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Approach on modeling complex deltas in data scarce areas: a case study of the lower Niger delta

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Abstract

Appendix A. Compared to coastal areas, river deltas which are located in coastal zone, 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. Generally, deltas are fertile and highly productive, attracting agricultural activities and trade and thus densely populated. 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 even the most basic necessary data (e.g water level) for performing such a task. Data availability is one of the most important factors for analysis, assessment and modeling of physical and other phenomena related to river and coastal systems. Although lower Niger delta is classified as one of the deltas of the world vulnerable to the effects of climate change, it has little availability of data for hydrologic and hydraulic modeling. Present paper will show how to model the possible effect of a rise in sea levels on the lower Niger delta, by dividing its coastline into 54 segments based on slope, elevation and presence of large estuaries. The segments are analyzed for vulnerability to flooding, erosion and inundation. The parts identified as the most vulnerable are modeled using Deltares' DFlow modelling methodology, using a flexible mesh for discretization of the modeled area. Satellite derived DEM is used to calculate an upstream rating curve for the Bonny River, and to provide topographic data. Sea level rise is represented by changes in the tidal level to reflect IPCC predictions of sea levels by 2050 and 2100. The results are analyzed for flooding and inundation, increase in land loss, water depth and flood extent as compared with no sea level rise scenarios. Also, dry and wet land losses are mapped and quantified within a GIS environment.

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1. Introduction

Flooding and inundation of coastal areas are some of the consequences of climate induced rise in sea levels. As the sea levels rise, low-lying coastal areas can be easily affected if no protective and adaptive measures are put in place. 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 [8]. Fluvial deltas depend on sediment supply from upstream rivers, while marine dominated deltas are shaped by marine processes of tide and waves. The Niger delta, crisscrossed by several rivers and creeks is river dominated (figure1).

Deltas are also susceptible to subsidence when there is reduction in sediment supply [9], and water or hydrocarbon extraction from underground sources [10]. In deltas where there is land subsidence in addition to SLR wetlands might be lost as the system will be unable to maintain its equilibrium [8]. 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 which can cause water logging and finally permanent inundation [1]. 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. 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 [11].

In well-developed coastal areas (e.g. 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 defenses are built against storm surges and SLR [9]. Measures to combat floods and limit inundation can be structural and non-structural. Examples of structural flood protection measures include dykes, embankments, levees, sea walls, and sand bags; while non-structural measures include wetlands, mangrove, beaches, and dunes. In low-lying deltas, planning for protection is essential for livelihood in order to avoid land loss through flooding and inundation (as well as their associated consequences like diseases and infection). 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 [12]. 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 saltation of underground water sources.

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. The Niger delta is one of such coastal areas with little data for coastal planning and management. The available contour map of Nigeria starts from 40m a.m.sl (which is the official topographic database) and thus excludes the entire Niger delta due to its low elevation. Due to this lack of data in many catchments, ancillary data like satellite imagery are used to study and plan for natural disasters (e.g. consequences of SLR) in developing countries. Although such data might not have the accuracy and precision of directly measured data, 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 [13]. This paper uses Satellite DEM and tidal water level data to undertake hydrodynamic modelling of flooding and inundation along the eastern end of the Niger delta

2. The study Area

The Niger delta (figure 1), is a low-lying delta with a large expanse of mangrove swamps stretching up to 50km inland in some places. Politically, it is made up of nine states in the southern part of Nigeria where the river Niger breaks into several tributaries. The climate is generally warm and humid with heavy and abundant rainfall average of 2000- 4000mm/year from the rain forest region to the coastal areas. The soil is mostly silty and easily saturated which reduces infiltration of rain water; this coupled with a very low gradient induces regular urban floods. The Niger delta also experiences flash flooding from the high rainfall intensities per hour which can be as high as 135mm/hr over a 15 minute period or 310mm/day, in places like Bonny, Calabar and Warri [14].

The Niger delta has abundant water sources including: creeks, lakes, estuaries and several streams. Apart from the River Niger which supplies most of the river discharge into the area, there are many other rivers that drain into the Atlantic ocean throughout the delta; some of these rivers are very large e.g. Qua Ibo, Imo and Cross river, others are smaller e.g. Bonny and Calabar. These rivers are independent of the Niger River, originating from upland areas with some as far as the Cameroun Mountains. River levels in the delta show low flow periods from December to April, a high flow period from April to October when there is peak rainfall from the north and locally, and a gradually declining flow period between October and December [14]. The Niger River bifurcates into the Nun and Forcados rivers as it flows through the Niger delta, with the Forcados Rivers taking 46% of the discharge and the Nun River taking 54%. The Imo River which is the second largest after the Niger is located to the east of the River Niger; it flows through 107km southwards and has a width range of 60m at the upper reaches and 1000m at the estuaries. All the rivers drain into the Atlantic ocean giving the delta its complex structure of land and estuaries. The Nigerian coast records higher sea levels between September and October [15]; this coincides with the rainy season upstream and flooding periods in the Niger delta [14].

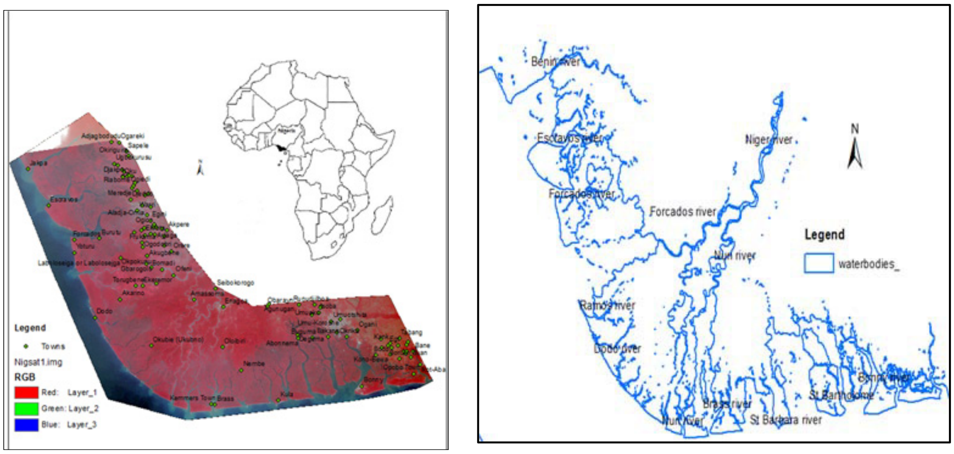

Fig. 1. (left) showing the Nigerian Niger delta; (right) showing the drainage system in the Niger delta

Vulnerable coastlines make it easy for sea water penetration into inland areas, so that the effects of coastal floods, storm surges are felt several kilometers from the coast. The coastline of the Niger delta stretches for 450 km with different physical properties like geomorphology, topography, slope, longshore current, erosion rate, and tidal height. The coastline (with only a single location showing existence of groyes), is only protected by its natural mangrove forests against storm surges. Out of the 320 settlements along the 450km coastline very few have canals (settlements with oil and gas facilities), dykes and water channels and where these exist, they are built through local efforts with no clear compliance with design standards [16].

The Niger delta coastline has been divided into 54 coastal segments based on differences in topography, slope and presence of large estuaries [13]. The coastline properties of topography and slope are considered most important because topography determines the lowest level of water that can flood an area, while slope determines the flooding extent. One of the areas found most vulnerable is the 45km stretch from segments 49 to 54 (figure 2, segment count is from left to right). The area records the highest tidal range in the Niger delta [6], has two major estuaries containing the Bonny-Calabar river system and a smaller estuary formed by a distributary of the Bonny River. The effects of SLR on this area is modelled here.

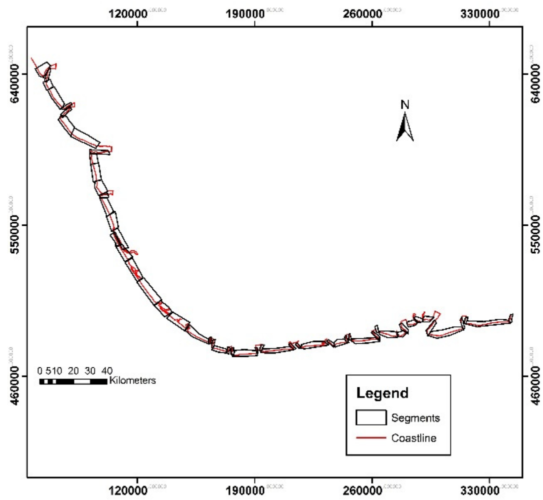

Figure 2: segment division of the Niger delta based on topography, slope and large estuaries.

3. Methodology

Scientists use climate models to project possible SLR levels for the future. The latest projection by the IPCC gives a range between 0.26-0.97m by 2100 [17]. These projections depend on scenarios that seek to predict possible conditions of climate change and the states of the coastal areas. This study considers the effects of SLR on the Niger delta by 2100, using SLR values from 0.2 to 1.0m. Deltares' DFlow modelling methodology using a flexible mesh for discretization of the modelled area is used here to check for increased possibility of flooding and inundation.

D- Flow uses unstructured grids that can consist of triangles, pentagons and curvilinear grids and 1D channel networks all combined in one mesh. Calculations are based on 2D shallow water formulation and it uses the staggered grid convention; by which the water levels are defined at the calculation points and nodes and the discharges are calculated at the reaches. D-flow can be simulated in 1D, 2D or 3D.

Like all hydrodynamic models, D-Flow requires boundary conditions at the upstream and downstream of the river reach, and the initial conditions of the system. Hydrodynamic models use discharge values/rating curves as upstream boundary conditions, and water level data as downstream conditions. For this study the Bonny and new Calabar rivers located on the eastern Niger delta are modelled. The two rivers are separated by a low lying floodplain but are hydrologically connected via various channels and forming a single system. The area has very low topography, virtually absent fresh water input, and the highest tidal range in the Niger delta [2]. For the modelling therefore, SRTM data was used to measure the river width, the heights of the tide gauges (Mean higher high water levels readings) between the upstream and the downstream points were used to determine the river slope, Manning's *n* values were used for river channel roughness. SLR values were added to tidal sea levels and used as the model downstream boundary condition. One month tidal data from two sources One month tidal data from two sources ([3]and [4]) were compared to verify the range of water levels and the correlation coefficient was over 0.99 (figure 3). Initial conditions for the river is the MLLW (mean lower low water). For river bathymetry, an unstructured grid was created for the Bonny in D-Flow. The grid consists of curvilinear grids in the river channel and triangular grid an area with a small island where a tributary meets the New Calabar River. The two grid types were merged together to get a single grid. D- Flow grids are made up of net nodes (corners of the cell), net links (cell edges that connect net nodes), flow nodes (cell circumference) and flow links (line connecting two flow nodes). In an ideal D-Flow grid topology, the cosine of the angle between the flow link and the net link (known as orthogonality), and the ratio of the areas of two adjacent cells (known as smoothness) should be equal to one [7]. The angle should therefore be 90^0 to ensure accurate hydrodynamic computations. The Bonny river has areas with sharp bends as well as distributaries, which make the creation of a perfect grid more difficult. The D-flow hydrodynamic model uses an unstructured grids (flexible meshes) that can be modified to represent the complexity of a river and floodplain system. The final grid used in this model has orthogonality of 0.045 showing that the smallest angle between the net link and flow link is 87.4^0.

In the model setup, the model upstream boundary condition used is set as zero because Bonny river flow is said to be primarily influenced by the tidal waters from downstream [2]. The model output was calibrated based on tidal water level measurements in the rivers, using measured roughness values and average flow velocity obtained [5]; who took measurements along the Bonny-New Calabar river system using 66 cross sections.

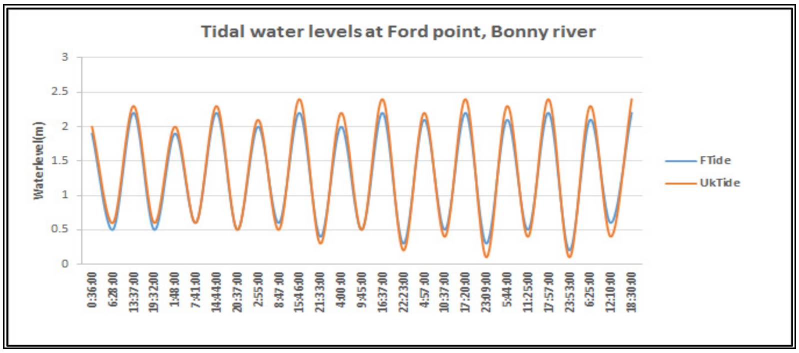

Fig.3. Comparison of two sources of tidal water level data for the Niger delta

4. Results

The model was run from 1st to 7th August, and the results used to calibrate the model using measured tide gauge water level readings at cross section 6 in Bonny river. The setup was adjusted using Manning's n values to find the find the best model. The final calibrated model had a correlation coefficient of 0.97 with the measured data (figure 4).

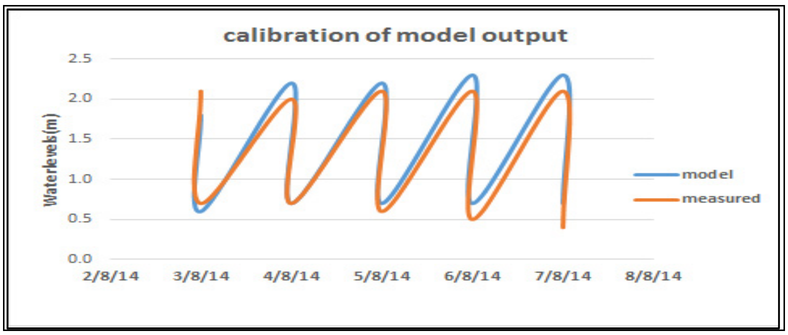

Fig. 4. Model calibration by comparing model result with tidal gauge data

Cross section 6 is the location of a tidal gauge station that gives daily tidal water levels. The width of cross section 6 and the slope of the river were measured using SRTM 30m DEM. The width, slope and maximum daily water levels were used to calculate the daily maximum discharge at that cross section using Manning's formula given as:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} (\frac{\partial h}{\partial x})^{1/2}$$

Where Q=discharge, A= area of the cross section, R=hydraulic radius, n=Manning's roughness value, $\partial h/\partial x$ = slope. The calculated Q was also used as a calibration measure for the model.

4.1. Water levels, water depth

Since the model had no discharge from upstream, it was easy to extend the grid and include another estuary connected to the Bonny River. The results with zero upstream discharge show that water levels will be higher with SLR. Figure 5 shows water levels at an observation point. The downstream boundary was adjusted by adding different values of sea level rise from 0.2 to 1m. The figure shows sea level rise values of 0.2 and o.4m have increase the water level. This increase in water levels will flood new areas at high tide (figure 6).

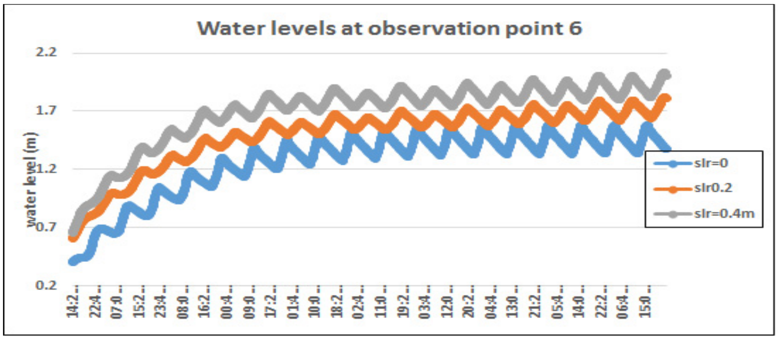

Fig. 5. Model water level output showing increase in water levels with sea level rise.

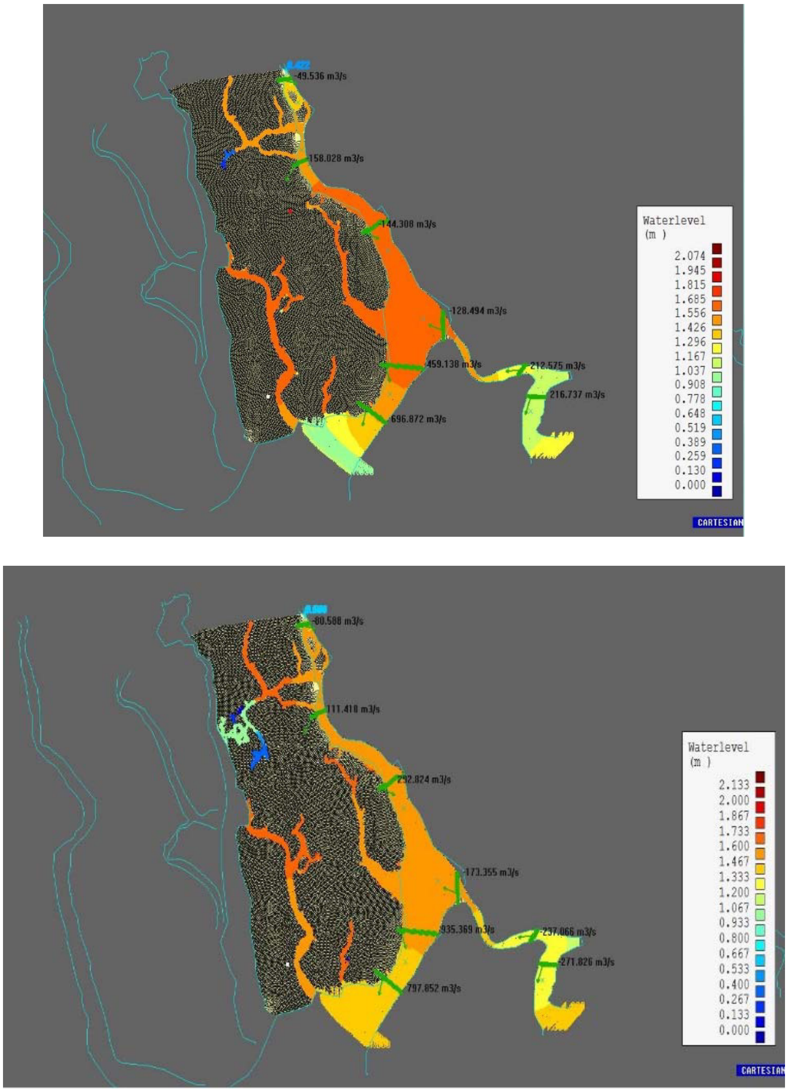

Fig.6: model results showing new areas covered by water with sea level rise. (Top) no SLR, (Bottom) SLR=0.4m.

4.2. Velocity

The average flow velocity in the Bonny –New Calabar river system is 0.3m/s (Epete, 2012), however with sea level rise, the river flow velocity will increase especially around bends and areas where the river cross section narrows (figure7). This is because the river system is dominated by tidal flow.

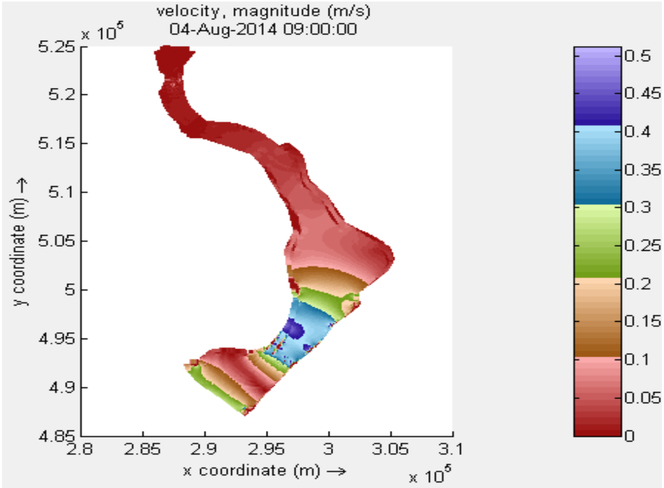

Fig. 7. Velocity changes that will occur with rise in sea levels in Bonny River.

5. Conclusion

Data availability is a challenge for many researchers especially in developing countries where many catchments remain ungauged or sparsely gauged. The Niger delta is one of the low-lying deltas that will be affected by rising sea levels, but it lacks essential data for hydrologic and hydrodynamic modeling. In this paper freely available SRTM DEM satellite data are used to provide river bathymetry and river cross section width. The data is combined with freely available tidal data to calculate discharge at a tidal water level point. The data thus obtained was used as input for a D-flow hydrodynamic model of the Bonny-New Calabar river system. The results obtained show possible effects of SLR on water level, flooding extent, water depth and the velocity of flow in Bonny River. Use of unstructured grid discretization of a modelling domain enables capturing of different flow patterns within the same model domain. This flexible mesh based method can be used to model complex ungauged deltas within limits of the data accuracy.

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