Geospatial and Geophysical Assessment of Climate-Driven Coastal Environmental Impacts in Selected Niger Delta Communities, Rivers State, Nigeria (1994–2024)

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ABSTRACT

Climate-driven coastal degradation is creating increasingly difficult environmental management and Environmental Impact Assessment challenges in the Niger Delta. This study integrates remote sensing, geographic information systems, coastal-vulnerability analysis, climate records, and community perceptions to assess environmental change in Bonny, Andoni, Opobo-Nkoro, and Kula, Rivers State, Nigeria, between 1994 and 2024. Landsat imagery from four temporal epochs was analysed using the Digital Shoreline Analysis System with 80 transects. The Coastal Vulnerability Index was calculated from geomorphology, coastal slope, relative sea-level change, significant wave height, tidal range, shoreline-change rate, and vegetation loss. Mangrove change was assessed using NDVI- and MVI-based classification, while temperature and rainfall trends were estimated from Nigerian Meteorological Agency records. Relative sea-level change was estimated by combining geocentric sea-level trends with vertical-land-motion information rather than treating satellite altimetry alone as relative sea level. The results indicate widespread shoreline retreat. Mean end-point erosion rates were −2.88 m/yr in Andoni, −2.42 m/yr in Bonny, −1.32 m/yr in Opobo, and −0.91 m/yr in Kula. Cumulative estimated land loss was 44.26 km², with 65–90% of transects showing net erosion. The estimated relative sea-level trend was +5.291 mm/yr, with uncertainty in the separate contributions of geocentric sea-level rise and land subsidence. Mean annual temperature increased by 0.0327°C/yr, while rainfall showed a weak negative trend. Mangrove loss was estimated at 6,187 ha, with accelerated loss during 2015–2024. Andoni and Bonny were classified as Very High vulnerability, while Opobo and Kula were classified as High vulnerability. Petroleum activity is recognised as a compounding stressor through hydrocarbon-related subsidence, dredging, access canals, reclamation, industrial infrastructure, oil pollution, and mangrove clearing. The separate contribution of these processes to shoreline retreat and vertical land motion could not be quantified; therefore, the shoreline rates represent net responses to combined climatic, geomorphic, and anthropogenic forcing. Adaptation projections were interpreted as conditional screening estimates. Benefit–cost ratios were not validated because the cost data, damage functions, discount rate, intervention effectiveness, and uncertainty analysis were not sufficiently specified.

Keywords: coastal vulnerability assessment, DSAS, geospatial analysis, Niger Delta, petroleum-related subsidence

INTRODUCTION

Climate change has emerged as the defining environmental challenge of the 21st century, exerting unprecedented pressure on coastal ecosystems, infrastructure, and human settlements worldwide [1, 2]. One of the most critical manifestations of this change is accelerating sea-level rise, which intensifies coastal erosion, increases flood frequency, and disrupts intertidal ecosystems, particularly in low-lying deltaic environments [3, 4]. In the context of Environmental Impact Assessment (EIA) and environmental management, these dynamics create complex, multi-dimensional challenges: the physical boundaries of coastal environments are shifting, waste disposal sites and infrastructure located in coastal zones are increasingly exposed to inundation and contamination risk, and the ecological buffers that traditionally protected communities from environmental hazards are being systematically eroded [5, 6].

The Niger Delta of Nigeria represents one of the world's most environmentally sensitive and geophysically dynamic coastal regions. Spanning approximately 70,000 km² across nine states, the Niger Delta hosts the third-largest mangrove forest in the world, extensive wetlands, complex estuarine networks, and a population of over 30 million people whose livelihoods depend on coastal and aquatic resources [7, 8]. It is also the epicentre of Nigeria's petroleum industry, with decades of oil exploration, pipeline construction, and industrial activity creating significant cumulative environmental impacts that compound the effects of climate change [9, 10]. Rivers State, located in the eastern Niger Delta, contains some of the most dynamically active coastal communities in Nigeria, including Bonny, Andoni, Opobo, and Kula communities that have experienced shoreline retreat, mangrove loss, and increasing flood exposure over recent decades [11, 12].

Climate-driven coastal change in the Niger Delta is occurring within a landscape that has been extensively modified by petroleum extraction and associated infrastructure. Hydrocarbon production may contribute to land subsidence through pressure depletion, reservoir compaction, and deformation of overlying sediments. Time-lapse seismic analysis in a Niger Delta field identified production-related pore-pressure depletion and reservoir compaction as mechanisms capable of producing localized subsidence [59]. A geomechanical study of an onshore coastal-swamp oilfield also predicted production-related compaction and surface deformation, while noting that the observed elevation change could not be explained by hydrocarbon withdrawal alone because consolidation, fault movement, and other geological processes may also contribute [60]. Multi-temporal InSAR observations in Warri further demonstrate measurable land deformation in an oil-producing environment, although groundwater withdrawal, urban loading, and oil and gas exploration could not be separated as independent causes [61].

Petroleum activity can also affect erosion without directly causing subsidence. Canals, dredging, port construction, harbour protection works, reclamation, jetties, tank farms, and other coastal infrastructure can modify sediment supply, interrupt longshore transport, and redistribute wave and tidal energy [62, 63]. Recent Sentinel-1 analysis identified reclamation near Bonny, industrial terminals, and other infrastructure as local controls on shoreline position, while treating oil-and-gas-related subsidence as a possible but spatially variable influence [26]. In parallel, oil spills and seismic-line clearing can damage mangroves, reduce root reinforcement and sediment trapping, and increase the exposure of intertidal sediments to tidal flushing and erosion [64–68]. These processes justify treating petroleum activity as a cumulative stressor, but they do not support attributing all observed shoreline retreat to oil operations.

The application of geospatial and geophysical methods to environmental assessment in coastal zones has advanced significantly over the past two decades. Remote sensing platforms, including the Landsat series (TM, ETM+, OLI), Sentinel satellites, and satellite altimetry systems such as AVISO, now provide continuous, multi-decadal records of coastal change at spatial resolutions and temporal frequencies that were previously unavailable [13, 14]. The Digital Shoreline Analysis System (DSAS), developed by the United States Geological Survey (USGS), provides a standardised, statistically robust framework for quantifying shoreline change rates from multi-temporal satellite imagery [15]. The Coastal Vulnerability Index (CVI), originally developed by Gornitz [16] and subsequently adapted for tropical and West African coastal environments [17, 18], integrates multiple geophysical parameters including coastal slope, geomorphology, wave height, tidal range, sea-level rise rate, and vegetation cover into a composite vulnerability score that directly supports EIA and coastal zone management decision-making.

In Nigeria, EIA is governed by the Environmental Impact Assessment Act (Cap. E12, LFN 2004) and regulated by the National Environmental Standards and Regulations Enforcement Agency (NESREA) [19]. However, the integration of geospatial and geophysical data into EIA practice remains limited, particularly for coastal projects involving waste disposal infrastructure, dredging operations, petroleum facilities, and industrial development in high-vulnerability zones [20]. The absence of spatially disaggregated, long-term shoreline change data and coastal vulnerability assessments in many EIA reports means that waste disposal sites and other environmental infrastructure are frequently sited without adequate consideration of dynamic coastal processes, sea-level rise trajectories, petroleum-related land deformation, and ecosystem-service dependencies [21, 22].

This paper presents an integrated geospatial and geophysical assessment of climate-driven coastal environmental impacts in four Niger Delta communities over a 30-year period (1994–2024). The study employs DSAS shoreline change analysis, CVI computation, NDVI-based mangrove assessment, AVISO satellite altimetry, and community perception surveys to provide a comprehensive, evidence-based characterisation of coastal environmental dynamics. The findings are presented within an EIA framework, with explicit discussion of implications for waste disposal site selection, flood hazard mapping, mangrove buffer zone delineation, petroleum-sensitive cumulative-impact assessment, and regulatory compliance in Nigeria's coastal zone. The paper contributes to the growing body of knowledge on the application of geophysics to environmental impact assessment in the Niger Delta and provides a replicable methodological framework for geoscientists and environmental practitioners working in similar coastal settings.

STUDY AREA

The study was conducted in four coastal communities within Rivers State, Nigeria: Bonny, Andoni, Opobo-Nkoro, and Kula. These communities are located along the southern coastline of Rivers State, within the eastern Niger Delta, and share direct exposure to the Atlantic Ocean and its associated wave energy, tidal dynamics, and sea-level variability. Rivers State is characterised by low-lying coastal plains, tidal creeks, and extensive mangrove swamps, making it highly susceptible to coastal erosion, flooding, and saltwater intrusion [23].

Bonny Island is located at the mouth of the Bonny River, approximately 55 km southeast of Port Harcourt. It is a densely settled community and a major hub of Nigeria's petroleum export industry, hosting the Nigeria LNG terminal and significant oil and gas infrastructure. Bonny is also exposed to petroleum-related shoreline modification, including reclamation, port and terminal infrastructure, dredging, and associated changes in sediment circulation, although the independent contribution of each activity has not been quantified in the present study [26, 32]. Andoni occupies the southeastern coastal fringe of Rivers State, characterised by highly exposed, low-lying deltaic plains with limited natural protection from Atlantic wave action. Opobo-Nkoro is situated at the Imo River estuary and benefits from partial protection afforded by the river's sediment plume and residual mangrove fringe vegetation. Kula is located along the Sombrero River in a more sheltered estuarine position, resulting in comparatively lower wave-energy exposure.

All four communities share similar geomorphological characteristics: unconsolidated sedimentary substrates (fine sands and silts), extensive intertidal mangrove forests, complex tidal creek networks, and very gentle coastal slopes. Human activities including oil exploration and production, sand mining, unregulated construction, dredging, reclamation, and artisanal fishing have modified the natural coastal systems of all four communities, creating conditions of heightened environmental sensitivity [24, 25, 26]. The communities collectively support a population of approximately 250,000 people, the majority of whom depend on fishing, farming, and trade for their livelihoods activities that are directly threatened by the coastal dynamics documented in this study [26].

The study area lies within the humid equatorial climate zone, characterised by mean annual temperatures of approximately 27°C, annual rainfall of 2,400–2,600 mm, and a bimodal rainfall pattern driven by the West African Monsoon. The region is subject to regular tidal flooding, storm surges, and episodic extreme precipitation events. The combination of high rainfall, low elevation, poor drainage, rapid sea-level rise, and petroleum-related landscape modification creates a particularly challenging environmental context for waste disposal infrastructure, coastal development, and ecosystem management [27].

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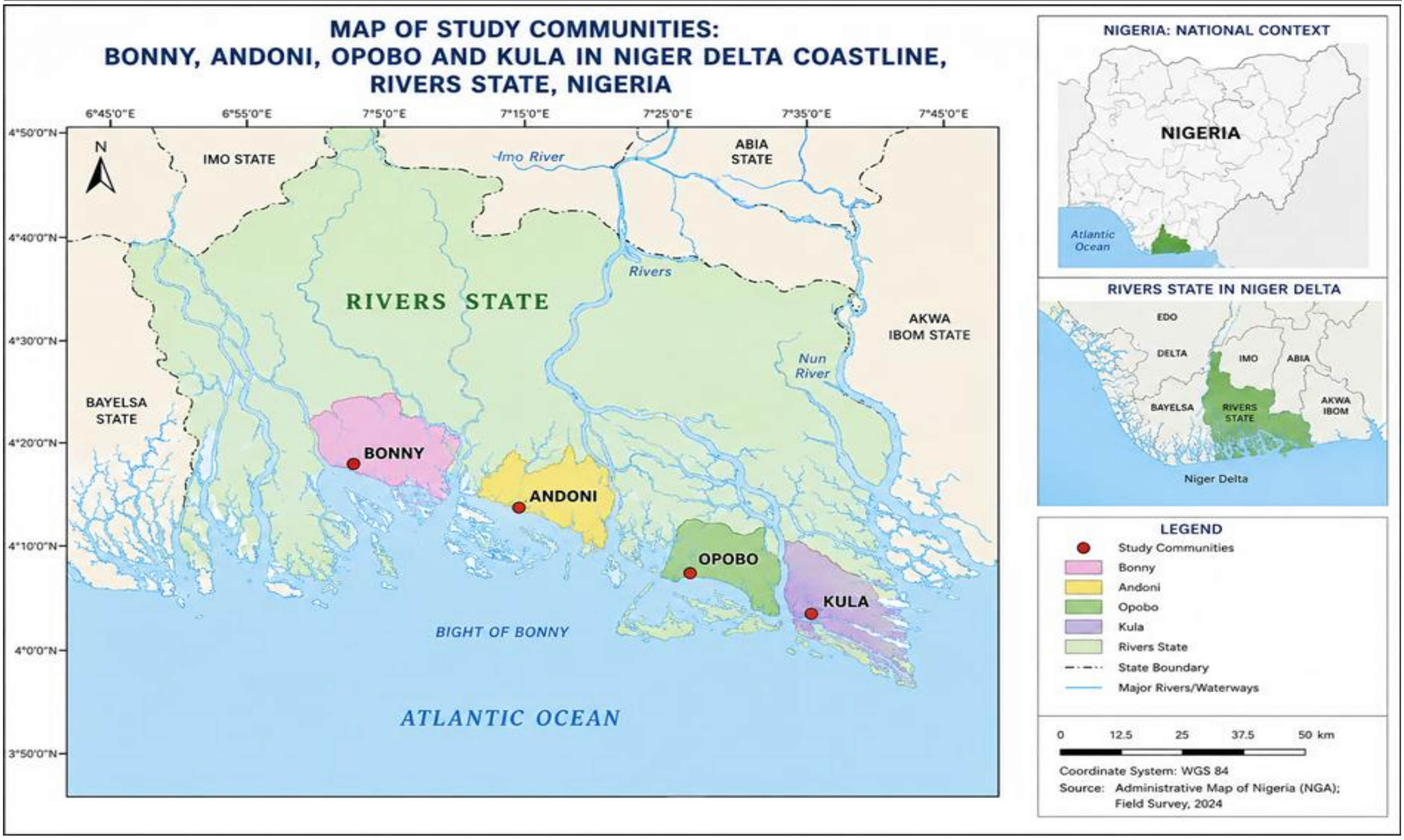

Figure 1: Map showing the four communities occupying low-lying deltaic terrain, unconsolidated sedimentary substrates, and extensive intertidal mangrove ecosystems.

MATERIALS AND METHODS

Research Design and Data Sources

This study adopted a mixed-methods research design, integrating quantitative geospatial analysis with qualitative socio-economic assessment. Landsat satellite imagery was acquired for four temporal epochs: 1994 (Landsat 5 TM), 2004 (Landsat 7 ETM+), 2014 (Landsat 8 OLI), and 2024 (Landsat 9 OLI-2). All images were acquired during the dry season (November–February) to minimise the confounding effects of seasonal rainfall on shoreline position and vegetation indices, and were geometrically corrected and radiometrically normalised using the dark object subtraction (DOS) method.

Sea-level observations were obtained from AVISO satellite altimetry. Relative sea-level interpretation incorporated vertical-land-motion information derived from InSAR. Vertical motion was treated as a net local signal rather than being assigned specifically to hydrocarbon withdrawal, groundwater extraction, natural compaction, or other individual processes. Climate data were obtained from the Nigerian Meteorological Agency (NiMet) Port Harcourt station for the period 1994–2024.

Petroleum activity was considered a cumulative-impact layer during interpretation but was not used as a causal explanatory variable in the DSAS calculations. The study did not include a co-located time series of hydrocarbon production, reservoir pressure, dredging volume, reclamation history, or spatially resolved oil-spill footprints. Consequently, the petroleum-related component of shoreline retreat and vertical land motion was not estimated separately.

Digital Shoreline Analysis System

Shoreline change analysis was performed using the Digital Shoreline Analysis System (DSAS) version 5.0 [15], an ArcGIS extension developed by the USGS. Shoreline positions were extracted from each epoch of Landsat imagery using the Modified Normalised Difference Water Index (MNDWI), validated through visual interpretation and GPS field verification. A baseline was established 50 metres inland from the most landward shoreline position, and 20 transects per community (80 total) were cast perpendicular to the baseline at 50-metre intervals.

Four DSAS statistical parameters were computed for each transect: (1) End Point Rate (EPR) — the distance between the oldest and most recent shoreline positions divided by elapsed time; (2) Net Shoreline Movement (NSM) — the total distance between the 1994 and 2024 shoreline positions; (3) Linear Regression Rate (LRR) — a least-squares regression of all four shoreline positions against time; and (4) Shoreline Change Envelope (SCE) — the total range of shoreline positions across all epochs. Combined measurement uncertainty was ±11.0 m, incorporating positional accuracy of satellite imagery (±10.5 m), digitisation error (±2.5 m), and tidal correction uncertainty (±3.2 m).

Coastal Vulnerability Index

The CVI was computed following the methodology of Thieler and Hammar-Klose [29] as modified by Gornitz [16], using seven parameters: (1) geomorphology; (2) coastal slope; (3) sea-level rise rate; (4) significant wave height; (5) mean tidal range; (6) shoreline-change rate; and (7) vegetation loss. Each parameter was rated on a scale of 1 (very low vulnerability) to 5 (very high vulnerability). The CVI was computed as:

$$CVI = \sqrt{\frac{G \times S \times SLR \times W \times T \times SC \times VL}{7}}$$

Classification thresholds were: CVI < 5 = Very Low; 5–9 = Low; 9–15 = Moderate; 15–25 = High; and >25 = Very High.

Mangrove Analysis, Sea-Level Trends, and Community Survey

Mangrove ecosystem loss was quantified through multi-temporal supervised classification of Landsat imagery using the Normalised Difference Vegetation Index (NDVI) and the Mangrove Vegetation Index (MVI). Classification performance achieved an overall accuracy of ≥87%, based on validation with GPS field-survey data. Sea-level trends were derived from AVISO satellite-altimetry data and analysed using linear regression, with statistical significance evaluated at $p < 0.05$.

Community perceptions of environmental impacts were assessed using a structured questionnaire survey involving 400 respondents, with 100 respondents drawn from each of Bonny, Andoni, Opobo-Nkoro, and Kula. The survey instrument comprised 40 items measured on a five-point Likert scale. The equal allocation of respondents across the four communities provided comparable community-level observations. The questionnaire assessed perceptions of flooding, shoreline retreat, saltwater intrusion, effects on housing and infrastructure, livelihood disruption, cultural impacts, and waste-related environmental contamination. Internal consistency was evaluated using Cronbach's alpha, which produced a reliability coefficient of 0.87, indicating high internal consistency among the questionnaire items. Survey responses were analysed using descriptive statistics. Mean Likert scores of ≥3.50 were interpreted as agreement, while scores below 3.50 indicated disagreement or uncertainty [31].

RESULTS AND DISCUSSION

Shoreline Change Dynamics

The DSAS analysis reveals pervasive and accelerating shoreline erosion across all four study communities over the 30-year period (1994–2024). Table 1 summarises the DSAS statistics for all communities. Andoni experienced the most severe erosion, with a mean End Point Rate (EPR) of −2.88 ± 1.86 m/yr and a mean Net Shoreline Movement (NSM) of −86.42 ± 55.89 m, indicating that the shoreline retreated an average of nearly 86 metres over three decades. The maximum erosion rate at Andoni was 6.87 m/yr, recorded along the exposed southeastern coastline where wave energy is highest and mangrove protection has been significantly reduced.

Ninety percent of Andoni's transects (18/20) recorded net erosion. Total estimated land loss for Andoni was 18.63 km² [33].

Bonny recorded the second-highest erosion rate (EPR = −2.42 ± 1.70 m/yr; NSM = −72.52 ± 50.85 m), with 85% of transects eroding and total land loss of 12.47 km². Opobo recorded intermediate erosion (EPR = −1.32 ± 1.37 m/yr; NSM = −39.70 ± 41.03 m), with 75% of transects eroding and total land loss of 7.82 km². Kula recorded the lowest erosion rate (EPR = −0.91 ± 0.85 m/yr; NSM = −27.33 ± 25.48 m), with 65% of transects eroding and total land loss of 5.34 km². Across all four communities combined, total land loss was 44.26 km² over 30 years [33, 34].

Critically, the temporal analysis reveals consistent acceleration of erosion: the mean EPR across all communities increased from −1.21 m/yr in the first decade (1994–2004) to −1.74 m/yr in the second decade (2005–2014) and −2.69 m/yr in the third decade (2015–2024) — a 122% increase from the first to the third decade. This acceleration has direct implications for EIA: waste disposal sites and infrastructure located within 100–200 metres of the current shoreline face a significant probability of inundation or erosion within their design life under business-as-usual conditions [35].

Petroleum-related controls on local shoreline change

The shoreline trends should not be interpreted as being controlled by climate forcing alone. Petroleum-related activities may have modified shoreline response in particular reaches through reclamation, dredging, terminal construction, sand extraction, and changes in sediment circulation. Along the Niger Delta coast, canals, dredging, harbour works, and upstream modifications have been identified as activities capable of altering sediment discharge and accelerating coastal change [62, 63]. In the Bonny sector, recent Sentinel-1 analysis identified reclamation associated with NLNG-related development as a local shoreline disturbance and also noted the influence of industrial terminal construction elsewhere along the Niger Delta coast [26]. Earlier Bonny Island analysis similarly associated shoreline retreat with industrial development, ports, dredging, vegetation removal, and sand mining [32]. These studies provide evidence of petroleum-related and infrastructure-related coastal modification, but their observational designs do not isolate the causal contribution of individual facilities from wave action, river discharge, sediment variability, sea-level change, and natural shoreline adjustment.

Table 1: Summary of DSAS Shoreline Change Statistics for All Communities (1994–2024)

Community	Mean EPR (m/yr)	Mean NSM (m)	Mean LRR (m/yr)	% Eroding Transects	Total Land Loss (km²)
Andoni	−2.88 ± 1.86	−86.42 ± 55.89	−2.88 ± 1.96	90%	18.63
Bonny	−2.42 ± 1.70	−72.52 ± 50.85	−2.35 ± 1.66	85%	12.47
Opobo	−1.32 ± 1.37	−39.70 ± 41.03	−1.28 ± 1.31	75%	7.82
Kula	−0.91 ± 0.85	−27.33 ± 25.48	−0.88 ± 0.79	65%	5.34
All sites	−1.88 mean	−56.49 mean	−1.85 mean	79% average	44.26 total

Note: EPR = End Point Rate; NSM = Net Shoreline Movement; LRR = Linear Regression Rate. Negative values indicate erosion. Source: Author's DSAS analysis.

Climate Change Trends and Petroleum-related Vertical Land Motion

The climate trend analysis confirms statistically significant changes in the principal climate variables. Mean annual temperature increased from 26.59°C in 1994 to 27.91°C in 2024, yielding a warming trend of +0.0327°C/yr ($R^2 = 0.63$, $p < 0.01$) and a cumulative increase of 0.98°C. The observed rate exceeds the global mean warming of approximately 0.02°C/yr [1], consistent with above-average warming documented in the

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West African coastal zone [36]. Annual rainfall showed a weak declining trend of −0.94 mm/yr ($R^2 = 0.009$, $p < 0.05$), with increasing variability in the most recent decade [38].

The estimated relative sea-level trend was +5.291 mm/yr, equivalent to 159.4 mm over the 30-year period. The trend combines geocentric sea-level variability and vertical land motion, and its interpretation includes uncertainty associated with the spatial co-location and integration of these datasets. Petroleum-related subsidence is a credible local amplifier because hydrocarbon production can reduce pore pressure, increase effective stress, and promote reservoir or sediment compaction [59, 60].

Evidence from the Niger Delta indicates that vertical motion is spatially heterogeneous and may also reflect groundwater withdrawal, urban or infrastructure loading, natural sediment compaction, channel erosion, tectonic deformation, and sediment-supply changes [61, 69, 70]. Time-lapse seismic analysis has identified production-related pore-pressure depletion and reservoir compaction in a Niger Delta field, but the resulting deformation was interpreted as being primarily at reservoir scale [59]. A geomechanical study of an onshore coastal-swamp oilfield predicted production-related compaction and surface deformation, but also noted that fault movement, consolidation of recent deposits, and other processes contributed to the observed elevation change [60]. In Warri, InSAR-derived deformation was associated with a combination of groundwater withdrawal, sediment compaction, urban development, and oil and gas exploration [61]. Conversely, time-lapse leveling and GPS analysis in another Niger Delta setting reported large but localized elevation changes concentrated in river channels and erosional slopes, without a positive relationship between the measured deformation and production or reservoir-pressure decline [69]. A coast-wide Nigerian assessment also found no simple relationship between subsidence and proximity to oil wells [70].

A fixed decomposition of approximately 3.2 mm/yr of eustatic sea-level rise plus 2.0 mm/yr of petroleum-related subsidence is not supported by the available evidence. The estimated trend is therefore interpreted as a combined relative sea-level signal whose individual components require further co-located geodetic and petroleum-production data. Petroleum activity is treated as a documented and potentially important local amplifier, not as a separately quantified regional cause of erosion.

Coastal Vulnerability Index Assessment

The CVI assessment indicates that Andoni and Bonny fall within the Very High vulnerability category, while Opobo and Kula fall within the High vulnerability category under the stated thresholds. Andoni recorded the highest score (94.49), reflecting maximum ratings across nearly all parameters: exposed deltaic plain (geomorphology = 5), very gentle coastal slope (slope = 5), highest relative sea-level rise rate (SLR = 5), highest wave energy (wave = 5), and most severe vegetation loss (vegetation loss = 5). Bonny scored 52.37 and was also classified as Very High. Opobo scored 23.57 and Kula 16.66, placing both communities in the High category because their scores fall between 15 and 25 [16, 29].

The classification of Andoni and Bonny as Very High vulnerability and Opobo and Kula as High vulnerability has important implications for EIA. In Very High CVI zones, detailed geophysical risk assessment should be required before approval of waste disposal facilities, industrial sites, dredging operations, and coastal infrastructure. High-vulnerability communities should also be subject to site-specific assessment, development setbacks, mangrove protection, and monitoring of vertical land motion. Petroleum-related infrastructure and subsidence should be evaluated as additional cumulative-impact factors rather than added to the standard CVI without a validated weighting framework.

Mangrove Ecosystem Loss

Multi-temporal NDVI and MVI analysis reveals a total mangrove loss of 6,187 hectares across all four communities over the study period. Andoni recorded the greatest loss (2,341 ha), followed by Bonny (1,847 ha), Opobo (1,123 ha), and Kula (876 ha). The rate of mangrove loss in the most recent decade (2015–2024) exceeded that of the first decade (1994–2004) by approximately 49%, reflecting the compounding effects of shoreline erosion, sea-level rise, oil pollution, and anthropogenic clearing [40].

The loss of 6,187 ha of mangrove forest has degraded the natural coastal protection system of all four communities. Mangrove forests provide wave-energy dissipation, shoreline stabilisation, sediment trapping, and flood-buffering functions [41]. The progressive removal of this natural coastal protection amplifies the vulnerability of coastal infrastructure, including waste disposal sites, to storm surge, tidal flooding, and erosion. EIA practitioners must account for the dynamic loss of mangrove buffer zones when assessing the long-term environmental risks of coastal development [42].

Petroleum activity provides an additional pathway for mangrove loss and declining shoreline resistance. Oil spills can coat sediments and mangrove roots, impair plant physiology, and produce persistent vegetation mortality. In Ogoniland, satellite and field observations identified approximately 393 km² of vegetation mortality and an estimated 730 km² of sublethal impact associated with major oil spills, with contamination persisting over time [66]. A more recent Earth-observation study in Rivers State identified substantial mangrove degradation near pipeline networks between 2016 and 2024, although the authors noted that oil spills, dredging, timber extraction, and other land-use pressures could not always be separated [67]. Seismic-line clearing in the Kalabari region of Rivers State also produced persistent mangrove damage, soil disturbance, increased tidal flushing, and reduced natural regeneration [68]. These studies support the interpretation that petroleum-related pollution and clearing can weaken natural coastal protection. However, the NDVI and MVI analysis in the present study cannot determine what proportion of the estimated 6,187 ha of mangrove loss was caused specifically by oil activity rather than erosion, salinity, natural mortality, settlement expansion, or other forms of clearing.

Community Perceptions of Environmental Impacts

The community survey ($n = 400$; Cronbach $\alpha = 0.87$) reveals strong and consistent agreement across all four communities regarding coastal impacts. Respondents strongly agreed that flooding frequency has increased (mean = 4.67), that shoreline retreat has destroyed homes and productive land (mean = 4.58), and that saltwater intrusion has contaminated freshwater sources and farmland (mean = 4.52). Infrastructure impacts were strongly perceived, with damage to roads, schools, and healthcare facilities confirmed (mean = 4.44). Respondents also expressed strong concern about contamination of water sources by floodwaters carrying waste and pollutants (mean = 4.38) and about the inadequacy of existing waste-disposal infrastructure in flood-prone areas (mean = 4.21) [43, 44].

These perceptions are consistent with the physical evidence of shoreline retreat, mangrove loss, flooding, and saltwater intrusion. Given the cross-sectional survey design and equal allocation of respondents among communities, the findings are interpreted as descriptive community-level evidence rather than population-representative estimates for all residents.

Future Projections and Scenario Analysis

Shoreline projections for 2025–2054 were developed from transect-level DSAS erosion rates. A linear continuation of the observed shoreline-change trend was applied to each transect, and projected land loss was estimated by comparing the projected shoreline with the 2024 shoreline in a GIS environment. The business-as-usual scenario assumed continuation of the observed erosion trend. The moderate- and high-adaptation scenarios were treated as conditional planning cases because intervention effectiveness was not calibrated with field data. Under business as usual, mean EPR was projected to reach approximately −2.5 to −3.5 m/yr by 2054, resulting in an estimated additional land loss of 75–105 km². The moderate-adaptation scenario included 3,000 ha of mangrove restoration and beach nourishment, while the high-adaptation scenario added 20 km of hybrid coastal protection along priority shoreline. Estimated land loss was 45–65 km² under moderate adaptation and 20–35 km² under high adaptation.

A sediment-budget study from southeast Nigeria estimated an annual nourishment requirement of 546,770 m³ for an eroding littoral cell [56]. A three-year replenishment interval was therefore used as a planning parameter, giving an estimated nourishment volume of approximately 1.64 million m³. A 30-ha mangrove-restoration trial in the Niger Delta provides local evidence that active restoration is feasible where contamination and hydrological conditions are addressed [57]. The selected adaptation measures are also consistent with lower-

Niger-Delta adaptation scenarios [52]. The 3,000-ha restoration area, 20-km protection length, and three-year nourishment interval were treated as planning parameters based on priority GIS areas and available Nigerian evidence, rather than as measured intervention requirements.

Because Nigerian studies do not provide complete, comparable unit costs for large-scale mangrove restoration, nourishment, and hybrid shoreline protection, published and regional benchmarks were used for sensitivity analysis. Mangrove-restoration costs were set at US$1,434–47,935/ha, with a median benchmark of US$8,143/ha [54]. Beach-nourishment costs were set at US$15.5–37.5/m³ [55]. Regional West African coastal-protection projects provided comparator costs of approximately US$9.2–26.8 million/km for revetment and related protection works [58]. These benchmarks are not site-specific Nigerian prices.

Intervention	Quantity	Unit-cost range	Direct cost range
Mangrove restoration	3,000 ha	US$1,434–47,935/ha	US$4.30–143.81 million
Beach nourishment	1.64 million m³	US$15.5–37.5/m³	US$25.42–61.50 million
Hybrid coastal protection	20 km	US$9.2–26.8 million/km	US$184–536 million

The resulting direct implementation cost was estimated at US$29.72–205.31 million for the moderate-adaptation package and US$213.72–741.31 million for the high-adaptation package. These values are screening estimates rather than site-specific engineering cost estimates.

ENVIRONMENTAL IMPACT ASSESSMENT IMPLICATIONS

The findings of this study have direct implications for EIA practice in Nigeria’s coastal zone, particularly for projects involving waste disposal infrastructure, industrial development, dredging, petroleum facilities, and coastal engineering.

First, waste-disposal site vulnerability mapping. The DSAS shoreline-change rates and CVI scores provide an empirical basis for delineating high-risk zones where waste-disposal sites should not be located or should require enhanced containment measures. The documented rate of land loss and the projected acceleration under business-as-usual conditions mean that setback distances established without dynamic shoreline and vertical-land-motion information may be insufficient to protect coastal waste infrastructure from inundation and erosion within its design life [19, 46]. In Very High CVI zones, detailed geophysical risk assessment should be required before any waste-disposal or hazardous facility is approved.

Second, dynamic flood-hazard-zone delineation. The reported sea-level trend and documented increase in flood exposure provide a quantitative basis for updating flood-hazard maps used in EIA. Geophysics-informed EIA should incorporate satellite altimetry, validated vertical-land-motion measurements, DSAS-based shoreline projections, and climate scenarios to establish dynamic flood-hazard zones [47].

Third, mangrove-buffer-zone protection. The documented loss of 6,187 ha of mangrove forest, combined with the 49% acceleration in loss rate in the most recent decade, demonstrates the need for stronger protection and monitoring. EIA should require retention of appropriate mangrove buffers around coastal development projects, spatial monitoring of approved clearing, and restoration proportional to unavoidable loss [41, 42].

Fourth, petroleum-sensitive cumulative-impact assessment. The convergence of relative sea-level rise, shoreline retreat, mangrove loss, petroleum-related subsidence, dredging, access canals, reclamation, industrial loading, oil spills, and vegetation clearing creates cumulative impacts that cannot be represented adequately by a climate-only assessment. Coastal EIA should combine DSAS shoreline rates and CVI outputs with spatial layers showing oil wells, pipelines, terminals, access canals, dredged channels, reclamation areas, spill footprints, mangrove degradation, and measured vertical land motion. Such an approach would identify locations where petroleum activity may amplify climate-related exposure without assuming that all observed erosion is caused by oil operations [62, 63, 67].

Fifth, geospatial infrastructure for EIA. Nigeria's regulatory authorities should establish a national coastal geophysical monitoring programme providing continuously updated shoreline-change data, validated vertical-land-motion measurements, sea-level observations, mangrove-condition maps, petroleum-infrastructure layers, and coastal-vulnerability information. Open-access dissemination of such data through a national geospatial portal would enhance the quality and consistency of coastal EIA across Nigeria [49, 50].

Sixth, petroleum-specific monitoring and attribution. Petroleum-affected coastal sites should be monitored using co-located InSAR or GPS, leveling, reservoir-pressure data, groundwater observations, shoreline transects, dredging records, and oil-spill inventories. These datasets are necessary to determine whether observed subsidence is regional, field-specific, localized, or primarily associated with non-petroleum processes [59–61, 69, 70].

CONCLUSIONS

This study has demonstrated the value of integrated geospatial and geophysical methods — DSAS shoreline-change analysis, Coastal Vulnerability Index computation, NDVI/MVI mangrove assessment, and AVISO satellite altimetry — for generating the quantitative, spatially explicit evidence base required for environmental impact assessment in dynamic coastal environments. The 30-year (1994–2024) analysis of four Niger Delta communities in Rivers State, Nigeria, yields the following principal conclusions.

Shoreline erosion is pervasive, severe, and accelerating. The total reported land loss of 44.26 km² across Bonny, Andoni, Opobo, and Kula represents a substantial transformation of the coastal landscape, with the mean erosion rate increasing by 122% from the first to the third decade of the study period. This acceleration reflects combined climatic and geomorphic forcing, including relative sea-level rise, vertical land motion, sediment-supply variability, progressive mangrove loss, and petroleum-related coastal disturbance.

The reported relative sea-level trend of +5.291 mm/yr identifies a substantial local coastal hazard, but its components require clearer co-location and uncertainty documentation. Hydrocarbon-related subsidence is a documented and physically plausible local amplifier because production-related pressure depletion can promote reservoir compaction and vertical land motion [59, 60]. However, the present dataset does not allow petroleum-related subsidence to be separated from groundwater withdrawal, natural sediment compaction, infrastructure loading, channel erosion, tectonic deformation, or other sources of vertical land motion.

Andoni and Bonny were classified as Very High vulnerability, while Opobo and Kula were classified as High vulnerability under the stated CVI thresholds. The total mangrove loss of 6,187 ha has reduced natural coastal protection and amplified exposure to wave action, storm surge, tidal flooding, and erosion. Oil spills, exploration-related clearing, dredging, access canals, reclamation, and industrial infrastructure should therefore be treated as compounding stressors in coastal EIA.

The geospatial and geophysical methodologies employed in this study provide a potentially replicable framework for integrating remote sensing and GIS into EIA practice across Nigeria's 853-km coastline. However, future attribution of petroleum-related effects requires co-located geodetic, petroleum-production, hydrodynamic, sediment-budget, and ecological data. The adoption of such monitoring, supported by a national geophysical information system, would strengthen Nigeria's capacity to manage coastal risks under combined climate and industrial pressures.

RECOMMENDATIONS

1. Establish a National Coastal Geophysical Monitoring Programme employing DSAS methodology, satellite altimetry, InSAR, GPS, and leveling to provide continuously updated shoreline-change and vertical-land-motion data for Nigeria's coastline.
2. Revise EIA setback distances for coastal waste-disposal sites, petroleum facilities, and industrial infrastructure to reflect documented shoreline retreat, relative sea-level trends, vertical-land-motion uncertainty, and future climate projections.

3. Mandate CVI assessment as a standard component of EIA for coastal development projects in Rivers State and across Nigeria's coastal zone, with Very High classifications triggering detailed geophysical and cumulative-impact assessment.
4. Establish enforceable mangrove-buffer protections around coastal development projects, with spatial monitoring and restoration requirements for approved mangrove loss.
5. Integrate dynamic sea-level projections, validated vertical-land-motion data, and DSAS shoreline projections into flood-hazard maps used in EIA.
6. Develop a petroleum-sensitive cumulative-impact assessment framework for the Niger Delta that integrates DSAS, CVI, NDVI/MVI, InSAR or GPS vertical-land-motion data, oil and gas infrastructure, dredging and reclamation footprints, oil-spill records, mangrove condition, and sediment-transport information.
7. Establish co-located monitoring at petroleum-affected coastal sites using InSAR, continuous or campaign GPS, leveling, reservoir-pressure data, groundwater observations, and shoreline transects to determine whether petroleum-related subsidence is regional, field-specific, localized, or secondary to other processes.
8. Invest in capacity building for geoscientists and EIA practitioners in remote sensing, GIS, DSAS, InSAR, coastal geophysics, cumulative-impact assessment, and uncertainty analysis.

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