RESEARCH ARTICLE

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Assessing The Impact of Sea Encroachment in Ilaje, Ondo State, Using Optical Satellite Imagery Analysis and Shuttle Radar Topography Mission

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Abstract

This study assessed the impacts of sea encroachment in Ilaje Local Government Area of Ondo State, Nigeria, using multi-temporal optical satellite imagery and the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). This study analyzed past and recent shoreline change trends, simulated elevation-based vulnerability to flooding, and predicted the potential effects of sea-level rise. Landsat images from 1995, 2000, 2005, 2010, 2015, 2020, and 2025 were analyzed to identify the shoreline, and shoreline changes were calculated using the End Point Rate (EPR) and Linear Regression Rate (LRR) in the Digital Shoreline Analysis System (DSAS). Elevation-based vulnerability maps were modeled using the SRTM DEM, and future inundation was projected using sea-level rise data. Results showed that erosion was more severe along the Ilaje coastline, with over 70 percent of the shoreline retreating at different rates, while only small sections experienced accretion. The inundation model, assuming a conservative rise of 0.269 m, indicated that more than 555 km^2 of land could be submerged, and a 1m rise could flood over 650 km^2 by the year 2150, an event that would affect settlements such as Ayetoro, Ogogoro, and Gbeke Eke. These findings emphasize why Ilaje communities are at risk of land loss, displacement, and livelihood impacts. The analysis concludes that sea intrusion poses a significant threat to the coastal ecosystem in Ilaje. This study recommends integrating the coastal zone into planning efforts, restoring mangroves as natural barriers, adopting stricter measures to prevent unsustainable human activities, and maintaining ongoing geospatial monitoring as part of a sustainable strategy for change.

Keywords: coastal management, sea encroachment, Ilaje, sea-level rise, shoreline change, inundation models.

1 Introduction

Over the past several decades, extreme coastal events have become more frequent and more destructive, particularly along the West African coast [1, 2]. Global sea level is also rising steadily and measurably,

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driven by thermal expansion—which causes water to expand—and melting ice, which adds more water to the system, as well as ocean circulation and sediment compaction; these processes are exerting increasing pressure on coastal ecosystems and the communities whose livelihoods depend on them [3, 4]. These processes do not remain confined to the ocean; instead, they accelerate shoreline retreat, intensify coastal erosion, and increase saline intrusion into freshwater systems, thereby disrupting ecological balance, causing economic instability, and destroying local livelihoods [5, 6]. Wong et al. [7] estimated that about 40 percent of the world's population lives within 100 km of the coastline, with a substantial proportion residing on land below 5 m above mean sea level [8]. Despite the high population already living in this delicate zone, future population projections indicate that the rate of growth in coastal areas will outpace that in inland areas [9], thereby attracting further development and subjecting the cities and communities in the coastal zones to serious socioeconomic and environmental pressures. This reveals that livelihoods, properties, and infrastructure will potentially be exposed to the consequences of sea-level rise, particularly in low-lying coastal regions where sea-level changes lead to flooding, saltwater intrusion, and shoreline retreat. If the rise in global sea level is left unaddressed, the consequences for many coastal populations will be severe [10].

In West Africa, 31% of settlements and major infrastructure are located along the coast. The region's low elevation makes it vulnerable to natural hazards such as coastal erosion and storm surges. For example, integrated coastal vulnerability assessments along the West African coast, including regions such as Côte d'Ivoire, have demonstrated that low-lying areas face compounding threats from rising sea levels, storm surges, and shoreline erosion, with significant implications for lives and infrastructure [11]. Similarly, in Ghana, satellite-based monitoring has documented significant shoreline erosion along the eastern coast, affecting thousands of inhabitants and critical infrastructure [12]. Due to rising sea levels, shoreline changes have resulted in the loss of about 70 kilometers of coastline in Mozambique, with projections indicating that by 2030, over 1.5 million people may be displaced [13]. Addressing these challenges requires enhanced regional cooperation and investment in adaptive measures to safeguard livelihoods and ecosystems.

Coastal communities in Nigeria are highly exposed to the impacts of sea-level rise, with studies in areas such as Brass Local Government Area demonstrating significant vulnerability among populations dependent on coastal resources for their livelihoods [14]. Advanced remote sensing technologies, including spaceborne Synthetic Aperture Radar (SAR) imagery, have demonstrated considerable potential for monitoring and predicting shoreline dynamics in lagoon coastal environments [15]. Sea level rise (SLR) has been a major driver of shoreline instability and has caused significant damage to coastal settlements [16]. In Nigeria, the coastal states are characterized by low-lying terrain and are highly susceptible to the impacts of climate change, including coastal storms, erosion, sea-level rise, and flooding [17]. Along the southwestern coast of Nigeria, the shoreline is continually changing due to erosion and accretion driven by coastal evolution processes, including wind, waves, and currents. These phenomena are natural, but their effects may seem alarming [18]. For instance, Popoola [17] conducted a spatio-temporal assessment of shoreline changes and the management of the transgressive mud coast in Nigeria. The study revealed that 49.8 km (64.67%) of Nigeria's Transgressive Mud Coast shoreline receded from 1986 to 2021. This ongoing erosion resulted in a loss of 15.1 km^2 of land to the Atlantic Ocean over 35 years, with predictions of an additional 1.26 km^2 loss by 2032. Inundation models indicated that sea-level rise could submerge around 201 km^2 of the mud coast, increasing to 551 km^2 by 2100 under the SSP5-8.5 scenario. The results also highlight significant risks to populations, infrastructure, and economic activities from future coastal flooding. Dada et al. [2] assessed coastal vulnerability along the West African coast to flooding and erosion. The results indicated that 64, 17, and 19% of WA coastal areas had high-to-very-high, moderate, and low-to-very-low CVI, respectively. The results further reveal that while geophysical variables contribute to coastal vulnerability in WA, socioeconomic factors, particularly high population growth and unsustainable human development at the coast, play a considerably larger role. Atayi et al. [19] evaluated shoreline changes and land use/land cover along the Keta coastal zone using multi-temporal remote sensing datasets. Their results showed that built-up areas increased from 14.71% to 18.43% and water bodies from 47.68% to 50.46% from 47. 68% to 50. 46%. Overall, the findings demonstrate a clear dominance of shoreline erosion within the municipality, accompanied by rapid urban growth

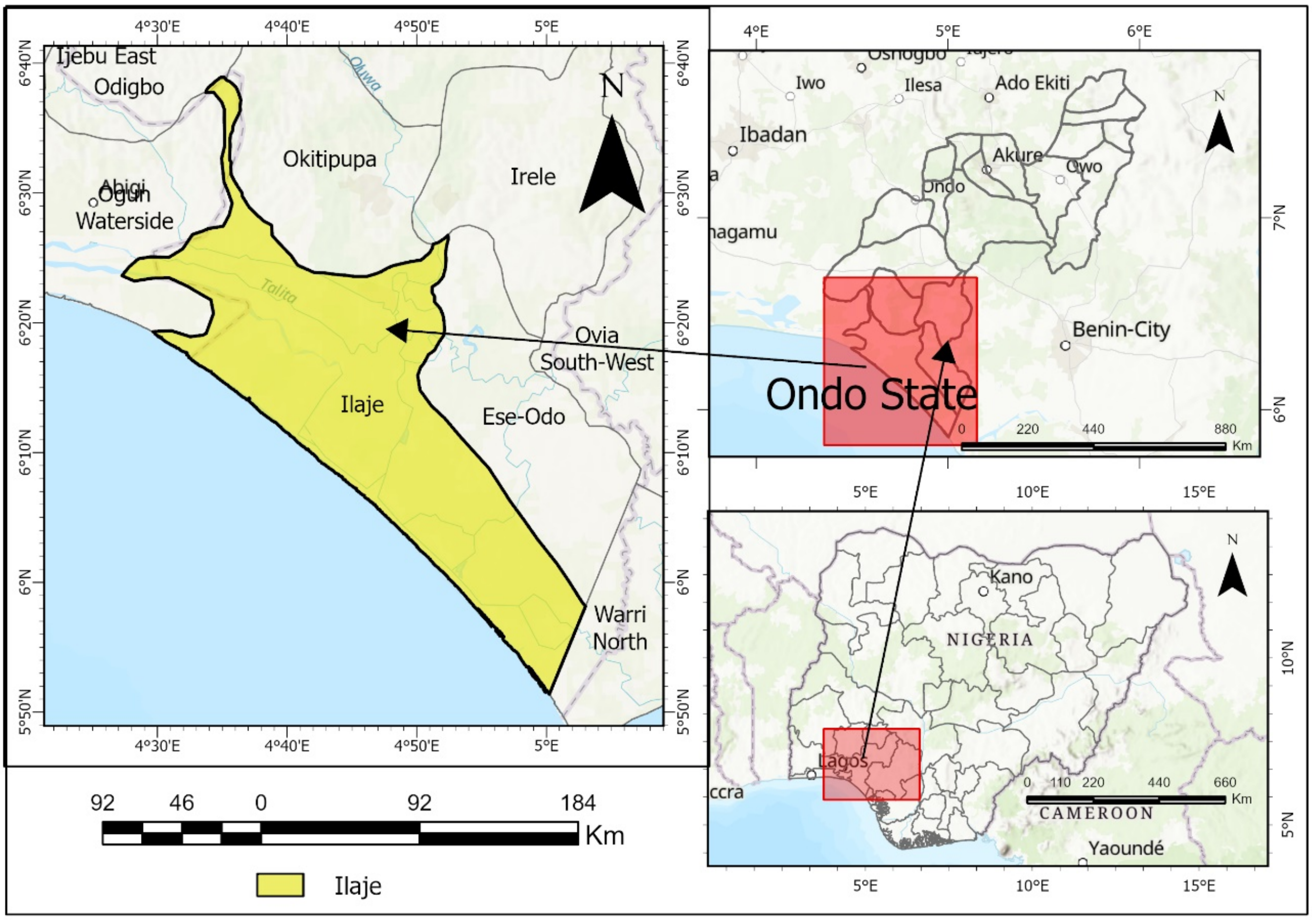


Figure 1. Map of Nigeria showing Ilaje LGA.

and increasing water coverage along the coastal belt.

Remote sensing and GIS approaches have been widely applied in assessing coastal vulnerability to sea-level rise in low-lying coastal regions globally [20]. Despite the increasing use of remote sensing and GIS technologies to monitor coastlines at global, regional and local scales, substantial knowledge gaps still persist regarding the driving processes and future risk exposure of the Ilaje coastline in southwestern Nigeria. Many studies along the West African coast have considered only one of the following: shoreline changes, coastal risk assessment, or the impacts of sea-level rise as an independent study [1, 2, 10, 12, 14, 15, 18, 21]. Even though such work contributed to a better understanding of coastal dynamics, it does not clearly highlight how ongoing historic shoreline retreat influences future risk exposure (i.e., flood impact) of highly vulnerable local coastal systems. Notably, few studies integrate analyses of shoreline changes and DEM-based flood models to address both the past evolution of the coast and the future exposure risk to sea-level rise along the Ilaje coastline [17, 22]. Consequently, the extent to which ongoing shoreline retreat may exacerbate future inundation risks and threaten coastal communities in the area remains poorly understood.

To address the gap, this study combined long-term shoreline change analysis and DEM-based inundation modelling to evaluate the impact of sea encroachment along the Ilaje coast in Southwestern Nigeria. The study evaluated both historical shoreline evolution over a 30-year period (1995–2025) and potential future inundation risks under projected sea-level rise scenarios up to 2150 using multi-temporal optical satellite imagery, DSAS statistical techniques, and SRTM-derived elevation data. This integrated approach provides a localized assessment of coastal vulnerability and supports coastal management, climate adaptation, and sustainable development planning in low-lying coastal environments.

2 Methods and Materials

2.1 Study Area Description

Ilaje lies in Southwestern Nigeria and is part of the western section of the Niger Delta coastal environment.

Geographically, the area extends between latitudes 6°05′ N and 6°30′ N and longitudes 4°30′ E and 5°05′ E [23] (Figure 1). It shares boundaries with Ese-Odo LGA to the north, Okitipupa LGA to the west, Ogun Waterside in Ogun State to the east, and the expansive Atlantic Ocean to the south.

Ilaje is renowned for its complex and delicate coastal terrain, comprising a network of muddy coasts, estuaries, tidal creeks, sand ridges, and lagoon systems. Prominent among these features is the Mahin Lagoon, which extends along the northern boundary of the coastal plain. The entire region is characterised by low-lying topography, with elevations ranging from 0.5 to 5 metres above mean sea level, making it highly susceptible to coastal erosion, tidal flooding, and sea-level rise [23]. The shoreline, particularly along the Mahin mud coast, extends for over 150 kilometres and has been under intense environmental pressure for decades, resulting in significant land loss and shoreline retreat. The area has a humid tropical climate, strongly influenced by its proximity to the Atlantic Ocean. It is characterised by high annual rainfall, averaging 2,500–3,500 mm, with most falling between April and October, consistently warm temperatures of 26°C to 29°C, and relative humidity rarely dropping below 80%. These climatic conditions are broadly consistent with those documented for the adjacent southwestern Nigerian coast, including the Lagos region [24]. These climatic conditions support lush vegetation and aquatic biodiversity but also increase the region's vulnerability to frequent coastal flooding and erosion during the rainy season, particularly when combined with tidal surges. Ilaje's natural vegetation is ecologically diverse, featuring dense mangrove forests, freshwater swamp forests, tropical rainforests, and patches of savanna grassland further inland. The mangroves, composed of species such as *Rhizophora racemosa* and *Avicennia africana*, are particularly vital for shoreline stabilisation and serve as nurseries for fish and other marine species. Over time, deforestation, oil exploration, sand dredging, and urban encroachment have degraded much of these ecosystems, exposing the region to environmental risks and biodiversity loss [25]. Ilaje is also a historically significant region, with its people traditionally engaged in fishing, boatbuilding, salt-making, and local trade. Communities such as Aiyetoro, Ugbonla, Moluwe, Awoye, and Zion-Pepe are well-known fishing settlements with a rich cultural heritage tied to their coastal environment [26]. According to the 2006 National Population Census, Ilaje had a population of about 290,615 people [27]. However, environmental challenges such as severe shoreline erosion, tidal flooding, and water pollution have led to the recurrent displacement and relocation of several communities in recent years [17, 22]. Environmental issues in Ilaje are critical. The area faces increasing shoreline erosion, frequent flooding of farmland and homes, and destruction of mangrove forests. These problems are exacerbated by climate-driven sea-level rise, which threatens to submerge large parts of the LGA unless addressed through sustainable solutions. Despite government initiatives such as the Aiyetoro Shoreline Protection Project, long-term solutions have been difficult to sustain. As one of Nigeria's most environmentally vulnerable coastal regions, Ilaje is a key area for studying and managing the impacts of coastal hazards and sea encroachment using modern geospatial techniques.

2.2 Data acquisition

The study requires analysis of shoreline change and SLR using seven multispectral, orthorectified Landsat images with path/row 190/56 and 30m resolution from 1995 to 2025, obtained from the United States Geological Survey (USGS) server. The Landsat images include the Thematic Mapper (TM) for 1995, the Enhanced Thematic Mapper Plus (ETM+) for 2000, 2005, and 2010, and the Operational Land Imager (OLI) for 2015, 2020, and 2025. The downloaded images were in the World Geodetic System 1984 (WGS84) coordinate system and were projected to UTM/WGS84 Zone 31N in ArcGIS. Shorelines were extracted from these images each year. To achieve better temporal consistency in shoreline extraction, Landsat images were selected, as much as possible, from the dry season (November-March), corresponding to the best available cloud-free images from the USGS Earth Explorer. This season's imagery was chosen because it is generally characterized by relatively stable weather conditions and reduced rainfall, resulting in less extreme variation in shoreline position than in the wet season. Images with less than 15% cloud cover were prioritized to minimize atmospheric interference and improve shoreline extraction. Although identical acquisition dates and tidal conditions were not available in every observation year, choosing images from the same seasonal period whenever possible helped reduce the impact of seasonal differences. The Shuttle Radar Topography Mission (SRTM) digital elevation model was obtained from the United States Geological Survey (USGS) server. The vertical uncertainty of the SRTM DEM exceeds the sea-level rise scenarios considered in this study (0.269–1.0 m). Consequently, the inundation analysis is not intended to provide precise estimates of future flood boundaries but rather to identify broad spatial patterns of relative exposure and vulnerability to sea-level rise. Despite this limitation, SRTM-derived elevation data have been widely applied in regional coastal vulnerability assessments and screening-level inundation studies. Sea-level rise data were obtained from the IPCC AR6 sea-level projection tool server. Location data were obtained from OpenStreetMap (OSM) and projected to UTM/WGS84 Zone 31N.

2.3 Shoreline dynamics

The images used for shoreline extraction were atmospherically calibrated and geographically referenced, and images with less than 15% cloud cover were selected to ensure consistency and repeatability in shoreline mapping across years. To ensure that the features registered on the images matched, the study location was zoomed in on Google Earth Pro each year. For shoreline extraction, the Normalised Difference Water Index (NDWI) was used to delineate the land-water boundary shown by the high-water line, and shoreline measures for the different years were derived using band ratioing. The Digital Shoreline Analysis System (DSAS) version 6.0.1 was used to calculate shoreline change statistics from multiple historic shoreline positions by casting 2km transects perpendicular to the 300m baseline, buffered from the shoreline toward the dry land area. The 2km transect spacing covered a large area of the coastline without creating a cluster of overlapping transects in highly complex areas. Similarly, the 300m baseline buffer ensured that the baseline would always lie inland of any possible shoreline location throughout the analysis period, thereby minimizing intersection errors and improving the reliability of shoreline change analysis. These were selected to ensure adequate shoreline representation, computational efficiency, and consistency along the study coastline. The transect values were then used to estimate shoreline change using two statistical methods: end-point rate (EPR) for short-term analysis and linear regression rate (LRR) for long-term analysis (1995-2025), as used by Popoola (2022). Larger spacing of the transects captures general shoreline change patterns, reflecting wider coastal trends rather than local differences. An appropriate baseline distance enhances the geometric accuracy of transect creation and reduces uncertainty in EPR and LRR estimates.

$$\mathrm{NDWI} = \frac{Green - \mathrm{NIR}}{Green + \mathrm{NIR}} \tag{1}$$

where $Green$ is the reflectance in the green band, and NIR is the reflectance in the near-infrared band.

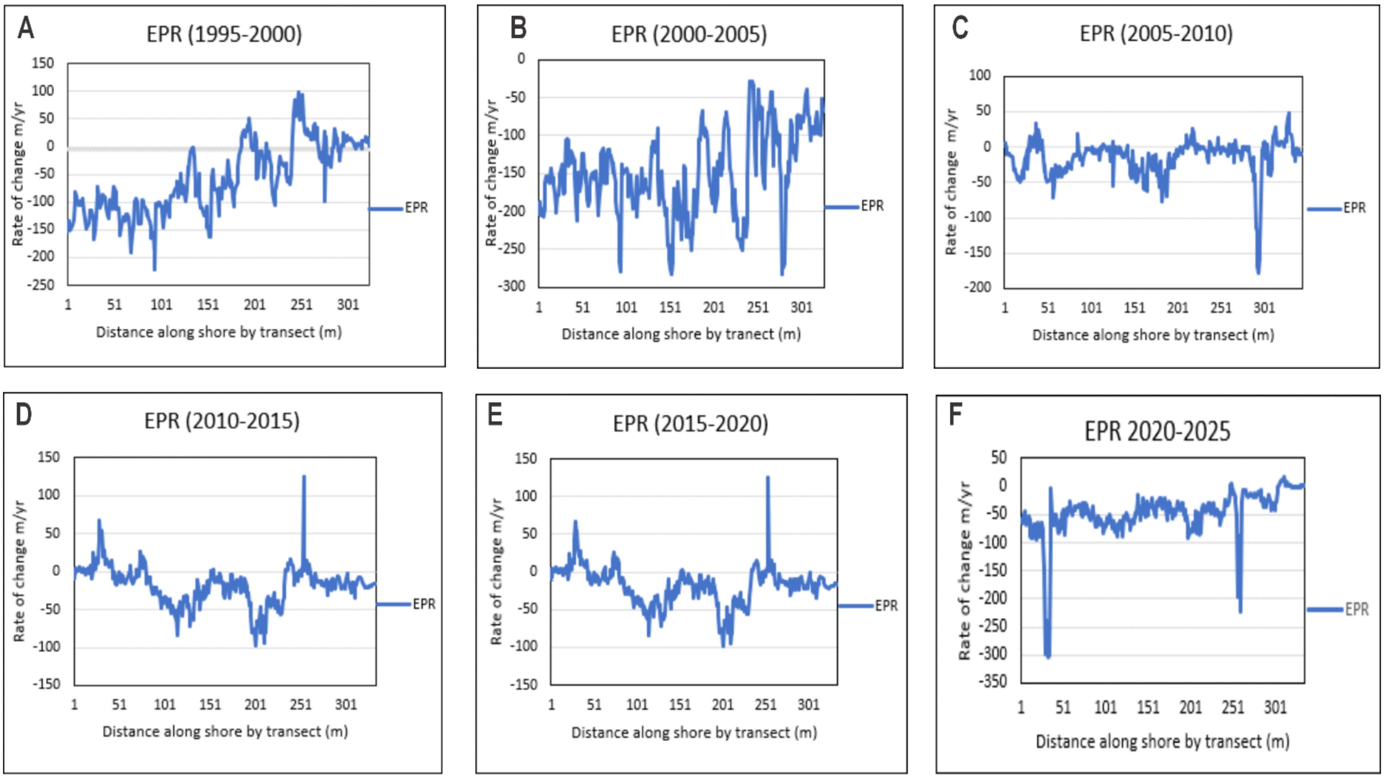
2.4 Uncertainty Analysis

The accuracy of EPR and LRR rates depends on the positional accuracy of the extracted shorelines. Shoreline uncertainty was estimated using the half-pixel method, considering the 30m pixel size and the spatial resolution of Landsat images, yielding an uncertainty of 15m per shoreline. Root-sum-square error propagation was applied to estimate the uncertainty between two shoreline positions, approximately $\pm$21.2m. The uncertainty in modelling inundation was estimated through the vertical accuracy of the SRTM DEM and the selected scenario. Inundation projections were made based on selected sea-level rise scenarios (e.g., 0.269m and 1.0m by the year 2150). Due to the uncertainty in the elevation value of the SRTM DEM, which is approximately $\pm$6m, larger than the sea-level rise scenarios of both, the SRTM DEM has the most important influence on the total uncertainty of predicted inundation boundaries; therefore, the inundation boundaries are not regarded as definitive flood lines but rather as potential flood-exposed zones for each selected sea-level rise scenario. Areas below the 0.269m and 1.0m thresholds are defined as directly exposed within each scenario. In contrast, the areas within the $\pm$6m DEM uncertainty range are defined as uncertainty zones.

2.5 Elevation-Based Vulnerability Modelling

The Shuttle Radar Topography Mission (SRTM) DEM, with 30m horizontal and 6m vertical accuracy, was used to simulate Ilaje's susceptibility to inundation. The following steps were followed:

DEM Pre-Processing: The DEM tiles within the study area were mosaicked, clipped to the Ilaje boundary, and reprojected to WGS 1984 UTM Zone 31N. To remove artefacts, sink filling and error correction were performed. Elevation Classification: The DEM was reclassified into known sea-level rise bands (0-1 m, 1-3 m, 3-5 m, etc.). Areas below 5 m above mean sea level were marked as high-risk zones, given Ilaje's low-lying geographical nature. Overlay Analysis: To create vulnerability maps, DEM classifications were overlaid with settlement layers, revealing individual



• Negative values represent erosion. • Positive values represent accretion.

Figure 2. Shoreline rate for 1995-2000, 2000-2005, 2005-2010, 2010-2015, 2015-2020, and 2020-2025.

communities and infrastructure vulnerable to flooding at different elevation levels. The SRTM DEM represents terrain elevation at a single point in time and does not account for subsequent topographic changes resulting from coastal erosion, sediment deposition, or other geomorphological processes. Therefore, the inundation mapping carried out in the study was intended to define the potentially vulnerable area based on the planned sea-level rise scenarios, not to recreate any future evolution of the topography. The inundation map is provided here as a regional view of coastal vulnerabilities. The inundation maps produced serve as regional vulnerability assessments that support coastal planning and decision-making.

2.6 Projection and inundation modelling of sea-level rise

To forecast future effects, the Intergovernmental Panel on Climate Change (IPCC AR6) sea-level rise projections for the high-emission scenario (SSP5-8.5) were combined with the SRTM DEM. Two scenarios were modelled: Near-Term Scenario (0.269 m increase): a conservative forecast for the upcoming decades. Extreme Scenario (1.0 m rise and higher): depicting the extreme long-term consequences in the year 2150. Inundation analysis was conducted in ArcGIS using the Raster Calculator, in which DEM cells were reclassified as inundated based on elevations lower than projected sea-level rise values.

3 Results

3.1 Shoreline change analysis

Shoreline change analysis of the Ilaje coast over the period 1995-2025 showed that coastal erosion was the primary coastal process. The DSAS statistics, including the End Point Rate (EPR) and Linear Regression Rate (LRR), indicated persistent shoreline retreat along the middle and eastern sectors of the coastline, with shoreline accretion in small areas of the west attributable to sediment accumulation. Disparities in the spatial and temporal dimensions of shoreline changes across the six observational intervals are largely attributable to wave and tidal currents, littoral drift, and anthropogenic activities such as sand mining and oil exploration. Shoreline changes are presented as positive values for accretion and negative values for erosion. The specific patterns of shoreline change for short and long-term are shown in Sections 3.2 and 3.3, respectively.

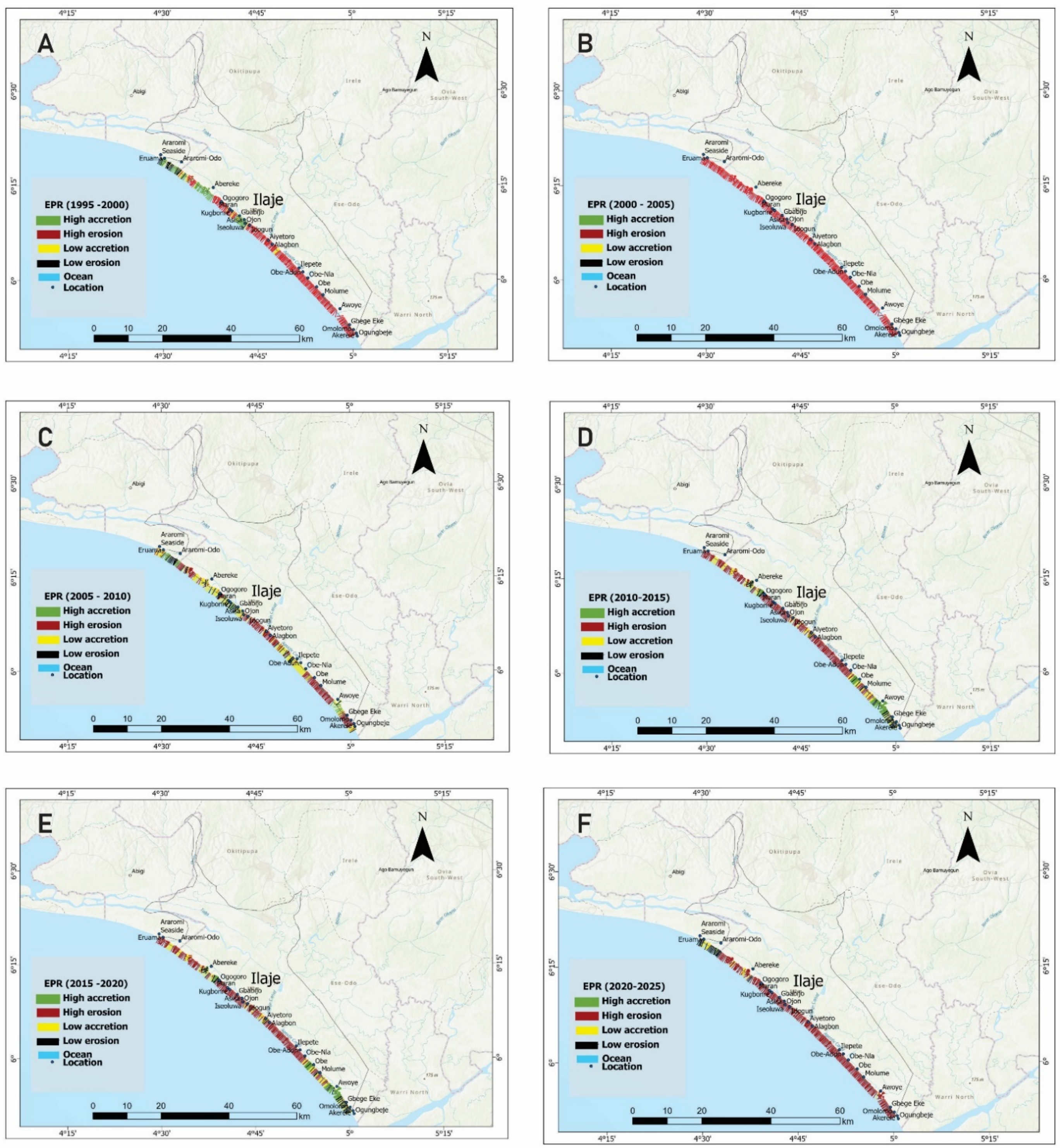


Figure 3. Shoreline change for 1995-2000, 2000-2005, 2005-2010, 2010-2015, 2015-2020, and 2020-2025.

3.2 Short-term Shoreline Change Analysis

The short-term analysis of shoreline dynamics used in this study covers six epochs: 1995–2000, 2000–2005, 2005–2010, 2010–2015, 2015–2020, and 2020–2025, as illustrated in Figures 2 and 3.

Between 1995 and 2000, the shoreline experienced substantial retreat, with localized maximum erosion rates at some transects reaching approximately -220 m/yr, particularly within the central and eastern sectors of the coastline (Figures 2(A) and 3(A)). Erosion accounted for 75.93% of the change, while accretion accounted for 24.07%. The eastern and central parts of the coast were the most severely affected, as communities such as Ayetoro, Ogogoro, Obe Nla, Obe Adun, Moluwa, Awoye, and Idogun suffered significant land loss. Nonetheless, accretion was also detected along parts of the coastline, indicating that sediment redistribution contributed to coastal development. From 2000 to 2005, erosion increased significantly and spread across the entire Ilaje coastline (Figures 2(B) and 3(B)). For 2005–2010, erosion accounted for 78.11% and accretion for 21.89% of shoreline change. For 2010–2015, erosion similarly dominated at 78.11% and accretion at 21.22%, indicating that the erosion-dominated pattern remained consistent across both intervals, and erosion again dominated. This highlights the dynamic nature of sediment transport, in which a section of the land can lose shoreline length while another gains it through sediment deposition (Figures 2(C, D), and 3(C, D)). Between 2015 and 2020, erosion accounted for 80.84% of shoreline change, while accretion accounted for 19.16%, with localized maximum erosion rates reaching approximately -255 m/yr at individual transects (Figures 2(E) and 3(E)). From 2020 to 2025, the results show 92.54% erosion and 7.46% accretion, with erosion rates reaching approximately -303.64 m/yr in the most severely affected shoreline segments (Figures 2(F) and 3(F)).

3.3 Long-Term Shoreline Change

The long-term shoreline change in the study area spans 1995 to 2025, and the spatial distribution of shoreline retreat and accretion is presented in Figure 4.

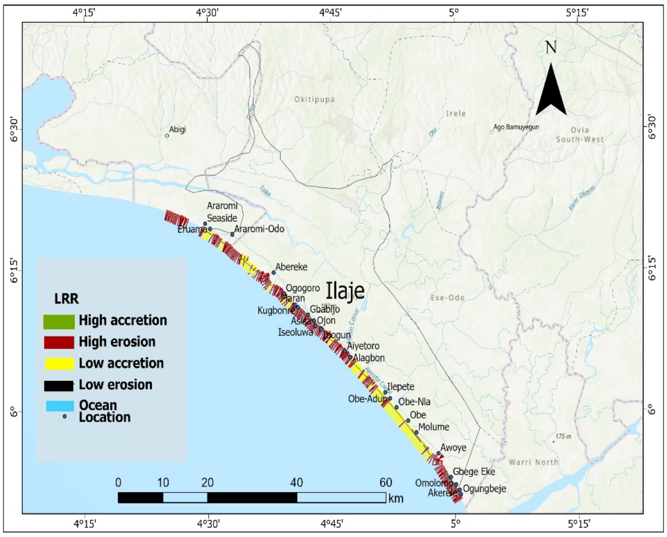


Figure 4. Shoreline change map for vulnerability to coastal erosion between 1995 and 2025.

The long-term shoreline changes trends over the period of 1995 – 2025 indicated erosion was the dominant coastal process for the major portions of the Ilaje coastline. The LRR results indicated ongoing erosion across most coastal zones, with a sustained long-term loss of substantial shoreline. While there was localized accretion in some parts of the western coastal zone due to sediments brought by the littoral and estuarine processes, the rates of accumulation were so minimal spatially that the localized accumulation was not adequate to compensate for the overall recession experienced along the coastline. Local communities that experienced heavy land loss over 30 years are Ayetoro, Ilowo, Oroto, and Olotu. These zones suffer severely from exposure to strong wave regimes, tides, and human activities such as sand mining and oil exploration.

3.4 DEM-Based Inundation Analysis and Long-Term Prediction

The DEM-based inundation maps generated for the 0.269 m and 1.0 m sea-level rise scenarios are presented in Figures 5 and 6, respectively.

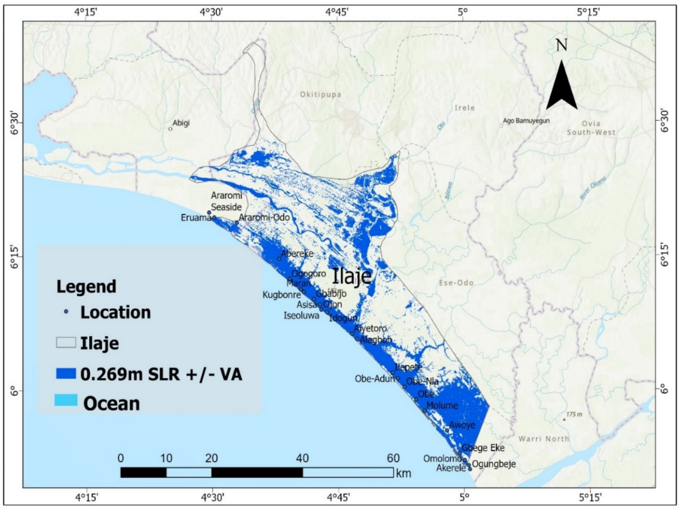


Figure 5. DEM-Based Inundation model at 0.269m sea level rise scenario.

4 Discussion

The shoreline change analysis has shown a consistent erosional trend along most of the Ilaje shoreline throughout the study period. The identified trend of erosion is similar to existing work along the Ilaje coast, showing ongoing shoreline retreat driven by the combined effects of wave forces, longshore drift, eustatic sea-level rise, and human impacts. The consistency of these trends across several observation intervals and their similarity to the already established trend along the Nigerian transgressive mud coast provide confidence in mapping these changes in response to seasonal inundation. Dry-season Landsat

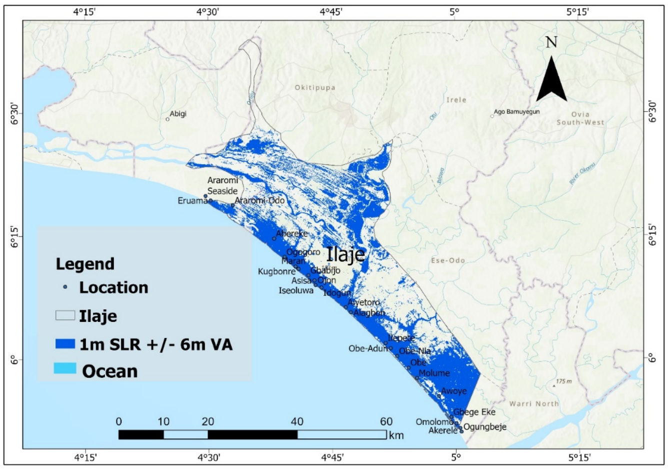


Figure 6. DEM-Based Inundation model at 1m sea level rise scenario.

satellite images (November-March) were used, and the over 3-decade observation period (1995-2025) reduces the impact of temporal hydrologic variation on shoreline delineation.

The inundation modelling for this study was conducted under two SLR scenarios (0.269 m and 1.0 m) for the year 2150, using terrain elevation data from the SRTM DEM with 30 m spatial resolution. The predicted potential extent of inundation was 555.348 sq km for the 0.269 m SLR scenario and 650.140 sq km for the 1.0 m SLR scenario. The simulated inundation extent was an estimate of potential exposure patterns under selected scenarios rather than the exact flood extent. However, the SRTM DEM used has an estimated vertical accuracy of $\pm$6m, which was considered a significant limitation in interpreting inundation and vulnerability assessment, especially for the 0.269 m SLR scenario. In the low-lying Ilaje coastal environment, where marginal changes in elevation significantly affect flood propagation and spatial exposure patterns, the $\pm$6 m vertical accuracy of the SRTM DEM complicates the determination of inundated versus non-inundated land, particularly within the marginal elevation zone. In the 0.269 m and 1.0 m scenarios, the land under the estimated SLR was classified as susceptible or potentially exposed, and, within the $\pm$6 vertical accuracy, was identified as an area of ambiguity requiring cautious interpretation. The 0.269m scenario was found to be more sensitive to DEM vertical accuracy, as its predicted SLR value was significantly lower than the value derived from the DEM-identified vertical accuracy. The 1.0 m scenario, however, provided a more comprehensive description of potential exposure and is therefore more suitable for long-term coastal planning purposes. Thus, the vulnerability analysis in this study is descriptive of relative spatial susceptibility and potential exposure patterns, and is primarily of value for large-scale coastal planning purposes.

Additionally, shoreline changes and inundation modelling serve complementary purposes within this study. The Landsat-derived shoreline analysis provides a quantitative assessment of horizontal change along the coastline over time, and the SRTM DEM was also utilized to assess potential inundation under a predicted future sea-level rise scenario based on static elevations. As the DEM is a single-epoch product of terrain elevation, the inundation analysis did not account for any vertical topographic change that may have occurred along the shoreline throughout the study time period (due to erosion, accretion, etc.), thereby introducing some uncertainty into the accuracy of projected inundation extents, especially along dynamic shorelines. However, the DEM remains suitable for mapping relatively low-lying regions vulnerable to future sea level rise on a broader regional basis, and thus these inundation maps can help assess areas that should be investigated further for vulnerability and planning. The inclusion of inundation analysis using DEM shows that the study area is highly vulnerable to sea-level rise (SLR) due to its low elevation and proximity to tidal and fluvial activities. The results indicate that even relatively small rises in sea level could cause widespread flooding with significant social, economic, and environmental effects. Figure 5 illustrates a 0.269m SLR scenario, one of the conservative short-term projections; 555.348 sq km of land would be flooded. This flooding already threatens communities such as Gbabijo, Ogogoro, Obe-Adun, Gbeke Eke, Ilowo, and others, especially those in low-lying areas in the state's central and eastern parts. These areas currently experience seasonal flooding and high tides; a further rise of up to 0.269m would worsen these issues, increase the number of floods, and reduce farmland and available land in these regions. In a 1 m SLR scenario,, the flooding would be enormous, affecting up to 650.140 sq km of land and inundating additional settlements, including Ayetoro, Ogogoro, Gbeke, Eke, and others, as shown in Figure 6. At this level, the effects would go beyond periodic flooding to the complete submergence of land and structures. The coasts would be hit hard, with roads, schools, health facilities, and fishing settlements at risk. This situation could also lead to the relocation of many coastal residents, affecting housing and food security.

Flooding of farms and fishing areas could reduce agricultural output, putting communities that depend heavily on natural resources at risk.

Long-term projections well before 2150 suggest that, under high-emission scenarios, sea levels could rise by up to 1 meter due to the combined effects of ocean thermal expansion, glacial melt, and ice sheet collapse. At this level, large areas of the study region would stay permanently submerged, and communities could be entirely drowned. Such a change would displace tens of thousands of people and lead to the loss of cultural heritage, social networks, and identities connected to ancestral lands. In both scenarios, flooding would have major ecological impacts. The ecosystems of coastal wetlands, mangrove forests, and estuarine systems would be damaged or destroyed, weakening their defenses against storms, erosion, and flooding. Such ecosystem damage would also cause biodiversity loss and reduce ecosystem services, including carbon storage and fish nursery habitats.

This illustrates a gradual rise in potential risks. At a small scale of sea-level increase (0.269 m), communities can adapt through modest engineering efforts, such as dykes and embankments. However, a 1 m rise makes adaptation more costly and complicated, and several settlements might need to be relocated. The forecast for 2150 indicates that large parts of the coastline could be entirely submerged, suggesting that only large-scale coastal protection or managed retreat can reduce the impacts.

5 Conclusions

This study assessed how sea encroachment impacts the Ilaje Local Government Area of Ondo State, Nigeria, using multi-temporal optical satellite images and Shuttle Radar Topography Mission (SRTM) DEM data over a 30-year period (1995-2025). Shoreline dynamics analysis, based on the End Point Rate (EPR) and Linear Regression Rate (LRR) techniques, indicated that the Ilaje coastline is predominantly erosive, with localized areas experiencing accretion. The results showed that over 70 percent of the coastline has undergone continuous recession, leading to significant land loss, displacement of settlements, and damage to coastal infrastructure.

The DEM-based inundation analysis highlights that the Ilaje coastline is highly susceptible to sea-level rise, demonstrating that even a modest increase of 0.269 m could potentially expose more than 555 sq km of land to inundation risk, while a 1 m rise could submerge more than 650 sq km of land, including major settlements such as Ayetoro, Ogogoro, and Gbeke Eke. These results indicate an impending threat to the socio-economic stability and ecology of Ilaje communities posed by sea-level rise, tidal flooding, and storm surges. The effects of sea intrusion are not experienced equally along the coastline. The most affected areas are the central and eastern regions, where wave energy, tidal currents, and human activities such as sand mining and mangrove deforestation are particularly pronounced. By contrast, accretion was minimal along the western coast, largely due to sediment deposition via littoral drift.

Ilaje faces a significant risk of land loss, habitat destruction, livelihood disruption, and displacement if urgent, sustainable measures are not implemented. Existing geospatial tools, such as satellite imagery and DEMs, are crucial for detecting, estimating, and modelling sea-level rise trends and provide reliable data for policymaking and coastal management strategies. Future studies could leverage open-source geospatial platforms, advanced machine learning algorithms, and artificial intelligence techniques to enable more detailed shoreline monitoring, dynamic inundation modelling, and improved prediction of coastal vulnerability under changing climate conditions.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Wantim, M. N., Mokosa, W. A., Jitiz, L., & Ayonghe, S. N. (2021). The utilisation of satellite imagery and

community perceptions to assess the impacts of sea encroachment in the West Coast of Cameroon at Limbe. *Journal Of The Cameroon Academy Of Sciences, 16*(3). [CrossRef]

[2] Dada, O. A., Almar, R., & Morand, P. (2024). Coastal vulnerability assessment of the West African coast to flooding and erosion. *Scientific reports, 14*(1), 890. [CrossRef]

[3] Intergovernmental Panel on Climate Change. (2014). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.). Cambridge University Press. [CrossRef]

[4] Cazenave, A., Meyssignac, B., Ablain, M., Balmaseda, M., Bamber, J., Barletta, V., ... & Wouters, B. (2018). Global sea-level budget 1993-present. *Earth System Science Data, 10*(3), 1551-1590. [CrossRef]

[5] Gbedemah, S. F., Amenyogbe, G. K., Frimpong, L. K., & Mensah, L. S. (2023, August). The Impact of Tidal Waves on Coastal Communities and the Resilient Strategies of People Around Keta and Anloga Communities in Ghana. In *Applied Research Conference in Africa* (pp. 391-406). Cham: Springer Nature Switzerland. [CrossRef]

[6] Dada, O. A., Almar, R., & Oladapo, M. I. (2020). Recent coastal sea-level variations and flooding events in the Nigerian Transgressive Mud coast of Gulf of Guinea. *Journal of African Earth Sciences, 161*, 103668. [CrossRef]

[7] Wong, P. P., Losada, I. J., Amez, S., Gattuso, J. P., Hinkel, J., Khattabi, A., ... & Santos, F. (2015). Coastal systems and low-lying areas. In *Climate change 2014 impacts, adaptation and vulnerability: part a: global and sectoral aspects* (pp. 361-410). https://hdl.handle.net/10779/uow.27702801

[8] Bukvic, A., Rohat, G., Apotsos, A., & de Sherbinin, A. (2020). A systematic review of coastal vulnerability mapping. *Sustainability, 12*(7), 2822. [CrossRef]

[9] Merkens, J. L., Reimann, L., Hinkel, J., & Vafeidis, A. T. (2016). Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change, 145*, 57-66. [CrossRef]

[10] Sarr, C. A. T., Ndour, M. M. M., Haddad, M., & Sakho, I. (2021). Estimation of sea level rise on the West African coasts: Case of Senegal, Mauritania and Cape Verde. *International Journal of Geosciences, 12*, 121-137. [CrossRef]

[11] Tano, R. A., Aman, A., Toualy, E., Kouadio, Y. K., François-Xavier, B. B. D., & Addo, K. A. (2018). Development of an integrated coastal vulnerability index for the Ivorian coast in West Africa. *Journal of Environmental Protection, 9*(11), 1171-1184. [CrossRef]

[12] Jayson-Quashigah, P. N., Addo, K. A., & Kodzo, K. S. (2013). Medium resolution satellite imagery as a tool for monitoring shoreline change. Case study of the Eastern coast of Ghana. *Journal of coastal Research, 65*(SI), 511-516. [CrossRef]

[13] Mucova, S. A. R., Azeiteiro, U. M., Filho, W. L., Lopes, C. L., Dias, J. M., & Pereira, M. J. (2021). Approaching Sea-Level Rise (SLR) change: strengthening local responses to sea-level rise and coping with climate change in Northern Mozambique. *Journal of Marine Science and Engineering, 9*(2), 205. [CrossRef]

[14] Efere, Z., & Ohwo, O. (2022). Vulnerability of Coastal Communities to Sea Level Rise in Brass Local Government Area, Nigeria. *Nigerian Journal of Environmental Sciences and Technology, 6*(1), 112-123. https://www.researchgate.net/publication/359523961

[15] Isiaka, I., & Tata, H. (2024). Futuristic prediction of the lagoon coast shorelines using spaceborne Synthetic Aperture Radar (SAR) imagery. *Nova Geodesia, 4*(2), 184. [CrossRef]

[16] Intergovernmental Panel on Climate Change. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

[17] Popoola O.O. (2022). Spatio-Temporal Assessment of Shoreline Changes and Management of the Transgressive Mud Coast, Nigeria. *European Scientific Journal, 18*(20), 99. [CrossRef]

[18] Opoola, L. O., Ibitoye, M. O., Komolafe, A. A., & Dada, O. A. (2025). Geospatial analysis of shoreline changes along the Southwestern coast of Nigeria over the past four decades. *Environmental Monitoring and Assessment, 197*(10), 1165. [CrossRef]

[19] Atayi, J., Twumasi, Y. A., Ning, Z. H., & Asare-Ansah, A. B. (2022). A study on the shoreline changes and land use/land cover along the Keta coastal zone. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 46*, 39-45. [CrossRef]

[20] Hastuti, A. W., Nagai, M., & Suniada, K. I. (2022). Coastal vulnerability assessment of Bali Province, Indonesia using remote sensing and GIS approaches. *Remote Sensing, 14*(17), 4409. [CrossRef]

[21] Adeaga, O., Folorunsho, R., Foli, B. A. K., & Akinbaloye, O. (2021). Assessment of shoreline change along the coast of Lagos, Nigeria. *Remote Sensing in Earth Systems Sciences, 4*(3), 186-198. [CrossRef]

[22] Dada, O. A., Agbaje, A. O., Adesina, R. B., & Asiwaju-Bello, Y. A. (2019). Effect of coastal land use change on coastline dynamics along the Nigerian Transgressive Mahin mud coast. *Ocean & Coastal*

Management, *168*, 251-264. [CrossRef]

[23] Ogunrayi, O. A., Mattah, P. A. D., Folorunsho, R., Jolaiya, E., & Ikuomola, O. J. (2023). A spatio-temporal analysis of shoreline changes in the Ilaje coastal area of Ondo state, Nigeria. *Journal of Marine Science and Engineering*, *12*(1), 18. [CrossRef]

[24] Fashae, O. A., & Onafeso, O. D. (2011). Impact of climate change on sea level rise in Lagos, Nigeria. *International journal of remote sensing*, *32*(24), 9811-9819. [CrossRef]

[25] Komolafe, A. A., Apalara, P. A., Ibitoye, M. O., Adebola, A. O., Olorunfemi, I. E., & Diallo, I. (2022). Spatio-temporal analysis of shoreline positional change of Ondo State coastline using remote sensing and GIS: A case study of Ilaje coastline at Ondo State in Nigeria. *Earth Systems and Environment*, *6*(1), 281-293. [CrossRef]

[26] Omitoyin, S. A., Ogungbure, A. P., & Osakuade, K. D. (2021). Assessment of Livelihood Vulnerability of Fisherfolks in Coastal and Freshwater Fishing Communities of Ilaje in Ondo State. *Asian Journal of Fisheries and Aquatic Research*, *11*(2), 1-14. [CrossRef]

[27] National Population Commission (NPC). (2006). *Population and Housing Census of the Federal Republic of Nigeria: National and State Population and Housing Tables*. Abuja, Nigeria. https://searchworks.stanford.edu/view/8626165

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