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Article

Spatiotemporal Morphodynamics of the Nigerian Coastline

Diepiriye C. Okujagu[1], Evelyn Bose Ekeinde[2]

1. Department of Geology, University of Port Harcourt, Choba, Rivers State, Nigeria

* Correspondence: diepiriye.okujagu@uniport.edu.ng

2. Department of Petroleum and Gas Engineering, Federal University Otuoke, Bayelsa State, Nigeria

Abstract: Integrated Remote Sensing (RS) and Geographic Information System (GIS) Technology was used to predict and model the morphodynamics of the Nigerian Coastline in order to highlight mor-phodynamic active areas of threat to Oil/Gas infrastructure within coastal zone. Satellite imagery for 1987, 2002, 2015 and 2016 of the Nigerian coastline were acquired and analyzed using ArcGIS 10.5.0 software, Digital Shoreline Analysis System (DSAS v4.4) and Malthusian exponential equation Results of the satellite imagery revealed average values of end point rate (EPR) 4.17m/year and least median square (LMS) 3.54m/year for 1987 to 2016. Shoreline Area Change (SAC) was developed to aid visualization of the digitized coastline as against the poor visualiza-tion using ArcGIS software. The rates of change shows that accretion is higher than erosion and erosion is higher than accretion for some of the periods.

Keywords: Nigerian Coastline, morphodynamics, Shoreline Area Change, accretion and erosion

1. Introduction

The study of changes in the form and structure of the coastline due to erosion, sedimentation, interaction and adjustment of the seafloor topography, bathymetry, anthropogenic processes and hydrometeorological factors (such as waves, tides and wind-induced currents) is called Coastline morphodynamics [1]. This study in contemporary times are carried out using multidisciplinary remote sensing and GIS technics, where time series satellite imagery are obtained for the area of interest and are analyzed for spatial and temporal morphodynamics. Coastline and shoreline, are commonly used interchangeably. The National Oceanic and Atmospheric Administration (NOAA) defines the shoreline as the intersection between the landmass and the water's surface, representing the demarcation line between the terrestrial and aquatic environments on nautical charts [2]. In tidally influenced regions, this line corresponds to the mean high water (MHW) level. Conversely, for confined coastal waters with minimal tidal fluctuations, the mean water level (MWL) may be employed [2]. The NOAA, also defines the “Coastline” as the water/land interface. Hence, the “shoreline” is used as a more general term than “coastline” [3]. In this research, the terms will be used interchangeably as they refer basically to the land/water interface.

Coastlines, the dynamic interface between land and sea, are subject to continuous transformation in response to a multitude of environmental factors. These primary drivers of shoreline change include waves, tides, wind regimes, episodic storms, sea level fluctuations, geomorphic processes (erosion and accretion), and anthropogenic activities such as coastal development, engineering projects, and resource extraction (oil, gas, and water). The shoreline itself serves as a record of these ongoing processes, reflecting both recent

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landform creation and destruction. Notably, wave action plays a particularly influential role in shaping coastal morphology, sculpting the distinctive landforms observed along shorelines [4]. Coastlines all over the world are experiencing severe and continuous changes and are extremely sensitive and susceptible to global climatic influence resulting in eustatic sea level rise and is often associated with land subsidence from hydrocarbon and ground water exploration. This has necessitated an urgent need for a comprehensive and systematic study of the Nigerian coastline with the integration of hydrometeorological datasets such as tidal, wind, wave, ocean current and satellite imagery data for an in-depth multidisciplinary geo-investigation of spatial and temporal modelling morphodynamics of the coastal region.

The value of coastlines cannot be over emphasized. This is because coastlines, beaches and seashores have both social and economic impacts for people living within and far away. Coastal zones are used for food production, transportation, defense, recreation, urban residential development and also have an increasingly, wide importance as a hub for tourism and energy (oil and gas) [5]. Hence, coastlines are characterized as the most productive areas accessible to man. United Nations (UN) estimates show that 66% of the world's populations live within few kilometers of the coast [6]. However, current climatic events and future climatic modeling, have showed that the coastline is an area at great risk due to rising global sea level, coastal pollution, exploitation of coastal energy, use of coastal zone as location for power plants and accelerated erosion due to human intervention. This most sought-after location worldwide is becoming the most hazardous because sand beaches, sea cliffs, and low lying areas are frequently subject to sea level rise, tides, ocean currents, population density, oil spills and storm surges, which leave devastating imprints [7]. With advancement in nano technology, our ability to influence the coastal environment is increasing, but our knowledge of the effects of this technology is not increasing at the same rate. Hence, there is the need for constant evaluation, analysis, investigation, research and study of coastline changes (morphodynamics) resulting from hydrometeorological factors such as tides, winds, waves, ocean currents, sedimentation, erosion and induced land subsidence resulting from oil, gas and water extraction. The Nigerian coastal zone faces a multitude of environmental challenges, including sedimentation (siltation), erosion, flooding, pollution (originating from oil spills, solid waste, and sewage), overexploitation of fishery resources, and the adverse effects of global climate change, particularly sea level rise. It is pertinent to note that there is lack of adequate morphodynamic study on the entire Nigerian coastline from its border with Benin Republic to Cameroon to document the extent of change and its overall impact on the coastal zone using remote sensing satellite imagery.

This study will focus on the analysis of time series Landsat satellite imagery of the entire stretch of the Nigerian coastline paths and rows of 30m resolution at 30m fixed scale using ArcGIS 10.5. Figure 1 below shows the study area States, paths and rows of the satellite imagery across the Nigerian coastline, in-line with the Worldwide Reference System (WRS) for Landsat data. Within the Worldwide Reference System (WRS), satellite imagery is divided into frames (scenes) identified by a unique combination of path and row numbers. The path number signifies the satellite's ground track, while the row refers to the latitudinal center of the image frame. As the satellite travels along its path, its instruments continuously scan the Earth's surface. The collected data is then segmented and correlated with telemetry information to create individual scenes [8].

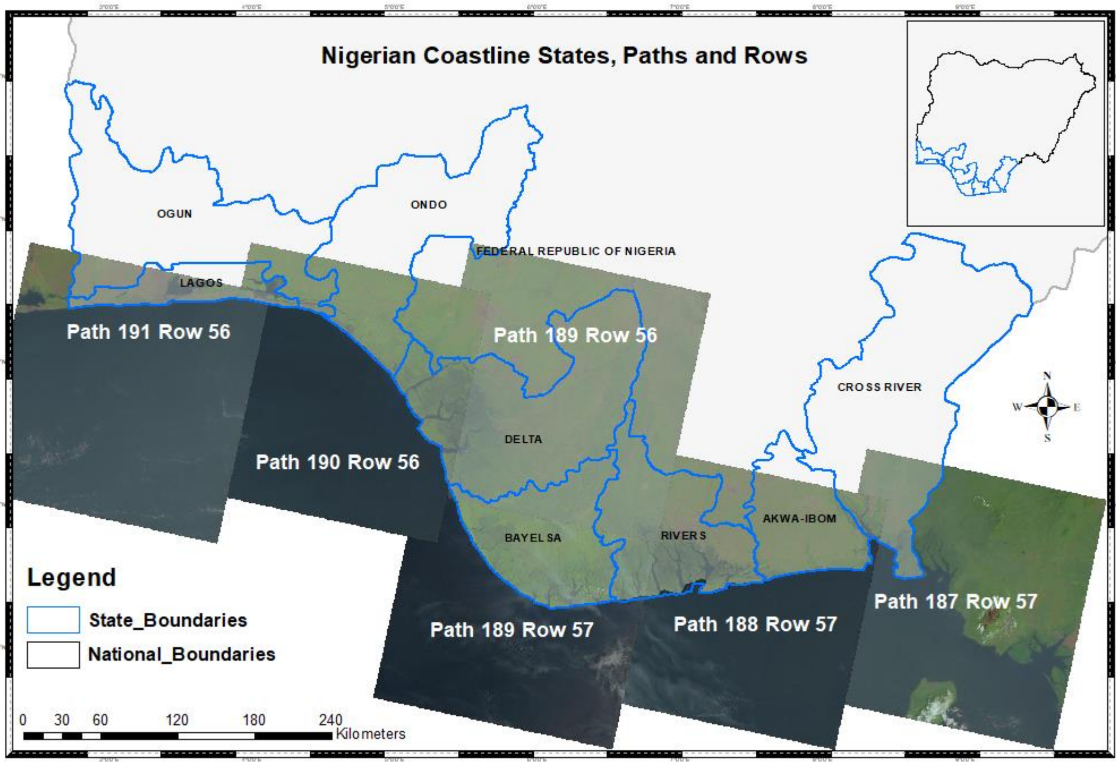

Figure 1. Nigerian Coastline States, Paths and Rows (Source - Research Author)

Nigeria, spanning latitudes 4°N-14°N and longitudes 2°E-14°E, boasts the largest landmass in Africa (910,768 km²) with a 13,000 km² coastal zone bordering the Gulf of Guinea [9]. This narrow strip teems with diverse ecosystems, rich natural resources, and a significant human population concentrated in nine coastal states (Akwa Ibom, Bayelsa, etc.) representing 25% of the nation [10]. The zone encompasses the continental shelf, Exclusive Economic Zone, and a network of rivers, creeks, and wetlands influenced by tidal variations [10]. Notably, the Niger Delta is a hotspot for mangrove ecosystems [11]. The Nigerian coastal zone is the backbone of the nation's economy. Oil and gas, primarily extracted from the Niger Delta, contribute 95% of foreign exchange earnings and 65% of government revenue [11]. Fisheries are another mainstay, providing a wealth of fish, shellfish, and other marine resources [12]. The continental shelf, ranging from 15 km to 85 km offshore, further supports these economic activities [13].

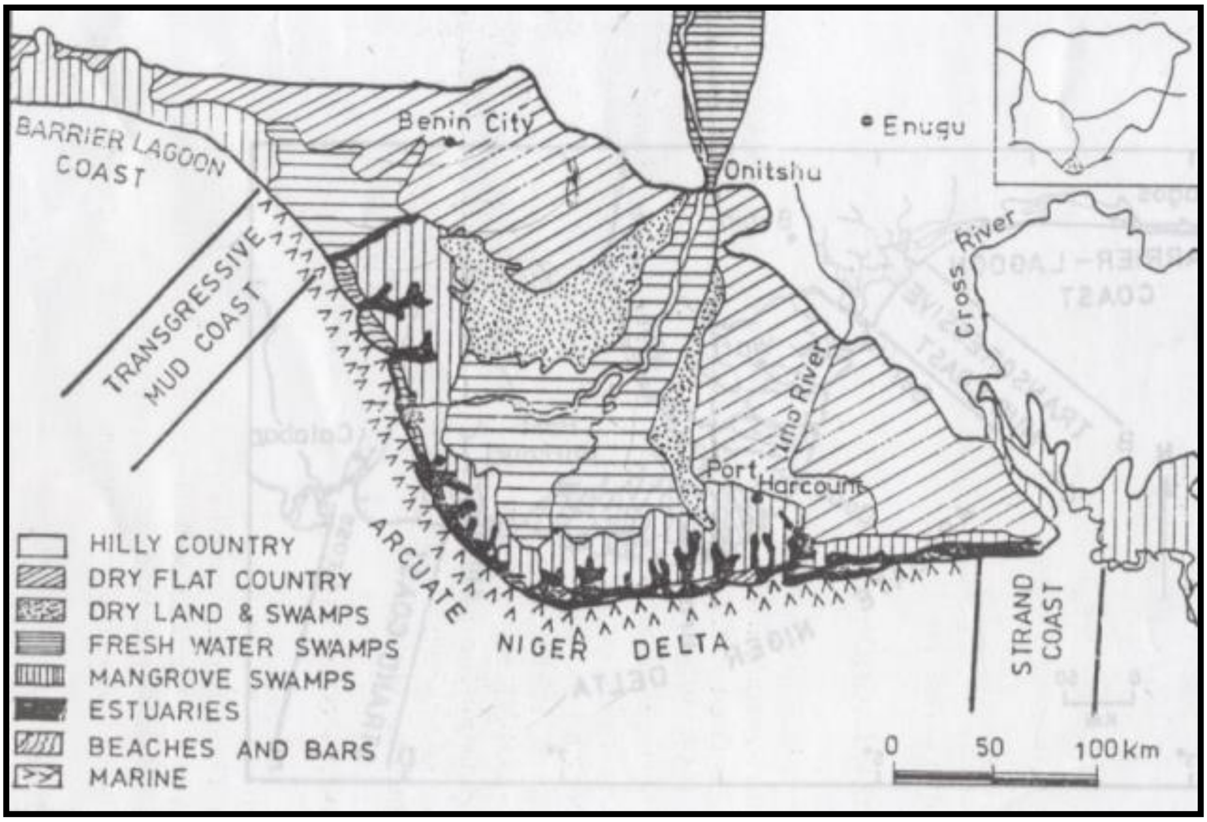

Figure 2. Map of Nigerian Coastal zone showing Physiographic features and adjacent landmass (After Short and Stauble, 1967)

2. Literature Review

Numerous studies have documented erosion as a dominant phenomenon along the Nigerian coast, with rates reaching 30 meters per year [14], [15]. Technical reports by NIOMR estimate contrasting rates of accretion and erosion at different locations [16]. Satellite imagery analyses have further quantified shoreline changes, revealing dominance of erosion over accretion in the Niger Delta [17], [18]. Studies by Anita and Nyong (1988) have classified different sections of the coastline based on their morphodynamic states, with implications for coastal engineering projects [19]. Research by Ogba et al. (2010) assessed the vulnerability of the Niger Delta to climate change, highlighting threats like inundation and increased salinity [20]. Shakirudeen et al. (2014) investigated the potential impact of sea level rise on coastal inundation, suggesting varying levels of risk depending on development scenarios [21]. Studies by Fadahunsi et al. (2012, 2013) and Eludoyin et al. (2011) have demonstrated the effectiveness of satellite imagery and remote sensing techniques in shoreline characterization and change detection [22], [23], [24]. Studies like Onwukanjo (2014) and Fabiyi (2015) have explored the impact of human activities on coastal ecosystems and land use patterns [25], [26]. Ajibola et al. (2017) investigated the relationship between coastline changes and property values [27]. Fatai et al. (2006) explored oil spill simulation models for oil response planning. While numerous studies exist, they often focus on specific regions or lack long-term data (above ten years) [28]. There's a need to integrate high-resolution satellite imagery for a more comprehensive understanding of coastline dynamics. Existing research primarily focuses on past and present changes. Future studies should explore software development for shoreline change prediction at continental scales.

3. Materials and Methods

3.1. Study Area

The area of study is the 853km stretched Nigerian coastline from the Nigeria/Republic of Benin boundary in the west to the Nigerian/Cameroon boundary in the East and the

Atlantic Ocean in the South, between latitude 4° 10′ to 6° 20′ N and longitude 2° 45′ to 8° 35′ E.

Figure 3. Map of Study Area (Edited after ESRI, 2017)

3.2. Methods of Data Analysis

3.2.1. Image Data Processing: - ArcGIS 10.5

Image data processing involved the following:

i. Geometric correction and georectification
ii. Spectral enhancement and Map rendering

3.2.2. Image Data Analysis: - ArcGIS 10.5 and DSAS v4.4

The methodology for image data analysis involved:

i. Coastline digitization (Vectorization and change mapping using Stretched rendered and shaded Relief images)
ii. Appending Shorelines
iii. Creation of Baseline
iv. Creation of Transects
v. Calculation of Statistics
vi. Creation of Change Envelope
vii. Clip transects to Shoreline Change Envelope

3.2.3. Change Statistics Analysis: - DSAS v4.4

Change statistics was done in ArcGIS using DSAS v4.4 and analysed in Microsoft excel.

3.2.4. DSAS Parameters Used:

The following settings as shown in Figure 4 below were applied to the digital shoreline analysis system (DSAS) software used for the change statistics analysis.

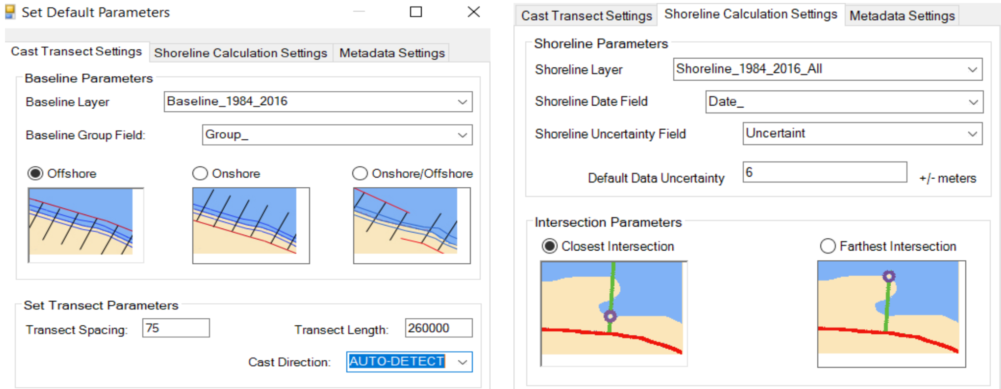

Figure 4. Default Parameters for DSAS

Note:

1) 75 meters was used as transect spacing (Figure 5 (A and B)) because that was the minimum spacing that could run with the dataset due to its largeness, as advised by Himmelstoss, Emily of United States Geological Survey (USGS).
2) 260,000 meters was used for the transect length from the baseline to the shoreline (Figure 5 (A and B)).
3) 6 meters was used for the data uncertainty: average Root Mean Square Error (RMSE).
4) Other settings are as specified in ArcGIS 10.5 during data preparation for DSAS analysis.
5) 100 transects was created at 228m intervals perpendicular to an horizontal baseline on the Bonny Island Coastline (Appendix 3.34 – 3.35).

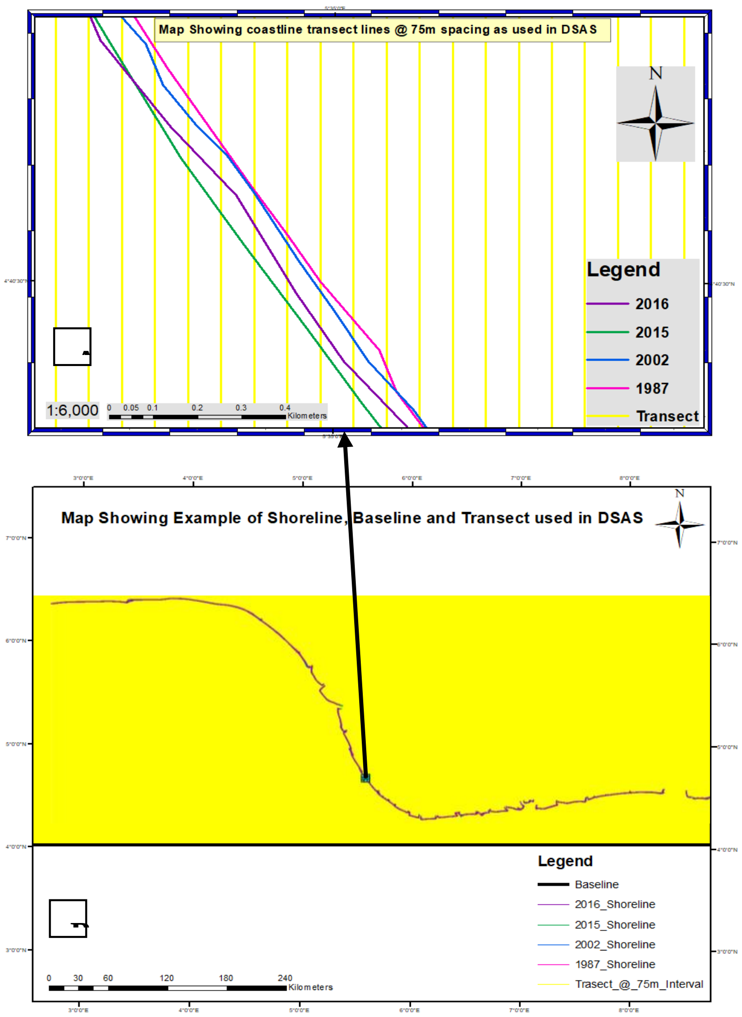

Figure 5. (A) An enlarged area of the coastline showing transect spacing as used in DSAS, (B) Example of shoreline, baseline, transect as used in DSAS and the specific area enlarged in Figure 4 above

3.3. Materials

3.3.1. Nature/Sources of Data

Datasets used for this research are; satellite imagery, shorelines, transects, baselines, and change statistics.

3.3.2. Image dataset

The image dataset used for this project are Landsat 8 (OLI & TIRS), Landsat 7 (ETM+), Landsat 5 (TM & MSS) and Landsat 4 (TM & MSS) for 1987, 2002, 2015 and 2016 (Appendix 3.1 – 3.33). All scenes are dry season images acquired at low tide to avoid seasonal effects on the analysis at 30 meters spatial resolution.

3.3.3. Vector dataset

Vector datasets used for this study include:

1. Shapefile for Nigeria, States, LGA's & Communities
2. Shorelines
3. Baseline

3.3.4. Geodetic Parameters

The following geodetic parameters were used in this study:

1. Ellipsoid: Clarke 1880(RGS)
2. Datum: D_Minna
3. Coordinate System Name: Minna_UTM_Zone_32N
4. Projection: Transverse_Mercator
5. False_Easting: 500000.000000
6. False_Northing: 0.000000
7. Central_Meridian: 9.000000
8. Scale_Factor: 0.999600
9. Latitude_Of_Origin: 0.000000
10. Linear Unit: Meter

3.3.5. Methods of Data Collection/Instrumentation/Analysis

Datasets such as georeferenced satellite imagery were received from Shell Nig. (SPDC P.H) and United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. While shorelines, transects, baselines, change statistics were generated from the georeferenced satellite imagery.

3.3.6. Validity/Reliability of Instrument

The Landsat dataset used for this research, corresponds to Landsat Level-1, indicating the highest level of correction applied for each image scene. The level of processing applied is fixed on the presence of ground control points (GCP), Digital Elevation Model (DEM). Elevation information, spacecraft and sensor (Payload Correction Data (PCD) information as can be found in the metadata (.MTL.txt) files that come along with Landsat Level-1 data products.

4. Results

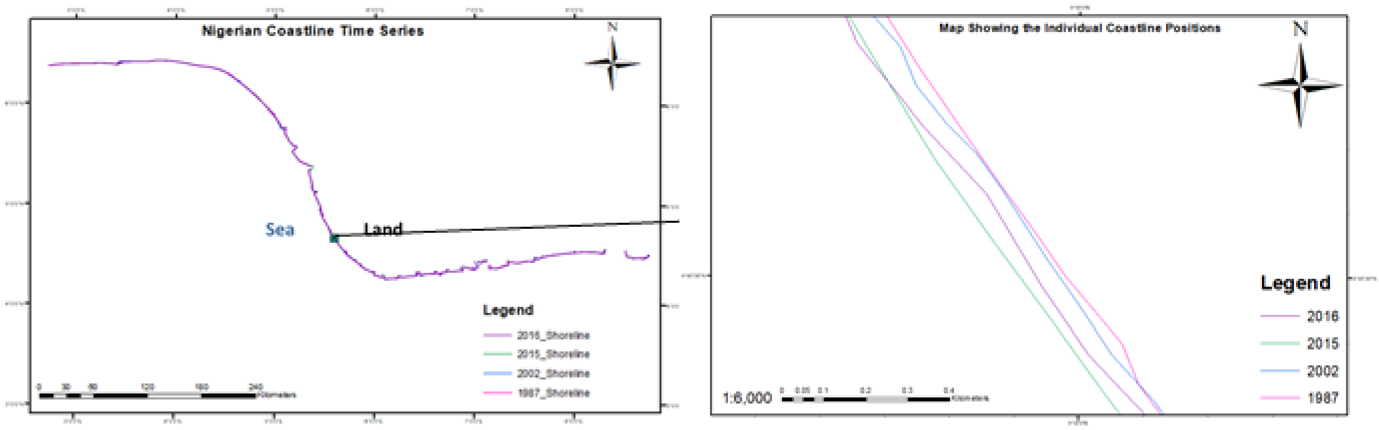

Figure 6. (A) Nigerian Coastline Time Series for 1987, 2002, 2015, and 2016 as seen in ArcGIS 10.5 software, (B) An enlarged Map of a section of Figure 6 (A) showing the Individual Coastline

Figures 6 (A) and (B) show the results of time series coastline positions for 1987, 2002, 2015 and 2016, at a macro-continental scale (100 km to 10,000 km) using ArcGIS 10.5 software. At this scale, it is not possible to clearly differentiate the individual coastlines as seen in Figure 6 (A), as they appear to be intertwined as one. Hence a portion of the coastline is enlarged at a micro-local scale as seen in Figure 6 (B), making it possible to differentiate the positions of the coastline across the years.

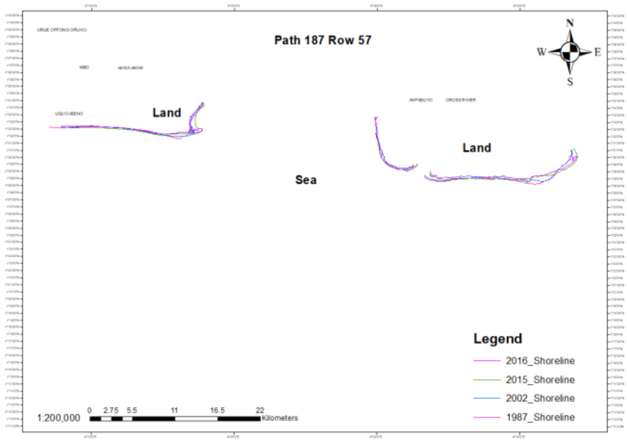

Figure 7. Map of Path 187 row 57

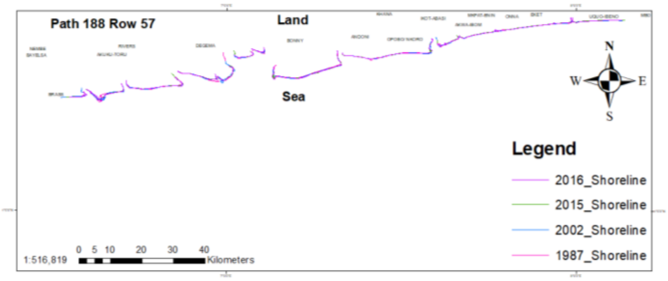

Figure 8. Map of Path 188 Row 57

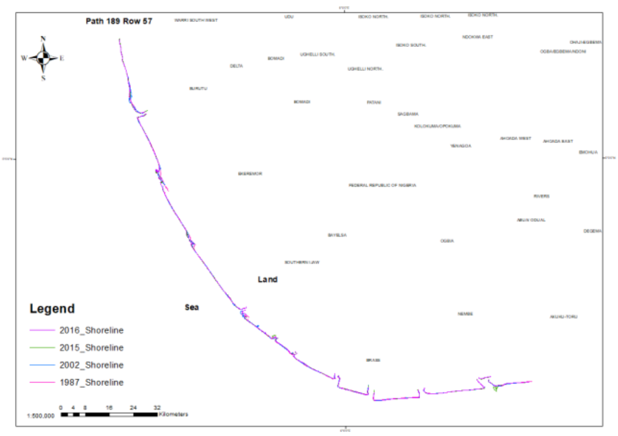

Figure 9. Map of 189 Row 57

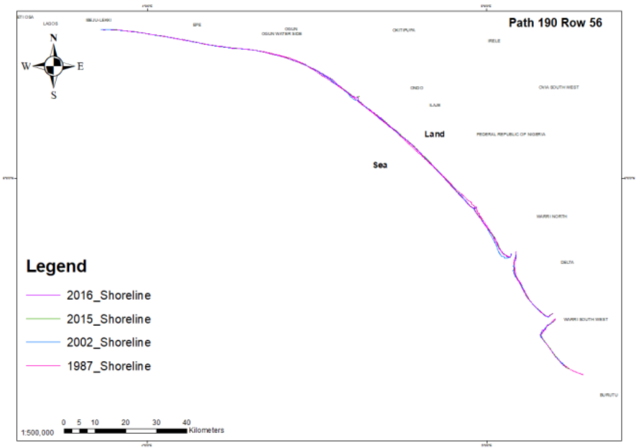

Figure 10. Map of 189 Row 56

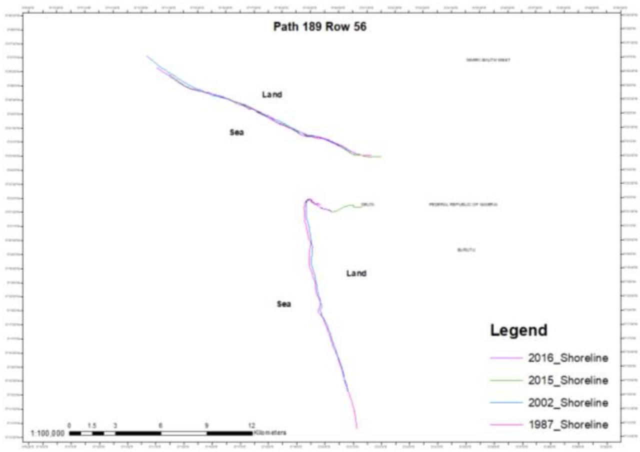

Figure 11. Map of 190 Row 56

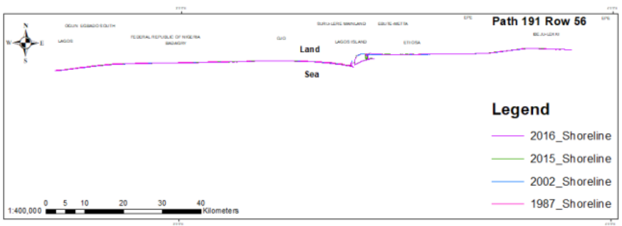

Figure 12. Map of 191 Row 56

Table 1. Coastline change summary for five periods

Years (Periods)		SCE	NSM	EPR	ECI	LMS
1987 to 2002	Erosion	-73.88	-71.5	-4.74	-0.03	-3.26
	Deposition	101.3	101.3	6.64	0.06	5.7
	Average	**87.59**	**86.4**	**5.69**	**0.045**	**4.48**
2002 to 2015	Erosion	-133.38	-91.8	-6.8	-0.07	-5.8
	Deposition	133.4	60.99	4.59	0.04	3.04
	Average	**133.39**	**76.40**	**5.70**	**0.055**	**4.42**
2015 to 2016	Erosion	-43.3	-26.61	-146.86	-2.45	-15.15
	Deposition	131.27	124.31	574.4	6.49	42.12
	Average	**87.29**	**75.46**	**360.63**	**4.47**	**28.64**
2002 to 2016	Erosion	-120.35	-107.44	-7.82	-0.06	-5.37
	Deposition	91.88	83.31	5.35	0.05	4.03
	Average	**106.11**	**95.38**	**6.59**	**0.06**	**4.70**

1987 to 2016	Erosion	-117.09	-116.91	-4.05	-0.02	-3.17
	Deposition	123.37	123.37	4.29	0.03	3.91
	Average	**120.23**	**3.23**	**4.17**	**0.02**	**3.54**

Table 2. Coastline Percentage (%) Change summary for the five periods

Years (Periods)		**EPR**	**Rate % Change**	**% Change**	**LMS**	**Rate % Change**	**% Change**
1987 to 2002	**Erosion**	-4.74	42	34	-3.26	36	25
	Deposition	6.64	58	66	5.70	64	75
	Average	**5.69**			**4.48**		
2002 to 2015	**Erosion**	-6.80	60	69	-5.80	66	78
	Deposition	4.59	40	31	3.04	34	22
	Average	**5.70**			**4.42**		
2015 to 2016	**Erosion**	-146.86	20	6	-15.15	26	11
	Deposition	574.40	80	94	42.12	74	89
	Average	**360.63**			**28.64**		
2002 to 2016	**Erosion**	-7.81	59	68	-5.37	57	64
	Deposition	5.35	41	32	4.03	43	36
	Average	**6.58**			**4.70**		
1987 to 2016	**Erosion**	-4.05	49	47	-3.17	45	40
	Deposition	4.28	51	53	3.91	55	60
	Average	**4.17**			**3.54**		

5. Discussion

It is noticed that increased deposition (very high accretion) was recorded from 1987 to 2002, 1987 to 2016, and 2015 to 2016, while increased erosion (very high erosion) was recorded in 2002 to 2015, and 2002 to 2016, using Usha et al 2015 classification scheme [29] (Table 3).

Table 3. Shoreline classification based on EPR, LRR and LMS (after Usha et al., 2015)

Category	**Rate of shoreline change (m/year)**	**Shoreline classification**
1	> -2	Very high erosion
2	> -1 and < -2	High erosion
3	> 0 and < -1	Moderate erosion
4	0	Stable
5	> 0 and < +1	Moderate accretion
6	> +1 and < +2	High accretion
7	> +2	Very high accretion

The results of this research are similar with findings of [15] for rates of erosion at Victoria beach in Lagos (25-30m/yr), Awoye/Molume in Ondo (20-30m/yr), Forcados (20-22m/y), and Escravos/Ogboiodo (18-24m/yr), Brass (16-19m/yr), Kulama (15-20m/yr), and Bonny (20-24m/yr). Periodic sand filling of Victoria beach and Forcados prevented the two beaches from becoming disaster areas. Akinluyi et al. (2018) assessed shoreline and associated landuse/ land cover changes along part of Lagos coastline, Nigeria and concluded that from 1984 to 1990 erosion was very high over deposition and from 1990 to 2000, erosion was high over deposition but from 2000 to 2016 deposition was high over erosion with overall rate of change 1990 to 2016 for erosion as -0.51m/year EPR (moderate erosion) and deposition 1.50m/year EPR (high accretion) [30]. These findings are in agreement with the results of this research, which shows that at different periods along the coastline we have erosion high and at other periods we have deposition high especially towards year 2016.

The area of change between 1987 to 2016 as seen in Tables 1 follow the same pattern as seen in the works of Obowu and Abam (2014) in their studies of Spatial and multi Temporal change analysis of the Niger Delta coastline using Remote Sensing and Geographic Information system. The study revealed that an average of 6855m^2 (46%) land loss over 8031m2 (54%) land gained [18].

The findings of this study on Niger Delta coastline changes (2002-2015/2016) align with previous observations by Adegoke et al. (2010). Utilizing Landsat imagery (MSS 1972 & ETM+ 2008), they documented a total change of 46.535 km^2 along the coastline. This change comprised erosion in 59.43% (27.65 km^2) of the area and accretion in the remaining 40.57% (18.88 km^2). These proportions are comparable to the patterns observed in the present study for the Niger Delta.

This study's findings on shoreline changes align with previous observations. Adegoke et al. (2010) documented a net accretion trend in the Forcados area (1986-2003) following erosion mitigation measures implemented by Shell Petroleum Development Company (SPDC) in 1986. Similarly, this study observed accretion dominance in the region (1987-2002, 2015-2016). These results support the notion that interventions can influence erosion patterns.

Further supporting this notion, Opuene (2015) observed long-term accretion as the dominant trend in Brass (Niger Delta) despite short-term periods of erosion. This highlights the dynamic nature of coastline change [31].

The observed dominance of accretion in this study also aligns with Viv (2012), who documented a net land gain (accretion) in the Mangrove Conservation Areas of Pamurbaya (2002-2014) [32].

These comparisons suggest a potential for managing coastal erosion through targeted interventions. Results of this study agree with results of Anirban et al (2012) research on "Automatic shoreline detection and future prediction: A case study on Puri Coast, Bay of Bengal, India for 1972 to 2010" [33]. The study showed deposition greater than erosion. This research results also correspond to the result of Barman et al (2015) on "Trends of shoreline position: an approach to future prediction for Balasore shoreline, Odisha, India for 1972 to 2010", which showed deposition higher than erosion in the north east part of Balasore shoreline [34]. However, Henry (2013) in his study of Mbo coastal area of Akwa Ibom state using Landsat images for 1990, 2000 and 2010 showed erosion dominant to deposition [35]. This is consistent with this study for 2002 to 2015 and 2002 to 2016 where erosion is higher than deposition.

Results of Shakirudeen et al (2014) affirmed the presence of accretion in Badagry area of the Nigerian coastline which may be result of dredging and coastal land filling [21]. This is in consonance with the findings of this research. Abiodun et al (2017) in Time Series Analysis of Shoreline Changes along the Coastline of Rivers State, Nigeria, revealed that from 1984 to 2000 accretion was 83% while erosion was 17%, while from 2000 to 2016, accretion was 10% with erosion 90% [36]. The overall change from 1984 to 2016 showed accretion 48% with erosion 52% signifying that from the year 2000, there was increase in erosion to a point before deposition began due to sand-filling/ sediment deposition and other human activities in the area to reduce the risk associated with coastal erosion. This result is in agreement with this research. Lakmali et al (2017), carried out research on the long term coastal erosion and shoreline positions of Sri Lanka for five years (2010 to 2016) and discovered that due to beach protective structures, areas of severe erosion were seen to have stable accretion growth [37]. This corresponds with findings of this research where areas of erosion where replaced with deposition.

Other studies with similar findings to this research include; Sumeyra Kurt et al (2010) in their study on coastline changes of Marmara, Black sea and Bosporos coast of Istanbul Turkey using Landsat images 1987 to 2007, with results revealing 97% deposition to 3% erosion [38]. Adriano et al (2003) used Landsat 5 TM images for 1989 and 1998 to identify changes in erosion and deposition along the northeast coast of Brazil; the results showed erosion dominant over the 10 year period [39]. This conforms to results of this study for 1987 to 2002, 2002 to 2015, and 1987 to 2016. Grigio et al (2005) studied changes along Guamare coastline in Brazil, using Landsat 5 TM images for 1989, 1998, 2000 and 2001 [40]. Results showed intense erosion (78%) for 1989 to 2001 which is similar to results of 2002 to 2015 and 2002 to 2015 of this research. Ekong (2017) used GIS to analyze Shoreline Change in Ibeno, Akwa Ibom State, Nigeria, from 1986 to 2008 [41]. The results showed an average erosion rate change of −3.9 m/yr and average accretion rate change of 2 m/yr. It was noted that the erosion was as a result of ongoing human and engineering activities at the river estuary along the shoreline while accretion near Exxon-Mobil was as a result of sand filling done in the past for settlement development. This result for Ibeno stands as a mini result for the entire Nigerian coastline as can be seen from the results of this research. Thus, coastal processes affecting Ibeno are similar to the coastal processes affecting the Nigerian coastline.

6. Conclusion

This study employed satellite imagery to analyze the entire 853 km stretch of the Nigerian coastline for spatiotemporal changes, making it the first such comprehensive analysis. The findings revealed a complex interplay between erosion and deposition along the coast. Compared to the 1987 baseline, deposition rates were significantly higher than erosion in 2002, 2015, and 2016. However, a comparison between 2002 and 2016 indicated periods of erosion exceeding deposition. These findings align with the presence of depositional and erosional landforms like sand spits, cuspate forelands, and barrier islands. Additionally, the high rate of deposition aligns with the calculations of the Equilibrium Point Rate (EPR) and Littoral Mobility System (LMS) models. The Niger Delta region, specifically, is believed to receive continuous sediment input from high rainfall runoff, rivers, and streams discharging into the area. This limited backwash further reduces erosion rates. These observations corroborate Moko et al. (2012) who identified factors like riverine sediment discharge and coastal reclamation projects as drivers of shoreline change. This research has two key contributions. First, it establishes the SAC software, a novel tool within ArcGIS that utilizes DSAS data for improved coastline area change monitoring and analysis. This cost-effective software can assist stakeholders in evaluating potential economic impacts of erosion and deposition on coastal infrastructure, including facilities, harbors, and communities. Second, the study enhances our understanding of the severity of coastal erosion and deposition threats in Nigeria, emphasizing their impact on oil and gas facilities and neighboring communities. This knowledge underscores the urgency of implementing effective mitigation measures such as riverbank and shoreline protection works. The observed dominance of deposition along the Nigerian coastline can be attributed to its structural morphology and the extensive length of the Niger Delta, which limits the fetch for significant wave action. However, the presence of erosion periods highlights the need for continued monitoring and adaptation of coastal management strategies.

7. Acknowledgments

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