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The Niger Delta's 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 geographic information systems (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 a literature search. Further on, 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 42.6 % of the Niger Delta is highly vulnerable to sea level rise, such areas being characterised 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 the 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 to look at river floods and mitigation strategies, due to an increase in precipitation and consequently in the 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).

Increases in sea surface temperatures cause thermal expansion, which increases the water level of the sea surface (IPCC, 2013), and as a result, the shoreline moves farther 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 Intergovernmental 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 limitations due to uncertainties in the response of the ice sheets and their effect on the global sea level. Other projections of a 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

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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 the 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 for replenishing the area, land subsidence will occur, as has been recorded in some parts of Japan, Indonesia and Venezuela (IPCC, 2007c).

Vulnerability as a concept represents 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 vary within a system; therefore, indicators are used to determine and measure it. Such indicators can be the ecological, political, technological and socio-economic factors of a system. The 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 indicators of vulnerability to river floods, due to SLR, is to represent data in geographic information systems (GIS), which enables comparison and deduction of 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 would occur on the river discharging into the sea. Data used for the assessment were DEMs, 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 layers 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 on a regional and national scale. In their study, Gornitz et al. (1991) assessed the vulnerability of the US 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 the 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 the 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 eastern 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 is therefore not easy to use for coastal management, which would need variables related to social conditions and human impact on the environment in order to determine a good view of all aspects entailed by the vulnerability of coastal areas. Consequently, a 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 groundwater level above sea level, river discharge, and water depth at downstream. The result shows the vulnerability levels of defined coastal segments to different types of impacts, and indicates that human impact on the en-

Table 1. List of selected variables for vulnerability assessment.

Variable (class)	Data type	Data source
Topography (E)	SRTM DEM	http://srtm.csi.cgiar.org/
Coastal slope (E)	SRTM DEM	Validation map from NASRDA data archives; http://srtm.csi.cgiar.org/
Geomorphology (E)	Geomorphologic map of the Nigerian coast	http://www.niomr.gov.ng/
Relative sea level rise rate (E)	Relative sea level rise rates for the Niger Delta Atlantic coast	http://www.niomr.gov.ng/
Annual shoreline erosion rate (E)	Measured annual erosion rate for the Nigerian coast	http://www.niomr.gov.ng/
Mean tide range (E)	Tidal data for the Nigerian coast	http://www.niomr.gov.ng/; http://wxtide32.com
Mean wave height E)	Wave height data for the Nigerian coast	http://www.niomr.gov.ng/
Population density (E)	Population distribution data per local government area	Nigerian National Population Commission http://population.gov.ng
Proximity to coast (E)	NigeriaSatX imagery and settlement map of the 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 of reduction in sediment supply from the Niger River	NDRMP – Environment and Hydrology report
Population growth rate (S)	Inter-census data	http://population.gov.ng
Groundwater consumption (S)	Data on % groundwater consumption	NDRMP – Environment and Hydrology report
Emergency services (R)	Information about presence and type of emergency services	National Emergency Management Agency (NEMA), http://nemanigeria.com
Communication penetration (R)	Data on settlement type, size, and location	NASRDA data archives
Availability of shelters (R)	Information on provision of shelters	NEMA, http://nemanigeria.com

E: exposure; S: susceptibility; R: resilience; P: physical; SO: social; HI: human influence

vironment has the highest effect for inundation. The method however does not consider social variables. McLaughlin et al. (2002) include socio-economic variables in calculating a CVI for erosion in Northern Ireland. Their CVI includes variables such as population, cultural heritage, roads, railways, land use 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. Indicator-based studies such as the ones just cited use variables whose ability to change and respond to various effects of SLR (e.g. flooding) can be related to the systems' susceptibility to the particular hazard under consideration. The results of such studies highlight the areas with characteristics that make them vulnerable to the effects of SLR, although the final proof of the vulnerability of an area will consist of several sources of information, among which are numerical models and data obtained via field work. The study presented herein uses the advantage of mapping CVI results in a GIS environment in order to analyse the Niger Delta's physical, social and human influence on the environment in case that a flooding event occurs on the Niger River. The coastal vulnerability index obtained as such is a composite one, and it is called the 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 that have relevance to coastal erosion, flooding/inundation and intrusion of sea salts (into underground water) are used (presented in Table 1) . The option to use 17 variables is based on the data availability for these indicators as documented and suggested in studies by Gornitz et al. (1991) for general coastal areas, and Ozyurt and Ergin (2009) for deltas. Similarly, Balica et al. (2014) and Ozyurt and Ergin (2009) documented social and human influence variables that are important for determining the vulnerability of coastal areas. 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

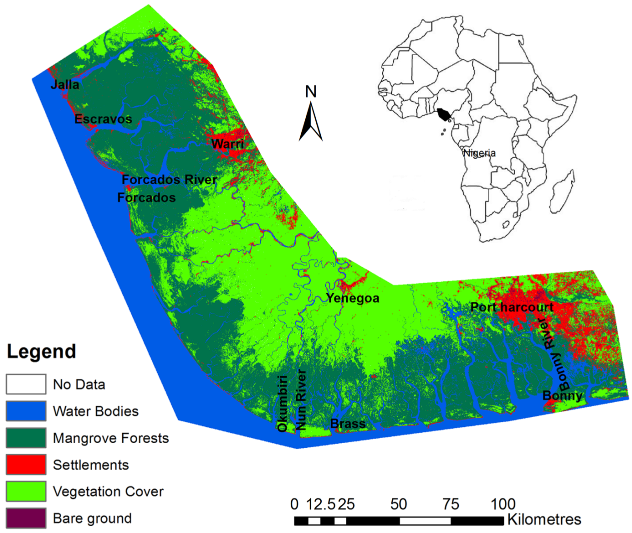

Figure 1. The Niger Delta land cover map.

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 to 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 high. For coastal areas, the relative sea level rise value is much more important than the eustatic sea level rise. In addition to the global average eustatic SLR of 3 mm yr^{-1}, the relative sea level rise in the Niger Delta includes subsidence levels of 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. The 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). Since deltas are replenished by upstream sediment supply, 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).

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 physically ranked variables (x_1, ..., x_n) as

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

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 into classes of exposure, susceptibility and resilience. Dinh et al. (2012) defined a coastal vulnerability index based on exposure, susceptibility and resilience factors as

$$\mathrm{CVI} = \frac{E \cdot S}{R}, \tag{2}$$

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

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 utilise the disaster as an opportunity for the future; thus, resilience variables enable a system to cope with and reduce the possible impact of the disaster on the exposed population.

While Eq. (1) enables the simplified combination of variable rankings to calculate the CVI for exposure, susceptibility and resilience, Eq. (2) enables the combination of the three indices to allow a ranking of vulnerability that acknowledges the importance of system resilience. Exposure and susceptibility variables increase the vulnerability of systems, while resilience variables enable systems to withstand and reduce the vulnerability to hazards. Therefore, the methodology used in the present research combines the two methods into a composite index which multiplies the exposure index by the susceptibility index and divides the product by the resilience index. 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 to as the 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;
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. $\mathrm{CV}_E\mathrm{I}$, $\mathrm{CV}_S\mathrm{I}$, and $\mathrm{CV}_R\mathrm{I}$ respectively);
5. use Eq. (2) to compute the $\mathrm{CV_{SLR}I}$ for each defined coastal segment, i.e.

$$\mathrm{CV_{SLR}I} = \frac{\mathrm{CV}_E\mathrm{I} \cdot \mathrm{CV}_S\mathrm{I}}{\mathrm{CV}_R\mathrm{I}}; \tag{3}$$

6. compare the $\mathrm{CV_{SLR}I}$ with results obtained for CVI based on physical variables only; and
7. indicate (through the $\mathrm{CV_{SLR}I}$) the coastal segments that are most in need of intervention in response to socio-economic conditions.

The developed methodology is herein exemplified in the case of the Niger Delta; however, its applicability is valid for any coastal area.

Rankings and ranges of variables are not the same across different systems, depending on the measured values. Three to five classes of ranking are found in the literature. Kumar and Kunte (2012) use three classes (i.e. low, medium, high), Yin et al. (2012) use four (low, medium, high, very high), while Dinh et al. (2012), Pendelton et al. (2010), Ozyurt and Ergin (2009), Thieler and Hammer-Kloss (1999) and Gornitz (1991) rank the measured ranges into five classes from very low to very high. The later approach is used in the present study of the Niger Delta, considering that such a refined classification will reduce considerably the uncertainty in computation of vulnerability. Tables 2, 3 and 4 show the ranges of values of exposure, susceptibility and resilience variables respectively, as considered in the present research, as well as their ranking from 1 (very low) to 5 (very high).

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

$$\mathrm{NV} = \frac{\mathrm{value} - \mathrm{min}}{\mathrm{max} - \mathrm{min}}, \tag{4}$$

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 selected indicators used for determining the $\mathrm{CV_{SLR}I}$ are detailed further.

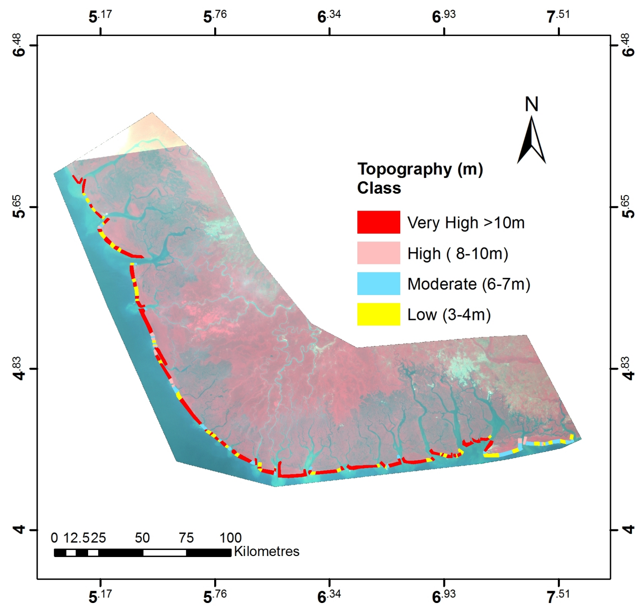

Figure 2. Niger Delta topography classification.

3.1 Selected indicators for exposure

The exposure indicators are selected based on their influence on coastal flooding, inundation, sea water intrusion to groundwater 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 above sea level, 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 a "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 (Dinh et al., 2012). The delineation and classification of the

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

			Ranking of values				
	Variables	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 (people per km^2)	SO	< 100	100–300	300–500	500–800	> 800
9	Proximity to coast	HI	> 800 m	600–800 m	400–600 m	200–400 m	100–200m

P: physical; SO: social; HI: human influence.

coastline slope ranges from 0 to 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 characterised by deltaic, sandy beach, and estuarine landforms. These characteristics (see Table 2) give it a "high" to "very high" ranking and make it very susceptible to erosion and wave action.

3.1.4 Relative sea level rise

Relative sea level/annum at 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 (1993–2010) 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).

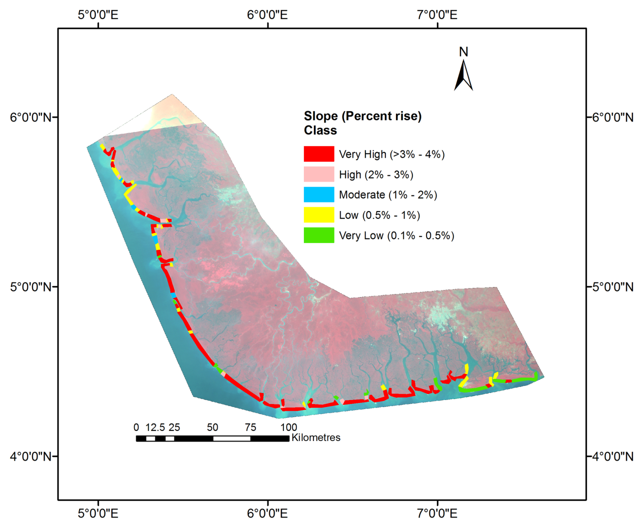

Figure 3. Niger Delta coastal slope classification.

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 20–25 mm yr^{-1} (Escravos), 16–20 mm yr^{-1} (Forcados), 15–20 mm yr^{-1} (Brass), and 10–14 mm yr^{-1} (Bonny). 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 a higher vulnerability than those with lower ranges. Mean tidal range is in general determined based on long-term tidal data. In case such data are 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 a "moderate" to "high" ranking (see Table 2); therefore, the Niger Delta is susceptible to storm surge and sea level rise.

3.1.7 Mean wave height

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

$$E = \frac{1}{16}\rho g H^2, \tag{5}$$

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 a high population density have a higher vulnerability than those with a lower population density (McLaughlin et al., 2002). The presence of human settlement increases the values 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, show that many settlements in the eastern end (from Bonny) have more than 500 people per km^2; hence, there is a "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 and wave action. The present study considered distances from the 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 of 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 groundwater 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) were used to rank the Niger Delta coastal aquifers, and the results show that the coastal aquifers are unconfined. Table 3 shows that unconfined aquifers have a "very high" vulnerability; therefore, the Niger Delta is vulnerable to salt water intrusion from SLR.

3.2.2 Aquifer hydraulic conductivity

The 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 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 day^{-1} (NDRMP, 2004). Coastal segments with hydraulic conductivities higher than 41 m day^{-1} have a "high" to "very high" vulnerability ranking (Table 3) and are vulnerable to salt intrusion from SLR.

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 day^{-1}	12–28 m day^{-1}	28–41 m day^{-1}	41–81 m day^{-1}	> 81 m day^{-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 %

P: physical; SO: social; HI: human influence.

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	*R*, SO	Absent No settlements on segment	Only present at the state level (remote area)	Only present at 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	*R*, 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	*R*, 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

P: physical; SO: social; HI: human influence

3.2.3 Reduction in sediment

Building of dams and other control infrastructure in the upstream of coasts impedes the flow of sediments and reduces the natural nourishment of delta areas (IPCC, 2007b). Areas where the percentage of sediment reaching the coasts is sustained over a 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, 2009). A high population growth rate will increase the number of people likely to be affected by the effects of SLR; therefore, areas with lower growth rates will have less vulnerability compared with those with higher growth rates. Inter-census data of the Niger Delta (1991–2006) show a growth rate of 2.9–3.1 %, which gives a "high" to "very high" vulnerability (Table 3).

3.2.5 Groundwater consumption

Inland intrusion of sea salts is likely to pollute underground aquifers and cause a shortage of drinking water in coastal areas. Areas that depend on groundwater as the main source of drinking water are more vulnerable than those with a low dependence on groundwater. Data on groundwater consumption in the Niger Delta, as compiled by NDRMP (2004), show the percentage of households/settlements 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 to 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 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, the 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 whom information reaches as well as the quality of the information provided. In Nigeria, NEMA through 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, 2010a). 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, later on, helps restore the affected community (NEMA, 2010b). 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 event 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 $CV_{SLR}I$ for the 450 km of the Niger Delta coast, 54 coastal segments are considered (Fig. 4). The segment division is based primarily on three main elements: elevation (Fig. 2); change in slope (Fig. 3); and the presence of large estuaries. Elevation and slope are important factors

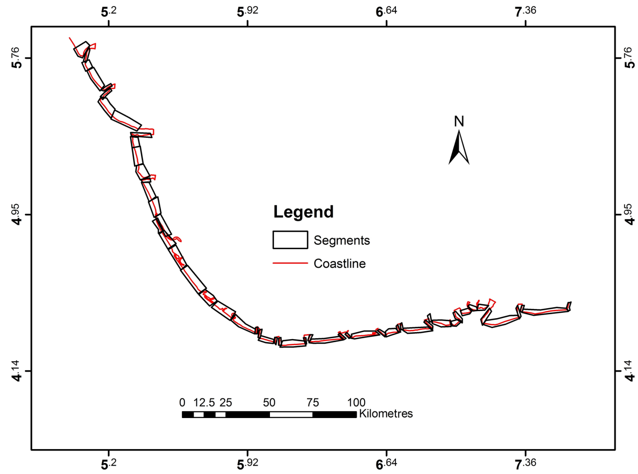

Figure 4. The 54 Niger Delta coastal segments assessed for vulnerability to SLR.

for flooding, since elevation determines the lowest level of water that could flood an area, and slope affects the flooding extent over an area. Therefore, each of the 54 segments shown in Fig. 4 defines an area with the slope and/or topography characteristics that make it different from the neighbouring segments. Sizes of the segments differ from one another in length; however, on average, the segment width is 4 km inland.

For each coastal segment, the exposure, susceptibility and resilience indicators are calculated and ranked. The range of results for the Niger Delta coastal segments are normalised using Eq. (4) and classified into five vulnerability classes (very low, low, moderate, high and very high) based on percentile ranges. Accordingly, the calculated results give the following ranges of vulnerability: 0.0–0.02 ("very low"), 0.02–0.03 ("low"), 0.03–0.07 ("medium"), 0.07–0.11 ("high"), and 0.11–1.0 ("very high"). As an example of the indicator ranking for the Niger Delta coast, segments 1–4, 52 and 54 are presented in Table 5. The most vulnerable segment (number 52) has a low slope (< 1 %), low topography (3–5 m), estuaries, very high hydraulic conductivity (> 81 m day^{-1}), very high population density (> 800 people per km^2), and settlements within 100–200 m of the coast. These attributes have thus made it highly vulnerable to SLR. On the other hand, the least vulnerable segment, number 1, has a high slope (> 4 %), a topography higher than 10 m, is uninhabited with no coastal infrastructure, and has a very low hydraulic conductivity (0–12 m day^{-1}). These attributes give it a very low vulnerability to SLR. (Segment count is from left to right.)

Figure 5 shows a plot of the calculated $CV_{SLR}I$ for the Niger Delta coastal segments. Analysing the results, it is seen that 42.2 % of the coastline has "very low" to "low" vulnerability, 22.2 % has "moderate" vulnerability, while 42.6 %

Table 5. Ranking per indicator and CVI results for six segments.

Segment no.	1	2	3	4	52	54
Variable (factor)			Ranking			
Topography (e)	1	1	2	1	4	2
Coastal slope (e)	1	1	4	4	4	5
Geomorphology (e)	5	4	5	5	4	4
Relative sea level rise rate (e)	5	5	5	5	5	5
Annual shoreline erosion rate (s)	5	5	5	5	4	4
Mean tide range (e)	4	4	4	4	3	3
Mean wave height (e)	5	5	5	5	3	3
Population density(e)	1	4	4	4	5	5
Hydraulic conductivity (s)	1	1	4	4	5	2
Proximity to coast (e)	1	4	1	4	5	5
Reduction in sediment supply (s)	5	5	5	5	5	5
Type of aquifer (s)	5	5	5	5	5	5
Population growth (s)	5	5	5	5	5	5
Groundwater consumption (s)	2	2	2	2	3	3
Emergency services (r)	1	1	3	3	1	5
Communication penetration (r)	1	1	4	4	1	5
Shelters (r)	1	1	1	1	1	1
$\mathrm{CVI}_{\mathrm{exposure}}$	5.56	19.88	31.43	44.44	60.00	47.14
$\mathrm{CVI}_{\mathrm{susceptibility}}$	3.16	3.16	6.32	6.32	8.66	3.87
$\mathrm{CVI}_{\mathrm{resilience}}$	0.33	0.33	1.15	1.15	0.33	1.66
$\mathrm{CVI}_{\mathrm{slr}} = \frac{\mathrm{CV}_E I \cdot \mathrm{CV}_S I}{\mathrm{CV}_R I}$	52.7	188.56	172.13	243.43	1549.2	154.9
Normalised result	0.02	0.11	0.10	0.15	1.0	0.09

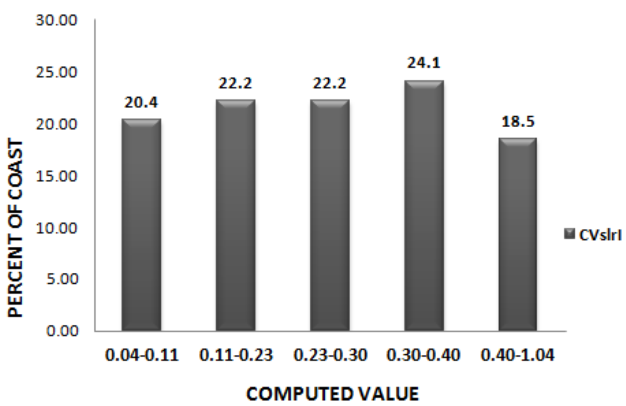

Figure 5. SLR CVI values.

has "high" to "very high" vulnerability, which is shown in Fig. 6.

In Fig. 6, the eastern end of the Niger Delta from Bonny to the southern end of Opobo (made up of six coastal segments: 49–54) is the longest stretch, with very high vulnerability to SLR. As shown in the case of segment 52, such areas with "high" to "very high" vulnerability are characterised by "very low" to "low" slopes, "very low" to "low" topography, "high" to "very high" mean wave heights, unconfined aquifers, the presence of a coastal infrastructure, a "high" population density, etc. These variables represent physical coastal properties, human influence, and social properties. The presence of human influence variables, such as coastal infrastructure and high population density, increase the probability of damage to lives and property when a disaster occurs. The combination of these properties has made the coastal segments highly vulnerable to SLR. The coastal segments classified as highly vulnerable to SLR will require mitigation measures to be applied against SLR.

The advantages of using a method such as the $\mathrm{CV_{SLR}I}$ include the facts that it takes into account existing social structures (in terms of favourable places to live/invest in infrastructure) and shows the level of vulnerability of choice areas. For example, the rankings of segments 1 and 2 for physical variables 1–7 (Table 2) are similar; however, their vulnerabilities are very different (Table 5), since, in the $\mathrm{CV_{SLR}I}$ method, human influence variables differentiate between the vulnerabilities of the two segments. While segment 1 has a "very low" vulnerability, segment 2 has a "high" vulnerability due to its high population density and the presence of many settlements along the coast. If the CVI calculation was based on physical factors only, both segments will have a similar vulnerability, and segment 2 will be given a "very low" vulnerability ranking; consequently, it will not be included in any adaptation plan. Thus, $\mathrm{CV_{SLR}I}$ results differentiate between the levels of intervention needed in coastal segments that might have the same physical properties but different social conditions. Another advantage of the $\mathrm{CV_{SLR}I}$

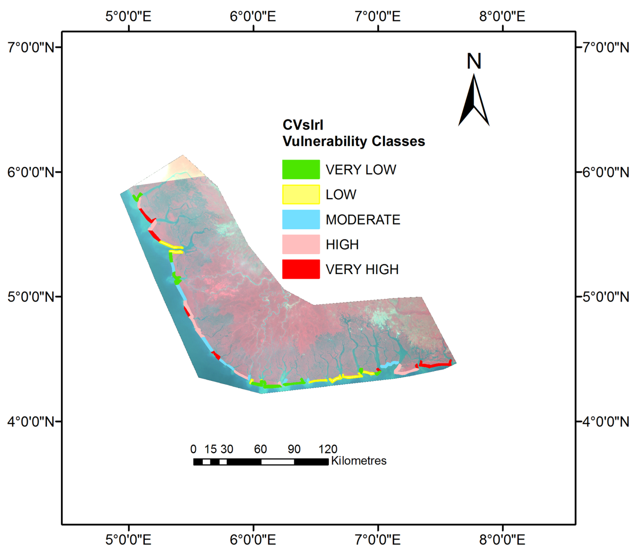

Figure 6. Niger Delta coast vulnerability levels.

is that it includes, in the vulnerability assessment, the human modifications of the coastal environment. Human influences (e.g. construction of sea walls, groins, ports) add to the overall cost of impacts of coastal hazards; therefore, there is the need to capture them in a vulnerability assessment. Moreover, $CV_{SLR}I$ ranking of vulnerability acknowledges the importance of system resilience in reducing the potential effects of SLR. The $CV_{SLR}I$, however, requires a wide range of data collection for the physical, social, and human influence factors, which might not be readily available. Different variables might be available in countries within the same region, making comparison difficult.

5 Conclusion

Highly vulnerable coastlines expose the inland areas to effects of SLR, serving as a gateway for inundation, storm surge and coastal erosion. The results of the $CV_{SLR}I$ for the Niger Delta show 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 shows that in terms of type of aquifer, aquifer hydraulic conductivity, population growth, sediment supply, and 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 an input for taking mitigation measures and helping decision makers to assess the effects of their measures on the function of the river system under consideration (Jonoski and Popescu, 2012; Popescu et al., 2010, 2014). The results of this study can provide a complementary source of data for the decision makers in planning mitigation/adaptation strategies for the Niger Delta. For example, the map (Fig. 6) can be used alongside other data to identify those areas that are most likely to be affected by flooding from the Niger River before a flood occurs. With the Niger River flooding frequently in recent times, mitigation/adaptation strategies can be planned for vulnerable areas, and not for the entire geographical region all at once. Also, the evaluation of resilience for the coastal segments which shows the ability of the system (people) to cope and adapt to the disaster can aid in mitigation/adaptation planning. Under resilience, we evaluated three variables, emergency services, communication penetration, and availability of shelters, which are services directly provided by the decision maker. The evaluation results can be useful in channelling more services to areas most in need.

Global studies undertaken by Ericson et al. (2006) and Nicolls and Mimura (1998) rank the entire Niger Delta as having moderate vulnerability. Such a ranking has been used in the literature as the "condition" for the Niger Delta, even though it was only based on the population likely to be displaced. The evaluation presented herein shows that parts of the Niger Delta are highly vulnerable to SLR. The results can be used to identify focus areas that need modelling of flooding to aid mitigation and adaptation planning. Hence, a combination of this study's results with physical models of flooding in the Niger Delta will provide a much better picture of the effects of sea level rise for the decision makers.

The segment division used in the study has constrained the scale of CVI calculations and reduced the possibility of generalising variable values along the Niger Delta coastline. For example, in the case of the "population density" variable, since the segments divide the coastline into smaller areas, we were able to use data provided per local government area to classify vulnerability instead of data per state (which is a much larger scale). The present study is however limited to onshore areas, and does not include the vulnerability of offshore areas or mitigation/adaption to SLR options. The mapping of vulnerability as presented in the study is within the limited bounds of the data accuracy and the scale of the study. Even though the local data used are acquired from official sources (see Table 1), there might still be uncertainties in the data collection and methods of processing that can not be accounted for because, officially, the data are accepted as reliable by the authorities in charge of managing the delta.

The influence of scale is such that some of the variables used in the study presented herein might not be applicable on a larger scale, as this would be a study of the vulnerability of the entire West African coast, where several rivers have to be taken into account in measuring the variable "reduction in sediment supply" or the variable "population growth rate", which are difficult to be included, because several countries in the region have different data and measurement techniques for population growth.

Such a study however would complement the overview of decision makers of the vulnerability 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 Nigerian coastline.

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