

Assessment of Shoreline Morphological Changes In Bonny and Kaa Communities of the Niger-Delta Region of Nigeria

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ABSTRACT: This study Assessed Shoreline Morphological Changes on Bonny shoreline. The mixed-method was used in the study to assess the Shoreline Morphological Changes on Bonny shoreline. Remotely sensed data was used to examine the susceptibility and coastal evolution of Bonny over 36 years (1984 -2020). Longer-term (1984- 2020) and short-term (2015-2020) shoreline change analyses were used to understand coastal erosion and accretion. From 1984-2020, the total average linear regression rate (LRR) was $-2.7\pm 0.18\text{m/yr}$ and from 2015-2020, it was $-3.94\pm 1.28\text{m/yr}$, demonstrating an erosional trend along the study coast. Although the rate of erosion varies along the study coast, the linear regression rates (LRR) results show a predominant trend of erosion in both the short and longer term. To quantify the anticipated future coastal erosion risk by 2040 along the study coast, the findings in this study show an overall average LRR of $-2.73\pm 0.99\text{ m/yr}$ which anticipates that coastal erosion will still be prevalent along the coast by 2040. And, given the current global climate change situation, it should be expected to be much higher than the current forecasting. The results showed how human activities and environmental interactions have evolved through time, causing coastal erosion. Removal of vegetation cover/back stop for residential and agricultural purposes, indicate that human activities significant contribute to the study area's susceptibility, rapid shoreline changes, and vulnerability to coastal erosion, in addition to oceanic and climate change drivers such as sea level rise and storminess. The coastal vulnerability index to coastal erosion was calculated using the Analytical Hierarchy Process weightings. It revealed that 67.55% of the study coast falls within

the high-very high vulnerability class while 32.45% is within the very low-low vulnerability class. The study therefore recommend that to protect lives and property, policymakers in the region need to set up good coastal zone management plans, strengthen adaptation measures, and make coastal communities more resistant to possible risks.

Keywords: Shoreline, Morphological, Bonny shoreline

I. INTRODUCTION

A shoreline is the boundary between water and land (or sand) that is visible at a specific time. The character of the shoreline is dynamic [9]. Shoreline morphology evolves as a result of the coastal zone's dynamic nature, as the shoreline modifies itself to preserve balance with shifting land- and marine-based processes [18]. Changes in the morphology of shorelines result from ongoing interactions between land and sea on various spatial and temporal scales in response to both natural and anthropogenic influences [20]. The natural and anthropogenic drivers of change cause impacts ranging from erosion to expansion of the built environment and inundation due to sea level rise [15].

Winds, storms, near-shore currents (wave-induced and/or tidal currents), relative sea-level rise, and slope processes are the primary natural variables that affect the morphology of the shoreline [5]. Construction of navigation works that reduce sediment delivery to the coast and subsidence brought on by ground fluid extraction are two anthropogenic factors that have changed the morphology of the shoreline [8]. The littoral zone's cross-shore and alongshore sediment movement, as well as the constantly fluctuating

water levels along the coastline owing to waves, tides, storm surge, etc., cause the shoreline to shift continuously throughout time [4]. Beach sand erosion results in the devastation of coastal environments and properties. The shifting shorelines act as a conduit for this vulnerability [5]. Due to the forces that can either deposit sand on the beach or erode it away, shorelines, particularly sandy shorelines, tend to change more quickly than rocky shorelines [10].

Coastal ecosystems such as wetlands, estuaries, and deltas provide goods and services, such as natural protection and flood control, shoreline stabilization, sediment retention and cycling, recreation provision and cultural heritage [7]. Utilization of the coast increased dramatically during the 20th century and this trend is virtually certain to continue through the 21st century [17]. Hence, coastal areas host significant populations and provide important socio-economic activities for regions worldwide [3]. Although the low elevation coastal zone accounts for only about 2 percent of the world's land area, about 10 percent of the world's population and 13 percent of the world's urban population live in the zone [16]. It is estimated that 50 percent of the world's population will live within 100 km of the coast by 2030 [19].

With the threat of accelerating global sea level rise, burgeoning coastal populations worldwide, as well as growing pressures on social and ecological systems, it is important to assess risk to the coastal environment [13]. Much of the West African coast is threatened by erosion. In the Gulf of Guinea region, the Niger Delta is at risk, as the coast extends westwards along the coast to Ghana. These populations are currently predominantly rural, but this is likely to change and each of the deltas is associated with at least one large and rapidly growing megacity. Thus, even as a result of urbanization alone, the delta populations are likely to grow much further [6].

Coastal managers and scientists require knowledge of both long-term and short-term changes occurring along the coast in order to plan and implement successful beach erosion management, flood zone demarcation, and ecosystem protection [14]. Furthermore, policymakers must create plans that best address current and future coastal development [13]. When evaluating shoreline morphodynamics, data from historical sources show where the shoreline was in the past, while data from contemporary sources show where the shoreline is right now. By combining the coastline data from the two sources,

it is possible to see how the shoreline changed over time to take its current form. This provides the baseline information to analyze the cyclic behavior of the shoreline in the short and long term and how other factors influence the lateral morphological change as well as estimate the shoreline's historic rates of change, enabling the prediction of the future position of the shoreline using various modeling techniques [2].

There are a number of remote sensing techniques commonly used to detect and monitor shorelines, such as aerial photographs, visual interpretation, and on-screen digitization; however, the accuracies of the different techniques are directly related to their spatial resolution. While the vertical accuracy might vary considerably, the horizontal accuracy, which actually determines the location of the shoreline, is typically of the same order of magnitude as the spatial resolution of its source data [11]. Information about where the shoreline is located, where it has been in the past, and where it is predicted to be in the future is fundamental to a broad range of investigations undertaken by coastal scientists, coastal engineers, and coastal managers [4].

Previous studies of the shoreline morphology of the Niger Delta were conducted by Ibe and Anita [12], Adegoke [1], and Obowu and Abam [18]. The study by Ibe and Anita [12] aimed to make a scientific input into long-term and large-scale coastal management planning, providing preliminary results and interpretations based on beach profiling and littoral environment observation. The work by Adegoke [1] attempted to fill the gap caused by the dearth of studies on recent shoreline changes using satellite imagery processed in a GIS environment (Erdas Imagine Version 8.7 and Arc Info 9.1). The research by Obowu and Abam [18] focused on coastline change detection and vulnerability assessment using remote sensing and geographical information system tools.

a. Aim and Objectives of Study

The aim of this research was to assess shoreline morphological changes on Bonny and Kaa shoreline, Rivers State. The specific objectives are to:

1. Identify the shoreline changing trend from 1984 to 2020 on Bonny and Kaa shoreline, Rivers State.
2. Ascertain the factors responsible for the observed changes occurring along the Bonny and Kaa shoreline, Rivers State.

II. MATERIALS AND METHODS

Bonny and Kaa Shore is situated at the southern edge of Rivers State in the Southern Niger Delta region of Nigeria. It was formally known as Ibani or Ubani town. It lies along the Bonny River (eastern distributaries and 6 miles upstream from the Bight of Biafra. It is located at latitude $4^{\circ} 26' 57''$ N and $4^{\circ} 31' 42''$ longitude $7^{\circ} 3' 8.1''$ and $7^{\circ} 9' 38''$. The Kaa River flows in a south-easterly direction into a large body of water which also flows almost vertically and slight south-easterly into the Bight of Bonny. It runs in between the two neighboring estuaries of the New Calabar River to the west and the Andoni River to the east. The Cawthome channel links the New Calabar channel and Bonny River estuary. Bonny covers a total land area of about 651.20km^2 .

The study area enjoys tropical hot monsoon climate due to its latitudinal position. The tropical monsoon climate is characterized by heavy rainfall from April to October ranging from 2000mm to 2500 mm with high temperature all the year round and a relatively constant high humidity. The relief is generally lowland which has an average of elevation between 0m and 20m above sea level. The vegetation found in this area includes raffia palms, thick mangrove forest and light rain forest. The soil is usually sandy or sandy loam underlain by a layer of impervious pan and is always leached due to the heavy rainfall experienced in this area. The study area is well drained with both fresh and salt water. Due to continuous heavy rainfall and river flow, the study area experiences severe flooding almost every year.

The geology of the area is comprised of alluvial sedimentary basin and basement complex

with mean grain size of 2.5mm – 3.0mm. Noticeable concentrations of dark-colour heavy minerals were found along the upper reaches of the active beach. The vegetation found in this area is comprised mostly of mangrove swamps; light rain forest and thick mangrove forest. The most common coastal plant found was the creeping vine *Impomoea aquatica*.

The tides occur with a period of approximately 12 hours and 25 minutes, and with amplitude that is influenced by the alignment of the sun and moon and the shape of the earth. The wind direction is dominantly in a southwesterly direction. The study area experiences two high and two low tides per day, with a tidal range which varies across the Niger Delta and has average value of 1.8 m. The difference in tidal amplitude is accentuated because of the low volumes and frequency of freshwater discharge at the sub deltas on the eastern side of the Arcuate Delta thereby allowing the marine processes to play a more active role in shaping the sub delta morphology.

It is generally erosional as compared to the more depositional active Western Delta shoreline. This can be attributed, primarily, to the configuration of the active river systems on the delta's surface. Oil and gas facilities such as the AGIP's major exporting terminal and other associated facilities are located along the vulnerable shoreline. The estimated population is in the region of 100, 000 and is likely to increase on the commencement of the LNG project. Retreat of the shoreline threatens coastal settlement, loss of recreational grounds and oil export handling facilities.

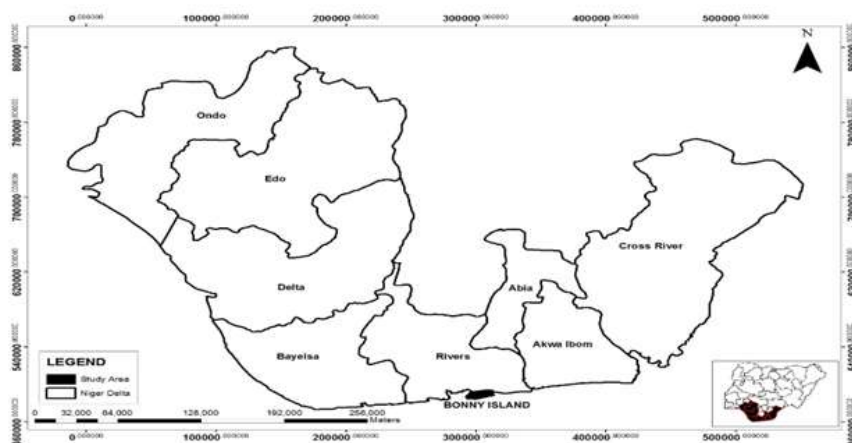




Figure 1 Map of Study Area

A mix scale approach involving the integration of primary and secondary data provided through government sources and data bases from other organizations. The raw spatial data and satellite images used in the research were procured through the United States Geological Survey (USGS) and the GIS laboratory of the Department of Geography and Environmental studies, University of Port Harcourt. Hard copy map of federal surveys, Nigeria of 1974 (1.500/620/9-74) with scale 1:50,000 and soft copy of map of federal surveys, Nigeria of 1974 (1.500/620/9-74) with scale 1:50,000 obtained from the office of the Surveyor-General, Nigeria will be used. The data sets to be used will include three Landsat images covering the study area for period spanning twenty (20) years, satellite images for three different years of 2000 and 2020. Landsat Thematic Mapper (LTM) of 2000 and 2020 of 30 X 30 meters ground resolution were acquired from the United States Geological Surveys (USGS) and actually used for the various analyses carried out. The method is typically GIS-based and involves a number of steps. A historical shoreline database of Bonny will be created using ESRI ArcGIS. Database for Bonny contains 3 historical shorelines spanning the time period from 2000 to 2020. Timing is a primary aspect in shoreline monitoring, both to collect data that actually represent the time interval under study (which can be short for single event analysis, or longer in order to retrieve a secular trend), and to meet the need for cost effectiveness.

The long-term shoreline variation was defined as the period (twenty years) necessary to relatively minimise the short-term changes and delineate the true long-term trend while the short-term shoreline variations was defined as the period (ten to fifteen years) necessary to capture shoreline changes due to possible storm events, seasonality of the wave climate, longshore migration of sand bodies or impacts of engineering activities like

beach nourishment. Each shoreline will be digitized from Landsat images in a polyline shapefile using ArcGIS to confirm the shoreline position. The shoreline proxy will be boundary between the dry and wet sand seen in the Landsat images. The other digitized shorelines will be appended on the recent Landsat image hence creating historical shoreline positions. A baseline polyline shapefile will be created and the outer offshore baseline constructed by hand through digitizing a line onscreen in Arc GIS and estimating a preferred location by eye in order to obtain desired transect orientations across the historical shorelines and parallel the general orientation of the historical shorelines in the GIS. Following the creation of the baseline, transect lines will be casted perpendicular to the baseline at a 50m spacing and transect length of 1000m spacing along the baseline. Transect lines will be intersected with the historical shorelines to produce a database of points, which will record the locations of historical shoreline positions along each transect through time. The estimate for shoreline position error will be set at 1m.

Statistics will be calculated for transects in the AMBUR (Analyzing Moving Boundaries Using R) software and stored in a data table with the confidence level calculated for linear regression set at 95%. Analysis will be done for the entire stretch of the Bonny shoreline as well as the study area. Subsequently, a projection of future shoreline positions based on calculated shoreline rate-of-change statistics. The area of accretion or erosion will also be measured using a polygon shapefile. Ground truthing on the entire study area will be conducted for one week. The aim is to gather information from the field and interview the people from the study area. The persons to be interviewed will be asked about the status of the shoreline in relation to previous years. Their responses will be corrected with the with the GIS analytical findings. A number of photographs will also taken of the

study site using a digital camera in order to capture the area's current appearance.

III. RESULTS AND DISCUSSION

a. Shoreline Change Analysis between 1981 and 2020

The analysis of the shoreline over the 40 years using geospatial and statistical techniques contributed to a better understanding

of the coastal variability along the shoreline. The performance of the shore lines for the years 1981, 1993, 2004, 2010, and 2020 were incorporated in the geo database, as well as the baseline and a total of 33,225 transects along the shoreline, of which 5937 were for Kuruma, 10,906 for Oloma, 6293 for Kalaibama, and 10,089 for Abalamabie. All transects were cut from the baseline to the farthest line, as shown in (Figure 4.1).

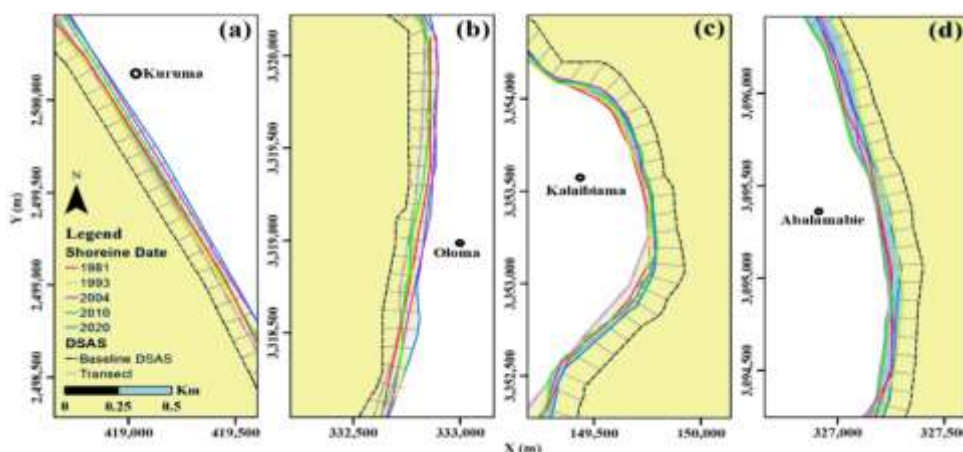


Figure 2 Shoreline:(a) Kuruma, (b) Oloma, (c) Kalaibama, and (d) Abalamabie.

The statistical models NSM, EPR, LRR, and WLR were obtained for a better understanding of the movements of the shoreline up to the present time. Considering the resolution of the image and the period analyzed, an uncertainty range for the rate of change in units of 0.75 m/year resulted. Because of the uncertainties, the results were obtained from the rate of change of the coast from the LRR with a confidence level of 95%.

The results of the shoreline movement revealed that there was significant land ward (erosion) and seaward (accretion) movement in

different parts of the shore, and this can differ greatly between the coastal stretches, which can range from more than 1km to tens of kilometers. Table 1 details the displacements in terms of the NSM and provides detailed information on the movements that occurred. Along the coasts, there were 22,295 transects with landward movement and 10,930 seaward movements. The longest landward distance was -2880.39 month ecoast of Kuruma, while the longest positive seaward distance was 1325.71 m on the coast of Kuruma.

Table I Shoreline changes by NSM.

Statistics	Kuruma	Oloma	Kalaibama	Abalamabie	KA
Number of transects	5937	10,906	6293	10,089	33,225
Average distance(m)	-39.61	-176.9	-105.46	-4.32	-81.57
Number of transects with a negative distance	4417	9558	2749	5571	22,295
Maximum negative distance(m)	-515.90	-2880.39	-1650.21	-176.94	-2880.39
Average of all negative distances(m)	-105.48	-210.54	-281.73	-30.95	-157.17
Number of transects with a positive distance	1520	1348	3544	4518	10,930
Maximum positive distance(m)	1325.71	747.76	278.6	318.92	1325.71
Average of all positive distances(m)	116.424	65.2	37.64	29	62.06

The EPR statistical analysis revealed that the changes were significant throughout the shore, which presented a rate of change of 2.16 m/year (Table 1), similar to that reported by, who analyzed the shoreline variability with EPR in the shore. The EPR does not consider the

variability between all the shorelines since it considers only the oldest and the current line. Therefore, in this research, the researcher discuss the results in terms of the LRR to account for all shorelines in the analyzed period and compared them with the results of WLR.

Table II Shoreline change rates by EPR.

Statistics	Kuruma	Oloma	Kalaibiana	Abalamabie KAA	
Average rate(m/year)	-1.32	-4.56	-2.69	-0.09	2.16
Maximum value erosion (m/year)	-26.54	-118.36	-42.83	-29.93	-118.36
Average of all erosional rates(m/year)	-3.23	-5.44	-7.39	-0.76	-4.20
Maximum value accretion(m/year)	66.09	40.25	7.21	16.58	66.09
Average of all accretion rates(m/year)	4.24	1.63	0.97	0.74	1.89

The LRR results (Table2) indicate an overall rate of change of -2.20m/year. A total of 72% percent of coasts with landward advancement

with an erosion rate of 3.86 m/year, while 28% demonstrated seaward gain with a rate of 2.05 m/year.

Table III Shoreline change rates by LRR.

Statistics	Kuruma	Oloma	Kalaibiam	Abalamabi Kaa	
	a	a	a	e	
Average rate(m/year)	-1.58	-4.57	-2.35	-0.31	-2.20
Percent of all transects that are erosional(%)	78.64	88.05	47.83	66.14	72.19
Percent of all transects that have statistically significant erosion(%)	33.54	36.36	3.91	10.14	21.91
Maximum value erosion (m/year)	-20.87	-118.0	-46.27	-5.92	-118.0
		2			2
Average of all erosional rates(m/year)	-3.33	-5.42	-5.88	-0.83	-3.86
Percent of all transects that are accretion (%)	21.36	11.95	51.17	33.86	27.62
Percent of all transects that have statistically significant accretion(%)	5.12	1.84	5.13	3.14	3.46
Maximum value accretion(m/year)	55.21	18.34	6.54	6.43	55.21
Average of all accretion rates(m/year)	4.89	1.75	0.89	0.7	2.05

With WLR, it assigns a higher weight to transect the intersection points with lower uncertainty values to obtain the line of best fit. However, the WLR values (Table 3) differ in centimeters from the LRR in the study. The overall rate of change for the WLR for the shore was -1.78

m/year, demonstrating a difference of 0.42 concerning the LRR. For this reason and the forecast of the futuristic position of the coast obtained from the LRR results, this research discusses the results mainly in terms of the LRR.

b. Analysis by Location

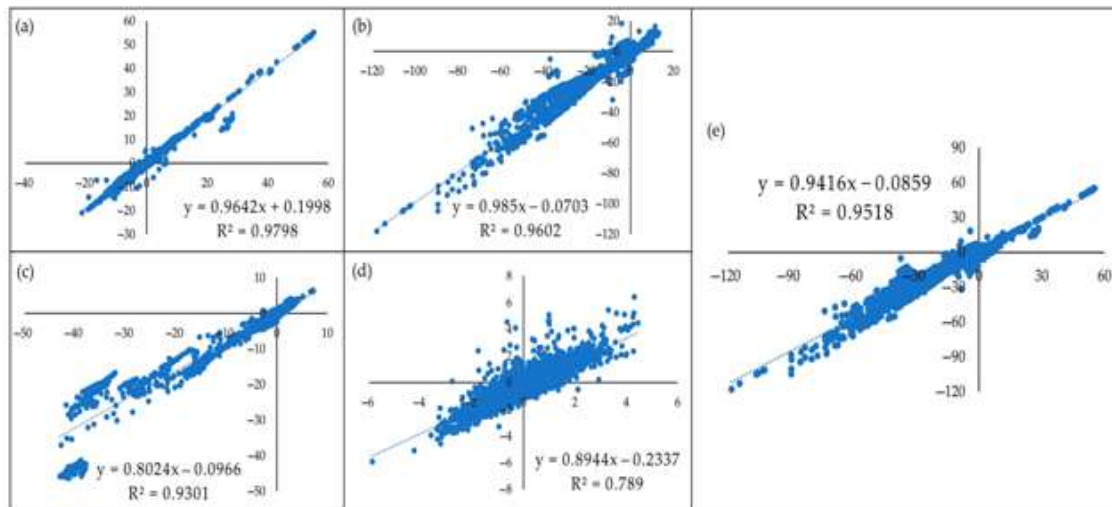


Figure 3 LRR change for the original and forecasted 2020 shoreline, (a) Kuruma, (b) Sonora, (c) Baja California, (d) Abalamabie, and (e) GC.

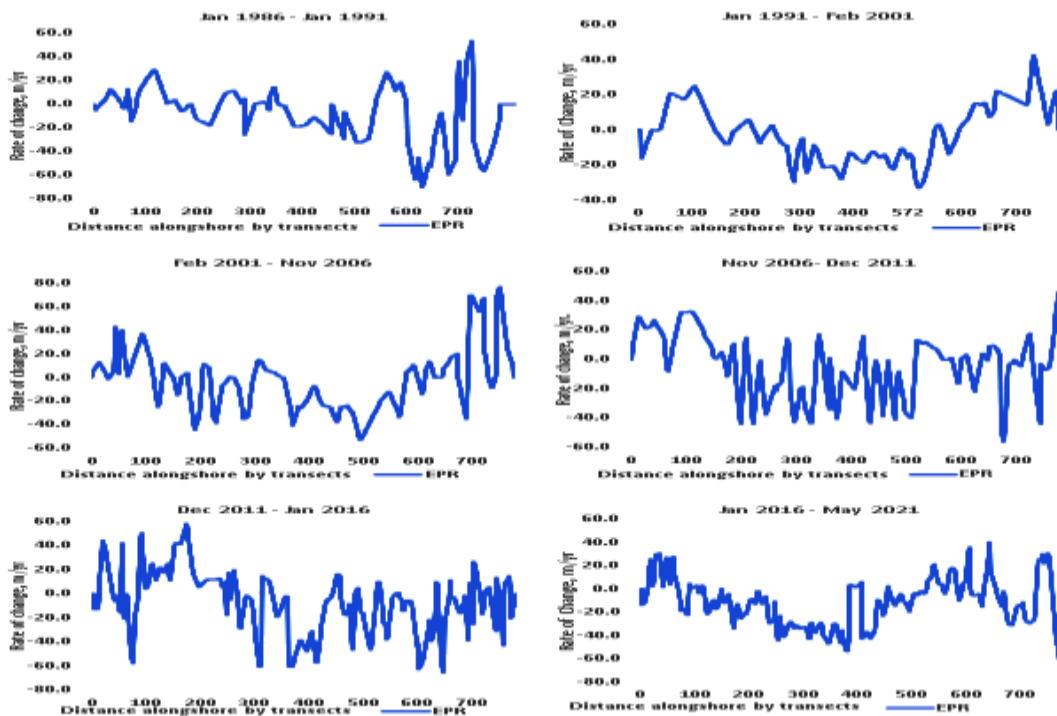


Figure 4 Shoreline change between 1986 and 2020

The short-term analysis of shoreline changes as used in this study includes 6 periodic intervals: 1986-1991, 1991-2001, 2001-2006, 2006-2011, 2011-2016, and 2016-2020 (Figure 3). The study reveals the erosional and accretional changes that have occurred along the shoreline over the 35 years considered. Between 1986 and 1991, the shoreline experienced a high rate of erosion

(Figure 4a). The EPR parameter shows that the shoreline experienced an average erosion rate of -22.11m/yr. and average accretion rate of +12.78m/yr. with a shoreline change of -9.33 m/yr. In terms of extent, 61.87% (48km) of the entire coast experienced erosion during this period while 38.13% (29km) experienced accretion, hence, erosion was predominant during this period. The

highest erosion rate was observed in the eastern part of the coast.

From 1991 to 2001, the erosion rates to od at -22.56m/yr. The accretion rate was 20.02 m/yr. This indicates a net change of -2.54 m/yr. for the shoreline. Results also indicate that 58.91% (45 km) of the entire shoreline experienced erosion in this period, and 41.09% (29 km) experienced accretion. Accretion was dominant in the eastern part of the coast and some sections of the western areas of the shore (Figure 4a). Between 2001 and 2006, the shoreline erosion rate was -23.76 m/yr and the accretion rate was +18.22 m/yr. Approximately 48% (37 km) of the total shoreline extent was accreted, while 52% (40km) eroded. As revealed in Figure 4a, erosion is dominant within this period with a net rate of -5.54m/yr. Erosion was predominant in the central section of the shoreline while accretion was predominant in the eastern section and the western section. EPR analysis between 2006 and 2011 shows that erosion rates were more intense in the central section of the coast. The erosion rate recorded was -24.17m/yr. the accretion rate was 17.6m/yr. The net rate of change was -6.57 m/yr. As shown in Figure 4a, some patches in the eastern sector also experienced low to high erosion within this period.

During the 2011-2016 period, increased erosion was observed in the western section of the coast compared to the previous period. Erosion remains the dominant phenomenon alongshore

(Figure 4b). The erosion and accretion rates recorded rate was -22.27 m/yr. and 15.95m/yr. respectively. 65.23% (50km) of the shoreline extent experienced erosion in this period, 32% (23 km) experienced accretion while 4km were stable. The net rate of change is -6.32m/yr. indicating high erosion during this period. In the 2016-2021 period, the erosion rate was -20.18 m/yr. accretion rate was 8.71m/yr. based on the EPR result. The net rate of change of erosion increased to -11.47m/yr. As revealed in Figure 4b, some parts of the shoreline's central area that experienced erosion during the last period were seen to have experienced accretion. Approximately 65.33% (50km) of the shoreline extent experienced shoreline erosion in this period.

c. Future Shoreline Forecast and Model Validation

This research forecasts the future position of the shoreline for the years 2030 and 2050, to understand the future dynamics of the coast. The period from 1981 to 2020 was used to forecast the shorelines, and the linear regression method and the application of the Kalman filter were chosen. The shoreline forecast with the LRR model showed significant shoreline setbacks (Figure 4.7) and revealed the same pattern as the coast changes between 1972–2020. Such a pattern was also observed along the coast of Catania, Southern Italy (Saxena et al. 2019).

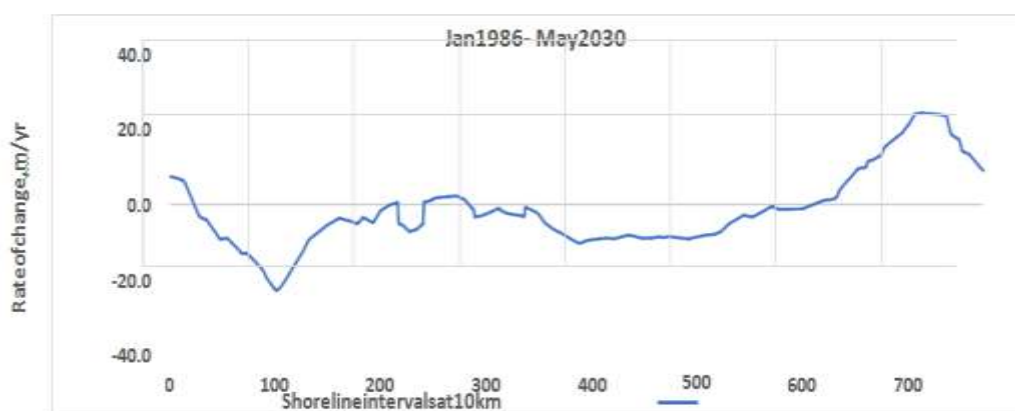


Figure 5 Shoreline change rate along the coast between 1986 and 2030

d. Trend of sea-level rise

According to Burningham & Fernandez-Nunez, (2020), two major factors can induce sea-level changes - one is global (mean sea-level change) while the other is regional (mean sea-level change) (extreme sea-level changes). The increase

in sea level is thus a significant phenomenon involving global and regional dynamics that exacerbate coastal vulnerability caused by climate change along every coast. The increase in sea level has a direct correlation with coastal inundation, and it can make a given coastal section highly

susceptible to flooding and saltwater intrusion along with the coastal slope, contributing to near shore area deterioration.

The thermal expansion of seawater and land ice melting contribute to sea-level rise [21]. Aside from constituting a significant threat to coastal marine ecosystems, rising sea levels substantiate much evidence of anthropogenic climate change. The increase in global atmospheric temperature induces an increase in seawater temperature and the resulting melting of ice, leading to a global rise in sea level [22]. Global experiments on sea-level rise have been widely carried out over the last two decades due to the availability of monthly mean sea level data by the Permanent Service for Mean Sea Level [23]. There are many means of deriving data for the computation of sea-level change, including satellite retrieval and direct measurements. In this study, the sea level measurements were sourced from the Nigerian Institute of Oceanography and Marine Research Database for the period covering 1986–2022. The assigned ranking value for coastal sea-level vulnerability varied between 1 and 5 (very low = 1, low = 2, moderate = 3, high = 4, and very high = 5).

In this study, the sea-level rise (SLR) vulnerability was categorized into very high (>3.2 mm/year), high (2.4–3.2 mm/year), moderate (1.6–2.4 mm/year), low (0.8–1.6 mm/year), and very low (<0.8 mm/year). The SLR recorded shows that much of the coast is low-lying with considerably high to very high vulnerability, with an average sea-level rise of 2.1 mm/year. Using the Bruun model, a study suggested that the Bonny coast is low-lying with about 1 to 3 m increase in sea level, with the Strand coast projected to experience more recession than other regions [24]. A similar vulnerability assessment associated with sea-level rise at the Badagry coast found that large segments of the coastline are vulnerable to sea-level rise, shoreline recession, and coastal flooding. This suggests that much of the Barrier, Mud, Delta, and Strand coast might be inundated and eroded by ocean water due to receding shoreline under rising sea levels. Sea-level rise is linked to coastal inundation, and when combined with unprecedented change in the coastal slope of a region, could cause any given coastal segment to be extremely susceptible to erosion, seawater intrusion into freshwater ecosystems, and loss of biodiversity, resulting in massive damage to the coastal shoreline and disruption of livelihoods of dwellers [25].

IV. DISCUSSION

As observed from the long-term shoreline variation, erosional processes dominate the central sections of the coast, with erosion rates as high as -65.67 m/yr recorded in this section and -76.2 m/yr towards the eastern section. Previous studies have also recorded high erosion rates, such as over -100 m/yr in some locations [26], [27]. Across the shoreline, the average erosion rate is between -1 and -25 m/yr. In previous studies, erosion rates are not far apart from this study, with [28] recording rates between -1 and -30 m/yr and [29] between -0.12 and -21.24 m/yr. The total land loss to erosion for the transgressive coast between 1986 and 2021 is 15.1 sq. km, which could trigger an additional 1.26 sq. km land loss by 2032. These rates are somewhat higher than previous studies which reported 10.6 sq. km [28] and 11.3 sq. km [26]. The variations may result from the shorter time periods considered, differences in duration of assessment, and the vegetation line proxy applied in [26].

The noticeable accretion in the western section of the coast is due to longshore drift of sediment from the Barrier-Lagoon coast from Lagos, rising sea levels, and sediment deposition. Localized erosion in the western section is attributed to human activities such as canalization and mangrove deforestation [24]. In the eastern sector of the shore zone, even with minimal visible erosion, more land loss occurred due to sea-level rise, as the region's topography is low-lying, ranging from 0.5 to 2 meters. Previous findings suggest that elevation in the eastern coastal communities such as Kalaibiana and Abalamabie ranges from 0.8 to 1.8 m, and these are frequently inundated during high tides [30], [27].

Sea-level rise has aggravated land loss in the transgressive mud coast, causing damage to coastal settlements. As revealed in [31], the coast experiences regular flooding due to large wave run-ups and astronomical tides. This has weakened interparticle bonds, making the sediments unconsolidated and more vulnerable to erosion by high-energy waves and tidal floods [30]. It was found that 201 sq. km (13.93%) of the mud coast is already inundated, with projections increasing to 551 sq. km by 2100 under AR6 RCP8.5 scenarios. The AR6 report predicted with high confidence that low-lying coasts will increasingly suffer from frequent and severe flooding and erosion this century. Comparing these results with previous studies [27], [32] reveals some variation. The findings in [27], using the Aerial Videotape-Assisted Vulnerability Analysis (AVVA)

technique, estimated that a 1-meter sea-level rise would inundate 2,016 sq. km of land in the transgressive mud coast, which is greater than the current study's results. However, the dataset used with AVVA had lower resolution (100–500 m) and wider uncertainties.

In contrast, [32] reported a smaller estimate of 199 sq. km inundation under a 1-meter SLR scenario, which underestimates the impact. This is likely due to lower elevation data resolution (90 m) and a vertical accuracy of ± 6.13 m, whereas this study used ALOS DEM with 30 m resolution and vertical accuracy of ± 4.95 m. This study also incorporated uncertainties into its maps and statistical summaries—something not done in [32], as suggested in [33].

Currently, there is displacement along the coast, as residents relocate away from advancing seawaters. Communities in the central and eastern coastal zones have been affected by wave action, storm surges, and the influence of estuarine tides. Many formerly inhabited areas—particularly in the east—are now flooded and at risk of worsening under a 1-meter SLR. The implications are severe: loss of life and property, land loss, displaced populations with emotional and psychological trauma, marine habitat destruction, reduced economic activity, vegetation loss, and disruption to livelihoods.

Overlay analysis of the inundation and shoreline change using the Linear Regression Rate (LRR) method (see Figure 11) showed that erosion was most intense in the central coast, accompanied by coastal land inundation. The western section experienced mild erosion and lesser inundation, while the eastern locations saw less present erosion but more land loss due to their lower elevation and the combined impact of Atlantic Ocean sea-level rise and estuarine tidal influx.

V. CONCLUSION

The study assessed changes along the Bonny coast using remote sensing and GIS techniques. Specifically, the study assessed shoreline retreat and sea-level rise-induced changes along the coast during the last 35 years. The results showed that the study area has experienced retro gradation, with a retreat of over 64% (49.8 km) of the 77-km long coast. This is due to insufficient sediment supply to prevent the landward retreat of the shoreline which in part is due to rising sea levels. This rapid rate of shoreline change indicates that retro gradation has triggered a land loss of 15.1

sq. km to the Atlantic over the last 35 years with the central sector of the coast the most vulnerable.

Climate change influences are also significant in changes across the shore zone as places inhabited by people before are now being inundated. Going by the AR6 RCP8.5 climate model that indicates that sea-level rise will exceed 1 m by the end of the century, this study established that 551 sq. km (38.18%) of the coast will be inundated with floodwaters. This will trigger the submergence of 150 buildings within 5 km of the shoreline. The population that will be affected is approximately 1,491. The observed patterns of shoreline changes in the study area are due to waves, rising tides, and anthropogenic forces along the coast which corroborates with findings from Dada et al. (2020) and Daramola et al. (2022).

RECOMMENDATIONS

1. In predicting long-term shoreline responses to climate change, integrating both long shore and cross-shore processes is essential. Understanding factors such as waves, tidal currents, sediment load changes, and human activities is crucial for comprehending shoreline dynamics. Coastal engineers' efforts to assess coastal storm strength and predict morphological changes, including shoreline erosion, are vital.
2. A unified framework for shoreline migration can help model shoreline transgression and coastal morphology changes, especially in response to sea-level rise. Atmospheric indices play a significant role in describing shoreline variability, emphasizing the importance of antecedent morphology in shoreline change assessments. Exploring probabilistic approaches, such as Bayesian networks, can help manage uncertainty in long-term shoreline change assessments.

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