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Research Article

Futuristic prediction of the lagoon coast shorelines using spaceborne Synthetic Aperture Radar (SAR) imagery

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Abstract

The coast is an extremely dynamic ecosystem that is subject to anthropogenic factors and sea level rise. All of this heightens the worry because it combines the elements that produce storm surges and tropical storms, which raise the possibility of shoreline shift and subsequent coastal erosion. The coastal zone is a prime example of a crucial ecosystem that is also highly dynamic, with shorelines that grow and contract in response to human activity, storm surges, tropical cyclones, and sea level rise. The shoreline that characterizes erosion and deposition is constantly changing, but accurate monitoring and mapping of these changes are made necessary by the ecosystem's economic viability. In this study, Sentinel-1 Synthetic Aperture Radar (SAR) imagery was used to forecast the futuristic position of the Lagoon Barrier shoreline in Lagos state, Nigeria. The Digital Shoreline Analysis Software (DSAS) statistics of End Point Rate (EPR) and Linear Regression Rate (LRR) were used to examine the shoreline projection. The study's findings demonstrated that shorelines movements can be monitored using Sentinel-1 SAR imagery owing to its characteristics that helps in distinguishing water from land. The shoreline projection indicated that general erosion would occur in this area at a rate of 1.45 meters per year. Communities in Ojogun, Okun-Ibese, Makoko, and Mobido are likely to be at risk from this erosion. With regard to the sustainable management of coastal zones, this research initiates a new endeavour for legislators and town planners.

Keywords: coastal erosion; Lagos; remote sensing; shoreline forecast; Synthetic Aperture Radar (SAR)

Introduction

A coastal zone, is a dynamic ecosystem characterized by coral reefs, mangrove forests, coastal flood plains, lagoons, beaches and dunes (Creel, 2003; Sheeja and Gokul, 2016; Zhu *et al.*, 2021) and often affected by several factors such as the wind energy and frequencies also by the rising sea level and storm surges. Any deviation in the coastal materials such as in the rock type, slope or soil type will impact the coastal zone (Wiafe *et al.*, 2013; Arjasakusuma *et al.*, 2021). Projected happenstances of climate change will further cause sea level and storm surge to rise to exacerbate coastal zone descent and this culminating effect will make the coastal environment become predisposed to the menace of flooding, erosion, saltwater intrusion and coastal subsidence (Spinosa *et al.*, 2021; Fashae *et al.,* 2022). Over 60% of the global urban settlement is positioned

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around coastal zones with over 5 million populations (Fashae *et al.*, 2022) and 12% of the world surface is occupied by resources and amenities from this zone (Costanza *et al.*, 1997; Grill *et al.*, 2019), a continuous deterioration of this environment means so many damages in terms of businesses, the livelihood of humans and animals, farmlands as well as the tourist attractions. The coastal zone change is however defined quantitatively from observing the shoreline variation either inward or outward from the ocean body. The interplay between the physical features of this dynamic ecosystem and the driving factors are very important subject in studying the position variation of shorelines (Olali, 2015; Pepe *et al.*, 2023). Coupled with the economic benefits generated from the coastal zone, it becomes important that they are monitored from time to time and the results are put into use for urban development and environmental management.

The lack of adaptation structures, rapid population growth, low-lying lands, and slow development have made the African coast extremely vulnerable to the effects of sea level rise (SLR) (Nicholls and Cazenave, 2010). Remarkably, Neumann *et al.* (2015) used remote sensing to conduct a comprehensive worldwide investigation into the impact of SLR on future coastal inhabitants. The results showed that eight African countries made the list of the top 25 countries vulnerable to SLR and coastal hazards, and additional results showed that Nigeria and Egypt were among the top fifteen vulnerable nations (Neumann *et al.,* 2015). This result emphasizes how urgent it is to complete the analysis to project the shorelines along the Nigerian coast in the future and to develop policy based on the results. Being a very resourceful coastal area habituating most of the oil exploration in the country as well as cultivation of rare class of fishes that ordinarily can only be fetched from other far west African states (Nwilo, 1997), Nigeria's coastline also serves as the source of attraction to tourist globally, especially the Lagoon Barrier Coast in Lagos state, a base for several beaches and relaxation centres. The posing economic viability of this area has seen an accompanying increase in the growth of inhabitants, businesses and infrastructures coupled with the sea level rise constitutes factors that drive shoreline change hence; the pertinence to determine the future position of the shoreline to cushion any associated effect of this positional change.

Shoreline changes have been studied using a variety of methods at local, regional and global scales with variant levels of accuracy. Some studies have utilized, remotely sensed satellite data (Bartsch *et al.*, 2020; Popoola, 2022), historical maps (Pepe *et al.*, 2023) as well as aerial photographs, LiDAR imagery and terrestrial/*in-situ* data. Recent advancements in the use of remote sensing techniques to monitor shoreline changes have shown promise in comparison to the traditional ground surveying method, which has proven to be relatively high in terms of cost, labour, and schedule (Klemas, 2013). Optical satellite imagery makes it simple to interpret, extract, and measure coastlines. Sadly, the imagery is created by passive sensors, which have several limitations, including the inability to retrieve data at night, a high cloud cover percentage, and a low spatial resolution of 30 meters, which determines the horizontal accuracy of the data (Gens, 2010). The European Space Agency (ESA) recently developed Sentinel-1 Synthetic Aperture Radar (SAR), a tool that has been effectively used to monitor flooding (Carreño and De Mata, 2019; Qiu *et al.,* 2021; Isiaka *et al.,* 2023) and changes in the shoreline (Zollini *et al.,* 2019; Bartsch *et al.,* 2020; Zhu *et al.,* 2021) with characteristics ability to produce image at night, through cloudy-skies or during extreme storm events with as low as 5 m spatial resolution which are some of it advantages over the passively sensed imagery. They also have a range of applications aside from the monitoring of coastal hazards but specific to coastal hazard monitoring are Synthetic Aperture Radars (SAR), LiDARs, Radar altimetry and scatterometers (Melet *et al.*, 2020). Of interest to this research is Sentinel-1 SAR data which operates in the C-band portion in four special imaging modes, i.e. Strip map (SM), Extra wide swath (EW), Wave (WV) and Interferometric wide swath (IW)) and large swath coverage of about 400 km per scene. With the promising abilities in the utilization of this data for coastal hazards monitoring, the technology which portrays an exceedingly exciting technology is quite underutilized in the monitoring of coastal hazards notably in the study area of this research.

By combining the high-resolution imagery obtained from the satellite and the great capability of the Geographic Information System (GIS) for data capturing, manipulation, processing and interpretation, the future position of the Lagoon Barrier coastline can be estimated creating an avenue for putting up measures that would manage the accompanying effects of this projection. In previous research, GIS technology has shown its promising strength in the handling of geospatial data like remotely sensed imagery to precisely, investigate shoreline changes (Oyinloye *et al*., 2016; Adefisan *et al.,* 2018; Akinluyi *et al.,* 2018; Fashea *et al*., 2022; Popoola, 2022; Pepe *et al*., 2023), however, no literature has used Sentinel-1 SAR imagery to forecast the future position of the Lagoon Barrier coastline in Lagos State. As an alternative to the previously used methodologies (Oyinloye *et al*., 2016; Adefisan *et al*., 2018; Akinluyi *et al*., 2018; Fashea *et al*., 2022; Popoola, 2022), this study presents an approach that uses extracted shorelines from Sentinel-1 Synthetic Aperture Radar (SAR) imagery to forecast the future position of the Lagoon Barrier Coast in Lagos State, Nigeria. Research output will provide policymakers, and planners with pre-informed knowledge of areas that need proper monitoring to maintain a sustainable environment as well as areas requiring development of adaptive infrastructures to withstand any associated futuristic hazard.

Materials and Methods

Study Area Description

Nigeria's second-longest coastline is found in Lagos State, the nation's economic hub. It is located between latitudes 6° 20' 0" and 6° 50' 0" and longitudes 3° 0' 0" and 4° 30' 0" (Figure 1). Businesses in the area have a long history of success, and as a result, a large number of people from near and far have immigrated to the state. The Lagoon Barrier Coast region of West Africa's coastline, which passes through Lagos State and forms the state's border with the Atlantic Ocean along the Gulf of Guinea coast, is the focus of this study. The state is bounded to the east by a portion of Ondo, to the north by a portion of Ogun State, to the west by the Republic of Benin, and to the south by the Atlantic Ocean. With more than 20% of the state's population living near the coast, the shoreline position is increasingly threatened. The majority of the coast's geological features are made up of sandstones and shales, along with lithographic features like sand, clay, and limestone. With an average annual rainfall of 880 to 890 millimetres per year, rising sea levels in the world's oceans, and saltwater intrusion, the shoreline of the Lagoon Barrier Coast is vulnerable to changing conditions (Affiah, 2023). This could result in the eviction of residents and have an impact on the state's revenue generation as these factors make the coast geomorphologically unstable and contribute to the loss and deposition of coastal areas with a spatial and temporal component, necessitating appropriate monitoring.

Data Acquisition

Sentinel-1 SAR imagery of 2022 was obtained for this research from the Alaska Satellite Facility. The imagery was acquired with considerations given to when storm surge is at the lowest throughout the year which was between November and March, thoughtfully; data for December were obtained due to its availability. VH polarization is best suited for such analysis because in coastal area monitoring, the combining capability of both ascending and descending image pairs helps to appropriately distinguish land from water hence, the choice of VH polarization. Synthetic Aperture Radar (SAR) carries two important information in its data which are the amplitude and the phase. The amplitude is sufficient for extracting shorelines hence, only the Ground Range Detected (GRD) SAR data was obtained for this work. The Interferometry Wide acquisition mode was embraced as it is the method for land application (Benzougagh *et al*., 2021) with a swath width of 250 km and spatial resolution of 5 m by 20 m.

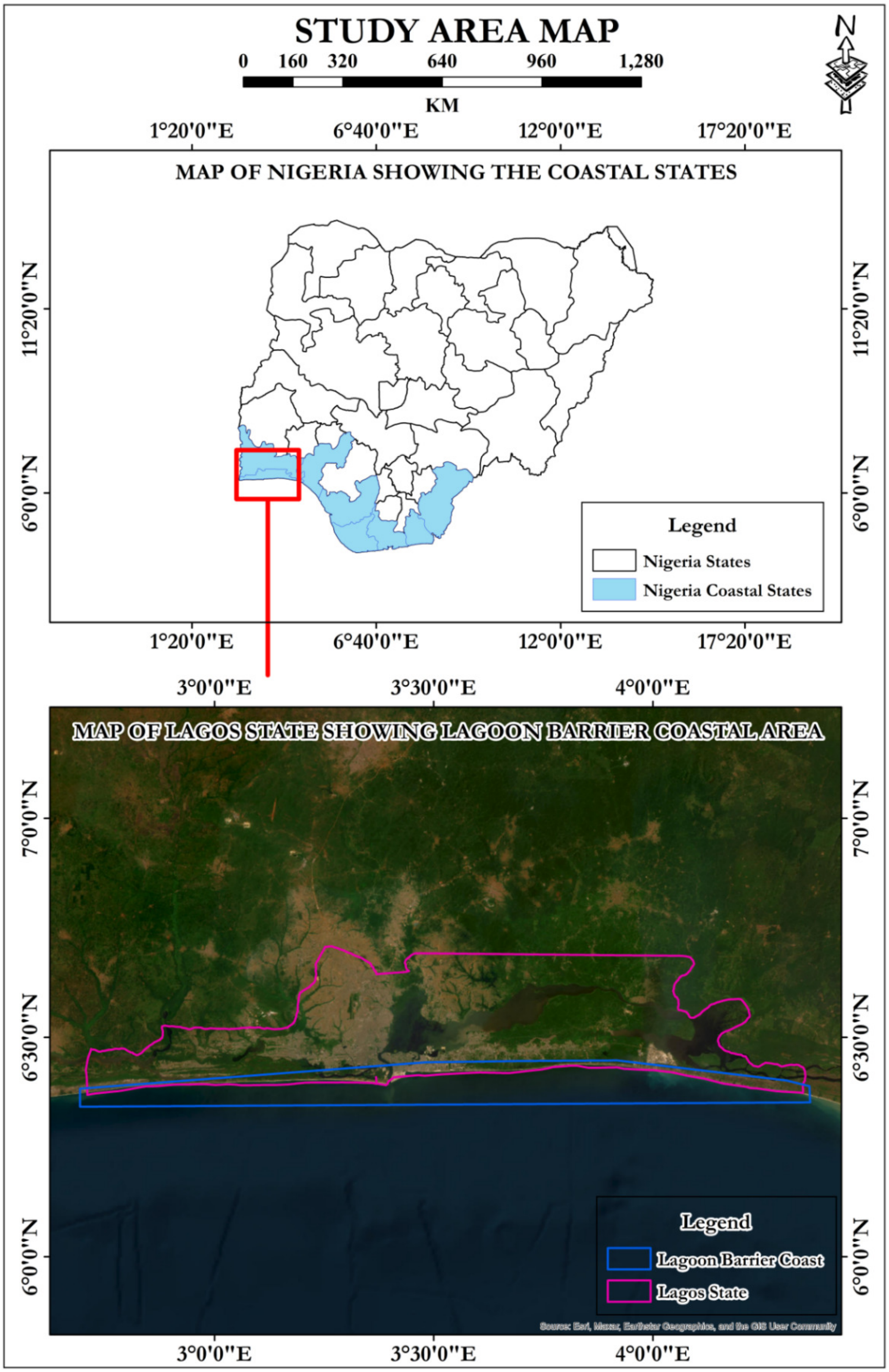

Figure 1. Study area (Source: Authors)

Sentinel-1 transmits signals and uses the received backscatter signal to map the earth. This imagery is armed with penetrating power through cloud with both day and night time capturing capabilities with a relatively high sensitivity to properties like surface roughness, topography, and dielectric constant (Yen and Kim, 2020) which are the characteristics that causes an accurate separation of water from land as compared to the difficulty in carrying out the same task with passive sensors imagery thus, the proposition of using Sentinel-1 in this research. A summary of the data used in this research is contained in Table 1.

Table 1. Data sources used for the research

Dataset	Granule name	Ascending or descending	Polarization/ Resolution	Data source
Sentinel-1 SAR	S1A_IW_GRDH_1SDV_ 20221222T180207_ 20221222T180232_046448_ 059085_5C1E	Ascending	VH/10 m	Alaska Satellite Facility (ASF)
Basemap	Nigeria States Shapefile	-	-	CESRA

Preprocessing and Processing Sentinel-1 SAR Imagery

With the aid of Sentinel Application Platform 9.0 (SNAP) Desktop, the preparatory procedures shown in Figure 2 were completed. SNAP is an open-source program whose features are open to improvement by multiple developers. This research paper embraced the program's capabilities for Sentinel-1 image analysis, which have proven to be quite useful.

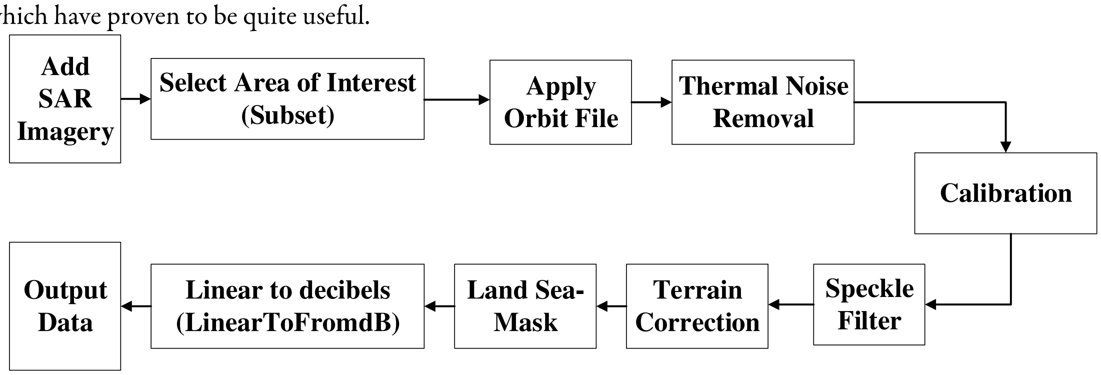

Figure 2. Workflow of Sentinel-1 GRD data processing

Using the subset function, the first step in pre-processing the software is to cut only the portion needed for this study. On the other hand, limiting the amount of Sentinel-1 data reduces processing run time rather than data quality. The next preprocessing step involves using the orbit file. When the updated orbit file is released online a few days after the imagery is acquired, SNAP automatically downloads it because the initial orbit files it acquired after acquiring the imagery are inaccurate. This updates the metadata of the Sentinel-1 data and aligns it with the correct satellite position. Eliminating thermal noise is the next step in the SAR pre-processing process. Sentinel-1 imagery is habituated to the noise surrounding the SAR receiver; this noise can be reduced by using the Thermal Noise Removal Command on SNAP to normalize the backscatter signal of the Sentinel-1 imagery. Subsequently, the Sentinel-1 image data is converted into meaningful physical radar backscatter digital values using the radiometric calibration technique. This allows one to distinguish between non-water and watery objects on the Sentinel-1 imaging. In this case, the processing output that was checked was only the sigma nought (σ^0). Sentinel-1 images often contain granular noise, which can be removed with the speckle filter command. This step is equally crucial as the others since the Sentinel-1 image could be misinterpreted if the granular noises are not removed. With a window size of 7 by 7 and a sigma of 0.9, Lee Sigma's single speckle filter was employed since it makes the fewest compromises with the radiometric and spatial resolution of Sentinel-1 data.

The imagery was not in the correct reference frame and was inverted when the SAR data was imported into SNAP. This gap was filled in with terrain correction, aligning the images with the way they are displayed. The coordinate system was set to UTM Zone 31N/WGS1984 Geographic Projection, and the terrain correction command was executed using Shuttle Radar Topography Mission (SRTM) DEM imagery of 1 arc-second with bilinear interpolation technique (used for resampling the image and Digital Elevation Model, DEM). The portion of the study area that represented the sea was hidden using the land-sea mask tool.

Using equation (1), the radiometric pixel values of the generated imagery are converted from linear to decibels (dB) as the final preprocessing step.

$$\sigma^0_{\mathrm{dB}} = 10 \log_{10} \sigma^0 \quad (1)$$

Where:

σ^0_{dB} Is backscatter image in dB and

σ^0 Is the output of the pre-processed image

The graph builder tool was used to assemble and integrate the entire pre-processing workflow, and the batch processing command was used to carry out the full pre-processing workflow as illustrated in Figure 2 to minimize processing time and computerization.

Shoreline Extraction and Statistical Analysis

Using ArcGIS Desktop 10.7, the shoreline was digitalized from the processed Sentinel-1 data into a polyline shapefile to verify the position of the coastline. Figure 3 illustrates the complete shoreline extraction workflow.

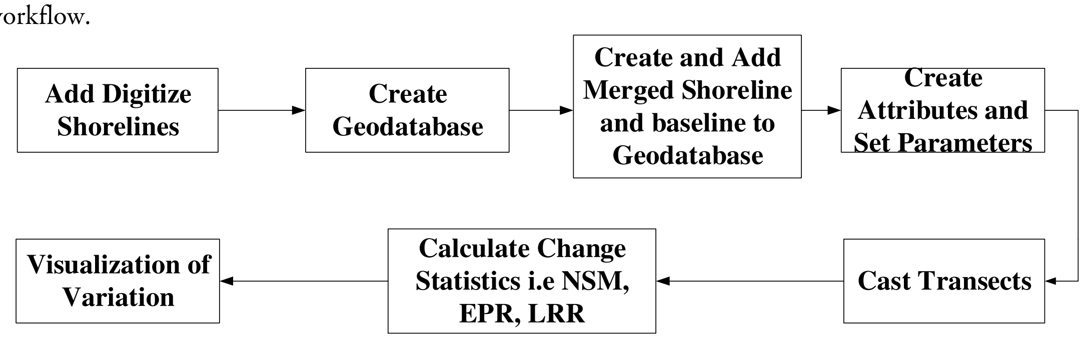

Figure 3. Shoreline Analysis Workflow

A geo-database was created in ArcGIS for the digitized shoreline position which comprised; year, ID, shape and uncertainty. The historical change was analysed using the Digital Shoreline Analysis System (DSASv4.3). DSAS in the ArcGIS environment was utilized to cast transects calculate statistical parameters for the shorelines and determine the projection of the shoreline in 2032. A hypothetical baseline was constructed offshore and parallel to the general orientation of the Lagoon Barrier shoreline. This was done to be able to assess the spatial and temporal movement trend of the shoreline positions. In this study, the projected shoreline position and the corresponding rates of change along Lagoon Barrier shorelines were determined using End Point Rate (EPR), and Linear Regression Rate (LRR). With a weighted linear rate parameter, the confidence interval was 99% and the data uncertainty was ±10m.

A baseline polyline shapefile was made, and the outer offshore baseline was built by onscreen digitization, to obtain the desired transect orientations across the historical shoreline and parallel the general orientation of the historical shoreline in the database. Transect lines perpendicular to the baseline are cast at 100-meter intervals and transect lengths at 500-meter intervals along the baseline after the baseline is constructed. The ten-year predicted shoreline position was carried out using the Kalman filter model as it helps to minimize the position error between the modelled and observed shoreline to improve the forecast.

It is important to remember that in shoreline analysis using EPR, and LRR, values above zero define accretion and values below zero indicate coastal erosion.

Results

Findings from this research show that the future predictions of the shoreline position considering the area to be eroded with a ten-year projection (i.e. position in 2032) showed that 58.33% of the total length of the lagoon coast shoreline will be eroded by 2032 and 41.67% of the shoreline is at the risk of being accreted shown in Table 2. By 2032, the lagoon shoreline would have changed at the rate of −1.45 m/yr which is a warning, indicating that the current trend of anthropogenic activities and the climatic factors like sea level, aquatic animals and the humans residing around the Lagoon coast are at high risk of being displaced from their habitats. With the percentage of the area projected to experience erosion in 2032, it is only important for policymakers to set out to make decisions and put-up policies that will mitigate the accompanying effects of coastal erosion. In the same way, the accretion concern also has to be dealt with because it also comes with the result of the loss of aquatic animals due to the retreat of the shoreline towards the water bodies.

Table 2. Shoreline Forecast Statistics by 2032

EPR (End Point Rate, m/yr)	Average rate	Number of erosional transects	Percent of all transects that are erosional	Number of accretional transects	Percent of all transects that are accretional	Uncertainty of average rate
2022-2032	−1.45	1057	58.33%	755	41.67%	+/−1.41

Further results show the Endpoint Rate between 2022 and 2032 to be between −32.3 m/yr to 27.1 m/yr (Figure 4). Coastal erosion is projected to be characterized towards the extreme eastern and western end and some parts along the Lagoon Barrier Coast with prediction to affect communities like Ojogun, Makoko, and Igbogun which have been changing at the rate of −32.3 m/yr to −5.1 m/yr. Communities such as Mawpo Ijebu and Iagbo are projected to be affected by erosion but at a rate lower than the former. These communities will likely experience loss of land along the coast at the rate of −1.7 m/yr to 0. Also, places like Ogungbe, Okun-Ibese and Agerige will experience accretion at the rate of 18 m/yr to 27.1 m/yr. These are communities that hold strong economic capability in Lagos state and hence steps to mitigate and prevent this happenstance should be taken and if possible curb the coming past of this projection. Also, the residents of these area need to be intimated on the dangers of shoreline change both its retreat and extension.

Areas Affected by Coastal Erosion and Accretion

The coastline change result was grouped into four susceptibility classes, with 4 being the most susceptible class to shoreline changes and 1 being the least susceptible. According to Mani Murali *et al.* (2013), accretion > 2 m is classified as very low susceptibility; accretion 2 m is classified as low susceptibility; 2 m erosion is defined as high susceptibility; and > 2 m erosion is classified as very high susceptibility. The rate of change of the predicted shoreline was classified in that manner (Figure 5) to further probe the vulnerability of communities along the Lagoon Barrier Coast.

The result confirms that at the predicted rate communities like Lekki have a very high susceptibility to erosion. This is a huge commercial hub of the state that contributes to the state's generated revenue and is home to prominent industries, as well as a commercial hub. Other communities at this level of susceptibility include Makoko and Igbogun. Places like Ago Hausa and Mawpo are also seen as highly susceptibility to erosion although at a rate lower than those of the former. Mobido, Idaso, Agerige and Oku-Ibese are some of the communities that are very lowly susceptible to coastal erosion.

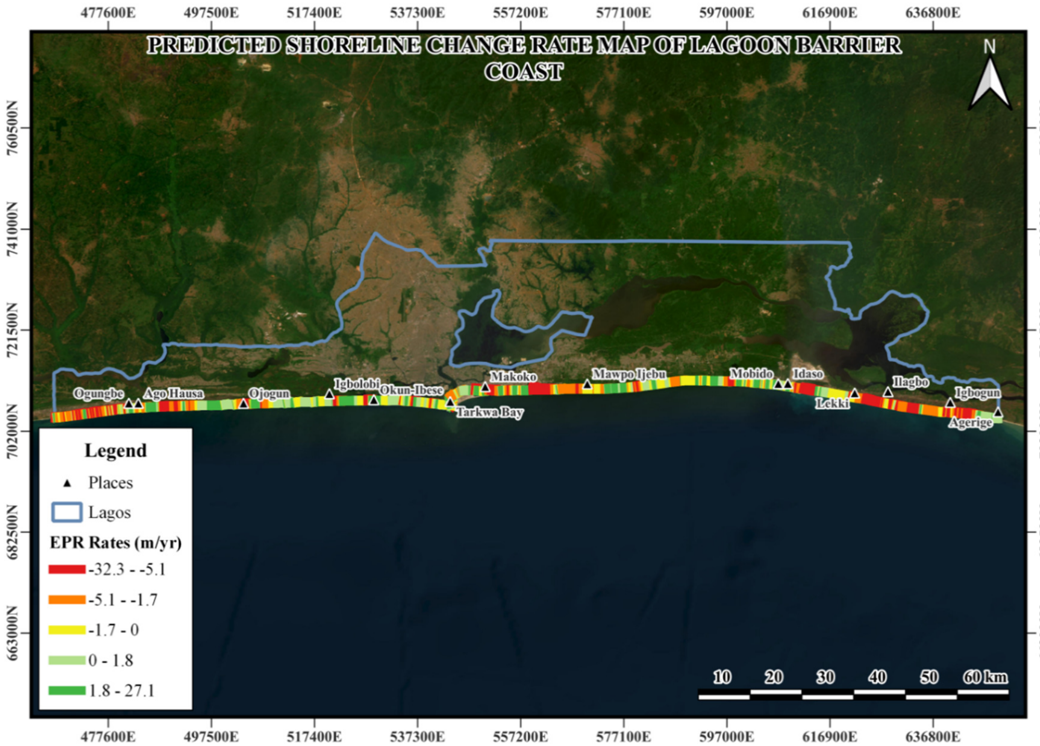

Figure 4. The predicted rate of change of shoreline by 2032. Background map: Google Basemap (**Source:** Authors)

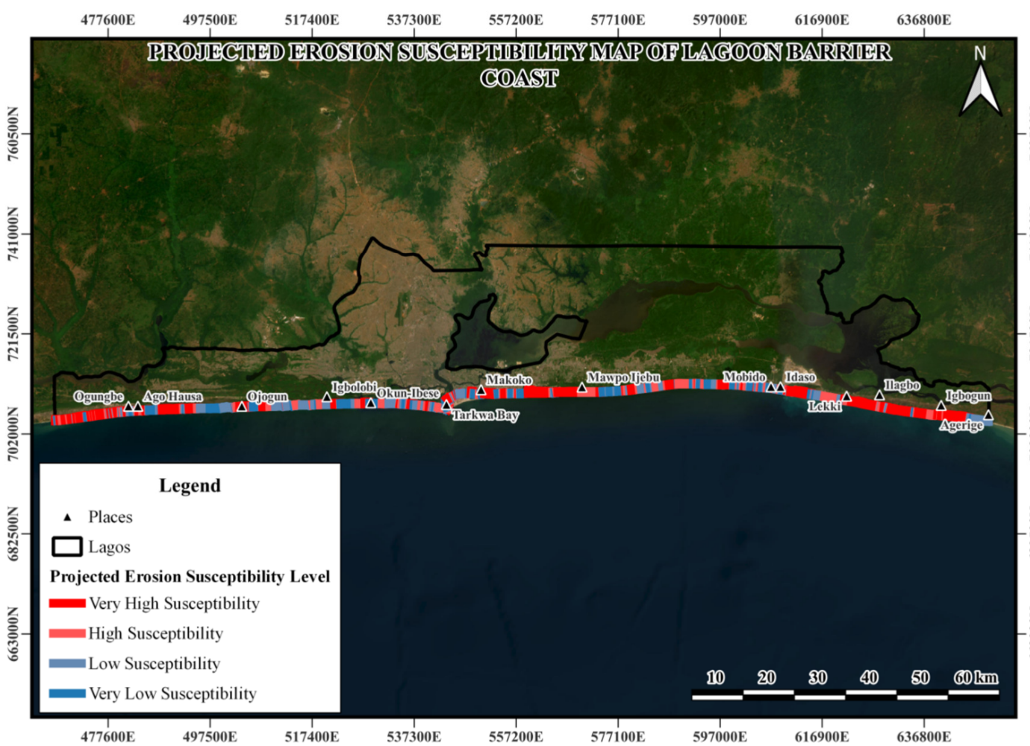

Figure 5. The projected Erosion Susceptibility Map in 2032. Background map: Google Basemap (**Source**: Authors)

While we cannot claim that the results are accurate due to the modelling used to predict these positions, they do provide us with an idea of where the Lagoon Barrier shoreline will be in the future. As shoreline position is known to be dynamic, shoreline erosion has an adverse effect on shoreline while shoreline accretion benefits coastal areas. Therefore, these findings will aid in the better planning and management of coastal lands by combining the benefits of Sentinel-1 SAR imagery with the power of the Kalman filter model in DSAS to predict the future position of the shoreline.

Discussion

The integration of GIS and remote sensing in shoreline monitoring has become very useful as seen in this research where it was been utilized to forecast the futuristic position of the Lagoon Barrier Shoreline in Lagos state. The mild forecasted rate of erosion identified in Lekki could be attributed to the land reclamation activities that have been paused and now the area is being developed with a variety of activities going on, especially the mirage of development being carried out in the Lekki coastal city resulting in this rise in rate of erosion as against the accretion recorded by Fashae *et al.* (2022). Although areas like Lekki and Okun-Ibese are characterized in the forecast to be affected by just mild erosion within the rate of 1.7 m/yr and 0 if measures are not put in place to subdue this, the rate may climb even higher than these projected scores causing damages to lives and properties. Relatively most communities along the western part of the Lagoon Barrier shoreline, by the projection, are being characterized with accretion while most communities in the eastern part are projected to experience erosion which could be a factor of the elevation above sea level as recognized in Fashae *et al.* (2022) where the maximum elevation above sea level is up to 14 meters in the eastern part while the maximum average elevation on the western stretch of the coastline records 5 meters which could be a major factor that could cause more erosion along the eastern stretch as opposed to more accretion in the communities along the western expanse of shoreline. One repercussion of this scenario is the migration of people from these eroded susceptible areas to places with fewer threats and this is not a sustainable solution to solve the problem of the shoreline change rather it causes the menace to take another course because the areas being emigrated to becomes overpopulated and increases the exploitation of the ocean bodies constituting to the increase in the erosion rate. Concerning erosion susceptibility, the entire Lagoon barrier coast is characterized by being very highly susceptible to erosion. Communities like Igbogun, Mawpo Ijebu, and some parts of Lekki. Being classified as highly susceptible puts the resources and tourist attraction facilities in these places at risk of being damaged (Eze *et al.*, 2016). This calls for collaboration between all the professionals in play under issues of environmental planning with policymakers to derive measures for ameliorating and slowing down the change process for a sustainable environment. In totality, coastal communities are very vulnerable to climate change and sea-level rise due to inadequate adaptation techniques and resilience. The severity of coastal erosion is increasing as the shoreline approaches communities. Displacement further inland may lead to conflicts over limited resources in resettlement locations. A future study that integrated a social impact assessment of these changes should be studied. This will provide further insight into the activities of the inhabitants of these identified susceptible areas and with further insight, a more integrated and sustainable measure can be derived to mitigate this happenstance.

Conclusion

While there are numerous methods available for examining shoreline change, remote sensing techniques remain a viable alternative to the terrestrial approach, as demonstrated in this study where the active remote sensing Sentinel-1 imagery has been successfully exemplified to extract shorelines from it, to the forecast of the position of the Lagoon Barrier Shoreline in Lagos state, Nigeria. The study's findings have helped highlight the position of the Lagoon shoreline in 2032 and also show communities that could be affected by the change in this projected shoreline. The result showed in general, a persistent trend of erosion in 2032 with communities like Ojogun, Makoko, and Mawpo Ijebu likely to have major part of their lands to have eroded. These findings showed that environmentalist need to take measures to mitigate all the accompanying hazards of the projected erosion. For the fact that this research provides the visualization and the rate of change of the shoreline in 2032, it gives policy makers, urban planners and other stakeholders in land management the opportunity to undertake further integrated study to come up with sustainable solutions to defeat this menace proving further the significance of this research. The research also provides an erosion susceptibility map which finds use case in environmental planning and the sustainable development of the environment. This work has established that it is possible to monitor the morphological changes on the Lagoon Barrier Coast coastline using GIS methods and Sentinel-1 SAR imagery. Since data is easily available and reasonably priced, using remote sensing techniques and tools such as DSAS facilitates the process of gathering data by producing additional analyses and graphs in around minutes.

Authors' Contributions

The authors were involved in all aspects of the research and writing process for the manuscript. They read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Adefisan EA, Adefowope ED, Okonma FC (2018). Geospatial Assessment of the Coastal Region of Southwest Nigeria. Global Scientific Journal 6(6):133-153.

Affiah UE (2023). Vulnerability of the Nigerian coast and communities to climate change induced coastal erosion. Doctoral dissertation, University of Glasgow.

Akinluyi FO, Adebola AO, Adeseko AA (2018). Assessment of shoreline and associated landuse/land cover changes along Part of Lagos Coastline, Nigeria. Contemporary Trends in Geoscience 7(1):59-71. *http://dx.doi.org/10.2478/ctg-2018-0004*

Arjasakusuma S, Kusuma SS, Saringatin S, Wicaksono P, Mutaqin BW, Rafif R (2021). Shoreline dynamics in East Java Province, Indonesia, from 2000 to 2019 using multi-sensor remote sensing data. Land 10(2):100. *https://doi.org/10.3390/land10020100*

Bartsch A, Ley S, Nitze I, Pointner G, Vieira G (2020). Feasibility study for the application of Synthetic Aperture Radar for coastal erosion rate quantification across the Arctic. Frontiers in Environmental Science 8:143. *https://doi.org/10.3389/fenvs.2020.00143*

Benzougagh B, Frison PL, Meshram SG, Boudad L, Dridri A, Sadkaoui D, Khedher KM (2021). Flood mapping using multi-temporal Sentinel-1 SAR Images: A case study – Inaouene Watershed from Northeast of Morocco. Iranian Journal of Science and Technology, Transactions of Civil Engineering 2:1481-1490. *https://doi.org/10.1007/s40996-021-00683-y*

Carreño CF, De Mata MM (2019). Flood monitoring based on the study of Sentinel-1 SAR images: The Ebro River case study. Water 11(12):2454. *https://doi.org/10.3390/w11122454*

Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, ... Van Den Belt M (1997). The value of the world's ecosystem services and natural capital. Nature 387(6630):253-260. *https://doi.org/10.1038/387253a0*

Creel L (2003). Ripple Effects: Population and Coastal Regions; Population Reference Bureau: Washington, DC, USA. *https://pdf.usaid.gov/pdf_docs/Pnadd169.pdf*

Eze MU, Alozie GC, Nwogu N (2016). Coastal erosion and tourism infrastructure in Lagos state. International Journal of Advanced Research in Social Sciences, Environmental Studies and Technology 2:227-239.

Fashae OA, Obateru RO, Adagbasa EG, Emeh CC (2022). Community-based assessment of coastal erosion in Lagos, Nigeria. Natural Hazards 114(3):3657-3682. *https://doi.org/10.1007/s11069-022-05536-z*

Gens R (2010). Remote sensing of coastlines: detection, extraction and monitoring. International Journal of Remote Sensing 31(7):1819-1836. *https://doi.org/10.1080/01431160902926673*

Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F ... Zarfl C (2019). Mapping the world's free-flowing rivers. Nature 569(7755):215-221. *https://doi.org/10.1038/s41586-019-1111-9*

Isiaka IO, Ajadi SA, Arowolo SA, Mustapha SO, Ndukwe KO, Oluoma CC (2023). Flood impact assessment in Koton Karfe using Sentinel-1 Synthetic Aperture Radar (SAR) data. International Journal of Environment and Geoinformatics (IJEGEO) 10(4):64-76. *http://dx.doi.org/10.30897/ijegeo.1348753*

Klemas VV (2013). Remote sensing of coastal hazards. In: Finkl C (Ed). Coastal Hazards. Coastal Research Library, Vol 1000. Springer, Dordrecht. *https://doi.org/10.1007/978-94-007-5234-4_2*

Mani Murali R, Ankita M, Amrita S, Vethamony P (2013). Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. Natural Hazards and Earth System Sciences 13(12):3291-3311. *https://doi.org/10.5194/nhess-13-3291-2013*

Melet A, Teatini P, Le Cozannet G, Jamet C, Conversi A, Benveniste J, Almar R (2020). Earth observations for monitoring marine coastal hazards and their drivers. Surveys in Geophysics 41:1489-1534. *https://doi.org/10.1007/s10712-020-09594-5*

Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. PLoS One 10(6):e0131375. *https://doi.org/10.1371/journal.pone.0131375*

Nicholls RJ, Cazenave A (2010). Sea-level rise and its impact on coastal zones. Science 328(5985):1517-1520. *https://doi.org/10.1126/science.1185782*

Nwilo PC (1997). Managing the impacts of storm surges on Victoria Island, Lagos, Nigeria. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences 239:325-330.

Olali O (2015). Assessment of shoreline morphological changes in Brass (Niger-Delta, Nigeria). Retrieved 2024 February 15 from *https://afribary.com/works/assessment-of-shoreline-morphological-changes-in-brass-niger-delta-nigeria*

Oyinloye MA, Ajayi GE, Olanibi JA (2016). Assessment of shoreline changes on Victoria Island in Eti-Osa local government area, Lagos State, Nigeria. Journal of Earth Sciences and Geotechnical Engineering 6(1):47-62.

Pepe M, Costantino D, Alfio VS (2023). A GIS Procedure to assess shoreline changes over time using multi-temporal maps: An analysis of a sandy shoreline in Southern Italy over the last 100 years. Geomatics and Environmental Engineering 17(3):107-134. *https://bibliotekanauki.pl/articles/2203960.pdf*

Popoola OO (2022). Spatio-temporal assessment of shoreline changes and management of the Transgressive Mud Coast, Nigeria. European Scientific Journal 18(20):99-127. *https://doi.org/10.19044/esj.2022.v18n20p99*

Qiu J, Cao B, Park E, Yang X, Zhang W, Tarolli P (2021). Flood monitoring in rural areas of the Pearl River Basin (China) using Sentinel-1 SAR. Remote Sensing 13(7):1384. *https://doi.org/10.3390/rs13071384*

Sheeja PS, Gokul AA (2016). Application of digital shoreline analysis system in coastal erosion assessment. International Journal of Engineering Science and Computing 6:7876-7883.

Spinosa A, Ziemba A, Saponieri A, Damiani L, El Serafy G (2021). Remote sensing-based automatic detection of shoreline position: A case study in Apulia region. Journal of Marine Science and Engineering 9(6):575. *https://doi.org/10.3390/jmse9060575*

Wiafe G, Boateng I, Appeaning-Addo K (2013). Handbook for coastal processes and management in Ghana. Choir Press.

Yen NH, Kim TL (2020). Coastline changes detection from Sentinel–1 satellite imagery using spatial fuzzy clustering and interactive thresholding method in Phan Thiet, Binh Thuan. Vietnam Journal of Hydrometeorology 6:1-10.

Zhu Q, Li P, Li Z, Pu S, Wu X, Bi N, Wang H (2021). Spatiotemporal changes of coastline over the Yellow River Delta in the previous 40 years with Optical and SAR Remote Sensing. Remote Sensing 13(10):1940. *https://doi.org/10.3390/rs13101940*

Zollini S, Alicandro M, Cuevas-González M, Baiocchi V, Dominici D, Buscema PM (2019). Shoreline extraction based on an active connection matrix (ACM) image enhancement strategy. Journal of Marine Science and Engineering 8(1):9. *https://doi.org/10.3390/jmse8010009*