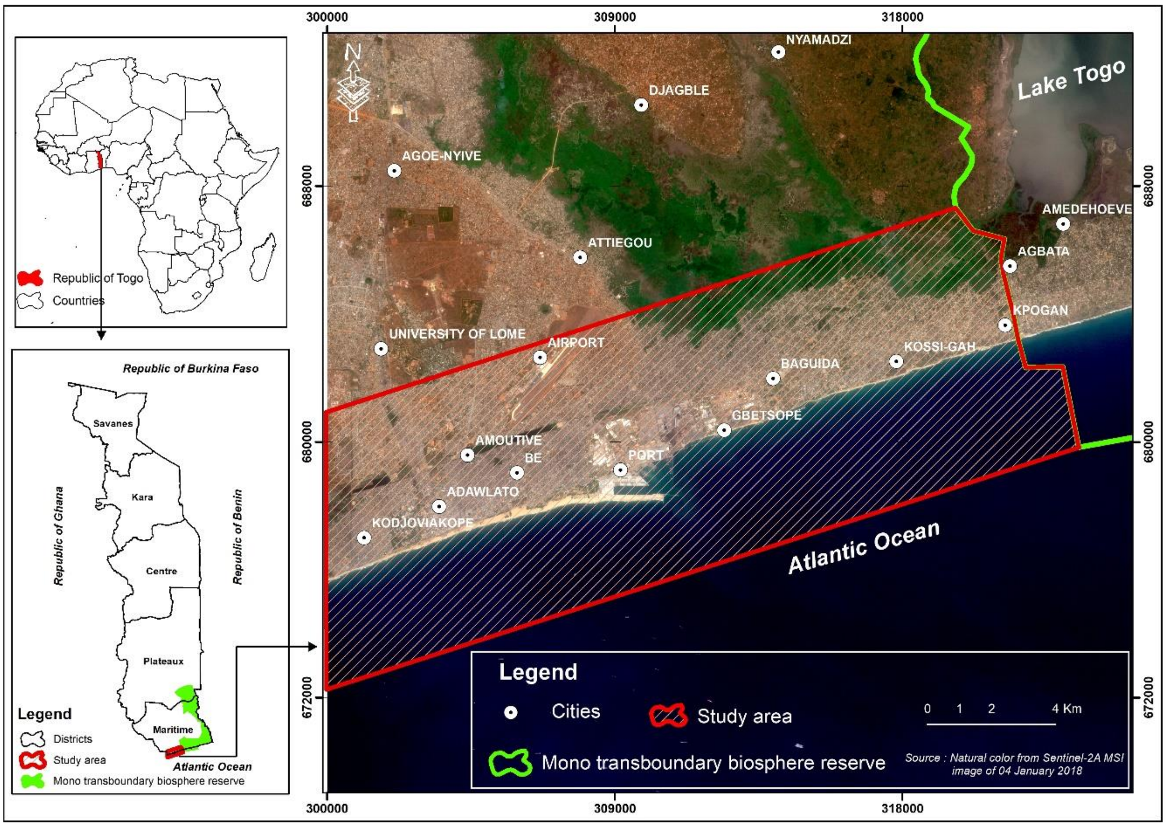
**Appendix H: Overview of the Attribute Table of the Housing Map for the Year 2020**

| | | Year : 2020 | | |
|---|---|---|---|---|
| **OBJECTID_1** | **DN** | **Code** | **OBJECTID** | **Area (kilometre square)** |
| 1 | 85 | 1 | 0 | 0.018698746 |
| 2 | 141 | 1 | 0 | 0.017598828 |
| 3 | 155 | 1 | 0 | 0.024598355 |
| 4 | 159 | 1 | 0 | 0.017598821 |
| 5 | 205 | 1 | 0 | 0.022698477 |
| 6 | 209 | 1 | 0 | 0.022498493 |
| 7 | 232 | 1 | 0 | 0.049496701 |
| 8 | 233 | 1 | 0 | 0.023798407 |
| 9 | 252 | 1 | 0 | 0.02289848 |
| 10 | 269 | 1 | 0 | 0.027398168 |
| 11 | 316 | 1 | 0 | 0.073095112 |
| 12 | 326 | 1 | 0 | 0.023998396 |
| 13 | 329 | 1 | 0 | 0.02079861 |
| 14 | 335 | 1 | 0 | 0.011399246 |
| 15 | 336 | 1 | 0 | 0.020598623 |
| 16 | 931 | 1 | 0 | 0.014499039 |
| 17 | 936 | 1 | 0 | 0.017198863 |
| 18 | 1005 | 1 | 0 | 0.03859741 |
| 19 | 1183 | 1 | 0 | 0.014399037 |
| 20 | 1192 | 1 | 0 | 0.035397643 |
| 21 | 1202 | 1 | 0 | 0.01689888 |
| 22 | 1483 | 1 | 0 | 0.037197508 |
| 23 | 1564 | 1 | 0 | 0.032797823 |
| 24 | 1653 | 1 | 0 | 0.020598622 |
| 25 | 1728 | 1 | 0 | 0.027698145 |
| 26 | 2628 | 1 | 0 | 0.017298845 |
| 27 | 2680 | 1 | 0 | 0.044197034 |
| 28 | 2743 | 1 | 0 | 0.018198785 |

## Appendix I: Geographic location of the Segment from Aneho to Agbata



**Appendix J: Geographic location of the Segment from Agbata to Aflao**



## Appendix K : Interface of InVEST Tools for Coastal Vulnerability Assessment