



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  $1.7 \text{ mm yr}^{-1}$ . In recent years satellite altimetry measurements (between 1993 and 2003) have shown an increase in this rate to over  $3 \text{ mm yr}^{-1}$  (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

5215

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 indicators 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

5216

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 Udipi 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

5217

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 ( $CV_{SLR}$ ). In order to determine and analyse the  $CV_{SLR}$  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

5218





### 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<sup>-1</sup>

5223

(Rosmorduc, 2012). In addition the Niger delta is subsiding at a rate of 25–125 mm yr<sup>-1</sup>, 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<sup>-1</sup>, Forcados 16–20 m yr<sup>-1</sup>, Brass 15–20 m yr<sup>-1</sup>, and Bonny 10–14 m yr<sup>-1</sup>. 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.

5224



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<sup>-1</sup> (NDRMP, 2004). Coastal segments with hydraulic conductivities higher than 41 m d<sup>-1</sup> 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).

5227

### 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

5228

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.

5229

Figure 5 shows a plot of the calculated  $CV_{SLR}$  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  $CV_{SLR}$  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

5230



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5233

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5234

**Table 1.** List of selected variables for vulnerability assessment.

Variable (class)	Data type	Data source
Topography (E)	SRTM DEM	<a href="http://srtm.csi.cgiar.org/">srtm.csi.cgiar.org/</a>
Coastal slope (E)	SRTM DEM	Validation map from NASRDA data archives; <a href="http://srtm.csi.cgiar.org/">srtm.csi.cgiar.org/</a>
Geomorphology (E)	Geomorphologic map of Nigerian coast	<a href="http://www.niomr.org">www.niomr.org</a>
Relative sea-level rise rate (E)	Relative sea level rise rates for Niger Delta Atlantic coast	<a href="http://www.niomr.org">www.niomr.org</a>
Annual shoreline erosion rate (E)	Measured annual erosion rate for the Nigerian coast	<a href="http://www.niomr.org">www.niomr.org</a>
Mean tide range (E)	Tidal data for Nigerian coast	<a href="http://www.niomr.org">www.niomr.org</a> ; <a href="http://www.wXtide32.com">www.wXtide32.com</a>
Mean wave height (E)	Wave height data for the Nigerian coast	<a href="http://www.niomr.org">www.niomr.org</a>
Population density (E)	Population distribution data per local Government area	Nigerian National Population commission <a href="http://www.population.gov.ng">www.population.gov.ng</a>
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	<a href="http://www.population.gov.ng">www.population.gov.ng</a>
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) <a href="http://www.nemanigeria.com">www.nemanigeria.com</a>
Communication penetration (R)	Data on settlement type, size, and location	NASRDA data archives.
Availability of shelters (R)	Info on provision of shelters	NEMA, <a href="http://www.nemanigeria.com">www.nemanigeria.com</a>

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





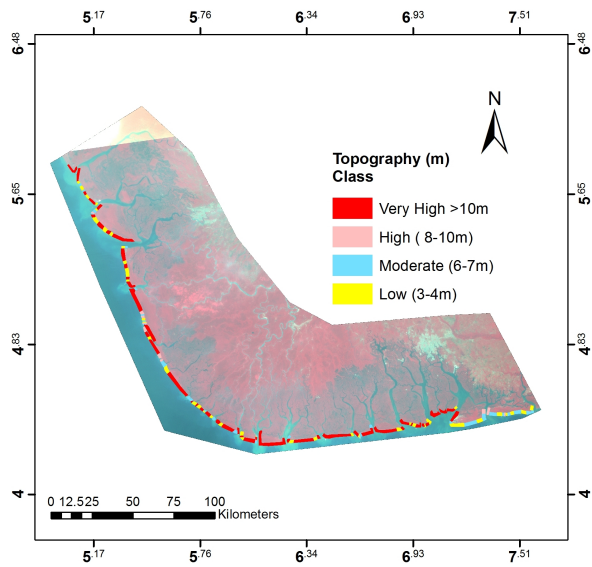


Figure 2. Niger Delta topography classification.

5241

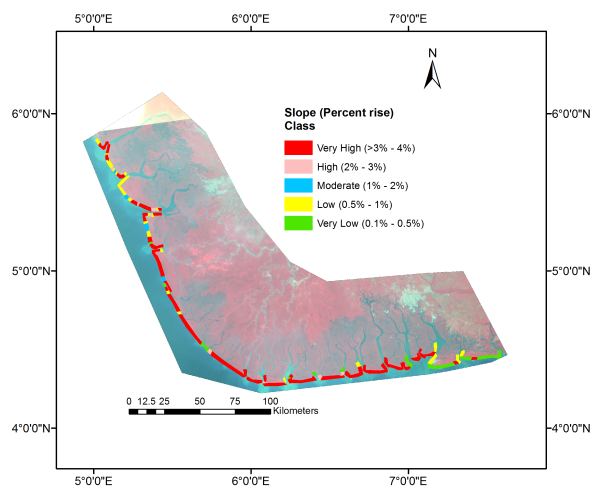


Figure 3. Niger delta coastal slope classification.

5242

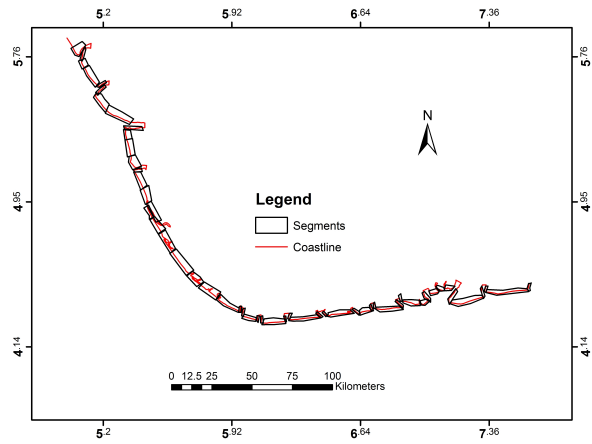


Figure 4. The 54 Niger Delta's coastal segments assessed for vulnerability to SLR.

5243

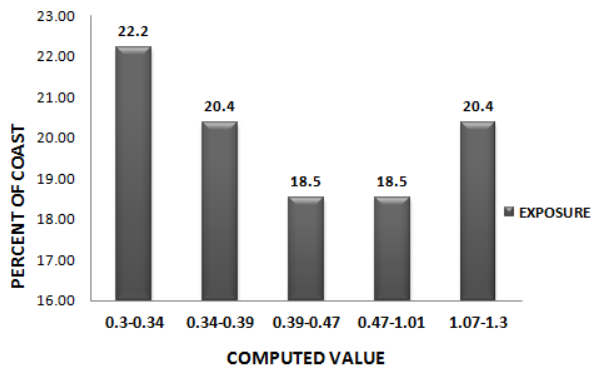


Figure 5. Exposure CVI values.

5244

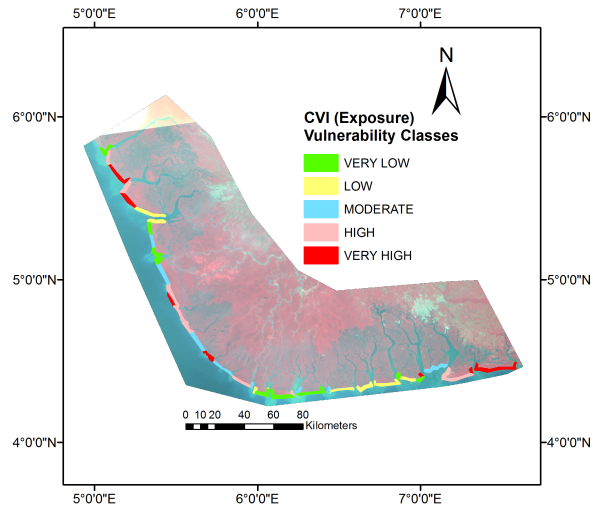


Figure 6. Niger Delta's coast vulnerability levels.