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Niger's Delta vulnerability to river floods due to sea level rise

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Abstract

An evaluation of vulnerability to sea level rise is undertaken for the Niger delta based on 17 physical, social and human influence indicators of exposure, susceptibility and resilience. The assessment used GIS techniques to evaluate and analyse the indicators and the index of coastal vulnerability to floods, if sea level rise conditions are occurring. Each indicator value is based on data extracted from various sources including remote sensing, measured historical data series and literature search. Further indicators are ranked on a scale from 1 to 5 representing "very low" to "very high" vulnerability, based on their values. These ranks are used to determine a similar rank for the defined coastal vulnerability index ($CV_{SLR}I$). Results indicate that 42.2 % of the Niger delta is highly vulnerable to sea level rise; such areas been characterized by low slopes, low topography, high mean wave heights, and unconfined aquifers. Moreover the analysis of social and human influences on the environment indicate high vulnerability to sea level rise due to its ranking for type of aquifer, aquifer hydraulic conductivity, population growth, sediment supply and groundwater consumption. Such results may help decision makers during planning, to take proper adaptive measures for reducing Niger Delta's vulnerability, as well as increasing the resilience to potential future floods.

1 Introduction

Within the last few decades the atmospheric and sea surface temperatures have been rising and climates worldwide are changing. With such changes floods are occurring more often and studies need to be carried out to see how to prevent floods. The classical approach is too look at river floods and mitigation strategies, due to increase in precipitation and consequently in frequency of high peak floods occurring in river systems (Bhattacharya et al., 2013; Castro Gamma et al., 2014; Fu et al., 2014; Leauthaud et al., 2013; Moya Quiroga et al., 2013).

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Increase in sea surface temperatures cause thermal expansion, which increase the water level of the sea surface (IPCC, 2013) and as a result the shoreline moves further inland. The warming of the atmosphere causes melting of mountain glaciers and polar ice sheets, thus increasing the rise in sea levels. Based on historical data eustatic sea level changes between 1950 and 2009 were on average 1.7 mm yr^{-1}. In recent years satellite altimetry measurements (between 1993 and 2003) have shown an increase in this rate to over 3 mm yr^{-1} (IPCC, 2007a).

Rise in sea levels has various consequences for low lying coastal areas such as inundation due to coastal flooding by incoming rivers and/or the sea; erosion; displacement of coastal wetlands; and inland intrusion of sea water (IPCC, 2007b; Van et al., 2012). Over the years, scientists have used climate models to generate projections of possible sea level rise (SLR) values by the year 2100. In its reports the Inter-governmental Panel on Climate Change (IPCC) had projected a rise of 0.18–0.5 m by the year 2100 (IPCC, 2013). This projection had its limitation due to uncertainties in response of the ice sheets, and their effect on the global sea level. Other projections of higher rise in sea level were made after the 2013 report, as data became available (Rahmstorf, 2007). These projections are of 0.26–0.97 m by the year 2100.

The effects of sea level rise (SLR), however, will not be uniform all over the world; some coastal areas will record higher sea levels than the global average due to land subsidence from contraction of soil materials. Relative sea level rise is the change in sea levels relative to the land elevation and includes land vertical movement in addition to global sea level rise values. Relative sea level rise values are higher in subsiding coasts like river deltas than the ones in stable coastal areas. Although subsidence occurs naturally in deltas, in the case of Niger Delta it is increased even more by oil extraction from underground sources (Ericson et al., 2006). Oil extraction might not affect an area if there are proper surveys and regulations that take care of this issue, as well as if there is normal sediment supply coming from upstream into the delta. However in situations where sediment supply from upstream is reduced or is inadequate to replenish the area, land subsidence will occur, as it has been recorded in some parts of Japan, Indonesia and Venezuela (IPCC, 2007c).

Vulnerability as a concept represents a potential damage and it is conditional upon the possibility of a hazard. Thus a system is said to be vulnerable when it has a high susceptibility to the effects of a hazard, and is unable to cope, recover or adapt (Balica et al., 2013). System vulnerability assessment to a certain hazard gives a measure of the degree of damage that might likely occur if the hazard happens without mitigation/adaptation measures put in place. Vulnerability levels are varying within a system therefore indicators are used to determine and measure it. Indicators can be ecological, political, technological and socio-economic factors of a system. A value of an indicator is used to represent the character of the system in a quantitative way (Cutter et al., 2008). Consequently an assessment of vulnerability to SLR requires a method that takes into account various indicators that reflect the effects of the SLR on the vulnerability itself. Due to the complex nature of a coastal system, such methods include assumptions that simplify coastal processes in order to enable the assessments to be useful.

One method to determine the values of the indictors of vulnerability to river floods, due to SLR, is to represent data in Geographic Information Systems (GIS), which enables for comparison and deduction on the relationships between the sources of the data. Heberger et al. (2009) used GIS and hydrodynamic modelling to estimate the potential impacts of SLR on population, infrastructure, ecosystems and property, in case a major flooding event will occur on the river discharging into the sea. Data used for the assessment were: DEM's, base flood elevation data, population block data, hydrological data, tidal data, data on geology, built up area data, etc. The results combined inundation and erosion layers with population block layer to determine the population at risk. Similarly, a GIS based coastal vulnerability assessment was carried out by Martin et al. (2012), based on physical and human induced vulnerability. The physical factors considered were: coastal systems, hydrology (sediment supply) and lithography while the human influence factors were road network, population density, population growth and urban land cover. The result was combined with an urban growth model to show the influence of anthropogenic factors on the final vulnerability of the area.

Another method for assessing vulnerability is the Coastal Vulnerability Index (CVI), which relates various factors that influence the degree of vulnerability of coastal areas in a quantifiable manner. The CVI concept introduced by Gornitz et al. (1991), uses information about the coast to quantify the relative vulnerability of coastal segments, to effects of SLR at a regional and national scale. In their study, Gornitz et al. (1991) assessed the vulnerability of the U.S coast to erosion and inundation effects of SLR by ranking sections of the coast according to their potential for change and relative importance for coastal management. Since 1991 the CVI methodology has been applied globally using different variables depending on the coastal area under study and the particular hazard being anticipated.

Pendelton et al. (2010) and Dwarakish et al. (2009) used six variables to assess the coastal vulnerability to sea level rise and coastal change for the northern Gulf of Mexico in Mexico and Udupi coastal zone in India, respectively. These six variables are geomorphology, coastal slope, mean wave height, mean tidal range, rate of shoreline change, and relative SLR, which are considered physical variables that characterise a coastal area, and relate to susceptibility of the shoreline to natural changes and its natural ability to adapt to changes in the environment. A similar methodology using different variables is demonstrated by Kumar and Kunte (2012) for the Chennai East coast in India to calculate the possible areas of inundation due to future SLR and land loss to coastal erosion. Yin et al. (2012), used elevation, SLR, slope, coastal geomorphology, shoreline erosion, land use, mean tidal range, and mean wave height to determine the areas of the Chinese coast that are most vulnerable to effects of SLR.

The CVI method is based on physical coastal variables and therefore it is not easy to be used for coastal management; which would need variables related to social conditions and human impact on the environment, in order to determine a good view on all aspects entailed by the vulnerability of coastal areas. Consequently modified CVI approach is developed, which includes variables that represent social, economic, and human-influence factors of the coast. Ozyurt and Ergin (2009) propose an improved CVI for SLR, and apply the methodology to assess the impact of SLR for the Goksu Delta in Turkey. The approach uses seventeen physical and human influence variables, namely: rate of SLR, geomorphology, coastal slope, significant wave height, sediment budget, reduction of sediment supply, river flow regulation, engineered frontage, groundwater consumption, land use pattern, natural protection degradation, coastal protection structures, tidal range, proximity to coast, type of aquifer, hydraulic conductivity, depth to ground water level above sea level, river discharge, water depth at downstream. Result shows the vulnerability levels of defined coastal segments, to different types of impacts and indicates that human impact on the environment has the highest effect for inundation. The method however does not consider social variables. McLaughlin and Cooper (2010) include socio-economic variables in calculating a CVI for erosion in Northern Ireland. Their CVI include variables such as population, cultural heritage, roads, railways, landuse and conservation status. The main outcome of their study is that socio-economic variables do not influence the scores of the CVI in a significant way. This result is due to the fact that socio-economic variables were assigned lower weights than to the physical variables.

The study presented herein uses the advantage of mapping CVI results in a GIS environment in order to analyze Niger Delta's physical, social and human influence on the environment in case that a flooding event will occur on the Niger River. The coastal vulnerability index obtained as such is a composite one, and it is called coastal vulnerability index due to SLR ($CV_{SLR}I$). In order to determine and analyse the $CV_{SLR}I$ for the Niger Delta, seventeen variables, presented in Table 1 are used. The seventeen selected variables are a sub-set of the coastal vulnerability indicators as determined and defined by Gornitz (1991), Ozyurt and Ergin (2009) and Balica et al. (2014). The variables are classified into exposure, susceptibility, and resilience classes based on their characteristics, following the methodology of Dinh et al. (2012).

This paper is structured in five parts. After the introduction and review of vulnerability methods, the case study area is presented, followed by a short description of the applied methodology. Results are presented in Sect. 4, followed by conclusions in Sect. 5.

2 Case study description

The Niger delta region (Fig. 1) is a low lying area consisting of several tributaries of the Niger River and ending at the edge of the Atlantic Ocean. It consists of several creeks and estuaries as well as a stagnant mangrove swamp. The region has an area of approximately 20 000 km^2, a 450 km coastline and is home to about 13 million people.

Nigeria's economy depends on oil and gas extraction from the Niger delta as the main source of foreign exchange, therefore many multinational oil and gas companies operate in the region and over 500 oil wells are located onshore. The extraction of oil and gas has increased land subsidence in the delta with values estimated to range from 25–125 mm yr^{-1} (Syvitski, 2008). Land subsidence lowers the topography of delta areas with respect to the sea and makes the relative sea level rise to be high. For coastal areas, the relative sea level rise value is much more important than the eustatic sea level rise. Compared to the global average eustatic SLR of 3 mm yr^{-1} the relative sea level rise in the Niger delta is 25–125 mm yr^{-1}, which makes it highly vulnerable to river floods due to the effects of sea level rise (SLR).

Other environmental problems in the Niger Delta that can be further exacerbated by SLR include construction of dams in the upstream and erosion of the coast. Niger River has a number of dams constructed upstream of the Niger Delta, with a total combined capacity of 30 billion m^3. The construction of dams reduced the estimated percentage sediment to the Niger Delta by 70 % (NDRMP, 2004). Deltas are replenished by upstream sediment supply therefore this condition makes the Niger Delta vulnerable to coastal erosion and land loss (IPCC, 2007c).

Erosion is already ravaging the Niger Delta; due mainly to natural causes (like river flow and ocean surge) and construction of bridges, canals and other coastal structures, which altered the natural course of the rivers (NDRMP, 2004).

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Based on population figures of 1995, Awosika et al. (1992) estimated that 600 000 villagers in the Niger-delta would need to be displaced in case of a 1 m sea level rise. However this estimate may be surpassed as the population of the Niger delta increased with a growth rate of over 3.1 % between 1991 and 2006 (NPC, 2010).

3 Vulnerability assessment methodology

Gornitz (1991) defined CVI on n number of physical ranked variables $(x_1, \ldots, x_n)$, as:

$$\mathrm{CVI} = \sqrt{\frac{x_1 \cdot x_2, \ldots, x_n}{n}}. \quad (1)$$

In Eq. (1) n represents the number of ranked variables. According to the CVI method, local variable values are measured and/or analysed and compared with documented ranges of values for that variable. The comparison allows a ranking of physical variables that shows the level of vulnerability.

Variables can be categorised in classes of exposure, susceptibility and resilience. Dinh et al. (2012) defined a coastal vulnerability index based on exposure, susceptibility and resilience factors as:

$$\mathrm{CVI} = \frac{E \cdot S}{R} \quad (2)$$

where E are exposure factors, S susceptibility factors and R resilience factors.

The methodology used in the present research combines the two methods. Because CVI can refer to different regions and causes, further on, the index of vulnerability to river floods in coastal areas, due to SLR is referred as Coastal Vulnerability to SLR Index ($\mathrm{CV_{SLR}I}$). The proposed methodology, to evaluate $\mathrm{CV_{SLR}I}$, has the following application steps:

1. choose variables that are relevant to the coastal processes in the study region;

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2. classify variables in exposure, susceptibility and resilience;

3. define coastal segments and determine for each of them the values of the variables chosen in the first step;

4. use Eq. (1) to calculate the CVI for exposure, susceptibility and resilience elements (e.g. CV_EI, CV_SI, and CV_RI respectively);

5. use Eq. (2) to compute the $CV_{SLR}I$ for each defined coastal segment, i.e.:

$$CV_{SLR}I = \frac{CV_EI \cdot CV_SI}{CV_RI}; \tag{3}$$

6. compare the $CV_{SLR}I$ with results obtained for CVI based on physical variables only;

7. indicate (through the $CV_{SLR}I$) the coastal segments that are most in need of intervention in response to socio-economic conditions.

The developed methodology is exemplified on the case of the Niger delta, however its applicability is valid to any coastal area.

The exposure variables are those inherent qualities of the system that position it for a likely hazard impact; they describe what is exposed to the threat (Cutter et al., 2008). Susceptibility variables are the characteristics of the exposed system that influence the level of harm from hazards (Birkmann, 2007). The resilience of a system implies the ability to adapt and even utilize the disaster as an opportunity for the future; thus resilience variables enable a system to cope and reduce the possible impact of the disaster on the exposed population.

Tables 2–4 shows the ranges of values of exposure, susceptibility and resilience variables respectively, as considered in present research, as well as their ranking from 1 (very low) to 5 (very high). Ranges and ranking are based on the ones documented in Dinh et al. (2012), Kumar and Kunte (2012) and Thieler and Hammer-Kloss (1999).

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The applied methodology divides the coast in segments. For each segment a $CV_{SLR}I$ is calculated, however these values present a wide range between a minimum (min) and a maximum (max) value, therefore results are normalized between 0 and 1 using the relation:

$$NV = \frac{\text{value} - \text{min}}{\text{max} - \text{min}} \quad (4)$$

where NV is the normalised value of the variable; value is the calculated index value for a coastal segment; max is the maximum value in that index; and min is the minimum value in that index.

The selection of the indicators, used for determining the $CV_{SLR}I$ are detailed further.

3.1 Selected indicators for exposure

The exposure indicators are selected based on their influence on coastal flooding, inundation, sea water intrusion to ground water sources and coastal erosion. All the chosen variables are physical properties of the coast except "Proximity to Coast" which is a human related variable.

3.1.1 Topography

The topography (elevation) of an area above the mean sea level influences how much of it will be impacted by rising sea levels because low lying areas offer less resistance to inundation in times of flooding and storm surges (Van et al., 2012). The elevation of the Niger Delta is extracted from SRTM DEM data using ERDAS Imagine 9.1 topographic analysis tools. The coastline has an average elevation between 0 and 10 m a.s.l., which is ranked as defined in Table 2. The coastline topography mapping, based on the defined ranking in Table 2, is shown in Fig. 2. It can be noticed that the eastern end (from Bonny) has "medium" to "high" topography (3–7 m a.s.l.), which makes the delta susceptible to flooding due to river flow and to storm surges coming from the sea.

3.1.2 Coastal slope

The slope of a coastal area is the degree of steepness with reference to the surrounding land. Slope determines the minimum level of water that can penetrate and inundate an area; therefore areas with lower or gentler slopes are more vulnerable to waves and tide action than areas with steeper slopes (Aich et al., 2010). The delineation and classification of the coastline slope ranges between 0 and 2.5 %. Figure 3 shows the classification of the slope and the fact that the eastern end (from Bonny) has a slope of 0.1–1 %, which gives it a "high" to "very high" vulnerability ranking; making it highly susceptible to inundation.

3.1.3 Geomorphology

Geomorphology describes landforms and processes that lead to the formation of landform patterns. The type of landform found on the coast determines its degree of vulnerability to erosion and its level of resistance to wave forces. Vulnerability ranking based on geomorphology is done such that cliffs and rocky areas have low vulnerability; lagoons and estuaries have high vulnerability; while beaches, deltas, and barrier islands have very high vulnerability (Pendelton et al., 2010). The Niger Delta geomorphologic zone is characterized by deltaic, sandy beach, and estuarine landforms. These characteristics (see Table 2) gives it a "high" to "very high" ranking and makes it very susceptible to erosion and wave action.

3.1.4 Relative sea level rise

Relative sea level/annum at the local level is a measure of the height of the sea above a certain datum averaged over a year and measured using tide gauges (Yin et al., 2012). The higher the sea level rise rate the more vulnerable an area is compared with those with lower rates of rise in sea levels. Satellite altimetry measurements (1993 to 2010) over the Niger delta coast show eustatic sea level rise rates of 3.03–3.39 mm yr^{-1}

(Rosmorduc, 2012). In addition the Niger delta is subsiding at a rate of 25–125 mm yr^{-1}, which classifies it as a "very high" relative SLR (see Table 2).

3.1.5 Annual shoreline erosion rate

The degree of erosion of a coastal area influences its response to rising sea levels. In view of coastal vulnerability, areas that are undergoing erosion will have high vulnerability while areas of accreting sediment will have low vulnerability (Kumar and Kunte, 2012). Niger delta values for annual erosion as published by NIOMR (2010) are: Escravos 20–25 m yr^{-1}, Forcados 16–20 m yr^{-1}, Brass 15–20 m yr^{-1}, and Bonny 10–14 m yr^{-1}. These are the values considered in the present study, because they cover the Niger Delta from west to east. The values show that the Niger delta has a "high" to "very high" ranking (Table 2) and is therefore very susceptible to more erosion from SLR.

3.1.6 Mean tidal range

The tidal range gives the difference between high and low tides and is linked to permanent and episodic hazards from sea level rise and storm surge (Yin et al., 2012). In view of coastal vulnerability, areas with large tidal ranges have higher vulnerability than those with lower ranges. Mean tidal range is in general determined based on longterm tidal data. In case such data is not available, hydrodynamic models are used to predict tidal levels based on tidal stations located within the areas of interest (Kumar and Kunte, 2012). Values of the tidal range for the Nigerian coast are generated using the wXTide32 tidal model, which predicts tides based on the algorithm developed by the US National Oceanic Service. Niger Delta measurements from eight tidal stations, along the delta coast, are used in the model. The results show a gradual increase from 1.74 m in the west, around Forcados River to 2.57 m in the east at Bonny River. The range (1.74–2.57 m) has "moderate" to "high" ranking (see Table 2); therefore the Niger delta is susceptible to storm surge and sea level rise.

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3.1.7 Mean wave height

Waves move coastal sediments from one place to another. The linear wave theory gives the wave energy as:

$$E = \frac{1}{16}\rho g H^2 \quad (5)$$

where E = energy and H = wave height.

According to Eq. (5) wave energy is directly proportional to the square of wave height, therefore the wave height can be used as a proxy for wave energy (Yin et al., 2012). Areas with high waves are more vulnerable than areas with low wave heights as they have more energy to move materials offshore. Values obtained from NIOMR (2010) give wave heights of 1.5 m for the western to middle Niger delta (from Jalla to areas around Okumbiri), and 0.5–1.5 m for the eastern end. These values have a "high" to "very high" ranking (see Table 2) and make the coast susceptible to flooding, erosion, storm surge and inundation.

3.1.8 Population density

Areas with high population density have a higher vulnerability than those with lower population density (McLaughlin et al., 2002). The presence of human settlement increases the value of risk, the likelihood of erosion and modification of the coastal area. The Niger delta population distribution data, as given by the local Government area shows that many settlements in the eastern end (from Bonny) have higher than 500 people per km^2; hence there is "high" to "very high" vulnerability risk to SLR (see Table 2).

3.1.9 Proximity to coast

The proximity of a settlement, infrastructure or land to the coast determines the level of its exposure to the effects of sea level rise such as storm surges, floods, erosion

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and wave action. Present study considered distances from shore using the 2012 NigeriaSatX satellite imagery. Locations of settlements within 0–1500 m of the coastline were determined and ranked. Table 2 shows that the shorter the distance from the coastline, the more vulnerable the settlement is to the effects of SLR.

3.2 Selected indicators for susceptibility and resilience

Based on the available data and the influence of social and human factors on the extent of damage that could occur at the occurrence of SLR, eight indicators of susceptibility and resilience are selected in the present study. The resilience indicators are the social variables that increase the ability of victims to cope with floods, inundation, loss of land from erosion, and intrusion of sea salts.

Like the exposure variables, the documented range of values/characteristics of the susceptibility and resilience variables are ranked from "very low" to "very high" vulnerability, as detailed in Tables 3 and 4, respectively. The indicators are explained in detail below.

3.2.1 Type of aquifer

The type of aquifer in a given area determines how vulnerable the ground water is to salt water intrusion. Confined aquifers are overlain by materials with poor permeability and are therefore less vulnerable to contamination than semi confined and unconfined aquifers, which allow interaction with the surface. Data from the NDRMP (2004) was used to rank the Niger delta coastal aquifers and the results shows that the coastal aquifers are unconfined. Table 3 shows that unconfined aquifers have "very high" vulnerability; therefore the Niger Delta is vulnerable to salt water intrusion from SLR.

3.2.2 Aquifer hydraulic conductivity

Hydraulic conductivity of an aquifer is the ability of the aquifer to transmit water. Its value depends on the type of material, for example gravel/sand have a higher hydraulic

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conductivity than clay/silt and therefore transmit water more easily. Areas with high hydraulic conductivity are more vulnerable to the effects of SLR than those with low hydraulic conductivity (Ozyurt and Ergin, 2010). The hydraulic conductivity of coastal aquifers in the Niger Delta ranges from 0.0002 to 120.6 m d^{-1} (NDRMP, 2004). Coastal segments with hydraulic conductivities higher than 41 m d^{-1} have a "high" to "very high" vulnerability ranking (Table 3) and are vulnerable to salt intrusion from SLR.

3.2.3 Reduction in sediment

Building of dams and other control infrastructure in the upstream of coasts impede the flow of sediments and reduce the natural nourishment of delta areas (IPCC, 2007b). Areas where the percentage of sediment reaching the coasts is sustained over long period of time have less vulnerability compared to areas where only a percentage of the normal sediments reaches them (Ozyurt and Ergin, 2010). The sediment supply to the Niger delta is 70 % less than in the past, due to construction of dams in the upstream (NDRMP, 2004). The value (i.e. 70 %) for reduction in sediment supply gives a "very high" vulnerability (Table 3), which makes the Niger delta susceptible to erosion from SLR.

3.2.4 Population growth rate

Population growth affects the environment in various ways with highly populated areas facing greater environmental challenges (UNFPA, 2008). High population growth rate will increase the number of people likely to be affected by the effects of SLR therefore areas with lower growth rate will have less vulnerability compared with those with higher growth rate. Inter-census data of the Niger delta (1991 to 2006) shows a growth rate of 2.9–3.1 % which gives a "high" to "very high" vulnerability (Table 3).

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3.2.5 Ground water consumption

Inland intrusion of sea salts is likely to pollute underground aquifers and cause shortage of drinking water in coastal areas. Areas that depend on ground water as the main source of drinking water are more vulnerable than those with low dependence on ground water. Data on groundwater consumption in the Niger delta, as compiled by NDRMP (2004) shows the percentage of households/settlement that depend on groundwater sources (boreholes and wells) for drinking and domestic use. Some areas have over 40 % dependence on groundwater giving them a high ranking. People living in such areas are vulnerable to salt water intrusion due to SLR.

3.2.6 Emergency services

Emergency service personnel are usually trained in first aid and search-rescue operations to enable them combat consequences of disasters. In rural remote communities these trained personnel are not available at the onset of disasters. Communities with trained and equipped emergency services are more resilient to the impacts of SLR compared to those without. In Nigeria, emergency services at the local level are coordinated by the Local Emergency Management Agency (LEMA) which establishes trained local community structures made up of local associations, religious bodies, clubs, schools etc. (NEMA, 2010a). Due to the presence of LEMA in every local government area in Nigeria, present study assumes that local community structures exist in all the Niger delta communities. However, the Niger Delta coast has small and isolated fishing communities which are less likely to have schools. The resilience ranking for such isolated communities is "very low" (see Table 4).

3.2.7 Communication penetration

The channel of communication determines the number of people to whom information reaches as well as the quality of information provided. In Nigeria, NEMA through

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its disaster prevention strategy provides information about impending disasters to vulnerable communities via print and electronic media as well as informal channels like traditional rulers, religious leaders, etc. (NEMA, 2010b). NEMA (LEMA) staff who disseminate this information are found in the Local government headquarters. Many settlements in the Niger delta are located far away from the local government headquarters and might not be easily reached. People living in such remote areas have less access to quality communication and are therefore less resilient to the effects of SLR, as compared with those living in cities (Table 4).

3.2.8 Availability of shelters

During a disaster, people are evacuated to shelters administered by trained personnel. Access to shelters determines the number of people that can be rescued in good time and helps restore later on the affected community (NEMA, 2010c). Areas with buildings located on safe sites that can be used as shelters are more resilient to the impacts of SLR than those without. In Nigeria buildings located on unaffected sites are used as shelters during flooding (e.g. schools), but where none is available emergency shelters are erected. The elevation of the Niger delta is generally low as shown in Fig. 3, therefore in the events of flooding, evacuation camps have to be erected. This gives the Niger delta a "very low" resilience ranking (Table 4).

4 Results and discussion

In order to calculate the CVI for the 450 km of the Niger delta coast, 54 coastal segments are considered. The segment division is based primarily on three main elements; elevation (Fig. 2); change in slope (Fig. 3); and the presence of large estuaries. The segments are represented in Fig. 4. The sizes of the segments differ from one another in length, however on average the segment width is 4 km inland.

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Figure 5 shows a plot of the calculated $CV_{SLR}I$ for the Niger delta coastal segments. Analysing the results it is seen that 42.6 % of the coastline has "very low" to "low" vulnerability, 18.5 % has "moderate" vulnerability, while 40.8 % have "high" to "very high" vulnerability, which is shown in Fig. 6.

Results show that the eastern end of the Niger delta (from Bonny to the southern end of Opobo; made up of six coastal segments) is the longest stretch with very high vulnerability to SLR. Coastal segments classified as highly vulnerable to SLR will require mitigation measures to be applied against SLR.

5 Conclusion

Highly vulnerable coastlines expose the inland areas to effects of SLR, serving as a gateway to inundation, storm surge and coastal erosion. The results of the $CV_{SLR}I$ for the Niger delta shows that 42.6 % of the coast is highly vulnerable to effects of SLR like flooding, erosion, and salt water intrusion into underground aquifers. These areas of the coast need to be protected against the negative effects of SLR.

Human influence on coastal environments can affect sediment supply and accelerate erosion, and should therefore be captured in vulnerability assessments. Analysis of social and human influence variables show that in terms of type of aquifer, aquifer hydraulic conductivity, population growth, sediment supply, groundwater consumption, the Niger delta is vulnerable to the effects of SLR. Moreover the location of many settlements in remote areas, far away from the local government headquarters, reduces the value of resilience to the effects of SLR.

Studies such as the one presented herein serve as a base for taking mitigation measures and helping decision makers to assess the effects of their measures in the function of the river system under consideration (Jonoski and Popescu, 2012; Popescu et al., 2010, 2014). The evaluation presented herein is done using best available variable values for the Niger delta; therefore this study results can be used to develop mitigation and adaptation measures against SLR for the vulnerable parts. Global studies undertaken by Ericson et al. (2006) and Nicolls and Mimura (1998) rank the entire Niger delta as having moderate vulnerability. Such ranking has been used in the literature as the "condition" for the Niger Delta, even though it was only based on population likely to be displaced.

Present study does not include, however the vulnerability of offshore areas or mitigation/adaption to SLR options. Such a study would complement the overview of decision makers in the area, and will allow them to take adaptation measures that would address in a coherent manner both the Niger Delta as well as the Niger Coastline.

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Table 1. List of selected variables for vulnerability assessment.

Variable (class)	Data type	Data source
Topography (E)	SRTM DEM	srtm.csi.cgiar.org/
Coastal slope (E)	SRTM DEM	Validation map from NASRDA data archives; srtm.csi.cgiar.org/
Geomorphology (E)	Geomorphologic map of Nigerian coast	www.niomr.org
Relative sea-level rise rate (E)	Relative sea level rise rates for Niger Delta Atlantic coast	www.niomr.org
Annual shoreline erosion rate (E)	Measured annual erosion rate for the Nigerian coast	www.niomr.org
Mean tide range (E)	Tidal data for Nigerian coast www.niomr.org; www.wXtide32.com	
Mean wave height (E)	Wave height data for the Nigerian coast	www.niomr.org
Population density (E)	Population distribution data per local Government area	Nigerian National Population commission www.population.gov.ng
Proximity to coast (E)	NigeriaSatX imagery and settlement map of Niger Delta	NASRDA data archive
Type of aquifer (S)	Data on aquifer types in the Niger delta	Niger Delta Regional Master Plan (NDRMP) – Environment and Hydrology report
Hydraulic conductivity (S)	Data on aquifer properties in the Niger delta	NDRMP – Environment and Hydrology report
Reduction in Sediment Supply (S)	Estimate on reduction in sediment supply from the Niger River	NDRMP – Environment and Hydrology report
Population growth rate (S)	Inter-census data	www.population.gov.ng
Groundwater consumption (S)	Data on % ground water consumption	NDRMP – Environment and Hydrology report
Emergency services (R)	Information about presence and type of emergency services	National Emergency management Agency, (NEMA) www.nemanigeria.com
Communication penetration (R)	Data on settlement type, size, and location	NASRDA data archives.
Availability of shelters (R)	Info on provision of shelters	NEMA, www.nemanigeria.com

Note: E = exposure, S = susceptibility, R = resilience, P = physical, SO = social, HI = human influence.

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Table 2. Data range and ranking of the exposure $CV_{SLR}I$ variables.

	Variables	Ranking of values					
		Class	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
1.	Topography	P	> 10 m	8–10 m	6–7 m	3–5 m	0–2 m
2.	Coastal Slope	P	> 3 %–4 %	2–3 %	1–2 %	0.5–1 %	0.1–0.5 %
3.	Geo-morphology	P	Rocks	Cliffs	Vegetated coasts	Lagoons estuaries	Barrier islands, beaches, deltas
4.	Relative SLR rate	P	0–1 mm	1–2 mm	2–3 mm	3–4 mm	> 4 mm
5.	Annual shoreline erosion rate	P	0–1 m	1–5 m	5–10 m	10–15 m	> 15 m
6.	Mean tidal range	P	> 6 m	4–6 m	2–4 m	1–2 m	< 1 m
7.	Mean wave height	P	0.3–0.5 m	0.5–0.8. m	0.8–1.1 m	1.1–1.4 m	> 1.4 m
8.	Population density	SO	< 100 people km^{-2}	100–300 people km^{-2}	300–500 people km^{-2}	500–800 people km^{-2}	> 800 people km^{-2}
9.	Proximity to coast	HI	> 800 m	600–800 m	400–600 m	200–400 m	100–200 m

Note: P = physical, SO = social, HI = human influence.

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Table 3. Data range and ranking of the susceptibility $CV_{SLR}I$ variables.

			Ranking of values				
	Variables	Class	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
10.	Type of aquifer	P	Confined		Leaky confined		Unconfined
11	Aquifer hydraulic conductivity	P	0–12 $m\,d^{-1}$	12–28 $m\,d^{-1}$	28–41 $m\,d^{-1}$	41–81 $m\,d^{-1}$	> 81 $m\,d^{-1}$
12	Reduction in sediment supply	HI	30 %	40 %	50 %	60 %	70 %
13	Population growth rate	SO	0 %	< 1 %	1–2 %	2–3 %	> 3 %
14	Groundwater consumption	SO, HI	< 20 %	20–30 %	30–40 %	40–50 %	> 50 %

Note: P = physical, SO = social, HI = human influence.

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Table 4. Data range and ranking of the resilience $CV_{SLR}I$ variables.

			Ranking of values				
	Variables	Class	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
15	Emergency services	P, SO	Absent No settlements on segment	Only present at the state level. (Remote area)	Only present at the local government level. (Village community)	Present in community but not formally trained. (Settlement located far from LG HQ).	Present in the community and formally trained. (City/Local government HQ/oil company).
16	Communication penetration	P, SO	None	Only through direct contact; Access to radio communication; Remote areas	Traditional rulers/town criers. Access to radio communication. Village settlement	Access to print and electronic media. Town/settlement located close to oil company.	Print and electronic media. City/Proximity to Local Government Hq.
17	Availability of shelters	P, SO	Absent	Available but not equipped with relevant facilities	Available/equipped with relevant facilities but located in another community	Available/equipped with relevant facilities but only accessible by boat	Available/equipped with relevant facilities and accessible by road/boat

Note: P = physical, SO = social, HI = human influence.

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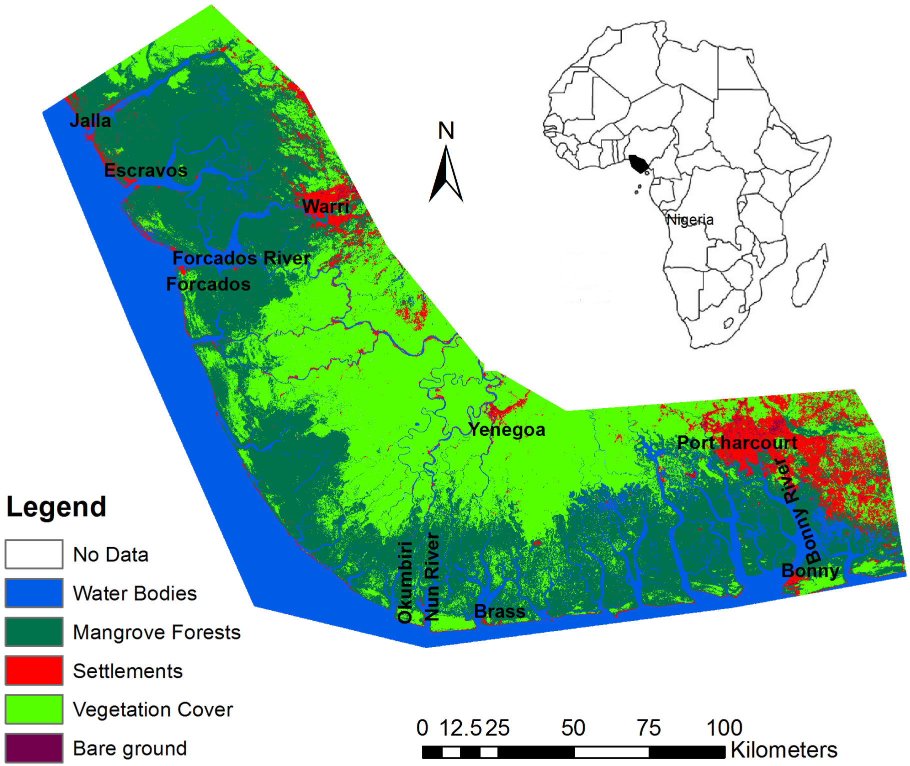

Figure 1. The Niger Delta land cover map.

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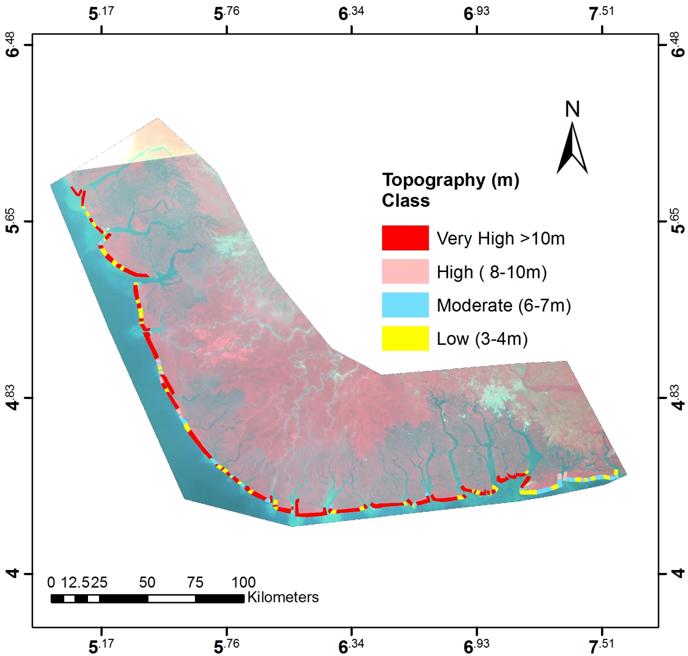

Figure 2. Niger Delta topography classification.

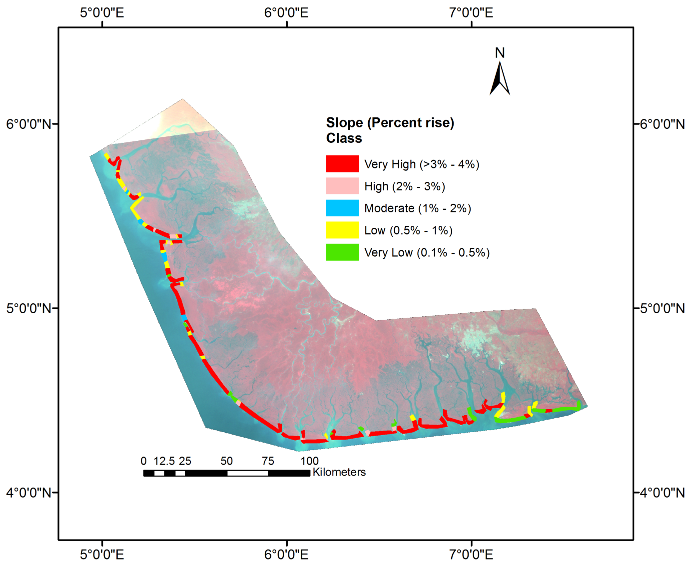

Figure 3. Niger delta coastal slope classification.

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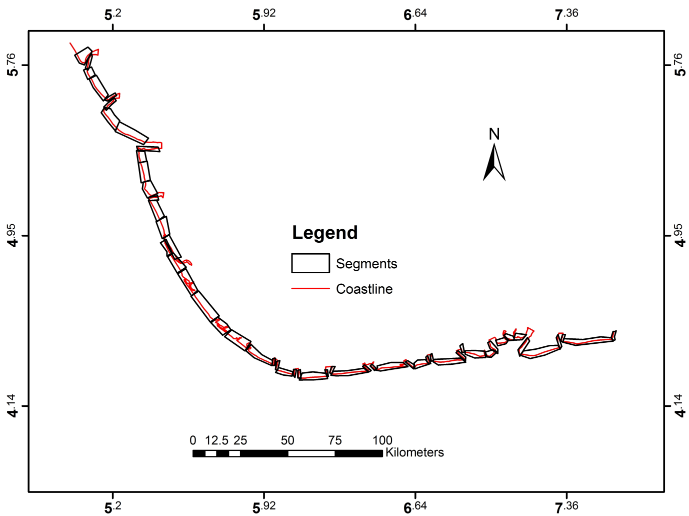

Figure 4. The 54 Niger Delta's coastal segments assessed for vulnerability to SLR.

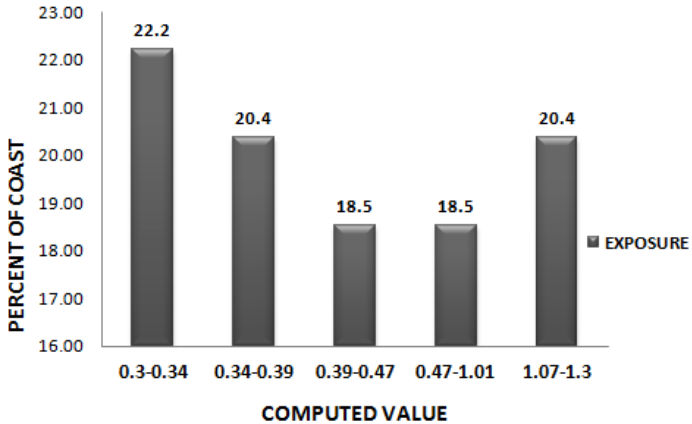

Figure 5. Exposure CVI values.

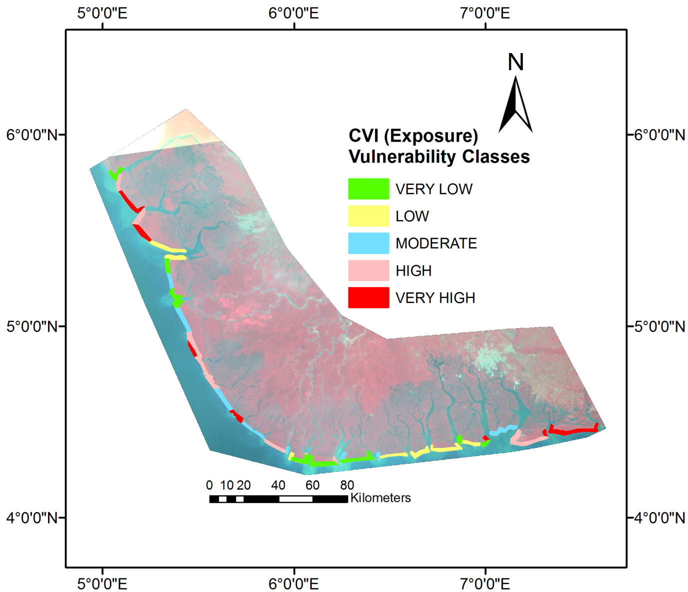

Figure 6. Niger Delta's coast vulnerability levels.

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