Satellite-Based Mitigation and Adaptation Scenarios for Sea Level Rise in the Lower Niger Delta

Zahrah Naankwat Musa

**SATELLITE-BASED MITIGATION AND
ADAPTATION SCENARIOS FOR SEA LEVEL
RISE IN THE LOWER NIGER DELTA**

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SATELLITE-BASED MITIGATION AND ADAPTATION SCENARIOS FOR SEA LEVEL RISE IN THE LOWER NIGER DELTA

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Dedication

Dedicated to the loving memory of my elder brother and greatest cheerleader, Kwapbial Karel Sallah. You are not here to cheer me bro, but I made it - just like you said I would.

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Summary

Accelerated sea level rise (SLR) is the most important climate change impact for coastal areas. The physical properties of deltas and anthropogenic activities make them vulnerable to the effects of the changing climate; however when evaluation of vulnerabilities is needed many coastal deltas lack necessary data for performing such a task. Leaving these coastal areas without adequate plans to combat sea level rise will cost vulnerable areas huge amounts of losses in lives and properties; e.g. as at 1995, it was estimated that in Nigeria alone, a no-response scenario will cost over \$18billion in losses including an estimated 17,000km² of wetland (Brown, Kebede, & Nicolls, 2011).

Data availability is one of the most important factors for analysis, assessment and modelling of physical and other phenomena related to river and coastal systems. Consequently, to reduce the effects of SLR through adaptation and mitigation, the IPCC recommended that coastal areas collect data on physical, social and economic parameters e.g. topographical, land-use, population, tidal wave and range (Dronkers, et al., 1990). Many developing countries however lack measuring equipment and long-term records; Africa generally lacks long-term observational data to aid hydrological research (Niang, et al., 2014). Long-term shoreline dynamics of the Nigerian coastline for instance cannot be predicted since the available data is insufficient to even explain fluctuations during the last hundred years (Orupabo, 2008).

The Niger delta has the highest sensitivity to climate change in Nigeria (it has a very gentle slope and low elevation) and its adaptive capacity is the second lowest in terms of socio- economic development of the country (FME, 2010). The Niger delta is also one of the coastal areas with little data for coastal planning and management, and consequently has poor availability of data for hydrologic and hydraulic modelling. Quantitative studies on the lower Niger delta have thus been limited by data availability and inaccessibility of parts of the delta (due to insecurity). Consequently, few quantitative studies using in situ data exist on the Niger delta; a quantitative study of the Niger delta by Awosika, et al., (1992) made use of aerial video data to estimate the cost of SLR and erosion losses for the Niger delta. However, subsequent studies by Ericson et al (2006), and Musa, et al., (2016) indicate that the area calculation by the study overestimated the extent of areas to be affected; thus, the value of losses might have been overestimated.

Use of satellite data helps bridge the data gap by providing ancillary data (imagery, elevation, altimetry etc.) that can be used to quantify the effects of SLR on the Niger delta. This thesis uses satellite data and other auxiliary information as the main sources of data for hydrodynamic modelling and GIS

analysis. This is a different approach as satellite data in water management and hydrology is normally used as a last resort and not the first point of choice since such data might not have the accuracy and precision of directly measured data. Studies have however shown that innovative methodologies by scientists have enabled better exploitation of satellite data to overcome the limitations and produce results with high correlation and manageable errors within present uncertainties (Musa, Popescu, & Mynett, A review of applications of satellite SAR, optical, altimetry and DEM data for surface water modelling, mapping and parameter estimation, 2015). This study aimed to assess the impact of SLR on the Niger delta land area, coastline, and surface water in an integrated way that will lead to practical recommendations for adaptation.

Using projected global eustatic SLR values of 19mm by 2030 and 35mm by 2050 in addition to subsidence, this thesis estimated that relative SLR (RSLR) for the Niger delta will range from 0.14m–0.44m by 2030, and 0.29m–0.96m by 2050. Using this RSLR values, the results show that a rise in sea levels of 0.14m already inundates areas in the Niger delta, and the flood extent increases with increase in SLR. Consequently, some 4.6–5.2% (viz. 1119.3–1254km²) of the Niger delta land area can be lost to inundation by 2030, and 4.9–6.8% (viz. 1175.9–1633km²) by 2050. Furthermore, the results indicate that without subsidence the inundation effect of SLR on the Niger delta will be minimal (since the eustatic values are just 19mm and 35mm by 2030 and 2050 respectively). Subsidence has therefore made the Niger delta very vulnerable to inundation by making the SLR values very high.

Flooding in the lower Niger River will be affected by rise in sea levels especially as the area continues to subside ([chapter 4](#)). The effects include earlier occurrence of downstream flooding, increase in water depth and flooding of areas further upstream (than would occur without SLR). This increase in flooding will be via expansion in lateral flooding extent in the *downstream* areas, but flooded areas will increase *upstream* because higher sea levels downstream will impede downward flow of flood waters which can result in a backwater effect and subsequent flooding of areas upstream. For the years without flooding from upstream, SLR will cause coastal areas downstream of the Niger River to flood earlier than usual. More so areas upstream of the Nun River, which remain dry in normal years, will get flooded when sea levels rise.

SLR will increase the occurrence of coastal flooding (this is indicated by the flood generated by even the lowest level of rise in sea levels) because water levels and water depths will be higher (as shown for example in the Bonny River), thus increasing land area flooding extent. The flow velocity will also increase with SLR, and coastal floodwaters will thus be transported faster along the river to places upstream. Consequently, flooding of land areas at high tide will increase due to higher water levels.

Furthermore, differences in flow velocity around narrow bends will also be higher with SLR than without, making river crossings more dangerous.

A new coastal vulnerability index called coastal vulnerability index due to SLR ($CV_{SLR}I$) was developed in this thesis. The $CV_{SLR}I$ evaluates coastline vulnerability due to SLR using 17 physical, social and human influence indicators of exposure, susceptibility and resilience ([Chapter 5](#)). The results showed that the variables that make a coastline highly vulnerable to SLR include (i) physical coastal properties, (ii) human influence, (iii) social properties. The reason being that human presence influences variables like coastal infrastructure and high population density, thus increasing the probability of damage to lives and property when a disaster occurs. More so, human interventions on coastal environments can affect sediment supply and accelerate erosion, and should therefore be captured in vulnerability assessments. Besides, the location of many settlements in remote areas, far away from the local government headquarters, reduces resilience to effects of SLR. The combination of these properties make coastal segments highly vulnerable to SLR.

In conclusion, this thesis shows that parts of the Niger delta are highly vulnerable to effects of SLR due to high RSLR, and therefore need adequate mitigation/adaptation measures to protect them. Thus possible coastal mitigation/adaptation interventions for the Niger delta were modelled and studied. This thesis thus recommends that sustainable local resilience practices already being used in parts of the Niger delta should be included in adaptation planning. These include: planting of Bamboo trees for erosion control; using sandbags as bridges and dykes for flood control; using flood receptor pits as temporary flood water storage; and developing community legislation against sand mining and indiscriminate tree felling. In terms of major mitigation/adaptation interventions, measures that can be used for the lower Niger delta include: construction of dykes, by-pass channels, flood-pits (reservoirs), storm surge barriers, coastline shortening and legislation to ensure compliance by all. Furthermore, to effectively adjust to living with SLR in the Niger delta the following strategies should be adopted: building new structures raised on stilts; and changing farm practices to become more resilient.

Samenvatting

Een versnelde toename van zeespiegelstijging is het meest belangrijke effect van klimaatverandering in kustgebieden. De laaggelegen ligging van delta's en de invloed van menselijke activiteit maken deze gebieden kwetsbaar voor de gevolgen van klimaatverandering. Om deze kwetsbaarheid te kunnen kwantificeren zijn meetgegevens nodig, die voor veel deltagebieden ontbreken. Maar als er geen adequate plannen worden gemaakt met maatregelen tegen zeespiegelstijging kan dit verstrekken gevolgen hebben voor mensenlevens en economische bedrijvigheid. Zo wordt alleen al voor Nigeria geschat dat de schade gemakkelijk kan oplopen tot 18 miljard USD, inclusief een verlies aan kustgebied van ca. 17,000 km² (Brown et al., 2011).

De beschikbaarheid van (meet)gegevens is een van de belangrijkste factoren om kustsystemen te kunnen analyseren en modelleren. Vandaar dat het IPCC heeft aanbevolen om met name in deze gebieden gegevens te verzamelen van fysische, sociale en economische processen, waaronder topografie, landgebruik, bevolkingsdichtheid, en getijwaterstanden (Dronkers et al., 1990). Probleem is evenwel dat er met name in ontwikkelingslanden een groot gebrek is aan meetapparatuur en historische gegevens. In grote delen van Afrika ontbreken afdoende waarnemingen om hydrologisch onderzoek te doen (Niang, et al., 2014). Zo kan het lange termijngedrag van de kustlijn van Nigeria niet worden voorspeld aangezien er onvoldoende gegevens beschikbaar zijn om de veranderingen van de laatste honderd jaar te kunnen verklaren (Orupabo, 2008).

De Niger delta is het meest gevoelig voor effecten van klimaatverandering in Nigeria (de delta ligt zeer laag en heeft een heel flauwe helling) en heeft een heel laag adaptief vermogen van socio-economische ontwikkeling in het land (FME, 2010). Er zijn betrekkelijk weinig betrouwbare gegevens om tot planvorming en beheer te komen, laat staan om hydrologische en hydraulische modellen te ontwikkelen. Studies naar de Lower Niger delta worden ook nog bemoeilijkt door de slechte toegankelijkheid van het gebied (vanwege de gevaarlijke situatie). Vandaar dat er weinig gedetailleerde studies bestaan. Awosika et al., (1992) maakte gebruik van luchtfotografie om een schatting te verkrijgen van de schade door zeespiegelstijging en erosie in de Niger delta. Vervolgstudies door Ericson et al., (2006) en Musa et al., (2016) geven aan dat deze schattingen aan de hoge kant waren en dat de schade wellicht overschat was. Door gebruik te maken van satellietwaarnemingen kan het gebrek aan in-situ meetgegevens worden opgevangen en kan toch een schatting worden gemaakt van de effecten van zeespiegelstijging in de Niger delta.

In dit proefschrift worden satellietwaarnemingen gebruikt als de belangrijkste informatiebron voor het ontwikkelen van GIS analyses en voor het hydrodynamisch modelleren van de delta. Dit verschilt van de conventionele aanpak van hydrodynamisch modelleren waarbij satellietwaarnemingen vaak als sluitstuk worden gebruikt en niet als voorkeursbenadering, gezien de beperkte nauwkeurigheid en precisie. Inmiddels zijn er echter innovatieve methoden ontwikkeld die een beter gebruik van satellietwaarnemingen mogelijk maken met een zeer beperkte foutenmarge binnen de huidige meetnauwkeurigheid (Musa et al., 2015). Op basis hiervan is in deze studie een schatting gemaakt van de effecten van zeespiegelstijging en zijn praktische aanbevelingen gegeven voor klimaatadaptatie.

Op basis van de geschatte eustatische waarden van zeespiegelstijging van 19mm in 2030 en 35 mm in 2050, en rekening houdend met voortgaande bodemdaling, komen de schattingen voor relatieve zeespiegelstijging in de Niger delta zoals berekend in dit proefschrift uit op 0.14m–0.44m in 2030, en 0.29m–0.96m in 2050. Berekeningen laten zien dat een stijging van 0.14m al tot overstromingen leidt in bepaalde gebieden van de Niger delta, die steeds groter worden naarmate de stijging toeneemt. Dit heeft als gevolg dat rond 2030 ca. 4.6–5.2% (d.w.z. 1119–1254 km²) van het land in de Niger delta verloren kan gaan door overstroming en rond 2050 zelfs 4.9–6.8% (d.w.z. 1176–1633 km²). De berekeningen laten tevens zien dat zonder bodemdaling het effect van eustatische zeespiegelstijging slechts zeer beperkt zal zijn. Bodemdaling is daarom een belangrijke factor bij het bepalen van de kans op overstromingen in de Niger delta. Andere resultaten van deze studie zijn:

Ook in de beneden rivier van de Niger delta wordt de kans op overstroming belangrijke mate bepaald door zeespiegelstijging in combinatie met bodemdaling. Meer stroomopwaarts wordt de kans op overstroming mede beïnvloed door de stuwkromme die zich naar bovenstrooms uitbreidt omdat de uitstroom in de delta zelf beperkt wordt door zeespiegelstijging. Zelfs als de bovenstroomse rivierafvoer beperkt is, dan nog zullen de laaggelegen gebieden in de Niger delta eerder overstromen dan gewoonlijk, als gevolg van zeespiegelstijging. Datzelfde geldt voor de bovenstroomse gebieden in de Nun rivier, die bij normale afvoeren droog blijven, zullen ook eerder overstromen. Ook voor de Bonny rivier geldt dat zelfs een geringe zeespiegelstijging tot een toename van het overstromingsrisico zal leiden, zoals aangetoond in voorbeeldberekeningen. Ook de stroomsnelheden zullen toenemen, waardoor de afvoer zich sneller langs de rivier zal verplaatsen en tot hogere waterstanden zal leiden. Bij hoge getijdewaterstanden zal dan ook meer land overstromen. Een ander gevolg van hogere stroomsnelheden zal zijn dat het gevaarlijker wordt om de rivier over te steken in de vele nauwe bochten die er voorkomen.

In dit proefschrift is een speciale index ontwikkeld die de kwetsbaarheid van kustgebieden bij zeespiegelstijging kan aangeven: de CVSLRI index. Deze wordt bepaald door 17 indicatoren voor fysische, sociale en menselijke invloeden die bepalend zijn voor de ontvankelijkheid voor en weerstand tegen overstromingen (Hoofdstuk 5). De resultaten geven aan dat de belangrijkste variabelen worden bepaald door (i) fysische eigenschappen van de kust, (ii) menselijke invloeden daarop, (iii) sociale kenmerken. Dit omdat menselijke ingrepen zoals het aanleggen van kustbescherming en bebouwing van de kuststrook, direct van invloed zijn op de kans van falen en het berokkenen van schade in geval van overstromingen. Daar komt bij dat menselijke ingrepen in de kuststrook van grote invloed kunnen zijn op het sediment transport (met name in deltagebieden) en daarmee op de stabiliteit van de kustdelta als geheel. Vandaar dat dit aspect meegenomen moet worden bij het vaststellen van de kwetsbaarheid. In geval van de Niger delta bestaan er veel kleine woongemeenschappen ver weg van lokale overheden, waardoor toezicht slechts beperkt mogelijk is. Ten gevolge hiervan zijn sommige gebieden nog extra kwetsbaar voor de gevolgen van zeespiegelstijging.

Samenvattend geldt dat in deze thesis is aangetoond dat bepaalde delen van de Niger delta bijzonder kwetsbaar zijn voor de gevolgen van zeespiegelstijging en dat adequate maatregelen voor mitigatie en adaptatie nodig zijn om deze te beschermen. Vandaar dat wordt aanbevolen om voort te bouwen op de aanwezige ervaring en bestaande praktijk bij het vaststellen van aanpassingsmaatregelen voor duurzaam kustbeheer in de Niger delta. Daartoe behoren ondermeer: het planten van bamboe struiken ten behoeve van erosiecontrole; het gebruik van zandzakken voor bruggetjes en dijkjes om overstromingen te controleren; het gebruik van kuilen voor het tijdelijk opslaan van overtollig water; het ontwikkelen van lokale voorschriften en verboden tegen het illegaal weghalen van zand en het kappen van bomen en andere vegetatie. Voor de beneden rivier van de Niger in het bijzonder gelden als belangrijkste interventie maatregelen: het aanleggen van dijken, nevengeulen, opvangreservoirs, het aanleggen van stormvloedkeringen, verkorten van de kustlijn, alsmede wet- en regelgeving die zorgen voor naleving door alle betrokkenen. Om effectieve aanpassing aan het ‘leven met zeespiegelstijging’ te garanderen zouden de volgende strategieën moeten worden toegepast: nieuwe constructies verhoogd aanleggen, bijv. op palen; landbouwmethoden zodanig aanpassen dat deze meer overstromingsbestendig worden.

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1

Introduction

Within the last few decades the atmospheric and sea surface temperatures have been rising and climates worldwide are changing (figure 1.1). Climate change has resulted from an accelerated increase in carbon dioxide and other greenhouse gas concentrations in the atmosphere (Williams & Ismail , 2015). 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 1.7mm/year. In recent years satellite altimetry measurements (between 1993 and 2003) have shown an increase in sea level rise rates to over 3mm/year (IPCC, 2007a). Over the years scientists have used climate models to project possible sea level rise (SLR) levels for the future. These projections are based on scenarios to predict possible conditions of climate change and the states of the coastal areas. 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 (e.g. Rahmstorf, 2007; Pfeffer, et al., 2008) were made after the IPCC (2007) report. As data became available, the IPCC revised its projections. Based on greenhouse gas emissions scenarios (known as Representative Concentration Pathways or RCPs), the IPCC projects that sea levels will rise by 0.28-0.98 m by the year 2100 (IPCC, 2013).

Climate change is a factor that will modify existing hazards and introduce new ones (Bogardi, Villagrán, Birkmann, & Renaud, 2005). Natural disasters have become more frequent in coastal areas and barrier islands and river deltas are experiencing accelerated erosion, flooding and marine transgression (Williams & Ismail , 2015). In the Mediterranean region for example, the effects of climate change observed are: decrease in the total amount of precipitation; increase in the number and intensity of extreme events such as floods and droughts; and a change in the seasonal distribution of precipitation (European Environment Agency (EEA), 2012). Along the west African coast, sea levels rise trends showed over 3mm/year from 1993 to 2010 (ESA, Space in Images: mean sea level trends, 2012).

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). Furthermore, SLR

will reduce the availability of fresh water for human consumption, and affect the fresh water habitat of fishes and other aquatic fauna and flora.

The effects of sea level rise (SLR), however, will not be uniform all over the world but will depend on the physical, socio-economical, and anthropogenic conditions of the coastal area. Consequently some areas will experience higher and more rapidly rising sea levels than others. 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 therefore higher in subsiding coasts like river deltas than the stable coastal areas.

Coastal delta landforms are formed by the combination of river flow, tides and waves; so that the dominant process determines the characteristic of the particular delta (Nicholls, Wong, Burkett, & Codi, 2007). Fluvial deltas depend on sediment supply from upstream rivers, while Marine dominated deltas are shaped by marine processes of tide and waves. Deltas are usually very rich in biodiversity and are known to expand with increased activity upstream like agriculture and land clearing which loosen the soil adding to amount of sediment transported downstream (Mcmanus, 2002).

Some deltas like the lower Niger delta are also rich in oil and gas (and other mineral resources) making them economically very important to their countries. Coastal deltas are susceptible to subsidence when there is reduction in sediment supply (Wesselink, et al., 2015), and water or hydrocarbon extraction from underground sources (Ericson, Vorosmarty, Dingman, Ward, & Meybeck, 2006). As hydrocarbon/water is extracted, the soil compacts to fill the void and land levels lower; as long as there is normal sediment supply and such extraction is regulated, this process might not be detrimental to the area. However where there is reduction in sediment supply to a delta, the land will subside thereby increasing residence time and reach of high tidal waters the land will subside thereby increasing residence time which can cause water logging and finally permanent inundation (Nicolls, Hoozemans, & Marchand, 1999).

Due to different levels of land subsidence therefore, deltas record different sea level rise values than the global average value; this is known as relative seal level rise. Relative sea level rise values are usually higher in subsiding deltas because it represents the change in sea levels relative to the land elevation and includes land vertical movement in addition to global sea level rise values.

Figure 1.1. Atmospheric (a) and Sea Surface (b) temperature rise. Retrieved on 11-10-2016, from http://data.giss.nasa.gov/gistemp/graphs_v3/, and <https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature>

In the US, the Gulf of Mexico records a relative sea level rise between 2 - 10mm/year, and the Atlantic coast records between 2- 4mm/year (Titus, et al., 2009). Compared to other coastal areas, river deltas have complex morphologies, because river waters and sediments are transported through the deltas into the sea. A delta can have many elements included, such as barrier islands, multiple estuaries, sand beaches, or mud coasts. It can be crisscrossed by rivers emanating from different sources and carrying different types of sediments; which differentiate the segments of the coast.

Problem statement

In preparation for consequences of SLR, the IPCC recommended that coastal areas collect data on physical, social and economic parameters e.g. topographical, land-use, population, tidal wave and range (Dronkers, et al., 1990). The physical properties of deltas and anthropogenic activities make them vulnerable to the effects of the changing climate; however when evaluation of vulnerabilities is important many coastal deltas lack necessary data (e.g. water level) for performing such a task. Data availability is one of the most important factors for analysis, assessment and modelling of physical and other phenomena related to river and coastal systems. Many developing countries however lack measuring equipment and long term records; Africa generally lacks long-term observational data to aid hydrological research

(Niang, et al., 2014). In well-developed coastal areas such as The Netherlands, measurements and records of hydrologic properties are kept, adequate provision is made for drainage of rain rainwater, river flows and groundwater, and coastal defences are built against storm surges and SLR (Wesselink, et al., 2015).

Leaving coastal areas without adequate plans to combat sea level rise will cost vulnerable areas huge amounts of losses in lives and properties; e.g. in Nigeria alone, a no-response scenario will cost over \$18billion in losses, including an estimated 17,000km² of wetland (Brown, Kebede, & Nicolls, 2011). It is therefore imperative to study the level of vulnerability of coastal areas to the effects of SLR like flooding, inundation, erosion, loss of wetlands and salinization of underground water sources even if data availability is scarce. Sea level data and information are strategic for planning and management of coastal areas, however many developing countries lack measuring equipment and long term records. Long-term shoreline dynamics of the Nigerian coastline for instance cannot be predicted as available data is insufficient to even explain fluctuations in the last hundred years (Orupabo, 2008). The lower Niger delta ([figure 1.2](#)) is thus one of the coastal areas with little data for coastal planning and management. Consequently, it has poor availability of data for hydrologic and hydraulic modelling.

The Niger delta has the highest sensitivity to climate change in Nigeria, and its adaptive capacity is the second lowest in terms of socio-economic development of the country (FME, 2010). It is one of the vulnerable coastal areas in the world due to its natural properties: a very low elevation and gentle slope. With an anticipated rise in sea levels of 0.5-1m for the Nigerian coast by 2100 (FME, 2010), large parts of the delta could be affected; with huge costs in both lives and property. Based on physical properties and human population to be displaced, studies by (Brooks, Nicolls, & Hall, 2006) and Ericson, et al., (2006), rank the Niger delta among the vulnerable coasts of the world. Many articles have been written and studies carried out on the possible effects of climate change and sea level rise on the coastal zone of Nigeria (Akinro, Opeyemi, & Ologunaba, 2008; Ogba & Utang, 2007; Awosika, French, Nicolls, & Ibe, 1992); many of these include response strategies and give possible mitigation methods to reduce any negative effects on the land and livelihood of the communities. However a look at the available literature shows that most studies are based on the general Nigerian coast with more emphasis on the Lagos coastal area. Few quantitative studies using insitu data exist on the Niger delta. A quantitative study of the Niger delta by Awosika, et al., (1992) made use of aerial video data to estimate the cost of SLR and erosion losses for the Niger delta. Subsequent studies by

Ericson et al (2006), and Musa, et al., (2016) indicate that the area calculation by the study overestimated the extent of areas to be affected thus the value of loss might have also been over estimated.

Quantitative studies on the lower Niger delta have been limited by data availability and inaccessibility of parts of the delta (due to insecurity). Use of satellite data helps bridge this gap by providing ancillary data (imagery, elevation, altimetry etc.) that can be used to quantify the effects of SLR on the Niger delta. Satellite remote sensing provides a source of hydrological data that is unhindered by geopolitical boundaries, has access to remote/unreachable areas, and provides frequent and reliable data (Jung, et al., 2010). Use of satellite data to estimate hydrological parameters continues to increase due to greater availability of satellite data, improvement in knowledge of and utilization of satellite data, as well as expansion of research topics. A very important catalyst to this growth in satellite data utilization is the ability to use it in a GIS environment. GIS enables comparison and deduction of relationships that exist amongst the complex data sources used for analysis. Thus relationships like the effects of land-use change on surrounding water bodies or water management are easily analysed and depicted. Consequently, satellite data is commonly used for: mapping of water bodies, testing of inundation models, soil moisture measurements, precipitation monitoring, estimation of evapo - transpiration, and mapping of flood extent.

Satellite data have been used for change assessment studies of the Niger delta (Twmasi & Merem, 2006; Ogoro, 2014), flood/erosion extent documentation and mapping (Ehiorobo & Izinyon, 2011; Eyers & Obowu, 2013). Flood inundation estimates for the Niger delta are based on GIS depictions of flooding extends from static overflowing of water on GIS layers; a method that generally over estimates the coverage area of flood waters and does not take loss through local drainage/runoff into account (e.g. Akinro, et al., 2008). This thesis uses satellite data and other ancillary information as the main sources of data for modelling and analysis. This is a different approach as satellite data in water management and hydrology is normally used as a last resort and not the first point of choice since such data might not have the accuracy and precision of directly measured data. However over time, innovative methodologies by scientists have enabled better exploitation of satellite data to overcome the limitations and produce results with high correlation and manageable errors; within present uncertainties (Musa, Popescu, & Mynett, A review of applications of satellite SAR, optical, altimetry and DEM data for surface water modelling, mapping and parameter estimation, 2015).

1.1 Study aims and objectives

The study has the general aim of assessing the impact of SLR on the Niger delta land area, coastline, and surface water in an integrated way that will lead to practical recommendations for adaptation.

The specific objectives will use satellite based data and spatial information to:

- Model the impact of SLR for Niger delta land areas, major rivers and coastlines.
- Create scenarios and run hydrodynamic models of effect of SLR on flooding from surface water.
- Measure and map sea level rise inundation extents based on topography and tidal variability.
- Identify and map the most vulnerable parts of the Niger delta coastline to SLR.
- Create adaptation scenarios for the Niger delta, and estimate the effect of each scenario implementation.

Fulfilling the objectives of the thesis should answer the following questions:

1. How can satellite data be applied in hydrological studies in delta areas?
2. With recent increase in flooding will sea level rise exacerbate the effects of river flooding? What is the effect on surface water?
3. What is the effect of SLR on coastal flooding and inundation?
4. How much of the land that can be lost to inundation?
5. How can the vulnerability of deltaic coastlines to sea level rise be evaluated?
6. What should be considered in planning for SLR adaptation? Are there existing sustainable options that can be used?
7. What are the possible effects of the mitigation/adaptation options on SLR impacts on the Niger delta?

1.2 Scope

The study covers the geomorphologic Niger delta area spanning from Jalla in Ondo on the west to Bonny on the east (Fig. 1.2). The vulnerability assessment is limited to the parts of the Niger

delta directly connected to the ocean and inland up to 45km; it does not include the entire political Niger delta as defined by the Nigerian government. The modelling aspect of the methodology only addresses issues concerning river flooding from the Niger River and excludes the following: flooding from other rivers within the area, rainfall/ runoff and other effects of the broad concept of climate change.

1.3 Thesis structure

The thesis is made of eight chapters structured to answer the research questions posed and fulfil the aims and objectives of the research.

Chapter 1: This introductory chapter presents the problem with the study area, and the existing gaps that created the need for the methodology used in the thesis (to solve the problem). The research questions, aims and objectives are also presented herein.

Chapter 2: The second chapter gives the background information on climate change induced sea level rise and its consequences for low-lying delta areas. The study area is described; its physical properties (slope, geomorphology, topography, aquifers etc.), hydrology, as well as the changes it is already undergoing that can be exacerbated by sea level rise. The available data used for the research are also described and their sources mentioned.

Chapter 3: In view of data scarcity, this chapter discusses how advanced data sources are used for surface water and coastal area studies; for modelling, mapping and parameter estimations. Use of high resolution insitu dredging data for river cross section estimation (for flood modelling) is also discussed.

Chapter 4: Using non-conventional data, the effects of sea level rise on river and coastal flooding are modelled, and the results presented in this chapter. The modelling objectives, data used, methodology, model setup, scenarios, and constraints are explained. The implications of sea level rise on flooding extent, water depth, and flood velocity are discussed.

Chapter 5: In this chapter the vulnerability of the Niger delta coastline to sea level rise is calculated based on seventeen physical, social and human influence variables; obtained from both conventional and advanced data sources. The variables are which divided into exposure, susceptibility and resilience variables, are used in a new methodology called the 'Coastal Vulnerability to sea level rise Index' (CV_{SLR}I) that combines the 'Coastal Vulnerability Index'

(CVI) with the 'Flood Vulnerability Index' (FVI). The advantages and disadvantages of the new index are discussed.

Figure 1.2. The lower Niger delta Nigeria, West Africa. SRTM DEM showing the topography of the area is

seen on the right.

Chapter 6: This chapter discusses the importance of considering the people's resilience when planning for sea level rise adaptation or mitigation. It considers the sustainability of local resilience practices (against flooding, erosion, etc.) already familiar to the people in a 'business as usual' scenario. A GIS based mapping of sea level rise inundation by 2030 and 2050 is also included.

Chapter 7: In this chapter, adaptation scenarios, possible options they entail, and the implications of each for delta areas are discussed and applied to the Niger delta. The effects on flooding /inundation extent, river water level/depth, and velocity are presented. A rough estimate of the cost of measures applied is also included.

Chapter 8: This chapter compiles the conclusions reached at each stage of the research. It discusses the research questions vis-à-vis the answers obtained within the thesis and makes recommendations where applicable. The limitations of the study and its constraints (based on assumptions made in applying the methodology), are also included.

Appendix: This is made up of two sections A, and B. Appendix A shows how SRTM compares with 40m contour data of Nigeria (using RMSE as accuracy measure). Appendix B shows results of river flood modelling for rivers Forcados and Nun.

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