Deltaic Sedimentary Environments in the Niger Delta, Nigeria

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Abstract

This study is focused on the geomorphology of surface sedimentary environments contained in the fluvial, tidal and wave-dominated areas of the Niger Delta. GIS techniques applied to high-quality Landsat and SPOT images were used to identify and map landforms and processes, as well as quantitatively characterise their metrics and spatial distribution. A detailed analysis shows that the extent of the Niger Delta is 70,000 km^2, contrary to previous publications that reported 75,000 km^2. The delta has also been remapped and classified into mega sedimentary environments: the upper deltaic plain is 69% of the total extent, while the lower deltaic plain and delta front are 25% and 6% respectively. Other subunits were distinguished and mapped within the upper deltaic plain such as fluvial channels, point bars, braid bars, oxbow lakes, and other lakes. Tidal channels, beaches and spits were identified in the lower deltaic plain and delta front. The geometries of these sedimentary bodies (landforms) appear to be relatively scale-invariant, thus meaning that from the measurement of some dimensional parameters (e.g. the length) it is possible to estimate all others (e.g. the width and overall extent). This is an aspect of great relevance in subsurface analyses where it is often difficult to predict the extent of sedimentary bodies. The correlation between channel width and length (r^2 =0.9), is the strongest relationship found between sedimentary body metrics.

Keywords: Sedimentary environments, Niger Delta, geomorphic units, landforms, recent sand body geometries, deltaic analogues.

1 Introduction

The Niger Delta is located in southern Nigeria in West Africa; it has been a research focus for the last few decades because it is a prolific oil and gas province. It is one of the largest regressive deltas in the world with an area (onshore and offshore) of 300,000 km^2 (Kulke, 1995). The Niger Delta is the sixth largest oil producing delta (Reijers, 1996), and top 20 oil producing region, in the world. The pioneering studies by NEDECO (1954, 1959, 1961), Hill and Webb (1958), Allen and Wells (1962), Allen (1963, 1965, 1970) and Oomkens (1974) have described the sedimentology, morphology, and physiography of the Niger Delta.

Allen (1965, 1970) used aerial photographs to delineate the lateral extent of the entire Niger Delta and its various sedimentary environments (also referred to as deposits, geobodies, and landforms in this paper) as shown in Figures 1 and 2. However, Allen's and other works (NEDECO, 1954, 1959, 1961; Allen, 1965, 1970; Oomkens, 1974) did not cover the quantitative and statistical aspects of the facies architecture and dimensions. So, the near-surface geology and the plan dimensional characteristic of the landforms in the Niger Delta are still

not fully studied, whereas this type of study has greatly advanced our understanding of other deltas around the world in recent years. In the Rhine-Meuse, for example, studies have included an estimate of the Holocene sediment budget, the paleogeographic reconstruction, the general geomorphology, the fluvial response to Paleocene climate change and an analysis of river channel and bar patterns (Erkens et al., 2006; Berendsen et al. 2007; Uehlinger et al., 2009; van Balen et al., 2010; Kleinhans et al., 2011). In the Mekong River delta, the Late Holocene evolution of the Mekong subaqueous delta was studied by Xue at al. (2010) as well as the geomorphological characterisation of the mixed bedrock-alluvial multi-channel network by Meshkova & Carling (2012). The Danube Delta is another well-studied area; its analysis demonstrated that it has multiple growth lobes, as the interplay between the delta-forming processes is varied in space (Bhattacharya and Giosan, 2003; Giosan et al. 2006; Giosan and Goodbred, 2007). Morphodynamic studies of deltas have also been carried out in the Indus (Giosan et al., 2006) and Mississippi deltas (Parker and Sequeiros, 2006). Studies of the Brahmaputra and Amazon deltas and others are documented in Sambrook-Smith et al., (2005), while the Mississippi, Missouri and Columbia rivers are the focus of Fisk (1947), Komar (1984), Blum and Roberts (2009), Edmonds and Slingerlands (2009). Other studies on deltas can be found in Woodrofe (2000), Ashton and Giosan (2007) and Hoyal and Sheets (2009).

The map of sedimentary environments in the Niger Delta has not been updated since the work of Allen (1965) and Short and Stauble (1967), both based on aerial photos. In this study, the sedimentary environments have been completely re-mapped, by using high-quality Landsat TM and SPOT colour satellite images. We have applied GIS technique to recent satellite images of the Niger Delta to identify and classify geomorphic units across a range of scale, within distinct mega sedimentary environments. As part of this exercise, the geometric dimension of each geomorphic unit were measured, and statistical equations and mathematical relationships were derived. In addition, the spatial extent and distribution of these geomorphic units have been analysed, which has given new information into the landforms and the processes that created them. Collectively, this information provides insights on similar environments that are now buried deep beneath the surface both in the Niger Delta and other deltas. This is of significant value to the petroleum industry; in reservoir characterization and modelling, analogues are fundamental to study and calibrate subsurface reservoir facies elements (Borer and Harris, 1991; Tyler and Finley, 1991; Grant et al., 1994; Sarg et al., 1999; White and Barton, 1999; Willis and Gabel, 2001; Wood, 2004, Jin et al. 2017; Pierik et al. 2017; Zimmermann et al. 2018).

2 Geology of the Niger Delta

The Niger Delta is in the southern part of Nigeria, between longitudes 3-9^{o} E and latitudes 4^{o}31'-5^{o}20'N and lies in the humid tropics (Short and Stauble, 1967; Allen 1970; Asseez, 1989). The western border is the Benin Flank and the eastern is the Calabar Flank (the flanks are regional rift faults); the southern coastal margin is open to the Atlantic Ocean (Asseez, 1989). The Niger Delta basin began to form in the Cretaceous when the African plate separated from the South American plate; the basin is bounded by rift faults on its northwestern and northeastern edges (Burke and Whiteman, 1973; Burke and Dewey, 1974; Olade, 1975; Whiteman, 1982; Fairhead and Blink, 1991; Guiraud and Maurin, 1991; 1993). The regressive clastic sequence in the Niger Delta started building in the Paleocene and has since then built sediments that now reach a thickness of 12,000 meters (Evamy et al, 1978). These sediments are deposited into six diachronous depo-belts i.e. sediments are younger

81 towards the Atlantic Ocean in the south. The depobelts are: (i) Northern Delta, (ii) Greater Ughelli, (iii) Central
82 Swamp I, (iv) Central Swamp II, (v) Coastal Swamp and (vi) Offshore, each separated from the other by
83 regional faults (Doust and Omatsola, 1990). The depobelts were by Tuttle et. al. (1999), who created a map that
84 shows the ages of the depobelts, from northern Niger Delta to the sea, using paleo-coastlines as boundaries on
85 plan-view and the regional faults on the section-view. The coastline has prograded seaward in discrete
86 successive stages for over 35 Ma (Tuttle et. al. 1999). A similar depobelt classification of the Niger Delta,
87 looking at the plan-view only was done by Oomkens (1974) and Allen (1963, 1965a), and it was focused on
88 Holocene (Quaternary) surface and near-surface sediments.
89
90 The sedimentary pile of the Niger Delta has been grouped into three stratigraphic units: the continental, paralic
91 and marine sequences based on the sand/shale ratio (Short and Stauble, 1967; Avbovbo, 1978). Evamy et al.
92 (1978) named these stratigraphic units the Akata, Agbada and Benin formations respectively from bottom to top.
93 The Agbada Formation is the target formation in the exploration of oil and gas. It is about 3000 meters thick and
94 ranges from the Paleocene to Recent. In the Agbada Formation, the shale intercalation forms the seal while
95 growth faults, associated roll-over anticlines, and antithetic faults are the main traps that enhance petroleum
96 accumulation (Asseez, 1989). The delta appears to be in near isostatic equilibrium and has grown in thickness
97 and volume in the absence of tectonic control (Stoneley, 1965).
98
99 **3 Data and Methodology: GIS data and digitized maps**
100 The raster Landsat TM and SPOT satellite imagery is the key dataset used to map all recognisable sedimentary
101 environments, which include the mega-environments: upper delta plain, lower delta plain, and the delta front,
102 each dominated with fluvial, tidal and wave-related deposits, respectively (see Figure 1). Within these mega
103 sedimentary environments, various subunits/environments are distinguishable based on their morphology and
104 following Bridge (2003). These include: distributary fluvial channels, tidal channels, braid bars, point bars,
105 oxbow lakes, crevasse splays, cut-off channels, other lakes and ponds, beaches, and spit. Landforms were
106 recognised and digitised from Landsat and SPOT satellite images using bands 5, 4 and 3 (RGB) and 4, 3 and 2
107 (RGB) respectively. The resolution of the satellite images, 20 m for Spot and 28.5 m for Landsat TM, was high
108 enough to resolve all studied landform. The mapping and identification of the various units and subunits were
109 based on pattern recognition considering elements of interpretation such as: tone, textures, shape, and pattern
110 amongst other elements, and most importantly, the natural association of these landforms. For example,
111 channels were identified because of their reflectance (water-filled part), tone and shape, all of which are clearly
112 different from the adjacent environments (e.g. floodplain). Other elements have proved to be more difficult to
113 map. For example, while the boundary between point bars and channels can be easily identified, that between
114 point bars and the floodplain is not always clear. While the former can be traced following the reflectance
115 contrast between water and sand, the latter requires the identification of the termination of the scroll-swale,
116 which is often water-logged. Accurate geo-referenced maps of the Niger Delta were created (Figures 1 and 2).
117 The size (width and length), aspect ratio, shape, orientation, connectivity and continuity of the identified
118 sedimentary environments were analysed in a GIS environment by using ArcGIS and the Hawth's Analysis
119 tools (http://www.spatialecology.com/htools/overview.php).
120

4 Results and Discussion

4.1 Extent of Niger Delta

There are inconsistencies in the reported area of the Niger Delta as published by Kravtsova et al. (2008); with eight different values reported ranging from 1,140,000 km^2 to 2,240,000 km^2. Some of these values are unrealistic and it is not clear if these include the submerged part of Niger Delta or not. As a result, the area derived from this paper is only compared with the work of Allen (1970) and Short and Stauble (1967); both of which have been quoted most frequently in publications. This study revealed that the terrestrial portion of the Niger Delta covers an area of 70,000 km^2, and with an axial distance of 221 km. The axial distance is measured from the landward tip at Onitsha to the coastline at the Sombreiro-Nun rivers (the farthest seaward protrusion of the coastline). The coastline is 650 km long; from the Rio-del River (east) to the Lagos Peninsula (west) (Figures 1 and 2). These figures (Figures 1 and 2) are very important as they serve as a reference in estimating dimension and areal extent of subsurface sandbodies. They are also important in estimating the rate of growth of the delta seaward or the impact of destructive processes, such as erosion, over time.

The area (70,000 km^2) of the Niger Delta is 5,000 km^2 less than the areal extent previously estimated by Allen (1970) and Short and Stauble (1967). The axial distance measured by Doust and Omatsola (1990) was 300 km, which is about 80 km more than the current result. The outer boundary of the Niger Delta, as defined by Short and Stauble (1967), was digitised and compared with that from this study. The differences between the extent of the Niger Delta in this study and the previous works could not possibly be related to coastal erosion since the Niger Delta is generally a prograding delta. The reduction in the area of the Niger Delta by six percent and in the axial length by 26 percent are possibly related to the different techniques used. Allen (1970) and Doust and Omatsola (1990) used aerial photographs, which are prone to errors due to mosaic “stitching” parallax effects (Curran, 1983). In this study, Landsat TM and SPOT images, which have a higher resolution and little or no distortion, were used, coupled with detailed algorithms and processing software (ArcGIS) which was used in the image interpretation and analysis of the areal extent.

4.2 Mega-sedimentary environments in the Níger Delta

The upper delta plain is the largest environment covering 69% of the entire Niger Delta, while the lower delta plain and the delta front cover 25% and 6% respectively (Figure 1). These zones (the upper delta plain, lower delta plain, and the delta front) are the three main mega-sedimentary environments in the subaerial and subaqueous Niger Delta (Allen, 1965, 1967, 1970; Short and Stauble, 1967; Doust and Omatsola, 1990).

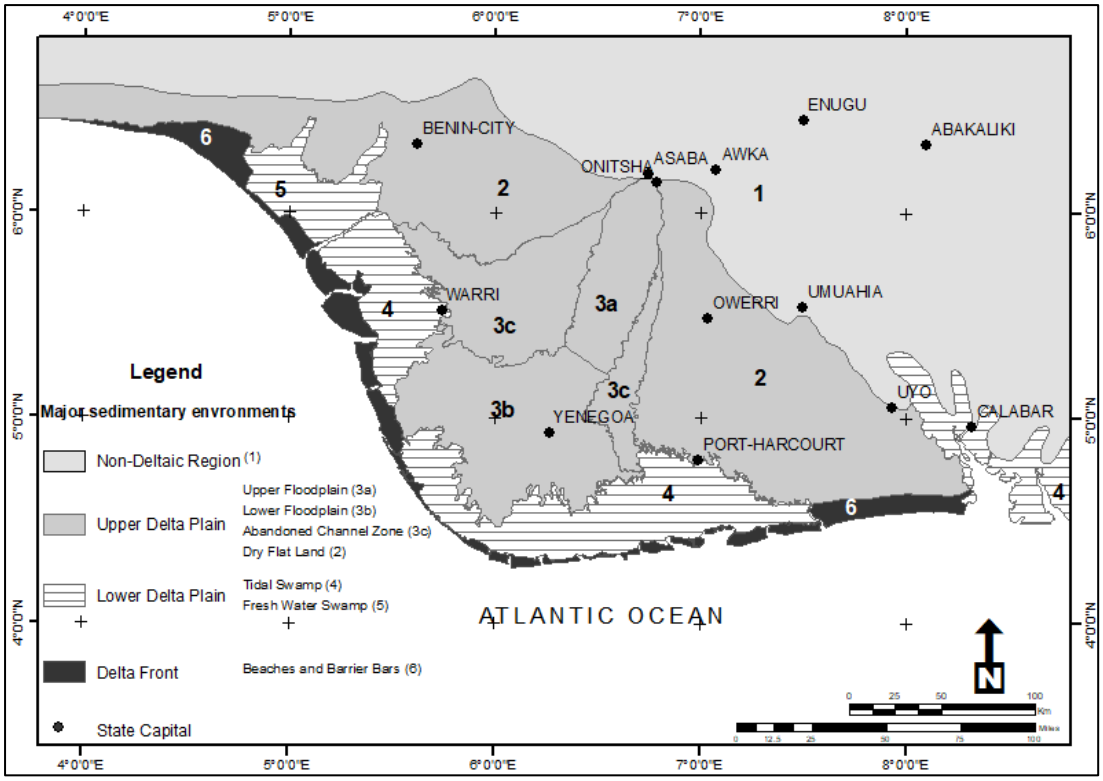

Figure 1: Map of major sedimentary environments in the Niger Delta; showing upper delta plain (continental), lower delta plain (transition) and the delta front (marine).

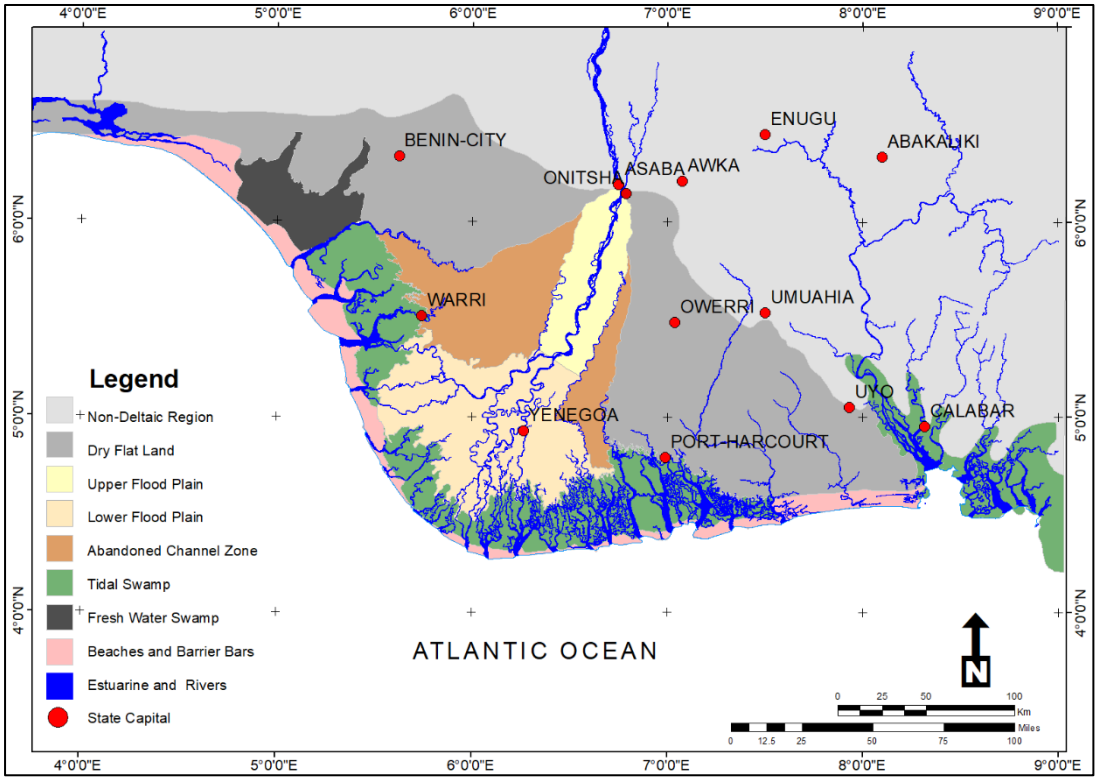

Figure 2: Map of Niger Delta showing major sedimentary environments.

4.3 Upper delta plain

The dry flat land, upper floodplain, lower floodplain and abandoned channels zone (floodplain transition zone) are all parts of the upper delta plain (Figures 1 and 2). In the upper delta plain, the abandoned channel zone (floodplain transition zone) is between the upper floodplain and the dry flat land. The Niger River runs through the upper delta plain and divides it into two approximately equal parts: the eastern part and the slightly larger western part (the area of the subunits will be reported in Sections 4.3.1, 4.3.2, 4.3.3 and 4.3.4).

4.3.1 Dry flat land

The dry flat land is the largest of the subunits in the upper delta plain, with an area of 27,413 km^2 and covering 61% of the upper delta plain. It borders the boundary between the Niger Delta and the hinterland (Figures 1 and 2) and is annexed to the upper delta plain since it is part of the Benin Formation (Short and Stauble, 1967). There are no obvious water-filled channels in the dry flat land within the resolution of the satellite image used. Therefore, the dry flat land is relatively stable and not impacted upon by recent deposition or erosion caused by rivers and tide. However, it is possible that ephemeral channels drain the dry flat land.

4.3.2 Upper floodplain geometry

A floodplain is the strip of land or a flat or smooth area adjacent to river channel which is normally covered during seasonal floods and subjected to sedimentation when the river overflows its banks (Miall, 1992; Bridge, 2003). In the Niger Delta, the upper floodplain is swampy and has a forest of tropical trees (Whiteman 1982). The upper floodplain of the Niger River starts from Onitsha (its apex, as shown in Figure 1) at the entry point of the river into the Niger Delta basin (see also Whiteman 1982). It is clearly demarcated from the abandoned channel zone by two rivers: the Orashi River in the east and the Ase River in the west (Figure 3).

The area of the upper floodplain is 3,166 km^2 with a length of 105 km, measured from Onitsha to the first point of its bifurcation at Asimabiri (Figure 3). The average width on either side of the Niger River is 31 km, though the western side can be 1 to 5 km wider than the eastern side. The ratio of the width of the upper floodplain to the width of the Niger River channel ranges from 4 to 19 (mode and average are 15) and increases downstream. Although, this ratio fluctuates along the course of the river, the average value does have a good statistical relationship, which can be used to predict the size of one of these elements when the other is known. Apart from channel width, it is likely that a combination of the volume of water released into the floodplain during river overflow, the topography, vegetation, climate, and hydrology constrain the geographic extent of the floodplain (Fagan and Nanson, 2004). The outer margins of the upper floodplain (at the boundary with the abandoned channel zones)are bordered by the rivers Ase and Orashi (Figure 3), which can also constrain the extent of the floodplain as they serve as conduits that can redirect water flow (also see Allen, 1965).

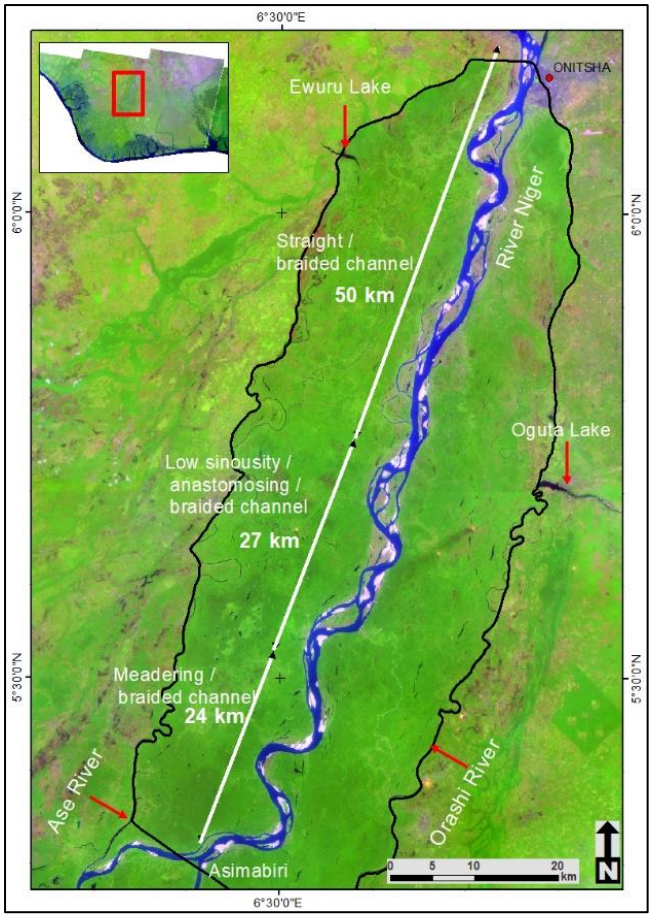

Figure 3: A satellite image of the upper floodplain showing the channel style of River Niger from the apex to the first point of bifurcation at Asimabiri. The entire length of River Niger is braided, changing from straight channel at the apex to meandering channel at the lower channel section.

4.3.3 Lower floodplain geometry

The upper limit of the lower floodplain is at Asimabiri, the first bifurcation point of the Niger River within the delta, which is also its boundary with the upper floodplain (Figures 1 and 4). The seaward boundary interfingers with the lower delta plain and, in some parts, with the beaches. The River Niger bifurcates first into two major distributary rivers (4^{th} order rivulets): the Forcados and the Escravos, then further into other rivers up to 1^{st} order rivulets from the main 5^{th} order terninal distributary channels (Olariu and Bhattacharya, 2006) (Figures 3 and 4) (stream ordering after Strahler, 1957). Other sub-environments found in this zone include: distributary fluvial channels, crevasse splay, point bars, ox-bow lakes, ponds, and cut-off channels.

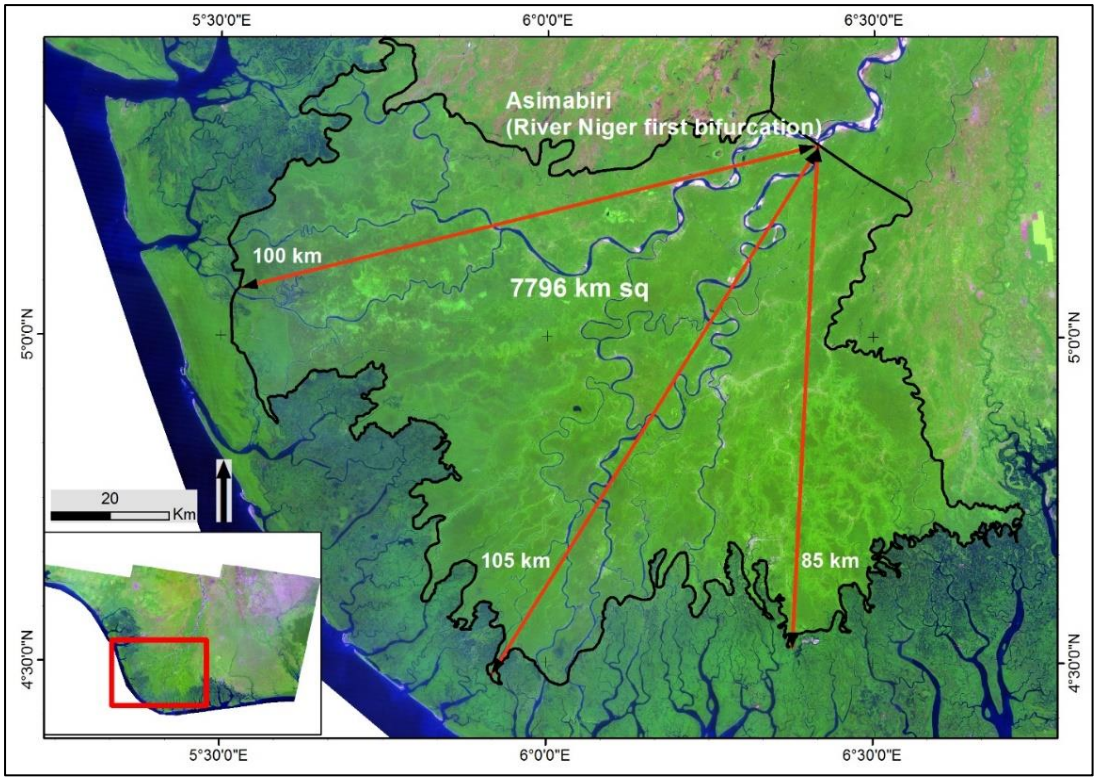

Figure 4: Map of the lower floodplain of River Niger, showing the maximum length in the three growth lobes

The lower floodplain fans out seawards from a minimum width of 30 km, at the upper boundary, to a maximum width of 140 km, downstream at the lower boundary with the lower delta plain; it covers an area of 7,796 km^2. The lower floodplain has three distinct growth lobes which reflect the dominance of sediment progradation from the feeder fluvial channels (Figure 4).The progradation is more at the center (105 km in length), and less in the east (85 km) and western (100 km) portions.

4.3.4. Abandoned channel zone

The zone of abandoned channels, or the floodplain transition zone, is a region between the dry land and the upper floodplain (as shown in Figures 1 and 2). The Ase and Orashi rivers are the boundaries between the abandoned channel zones and the upper floodplain on the west and east respectively.

The western zone of the floodplain transition covers an area of 4,902 km^2, which is about three times the area covered by the eastern side (1,565 km^2). The elevation of the abandoned channel zone is slightly higher than the lower delta plain. It is possible that this topographic difference at the southern boundary of the abandoned zones roughly coincided with ancient coastline at some point in the development of the delta. Therefore, the abandoned zone could have been formed under a unique set of delta-forming conditions (preferentially fluvial dominated, given the abundance of fluvial channel traces). The sediments at that time could have prograded more toward the west, causing the western zone to grow more than its eastern counterpart. The traceable channels on these zones run north-south and radiate from the apex of the Niger Delta like the present-day Niger River. Given their convergent geometry, it is likely that the abandoned channels in both zones (east and west)

were originally connected to the Niger River but later disconnected due to channel or delta switching. It is less likely that these channels formed in-situ as is common in semi-arid regions (Fagan and Nanson, 2004).

The abandoned channels are not filled with water, but they can be ephemeral and key in draining these regions during and after flooding. Bridge (2003) described similar features as "drainage channels". It is possible that, in the geologic past, these abandoned channels were major conduits through which sediments were supplied to the Niger Delta's coastal margin. Now sediment supply through these abandoned channels is discontinued. This implies that the tidal channels they are supposed to connect and feed sediment to are now starved of sediment supply. So, those tidal channels, which are either side of the Niger Delta coastal margin, have fewer sediments deposited in them, as reported by Doust and Omatsola (1990). As a result, the tidal channels in the tidal-process dominated western flank (Figure 18a; e.g. Benin, Escravos and Forcados channels) and eastern flank (Figure 18b; e.g. Bonny, New Calabar, and Sombreiro channels) are wider than in the central flanks, where sediment supply is continuous and connected to active fluvial channel.

The abandoned channels can contain water in the form of lakes or ponds for a considerable length of time after becoming inactive and before eventually being completely silted up or filled with clay deposits (Nichols, 1999; Miall, 1992). The transition zone hosts other sub-units like: cut-off channels, crevasse splay, over-bank deposits, ponds, and lakes. Activities such as farming have left these zones on either side of the Niger River with little natural vegetation.

4.4 Lower delta plain and delta front

The lower deltaic plain and the delta front are mega-sedimentary environments of the Niger Delta, within which tidal swamp, tidal flats, beaches, spits, and estuaries are contained, as shown in Figures 1, 2, and 3. The lower deltaic plain is separated from the upper deltaic plain by a bayline (Bhattacharya 2006 and 2010). The bayline is marked by the boundary defining estuarine (tidal channels) termination, beyond which tidal incursion is insignificant. The entire delta front is rimmed with elongate beaches and barrier islands typical of wave-influenced delta fronts (Olariu and Bhattacharya 2006; Ainsworth et al 2011). Tidal channels are ubiquitous in these regions; these cut through the delta front, dividing it into blocks of beaches-barrier islands. The areal extent of the lower deltaic plain is 16,625 km^2 which is 25% of the entire area of the Niger Delta while the delta front covers 4,138 km^2 and is 6% (Figures 1, 2 and 3). The areas of the lower deltaic plain and the delta front together are 20,763 km^2.

Oomkens (1974), who studied the Quaternary (Holocene) Niger Delta, reported that the area of lower delta plain is about 5,000 km^2 which is considerably less than the area recognized in this work. Also, Allen (1970) reported that the area of the tidal swamp (lower deltaic plain) is 9,000 km^2, which is about half of that from this study. The method or technique used by Oomkens (1974) and Allen (1970) respectively to estimate the areas were not clearly stated in their papers. Therefore, result from this work is considered more reliable as it is extracted from high-quality satellite images with ArcGIS.

4.4.1 Tidal (Mangrove) swamp environment

The mangrove swamps have been formed wherever the tide pushes saltwater inland through the tidal and transverse channels and creeks. Mangrove swamps extend 480 km on the southern margin parallel to the coast (Figure 1). In the axial parts of the delta, the swamp belt is mostly 8-16 kilometres across, merging with the lower floodplain at the northern boundary (Allen, 1965a). Swamp width, measured in North-South direction, increases to 30-40 km on the delta flanks. In the marginal estuaries of the Calabar and Rio del Rey, east of the delta, the swamps are sparse, terminate at the sea and pinch out landward.

4.5 Geometries of landforms associated with the upper deltaic plain

In the upper delta plain landforms include: fluvial river channels, point bars, braid bars, lakes, ponds, and ox-bow lakes. These sand bodies play a significant role in the storage of oil and gas when preserved in the subsurface. In the following subsections, the geometries and reservoir implications are discussed.

4.5.1 Channel geometries of the Niger River

The section of Niger River from proximal to distal covers variable segments which include: low sinuosity (Sinuosity Index, S.I. less than 1.5) straight and braided channels (50 km) ; low sinuosity anastomosing channels and braided rivers section (27 km); high sinuosity meandering channels and braided section (24 km) (Figure 3). This morphological classification is typical of many other river systems (Ferguson, 1987; Nanson and Knighton, 1996; Schumm et al., 2000; Schumm, 2005; Kleinhans and Van den Berg, 2011). The Niger River is a distributive channel system and has typical dendritic channels (Howard, 1967), which are controlled by topography, hydrodynamics, and geology. The entire length of the River Niger is characterised by the presence of braid bars, indicative of high sediment discharge (Bridge 2003, p. 154); their abundance progressively reduces downstream.

4.5.2 Channel width variation downstream

The length of the Niger River from Onitsha to the coast on the Forcados arm is 327 km and nearly the same (321 km) on the Nun River arm. Like other rivers (Kleinhans, 2010; Kemp, 2004; Luchi et al, 2010; White et al, 2010; Davidson et al, 2011), the Niger River channel width decreases from the apex to the coast linearly, ranging from 4000 m to 200 m (1500m is the mode), while its depth increases, thus keeping the volume of water fairly constant (Olariu and Bhattacharya 2006). The Niger River width generally decreases linearly by 30 m every 2000 m moving downstream (Figures 4 and 5). However, after points of bifurcation, the reduction in channel width is drastic with significant impact on the overall channel width gradient (Edmonds and Slingerland, 2007, 2008, 2009). For example, there is a significant step-down in the width of the Niger River after the first bifurcation at Asimabiri, beyond which the Braiding Index (sensu Friend and Sinha, 1993) also reduces drastically, implying a low gradient. Braiding Index BI is the braid channel ratio (L_{ctot}/ L_{cmax}). L_{ctot} is the sum of the mid-channel lengths of all the segments of primary channels in a reach and L_{cmax} is a measure of the mid-channel length of the widest channel through the reach (sensu Friend and Sinha, 1993). The channel shows high variability in width further downstream, which is due to the presence of braid bars. These braid bars reduce channel width and their blocking effect varies along-channel flow velocity, which, and in turn, causes the intensity of bank erosion and deposition to also vary. This factor is responsible for the high variability in the channel width in the Niger River. Distributary channel (tidal channel) width increases geometrically

downstream because of tidal impact, which is highest at the coast and wanes landward. It is, in fact, a marker for distinguishing between fluvial and tidal channels in the Niger Delta.

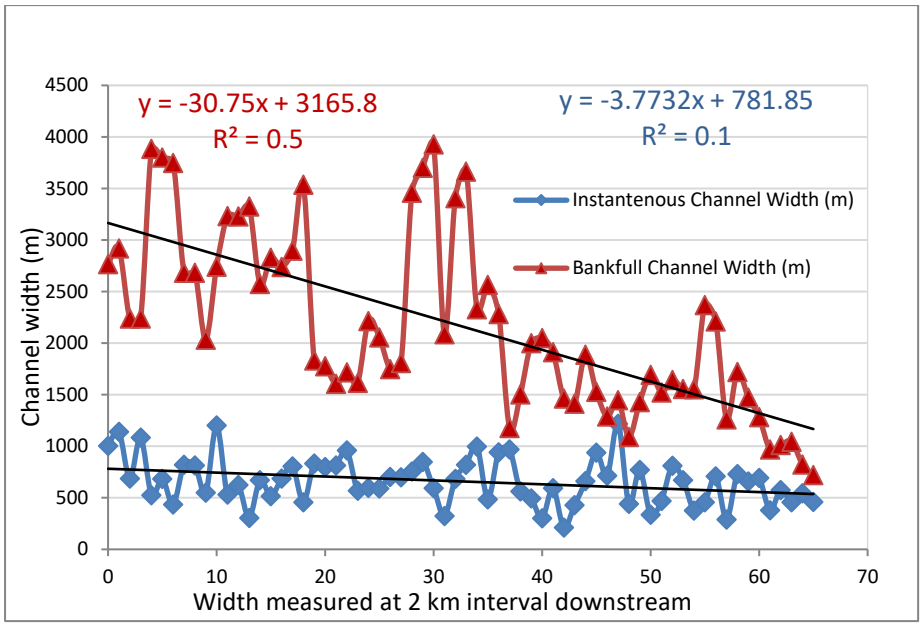

Figure 5: Channel width variation of River Niger (from Onitsha i.e. graph origin to the first bifurcation at Asimabiri). Instantaneous channel width (blue) is the width as seen on the images interpreted, it measures the part of the channel covered by water. While bank-full channel measurement assumes that mid-channel and side-bars were submerged. So, its measurement extended beyond the water body to the thickly vegetative side of the river bank, in some areas.

4.5.3 Sinuosity Index of channels

The Sinuosity Index (sensu Spagnolo et al., 2008) of the Niger River ranges from 1.3 to 2.9 and increases downstream. The sinuosity of Imo (east), Sombreiro (east) and Escravos (west) rivers are high, with an average and modal sinuosity above 2.0. As the discharge of the channel's flow wanes, the meanders grow larger and the sinuosity of the fluvial channel increases towards the coast (Seppala, 2013; Nichol, 1999). The sinuosity of the channels farther away from the axis of the Niger Delta to the flanks is generally higher than that of the main Niger River channel. Therefore, sinuosity not only increases downstream but also increases outward from the axis of the Niger Delta. The factors that control the spatial variation in sinuosity in the Niger Delta are not clear but there seems to be a relationship between channel length and width. The sinuosity of the channels that are long and narrow is generally higher than 2.0 (see Figures 15 and 16). There is also a progressive increase in sinuosity with stream order, particularly from fifth order to first order, in distributary channels.

4.5.4 Point bars

Point bars form inside bends of rivers below the slip-off slope (i.e. they form by accretion inside an expanding loop or meander of a river). On the satellite image, point bars were identified in the meandering portion of the river, based on texture and pattern on the image. The vegetation within the point bar shows a lighter green reflectance as compared to the adjacent floodplain which is darker green reflectance. Also, within the mapped point bars, the scroll and swale topography are evident: at the scroll (ridge), the vegetation is dense; whereas at the swale (trough), the vegetation is sparse and sometimes the sands are exposed, showing high (if bare) or

darker (if water-filled) reflection. The side of the point bars in contact with the main fluvial channel is easily delineated by the blue water body. In general, the topographic pattern makes it easy to identify, map, and measure the scroll-swale width. The active sandy bars are separated from the vegetative part by channels; as such they are not really considered as part of the point bars. Although these landforms are transient and ever-changing, sometimes even merging with braid bars to form complex assemblages, characterisation of their morphology has been attempted here based on what we were able to observe and measure on the satellite imagery. Hopefully, this gives an overview of the range of geometries that might be of relevance, for example, to analogue studies.

There are 24 point bars mapped in the Niger Delta and their geometric dimensions are presented in Table 1. They are all associated with the fluvial channels and mainly within the upper delta plain covering the upper and lower floodplains. Traces of other point bars associated with other ephemeral channels were also observed in the upper floodplain. Four representatives point bars are shown in Figure 6. The length of all mapped point bars varies between 1,500 m and 10,021 m and 91% of the length is below 5000 m. The width of the point bars ranges from 650 m to 5,026 m (with a mode of 2500 m). The swales–scroll width (accretion bounding surfaces) ranges from 76 m to 310 m (mostly 200 m). The ratio of point bar length to width ranges from 0.5 to 3.7 and the ratio of the point bar width to main channel width ranges from 1.7 to 10.6. The length, width, and area of point bar, sinuosity and channel length and channel width associated with the point bar are plotted to validate the dependence of a set of these parameters to one another. The plots of point bar length against area (Figures 7 and 8) and the point bar width against area (Figure 9) demonstrate a significant relationship. The length and width of point bars correlate positively with the overall size (area), with a correlation coefficient varying from 0.8 to 0.9. The summary of the relationships derived from these plots is also shown in Table 1 and in the empirical equation (Equation 1).

This study shows that a ratio between 2 to 10 exists between point bar width to channel width (see Table 1 and Equation 1)**.**

$W_P = cW_{ch}$ (regardless of sinuosity) .....Equation 1

Where: W_p = point bar width

W_{ch} = channel Width,

c = a parameter that ranges from 2 to 10

The point bar width is generally about half the point bar length, except in zones of high sinuosity (SI > 2.5); where point bar width tends to be equal to, or higher than, the point bar length (see plots in Figures 7,8 and 9).

The results of this study are similar to those from Leopold et al. (1964). Their equation is one among many equations that relates point bar width with channel width at a uniform sinuosity of 1.5, with c ranging from 2 to 12 (Leopold and Wolman, 1960; Leopold et al, 1964). Other studies of point bars and related fluvial bodies by Fielding and Crane (1987), Bryant and Flint (1993), Cuevas Gozalo and Martinius (1993), North (1996), De Rooij et al, (2002) and Ghinassi et al, (2016) have shown that relationships exist between parameters such as

thickness, length, width, volume, river sinuosity and bend tightness. Also, and importantly, they confirm that most fluvial landforms are scale invariant.

The overall geometry of point bars is not only influenced by sediment erosion and deposition along the channel bank but also by bank stability, and the river hydrodynamics. In turn, bank stability depends on the geology and vegetation. Braiding can also affect the formation and geometry of the point bars; as areas with high braiding index have fewer point bars. However, from this study, point bars are mostly associated with meandering sections of the channel (Figures 7, 8 and 9). The statistical relationship between point bar parameters and channel parameters identified here (Equation 1) could be used to estimate point bar length or width when the other parameter is known. This is important for the characterisation of subsurface sedimentary bodies.

Chute or cut-off channels are developed across the top of abandoned point bars as a result of flood events or braiding, during which the main channel is choked with sediment. They are essential to demarcate point bars from the floodplains. Apart from the chute channel associated with the Niger River, other isolated channels (or ponds) are abundant in the floodplain of the Niger Delta.

417 Table 1: Point bar geometric dimensions in the Niger Delta of River, Forcados and Nun arm inclusive.

Point bar geometric dimensions											
Point bar Name	Associated River	Point bar Area (km^2)	Point bar Length (m)	Point bar Width (m)	Average scroll Width (m)	Channel Length (m)	Channel Width (m)	Sinuosity Index	Point bar Length/Width	Point bar Width/Channel Width	Point bar Scroll width/Width
PB 01	River Niger	15	3270	3816	171	5244	683	1.60	0.9	5.6	22.3
PB 02	River Niger	10	2983	2299	185	4300	848	1.44	1.3	2.7	12.4
PB 03	River Niger	12	3865	3327	241	5798	812	1.50	1.2	4.1	13.8
PB 04	River Niger	36	10021	4790	310	11756	829	1.17	2.1	5.8	15.5
PB 05	River Niger	21	5232	3856	185	6972	899	1.33	1.4	4.3	20.8
PB 06	River Niger	24	4558	5026	216	7573	579	1.66	0.9	8.7	23.3
PB 07	River Niger	19	4876	3784	243	6564	615	1.35	1.3	6.2	15.6
PB 08	Forcados	5	1749	2884	163	3581	415	2.05	0.6	6.9	17.7
PB 09	Forcados	11	3702	2722	141	5191	398	1.40	1.4	6.8	19.3
PB 10	Forcados	21	4548	4398	176	6700	703	1.47	1.0	6.3	25.0
PB 11	Forcados	9	5081	1761	164	5929	532	1.17	2.9	3.3	10.7
PB 12	Forcados	1	1559	798	76	1776	276	1.14	2.0	2.9	10.5
PB 13	Forcados	2	2346	650	130	2504	346	1.07	2.9	1.9	10.5
PB 14	Forcados	1	1957	743	82	2162	416	1.10	3.0	1.8	5.0
PB 15	Nun	4	2736	1017	131	2997	406	1.10	3.7	2.5	9.0
PB 16	Nun	3	2408	3936	135	5378	372	2.23	2.4	10.6	7.7
PB 17	Nun	4	1941	2222	130	3476	385	1.79	0.5	5.8	29.2
PB 18	Nun	5	3715	729	131	3910	429	1.05	1.7	1.7	17.1
PB 19	Nun	5	2382	1879	138	3183	510	1.34	3.3	3.7	5.5
PB 20	Nun	6	2007	3489	144	4704	360	2.34	1.1	9.7	13.6
PB 21	Nun	4	1843	2410	131	3371	439	1.83	0.5	5.5	24.3
PB 22	Nun	10	2868	3257	291	4707	438	1.64	1.2	7.4	18.4
PB 23	Nun	5	1961	2820	241	3709	300	1.89	0.6	9.4	11.2
PB 24	Nun	4	1737	2637	159	3961	296	2.28	0.6	8.9	11.7

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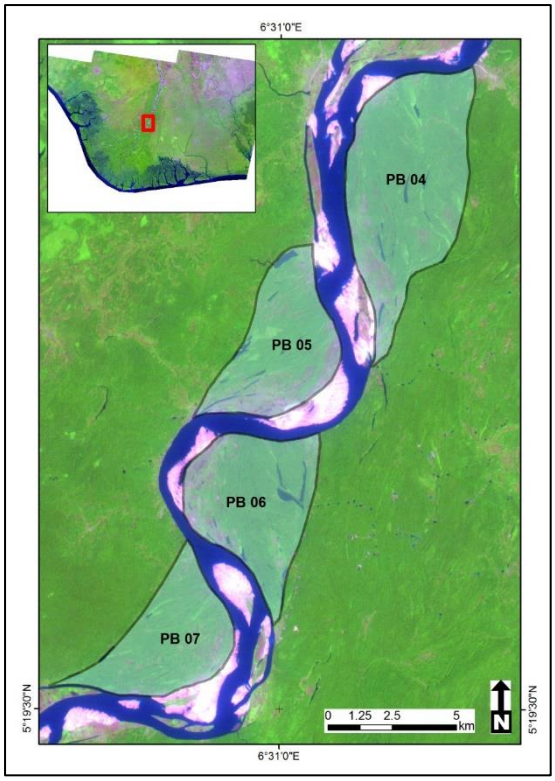

Figure 6: An example of point bars mapped along the River Niger (PB 04 to 07). These were then measured in ArcGIS to produce a quantitative characterisation of point bars in the Delta.

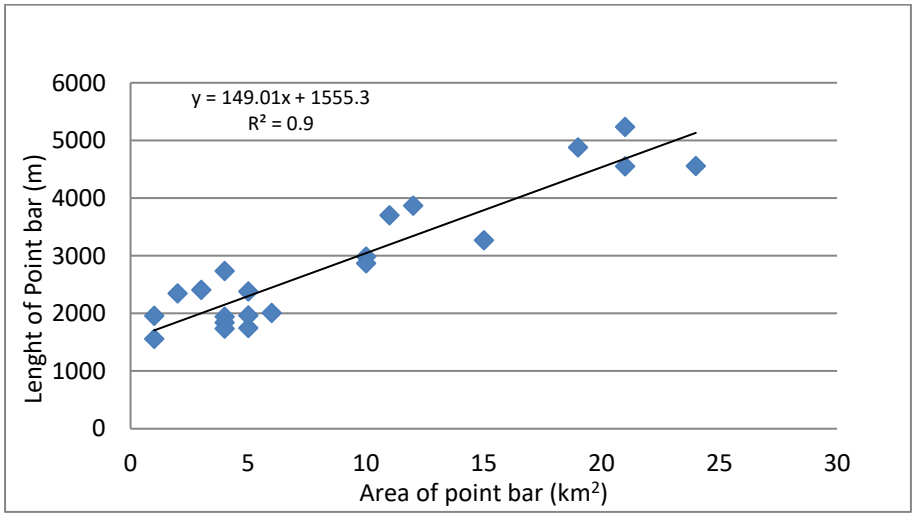

Figure 7: Plot length against the area of the point bar. The R^2 is 0.9; it shows a significant relationship between the length and the area of the point bars mapped, i.e. the larger the area the higher the length.

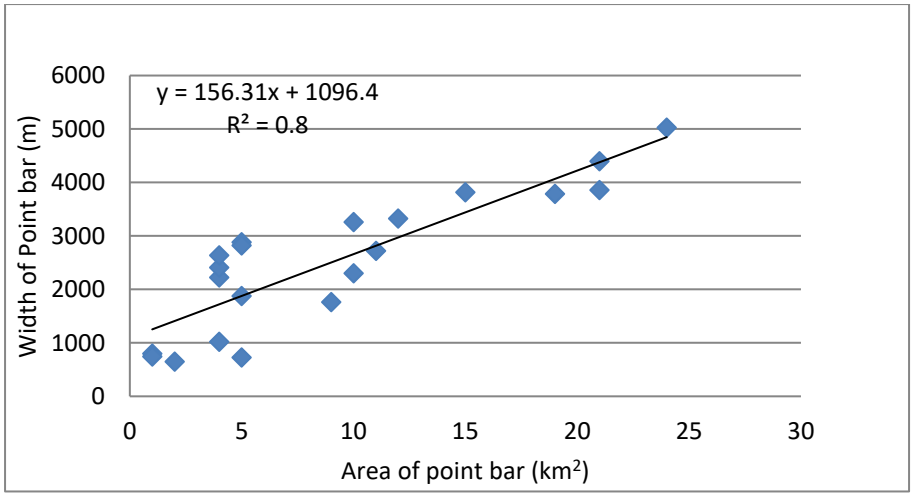

Figure 8: Plot of width against the area of the point bars. The R^2 is 0.8; it shows a significant relationship between the length and width against the area of the 24 point bars mapped, i.e. the larger the area the wider width.

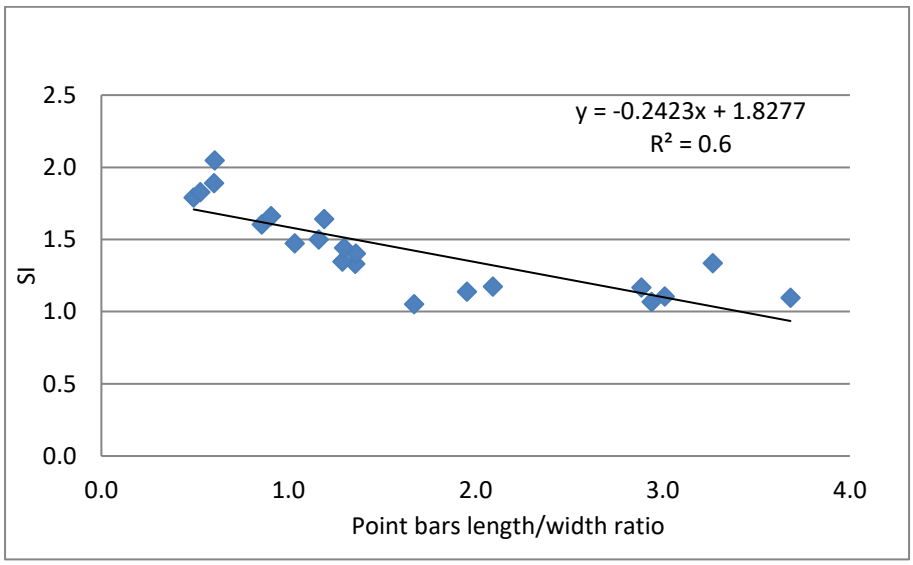

Figure 9: Plot of Sinuosity Index (SI) against point bars length/width ratio. The R^2 is 0.6; it shows a significant relationship between the SI and the point bar length/width i.e. the SI and the point bar length/width ratio do depend on each other significantly for values of SI less than 2.0

4.5.5 Braid Bars, Bar Assemblages

Braid bars are transient, they could change in shape and location based on a number of factors such as vegetation, the volume of water and sediments, slope gradient etc. (Bridge 2003, p. 149). Some could be submerged as the water level rises or exposed as it falls. Transient braid bars can split into small components of bar assemblage, while others might merge to form compound bar assemblages. The description of braid bar geometry is based on what was visible through the satellite images and will change with the natural evolving of the bars. However, it provides an overview of possible shapes and sizes that might be of relevance to subsurface studies. The mapped braid bars in the Niger Delta are grouped into four classes based on the landform they are associated with. These groups include: mid-channel bars, bank-attached bars, chute channel bars, and point bar-

attached bars (Figure 10). The mid-channel bars are the most common feature, constituting 57% of the braid bars in the Niger Delta. A total of 82 individual mid-channel bars were mapped out, of which 34 are associated with fluvial channels and 48 with tidal channels. However, the bars associated with fluvial channels are the only ones discussed here. The bank-attached channel bars are the second most common (27%), while the chute-channel bars and the point bar-attached bars represent only 14% and 1% respectively of the entire population. Figure 10 shows an example of a bar assemblage made up of mid-channel bar (MCB); MCB 07b-d. They seem to have formed as a single bar, later separated by channels into MCB 01a, MCD 01d and MCB 01e. MCB 01e is a new extension of the bars assemblage, while MCB 01a was a separate bar now merged with the other bars to form a bar assemblage. BAB 01 is a new bar growth, though separated from the bank by chute channels. They are classified as bank-attached bars as their build-up would have been initiated by the deposition at the bank. MCB 02 appears to be separated from an island by anabranch channels on both sides.

The Niger River system is highly braided (simple braid bars) along its entire stretch. The Braiding Index (BI), decreases downstream from 1.09 at its peak to 0.16 at the Forcados and Nun arms of the Niger River. There are many parameters used by different authors to measure the Braiding Index (BI) (Egozi and Ashmore 2008), including the Channel Count Index preferred by Egozi and Ashmore (2008). However, Friend and Sinha (1993) method was used in this study because it also takes sinuosity into account. The L_{cmax} is the mid-channel length of the widest channel through the reach and L_{ctot} is the sum of the mid-channel lengths of all the segments of primary channels in a reach (entire channel length, which is more than 10 times the average channel width as recommended by Egozi and Ashmore (2008)), and the Braiding Index BI is the braid channel ratio (L_{ctot}/ L_{cmax}).

The area of mid-channel (fluvial) bars ranges from 0.012 km^2 to 6 km^2 (mode is 3 km^2), the length ranges from 166 m to 8,053 m (mode is 1900 m) and the width from 82 m to 1,544 m (mode 120 m). The length to width ratio ranges from 0.65 to 6.85. The area of mid-channel (tidal) bars ranges from 0.005 km^2 to 7 km^2, the length ranges from 142 m to 5,972 m and the width from 54 m to 2,062 m. The length to width ratio ranges from 1.03 to 8.20. The coefficients of regression of the plot of braid bar length against width, length against the area, and width against area fall between 0.8-0.9 mainly. The bar length and width are strongly correlated (Figures 11, 12 and 13). The observed outliers in some plots were associated with composite (amalgamated) mid-channel braid bar. The results found here are comparable to those found elsewhere (Komar, 1984; Sambrook-Smith et al, 2005; Kelly, 2006), which again confirms that the relationship between bar length and width is scale-invariant.

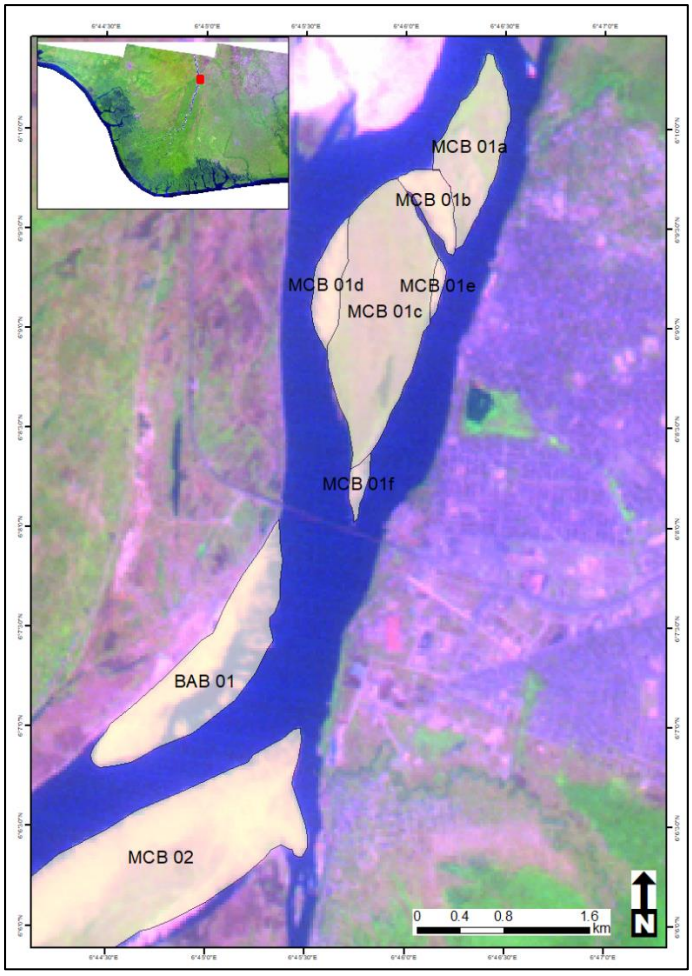

Figure 10: Section of River Niger showing two types of braided bars: bank-attached bars (BAB) and mid-channel bars (MCB).

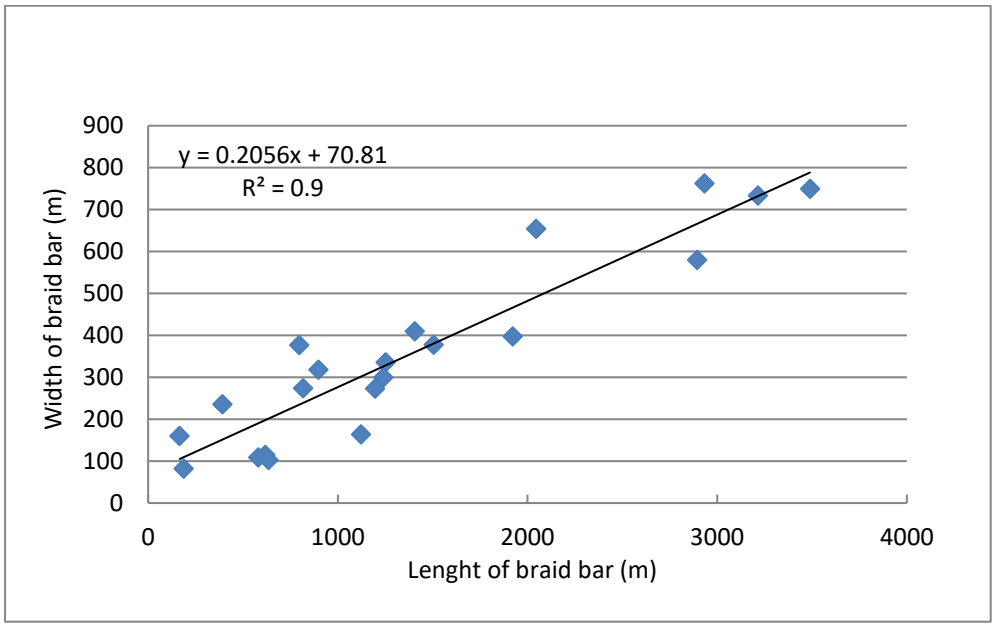

Figure 11: Plot of mid-channel bar width against length. The R^2 is 0.9; it shows a significant relationship between the width and length of fluvial mid-channel bars i.e. the width and length of fluvial mid-channel bars do depend on each other significantly when composite bars are excluded. Thus width-length relationship is stronger in single bars.

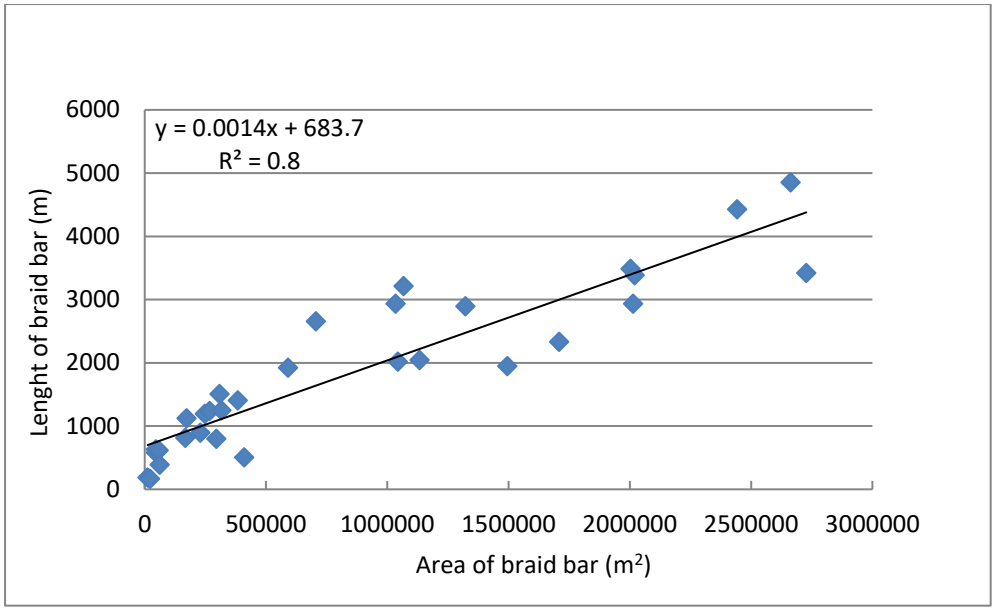

Figure 12: Plot of mid-channel bar length against the area. The R^2 is 0.8; it shows a significant relationship between the length and area of fluvial mid-channel bars i.e. the length and area of fluvial mid-channel bars do depend on each other significantly.

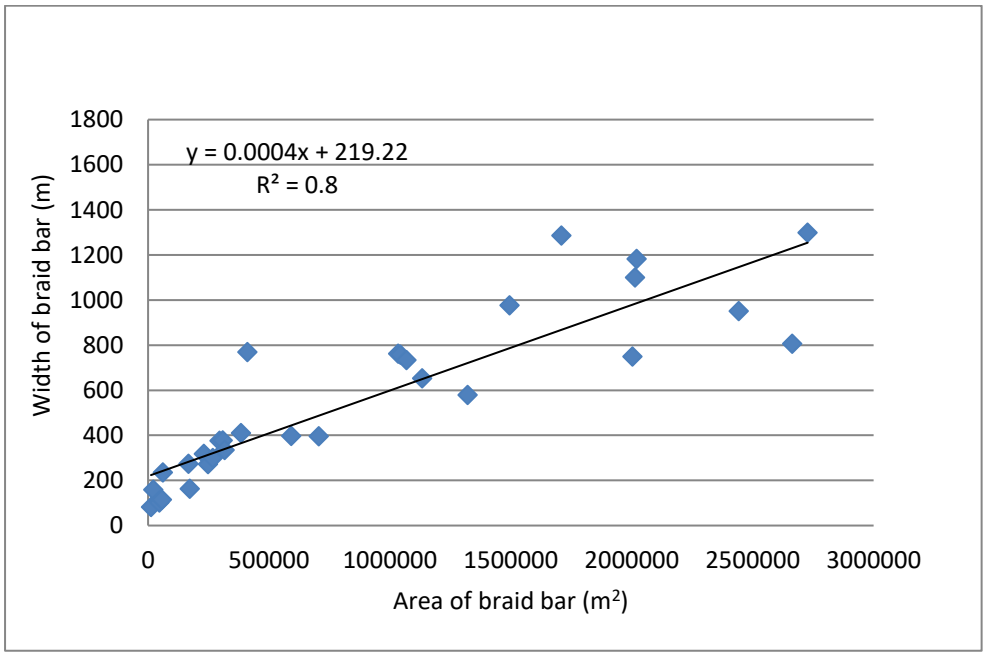

Figure 13: Plot of mid-channel bar width against the area. The R^2 is 0.8; it shows a significant relationship between the width and area of fluvial mid-channel bars i.e. the width and area of fluvial mid-channel bars do depend on each other significantly.

4.5.6 Oxbow lakes.

Oxbow lakes develop by a cut-off of a meander loop; they are usually filled with fine-grained floodplain deposits or abandoned point bar deposits (Miall, 1992). Oxbow Radius of Curvature is the average distance from the channel's bank at any point to the center of the ox-bow lake or point of intersection of two radii. It can be half the

ox-bow diameter (Reading, 1996). Oxbow deposits exhibit a typical fining-upwards sequence (Erskine et al, 1982). The oxbow lakes in the Niger Delta have a mean length of 2000 m and its width ranges from 32 m to 500 m with an average width of 135 m and mode of 162 m. The radius of curvature ranges from 32 m to 1432 m as shown in Figure 14 and 15. Oxbow lakes in the Niger Delta are mostly located at Aghoro and Ayamasa, while other small-scale ones are observed in the upper floodplain. Most oxbow lakes tend to be found outwards from the axial region, where the channels are very sinuous. For example, oxbow lakes were observed along the channel of the Imo River, which has a very high sinuosity (SI of 3.0 and above). The geometry of oxbow lakes in the Niger Delta conforms to that in the Mississippi Delta described by Holbrook and Alexandrowitz (2011).

Constantine and Dunne (2008) observed that oxbow lakes are produced by meander cut-off, which correlates with sinuosity. Diaras et al (2013) explained that topography can influence flooding and cutoff channel initiation as well. In particular, it has been observed that where the topography is low, overflooding is more frequent and cutoff and oxbow lakes are more likely to occur (also see Fagan and Nanson, 2004). That is why most Niger River oxbow lakes are also associated with channels in low relief areas of the lower delta plain. Oxbow lakes are generally filled with fine sediment, within which lenses of coarse sediment are contained. Once buried, these have significant reservoir implications as the fine sediments can act as clay plugs (Dieras et al, 2013).

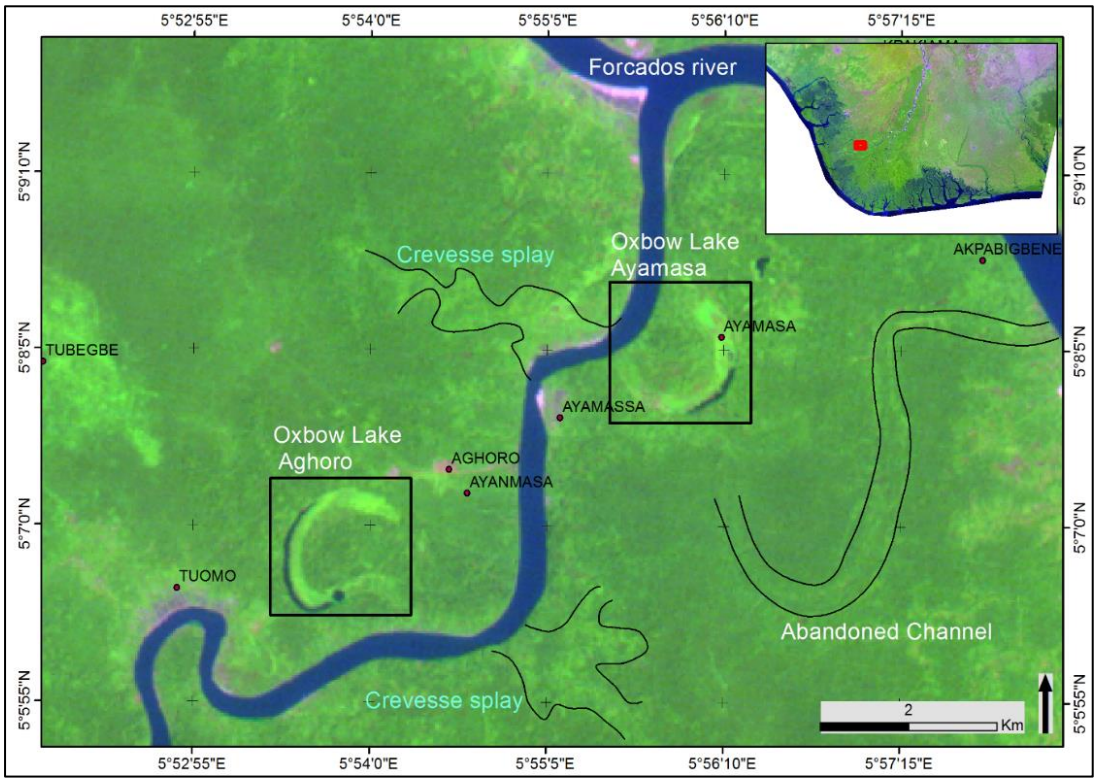

Figure 14: A satellite image showing Oxbow lakes at Ayamasa and Aghoro, from a section of Forcados River.

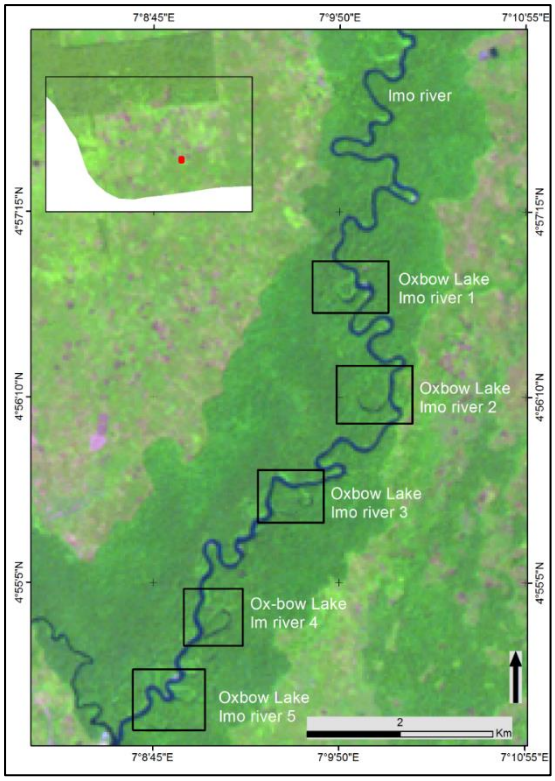

Figure 15: A satellite image showing the Imo River where the sinuosity of the channels that are long and narrow is generally higher than 2.0. There is also a progressive increase in sinuosity with stream order, particularly from first to third order.

4.5.7 Other lakes, Ponds and Cut-Off Channels

Other lakes and ponds are frequent in the Niger Delta, and include, amongst others, Ewuru Lake in the west and Oguta Lake in the east, the largest lakes in the Niger Delta (Figure 16). A pond is a naturally-standing body of water that is usually smaller than a lake. They may occur in floodplains or abandoned channels (Keddy, 2010) either isolate or part of a river system. Ewuru Lake is 8 km long and 300 m wide; Oguta Lake is 20 km long, with an average width of 600 m. The two lakes are elongated along a similar orientation, about 115^{o}N in azimuth, which differs from the general N-S orientation of most Niger Delta channels (fluvial and tidal). It is possible that the lake orientation is controlled by the structural influence of underlying regional faults that separate the depobelts in the Niger Delta (Doust and Omatsola, 1990, Stokes and Mather., 2003, Roberts et al, 2012). These trend east-west and run parallel to the coastline. Most other lakes and ponds are found within the upper floodplain and are shorter, with lengths ranging from 800 m to 3000 m, while their width ranges from 90 m to 280 m. They are interpreted as abandoned cut-off channels of the Niger, Ase, and Orashi rivers as they are aligned in the same direction of flow of these rivers (N-S). They could also play a role in draining the floodplain during and after flooding (Fagan and Nanson, 2004).

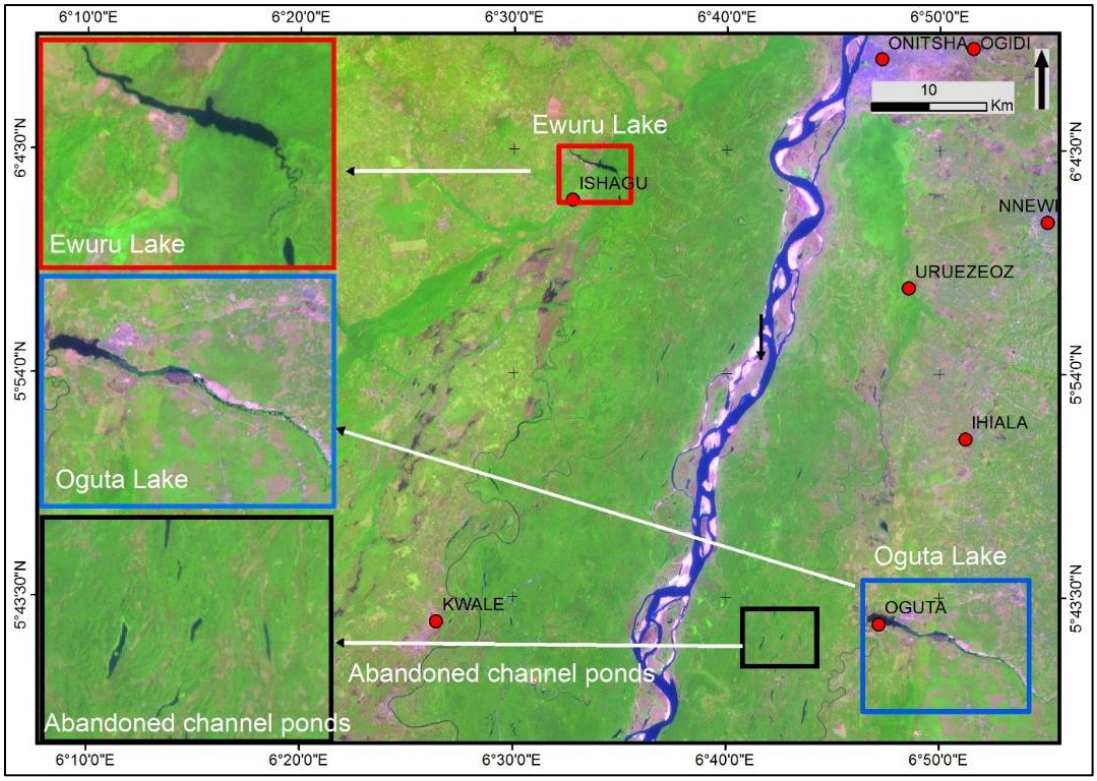

Figure 16: Satellite image of the Ewuru and Oguta lakes, other lakes, ponds, and cut-off channels.

4.6 Geometries of landforms associated with the lower deltaic plain and delta front

Distinct landforms, such as tidal channels (estuarine), beaches and spits braid bars, were mapped in the lower delta plain and measured. The dimension and spatial distribution of these landforms, especially those at the coastal margin, was also used to inform their classification, using Ainsworth et. al (2011) plan-view morphodynamic model. This is a classification model in which the relative influences of tidal, wave and fluvial processes are inferred, looking at the architecture of the landforms and/or either the absence or presence of some components of the landform assemblage (Ainsworth et. al., 2011, and Vakarelov and Ainsworth, 2013). For example, a tidal channel having tidal flats present or absent could indicate the influence of tidal or fluvial process respectively, whereas the presence of beaches indicates the influence of wave processes.

4.6.1 Tidal channels (Estuarine)

The most common morphological elements of the swamp area are the main tidal channels, creeks and inter-creek flats (Figures 17, 18a-d). The tidal channels are typically straight or gently curved and are aligned perpendicular to the coast with the depth ranging from 9 to 15 m (Oomkens, 1974). Many are direct extensions of upland rivers, carrying a mix of fresh and salt water. Smaller meandering creeks interconnect these major tidal channels. The network of tidal channels and creeks breaks up the swamp into a jig-saw of irregular-shaped tidal flats bordered by deep channels, which flood and drain the tidal flats. The inter-creek flats have low relief and show dendritic patterns. These may stem from the densely-vegetated tidal flats (Allen, 1965). At slack tides, the creek waters become still, so that clay-silt floccules, suspended in the brackish waters, become deposited. Once deposited, these cohesive fines are difficult to remobilise and erode.

To establish the fluvial, tidal and wave influence on these landforms, we looked at the presence or absence of beaches at the delta front, mouth bar and tidal flat within the tidal channel and whether tidal channel terminated at the bay-line or are connected to the fluvial channel in the upper deltaic plain. Comparing these to the template by Boyd et al. (1992) model, Ainsworth et. al. (2011), and Vakarelov and Ainsworth (2013), the results show that the overall geomorphic expression of the processes of river, tide and wave varies per group of tidal channels across the delta, dividing it into zones that fit into different parts of the ternary system or category of delta classification:

1. Tide-Wave channels are most common to the west, an area characterised by wide beach ridges, disconnected tidal channels, evidence of sediment starvation, and the absence of mouth bar. Boyd et al. (1992) model captured this region as progradational and affected by wave and tidal power. The area is not tide-dominated but tide-influenced (after Hori and Saito 2007). It is classified as **Tw,** i.e. tide-dominated and wave-influenced, following Ainsworth et al. (2011) (Figures 18a and b).
2. Fluvial-Wave channel landforms are present towards the centre of the lower delta plain, an area characterised by narrow, almost absent beach ridges, connected tidal channels, and spits. In Boyd et al. (1992) model, this region is considered progradational, affected by decreasing wave and tidal power but increasing fluvial power and sediment supply. Using Ainsworth et al., (2011) classification, this area would be classified as **Fw** (i.e. fluvial-dominated and wave-influenced, Figure 18c).
3. Tide-Wave channel landforms are typical of the east, where wide beach ridges, wide disconnected tidal channels and signs of sediment starvation are common, while there is no mouth bar. In Boyd et al. (1992) model, this area can be considered progradational, with an increasing wave and tidal power). Using Ainsworth et al., (2011) classification, it is **Tw** i.e. tide-dominated and wave-influenced (Figures 18a and b).
4. Tides are the dominant process to the Far East channel, where no beaches are found but transgressive tidal flats are present. Cross and Rio del Rey rivers are high-energy transgressive estuaries (Whiteman 1982). In Boyd et al. model (1992) model this region fits into the tide-dominated estuary class, which is transgressive with increased tidal power. In Ainsworth et al., (2011) classification the area will be classed as **Tf**, i.e. tide-dominated and fluvial-influenced (Figures 18d).

Although, we have divided the Niger Delta into four zones with each zone having a unique landform in response to the dominant delta forming process(es), the overall geomorphic expression of these processes of river, tide and wave across the entire Niger Delta is considered as a sum of the processes in the four subzones. Therefore, in the context of Ainsworth et. al. (2011), and Vakarelov and Ainsworth (2013) model, using the landforms of the lower-delta plain and delta front, the Niger Dela is essentially classified as tide-dominated, wave-influenced and fluvial-effect (Tw*f*). This implies that the Niger Delta is classified as a mixed delta using the tripartite model in agreement with previous publications (Short and Stable 1967, Doust and Omatsola, 1990)

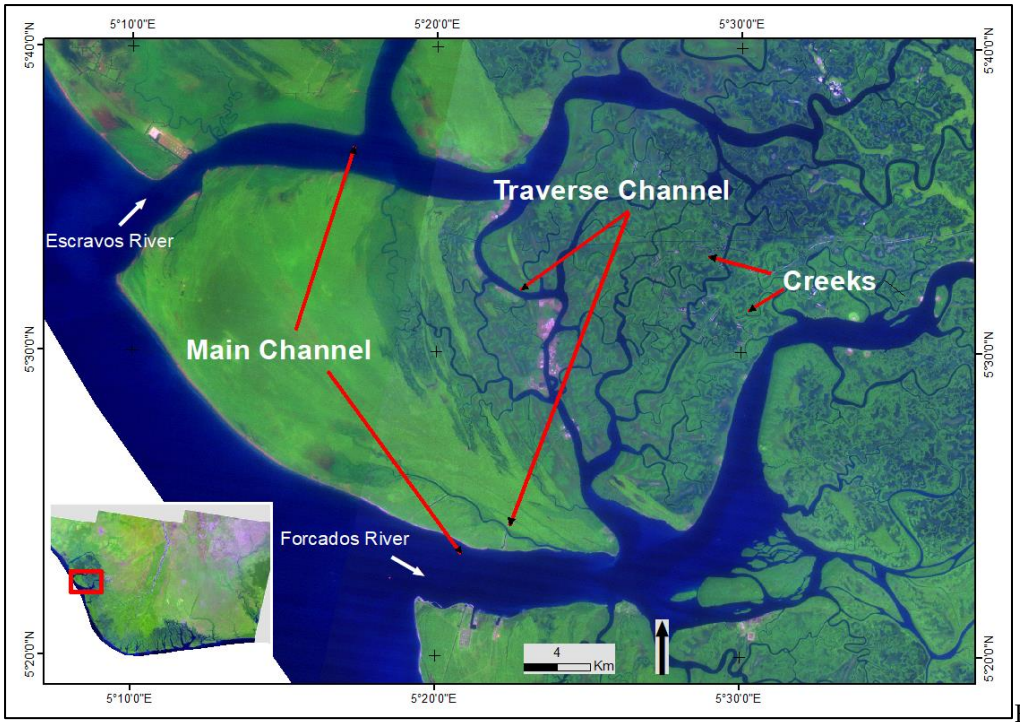

Figure 17: Western tidal channels: part of the lower delta plain and delta front showing the channel style of the main tidal channel running perpendicular to the coastline.

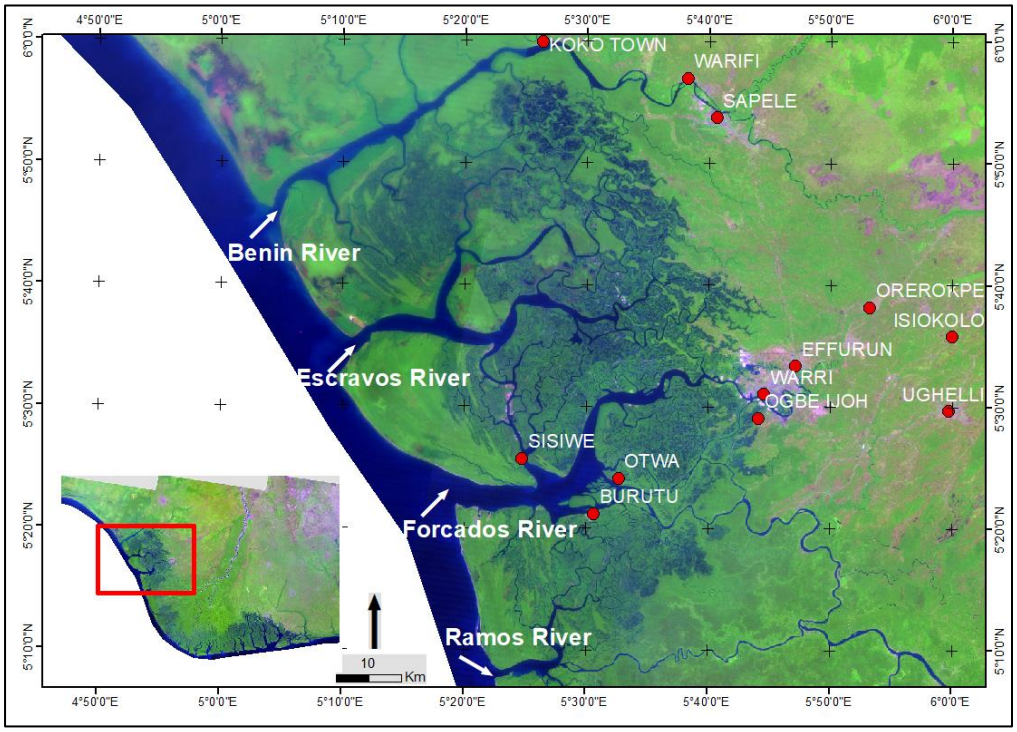

Figure 18a: A satellite image of the western tidal channels (in blue). These are wider than the central tidal channels in Figure 18c. This is due to the impact that high tides have on these western channels because they are connected to abandoned channels and therefore starved of sediment supply, it is classified as **Tw,** (i.e. tide-dominated and wave-influenced, following Ainsworth et al. 2011).

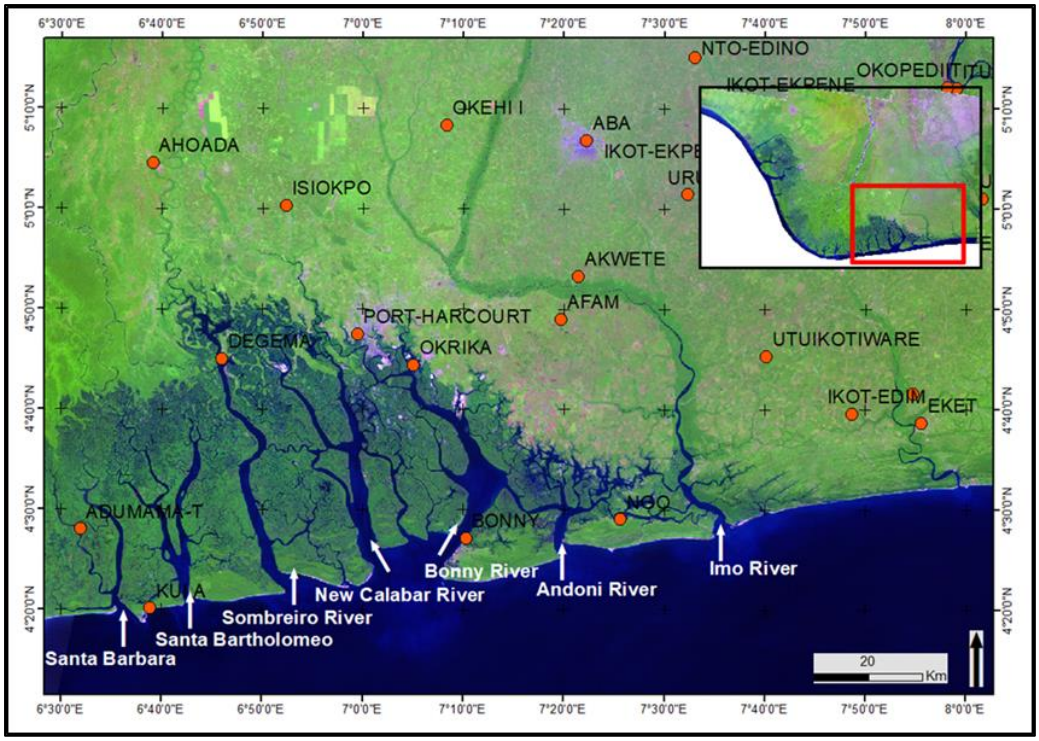

Figure 18b: A satellite image showing the eastern tidal channels (in blue). These are wider than the central tidal channels in Figure 18c because are connected to abandoned channels, and therefore are starved of sediment supply and more strongly impacted by the action of high tides. it is classified as **Tw,** i.e. (tide-dominated and wave-influenced, following Ainsworth et al. 2011).

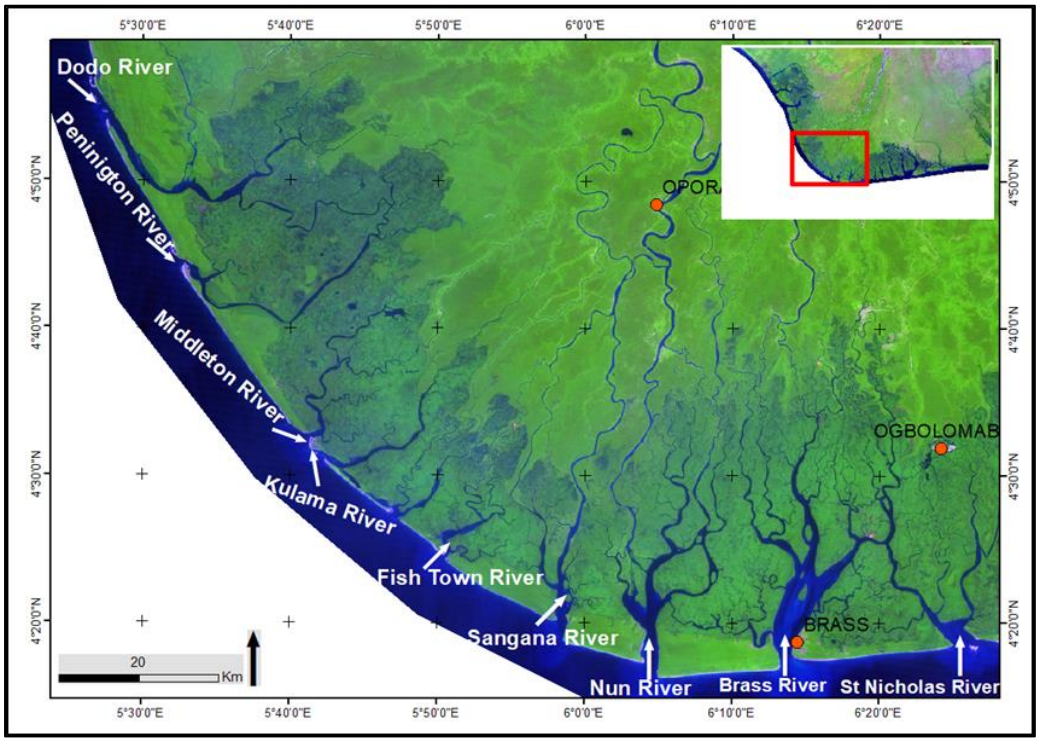

Figure 18c: A satellite image showing the central tidal channels. These are narrower than the western and eastern tidal channels in Figures 18a and b. The tidal channels at the central part of the Niger Delta are directly connected to fluvial channels (active) that supply sediment into the ocean through them. With high sediment supply, the impact of the tide in widening them is reduced, thus channels in this zone of high sediment flux are narrower. It is classified as **Fw** (i.e. fluvial-dominated and wave-influenced, following Ainsworth et al. 2011).

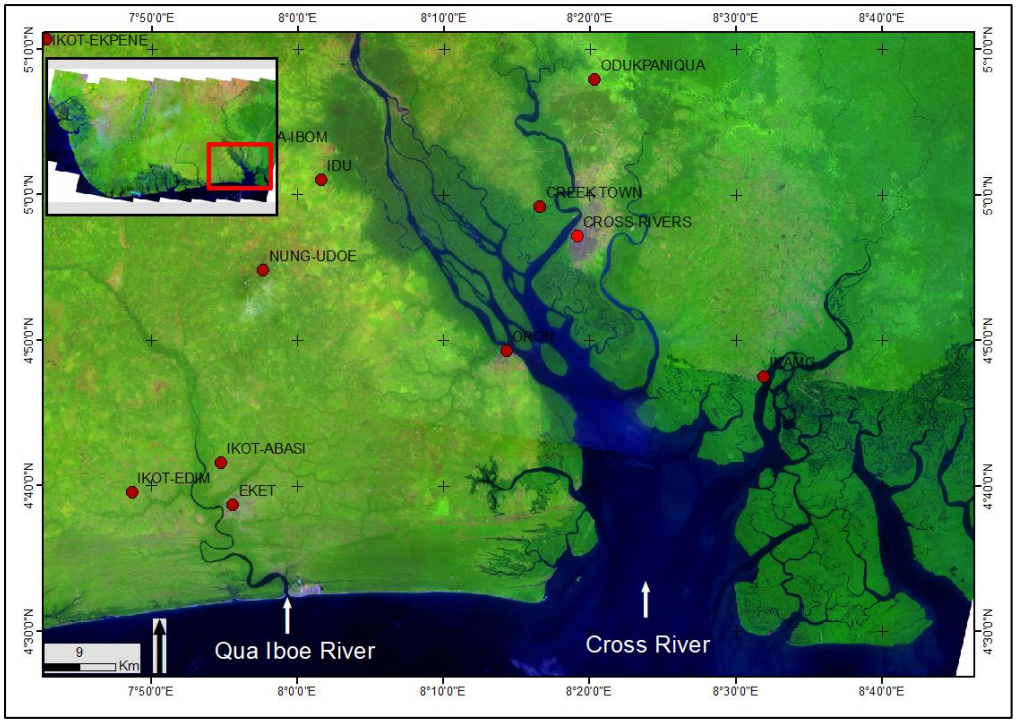

Figure 18d: Far-East channels showing the channel style of the main tidal channel running perpendicular to the coastline. The widest shows evidence of tidal flats which indicates high tidal impact with no obvious evidence of wave impact. it is classified as **Tf**, (i.e. tide-dominated and fluvial-influenced, following Ainsworth et al. 2011).

4.6.1.1 Tidal channels width variation

Tidal channel width variation along the channel profile was plotted for 21 tidal inlets. The results from these plots (Figure 19) shows that width of the tidal channels reduces exponentially upstream (see the relationship in equations), moving from the coast, where the width is widest, towards the channel head. In contrast, fluvial channel width decreases downstream linearly. This is a key characteristic to distinguish tidal and fluvial channels in the Niger Delta and can be of relevance in understanding the paleogeographic context of subsurface deposits. Similar trends have been identified elsewhere (Wright et al., 1973; Pethick, 1984; Eisma, 1998; Fagherazzi & Furbish, 2001; Harris at al., 2002; Marani et al., 2002; Davies & Woodroffe, 2010; Hughes, 2012). The relationship between tidal channel width and distance along the channel for the Niger Delta can be summarised as:

$$Y=0.8952e^{-2.913x} \quad \text{Equation 2}$$

Equation 3 is the general form of Equation 2

$$Y=W_m e^{-rx} \quad \text{Equation 3}$$

Where

- Y = Tidal channel width at any point along the channel
- W_m = Tidal channel mouth width (547 m-6000 m, mostly 1000 m-5000 m)
- x = Distance along channel
- r = Rate of change of channel width

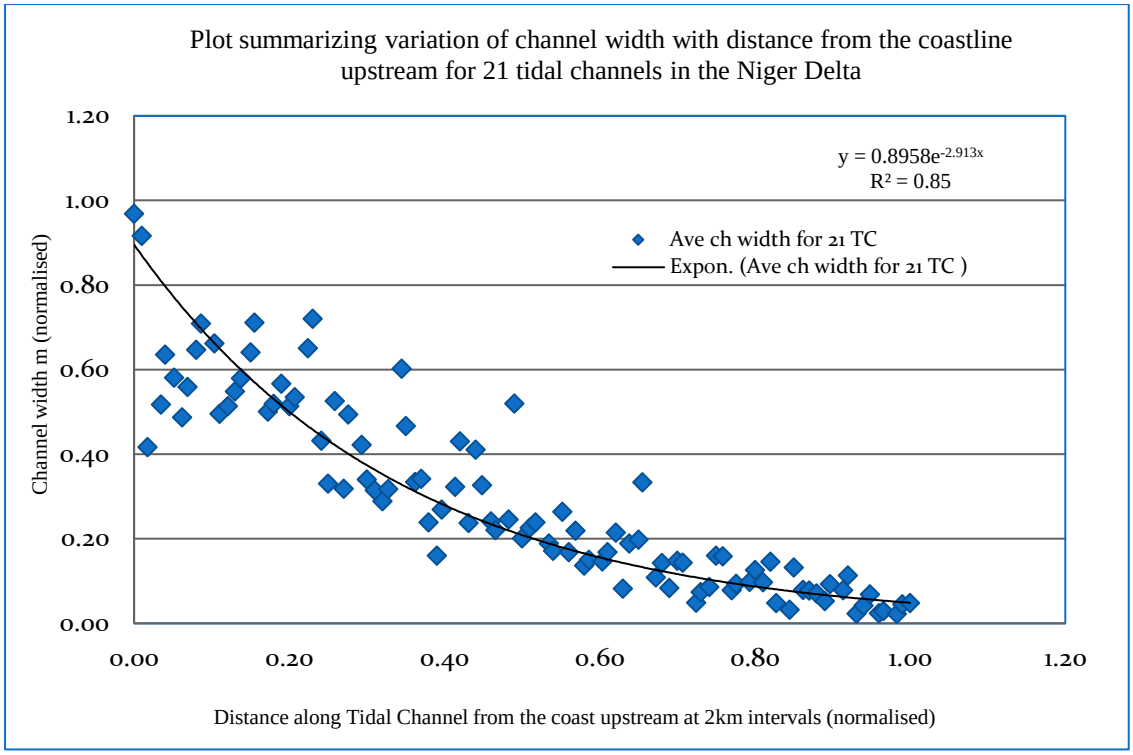

Figure 19: Plot summarizing variation of channel width with distance from the coastline upstream for 21 tidal channels in the Niger Delta

4.6.2 Beaches, Barrier bars and Islands

The ridges and swales have been constructed by the lateral or offlap accretion of successive sediment layers culminating in low ridges (Figure 20). In general, the youngest set of ridges and swales closest to the sea are sparsely covered by vegetation, having been impacted upon by strong wave action. The outer meander bank is generally high and steep, commonly showing a section in levee or backswamp sediments. The beach ridges are separated, one from another, by deep tidal ebb-flood channels leading to the swamps. The entire coastal margin of the Niger Delta is rimmed with elongate beaches and barrier islands (as reported by Allen 1965, Whiteman, 1982). There are 20 beach ridges separated from each other by tidal inlets, as shown in Figure 20.

These beaches are longer and wider on the eastern and western flanks and thin-out in length and width towards the centre of the delta coastline. The beaches are narrower in the central part because fluvial action is predominant, while at the flank tide and wave processes are predominant and support beach formation. Beaches are completely absent in the far-east Cross River; the tidal action is predominant here as compared to any other part of the Niger Delta coastline. The beach ridges are important because they indicate progradation of strand plain (ancient coastlines) and thus are associated with sea level fluctuation (Otvos, 2000).

The ridge and scroll orientation in all the beaches are parallel to the coastlines, except the Imo-Qua-Ibo beach (Figure 20-part B) that displays more than three distinct sets of accretion ridges. This is interpreted to have been formed at different times and a possibly different set of environmental conditions. The Cross-River supplies most of the sediment to this region. The area is characterised by tides higher than 4 m (macrotidal), whereas other

regions have tides lower than 2 m (microtidal to mesotidal) (Oomkens, 1974); this could account for the difference in overall morphology of the tidal inlets too. Tidal channels' width ranges from a few hundred meters to 12 km but is mostly about 5 km. The larger ridges, consisting of bundles of the smaller ones, are as long and reach widths of 1.5 km.

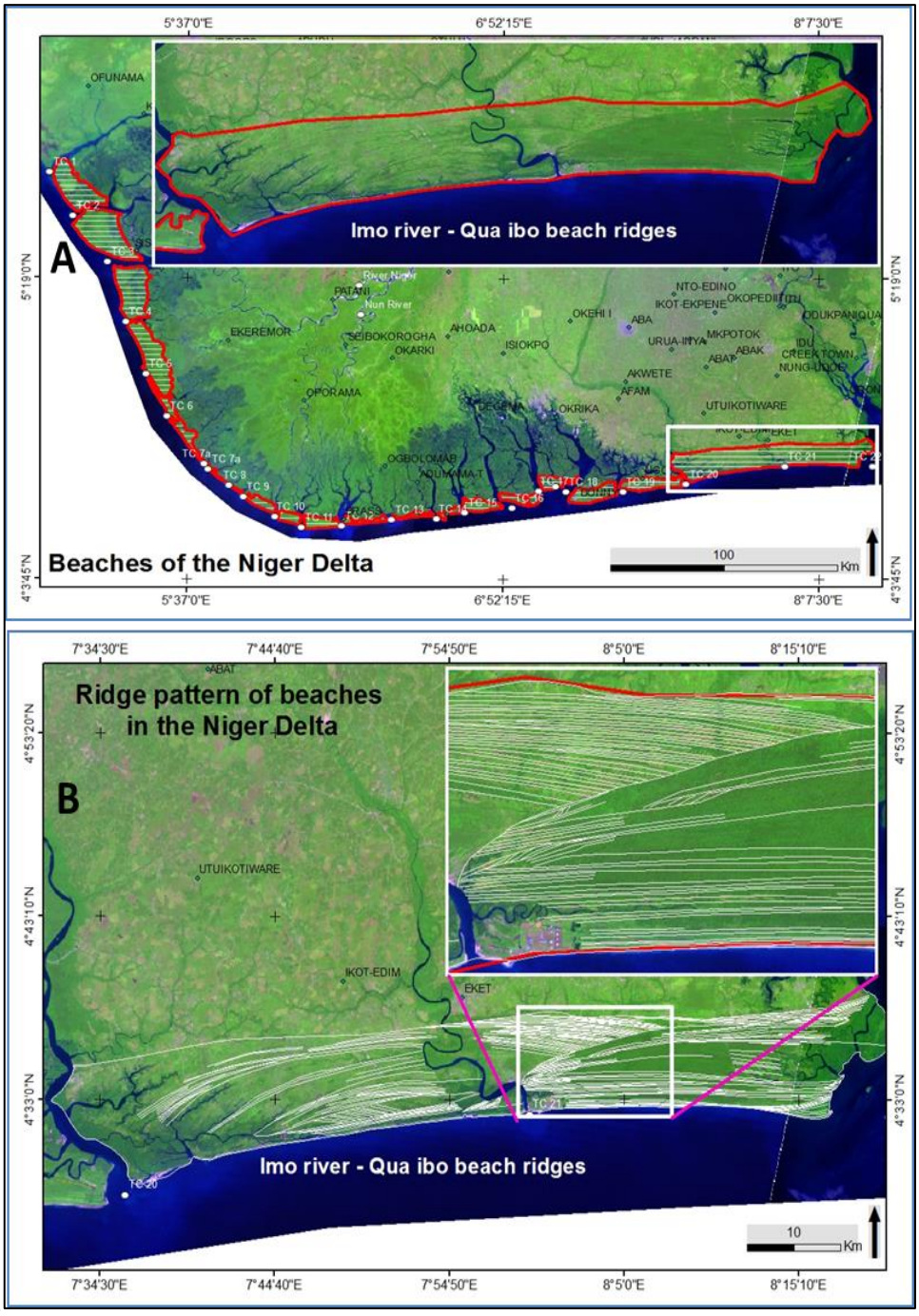

Figure 20: **A**- Mapped beaches in the Niger Delta. Insert: Imo-Qua-Ibo Beach. **B**-Imo-Qua-Ibo Beach; the longest and the most complex with more than three generations of accretions ridges (i.e. ridges are different in pattern and directions unlike the rest in the Niger Delta)

4.6.3 Spit

Spit landforms were observed and mapped in the central part of the Niger Delta coastline (Figure 21). Spits are the physical expression of wave actions and longshore drifts. They grow in the direction of littoral drift forming larger beach ridges with time., It is suggested that the smaller ridges result either from changes in sand supply along the beaches or from the march of offshore bars onto the exposed beach (NEDECO, 1954; 1961). Spits record major changes in the shape of the coast resulting from changes in river and the tidal regime, the direction of wave attack, and sand supply. The breaking swell releases much physical energy on the beaches. Sand is incorporated into the beaches wherever made available to the wave-generated longshore currents.

The presence of spits in the Niger Delta indicates that the delta morphology is influenced by waves (Ashton and Giosan 2007, Bhattacharya and Giosan, 2003). They are of concern in this study because of the role they play in sediment redistribution and on delta morphology. Spit bidirectional morphology (Figure 21) shows that the longshore drift in the Niger Delta is bidirectional (this paper, Allen 1965; Whiteman, 1982).

As the wave action hits the coastline at the apex, it diverges to the east and west causing sediment redistribution with a strength of wave force and longshore current strong enough to override tidal influence in this region. As the spits grow, they tend to cover the channels and subsequently increase the angles of the channels to the coastline. This, in turn, reduces the dispersive impact of tides on one hand and increases delta progradation from sediment influx from the river on the other hand (Ashton and Giosan 2007, Wright and Coleman, 1973; Bhattacharya and Giosan, 2003). The horizontal distance between tide marks ranges typically from 50 to 150 m, and the slope of the intertidal part of the beach generally ranges from 1:100 to 1:50 (NEDECO, 1954, p. 84).

Using the FitzGerald et al. (2001) model the spit accretion in the Niger Delta fits into the “Time 1; Inlet Migration and Spit Breaching”, while most of the other tidal inlets fit into the “Time 1; Stable Inlet Processes”. In both cases, sand bypasses the tidal inlet (FitzGerald et al., 2001; FitzGerald et al., 2012). Also, using the tidal asymmetry model by Bhattacharya & Giosan (2003) for the classification of wave-influenced deltas, tidal inlet morphology in the Niger Delta shows that fluvial, tidal and wave influence varies along the coastline. Most tidal inlets at the central part of the Niger Delta fit into the asymmetric and deflected end members (Figure 18c), which indicates higher sediment discharge and longshore drifts and is typical of deltas preserving a lower proportion of fluvial-derived mud (Bhattacharya & Giosan, 2003, Bhattacharya, 2006; 2010). At the flanks, the inlets fit into the second row-symmetric (Figures 18a and 18c), an indication of deltas comprising more heterolithic deposits. This is a clear indication of the differential influence of the river sediment discharge and the dispersive effect of the longshore drift. The morphology and spatial distribution of the landforms (tidal channels, beaches and spit) were used to characterise each coastal zone, following the delta ternary classification and the asymmetry and spit accretion models of Bhattacharya & Giosan (2003) and FitzGerald et al., (2001).

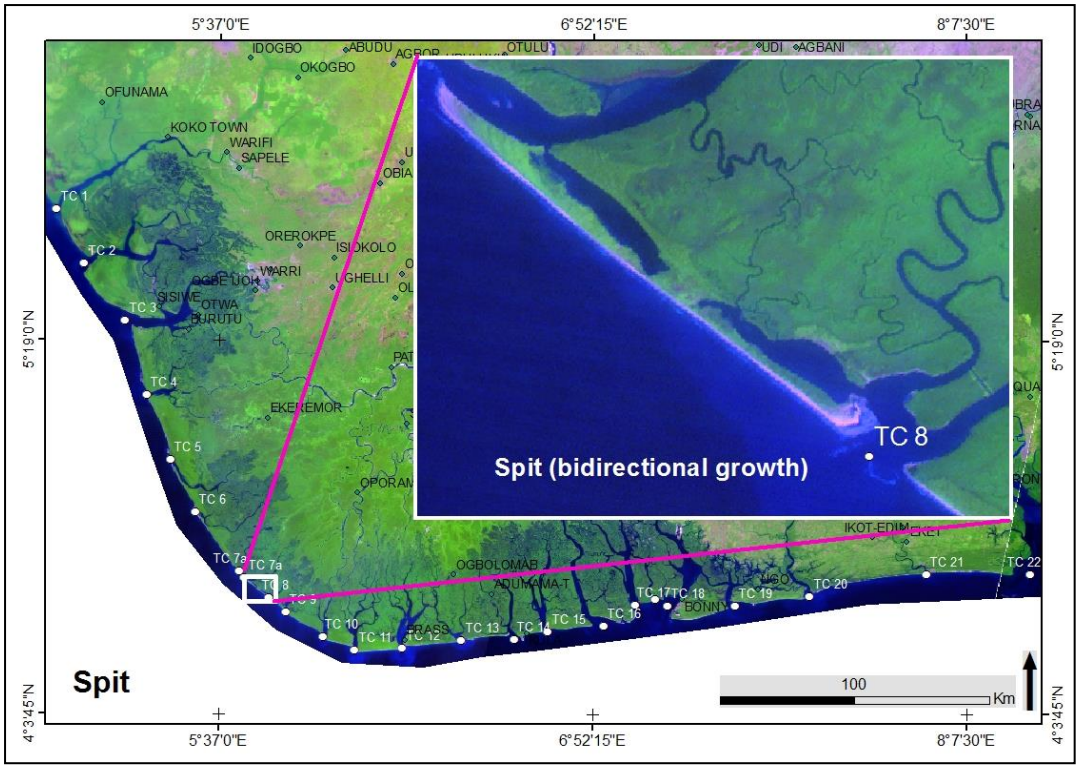

Figure 21: Bidirectional spit development at the apex of the Niger Delta. Spit development is common in the central part of the Niger Delta.

5 Summary and Conclusion

The sedimentary environments in the Niger Delta include a mix of fluvial, tidal and wave-related deposits and landforms, thus indicating that the Niger Delta is a mixed delta. The extent of the delta has been revised from the original works of Allen (1965) and Short and Stauble (1967). Analysis from this study reveals that the area of the entire Niger Delta is 70,000 km^2, of which the upper deltaic, lower deltaic and delta front portions are 69%, 25%, and 6% respectively.

Each of these three main environments is characterised by distinct sedimentary and geomorphological processes and landforms. Therefore, using Ainsworth et. al. (2011) and Vakarelov and Ainsworth (2013) model and applying it to the landforms of the lower-delta plain and delta front, the Niger Delta is essentially classified as tide-dominated, wave-influenced and fluvial-effect (Tw*f*).

The upper delta plain is further divided into: dry flat land, upper floodplain, lower floodplain, and the abandoned channel zone. The dimensions and spatial analysis of each of these zones revealed that they are mostly influenced by fluvial activities, unlike the lower delta plain and delta front that are dominated by tidal and wave-related activity respectively.

Also, the geometric analysis of constituent landforms in these zones indicates that the fluvial channel width reduces downstream linearly, contrary to the tidal channel width that increases exponentially downstream. Point bar width and length, as well as point bar width and channel width, show strong correlation and dependence.

Also, braid bars width, length, and area show strong correlation and dependence with each other. The width of the upper floodplain is fairly constant, implying that the change in its ratio (floodplain width to channel width, along the same path) downstream is not controlled by the change in channel width. Therefore, the variation of floodplain width does not depend on the width of the channel that floods them.

The orientation of most cut-off channels follows the dominant N-S orientation of the whole delta system. However, the two largest lakes of the area, Ewuru, and Oguta lakes, follow an E-W orientation, likely controlled by the underlying E-W regional faults of the Niger Delta.

Overall, results from this study offer invaluable information on the spatial distribution and dimensions of these sedimentary environments. The ratios and correlations of the dimensions of these sand bodies remain scale-invariant, regardless of the variations in their size. The geometry and spatial distribution of these geobodies are not only ideal to develop and/or test geomorphological models attempting to predict the evolution of deltas (dominance, influence or effects of delta forming processes) but they are also vital in predicting the distribution of sand bodies in the subsurface. The dimensional analysis of individual sand bodies is key in reservoir modelling to constrain facies proportions and to estimate the unknown dimension based on the statistical relations presented here. This study is particularly important because the results can be used as analogue with which the geometry and distribution of buried landforms can be constrained, within and beyond the Niger Delta.

6 Acknowledgment

Chinotu Franklin George would like to thank his sponsor: Petroleum Technology Development Fund (PTDF) and SPDC Port Harcourt for providing the satellite images used. He expresses his gratitude to his mentors: Dr. K. O. Ladipo and late Professor L. C. Amajor, and to Ms. Okwuchi Omekara for the technical support, she offered for data assembly.

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