



GSJ: Volume 9, Issue 1, January 2021, Online: ISSN 2320-9186

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## Coastal Vulnerability Assessment of Saint-Louis /Senegal to Sea Level Rise

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### Abstract

Sea level rise is one of the most certain effect of global warming with serious consequences on coastal ecosystems and local communities. The physical impacts are obviously related to such disasters as coastal erosion, inundations and displacement of low lands like deltas and estuaries. Estuarine ecosystems are both subject to marine and fluvial dynamic; they are endowed with rich biological diversity but actually facing disastrous effects of climate change (inundation, coastal erosion, and salinization) and anthropogenic activities (infrastructures and over exploitation of resources). This study is aimed at assessing vulnerability of Saint-Louis (Senegal River estuary) through the Coastal Vulnerability Index model and GIS based analysis. It involved the combination of a set of both physical and geological variables. Physical factors include the geomorphology of the area, shoreline change rate and coastal slope while geological parameters were more or less related to sea level rise, tidal range and wave height. Data were acquired from different sources: geomorphologic information was provided by extensive literature review and onsite direct observation; coastline change analysis from 1978-2018 was done using Landsat images (Multispectral Sensor: Landsat 1, 2, 3), TM (Thematic Mapper: Landsat 4 and 5), ETM+ (Enhanced Thematic Mapper: Landsat 7) and OLI and TIRS (Operation Land Imager/ Thermal Infrared Radiation: Landsat 8) and the Digital Shoreline Analysis System; while coastal slopes were extracted from an SRTM (Shuttle Radar Topography Map) of 1 Arc-Second Global Elevation Data (30m resolution) obtained from USGS platform. However, geological data from 2008-2018 were acquired from NOAA (National Oceanographic and Atmospheric Administration) and UHSLC (University of Hawaii Sea Level Center). The Coastal Vulnerability Index model was used in this study. Results show that 25.98% of the coast was at low vulnerability, 1.49% at moderate while

42.9% of the shoreline was classified as high vulnerability and 29.58% as very high vulnerability. Given these outputs, the study also examined adaptation strategies and measures put in place by local communities and authorities to face coastal disasters.

Key Words: Estuary, Erosion, Coastal Vulnerability, Adaptation,

## **Study Background**

Vulnerability has been defined as the variable propensity of a given society to undergo damages arising from the manifestation of a natural or anthropogenic phenomenon (D'Ercole 1994). In this context the concept is defined as "vulnerability in the broad sense" as opposed to the more strict and applied sense. Therefore, vulnerability of communities and human activities to natural hazards or environmental problems is a significant phenomenon of what is today recognized as a "risk society" (Beck, 2001) or a vulnerable society (Fabiani, Theys, 1987), where the IPCC assimilated it to "The degree to which a system is susceptible to, and unable to cope with the effects of climate change, including climate variability and extremes. Vulnerability is function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity". The Earth Summit (Rio de Janeiro, June, 1992) marked the rise of awareness about climate Change and its repercussions Worldwide. Nowadays, there is scientific consensus, based on an overwhelming body of evidence, that global climate is changing. In coastal areas Climate change is expected to result in a rising sea level and increase of the frequency and the intensity of extreme weather events with significant impacts on coastal communities and ecosystems.

In West Africa, the main concerns of coastal areas stem from the degradation of biodiversity and coastal habitats, due to pollution, seawater intrusion and coastal erosion. In addition, the construction of dams leads to a reduction in the volume of fresh water and decrease in sediments likely to be discharged toward the coast. Senegal is a West African country widely open to the Atlantic Ocean with 700km of coastline. This area is structured around the Cape Verde peninsula and three mouths represented by the Senegal River, the Sine Saloum and the Casamance which form estuarine environments with very rich and varied ecosystems. However, this coastline is increasingly subject to anthropogenic pressure and other natural phenomena such as sea level rise, erosion, salinization, degradation of natural habitats. The Senegal River estuary runs through the flat and quasi flooded region of Saint-Louis, and separated from the ocean by the "Langue de Barbarie" Sand strip of about thirty kilometers stretching from north to south of Saint-Louis, from the Mauritanian border to the mouth of the Senegal River. The Langue de Barbarie constitutes the main buffer area with the Atlantic and is housing since centuries the conservative fishermen communities of Guet-Ndar and

## Goxxumbacc.

Today the future of the Langu de Barbarie is quite uncertain because of ecological disturbances with huge degradation of natural habitats and infrastructures emanating from sea level rise and resulting coastal erosion and flooding. Based on the examination of old maps, a decline of 4000 m from the coast of the Langu de Barbarie to the right of St. Louis was noted between 1660 and 1922 with a corresponding rate of 15 m per year (Barbey, 1967). From 1856-1926, measurements made from benchmarks showed a beach retreat of St. Louis of about 125 m in 70 years (Guilcher and Nicolas 1954), corresponding to an average annual decline of 1.8 m. In 1975 a beach retreat of 1,2m had been recorded while this rate shifted to 3,2m in 1989 (DEEC, 2005). “The city is already subject to significant risk of river flooding, which would intensify with sea level rise, impeding the outflow of river water into the ocean such that by 2080, 80 percent of the city could be submerged annually” (World Bank, 2013). According to (Dia,2000), the high degree of vulnerability of the city of Saint-Louis can be mainly attributed to extensive low lying coastal area, high population density, high rate of coastal environment degradation. Serious erosion has been observed on a local scale. Some elderly people of the local communities mentioned that the beach used to be much wider when they were young. Since the opening of the new mouth in 2003, the lower estuary is often subject to serious erosion disturbing the ecological system and inducing both loss of human settlements and economic assets as experienced by the populations of the village Doun Baba Dieye. In 1994, the advancing sea and flooding caused displacement of the village “Keur Barka” to the present site. Today, the original site is occupied by mangroves. According to (Kane.C 2010), 8 houses had been abandoned to the sea in 2007, the following year; more damages had been recorded in about 10 houses, in 2009; 3 houses uprooted by the sea and the number shifted to 20 houses destroyed and about 52 families displaced or relocated in 2010. Despite various interventions or logistics, real solutions or mitigation measures are yet to be felt while the situation is worsening. However, the majority of studies carried out so far in Saint-Louis were mostly based on deterministic approaches aimed at quantifying coastal erosion using Non Rectified Arial Photographs, Cadastral Maps as well as Topographic and socioeconomic surveys. Till now there is no evaluation of the physical or socioeconomic vulnerability of Saint-Louis to sea level rise even if in 2006, Senegal launched its *National Adaptation Plan to Climate Change* aimed at identifying vulnerabilities and needs of urgent and effective adaptations measures to Climate Change with particular attention given to coastal areas. This study arise then from the need of analyzing and mapping vulnerability of the Senegal River estuary (Saint-Louis) by proposing a newer approach based on the CVI model.

## Methodology

### Study area

Our study area concerns the locality of Saint-Louis or *Ndar* in Wolof. Former capital of the Senegalese French colony from 1673 to 1902, Saint Louis is located along the northwest coast of Senegal. The Senegal River estuary is located over there and specifically covers the geographical area between the Diama dam and the sandy sprit of langue de Barbarie, the end of which marks the position of the mouth of the Senegal River. It is a potentially rich area with varied ecosystems and diverse economic activities subject to the influence of particular hydrological factors, including the mix up of fresh and saline marine waters.

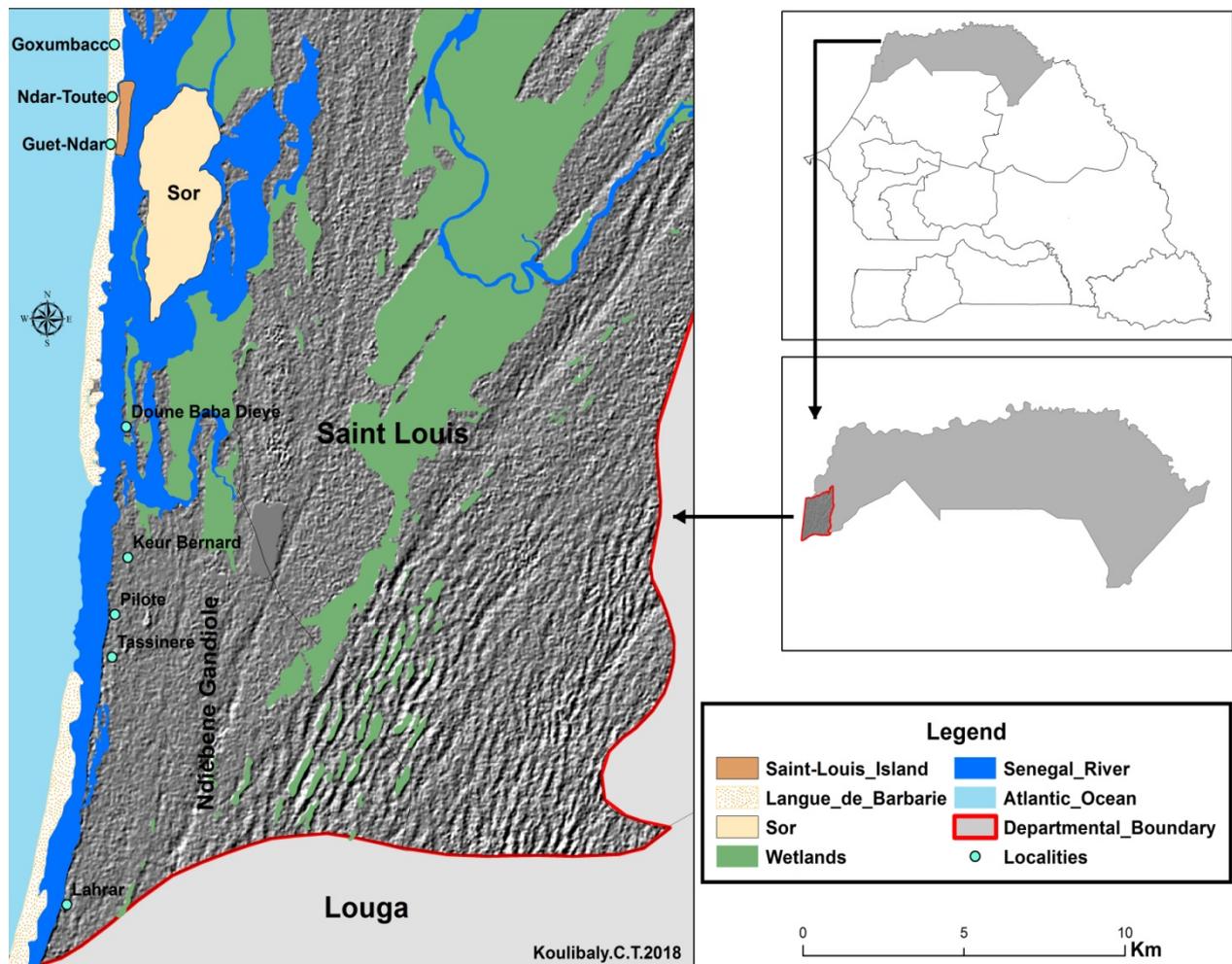


Figure 1: Location of Saint-Louis and coastal localities

The relief is made up of sand dunes and depressions which formerly constituted drained valleys. The coastal morphology is globally represented by recent white sand dunes dated from the sub-current to present (2,000 to 1,800 BP). These deposits, also known as coastal dunes or living dunes, are characterized by their mobility strongly influenced by the littoral drift. They are north-south oriented and parallel to the coast. The Langue de Barbarie sand strip is totally made up of these white dunes of 200 m to 400 m widths and forms a line

between the ocean and the Senegal River (Seye, 2005). The vegetation is poorly developed and mainly represented by halophil species thanks to the coastal environment. The area is also marked by moderate temperatures with maximums around 28 ° C in July and August and minimums of 18 ° C from November to February (Sall et al. 2011). Like the whole country, Saint-Louis is subject to the alternation of a rainy season from July to September and a dry season from October to June. However in this particular area of the country, rainfall rarely exceeds 350 mm per year with a recent observed decrease due to climatic disturbances. *Wolofs*<sup>1</sup> tribes mainly “*Lebous*<sup>2</sup>” fishermen are the major dwellers of Saint-Louis and occupy the Northern and populated part of the Languedoc de Barbarie; *Fulas*<sup>3</sup> and *Moors*<sup>4</sup> are also represented in the area; they are usually farmers and livestock breeders located in the lower estuary so called the Gandiolais. Economically, fishing and agriculture remain the major traditional activities since independence (1960). Widely opened to the Atlantic Ocean, Saint-Louis houses the third largest fishing harbor in Senegal and plays a key role in food security and economy generating. Categorized Unesco Site in 2000, the locality is of huge tourism potential because it preserved remarkable colonial architecture illustrated by the variety of colors of old buildings including alternation of wooden and iron balconies with the decorated doors and windows frames and the double-pitched roofs covered with red tiles. Moreover, the area is also hosts amazing estuarine landscape attracting several species of migratory birds and marine turtles.

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<sup>1</sup> Wolofs are an ethnic group located in Senegal, The Gambia, and Mauritania. In Senegal, close to 44% of the population declare themselves Wolof. This tribe, made of farmers, fishermen and traders mainly occupies the northwestern regions of Senegal.

<sup>2</sup> Assimilated as a sub-group of the Wolof tribe, the Lebous a community mainly concentrated in the Cape Verde peninsula (Dakar) since 1430, they are also located throughout the Northern coast of Senegal. They are traditionally fishermen although a minority also practices agriculture.

<sup>3</sup> Fulas or Fulani are ethnic groups located in more than twenty West African countries. Predominantly nomad herders, their mobility favored exchanges and interbreeding with other populations.

<sup>4</sup> Originated from the Western Sahara regions, moors are mainly established in the northern regions of Senegal. Livestock breeding is their main activity.



Plate 1: Environment of Saint-Louis with Colonial Buildings, Faidherb Bridge, fishing activity and the Lower estuary

### **Data Acquisition**

This study on coastal vulnerability involved the analysis and combination of various data acquired from diverse sources. Both primary and secondary information were used. The primary information was acquired from the field through visits, interviews, onsite observation, GPS mapping and photographs.

The secondary information mainly concerned geospatial data as:

- Digital elevation models/ topographical maps such as SRTM (Shuttle Radar Topography Map) of 1 Arc-Second Global Elevation Data (30m of resolution). The SRTM was mainly used to extract elevations and slope values for the completion of our study.
- Satellite Landsat imageries of different dates: 1978, 1988, 1998, 2008, and 2018 by MSS (Multispectral Sensor: Landsat 1, 2, 3), TM (Thematic Mapper: Landsat 4 and 5), ETM+ (Enhanced Thematic Mapper: Landsat 7) and OLI and TIRS (Operation Land Imager/ Thermal Infrared Radiation: Landsat 8) from the United States Geological Survey platform were also used to extract shorelines and then run shoreline change analysis using DSAS (Digital Shoreline Analysis System) in Arcgis10.1.

Date of acquisition	Sensor	Resolution (m)	Path/Row	Cell size(m)	Coordinate system/Datum	Zone
1978-06-19	LANDSAT_3/MSS	60	221/49	60/60	UTM/WGS84	28
1988-03-01	LANDSAT_4/TM	30	205/49	30/30	UTM/WGS84	28
1998-02-26	LANDSAT_5/TM	30	205/49	30/30	UTM/WGS84	28
2008-01-29	LANDSAT_7/ETM+	30	205/49	30/30	UTM/WGS84	28
2018-01-16	LANDSAT_8/OLI	30	205/49	30/30	UTM/WGS84	28
2014-23-09	SRTM	30	-	30/30	UTM/WGS84	28

Table1: Details of Landsat and DEM used in the study

-The last set of information was about the geomorphology of the area as well as geological parameters such as sea level rise, the tidal range and wave height. The information on the geomorphology of our study area was provided by an extensive literature review and onsite observation while oceanographic information were generously obtained and calculated from such platforms as (National Oceanographic and Atmospheric Administration) and UHSLC (University of Hawaii Sea Level Center).

### Data Analysis

The determination of the coastal vulnerability index both required a statistical and geospatial analysis of obtained data. Quantitative and deterministic approaches of coastal hazards assessment are widely used in mapping physical vulnerability of coastal areas. These methods are mainly based on direct and deterministic quantification of how the coast will be eroded and / or flooded under a given assumption of a sea level rise. However, it is important to emphasize that coastal systems are too complex to be modeled deterministically over time; where the need of multi-criteria approaches leading to the assessment of physical vulnerability based on a number of indicators: geomorphology, topography, oceanography, etc. The coastal vulnerability index is a multi-criteria model proposed and used for the first time by Gornitz (1990, 1991) in the study of the physical vulnerability of US coasts to sea level rise. It involves a numerical and cartographical approach used in the classification of different sections of the coastline in term of potential damages emanating from climate change. This study is based on a CVI model developed by Thieler & Hammar-Klose (1999) and similar to that used by Gornitz (1994) which involved the combination of six key variables that influence the coastline evolution of a designated area:

- The Geomorphology of the area

- The Coastal Slope
- The Relative Sea Level Rate
- The Shoreline Rate Rates changes(Erosion/Accretion)
- The Mean Tidal Range
- The Significant Waves Height

Each of these Variables is given risk values and each value is assigned to a particular scale ranging from 1 (Very Low) to 5 (Very High) as described in the table below:

<b>CVI Ranking</b>					
	Very Low	Low	Moderate	High	Very High
Variable	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts, fiords, fiards	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary , Lagoon	Beach barriers ,Sand Beaches Salt Marsh, Mud flat, Delta, Mangrove, Coral reefs
Coastal Slope (%)	> 0.2	0.2 - 0.07	0.07 - 0.04	0.04 - 0.025	< 0.025
Relative Sea level change (mm/year)	< 1.8	1.8 – 2.5	2.5 - 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/accretion (m/yr)	>2.0	1.0 - 2.0 Accretion	-1.0 - +1.0 Stable	-1.1 --2	< -2 Erosion
Mean tide range (m)	>6	4.1 - 6	2.0 - 4	1.0 – 1.9	< 1.0
Mean wave height (m)	< 0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	> 1.25

Table 2: CVI Ranking (Thieler & Hammar-Klose 1999)

All of these information items are incorporated in a GIS data base and assigned to the concerned coastline; the calculation was done through ArcGis statistical tool. The CVI provides by a quantitative estimation of the physical vulnerability given by the following formula:

$$CVI = \sqrt{(a \times b \times c \times d \times e \times f) / 6},$$

Where:

- Geomorphology of the area
- Coastal Slope (%)

- c. Relative Sea Level Rate (mm/year)
- d. Shoreline Rate changes : Erosion/Accretion (m/year)
- e. Mean Tidal Range (m)
- f. Significant Waves Height (m)

The calculation and mapping of the CVI needed to build a strong GIS data base putting together all variables in an attribute table. These CVI variables were differently analyzed:

**-The Geomorphology:** the geomorphology of the area was analyzed through extensive literature review. It was mainly focused on studies on the Langue de Barbarie sand strip and based on the geomorphological classification scale of the CVI model.

**-Coastal Slope: It involved the GIS analysis of an SRTM** (Shuttle Radar Topography Map) of 1 Arc-Second Global Elevation Data (30m of resolution) acquired from the United States Geological Survey platform. The SRTM was projected in UTM (Universe Transverse Mercator), ZONE 28N referred to the WGS 84 (World Geodetic System 1984) and slopes were extracted through the “Spatial analyst tool” of ArcGis10.1 and expressed in percentage (%). The slope analysis was also focused on the whole Langue de Barbarie sand sprit and then classified and mapped at the convenient scale showing the areas with gentle slopes and those with steep slopes before being assigned and joined to the coastline for CVI calculation. Finally, an area analysis was also done using “zonal statistics as table” tool which provided and calculation of areas (Ha) occupied by each slope value across the study area.

**-Relative Sea Level Rise:** Sea level rise was estimated from fast delivery data of the tidal gauge of Dakar acquired from UHSLC (University of Hawaii Sea Level Center) through its station 223. These data mainly involved hourly and daily tides excel sheets from 2008 to 2018. After verification, daily, monthly and then annual means were calculated using Excel and a trend has been determined to estimate sea level rise through linear regression function ( $y= ax + b$ ).

**-Shoreline erosion and accretion:** the most critical stage of the study, was calculated from 1978 to 2018 and were analyzed and mapped using satellite Landsat imageries of different dates: 1978, 1988, 1998, 2008, and 2018 through the Digital Shoreline Analysis System (DSAS) in Arc Gis 10.1. Composites were created and images were geometrically verified before extracting coastlines using land/water interface detection techniques. In this study, unsupervised and supervised classification was used to create from composites a binary image of 2 classes (land and water) showing clear separation of immersed and emerge bodies. The raster image was then converted into vectors and shorelines were extracted through digitizing

process. Coastlines from different dates were then put together and then transects were built and change rate calculated from DSAS using the LRR (Linear Regression Rate) as calculation method. The annual Error (E) was finally determined using the following formula elaborated by (Hapke et al., 2006) based on landsat imaged uncertainties and time:

$$E = \frac{\sqrt{d_1^2 + d_2^2}}{T}$$

Where  $d_1$  and  $d_2$  represent the estimated uncertainties of

the different Landsat images and T is the time (years) elapsed between images. In this study, the annual Error (E) ranges from  $\pm 1.8$  to  $\pm 2.2$  m/year.

**-The Mean tide range:** The mean tide was also calculated using the fast delivery tidal data provided by UHSLC through its station 223 from 2008-2018. The tidal range was then determined from the calculated annual tidal means by the difference between extreme maximum and extreme minimum water level.

**-Mean Wave Height:** wave heights ( $H_s$ ) of 2008-2018 were extracted from WW3 (Wave watch 3) model acquired from NOAA (National Oceanographic and Atmospheric Administration). Daily data were provided in Grb2 format and extracted through XyGrib-1.2.6 software and conserved in excel sheets before being combined together and sent into ArcGis 10.1 statistical tool for mean weight calculation and graph generation.

## Results and Discussion

The results of our multiple analyses are presented for each variable and then finally combined to provide the CVI of our study area.

### Geomorphology

The coastal geomorphology of the Senegal River estuary is mainly characterized by a Sand strip of about 30 Km length called Langu de Barbarie generally made of white colored sand dunes system that took place after the Nouackchottien marine transgression. These dunes stand between the sandy beach and the semi fixed dunes located inland. These formations bear sandy soils called “raw intake soils”, composed of material resulting from a mixture of quartz and limestone. According to Nicolas (1953) this sand strip is geomorphologically divided into 3 different zones: a maritime zone or external shore under the influence of marine dynamics dominated by erosion process; a intermediary stable wind turbine zone (high beach and vivid coastal dunes) under the influence of the wind; a fluvial zone or internal shore dependent on fluvial dynamics where sedimentation is more felt. The morphological dynamic is driven by the phenomenon of erosion and sedimentation. Marine dynamics play a key role

in the construction and erosion of the coastline. In fact, approximately 600,000m<sup>3</sup> of sand are brought annually to the southern end of the Langue de Barbarie (Kane, 1997). Fluvial inflows shape the internal shore by erosion phenomena, especially during flood periods, this erosion being today more significant depending on the retention of the Diama dam (Kane, 1997). It is also important to emphasize that the estuary is also occupied in some of its part by mangrove ecosystems but at a limited scale because of their actual state of degradation mainly due to hydrological disturbances since the erection of the Diama dam. According to the coastal vulnerability index of geomorphological variables our study area can be ranked 5 meaning “very High Risk”. Even if it is an estuary, it is essentially made of sandy beaches and some mangrove swamp forest including salt marshes.

<b>CVI Ranking</b>					
	Very Low	Low	Moderate	High	Very High
	1	2	3	4	5
<b>Geomorphology</b>	Rocky, cliffed coasts, fiords, fiards	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary, Lagoon	Beach barriers, Sand Beaches Salt Marsh, Mud flat, Delta, Mangrove, Coral reefs

Table 3: CVI ranking of geomorphological variable of the study area

### Coastal Slope

Coastal slopes were extracted from a Digital Elevation Model (Shuttle Radar Topography Map) of 1 Arc-Second Global Elevation Data (30m of resolution) and analyzed in 2 ways: the first one involved a global analysis of slopes across the Langue de Barbarie sand strip based on surfaces (Ha), the second one was focused on the main beach and based on the length by spatially joining slope values to the coastline.

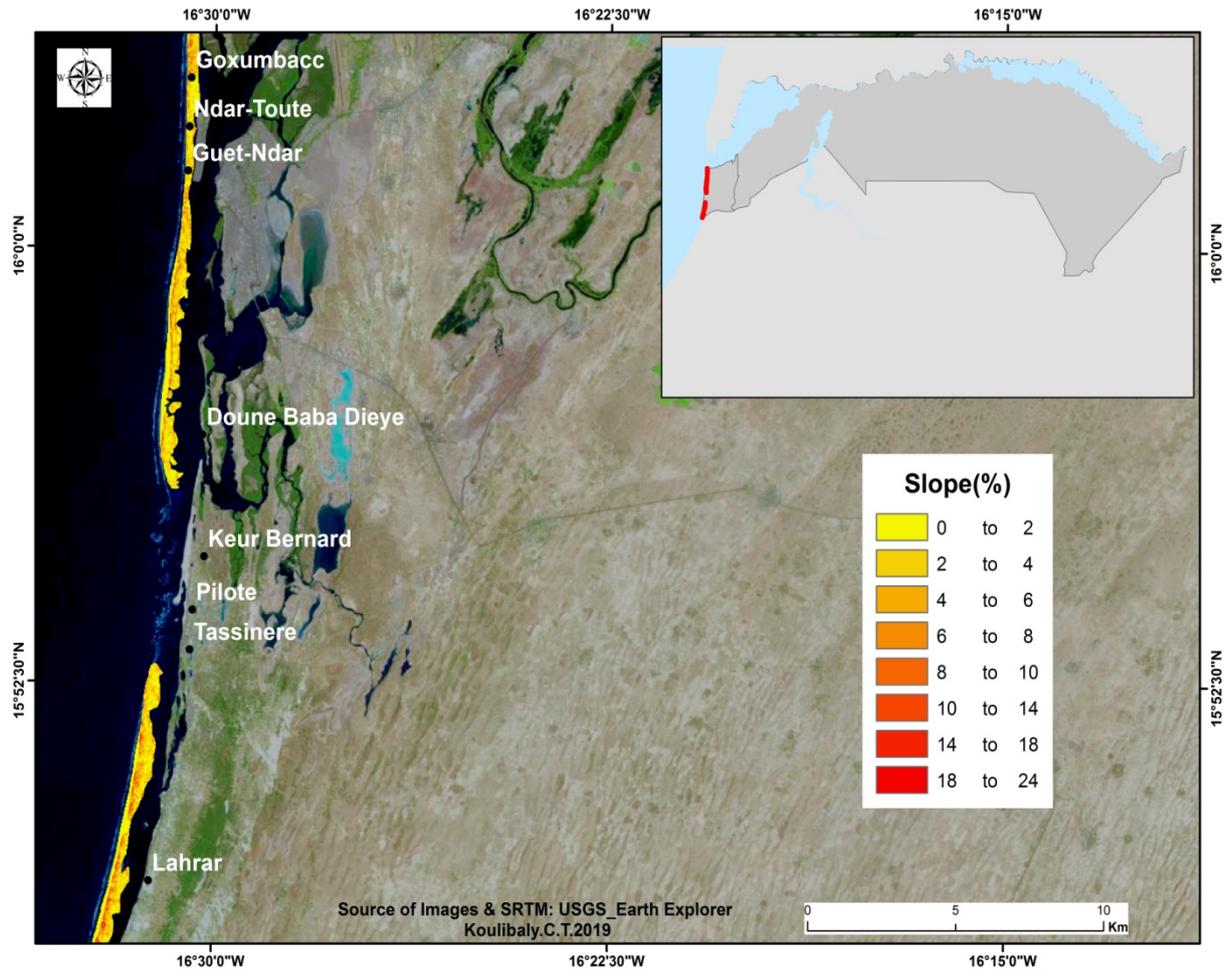


Figure 2: Spatial distribution of slope across the “Langue de Barbarie”

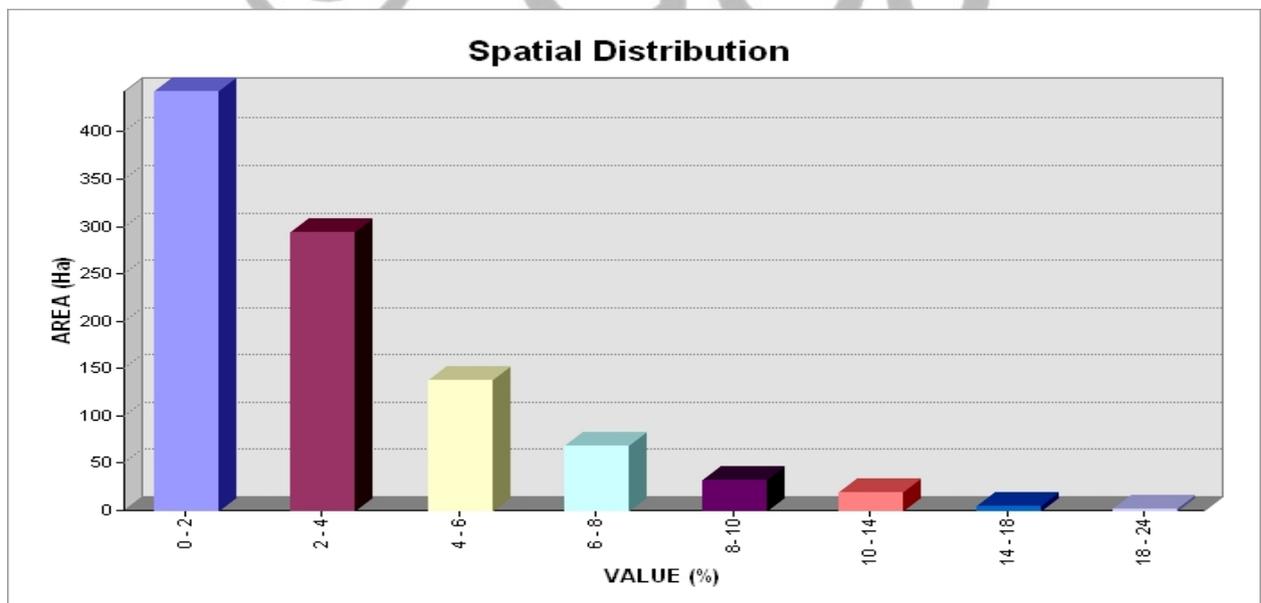


Figure 3: Spatial variation of slopes values across the “Langue de Barbarie”

Figure 2 and 3 show the global distribution of extracted and classified slope values throughout the Langue de Barbarie Sand strip. It reveals that more than 442.62 Ha of the area is occupied by slopes of 0-2 %, 293.67 Ha by slope values of 2-4%, 136.98 Ha surfaces of 4-6% slopes and 68.49 Ha occupied by slope ranging from 6-8 % while values from 8-10%, 10-14%, 14-

18% and 18-24% respectively occupy 31.86 Ha, 19.44 Ha, 3.96 Ha and 0.81. This situation attests the flatness of Saint-Louis where gentle slopes globally occupied close to 94% of the total area.

Toward the main beach, the spatial join of slope value to the coastline revealed that 19.130 km of the coastal length is occupied by the value 0%, 1.570 Km by 1%, 0.883 Km by 2% and 8.022Km by values beyond 2%. This shows in percentage that in the main beach, 64.6% of the coastline is level (slope value of 0%) attesting that the majority of the coastline is at high risk.

### Relative Sea Level change

Relative sea level change was calculated from Dakar tidal gauge observations from 2008-2018.

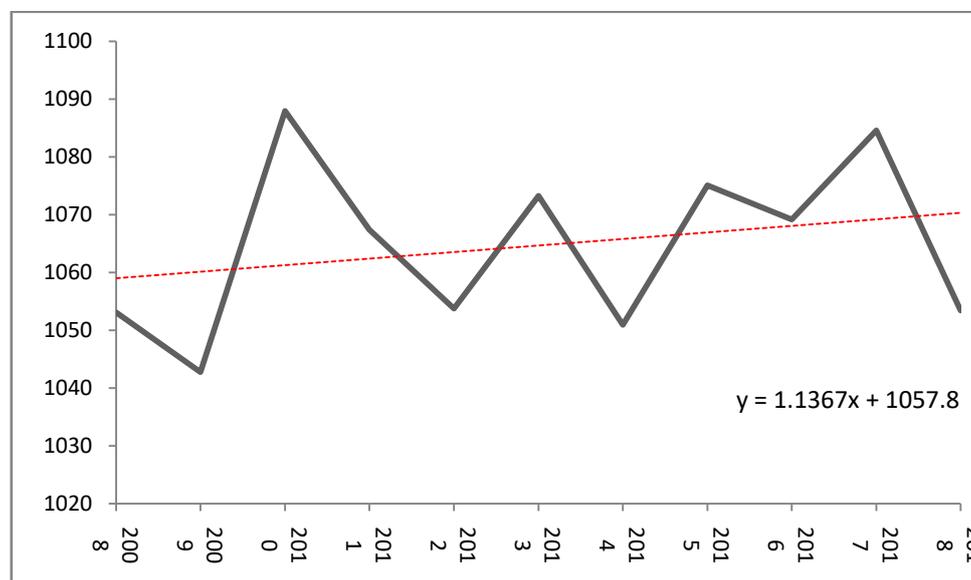


Figure 4: Sea Level change from 2008-2018

Analysis from tidal gauges observation estimated that from 2008-2018, the sea level rose by 1.13mm/year. However, the preliminary estimations of Woppelman (2008) based on a long term linear trend (100 years) yielded a value of 1.44mm of sea level rise over the past hundred years. This situation attests an ongoing and non neglectable rising sea but till now classified as low vulnerability by the CVI model used in this study.

### Shoreline erosion/accretion (m/year)

Shoreline change analysis done through DSAS(Digital Shoreline Analysis System) revealed that from 1978-2018 the coastline was subject to a mean shoreline change rate of -1.31m/year showing a important beach retreat accompanied with serious sedimentary deficit.

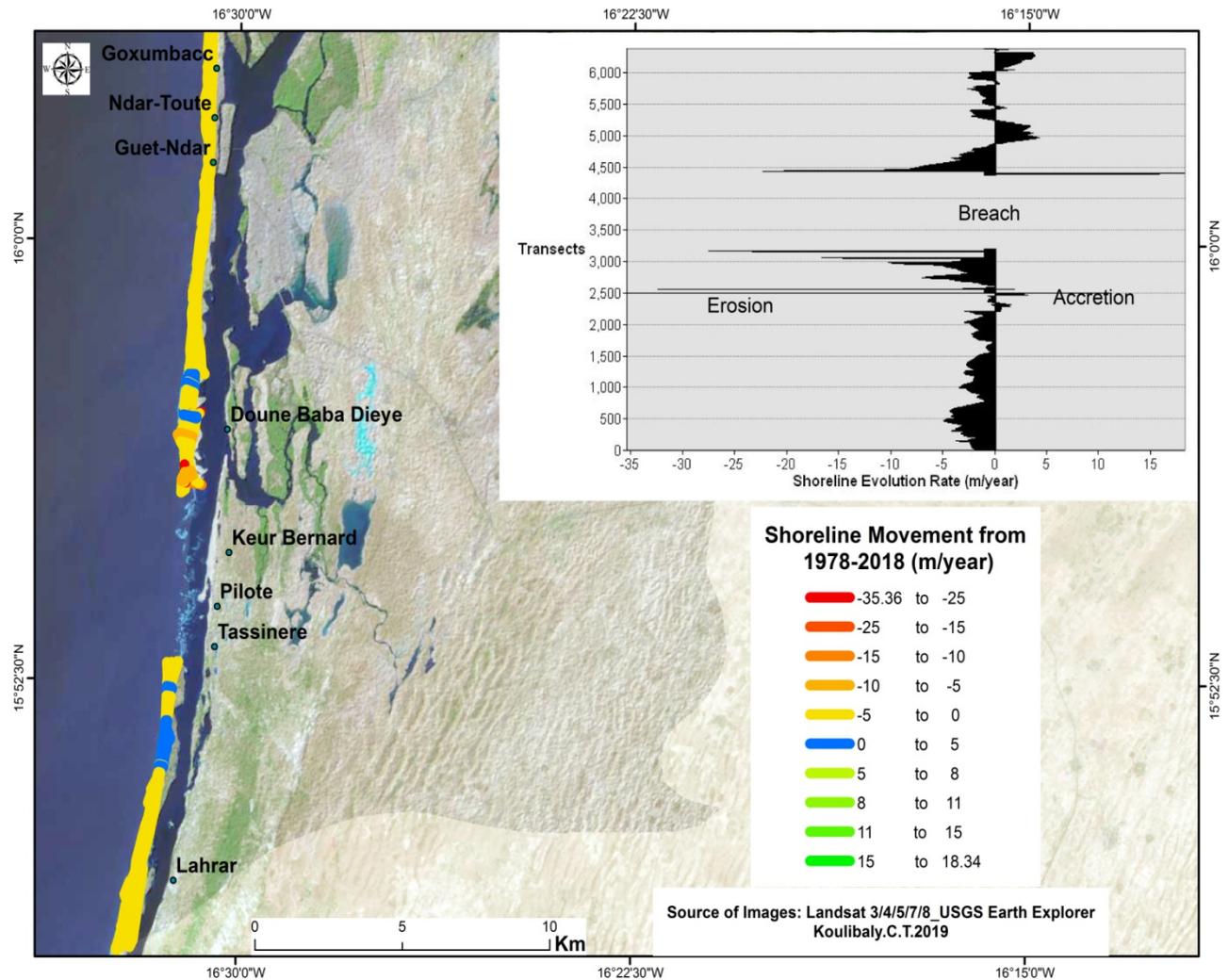


Figure 5: Shoreline erosion/accretion from 1978-2018

From the considered period, both phenomenon of erosion and accretion were recorded across the coastline. The rate of coastal erosion ranged from -0.1m to -35.36 m/year while accretion rate varied from 0.11 to 18.34m/year. The processes were marked with strong spatial variability, some areas located northward such as the fishermen villages of Guet-Ndar, Ndar Toute and Goxumbacc were respectively affected with shoreline retreat of -1.53m/year (Guet-Ndar), -2.94m/year (Ndar Toute) and -1.9m/year (Goxumbacc) while the highest rates of erosion (-9.39 to 35 m/year) have been recorded around the new mouth also known as the “Breach” commonly called “Beul bi” by locals. The process of erosion is also taking place in the south as the new mouth is evolving southward with coastline retreat ranging from -0.94 to -1.17m/year. Rare phenomenon of accretion is located down the center and in the south varying from 0.55 to 18m/year.

### Mean Tide Range (m)

Tidal range was calculated from hourly and daily tidal gauges fast delivery data provided by the station 223 from 2008-2018. From the considered period the calculated tidal range was estimated at 0.045m which was ranked “Very High” vulnerability by the CVI model.

## Mean Wave height (m)

Wave height analysis from acquired Wave Watch III (WWIII) model from 2008-2018 revealed a maximum wave height of 4.6m by a minimum of 0.7m.

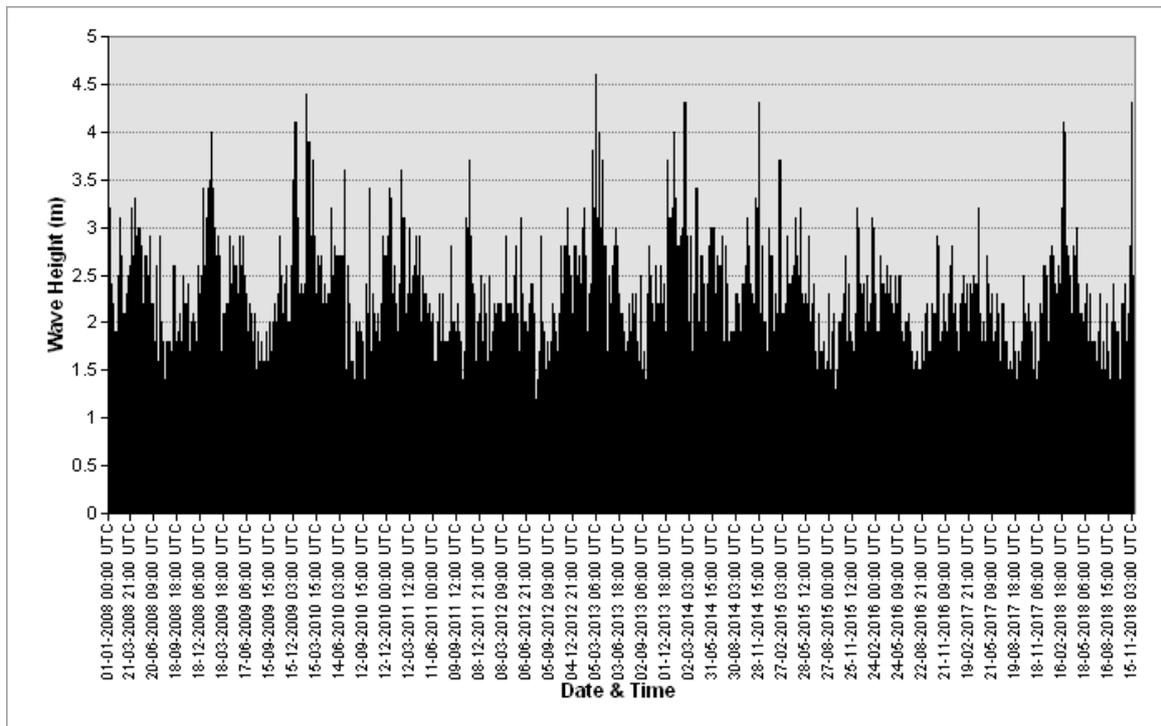


Figure 6: Wave Height from 2008-2018

Over the considered period the mean wave height was estimated at 1.76m revealing “very high” vulnerability of the coastline from 2008-2018.

## Coastal Vulnerability Index in 2018

The major aim of this study is to assess a coastal vulnerability of the Saint-Louis in 2018. The six ranked variables were assigned to the coastline in a GIS database and CVI was calculated using the formula. Categorization from Low-Moderate-High-Very High vulnerability was done using 4 equal intervals and each CVI value falls in its relevant interval. In this study, the calculated CVI ranges from 7.90 to 22.82 with a mean of 15.45 and a standard deviation 4.22. Values from 7.90 to 11.63 were assigned to low vulnerability. Moderate vulnerability values lie from 11.64-15.36. Values from 15.37-19.09 were classified as High Vulnerability and CVI values greater than 19.09 were categorized very high vulnerability.

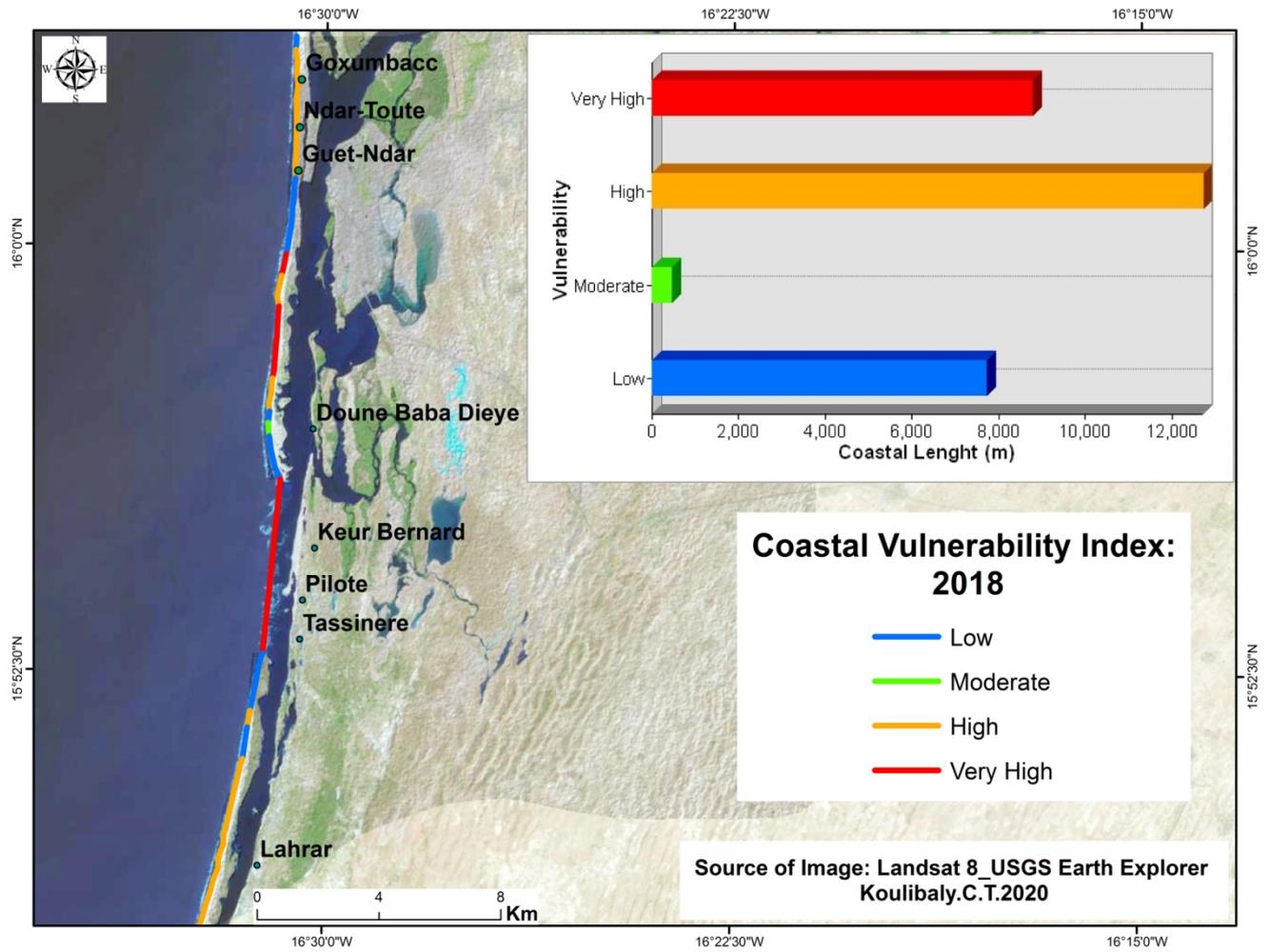


Figure 7: Coastal Vulnerability Index of Saint Louis

In this map of the CVI, blue refers to areas at low vulnerability, green represents moderate vulnerability, orange refers to zones at high risk and red was assigned to area at very high vulnerability.

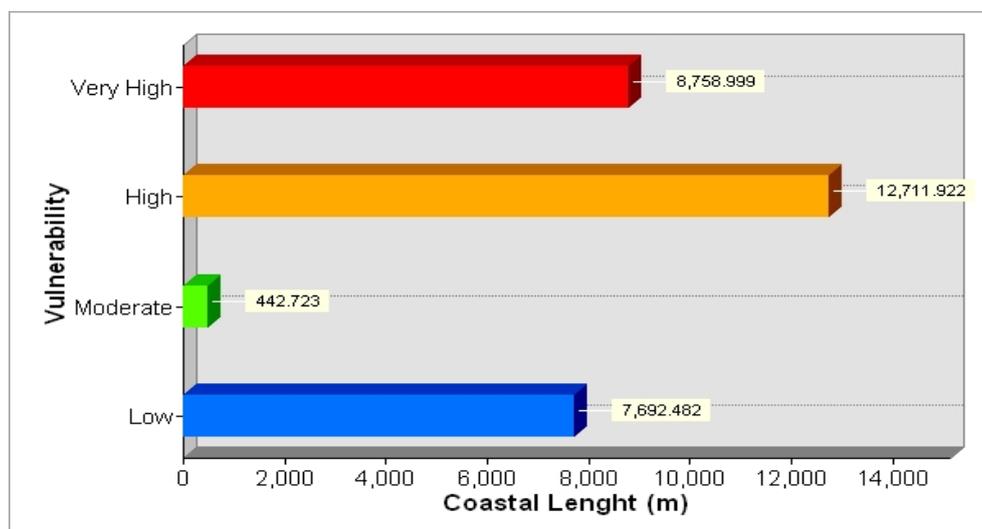


Figure 8: Vulnerability according to coastal length

Projected to the coastline length, it appears that 7,692 m of the coastline is at low vulnerability, 442.72 m at moderate vulnerability. It also appears that the majority of the

coastline has been classified at high and very high vulnerability with respectively 12,711.9 m and 8,758.9m. In terms of percentages the results showed that 25.98% of the coastline has been classified as low vulnerability, 1.49% at moderate vulnerability, about 43% categorized at high vulnerability and 29.58% as very high vulnerability.

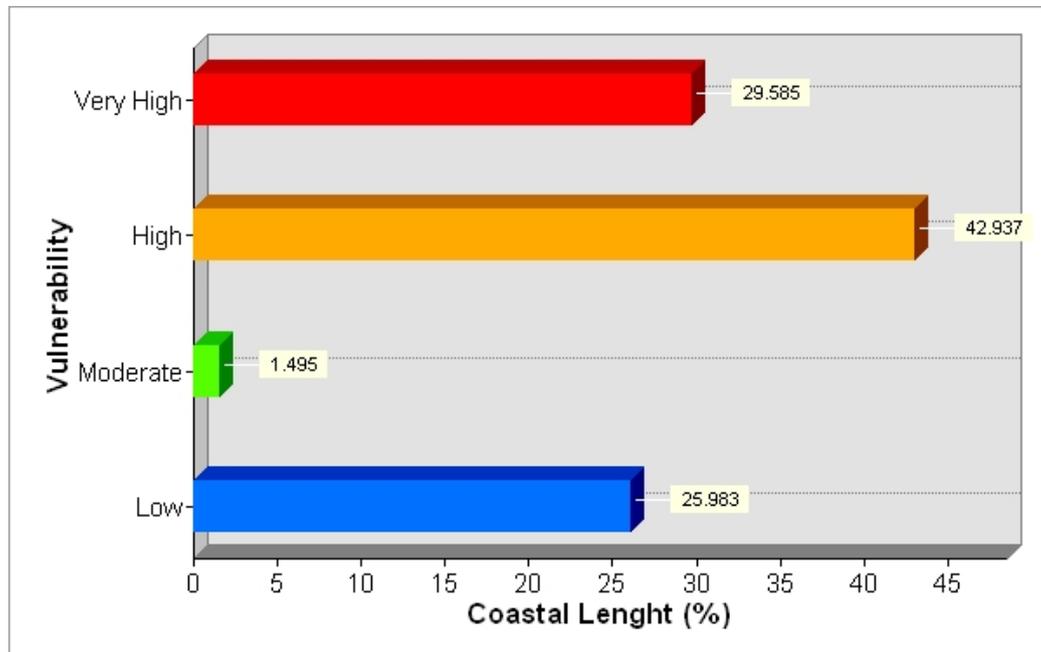


Figure 9: Vulnerability of coastline length in percentage

This analysis shows that more than 70% of the coast is highly vulnerable. The provided map showed that the major areas of high and very high vulnerability were mainly the 2 populous fishermen villages of Guet-Ndar, Goxxumbacc as well as the area of the new mouth and the south south around the village of Lakhrar. This high level of vulnerability of the coastline both emanates from natural and anthropogenic factors.

The first driver of the vulnerability of the Senegal River estuary remains the natural terrain: the area is relatively flat and made of sandy shores characterized by gentle slopes. As attested by our analysis, about 64.6% of the main beach is level ( slope value =0%) while at the global view about 94% of the Langu de Barbarie sand spit is occupied by gentle slopes (0-9%). Commensurately, a second analysis of the DEM based on elevation (m) across the whole department of Saint-Louis revealed that 8.02% of the entire area is below the sea level (-13-0m) and about 73% from 0-10m making the estuary vulnerable to such events as storm surges, coastal erosion and inundation. In addition to this, the coastal zone is geomorphologically made of coastal plains with sand dunes deposits highly subject to erosion. Like all estuaries, Saint-Louis is both subject to marine and fluvial dynamics. Over the last decades it had been observed that the marine dynamic is becoming more aggressive and agitated. From 2008 to 2018 an amazing Mean wave height of 1.76m with swells

frequently reaching 4 m in addition to an extreme tidal range of 0.045m were recorded attesting to a state of high vulnerability ever with frequent storm surges and serious damages on local communities and their environment.

The second set of drivers concerns anthropogenic factors, including high density population, poor urbanization and resilient infrastructures. The coastal area of Saint Louis has obviously recorded an exponential population growth caused by rapid occupation of the three core parts of the city as the Langue de Barbarie, the “Saint Louis Island” and the main land “Sor”. A land use analysis done with LANDSAT\_3/MSS (1978) and LANDSAT\_8/OLI (2018) through ArcGIS10.1 revealed that areas occupied by human settlements from 1978 to 2018 have been multiplied by almost 9 and passed from 599.4 Ha to 5330.34 Ha with a particular concentration of installations toward the coastline.

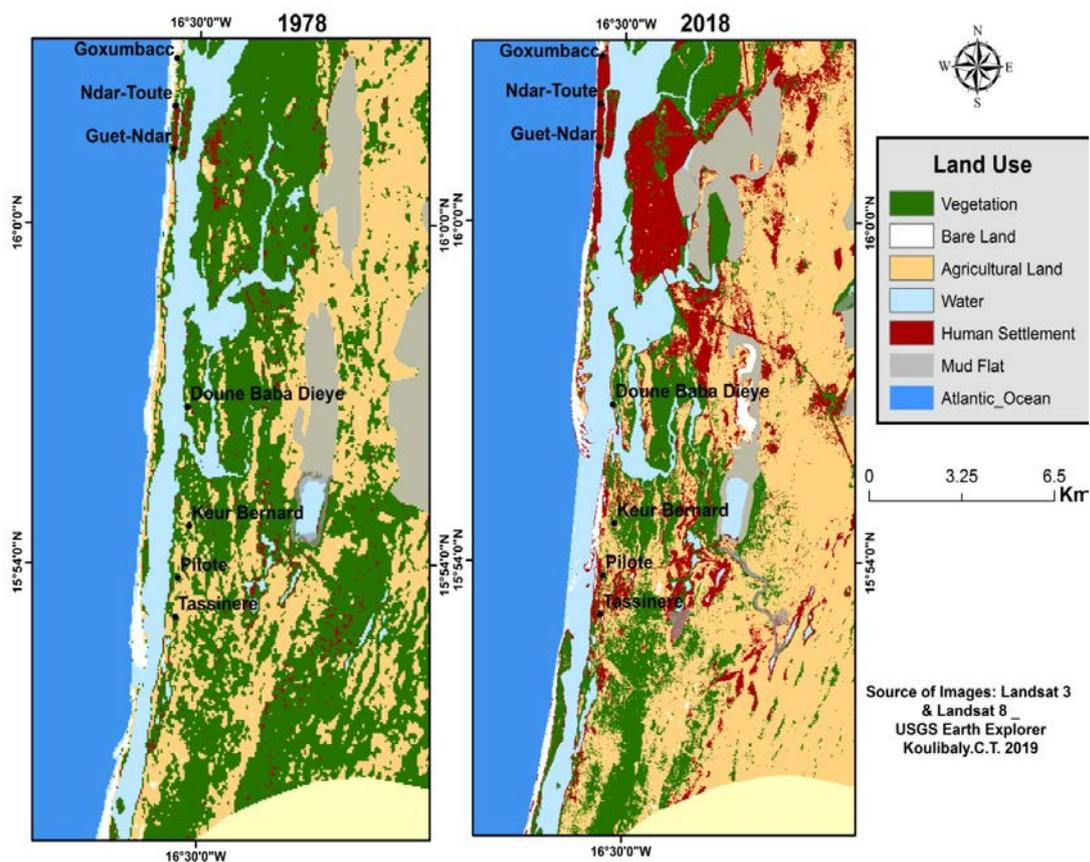


Figure 10: Land use changes from 1978 to 2018

It has been observed that most vulnerable areas such as the section stretching from fishermen villages of GuetNdar and Goxxumbacc has been highly or entirely occupied. In addition to this high density occupation, there is serious urbanization problem along the coastline; settlements are growing like mushrooms without any respect of building norms. Moreover, some dwellers found onsite confessed that they are still extracting sand beach for construction.

The vulnerability of the estuary can also be explained by hydrological transformations induced by water control infrastructures with serious morphological modifications in the coastal area. Such facilities like dams are one of the major factors of sediment deficit of the Langue de Barbarie sand spit. It is important to point out that the Senegal River has a long tradition of hydraulic infrastructures. As response to the recurrent series of drought during seventies, a huge project of fresh water management had been put in place. Therefore, the erection of two dams was essential to ensure the sustainability of water resource in the region. For this purpose, the Diama and Manantali Dams have been respectively erected downstream and upstream the Senegal River. The principal aim of the transnational dam of Diama was to stop saline intrusion during the dry season and to stock enough volume of water for domestic and irrigation purposes. This facility also created an artificial lake of 235 Km<sup>2</sup> with a capacity of over 250 m<sup>3</sup> millions destined to irrigate 120.000 ha of land and freshwater supply. This changed hydrological regime of the Senegal River related to the dams of Diama (downstream) and Manantali (upstream) has had strong impacts on the morphological evolution of the region. They were indeed essential but did not take into account factors such as the sedimentology and ecology of the estuarine environment.

The colonial city of Saint-Louis is also highly vulnerable to natural disaster. It has been mentioned above the morphology of the city make it vulnerable to flooding and coastal erosion. The phenomenon of flooding usually occurs during the raining season and especially when the Diama dam is suddenly opened and delivers important discharge that creates a quick rise of water level downstream. During the flood of 2003 the local authorities urgently decided to create a runoff canal at 7km downstream Saint-Louis aimed at creating a closer opening for the river discharge to reach the sea. The opening occurred during the night of 3 to 4 October 2003. This breach was about 4m wide; 100m long and 1,5m deep. However it rapidly grew, widening from 4 to 600m already on the 6 of October (after 3 days) followed by a higher sea tide than the average. Furthermore, when the rough sea hits, the southern part of the canal is subjected to further erosion while the northern part accumulated little sedimentation. This phenomenon keeps widening the canal constantly (K. Diagne et al, 2009). The marine hydrodynamic has been strongly affected by that artificial opening that henceforth constitutes the Senegal River mouth. The amplification of the tidal range throughout the estuary is the first obvious consequence of that created mouth. From daily readings recorded downstream of Diama dam (i.e. 23 km north of the city) between January 2001 and January 2006, several studies (Dumas and Mietton, 2006; Mietton et al, 2006) have highlighted that Semi-diurnal tide changes are occurring in several ways. On one hand, the maximum daily tidal range has tripled, going from 0.30 m (2001-2002 average) to 0.93 m

(2004-2005 average). On the other hand, tidal cycles are now more clearly felt all year round, even during high winter waters.

In addition of being impacted by serious sediment deficit, the protective Langue de Barbarie sand spit is strongly affected by the artificial the mouth or breach.



Plate 2: Ongoing erosion in the locality of Guet-Ndar and the Lower estuary

Serious process of coastal erosion has been observed throughout the Langue de Barbarie sand spit. In the traditional fishermen villages of Guet Ndar, Ndar Toute and Goxxumbacc the situation is just apocalyptic and desperate with huge socio economic damages including loss of social amenities and even human casualties; in such areas, local dwellers are actually living in perpetual fear of being uprooted by the sea. Towards the lower estuary, villages like Pilote and Tassinere that were protected by the Langue de Barbarie sand spit are actually facing the new mouth and then exposed to such events like surges with disastrous consequences on human settlements and touristic infrastructures. In addition to erosion the lower estuary also known as “Gandiolais” generally housing farmers and breeders is facing gradual salinization of water resources with serious environmental and socioeconomic impacts.

Several adaptation strategies have been observed at the local scale. They are either community based, put in place by local authorities or rather touristic investors.

Community based adaptation strategies are usually crude, temporary and not adapted to face such events as storm surges. It mainly involves desperate attempts to contain the sea using sand bags. This community adaptation measure has been observed throughout the coastline; bags are usually filled with sand beach, superposed and aligned along houses as barrier against the sea; in some cases dwellers are also using fishing nets to envelop the sand bags for more resistance. According to them, when the sandbags are outlined together they will be hardly uprooted. However, this technique of low expenditure is just for temporary defence, sand Bags have short life expectancy due to lack of resistance to physical damage and UV sunlight effects.



Plate 3: Community based adaptation strategies at Guet Ndar and Tassinere

Beside these communities based adaptation strategies, other structural infrastructures involving huge engineering were also observed along the shore. These protective measures are mainly represented by the sea wall of Ndar Toute erected by colonial masters in 1962 and the recent dyke of Goxxumbacc built in 2019 by local authorities. However, the seawall of Ndar toute is nowadays old, in state of deterioration and is longer playing its protective role, while the new dyke of Goxxumbacc is just covering 1.6km over 3.5km.



Plate 4: (a) Sea Wall of Ndar Toute (1962), (b) Dyke of Goxxumbacc (2019)

In addition to these 2 facilities, it has been noted that in the lower estuary, touristic investors are mobilizing their effort to protect their amenities (guest houses, camps) against the sea mainly using ripraps, concrete walls and also tetrapods.



Plate 5: ripraps and tetrapods immersed to protect a tourist camp at Gandiol

Besides these structural facilities of shoreline protection, nature based adaptation strategies are also experimented in the estuary. Among these non structural methods, reforestation of *Casuarina equisetifolia* tree locally named *Filao* is mostly applied along the Sand spit. That program of dunes stabilization has been initiated since 1981 and is still encouraged by the local authorities.



Plate 6: Plantation of filaos along the Langue de Barbarie Sand Spit

Relocation is also an adopted measure by local authorities. Many families from the fishermen communities of GuetNdar and Goxxumbacc, victims of sea level rise have been relocated in

land. Nowadays, the sites of “Khar yAllah” and “Boudiouck” are actually housing more than 150 displaced families in difficult conditions including poor sanitation and restricted access to water and electricity. In the refugee camp of Boudiouck it has been observed that victims are installed in 336 provisional habitation facilities that hardly respect human dignity; water is sold to them and they hardly access to power (electrification). Moreover, these refugees also called ‘the forgotten’ confessed that they are suffering from excessive heat and insecurity in these provisional habitations tents while being exposed to snakes and scorpions as well as storms during the raining season. Finally, this relocation raised the issue of identity because according to them it has been difficult to be displaced leaving behind their native habitat as well as their traditional activities and unique sources of livelihood.



Plate 7: Relocation camp of Boudiouck

## Conclusion

The present paper raised the complexity of the coastal vulnerability study of the Senegal River estuary. It revealed that the vulnerability of Saint-Louis is both related to the combination of natural and anthropogenic factors. In addition of being a fragile environment characterized by its flatness with gentle slope and aggressive marine hydrodynamic, the estuary has been deeply affected by human intervention mainly through population growth, anarchic occupation and resilient infrastructures. The applied Coastal Vulnerability Index showed that more than 70% of the coastline is at high vulnerability mostly felt in the populous fishermen villages of Guet-Ndar, Ndar Toute, Goxxumbacc and around the new artificial mouth. The situation in these areas is at limit desperate even if some adaptation strategies have been put in place. Adaption is the biggest challenge faced by these coastal communities considering the level of poverty prevailing there where the majority is usually of low income. The community based adaptation strategies are obviously not adapted to face the strength of the sea; some facilities as the sea wall of NdarToute are actually old and dated since colonial

masters while reaction of local authorities is taking place at lower pace even if some efforts have been recently felt. It is also important to point out the fact that these efforts came a bit late and don't cover and protect the entire dedicated area. Finally, relocation of impacted coastal communities is not an easy task; it should be well planned with adapted and decent welcoming infrastructures supported by gradual accompanying measures.

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