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Assessment of Natural Geohazards in the Niger Delta Coast, Nigeria

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Abstract

The coastal zone is a dynamic environment under hydrodynamic forcings and adverse consequences of geohazards with potential for disasters. In this this studies, ASTER DEMs and LandSat 4,5 imageries have been analyzed in ArcGIS to determine the amount and rates of coastal subsidence, shoreline movements and coastal erosion and supplemented with secondary tide and wave data to model wave conditions in the face of climate change. Results indicates that the average ground subsidence was -2.6m at a rate of - 0.144m/yr. on the Bayelsa coast and -3.75m at a rate of -0.208m/yr on the Rivers coast. The rate of coastal erosion along the Akwa Ibom, Rivers and Bayelsa States in the Niger Delta coastline depicts a linear erosion of -13,054m, -17,519m and -81,532m in Akwa Ibom, Rivers and Bayelsa respectively with erosion rates of -5.5m/yr along Akwa Ibom, -7.2m/yr along Rivers and -11.1m/yr along the Bayelsa coastline. The net shoreline retreat equivalent of incidental erosion was -8,590m along the Akwa coastline, -9,240m along Rivers coastline and -70,383m along the Bayelsa coastline. Modeled hydrodynamics parameters predicted waves with mean wavelength of 178.95m, wave celerity of 13.01m/sec, group wave celerity of 11.27m/sec with maximum horizontal velocity of 0.4m/sec exerting an energy flux of 15, 902.00w/m. In considerations the stack realities of climate change, vulnerability assessment, integrated coastal zone management and climate change adaptation strategies for coastal protection are recommended.

Keywords: *coastal hazards, coastal subsidence, sea level rise, coastal erosion, climate change*

Introduction

Coastal zones are an amalgamation of sub-environments such as shelf, shoreface, surf zone, beach, barrier island, dune, delta/mouth-bar, estuary, lagoon, tidal river, tidal inlet, tidal flat, swamp and tidal creek. They extend from the continental shelf edge landward to the limit of tidal incursion, spanning from surface to several hundred metres (Antia, 2019).Due to their abundant natural resources, coastal zones are one of the world's most densely populated regions with essential infrastructure and complex socio-economic systems (Marzouk and Azab, 2024). Coastlines and coastal zones are dynamic environments, their nature varying with tectonic setting, rates of sediment supply; and magnitudes and directions of the surf zone hydrodynamic forcings within the geomorphological framework. Geohazards are geological and fluid-dynamic conditions or processes that can lead to the movement of the ground, soil cover, rock, fluid or gas during sudden episodic events or slow progressive deformations (Randolph and Gourvenec, 2011). Coastal vulnerability to geohazards is escalated by climate change dynamics such as extreme weather conditions and associated storm surges, wave attacks, episodic flooding, sea level rise and coastal erosion which are exacerbated by other hazards such as ground subsidence, landslide and cliff collapse. The intensity and frequency of earthquakes and tsunami hazards is also accelerated by climate induced rainfall which infiltrates into and amplify the crustal weight (Lungren, 2019, Blackett, 2023) and shear stress; reduce the effective normal stress on crustal planar weaknesses and fault zones and resulting in increased earthquakes (Larroque, and Bonhorff, 2024). Abija *et al.* (2022) noted that abrupt, stick-slip and spontaneous shear displacement of crustal fault blocks due to stress perturbations is the causative mechanism of induced earthquakes. McGar *et al.* (2002) noted that stress changes as low as 0.01mPa can trigger seismic events.Geotechnically, swelling and shrinkage of fine-grained soils, drying and heaving under increased temperatures in addition to the natural hazards potentially increases the risks posed to coastal infrastructures that support coastal cities and community livelihood. The characteristic coastline morphology also changes in response to submergence and or emergence under endogenic tectonic activities and shaped by exogenic processes. Coastal ground subsidence may amplify rise in sea level, coastal flooding, erosion and coastline retreat; wetland loss and ecosystem destruction (Doornhof *et al.* 2006). In low lying coastal deltas, it is the major underlying factor that control relative sea level rise in addition to eustatic rise. Coastal erosion also depends largely on the rates of sediment supply, lithospheric upliftment and or subsidence, wave and current forces; and the equilibration of the beach profile (Abija *et al.* 2020). The beach profile equilibrium may also be

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overwhelmed by episodes of high wave energy which can cause net sediment losses; the net volumetric change depending on the intensity and duration of total wave energy, beach slope angle and hydrodynamic forcings. Sea level changes have been reported in various IPCC assessment reports as a key feature of climate change (Oppenheimer *et al.* 2019) with devastating effect on coastal communities and coastal livelihood systems and infrastructures are not spared from the disastrous impacts of climate induced sea level rise (Vallejo and Shetima, 1997). The impacts include potential for erosion, differential settlement and or ground tilting capable of affecting roads, rails, water and gas mains; and damage due to tensile and compressive strains developing as a result of uplift and subsidence. Coastal flooding, sea level rise and erosion can be responsible for significant economic losses in the form of structural damage and high maintenance costs of roads and transportation networks, hydraulic infrastructure, river embankments, sluice gates, flood barriers, pumping stations, sewage systems, buildings, and foundations. Coastal ground subsidence has been reported to increase relative sea level rise, frequency of flooding, damage to industrial and transportation infrastructure and substantial loss of wetland habitats (NRC, 1991). The salinization of agricultural lands caused by rise in sea level in subsiding areas also can lead to loss of food productivity in cultivated soils (Machado and Seralhero, 2017) and salt marshes and mangroves of coastal wetlands which constitute carbon sinks with enormous potential for terrestrial carbon capture and sequestration as climate change reducing agents are also destroyed by the rising sea levels. Zhu *et al.* (2010) noted that salt marshes and mangroves will be drowned by any rise in sea level and encroachment of saline sea waters and all plants can be killed by salt solution if the concentration increases (Flowers, 1981)). Biodiversity in coastal ecosystems is also threatened by sea level rise induced salinization of coastal salt marshes and mangroves (Pereira *et al.* 2018). The impacts of land subsidence can be localized in coastal areas exceeding that of projected eustatic rise due to climate and permanent changes in beach gradient capable of causing altered response to wave dynamics (Humphries, 2001). It increases flood vulnerability and hence contributes to major economic damage and loss of lives and infrastructures in coastal cities (Erkens *et al.* 2015); the total damage associated with land subsidence worldwide is estimated at billions of dollars annually (Erkens *et al.*, 2015). Wong *et al.*, (2014) adduced that coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise. The IAHS, (1991)has predicted that many more areas are likely to subside in the next few decades as a result of accelerated exploitation of natural resources especially ground water in order to meet the demands of increasing population and industrial development. Also, rapid tectonic subsidence caused by flexural depression of the lithosphere due to high sedimentation rates is associated with coastal deltas (Morgan, 1970). There is also serious concern about tectonic subsidence being a potential contributor to accelerated relative sea-level (RSL) rise, coastal erosion, and wetland loss (Tornqvist *et al.*, 2006). Coastal subsidence in low lying coastal zones include natural phenomena such as hydrocompaction and consolidation settlement of recently deposited sediments (Bruno, 2001, Zoback, 2007), tectonics induced submergent and emergent coastlines caused by the abrupt cessation of crumpling and shifting of the migrating tectonic plates (Montgomery 2006), lithospheric flexure (Blyth and de Freitas, 1984) and stress concentration at the tips of subsurface faults when the fault segment moves (Vallejo and Shetima, 1997). It may also be due to the release of accumulated strain energy during fault slippage and the accompanying ground shaking while uplift may be associated with fault end induced stress release, oxidation and shrinkage of organic deposits, catastrophic development of sinkholes in karst terrain and dissolution of limestone, dissolution of salts or other soluble formation and natural consolidation of materials in sedimentary deposits, earthquake induced liquefaction and associated consolidation, and reduction in pore spaces, secondary consolidation and compaction of organic materials, and regional plate tectonics movement (coseismic and asesimic) (Elwary *et al.*, 1998). Anthropogenic causes include fluid extraction such as groundwater overdraft (Gamboleti and Teatini, 2015, Montgomery, 2006), oil/gas, and geothermal fluids extraction (Doornhof *et al.* 2006, Zoback, 2007) and lack of sedimentation due the construction of civil infrastructures such as dams and reservoirs upstream of the depositional basin.Gambolati and Teatini,(2015) adduced that land subsidence and uplift, ground ruptures, and induced seismicity are principal geomechanical effects of aquifer overdraft with major environmental consequences and this is imminent in coastal deltas. Whereas natural subsidence amounts to centimeter to meter scale in centuries, anthropogenic subsidence may amount to meters in decades (Jelgersma, 1996). Studies of rates of ground subsidence are very relevant in low lying coastal deltas

(Erkens *et al.* 2017) because deltas receive huge volumes of sediments as slurries which can become compacted due to consolidation settlement under gravitational loads of their self-weight (Chang-Xing et al 2007). It must also be accounted for in the prediction of sea level rise over the next century (Jelgersma, 1996) and estimation of ground displacement in the safe design of structures around regions with high susceptibility (Vallejo and Shetima, 1997). Ground subsidence rates of -3mm/year and a minimum of -1mm/year have been reported in the low-lying Nile, Rhone, Po and Ebro deltas causing a relative rise in sea level of 1m and anthropogenic pressures from river flow control, diminished sediment loads, elimination of delta plain flooding, and groundwater abstraction have been implicated to worsen the risk of sea level rise, land loss and salt water encroachment at delta plain margins (Stanley, 1997).

The Niger Delta coastline stretches over a length of 560 km covering an area of 75,000 sq·km, about two-thirds of the entire coastline of Nigeria and accounting for 7.5% of Nigeria's landmass with the coastal populations increasing erratically from about 20% in 1993 to approximately 30% in 2011 (Folorunsho, et al. 2023). The delta is composed of erodible barrier islands of sediments at different levels of densification (Abam et al. 2004). It has an ecosystem that provide the best conditions for growth of vegetation and habitat with varieties of trees and plants (Ajao, 1994). Coastal erosion, coastline retreat and land loss has been reported by Awosika et al., (1990), Dada et al. (2016), Adegoke et al., (2010) and(Eludoyin et al. (2002). Abija, (2019a)noted that sea level rise and coastal erosion in the Niger delta region are major geohazards threatening the region. In spite of the reports on sea level rise, coastal erosion, coastline retreat and wetland losses, there is a paucity of research on the causative factors and or relationship between subsidence and the sea level rise in the delta.

This study was aimed at evaluating coastal subsidence and erosion and proffering natural and engineered systems for coastal protection.

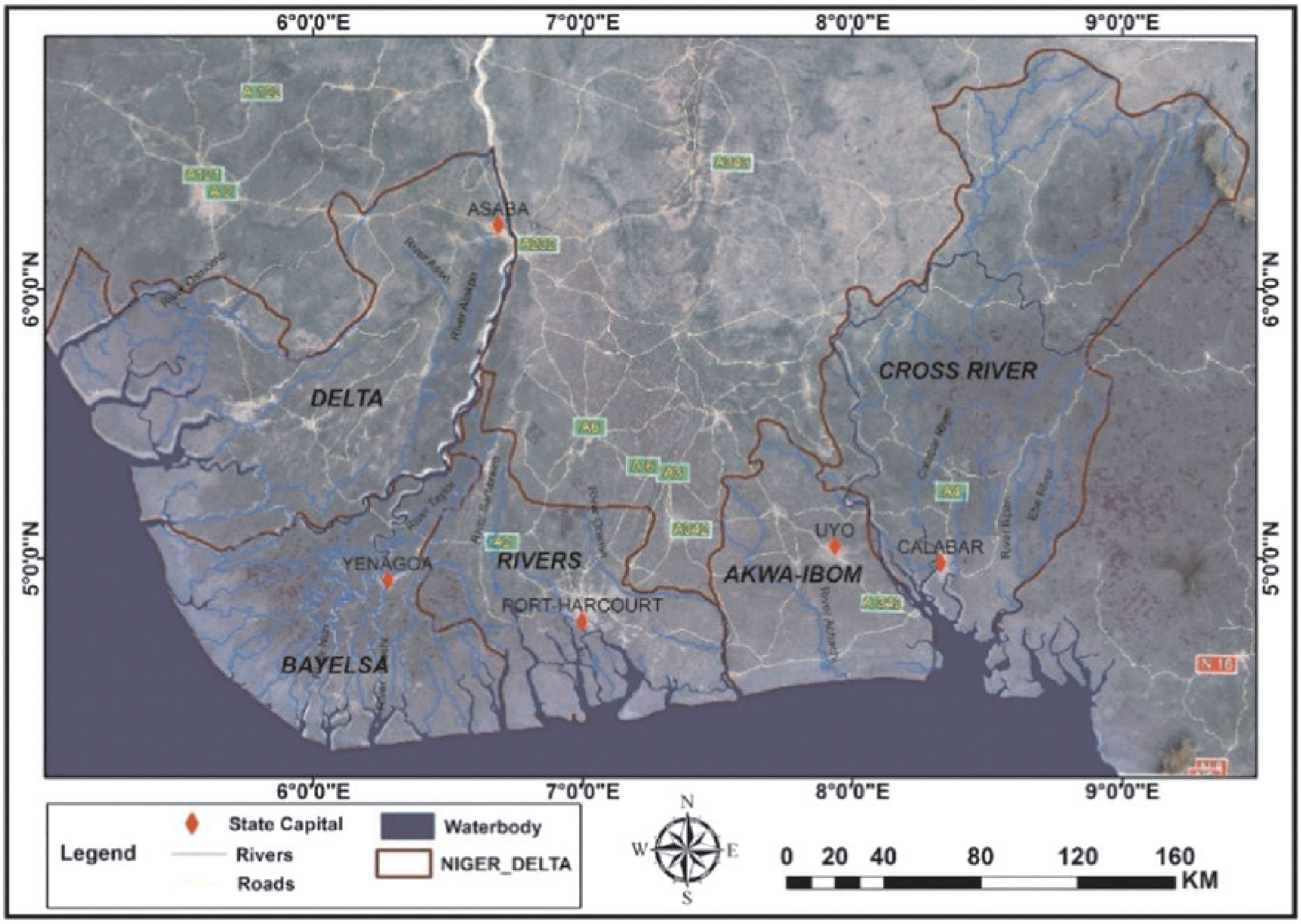

Fig. 1: Map of the study area showing the Niger Delta coastline.

Study Area

Climate and Hydrometeorology

The study area (Figure 1) is coastal plain, poorly developed with fresh forest vegetation (Abija *et al.* 2018). The climate is tropical equatorial and temperatures range from 26°C and 27 °C during the dry months of February to March and about 24°C during wet months of June and September. Daily temperatures oscillate between 31.7 °C and 23 °C in the dry season; highest average values of humidity reach 90% in August as against an average minimum of 74 % in February. Rainfall is most intense (>3500 mm) between April and October, the values being 5 - 7 times higher than in November to March (500 mm). Wind and wave conditions along the Nigerian coast can be distinguished into three namely calm (November - January), transition (February - April) and storm (May - October) (Abija, 2019a, Antia, 1989). Hydrologically, the Niger delta is dissected by a dense network of rivers and creeks draining the area and transporting water and sediments from the hinterland to the Atlantic Ocean (Abam, 2016). Thedriving force of ecological problems in the region stems from the network of surface water dynamics which have created a complex and fragile ecological region divided into smaller ecological zones distinguished by variation of the hydrological characteristics (Abam, 2001). The delta is an active sedimentary basin with characteristic network of rivers and creeks transporting water and sediments from the continent to the delta front and the Atlantic Ocean. Its shape is curved as a result of the drainage system, alluvial valleys, deltaic plains, receiving basin, distributive network, and fluvial/marine processes directly impacting on the delta. The arcuate nature represents one of the 5 morphological regions along the Nigerian coast from west to east (Sexton and Murday, 1994). Hydrometerologically, Fubara *et al.* (1988) subdivided the Niger Delta into three hydrometeorolical zones as coastal, transition mangrove and freshwater zones. The coastal zone is made of sand bars and ridges under ebbing and flooding tides of the coastal saline waters. The soils are dominantly cohesionless sands and gravels with high plasticity clays in places. The transition (mangrove) zone is very significant in terms of engineering geology due to the preponderance of very plastic and cohesive clays and muds which are termed "chicoco swelling muds". These soils have a friction angle varying from 1^0 – 8^0 and sometimes zero under saturated conditions (Teme 2018, Abija, *et al.* 2018) and depth of occurrence ranges from 10 – 15m and in exceptional places can extend up to 35 – 42m (Teme 2018). Below these clayey/muddy layers, underlie well graded sands at varying levels of consolidation. The freshwater zone consists of the upper Niger Delta dominantly composed of cohesionless silty and lateritic soils characterized by acidic clayey soils.

Tectonic Framework and Subsurface Fluid Resources

The Niger Delta is an arcuate, extensional, tertiary basin in a passive tectonic setting. Its evolution was controlled by a rift-rift-rift triple junction rifting along Cretaceous equatorial fracture zones, opening of the south Atlantic and separation of Africa from South America (Burke *et al.* 1971, Olade, 1975, Wright, 1989). The equatorial fractures which cut into the continent are the Chain, Charcot, Ascension, and Romanche fracture zones (Lehner and De Ruiter, 1977) that cut into Nigeria's basement complex. Burke, (1976) believed mantle convection currents were responsible for continental rifting and rift extension transcends into the Benue trough, a failed arm of the triple junction. Rift opening started in the Late Jurassic and persisted into the Middle Cretaceous (Lehner and De Ruiter, 1977) accompanied by gravity tectonism as the primary deformational process and induced deformation in response to shale mobility in the Niger Delta basin region (Kulke, 1995). The sedimentary Formations of the Niger Delta are the Akata Formation which is the basal unit and shale source rock, the intercalated sandstones and shales of Agbada Formation overlying the basal unit and the topmost Benin Sands at varying degrees of consolidation (Abija, 2019b). Three petroleum systems namely; the Lower Cretaceous lacustrine system, the Upper Cretaceous – Lower Miocene system, and the Tertiary deltaic petroleum system have been recognized in the basin dominated by structural plays and some stratigraphic traps. The kerogens include Types II and III and the principal petroleum system; the Tertiary deltaic (Akata-Agbada) Petroleum System consists dominantly of types II - III and III kerogens (Haack *et al.* 1998, Tutle *et al.* 1999). The hydrogeology of the Niger delta is dominated by the Benin Formation, which serves not only as aquifer but also facilitates recharge of groundwater in the region. The main body of groundwater in the Niger Delta is contained in the extensive sand and gravel layers which are interspersed with shale and clay layers within the formation (Abam *et al.* In Press).

Materials and Methods

Assessment of Coastal Subsidence, Erosion and Coastline Retreat

The research materials include digital elevation models acquired in years 2000 and 2018 sourced from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Digital elevation models provide an effective method of quantitative analysis of surface morphology and processes. ASTER DEMs have been reported to capture high spatial resolution cloud free images of the Earth in 14 spectral bands and consists of 3 different spatial resolutions namely visible and near infrared DEMs at 15m ground resolution, short wave infrared at a ground resolution of 30m and Thermal infrared at a ground resolution of 90m (Fujisada, 1994, 1998, Abija *et al.* 2020b). Elevation data analysis involved georeferencing, geometric rectification and image enhancements using ArcGIS 10.3 tools. Geometric rectification of each image followed standard procedures in the ArcGIS 10.3 software correcting pixel location errors to establish correspondence between the ground and the exact locations on the image. Images were enhanced through linear stretching technique to the different spectral bands thus modifying the distribution and range of digital numbers of the image pixels to improve coverage of a larger range within the stretched image as recommended by Lillesand *et al.* (2008). False colour composite images were the spectral bands being selected to enhance the elevation image quality. Images were processed to improve the quality as rectification is accomplished on the basis of well-distributed ground control points located on both the images and the map of the area (Olmanson, *et al.* 2001). Ground elevations were extracted from 80 points at specific stations along the coast by establishing the location coordinates. In an oilfield where well head elevations were available, ground control points were established by adding the well locations using well's X. Y and Z coordinates to provide the integrity of the maps clipped from the DEM and ortho-rectified ground elevations extracted from years 2000 and 2018 digital elevation models. Results of digital elevation models for 2000 and 2018 have been presented. Analysis of shoreline movement between 1991 and 2018 was achieved using the polyline tracing tool in ArcGIS and 1991 LandSat 4,5 and the 2018 enhanced thematic mapper images (Abija *et al.* 2020a). Coastline sections corresponding to rising sea level and coastal erosion as well as coastline recession and accretion were mapped and 20 data points randomly stationed and ground elevation values extracted from the digital elevation models of years 2000 and 2018 respectively. A total of 80 elevation stations and data points along the Bayelsa and Rivers states sections of the Niger Delta coast were established and corresponding elevations extracted. Elevation data were analyzed and contoured into maps using Surfer 13.

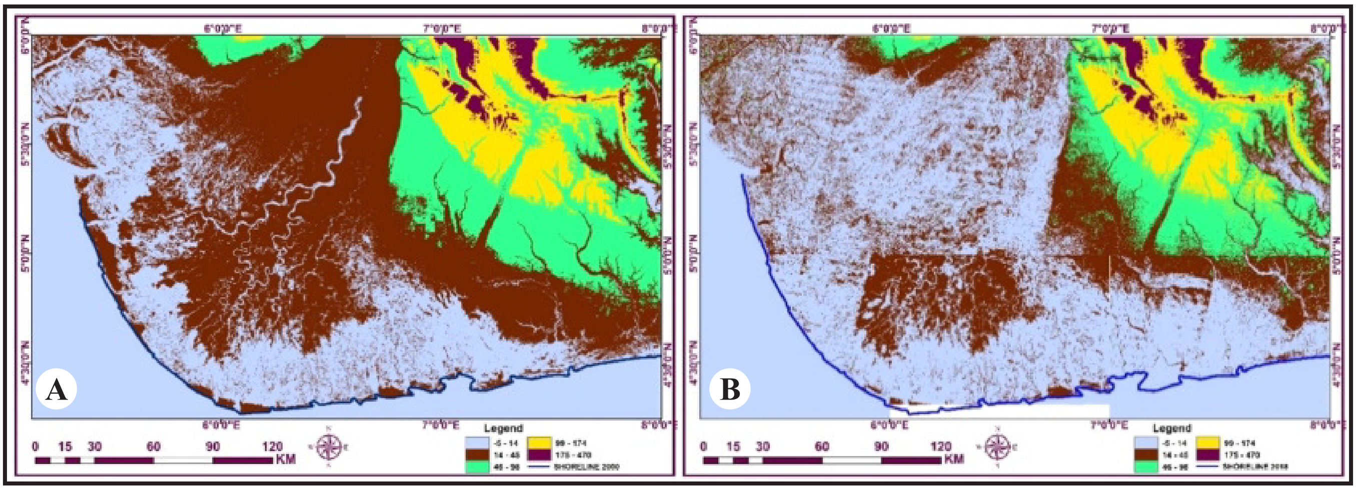

Fig. 2: ASTER Digital Elevation Models of the Niger Delta (a) Year 2000 (b) Year 2018

Assessment of Hydrodynamic Parameters

Littoral drift, the wave-driven longshore transport of sediments on any coastal shoreline is a direct consequence of wave and current action as well as the morphology of the beach environment. Once exposed to large enough forces or shear stresses by water movement due to current or wave orbital velocities or a combination of both, subsea bed sediments will be mobilized and transported as suspended or bed load. The rates and patterns of coastal erosion are controlled by the movement of sand and the sedimentation processes. Therefore, it is important to assess, determine and model the magnitude and direction of the hydrodynamic parameters such as wave conditions at the site and the possible variations over the site plus the adjoining areas, the current conditions as well as the variations of these over the area, the water-level conditions, i.e. tide, storm surge and wave set-up, the bathymetry (the depth variations) in the area, the sediment characteristics over the area and the sources and sinks of sediment, such as rivers, eroding coasts or tidal inlets within the coastal profile. Sediment transport distribution and budget which is known to increases proportionately with wave height and wave incidence angle; and inversely with grain size depend on exact field data at the site. The significant wave height is important for evaluating the impact of climate change because it can help predict the frequency and intensity of extreme wave events (Zhu and Huang, 2024). The significant wave height and deep-water wave angle of incidence are therefore critical design requirements for protecting the coastal zones from climate impacts. The significant wave height is the average height of the highest one-third of waves in a given period (Munk, 1944) and is a measurement used in physical oceanography to estimate the size of wind and swell waves in coastal areas.It's usually defined as four times the standard deviation of the surface elevation and given in equation (4).

$$\boldsymbol{H1/3 = \sum_{m=1}^{1/3N} Hm} \text{ .... } (1)$$

where H_m represents the individual wave heights, sorted into descending order of height as m increases from 1 to N. Only the highest one-third is used, since this corresponds best with visual observations of experienced mariners, whose vision apparently focuses on the higher waves (Munk, 1944, Holthuijsen, 2007). Wave height data were obtained from surf-forecast.com for the period 30th November to 5th December, 2024 and hourly duration of 24hours. The wave angle of incidence at deep water (α_0) for which 20m was used as deep water is the angle between the wave propagation direction and the normal to the coastline or the angle between the wave front and the coastline. The deep-water angle of incidence is often denoted α or θ; the wave incidence angle at the depth contour where waves start breaking (Karsten, 2004). The angle at which waves approach the shore is influenced by the wind direction, the coastline's orientation, and the degree of refraction. The deep-water wave angle of incidence has been computed from the wave direction as the angle between the wave's direction of motion and a line that is perpendicular to the reflecting boundary – the shoreline.

Table 1: Tide and wave parameters along the Nigerian Coast (30th November – 5th December, 2024) (Source: surf-forecast.com)

	30/11/2024			1/12/2024			2/12/2024			3/12/2024			4/12/2024			5/12/2025		
	AM	*PM*	*Night*	*AM*	*PM*	*Night*	*AM*	*PM*	*Night*	*AM*	*PM*	*Night*	*AM*	*PM*	*Night*	*AM*	*PM*	*Night*
Wave height (m)	0.3	1.3	1.5	1.1	1.5	0.7	1.3	1.6	1.4	1.3	1.1	1.6	1.1	1.5	1.4	0.9	1.3	1.1
Wave direction	SW	SSW	S	SW	SSW	S	SW	SSW	SSW	SSW	SW	SW	SW	S	SW	SW	S	SW
	225	202.5	180	225	202.5	180	225	202.5	202.5	202.5	225	225	225	180	225	225	180	225
Wave period	13	10	12	11	12	14	14	14	14	13	16	14	14	15	13	13	12	12

Results and Discussion

Coastal Subsidence

Table 1.0 and figure 2 presents extracted ground elevation results for the 2000 and 2018 years. The average ground elevation on the Bayelsa section of the Niger Delta coast was 2.8 ranging from 1.0 – 5.0m in 2000 (figure 3a) and was 0.2m varying from 0 – 1.0m in 2018 (figure 3b). The average ground subsidence (vertical ground displacement) was -2.6m varying from -1.0 to -5.0m at a rate of - 0.144m/yr. ranging from 0.05 to 0.28m/yr. On the Rivers State section of the coast, the average ground elevation was 4.05m ranging from 1 – 7.0m in 2000 and 0.3 varying from 0 – 1.0m in 2018 indicating that the average ground subsidence was -3.75m ranging from -6.0 to 0.0m (figure 3c) and a rate of -0.208m/yr ranging 0.0 – 0.333m/yr. Coastal land subsidence as high as -5.0m was measured in coastline segments marked by a relative rise in sea level causing indicate net shoreline retreat and erosion of 81,532 m (Table 1), wetland loss and ecosystem destruction between 1991 and 2018. Along the Rivers State coastline, land subsidence as varies from -2.0m to -5.0m causing a coastline retreat of 17,519m between 1991 and 2018 (Figure 4). Observed ground uplift along the Rivers State segment of the coast range from 2.0m to 8.0m causing the coastline recession. The end point rate depicting the rate of shoreline migration showed rates of 11.1 m/yr. and 7.2 m/yr. in Bayelsa and Rivers States respectively. Measured shoreline recession and or accretion were 11,149 m, 8,272 m and 4,464 m at rates of 5.3 m/yr., 4.6 m/yr., and 2.8 m/yr. in Bayelsa, Rivers and Akwa Ibom States (Table 2) respectively.

Table 2: Summary of ground elevations and vertical ground displacement characteristics.

Coastline section	Elevation 2000 (m)			Elevation 2018 (m)			Vertical Ground Displacement			Rate of Vertical Ground Displacement (m/yr.)			Mode of Ground Displacement
	Min	Max	Ave	Min	Max	Ave	min	Max	Ave	Min	Max	Ave	
Bayelsa Accretion	0	1.0	0.35	1.0	6.0	4.55	1.0	6.0	3.3	0.056	0.333	0.183	Uplift
Bayelsa Erosion	1.0	5.0	2.8	0	1.0	0.2	-1.0	-5.0	-2.6	0.05	0.28	-0.144	Subsidence
Rivers Accretion	0	1.0	0.45	1.0	10.0	.35	1.0	8.0	4.0	0.056	0.444	0.22	Uplift
Rivers Erosion	1.0	7.0	4.05	0	1.0	0.3	0	-6.0	-3.75	0	0.333	0.208	Subsidence

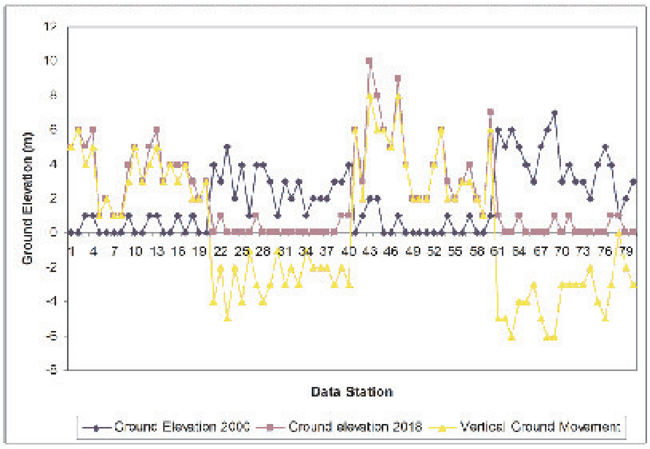

Fig. 2: Variation of ground elevations along the Bayelsa, Rivers and Akwa Ibom section of the Niger Delta coast.

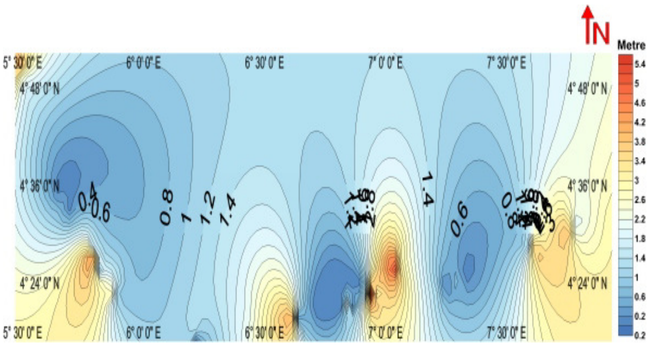

Fig. 3a: Ground elevation contours along and around the Niger Delta coastal zone in 2000

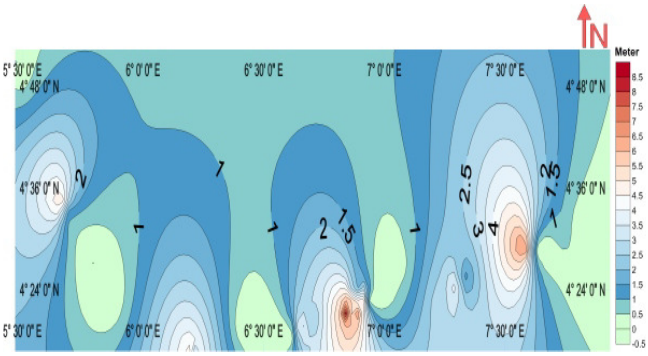

Fig. 3b: 2018 ground elevation contours along the Niger Delta coastline

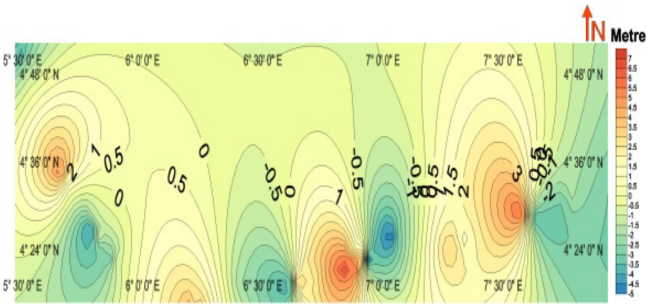

Fig. 3c: Ground subsidence contour map of the Niger Delta coastal zone

Figure 4 indicates submergent and emergent coastline segments suggesting the influence of neotectonics as possible causal mechanism for the relative rise in sea level, coastal erosion and coastline retreat along the Niger Delta coast. This implies drowning of mangroves by saline seawater and removal by erosive influences of hydrodynamic forcings. Salt water encroachment and submarine underground discharges will adversely affect the mangroves; sea grass population will decline with increased Salinization, higher temperature and CO_2 content of sea water, storm activities and increased intensity of ultraviolet light thereby diminishing their potential for terrestrial sequestration of carbon and exacerbating global warming and climate change. Zhu *et al.* (2010)noted that land subsidence contributes to relative rise in sea level in coastal deltas than any other factor and the associated shoreline retreat causing coastal squeeze in areas between the rising sea level and hard defenses. The coastal habitats are also forced to migrate inland to keep pace with the rising sea. In terms of ecosystem destruction there is an increased shift in

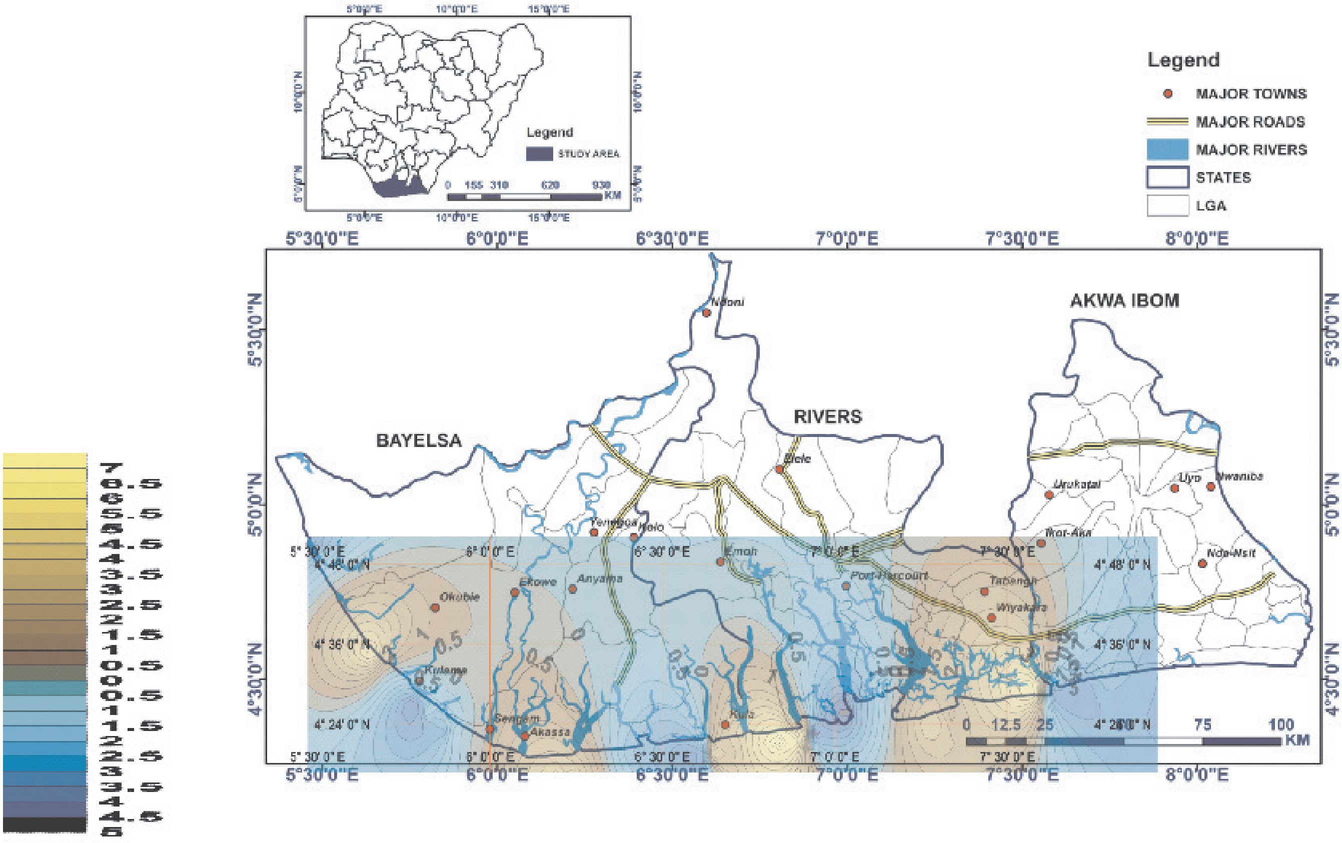

Fig. 4: Emergent and submergent coastline segments along the Bayelsa and Rivers States sections of the Niger Delta coastline (between 2000 and 2018).

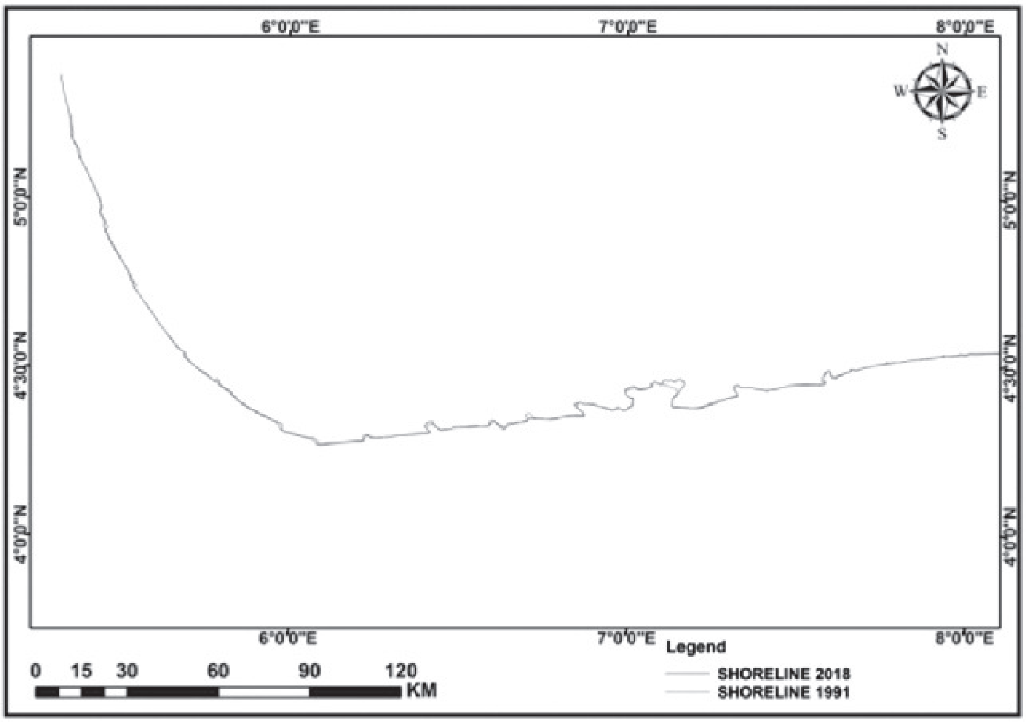

Fig. 5: Extracted shoreline showing the basin wide net movement (1991 – 2018)

distribution and abundance of valuable marine habitats, species and biodiversity; accelerated speed of exotic and invasive species, more frequent coral bleaching and increased mortality, loss of coastal wetland ecosystem, fish breeding grounds, and growth in spread of marine dead zones.

Coastal flooding, Erosion and Shoreline Retreat

The rate of coastal erosion along the Akwa Ibom, Rivers and Bayelsa States in the Niger Delta coastline depicts a linear erosion of -13,054m, -17,519m and -81,532m in Akwa Ibom, Rivers and Bayelsa respectively with erosion rates of -5.5m/yr along Akwa Ibom, -7.2m/yr along Rivers and -11.1m/yr along the Bayelsa coastline. The net shoreline retreat equivalent of incidental erosion was -8,590m along the Akwa coastline, -9,240m along Rivers coastline and -70,383m along the Bayelsa coastline (Figure 5 and Table 2). Results are in agreement with reports by Abija, (2019), Abija *et al.* (2020), Awosika *et al.*, (1990). Dada *et al.* (2016) and Adegoke *et al.*, (2010) underscoring thevulnerability to flooding and erosion. Coastal communities such as Kulama (Bayelsa), Sangana (Bayelsa), Ganigbene (Bayelsa), Abadikiri (Bayelsa), Ebidorgbene (Bayelsa), Anyama (Bayelsa), Obianga (Rivers) and many more located within the subsidence bowls or submergent coastlines with a preponderance of coastal erosion are at risk of extinction just like Kolouma I which has been completely wiped out. Estuarine rivers in subsided and or submergent coastlines segments include St. Barbara, Calabar river, Fish Town river, Sengana river, St Nicholas River and St. Bartholomew (Figure 4) are eroded by recession of alluvial channel banks which occurs as a sequence of mass movements or by gradual dissolution of bank materials. Estuarine rivers in uplifted or emergent coastline segments include rivers Nun, Brass, Sombreiro, Andoni and Opobo. Some inland coastal communities such as Okrika, Nembe, Yenagoa, Amasoma, Oloibiri, and parts of Port Harcourt., Emoh and Ikot Abasi (AKS) are gradually sinking. The natural causes of shoreline erosion recognized by (USACE, SPM, 1984) to include sea level rise, variability in sediment supply to the littoral zone, storm waves, wave and surge, overwash, deflation, longshore sediment transport, tectonic subsidence and sorting of beach sediment as well as anthropogenic causative factors such as induced land subsidence from removal of subsurface resources, interruption of material in transport, reduction of sediment supply to the littoral zone, concentration of wave energy on beaches, increase water level variation, change natural coastal protection and removal of material from the beach are believed to be acting on the coastal delta.

Table 3: Net shoreline movement, erosion and accretion along the Niger Delta Coast, Nigeria

Coastline section	Period	Linear Coastal Erosion (m)	Rate of Erosion (m/yr)	Net Shoreline Retreat
Akwa Ibom	1991 – 2018	-13,054	-5.5	-8,590
Rivers	1991 – 2018	-17,519	-7.2	-9,240
Bayelsa	1991 – 2018	-81,532	-11.1	-70,383

Seismicity in the Region

Though the Niger Delta basin was thought to be aseismic, there have been recent occurrences of earth tremors such as the 4.5 magnitude Benin event of 13/3/2000, the Abomey Calavi earth tremor of 11/9/2009 near Benin (Eze *et al.* 2011), the Igbogene (Yenagoa), Bayelsa event of 10/8/2016 and a reported 2016 tremor in Rivers State in the Niger Delta basin (Abija *et al.* 2022). The orientation of Cainozoic regional faults in the basin aligning in the same direction with the maximum stress orientation suggest tectonic reactivation (Abija, 2019, Abija and Tse, 2016) as a causal mechanism for the rise in seismic activities. Climate change impacts of increased groundwater load and driving force on the fault planes, portends greater risk of seismicity in the region. Associated seismic hazards include ground liquefaction and submarine and onshore slope instabilities and failures with attendant slides. Seismic triggering could also cause tsunamis which are long-period gravity waves generated by such disturbances as earthquakes, landslides, volcano eruptions, and explosions near the sea surface. Where present, seismic risks and hazards will impact the of coastal livelihood systems and foundations and superstructure of coastal infrastructure.

Wave and Hydrodynamic Conditions

The significant wave height along the Niger Delta and the Nigerian coast within the surf zone depicts a maximum value of 1.5m (figures 6a and 6b) within the surf zone and region of influence in the design of coastal protection. It is an average of the largest 33% of waves, which are more important than smaller waves in many applications. For example, the largest waves in a storm cause the most erosion on a beach. Varying beach mobility and or stability index depicted by the Iribarren characterize of the beaches with high values (>> 33) suggests highly dissipative beach condition or low mobility tendency (Abija, 2018). This however, has been determined to range from 0.16 -0.18 in 2024 depicting a decrease in beach stability with results decreasing with the wave angle of incidence from 45^0 to zero degrees. Predicted breaker heights shows a range from 1.76m to 1.99m increasing with decrease in angle of incidence (45^0 – 0^0). The breaking wave height increases from 1.76m to 1.99m with decrease in angle of incidence in the breaker zone while the angle of incidence decreases at the breaker zone from 10.41^0 to zero degrees (0^0) with a decrease in shoreline angle of incidence. The breaking water depth increases from 2.85 to 3.24m as the angle of incidence decreases while the beach mobility index depicted by the Iribarren number decreases 0.18 – 0.16 (Table 5). Numerical back analysis using the significant wave height, shoreline angle of incidence and peak wave period for a beach characterized by fine sand materials indicates a mean wavelength would be 178.94m with a maximum vertical velocity of 0.4m/sec, horizontal velocity of 0.24m/sec, wave celerity of 13.01m/sec, group celerity of 11.27m/sec and a wave energy flux of 15,902.00w/m (Table 6) along the coast.

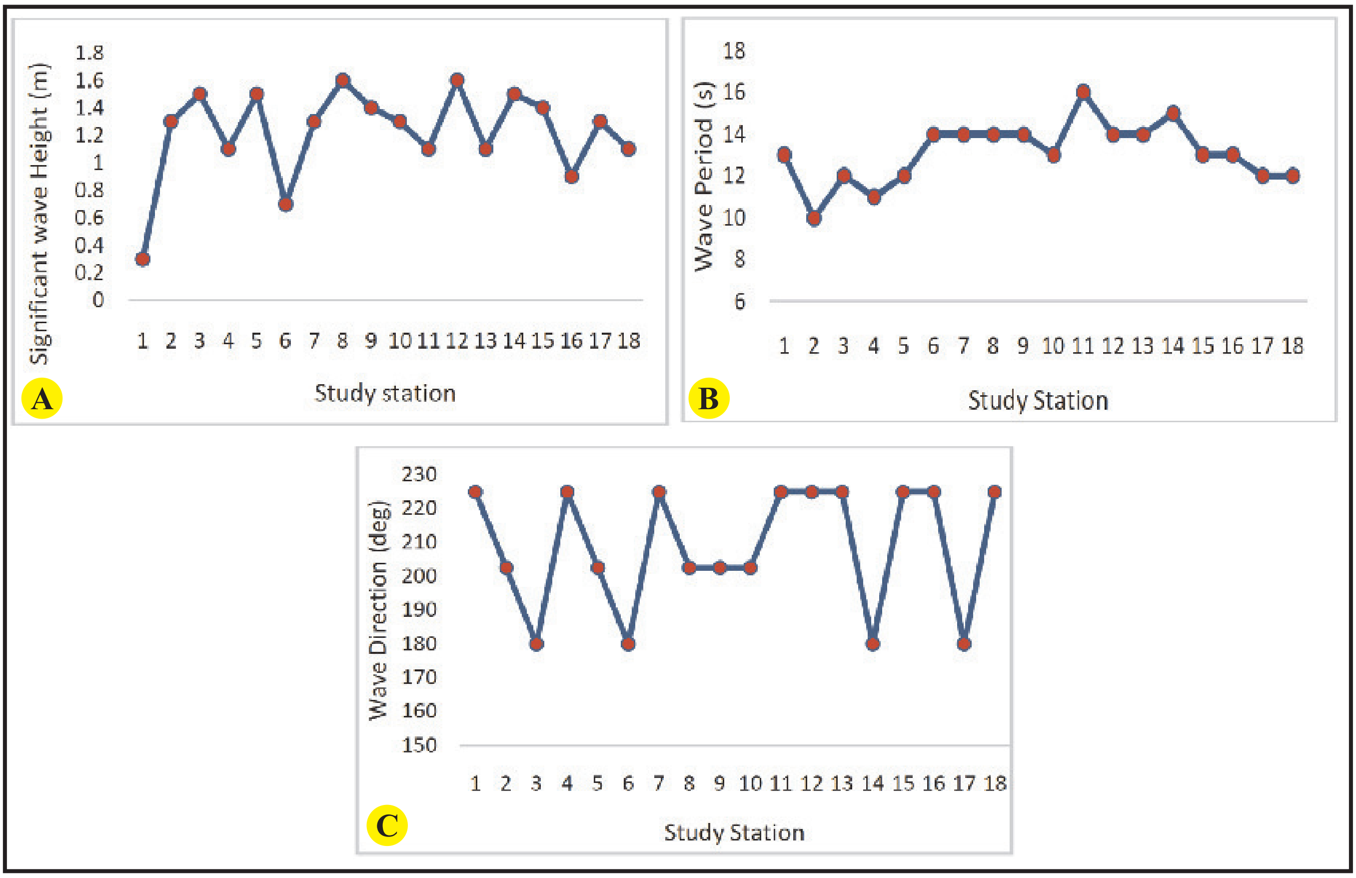

Fig. 6: (a) Variation of the magnitude of the significant wave height along the Coast 30th November – 5th December 2024. **(b)** Variation of the wave period along the Coast. **(b)** Variation of the wave direction along the Coast

Table 4: Magnitude of the hydrodynamic parameters along the coast for the period 30th November to 5th December, 2024.

	30/11/2024			1/12/2024			2/12/2024			3/12/2024			4/12/2024			5/12/2025		
	AM	PM	Night	AM	PM	Night	AM	PM	Night	AM	PM	Night	AM	PM	Night	AM	PM	Night
Wave direction	SW	SSW	S	SW	SSW	S	SW	SSW	SSW	SSW	SW	SW	SW	S	SW	SW	S	SW
	225	202.5	180	225	202.5	180	225	202.5	202.5	202.5	225	225	225	180	225	225	180	225
Wave angle of incidence	45	22.5	0	45	22.5	0	45	22.5	22.5	22.5	45	45	45	0	45	45	0	45

Conclusion and Recommendations

The effects of extreme flooding, sea level rise and coastal erosion are evident in the delta region with the complete erosion of coastal communities and damages to coastal infrastructure. Climate change will increase

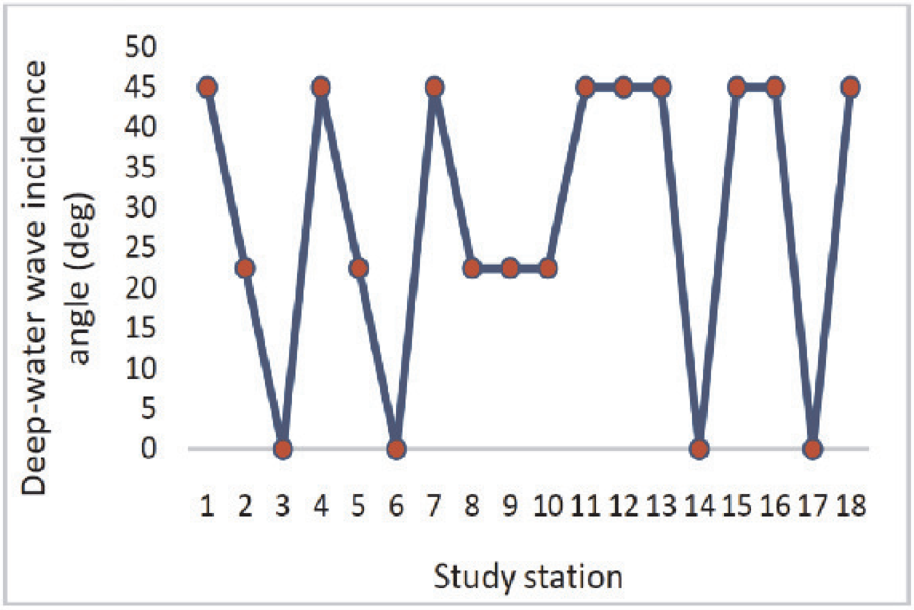

Fig. 7: Variation of the wave incidence angle along the shoreline

Table 5: Variation of breaking wave characteristics with angle of incidence

Parameters	In put Magnitude			Parameter	Predicted Results		
	1	2	3		1	2	3
Significant wave height (m)	1.5	1.5	1.5	Breaking wave height (m)	1.76	1.93	1.99
Peak wave period (s)	16	16	16	Breaking wave angle of incidence	10.41	5.77	0
Water depth	20	20	20	Breaking water depth (m)	2.85	3.12	3.24
Angle of incidence	45	22.5	0	Iribarren No (Surf Scaling Parameter)	0.18	0.17	0.16
Material	Fine Sand	Fine Sand	Fine Sand	Breaker type	Spilling	Spilling	Spilling

Table 3: Back analysis and numerical modeling of the sea state wave parameters along the coast for the period November – December, 2024

Parameters	Modeled results
Mean Wave Length (m)	178.95
Wave Celerity (m/s)	13.01
Group Celerity (m/s)	11.27
Relative Depth	0.11
Regime	Intermediate waters
Max. Horizontal Velocity (m/s)	0.40
Max. Vertical Velocity (m/s)	0.24
Mass Flux (kg/ms)	108.45
Radiation Stress (N/m)	1,740.25
Energy Flux (w/m)	15,902.00

the frequency and intensity of the waves as well as energy flux further exacerbating the coastal flooding, erosion and shoreline retreat. The predicted mean wavelength of 178.95m with single wave celerity of 13.01m/sec and group wave celerity of 11.27m/sec with potential to rise implies high risk to coastal communities and livelihood systems that require emergency response. The larger waves in a storm would cause the most erosion on a beach.

It is therefore recommended that site specific investigations be carried out to assess and design climate change adaption systems for protection of the coastal communities. The institution of government policies and declaration of emergency in coastal zone management is highly recommended.

References

Abam, T. K. S., Mogaba, P. M. and Abija, F. A. (In Press). Assessment of Groundwater Potential in parts of the coastal Niger Delta, Nigeria: Implications for well design. *American Journal of Water Science and Engineering*

Abam, T.K.S. (2016). Engineering Geology of the Niger Delta. *Journal of Earth Sciences and Geotechnical Engineering, 6, no. 3, 2016, 65-89*

Abam, T. K. S. (2001). Regional hydrological research perspectives in the Niger Delta. *Hydrological*

Science Journal. 46 (1), 13 – 25.

Abam, T. K S, Gobo, A.E. and Opuaji, T. (2004). Spatial and temporal patterns of coastal erosion in the Niger Delta. Global Journal of Geological Sciences, Vol. 2, No. 1, pp. 79 – 90.

Abija, F. A., Abam, T. K. S., Teme, S. C. and Eze, C. L. (2022). Predicting the potential for induced earthquakes due to long term oil/gas production in the Niger Delta basin, Nigeria. Journal of Mining and Geology Vol. 58(1) 2022. pp. 129 – 146.

Abija, F. A., Abam, T. K. S., Teme, S. C. and Eze, C. L. (2020a). Ground subsidence and intermontane topographic depressions above a producing oilfield: a link to flood vulnerability in the Niger Delta basin, Nigeria. J. of Earth Science and Climatic Change, 11 (9).

Abija, F. A., Abam, T. K. S., Teme, S. C. and Eze, C. L. (2020b).Relative sea level rise, coastline variability and coastal erosion in the Niger Delta, Nigeria: Implications for climate change adaptation and coastal zone management. Journal of earth Science and Climatic Change, 11(9)

Abija, F. A. (2018). Assessment of coastal modification and surf zone induced erosion in Itak Abasi beach, Eastern Niger delta, Nigeria. Environmental and earth Science Research Journal, Vol. 6, No. 2

Abija, F. A., Teme, S. C. and Oborie, E. (2018). Geotechnical Considerations for the Design and Construction of Foundations in a Marshy Stream Channel of Iwochang - Ibeno, Eastern Niger Delta, Nigeria. *Electronic Journal of Geotechnical Engineering, 2018 (23.04), pp 705-722.*

Abija, F. A. (2019). Paleokinematic reconstruction and wellbore breakout analysis of in situ stress orientation in a Niger Delta Oilfield: Implications for tectonic reactivation in Nigeria (2019. *Journal of Earth Sciences and Environmental Studies 4(6) p:789-805*

Abija, F. A. and Tse, A.C. (2016). In situ stress magnitude and orientation in an onshore field, Eastern Niger Delta. Implications for directional drilling. SPE MS 184234 published on onepetro.org. doi:10.2118/ 184234-MS, pp. 1 - 15.

Adegoke, J. O., Fageja, M., James, G., Agbaje, G. Ologunorisa, T. E. (2010). An assessment of recent changes in the Niger Delta Coastline Using Satellite Imagery. *Journal of Sustainable Development, 3, No. 4. Pp. 277 – 296.*

Ajao, E. A. (1994). Coastal aquatic ecosystem conservation and management strategiesin Nigeria. Southern African Journal of Aquatic Science, 20, (1-2) Pp. 3-22.

Antia, E. E. (2019). Environmental geological mapping of coastal hazards. A lead paper presentation at the 2nd International Association for Engineering Geology and the Environment Africa Regional Congress, Abuja, Nigeria, October 29, 2019

Antia, E.E. (1989). A short term study of the effect of changing coastal condition on some geomorphological elements on Nigerian beaches. *Zeitschrift F. Geomorpphologie, 73: 1- 16*

Awosika, L. F., Ibe, A. C. and Udo-Aka, N. A. (1990). Impact of sea level rise on the Nigerian coastal zone. *In Changing Climate and the Coast. 2, 67 – 78.*

Blyth, F. G. H and de Freitas, M. H. (1982). *A Geology for Engineers*. New Delhi: Elsevier India . Private Ltd.

Blackett, M. (2023): How climate change might trigger more earthquakes and volcanic eruptions. https://theconversation.com/how-climate-change-might-trigger-more-earthquakes-and-volcanic-eruptions-210841

Bruno, M. S. (2001). Geomechanical analysis and decision analysis for mitigating compaction related casing damage. SPE 71695. Pp. 1 – 13.

Burke, K. (1976). The Chad basin: an active intracontinental basin. In Bott, M. P. H. (Ed). Sedimentary basins of the continental margins and cratons. *Tectonophysics, 36, 197 – 206.*

Burke, K., Desauvaygie, T. F. G., and Whiteman, A. J. (1971). The opening of the Gulf of Guinea and the geological history of the Benue depression and Niger Delta. *Nature Physical Sciences, 233, 51 - 55*

Chang-Xing, S., Dian, Z., Lianyan, Y., Binguan, L. Zulu, Z. and Onyang, Z, (2007). Land subsidence as a result of sediment consolidation in the Yelow River Delta. J. of Coastal research, 23 (1), 173 - 161

Dada, O. A., Li, G., Qiao, L., Ding, D., Ma, Y., and Xu, J. (2016). Seasonal shoreline behaviour along the arcuate Niger Delta coast: complex interactions between fluvial and marine processes. *Continental Shelf Research, 112, 51 – 67.*

Doornhof, D., Kristiansen, T. G., Nagel, N. B., Pattillo, P. D., and Sayers, C. (2006). Compaction and Subsidence. *Oilfield Review, Autum, 50 – 67.*

Elwary, H., Johnson, J. Dill, R. and Flick, R. E. (1998). Offshore subsidence monitoring programme and possible mitigation measures. Report prepared for Macpherson Oil Company, Santa Monica and Coastal Environments, Encinita, California. 141pages.

Eludoyin, O. S., Oduore, T. and Obafemi, A. A. (2012). Spatio-temporal analysis of shoreline changes in Bonny Island, Nigeria. *Ethiopian Journal of Environmental Studies and Management. 5 (2), 123 – 130*.

Erkens, G. Bucx, T., Dam, R., de Lange, G. and Lambert, J. (2015). Sinking coastal cities.Proc. IAHS, 372, 189–198, proc-iahs.net/372/189/2015/ doi:10.5194/piahs-372, pp. 189- 198.

Eze, C.L., Sunday, V.N., Ugwu, S.A, Uko, E.D and Ngah, S.A (2011) "Mechanical Model for Nigerian Inter-plate earth Tremors.

Flowers, T. (1981). Effects of salinity on plant growth and crop yields. Environmental stress in plants, Vol. 19, pp 101 – 119.

Folk, R. L. and Ward, W. C. (1957). Brazos river bar: A study of the significance of grain size parameters. J. of Sedimentary Geology, vol. 27, pp. 3-27.

Folorunsho, R., Salami, M., Ayinde, A. and Gyuk, N. (2023) The Salient Issues of Coastal Hazards and Disasters in Nigeria. Journal of Environmental Protection, 14, 361-372.

Fubara, D. M. J., Teme, S. C., Mgbeke, T. and Abam, T. K. S. (1988). Hydrometeorologicl zones of the Niger Delta. Technical Bulletin No 1., Institute of Flood and Erosion Control, Rivers State University of Science and Technology, Port Harcourt, Nigeria.

Fujisada, H., (1994). Overview of ASTER instrument on EOS-AM1 platform. In Proceedings of SPIE, 2268, pp. 14–36.

Fujisada, H., (1998). ASTER Level-1 data processing algorithm. IEEE Transactions on Geoscience and Remote Sensing, 36, pp. 1101–1112.

Gambolati, G., and P. Teatini (2015), Geomechanics of subsurface water withdrawal and injection, *Water Res., 51, 3922–3955,*

Haack, R. C., Sundarraman, P., Diedjormahor, J. O., Gant, M. J. and Dahl, J. (1998). Niger Delta Petroleum Systems. AAPG Abstracts.

Holthuijsen, L.H. (2007), Waves in oceanic and coastal waters, Cambridge University Press, p. 242, ISBN 978-1139462525

Humphries, L. (2001). A review of relative sea level rise caused by mining-induced subsidence in the coastal zone: some implications for increased coastal recession. *Climate Research, 18: 147–156.*

IAHS (1991(. Proceedings of the Fourth International Symposium on Land Subsidence, held at Houston, Texas, 12-17 May 1991. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire OX10 8BB, UK. IAHS Publication No. 200.

Jegelsma, S. (1996). Land subsidence in coastal lowlands: In Milliman, J. D. and Haq, B. U. (eds). Sea level rise and coastal subsidence. Coastal Systems and Continental Margins, Vol. 2, Springer Dordrecht Pp. 47 – 62.

Karsten, M. (2004). Shoreline management guidelines. DHI Water and Environment, 294pp.

Kulke, H., 1995, Nigeria, *in,* Kulke, H., ed. Regional Petroleum Geology of the World. Part II: Africa, America, Australia and Antarctica: Berlin, Gebrüder Borntraeger, Pp. 143-172.

Kumar, J., Mohan Rao, V. B. K. (2002). Seismic bearing capacity factors for spread footings. *Geotechnique, vol. 52 (2), pp. 79 – 88*.

Larroque, C. and Bonhorff, M., (2024). Climate change will lead to an increase in earthquakes https://www.polytechnique-insights.com/en/columns/planet/climate-change-will-lead-to-an-increase-in-earthquakes

Lehner, P., and De Ruiter, P.A.C. (1977). Structural history of Atlantic Margin of Africa: *American Association of Petroleum Geologists Bulletin, 61, 961-981.*

Lillesand, T., Kiefer, R., and Chipman, J. (2008). Remote sensing and image processing Interpretation. 6th edn. New York: John Wiley and sons 756pages

Lundgren, P. (2019). Can Climate Affect Earthquakes, Or Are the Connections Shaky? NASA Science Editorial Team. https://science.nasa.gov/earth/climate-change/can-climate-affect-earthquakes-or-are-the-connections-shaky/

Machado, R. M. A. and Seralhero, R. P. (2017). Soil salinity: effects on vegetable crop growth. Management practices to prevent and mitigate soil salinization. Horticulture, 3:30 pp 1 – 30.

Marzourk, M. and Azab, S. (2024). Modeling climate change adaptation for sustainable coastal zones using GIS and AHP. Environ Monit Assess (2024) 196:147. Pp1-24.

McGarr, A., Simpson, D., and Seeber, L (2002). Case Histories of Induced and Triggered Seismicity. International handbook of earthquakes and Engineering seismology, Volume8 1a. pp. 647 – 661

Montgomery, C. W. (2006). Environmental Geology, 8th edn. New York: McGraw-Hill Companies INC, 556pages

Morgan, J.P., (1970). Depositional processes and products in the deltaic environment, in Morgan, J.P., ed., Deltaic sedimentation. Modern and ancient: *Society of Economic Paleontologists and Mineralogists Special Publication 15, 31–47.*

Munk, W. H. (1944). Proposed uniform procedure for observing waves and interpreting instrument records. La Jolla, California. Waves project t at the Scripps Institution of Oceanography.

NRC, (2010). National Research Council - Adapting to the Impacts of Climate Change. Washington, DC: https://doi.org/10.17226/12783

Olade, M.A. (1975). Evolution of Nigeria's Benue Trough (Aulacogen): a tectonic model. *Geol. Mag. 12, 575 – 583.*

Olmanson, L. G., Kloiber, S. M., Bauer, M. E. and Brezonik, P.L. (2001). Image processing protocol for regional assessments of lake water quality. Public Report series #14Water Resources Centre and Remote Sensing Laboratory, University of Minnesota St. Paul, MN 55108 11pages.

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, (2019): Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. https://doi.org/10.1017/9781009157964.006.

Pereira, C. S., Lopes, I., Abrantes, I., Sousa, J. P., and Chelinho, S. (2018). Salinization effects on coastal ecosystem: a terrestrial model ecosystem approach. Philosophical Transactions of the Royal Society B. Biological Sciences

Randolph, M. and Gourvenec, S. (2011). Offshore Geotechnical Engineering. N. Y: Spon Press, 558pages.

Stanley, D. J. (1997). Mediterranean deltas: subsidence as a major control of relative sea level rise. CIESM Science Series No 3. Transformation and evolution of Mediterranean coastline. *Bull. Institut Oceanographique. 32pages*

Sexton, W. J. and Murday, M. (1994). The morphology and sediment character of the coastline Nigeria – the Niger Delta. J. of Coastal res., 10(4), 959 – 977.

Teme, S. C. (2018). The place of engineering geology and geotechnics in the design of building foundations in the Nigerian Niger Delta sub-region. Proceedings of the first and second international conferences of the Nigerian Association for Engineering Geology and the Environment, Vol. 1, 2028. Pp. 14 – 28.

Tornqvist, T. E., Bick, S. J., van der Borg, K. and de Jong, A. F. (2006). How stable is the Mississippi delta? *Geological Survey of America Publication, 34 (8), 697 – 700*

Turtle, M. L. W., Charpentier, R. R. and Brownfield, M. E. (1999). Chapter A. The Niger delta Petroleum system; Niger Delta province, Nigeria, Cameroon and Equatorial Guinea, Africa. US Department of Interior, USGS open file report No. 99 - 50-H View Article

USACE, SPM, (1984). Shore protection Manual, vol. 1, Coastal Engineering Research Center Department of The Army, US Army Corps of Engineers.

Vallejo, L. E. and Shettima, M. (1997). Fault movement and its impact on ground deformations and engineering structures. In Kanamori, Earthquakes Proof Design and Active faults. Elsevier B. V. Pp. 43.

Wright, J. B. (1989). Review of the origin and evolution of the Benue Trough in Nigeria. In Kogbe, C. A. (Ed): Geology of Nigeria, 2nd edition. Jos: Rock View Nigeria Ltd.359 - 364

Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y. and Sallenger, A. (2014): Coastal systems and low-lying areas. In: Climate Change (2014). Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

Zhu, X. and Huang, W., (2024). Assessing extreme significant wave height in China's coastal waters under climate change. Frontiers in Marine Science, Vol. 11:1494127, pp. 1 – 10

Zhu, X., Linham, M. M. and Nichoils, R. J. (2010). Technologies for climate change adaptation: coastal erosion and flooding. Danmask Tekniske Universitet, Risq National Laboratory for Baeredygtig Energi. TNA Guidebook Series.

Zoback. M. D. (2007). Reservoir Geomechanics. New York. Cambridge University Press.505pages.