Original Research Article

Assessing the physical vulnerability of the coastal area of Nigeria to climate change

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Abstract: This study assessed the physical vulnerability of the coastal area of Nigeria to climate change effects using indices generated from a group of factors including relief, rock types, landforms, and erosion/deposition rates. Results show the very-high vulnerability class covering the largest proportion, about 53% of the area, amounting to about 23,850 km^2, largely found in the Niger Delta region. The next, high-vulnerability class covers 17%, about 7650 km^2, found mostly in Lagos State and the northern fringes of the Niger Delta region. The other classes i.e., moderate, low, and very-low vulnerability extend over 10% (4500 km^2), 13%, (5850 km^2) and 7% (3150 km^2) of the coastal area, respectively. While the moderate-vulnerability class is found only in the western part of the coastal area, the low and very-low vulnerability classes dominate the extreme eastern flank and some northern edges of the western part. The low-vulnerability class is found mainly in Ondo, Ogun, Akwa Ibom and the Cross River States. The very-low vulnerability class is found covering the Ewen community of Cross River State only. Given that 70% of Nigeria's coastal environment falls within very-high and high vulnerability classes, the region is evidently very vulnerable to the impacts of climate change.

Keywords: Nigeria; coastal area; Niger Delta; climate change; physical vulnerability; geographical information system

1. Introduction

The coastal region of Nigeria is very important considering its rapidly expanding population, and its high concentrations of residential, commercial, educational, military, tourism, and industrial facilities including its vast oil fields and infrastructure[1]. Incidentally, this zone is the most at risk in terms of the adverse impacts of climate change[2–11]. Some of the most reported impacts of climate change in Nigeria are extreme weather events, changes in the timing of seasons, and sea level rise[12,13]. These are most phenomenal in the coastal areas. Sea-level rise, for example, can potentially lead to severe coastal recession, as well as an increase in coastal flooding[14,15] and subsidence[16]. Already, many settlements along the coast have been lost to the rising sea level and other geophysical processes such as storm surges and coastal erosion[17]. The most important step in facilitating coastal management is the development of coastal vulnerability assessments[18]. Vulnerability is the degree, to which a system, which may be social or natural, is susceptible to, or unable to cope with adverse consequences of climate change, including climate variability and extremes such as runaway temperature and intense as well as very heavy precipitations[19].

There have been several studies on the impacts of and adaptation to climate change in Nigeria[7,20–28]. However, very few of them[21,23,26,28–33] have focused on the coastal environment. Even the latter researchers have concentrated their attention on the social-economic aspect of the vulnerability of the marine environment to the impacts of climate change. There has thus been limited analysis of the physical elements of the vulnerability of the coastal area to the impacts of climate change. Of course, a major challenge is the paucity of critical data sets on the physical features of the area coastal environment of Nigeria in forms that are

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amenable to quantitative vulnerability assessment. Adesina and Odekunle[23] attempted to address this challenge, but this was limited to a few data points and physical parameters in the coastal region of Nigeria. This paper is an attempt to address the gaps in the previous studies using denser data points, a larger number of physical parameters, and geographic information system tools. The target is to achieve a clearer assessment of the physical vulnerability of the coastal areas of Nigeria to the impacts of climate change that may be used in conjunction with other analyses for policy development as well as the implementation of adaptation actions and programs for the coastal environment.

2. Study area

The study is focused on the coastal zone of Nigeria, at the southern fringe of the country. It lies approximately between latitudes 4° and 6°45′N and Longitudes 2°40′ and 8°40′E and spans an area of about 45,000 km^2. The area is bordered in the north by the hinterland part of the country, in the east by some parts of Cross River State, and in the west by the Republic of Benin. The Gulf of Guinea, a portion of the Atlantic Ocean, forms its southern border (**Figure 1**). Although the zone runs approximately along the southern boundaries of eight states of the country namely: Lagos, Ogun, Ondo, Delta, Bayelsa, Rivers, Akwa-Ibom, and Cross River, its inland extent annexes some southern parts of Edo State (**Figure 2**). Nigeria's shoreline spanning this space is the longest in the West Africa sub-region, extending from near Porto Novo, Benin Republic in the west to near Bakassi Peninsula in the east, covering about 850 km (FME, 2014). In terms of physical features, the zone can be divided into three zones: the extensive Badagry-Lagos-Epe-Lekki Lagoon system in the western part, a central vast area of the low-lying flood plain of the Niger Delta system, and the Cross-River estuary system in the eastern part[34]. In general, this zone which has been described as coastal margins and swamps is flat and low-lying and below 30 m above sea level[35].

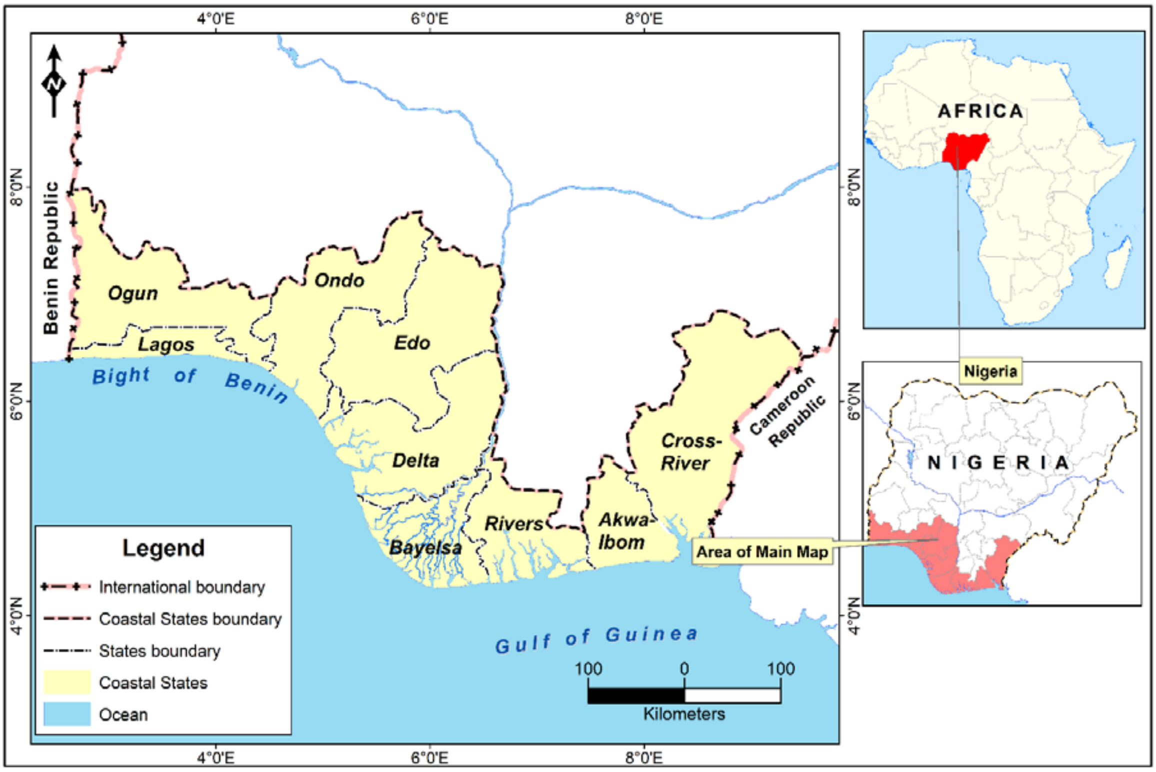

Figure 1. Map of Nigeria, showing the coastal states.

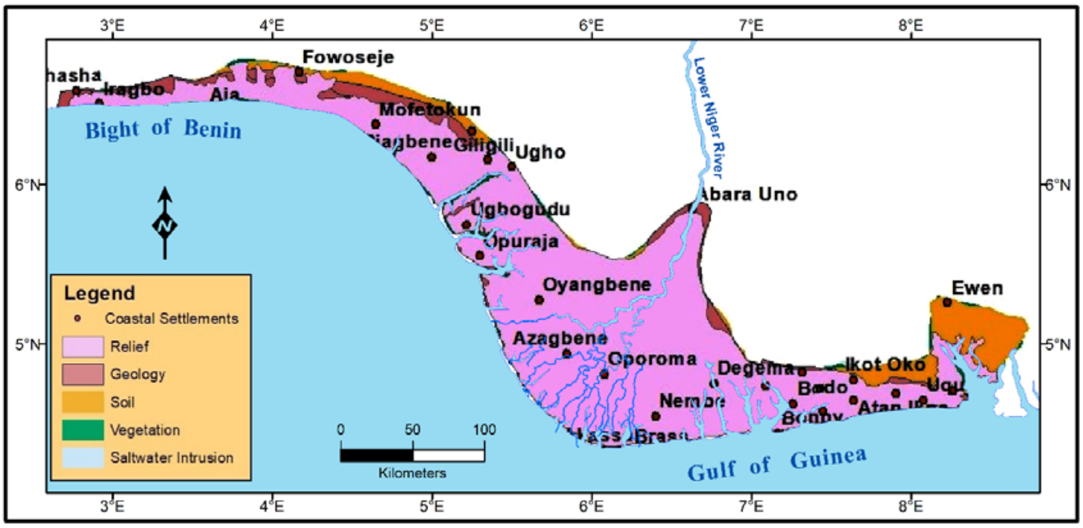

Figure 2. Coastal zone of Nigeria with some selected locations.

The major drainage system in the region is the mouth of the river Niger which is made up of broad fan-shaped pieces of land that form the most extensive flat area along the coast[35]. There are also shorter rivers including Ogun, Osun, Osse, and Osiomo, in the western part of this region, and Imo from Udi Plateau as well as Cross from Kumba Cameroon Mountain in Cameroon in the eastern part. All the rivers discharge into the Atlantic Ocean. The area experiences two seasons- the wet and dry seasons. On average, the wet season runs from February to November to give way to the dry season. The seasons roughly correspond to the periods when tropical continental air mass (cT) and tropical maritime air masses (mT) and their associated winds dominate most parts of the region, respectively[35,36]. The mean annual rainfall varies from 1480 mm in Ikeja, through 2540 mm in Port Harcourt to 2930 mm in Calabar (IITA data 1980–2018). The climate is relatively dry and cool with day temperatures of 27 °C to 30 °C and night temperatures of between 20 °C and 22 °C on average. The mean monthly figure is around 26 °C. The annual temperature range is as low as 3 °C (IITA data 1980–2018). The dominant vegetation types in the area are freshwater swamps and mangrove forests.

3. Materials and methods

3.1. Data collection

The key physical parameters that were used for this study are relief, rock types, landforms, and erosion/deposition rates. The datasets for these were sourced from SRTM-30M DEM CGIAR of the Nigerian Geological Survey Agency, Abuja; SPOT-5 and Geo-eye imageries[37]; Nigeria’s topographical maps of 1967 and ASTER DEM of 2012, respectively. The spatial and temporal characteristics of the various datasets are contained in **Table 1**.

Table 1. Characteristics of satellite imageries used for this study.

Satellite	Spatial resolution	Temporal resolution
Spot 5	2.5 to 5 m in panchromatic mode 10 m in multispectral mode	26 days
ASTER DEM	VNIR (visible and near-infrared) bands 1, 2, 3N, 3B1: 15 m SWIR (shortwave infrared) bands 4–9: 30 m TIR (thermal infrared) bands 10–14: 90 m	16 days
GeoEye	0.5 m panchromatic 1.84 m-multispectral	8.3 days at 770 km altitude
SRTM DEM	30 m	Multi-day

3.2. Data analysis

Vulnerability of a coastal zone can be determined in different ways. Anfuso et al.[38] has recognized four approaches that can be grouped into the following clusters: 1) index/indicators-based methods, 2) methods based on dynamic computer models, 3) GIS-based decision support tools, and 4) visualization tools[39]. The most applied approach among these, probably for their easy comparison of the vulnerability of different areas, is the index/indicators-based methods[40] which are adopted by Gornitz[41]. In this study, means and percentages of relief, rock types, landforms, and erosion/deposition rate indices were analyzed with the aid of simple descriptive statistics. The vulnerability analyses were carried out by adopting the coastal risk classification scheme developed by the study of Gornitz[41] (**Table 2**). The Gornitz scheme is one of the most frequently used classifications in the literature and was adopted because it allows the characterization of the physical parameters for various selected points in the study area. However, as a result of the paucity of data, the sea level rise index was not included. The study area was segmented into cells of equal sizes using Fishnet tools in ArcGIS, which enables the creation of a feature class made up of a net of rectangular cells. The grids were then harmonized with the raster resolution (93 m^2) of the digital elevation model (DEM) data used. All other layers were rasterized to that spatial resolution i.e., 93 m^2. In each cell, the relevant coastal vulnerability indices (CVI) including relief, rock types, landforms, and erosion and deposition rates were evaluated to generate index values. The evaluation, which yielded CVI scores for all the cells was carried out with the aids of spatial analysis, raster calculator, and trigonometry functions in ARGIS 10.2.2 using Equation (1) (i.e., the square root of the product of the ranked variables divided by the total number of variables). This approach has been widely used[42]. The CVI value for each cell was achieved by examining the individual parameters already ranked on the Likert scale of 1 to 5 (**Table 2**), corresponding to very low, low, medium, high, and very high vulnerability classes. A very-high vulnerability class is thus an area with very low relief (<9 m), undifferentiated sands, gravels & clays (Quaternary) rock types, landforms dominated by barrier and bay beaches, mudflats, deltas, and ≤−2.1 erosion rate (mm/year), while a very-low vulnerability class refers to an area with a relief value >49.0 m, dominated by the basement complex (Precambrian) rock type, having rocky, cliffed coast landforms, with ≥2.1 accretions (mm/year). The last step involved the ranking of CVI results which was done by defining five classes for the numerical results of Equation (1) (**Table 3**).

3.3. Mapping the vulnerabilities

Based on the values obtained from the vulnerability indices, the entire coastal areas of the country were mapped first on the basis of each of the parameters and then on the aggregate. Unlike the ranking of the CVI of three classes used by Soukissian et al.[8] and Khouakhi et al.[18], this study adopted the CVI ranking scheme of five classes of Basheer et al.[43]. Using a scheme of three classes will be too coarse to define and explain the detailed vulnerability status of a relatively large unit area.

Table 2. Coastal risk classes.

Category	Very low	Low	Moderate	High	Very high
Coastal parameters	1	2	3	4	5
Relief (m)	>49.0	25.1–49.0	17.1–25.0	9.1–17.0	<9
Rock types	Basement complex (Precambrian)	Undifferentiated sedimentary rocks cretaceous	Undifferentiated sedimentary rocks tertiary	Coastal plains, sands & clays (Quaternary)	Undifferentiated sands, gravels & clays (Quaternary)
Landforms	Rocky, cliffed coast	Medium cliffs, indented coast	Low cliffs, salt marsh, coral reefs, mangrove	Beaches (pebbles), estuary, lagoon mangrove	Barrier and bay beaches, mudflats, deltas
Erosion/deposition rate (mm/year)	≥2.1 accretion	1.0 – 2.0 stable	−1.0 – 1.0 erosion	−1.1 – −2.0 erosion	≤−2.1 erosion

Adapted from Gornitz[41].

$$\mathrm{CVI} = \sqrt{\frac{a \times b \times c \times d}{n}} \tag{1}$$

where, *a*, *b*, *c*, and *d* are the values of relief (m), rock types, landforms, and erosion/deposition rate while *n* is the number of the vulnerability indices considered.

Table 3. Ranking of the coastal vulnerability index (CVI).

Vulnerability class	Very low (VLv)	Low (Lv)	Medium (Mv)	High (Hv)	Very high (VHv)
CVI	<0.44	0.45–2.62	2.63–6.97	6.98–14.3	>14.3

4. Results and discussion

4.1. Vulnerability to climate change based on relief

Figure 3 shows the vulnerabilities of the different parts of the coastal area of Nigeria with respect to relief. It shows that close to half (46%) of the coastal area falls into the very high vulnerability class which represents an area of 20,700 km^2. Generally, this area falls between 0 m and 9 m heights above sea level. In this zone are Iragbo and Ajah communities located in the extreme southern part of Lagos State in the western flank; Mofetokun and Biagbene settlements of Ese Odo in Ondo State; Ugbogudu and Opuraja communities in Delta State; the north-western and southern western portions of Onyagbene and Nembe communities in Bayelsa State; the entire Akasa, Brass, and Odioma communities in the southern fringe of also in Bayelsa State; Degema, Okrika, Bodo, Opobo and Bonny communities in the extreme southern portion of River State; and parts of the southern portion of Ebughu and Ewen in Cross River State. The high vulnerability is the second largest class, covering 32% of the entire coastal area and amounting to 14,400 km^2. The elevations of areas falling in this class range between 9 and 17 m above sea level. The major settlements here include the north-eastern part of the Iragbo community in Lagos State; the Fowoseje community in Ogun State; Giligili in Edo State; Ugho, Azagbene, Abara Uno, and the eastern part of Onyagbene in Delta State; and Nyokuru and Uquo communities in Akwa Ibom State. The moderate, low and very low vulnerability classes cover 11%, 7%, and 3%, amounting to 4950 km^2, 3150 km^2, and 1350 km^2 of the coastal area, respectively. The moderate vulnerability class falls between 17 m and 25 m above sea level. It covers the Ago Shasa community and extends to the northern part in the western flank with some interruptions by the very high class; and Afam Uko Afam as well as Nyokuru communities in Akwa Ibom State. The class is also found sparsely covering part of the southern area of the Abara Uno community of Delta State.

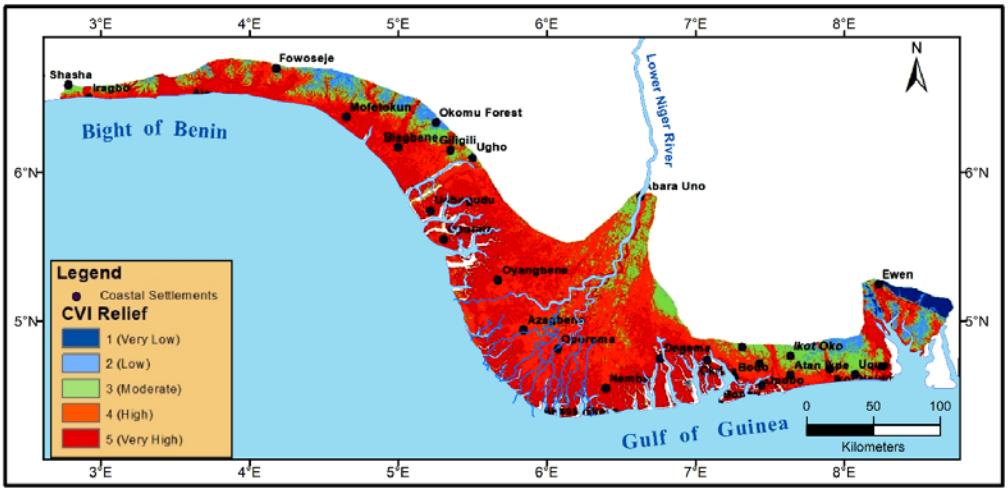

Figure 3. Vulnerability of the coastal area of Nigeria to climate change, based on the relief.

While the low vulnerability class is found in the northern edges of Ogun, Ondo, and Edo State on the western flank and Akwa Ibom State on the eastern side, the very low vulnerability is dominant in the northern fringes of Cross River State. These two classes are also found on an island located at the extreme end of River State in between the southern Degema and Okrika communities. Their elevations range between 25 m and 49 m and, 49 m and 96 m above sea level, respectively. The results obtained in this study have shown that more than 70% of the coastal area of Nigeria falls into very-high and high vulnerability classes and is generally below 30 m above sea level. These vulnerability patterns are defined by the relief of the area corresponding to those reported by Iloeje[35,44]. They show in general that there is a relationship between the elevation of the different parts of the coastal area and their vulnerabilities to the impacts of climate change. For instance, the lower the elevation, the higher the severity of its inundation from hinterland flood water and sea level rise. This has implications for land resource management in the area. It implies for instance, that the management should be done with due cognizance to variations in elevation. Thus, for instance, the preservation of the forest communities particularly in Cross River and the Akwa Ibom States must continue to be pursued, to protect the land from the anticipated impacts of inundations that could be up to 1 metre above sea level by 2100, as projected by the study of USAID[12]. The results of the study also corroborate that of Folorunsho and Awosika[45], which suggests that the entire coastal area of Nigeria may be endangered by the impacts of climate change.

4.2. Vulnerability pattern based on rock types

Figure 4 shows the vulnerability of the coastal area of Nigeria to climate change, based on rock types. The rocks include (i) the Precambrian basement complex, (ii) the undifferentiated sedimentary rocks-Cretaceous, (iii) the undifferentiated sedimentary rocks-Tertiary, and (iv) the coastal plain, sands and clays, and (v) the undifferentiated sands, gravels, and clays in that order. As shown on the map, the group of undifferentiated sands, gravel and clays covered the largest portion of the coastal area. This is about 73.9% of the total area, which translates to approximately 29,590.27 km^2. The results also indicate that the area falls within the zone of a very high level of vulnerability particularly because of its high degree of susceptibility to erosion and thus lower elevation closeness to the sea. In this area are the Iragbo community in Ogun State, Aja settlement in Lagos State, Mofetokun and Biagbene of Ese-Odo in Ondo State, Ugbogudu and Opuraja; and Abara Uno of the southern and northern regions of Delta States respectively; Onyagbene, Azagbene, Nembe, Oporoma, Akasa, Brass and Odioma all in the Bayelsa States. It also covers the entire southern portion of the River State, Degema community, Okrika, Opobo and Bonny settlements. The extreme southern end of Akwa Ibom States and the Ebughu community in the Cross River States are also included. The zone is presented in red colour on the map. Following the very-high vulnerability class is a group of coastal plains, sands, and clays (Quaternary) which occurs directly northwards of the undifferentiated sands, gravels and clays group. This area falls within the high vulnerability with a total area of about 8422.26 km^2. It is presented in orange colour on the map. The proportion of the area covered is 21.1%, which is the second largest. The area is found in patches on the northern fringes of the coastal states. Parts of the settlements in this group include Fowoseje in Ogun State, Ugho in the Delta States, and Afam Uko Afam in River State. The remaining portions of the map are differentiated with green, light blue and deep blue colours representing other groups of undifferentiated sedimentary rocks-Tertiary (moderate vulnerability); undifferentiated sedimentary rocks-Cretaceous (low vulnerability); and the Precambrian basement complex (very low vulnerability) respectively. These groups cover the land areas of about 1.2%, 3.0%, and 0.8% of the zone respectively. While the class of moderate vulnerability is found in Ago Shasha and some southern portions of Cross River State, the ‘low’ and ‘very low’ classes are observed traversing the middle of the coastal area of Cross River State in the north-south direction. In sum, the results have shown that about 95% of the coastal area of Nigeria is found to be in the classes of very high and high vulnerability to sea level rise associated with global warming. These areas have consequently been experiencing coastal erosion[46]. Given the larger proportion of the coastal environment classified as having very high- and high vulnerabilities, it can be concluded that almost all of the coastal area of Nigeria is at risk of the impacts of climate change. French et al.[47] have earlier pointed to the likelihood of this. They had noted that a one-metre level rise would render over 800 villages in the Niger Delta area of the country uninhabitable. In the same vein, Folorunsho and Awosika[45] have observed that with the trends in sea-level rise in Nigeria, there is a likelihood that up to 17,000 km^2 of wetlands may be lost in the coastal area. This could be in addition to the inundation and erosion of barrier systems along the western coast of the country. Furthermore, the coastal environment of Nigeria is at the risk of loss of coastal cities' land base, water resources, and infrastructure, due to inundation, flooding, saline intrusion, and coastal erosion[48].

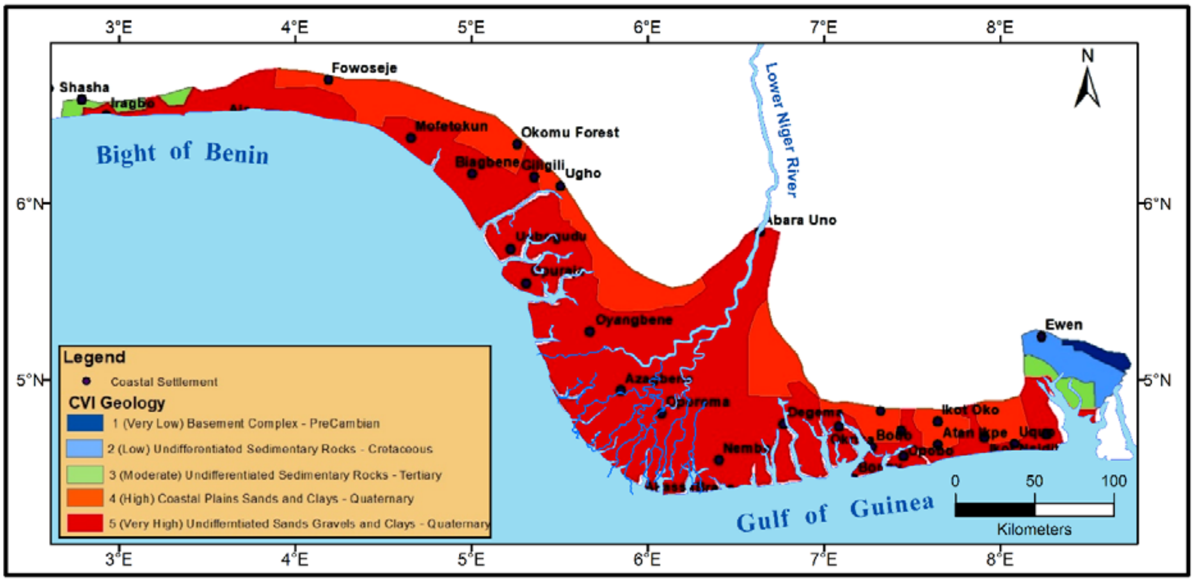

Figure 4. Vulnerability of the coastal area of Nigeria to climate change, based on rock types.

4.3. Vulnerability pattern based on landforms

Figure 5 shows the map of the vulnerability assessment of the coastal area of Nigeria based on landform indices. The figure has three colours red, orange and green, differentiating the various vulnerability classes in the area. While the portion with red colour represents a very high vulnerability area, orange and green colours represent areas of high and moderate vulnerabilities, respectively. The three categories defined here fall within three of the five coastal risk classes of Gornitz[41]. The first is a class of Barrier and Bay beaches and Mudflats Deltas (red colour). This is followed by the class of Beaches pebbles, Estuary and Lagoon mangrove (brown); and lastly, the class of low cliffs, salt marsh, coral reefs and mangrove (pink). The class of Barrier and Bay beaches and Mudflats Deltas covers the central region of the coastal area. It falls within the area of very high vulnerability. In terms of proportion, it is about 66% portion of the zone, translating to about 26,345.59 km^2. The communities in this region include Opuraja, Ugbogudu and Abara Uno of Delta States; the whole of Nembe, Oporoma, Azagbene, Onyagbene, Akasa, Brass and Odioma in Bayelsa State; and Degema, Okrika, Bodo and Bonny in River State. The results indicate that based on these indices, the whole of Delta, Bayelsa and the western part of River States fall within the class of very high vulnerability. Next to the very high vulnerability is the class of beaches pebbles, estuary and lagoon mangrove which falls within the area of high vulnerability. This class covers 20% of the zone amounting to a total area of about 8269.98 km^2. It is located at the western end of the coastal zone. In this area are communities including Ago Shasha and Fowoseje in Ogun State; Iragbo and Aja in Lagos State; and Mofetokun and Biagbene in Ondo State. The last is the area with low cliffs, salt marsh, coral reefs and mangroves. This falls within the moderate vulnerability class and is found in the eastern part of the zone. It represents 13.3% of the coastal zone, amounting to 5350.80 km^2. Within this area are seven different communities including Ewen and Ebughu in the northern and southern ends of the coastal area of Cross River State respectively; Opobo, Atan Ikpo, and Nyokuru in the eastern part of River State; and Uquo in Akwa Ibom State.

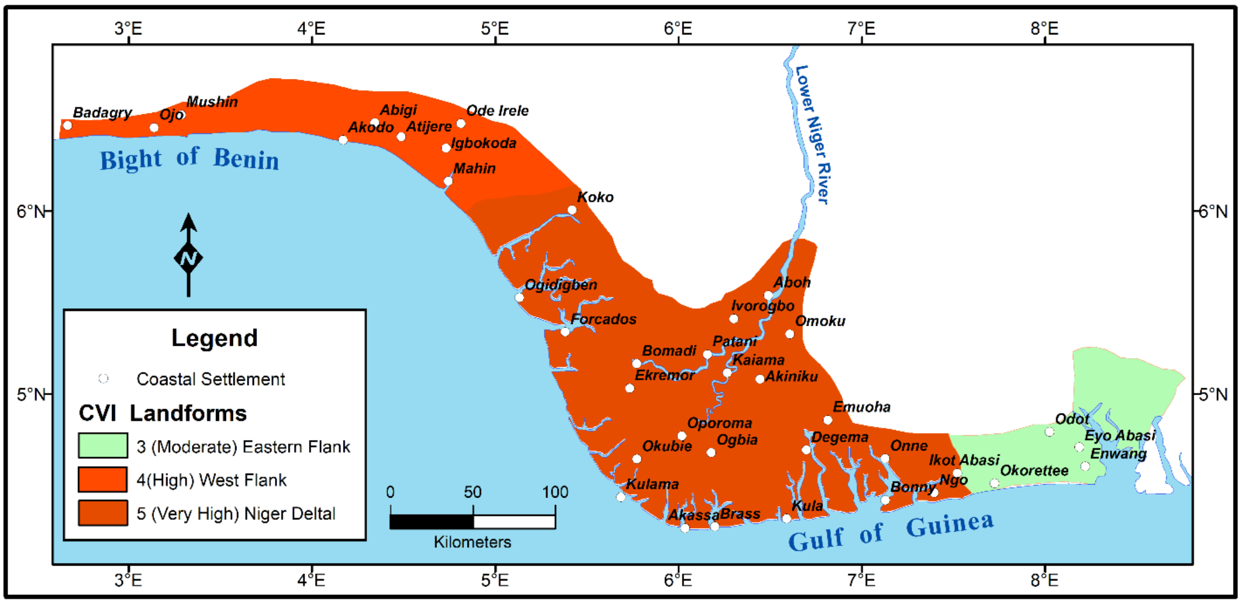

Figure 5. Vulnerability of the coastal area of Nigeria, based on the landform classes.

4.4. Vulnerability patterns based on erosion/deposition rates

Figure 6 shows the vulnerability of the coastal area, considering erosion and or deposition rates. The analyses yielded five vulnerability classes. These are very-high, high, moderate, low, and very low. The very-high vulnerability class covers the largest portion of the area, approximately 19,575 km^2, representing 43.5% of the zone. The communities covered include Abara Uno in Delta State; Azagbene, Oporoma, Nembe, Akasa, Brass, and Odioma in Bayelsa State. Also found in this area are Degema, Okrika, Opobo, and Bonny settlements in River State. Following the very-high vulnerability class is high vulnerability, covering about 10,305 km^2. This is approximately 22.9% of the coastal zone. The area covers the entire part of Delta State including Ugbogudu and Opuraja communities except for the eastern portion made up of the Abara Uno community in the northern part of the State. Another community in this class is Onyagbene in the western section of Bayelsa State. This class is followed by the moderate vulnerability category, representing 8.2% of the entire coastal area i.e., about 3690 km^2. In this class, they are Iragbo and Aja communities in Lagos State; and Ago Shasha and Fowoseje in Ogun State. All these communities are located on the western flank of the coastal area of Nigeria. Other classes are the low and very low vulnerability categories. The two cover 5445 km^2 and 5985 km^2 of the zone, representing 12.1% and 13.3%, respectively. The communities found in the low vulnerability class are Mofetokun and Biagbene of Ondo State; and Giligili of Delta State, while those of the very low vulnerability class are Ewen and Ebughu in Cross River State; and Uquo, and Ikot Nsidibe in Akwa Ibom State. The results obtained in this study thus show that the whole central region and the western flank of the coastal zone of Nigeria fall within the very-high, high, and moderate vulnerabilities classes, considering erosion/deposition rates. The three classes accounted for more than 74% of the entire coastal area, suggesting that the area could be witnessing more erosion than accretion, with the arcuate Niger Delta area being the most impacted. These results suggest that Nigeria must provide an effective and appropriate land management response to contain the challenges of erosion and deposition that may be escalated by the intensifying climate change.

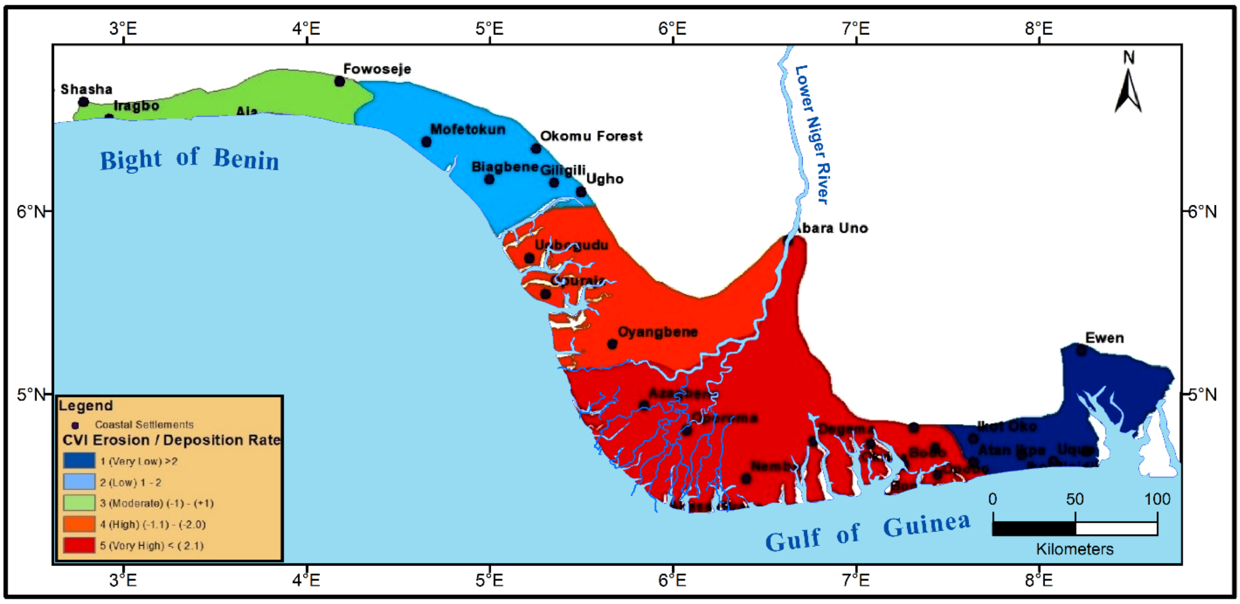

Figure 6. Vulnerability of the coastal area of Nigeria, Based on the erosion/depositional rates.

4.5. Vulnerability to climate change in the coastal area of Nigeria

Figure 7 depicts the spatial pattern of vulnerabilities in the study area based on a combination of the assessment of the four parameters earlier presented, i.e., relief, landform, rock types, and erosion/deposition rates. The results show that the very-high vulnerability class has the largest proportion, covering about 53% of the area, amounting to a total land area of about 23,850 km^2. The key communities in this area include Ugbogudu, Opuraja and Abara Uno communities in Delta State; Onyagbene, Azagbene, Oporoma, Akasa, Brass and Odioma communities in Bayelsa State; and Degema, Okrika, Bodo, Opobo and Bonny communities in River State. The extreme western part of Akwa Ibom State also falls in the very-high vulnerability class. The next class, which is high vulnerability, covers 17% of the coastal area. This proportion translates to 7650 km^2. The class is most extensive in Lagos State, extending to cover Iragbo and Aja communities. It is also found in the northern fringes of the Niger Delta region. The other classes i.e., moderate, low, and very-low vulnerability classes cover 10% (4500 km^2), 13%, (5850 km^2) and 7% (3150 km^2) of the coastal area, respectively. While the moderate class is found only in the western part of the coastal area, the low and very low classes dominate the extreme eastern flank. They are also found in the northern edges of the western part. Communities such as Fowoseje in Ogun State and Biagbene and Mofetokun in Ondo State, fall within the moderate vulnerability class. Such communities as Ago Shasha in Ogun State; Atan Ikpo and Uquo in Akwa Ibom State; and Ebughu of Cross River State, belong to the low vulnerability class. The very low class is found covering the Ewen community of Cross River State. The results of this study are largely in agreement with those of many previous studies. They underscored the point that the whole of the Niger Delta sub-region is critically vulnerable to the impacts of climate change. Many studies[49–51] have pointed out that the greatest challenges of climate change along the coast of Nigeria are expected in the Niger Delta. One reason for this is that several decades of oil extraction in the region have caused devastation to the physical environment, making it much more susceptible to suffering the adverse effect of climate change. The next most vulnerable is the western flank, particularly around Lagos and Ogun States. Inundation by ocean water is a particularly significant threat. This has for example been reported by USAID[12]. The summary of the physical vulnerabilities in the coastal States of Nigeria is shown in **Table 4**. For example, Lagos State in the extreme western part of the coastal area, in terms of relief falls within very-high and high vulnerabilities while on the basis of erosion/deposition rates, it is within high vulnerability. Meanwhile, Bayelsa State in the core Niger Delta of the coastal area falls within very-high, high, and medium vulnerability, while, in terms of erosion/deposition rates, it falls within very-high and high vulnerability.

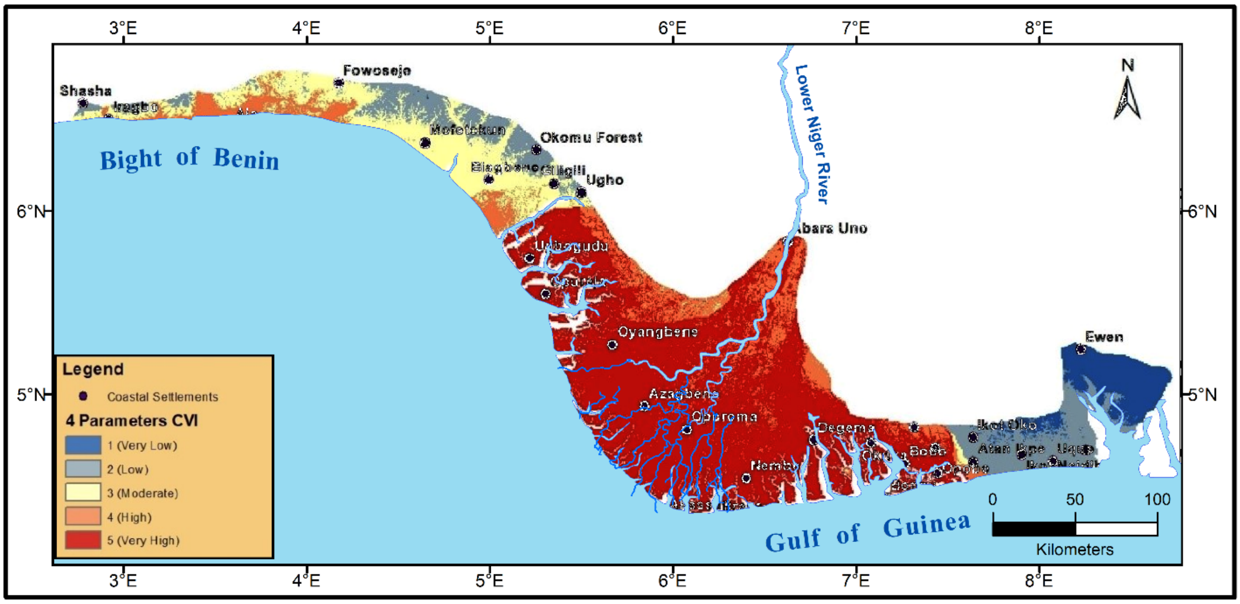

Figure 7. Vulnerabilities of the coastal environment of Nigeria to climate change (based on relief, rock types, landforms, and erosion/depositional rates vulnerability indices).

Table 4. Summary of physical vulnerabilities in the coastal states of Nigeria.

States	Physical vulnerability indices & vulnerability classes			
	Relief	**Rock types**	**Landforms**	**Erosion/depositional rates**
Lagos	(i) VHv (ii) Hv	(i) VHv (ii) Mv	(i) Hv	(i) Hv
Ogun	(i) VHv (ii) Hv (iii) Lv	(i) VHv (ii) Hv (iii) Mv	(i) Hv	(i) Hv (ii) Lv
Ondo	(i)VHv (ii)Hv (iii) Mv	(i) VHv (ii) Hv	(i) Hv	(i) Lv
Edo	(i) Mv (ii) Lv	(i) VHv (ii) Hv	(i) VHv (ii) Hv	(i) Lv
Delta	(i) VHv (ii) Hv (iii) Mv	(i) VHv (ii) Hv	(i) VHv	(i) VHv (ii) Hv
Bayelsa	(i) VHv (ii) Hv (iii) Mv	(i) VHv (ii) Hv	(i) VHv	(i) VHv (ii) Hv
Rivers	(i) VHv (ii) Hv (iii) Mv (iv) Lv (v) VLv	(i) VHv (ii) Hv	(i) VHv (ii) Mv	(i) VHv (ii) VLv
Akwa Ibom	(i) VHv (ii) Hv (iii) Mv (iv) Lv	(i) VHv (ii) Hv	(i) Mv	(i) VLv
Cross River	(i) VHv (ii) Hv (iii) Mv (iv) Lv (v) VLv	(i) Mv (ii) Lv (iii) VLv	(i) Mv	(i) VLv

(i) VHv = very high vulnerability (ii) Hv = high vulnerability (iii) Mv = moderate vulnerability (iv) Lv = low vulnerability (v) VLv = very low vulnerability.

5. Conclusion

The study assessed the physical vulnerability of Nigeria's coastal area to the impacts of climate change. The vulnerability was examined with respect to a group of four factors including relief, rock types, landforms, and erosion/deposition rates. The indices generated from these groups of factors were used to compute the vulnerabilities of the various parts of the area to the impacts of climate change. Five vulnerability classes were defined as very high, high, moderate, low, and very low vulnerabilities.

The very high vulnerability class covers more than half (53%) of the area, which is about 23,850 km^2, is found mainly in the Niger Delta region. The next most important class i.e., the high vulnerability class, covers 17% of the coastal area, i.e., about 7650 km^2, and is found mostly in the coastal area of Lagos State and the northern fringes of the Niger Delta region. The other classes i.e., moderate, low, and very low vulnerability extend over 10% (4500 km^2), 13%, (5850 km^2), and 7% (3150 km^2) of the coastal area, respectively. While the moderate vulnerability class is found only in the western part of the coastal area, the low and very low vulnerability classes dominate the extreme eastern flank. They are also found in the northern edges of the western part. The low vulnerability class is found mainly in Ondo, Ogun, Akwa Ibom State, and the Cross River States. The very low vulnerability class is found covering the Ewen community of Cross River State only.

Managing the challenges of climate change in Nigeria's coastal environment should be guided by the findings of a study like this. First and foremost, it is shown that the Niger Delta environment is the most vulnerable to climate change impacts along Nigeria's coastal area. This calls for concern as climate change intensifies. The precarious condition of the Niger Delta and the Lagos flank of the coastal area in particular must attract greater attention of the government. The Niger Delta is still defined in overall socio-economic terms, by poverty, and environmental degradation[52]. Efforts must be more focused on strategic development or strengthening socio-economic resilience in the region to reduce the adverse consequences of the impact of climate change as experienced in many parts of the delta in October and November 2022. This obviously must be complemented by physical development that reduces the impact of climate change. It is often acknowledged, for example, that, about a third of the Netherlands including Schiphol Airport is below sea level, yet it is well protected from coastal erosion. That country is reputed for having a strong coastal protection policy that has been effective for many decades. Nigeria can take a lesson from this. Given the very strategic position of the Niger Delta to the economy of Nigeria, there is a need for government to invest in such physical development as channelization and coastal fortification that can help to further reduce the impacts of climate change in the region.

Furthermore, with the identification of the spatial variability and differences in the vulnerability drivers using physically-based indices, the findings of this study are useful for policymakers and coastal managers in Nigeria in considering mitigation measures that are directed toward the management of coastal challenges. These include mangrove afforestation to contain soil erosion/deposition; reviewing coastal land use and putting in place community-based management strategies for sustainability; development of dikes to reduce coastal erosion; and building of seawalls and groins to prevent inundations associated with sea level rise. In doing these, further studies are required in such areas as geography, engineering, geology, geophysics, oceanography, geodesy, meteorology, and climatology, focusing specifically on the coastal environment. This will improve the understanding of the dynamics of the features of the coastal region that can help in streamlining climate change response actions.

The vulnerability assessment in this study is based on the physical parameters of the coastal environment only. As earlier noted, the climatic elements and socioeconomic parameters of coastal vulnerability had been investigated in a number of previous studies. An obvious gap here that needs to be addressed by further studies is producing a holistic vulnerability assessment of the coastal environment of the country. This requires considering the totality of the socio-economic parameters as well as the physical attributes of the region in the quantification of its vulnerability to the impacts of climate change. A critical challenge here however is that substantial financial and human resources are required. It is already an advantage that the Nigerian Government is making its budgetary allocations climate-responsive. However, this type of research requires attention to attract deserved funding. More efforts are needed to attract bilateral and multilateral funding for climate research. The current level of participation in climate research in the country is relatively low. For instance, although there is an expanding pool of experts in remote sensing and GIS in the country, their skills are mostly not geared toward climate change research. These experts need to be attracted to climate change research to secure the needed critical mass of specialists for vulnerability assessment. This is especially because detailed land use analyses are critical components of responding to the impacts of climate change. As land use is dynamic and highly variable, it is difficult to capture on satellite imageries, the use of global land cover and land use reference data[53] and the advanced form of deep learning—the U-Net model[54] will be extremely important in harvesting relevant data for the vulnerability assessment.

Author contributions

Conceptualization, AOA and TOO; methodology, AOA, TOO and FAA; software, AOA and TOO; validation, AOA, TOO and FAA; formal analysis, AOA, TOO and FAA; investigation, AOA and TOO; resources, AOA and TOO; data curation, AOA, TOO and FAA; writing—original draft preparation, AOA and TOO; writing—review and editing, AOA, TOO and FAA; visualization, AOA, TOO and FAA; supervision, TOO and FAA; project administration, TOO. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. UN-Habitat. *State of the World's Cities 2008/2009—Harmonious Cities.* UN-Habitat; 2008.
2. Adefolalu DO. Climate change and economic sustainability in Nigeria. In: Proceedings of the International Conference on Climate Change and Economic Sustainability; 12–14 June 2007; Awka, Nigeria. pp. 36–49.
3. Ogba CO, Utang PB. Vulnerability and adaptations of Nigeria's Niger Delta coast settlements to climate change-induced sea level rise. In: Proceedings of the Strategic Integration of Surveying Services FIG Working week; 13–17 May 2007; Hong Kong SAR, China.
4. Nwafor JC. Global climate change: The driver of multiple causes of flood intensity in Sub-Saharan Africa. In: Proceedings of the International Conference on Climate Change and Economic Sustainability; 25 July 2007; Awka, Nigeria. pp. 12–14.
5. Odjugo PAO. Some effects of gas flaring on the microclimate of yam and cassava production in Erhorike and Environs, Delta State, Nigeria. *Nigerian Geographical Journal* 2007; 5(1): 43–54.
6. Odjugo PAO. Quantifying the cost of climate change impact in Nigeria: Emphasis on wind and rainstorm. *Journal of Human Ecology* 2009; 28(2): 93–101. doi: 10.1080/09709274.2009.11906223
7. Odjugo PAO. Regional evidence of climate change in Nigeria. *Journal of Geography and Regional Planning* 2010; 3(6): 142–150. doi: 10.5897/JGRP.9000119
8. Soukissian TH, Ntoumas MC, Anagnostou C, Kiriakidou C. Coastal vulnerability of eastern Saronikos Gulf to intense natural events. In: Proceedings of the Twentieth International Offshore and Polar Engineering Conference; 20–25 June 2010; Beijing, China.
9. Ekanade O, Ayanlade A, Orimogunje IOO. Geospatial analysis of potential impacts of climate change on coastal urban settlements in Nigeria for the 21st century. *Journal of Geography and Regional Planning* 2008; 1(3): 049–057.
10. Lionello P, Scarascia L. The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast. *Regional Environmental Change* 2020; 20: 31. doi: 10.1007/s10113-020-01610-z
11. Mattei G, Di Luccio D, Benassai G, et al. Characteristics and coastal effects of a destructive marine storm in the Gulf of Naples (Southern Italy). *Natural Hazards and Earth System Sciences* 2021; 21(12): 3809–3825. doi: 10.5194/nhess-2021-224
12. USAID. Climate risk profile: Nigeria. Available online: https://reliefweb.int/attachments/eb719bef-1a7c-3f94-bdfe-37209f224423/2019_USAID-ATLAS-Nigeria-Climate-Risk-Profile.pdf (accessed on 17 January 2023).
13. Gbode IE, Adeyeri OE, Menang KP, et al. Observed changes in climate extremes in Nigeria. *Meteorological Applications* 2019; 26(4): 642–654. doi: 10.1002/met.1791

14. Woodruff JD, Irish JL, Camargo SJ. Coastal flooding by tropical cyclones and sea-level rise. *Nature* 2013; 504(7478): 44–52. doi: 10.1038/nature12855.
15. Aucelli PPC, Di Paola G, Rizzo A, Rosskopf CM. Present-day and future scenarios of coastal erosion and flooding processes along the Italian Adriatic coast: The case of Molise region. *Environmental Earth Sciences* 2018; 77(10): 371. doi: 10.1007/s12665- 018-7535-y
16. Ciro Aucelli PP, Di Paola G, Incontri P, et al. Coastal inundation risk assessment due to subsidence and sea level rise in a Mediterranean alluvial plain (Volturno coastal plain-southern Italy). *Estuarine, Coastal and Shelf Science* 2017; 198: 597–609. doi: 10.1016/j.ecss.2016.06.017
17. Federal Ministry of Environment. Nigeria's Second National Communication under the United Nations Framework Convention (UNFCCC) on climate change. Available online: https://unfccc.int/resource/docs/natc/nganc2.pdf (accessed on 8 June 2023).
18. Khouakhi A, Snoussi M, Niazi S, Raji O. Vulnerability assessment of Al Hoceima bay (Moroccan Mediterranean coast): A coastal management tool to reduce potential impacts of sea-level rise and storm surges. *Journal of Coastal Research* 2013; (65): 968–973. doi: 10.2112/SI65-164.1
19. IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Intergovernmental Panel on Climate Change; 2008.
20. Adejuwon SA. Impact of climate variability and climate change on crop yield in Nigeria. In: Proceedings of the Stakeholders' Workshop on Assessment of Impacts and Adaptation to Climate Change (AIACC); 20–21 September 2004; Ile-Ife, Nigeria. pp. 271–279.
21. Odjugo PAO. The impact of natural gas flaring on microclimate and yield of melon (Citrullus Lanatus) in the Niger Delta Region of Nigeria. *Ife Research Publications in Geography* 2011; 10(1): 164–172.
22. Odjugo PAO. Analysis of climate change awareness in Nigeria. *Journal of Scientific Research and Essays* 2013; 8(26): 1203–1211. doi: 10.5897/SRE11.2018
23. Adesina FA, Odekunle TO. Climate change and adaptation in Nigeria: Some background to Nigeria's response—III. In: 2011 International Conference on Environmental and Agriculture Engineering IPCBEE; 29–31 July 2011; Chengdu, China. pp. 146–154.
24. Ifatokun IP. Climate change adaptation in Goronyo local government area, Sokoto State, Nigeria: The case of rural water supply in semi-arid region. *Journal of Sustainable Development in Africa* 2013; 15(8): 42–56.
25. Ani KJ, Anyika VO. The impact of climate change on food and human security in Nigeria. *International Journal of Climate Change Strategies and Management* 2022; 14(2): 148–167. doi: 10.1108/IJCCSM-11-2020-0119
26. Malley CS, Omotosho D, Bappa B, et al. Integration of climate change mitigation and sustainable development planning: Lessons from a national planning process in Nigeria. *Environmental Science & Policy* 2021; 125: 66–75. doi: 10.1016/j.envsci.2021.08.022
27. Koko AF, Wu Y, Abubakar GA, et al. Thirty years of land use/land cover changes and their impact on urban climate: A study of Kano metropolis, Nigeria. *Land* 2021; 10(11): 1106. doi: 10.3390/land10111106
28. Toka SO. Change in land cover, rainfall and flood incidence in Eti-Osa, Lagos, Nigeria. *South African Journal of Geomatics* 2022; 11(2): 202–217. doi: 10.4314/sajg.v11i2.3
29. Adelekan IO. Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization* 2010; 22(2): 433–450. doi: 10.1177/0956247810380141
30. Enete AA, Amusa TA, Nwobodo CE. Climate change and cassava processing in southeast, Nigeria. *Tropicultura* 2013; 31(4): 272–282.
31. Akukwe TI, Ogbodo C. Spatial analysis of vulnerability to flooding in port Harcourt metropolis, Nigeria. *SAGE Open* 2015; 5(1): 1–19. doi: 10.1177/2158244015575558
32. Adelekan I, Fregene T. Vulnerability of artisanal fishing communities to flood risks in coastal southwest Nigeria. *Climate and Development* 2015; 7(4): 322–338. doi: 10.1080/17565529.2014.951011
33. Adelekan I, Fregene T. Vulnerability of artisanal fishing communities to flood risks in coastal southwest Nigeria. *Climate and Development* 2015; 7(4): 322–338. doi: 10.1080/17565529.2014.951011
34. Anyanwu PE, Alegbeleye WO. Utilization of the coastal areas for Aquaculture in Nigeria. In: *Coastlines of West Africa*. American Society of Civil Engineers; 1993. pp. 67–74.
35. Iloeje NP. *A New Geography of Nigeria*. Longman Schools Division; 1981.
36. Ojo O. *The Climates of West Africa*. Heinemann; 1977.
37. (GeoEye-1—Earth Online (esa, .int)). Available online: https://earth.esa.int/eogateway/missions/geoeye-1 (accessed on 20 August 2023).
38. Anfuso G, Postacchini M, Di Luccio D, Benassai G. Coastal sensitivity/vulnerability characterization and adaptation strategies: A review. *Journal of Marine Science and Engineering* 2021; 9(1): 72. doi: 10.3390/jmse9010072
39. Sekovski I, Del Río L, Armaroli C. Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy). *Ocean & Coastal Management* 2020; 183: 104982. doi: 10.1016/j.ocecoaman.2019.104982

40. Rangel-Buitrago N, Anfuso G. *Risk Assessment of Storms in Coastal Zones: Case Studies from Cartagena (Colombia) and Cadiz (Spain).* Springer Cham; 2015.
41. Gornitz V. Global coastal hazards from future sea level rise. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1991; 89(4): 379–398. doi: 10.1016/0031-0182(91)90173-O
42. Abuodha PAO, Woodroffe CD. Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast Australia. *Journal of coastal conservation* 2010; 14: 189–205. doi: 10.1007/s11852-010-0097-0
43. Basheer Ahammed KK, Mahendra RS, Pandey AC. Coastal vulnerability assessment for eastern coast of India, Andhra Pradesh by using geo-spatial technique. *Geoinformatics & Geostatistics: An Overview* 2016; 4: 3. doi: 10.4172/2327-4581.1000146
44. Iloeje NP. *A New Geography of Nigeria*, 1st ed. Longmans of Nigeria; 1965.
45. Folorunsho R, Awosika LF. Nigerian meteorological induced changes along the Nigerian coastal zone and implications for integrated coastal zone management plan. In: Proceedings of BORDOMER '95, International Convention: Rational Use of Coastal Zone; 6–10 February 1995; Bordeaux, France. pp. 804–811.
46. Croitoru L, Miranda JJ, Khattabi A, Lee JJ. The cost of coastal zone degradation in Nigeria: Cross River, Delta and Lagos States. Available online: https://openknowledge.worldbank.org/handle/10986/34758 (accessed on 17 August 2023).
47. French GT, Awosika LF, Ibe CE. Sea-level rise and Nigeria: Potential impacts and consequences. *Journal of Coastal Research Special* 1995; (14): 224–242.
48. USAID 2018. Climate risk profile: Nigeria. Available online: https://www.climatelinks.org/sites/default/files/asset/document/2019_USAID-ATLAS-Nigeria-Climate-Risk-Profile.pdf (accessed on 18 January 2023)
49. Okude AS, Ademiluyi IA. Coastal erosion phenomenon in Nigeria: Causes, control and implications. *World Applied Science Journal*. 2006; 1(1): 44–51.
50. Etuonovbe AK. The devastating effect of flooding in Nigeria. In: Proceedings of the FIG Working Week 2011—Bridging the Gap between Cultures; 18–22 May 2011; Marrakech, Morocco. pp. 1–15.
51. Uyigue E, Ogbeibu AE. Climate change and poverty: Sustainability in the Niger Delta region of Nigeria. In: Proceedings of the 2007 Amsterdam Conference on the Human Dimensions of Global Environmental Change; 24–26 May 2007; Amsterdam, Netherlands.
52. Wils I. Repositioning the Niger Delta as the economic hub of Nigeria: The strategic fundamentals. Available online: https://www.nembeibeusa.org/post/repositioning-the-niger-delta-as-the-economic-hub-of-nigeria-the-strategic-fundamentals (accessed on 19 August 2023).
53. Fritz S, See L, Perger C, et al. A global dataset of crowdsourced land cover and land use reference data. *Scientific Data* 2017; 4(1): 170075. doi: 10.1038/sdata.2017.75
54. Banquet A, Delbouve P, Daams M, Veneri P. Monitoring land use in cities using satellite imagery and deep learning. Available online: https://www.oecd.org/publications/monitoring-land-use-in-cities-using-satellite-imagery-and-deep-learning-dc8e85d5-en.htm (accessed on 17 August 2023).