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GEOMORPHOLOGICAL MAPPING OF PART OF THE NIGER DELTA, NIGERIA USING DEM AND MULTISPECTRAL IMAGERY

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ABSTRACT

This study utilised geo-information technology to carry out a geomorphological mapping of a part of the Niger Delta. Satellite image analysis was based on bi-annual seasonal approach using a combination of visual analysis of the geometry, site, situation, colour, and season for analysis of the non-topographic features. The study also utilised virtual and onsite fieldworks and existing geomorphologic information to interpret and analyse topographic and bathymetric features. First-order topographic features (elevation) and second level features including slope, aspect, curvature and mathematically exaggerated shaded relief were extracted from DEM. Relief classification was based on average elevation differences, hill shade, slope, and aspect. Three main non-topographic landforms were identified; the permanent rivers with stable meanders, perennially-active systems of creeks and fluvial landforms including scroll bars and oxbows. With the exception of higher elevation values towards the north-western fringe, the elevation ranges between mean sea level and 1 metre above sea level thus establishing a somewhat flat terrain. These areas were filled with meandering streams, sinuous creeks and watercourses flanked by mangrove vegetation. In the north-western area, elevation rose close to approximately 4 metres in most of the area with a peak of 10 metres. Generally, the cumulative area-slope analysis yielded a deltaic plain with generalised slope ≤ 2^0. Overall two elevation-based geographically differentiated morphological units were identified; tidal mudflats and saltmarshes. The study recommends that to provide needed information for resource planning and management, further investigation should be carried out with a view to modelling probable ecological and geomorphological changes in the entire Niger Delta.

Keywords: Remote sensing; Coastal geomorphology; Geomorphologic units; Tidal mudflats; and Saltmarsh landform.

INTRODUCTION

Geomorphological mapping plays a fundamental role in the understanding of the multifarious nexus between earth process, geochronology, natural resources, natural hazards, landscape evolution and possibly landscape changes (Bishop and Shroder Jr., 2004; Bishop, James, Shroder Jr. & Walsh, 2012; Isola, Bini, Ribolini, Zanchetta & D'Agata, 2017; Palmtag, Cable, Christiansen, Hugelius & Kuhry, 2017; Zhang *et al*., 2017). Besides, the end product of geomorphological mapping is a coalesce of several procedures involving apportioning of the terrain into distinct spatial units or entities based on variables that include morphology, genetics, composition and structure, chronology, environmental systems association (land cover, soils, ecology) as well as spatial topological relationships of surface features (landforms) (Bishop, Shroder Jr., & Colby, 2003; Minár, Evans, & Krcho, 2013; Schillaci, Braun & Kropáček, 2015; Palmtag *et al*., 2017; Zhang *et al*., 2017). There are five distinct scientific complexities and issues that are associated with geomorphological mapping as stated by Bishop *et al* (2012). These include; (a) establishment of comprehensive taxonomic/classification schemes; (b) possibility of geomorphologic mapping at a variety of scales; (c) characterising indeterminant boundaries; (d) establishing universally applicable criteria for characterisation; and (e) obtaining objective repeatable results. In an attempt to resolve these issues, several studies have been conducted to provide place-based contextual responses to the development of geomorphologic taxonomic schemes for landforms with the use of geospatial technologies in some parts of Europe and the Americas (Bishop *et al*., 2012; Tucker & Hancock, 2010; Hengl & Rueter, 2009).

Historically, the development of geospatial technology i.e. the use of remotely sensed data and Geographic Information Systems (GIS) typifies the emergence of a technology fashioned after the military in which airborne methods became vital to assess the opposing lines. This period was prelude to the development of the photographic camera, the lens and photographic image production which were developed and advanced in this region as far back as the early 19th century. Subsequently, the technology diffused to civilian use paving the way for its emergence in the academics and other resource management uses.

In geomorphologic analysis, the best illustrations are mere graphic depictions in the form of block diagrams and graphic impressions that were highly erroneous with exaggerated landform expressions. These artistic illustrations, though guided in landform representation and interpretation, lack quantification which is key to understanding the geomorphic processes and probable landforms that could occur as a result of such change (s). As a result, geomorphic studies were limited to in situ sample collections and point-based analysis. The possibilities of topographic mapping involving less erroneous 3-D mapping and geovisualisation possibilities of landforms emerged during the decades sequel to the end of the Second World War. This was the period when aerial photographs became the latest tool in surficial landform mapping through the use of both vertical and oblique aerial photos based on various photogrammetric techniques. The level of quantification greatly improved with the use of thermal photos and stereo-mapping procedure, which permits cartographic modelling of land surface with 3-D possibilities. Through this procedure, landform slope, angle of inclination, altitude, and aspect became measurable. The main drawback of this, however, is that it lacks global coverage with availability limited only to special missions within the localised areas of the developed world (Bishop *et al*., 2012). At the turn of the 20th century, advances in earth observation sensors with space-borne components led by Landsat, SeaSat, as well as series of airborne and special missions such as the Shuttle Radar Topographic Mission (SRTM) and the use of unmanned aerial vehicles (drones technology) have expanded the use of remote sensing technologies.

Since the phenomenon of modelling follows mapping in the earth sciences, the same was evident in geomorphology. The development of the science of the geographic information in which phenomena modelling is now possible with various 2-D and 3-D mapping technologies based on several software data formats. Also included is the development of a database management system that provides feature attribute information editing, and updating. Advances in geobrowsers such as Google Earth, NASA World wind, Microsoft Bing Maps and others have also provided added opportunities to the use of these geospatial technologies as tools for virtual fieldworks, virtual landform mensuration, offline and online landform mapping amongst other possibilities. Assessment and modelling of earth shaping events are now a possibility, such that gradual soil creep can be measured while the possibilities of gully formation can be assessed remotely (Ruszkiczay-Rudiger, Fodor, Hovath, & Telbisz, 2009; Tucker & Hancock, 2010; Connallon & Schaetzl, 2017).

These have also birthed a new branch of geomorphology known as geomorphometry (Bishop *et al*., 2003; Gressler, Pike, MacMillan, Hengl, & Reuter, 2009; Hofierka, Mitasova, & Neteler, 2009; Bishop *et al*., 2012). With geomorphometry aided by geoinformation technology, the geographic landscape is now better understood in terms of the gradual and swift processes shaping the earth (Khadri, Thakare, & Armal, 2015) including the processes of land change and earth change driven by intrinsic and extrinsic processes. The multispectral remote sensing has been used in mapping process-driven earth change in coastal areas such as Lagos (Odunuga *et al*., 2013). It has also been utilised to understand the nexus between geological formations and surficial geomorphology of an area with manifestations of lineaments and the consequential landforms (Sivakumar, 2015). In the same fashion, Minár *et al*., (2015) have established the fact that quantitative assessment driven by various measures derived from various geospatial sources are fundamental to understanding both the process and products of land change. A key tool that has been used for surficial geomorphometry is the digital elevation model (DEM) whose advanced form is referred to as the digital terrain model (DTM) or the digital surface model (DSM). This integrated depiction of elevation is a measure of the assessment of landforms and changes can be used to monitor probable changes. Temovski & Milevski (2015) conducted a study in Macedonia to assess the changes in the fragile karst landscape of the country using the DEM and stratified Landsat-derived landcover. Also, Isola *et al* (2017) produced a 1:25,000 geomorphology map of the lower plain of the Ceyhan River (Adana Province, Turkey) using GPS, Landsat ETM+ and ASTER DEM. Geomorphometry has been extended beyond the surficial to the seabed and marine with a series of multispectral, LiDAR, SoNAR and thermal applications used for the development of the seabed bathymetry and associated marine geomorphology data (Lecours, Dolan, Micallef & Lucieer, 2016).

The coastal Niger Delta is one of the most ecologically-complex and environmentally-diverse ecosystems in the world. The area is abundantly rich in geological resources yet with fragile ecosystem including coastal dynamics, swamps and series of wetlands. Undoubtedly, these are pointers to possible landform alterations. Several studies have been conducted on the Niger Delta that examine coastal morphology, physical processes, and near-surface dynamics of the area.

These were conducted in the 1950s, 60s and the early 1980s specifically to understand the different classifications of the coastline, riverine processes, near-shore ocean processes, sediment character, coastal flooding and baseline mapping (Fabiyi & Yesuf, 2013; Sexton & Murday, 1994). Even though there were attempts to provide a base for the understanding of the baseline surface geomorphology in the works such as Allen (1970) as stated by Sexton & Murday (1994), some of these were based primarily on a quasi-quantitative analysis of the fluvio-marine processes, sedimentology, and the simultaneous erosional and depositional processes taking place at the eastern and western flanks of the Niger Delta.

Currently, the landscape of the Niger Delta with series of alterations is governed by a mixture of natural and anthropogenic processes operating at a scale that is better captured by geospatial technology. The extent of human activities on the natural landscape needs to be investigated in line with the current landforms in order to ascertain their geo-ecological implications. This study will also provide the basic landform characterisation of the Niger Delta is important for targeting hydrocarbon trap/deposits, detection of seismic zones, erosion, flood control and management. It is against this background that this study is conceived to develop a GIS-based procedure for the identification and extraction of the morphological features of the western section of the Niger Delta. This is based on the use of digital elevation model and multispectral imagery to map out the different geomorphological units, and the respective landforms of the area.

The Study Area

The study area occupies a significant portion of the entire Niger Delta basin (Fig. 1a) referred to as the Western Delta flank owing to its distinct geomorphic processes when compared to the central and eastern flanks. The western delta flank is geographically defined by the basins of three major rivers - Benin, Escravos, and Forcados. It lies approximately between longitude $5^{0}12'$ and $6^{0}4'$ East of the Prime Meridian and latitudes $5^{0}1'$ and $5^{0}47'$ North of the Equator. It covers a land area of approximately 6,800 km^2. The extent of the coastline stretches for about 45 kilometres across the curvilinear expanse between the River Benin and Escravos River at the southwestern end of the study area (Fig. 1a). This section occupies a significant aspect of the largest river delta in Africa discharging an average of over 30,000 m^3 volume of water per second into the Atlantic Ocean (Goudie, 2005).

The Western Delta flank lies mostly in Delta State of Nigeria while a fraction extends into Edo State (Fig. 1b). It covers a total of 15 Local Government Areas (Sapele, Okpe, Ethiope East and West, Ughelli North and South, Uvwie, Warri South, Southwest, and North, Bomadi, Burutu, Patani and Udu in Delta, while it covers parts of Orhionmwon Local Government Area of Edo State.

The mean annual rainfall of the area reaches as high as 3000 mm and the mean annual maximum temperature averages $27.8^{0}C$. As an area within the humid tropics, recorded humidity is high all year round; this could be as high as 90%. Geologically, the area lies within the Western Niger Delta sector of the extensive sedimentary basin of West Africa. This is typified by beach ridge sands and mounds at the coastline base; extensive mangrove swamps, lagoonal marshes and back freshwater swamps; deltaic basins and tidal flats; and Sombreiro-Warri deltaic plains

(Wright, Hastings, Jones and Williams, 1985). The vegetation of the area is pre-dominantly mangrove and freshwater swamps, tidal flats, palm bush as well as marsh typified by low elevation green-swards. Soils are deeply and poorly drained clay loam, sandy loam surfaces and sandy clay loam soils mostly of alluvial origin and freshwater swamps. Elevation is generally low with 0 m above mean sea level at the coast and water surfaces to about 15 metres further inland. The southwesterly wind with direction averaging 200^{0} to 230^{0} dominates the coast of Nigeria. This is active all-year-round with higher intensity in stronger and sustained winds during the wet season from June through to November. The wave regime that accompanies this wind has a pronounced effect on the coastal morphology and the resultant landforms in the form of depositions and formation (Sexton & Murday, 1994).

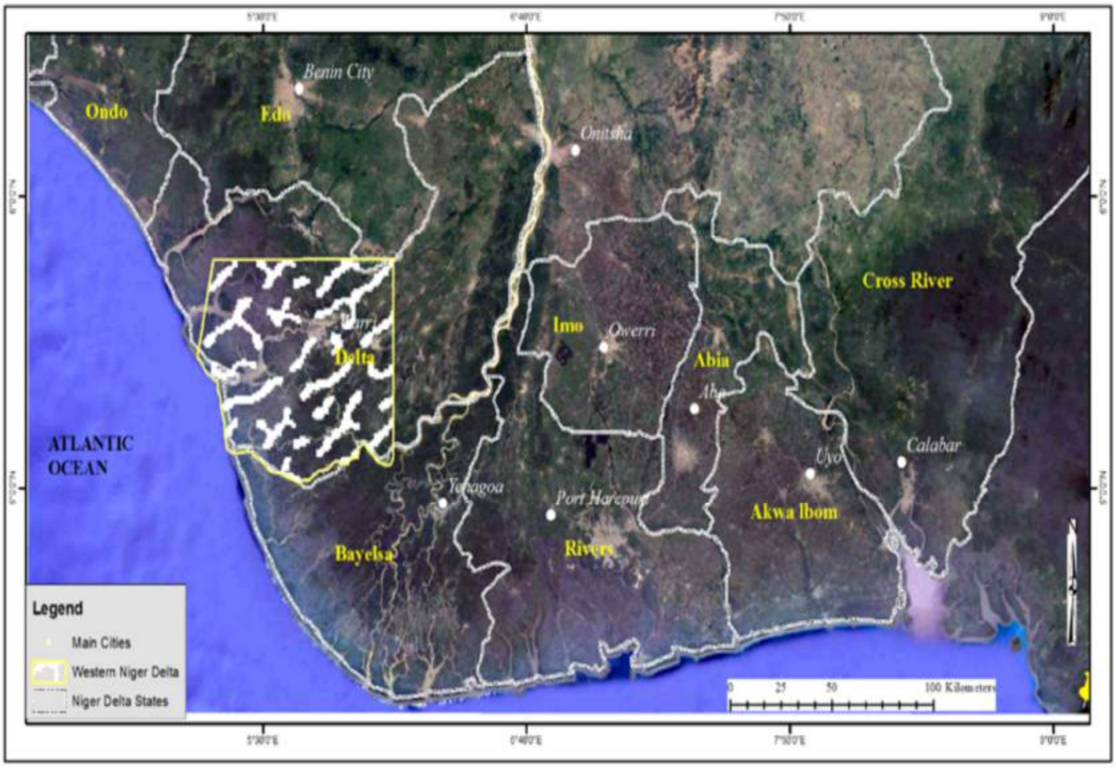

Figure 1a: Google Earth image map of the extended Niger Delta displaying the political divisions (States) and the shaded aspect of the Western Niger Delta (The Study Area). The image map further depicts the littoral form of the Niger Delta and the morphology of the coastline and the Atlantic Ocean.

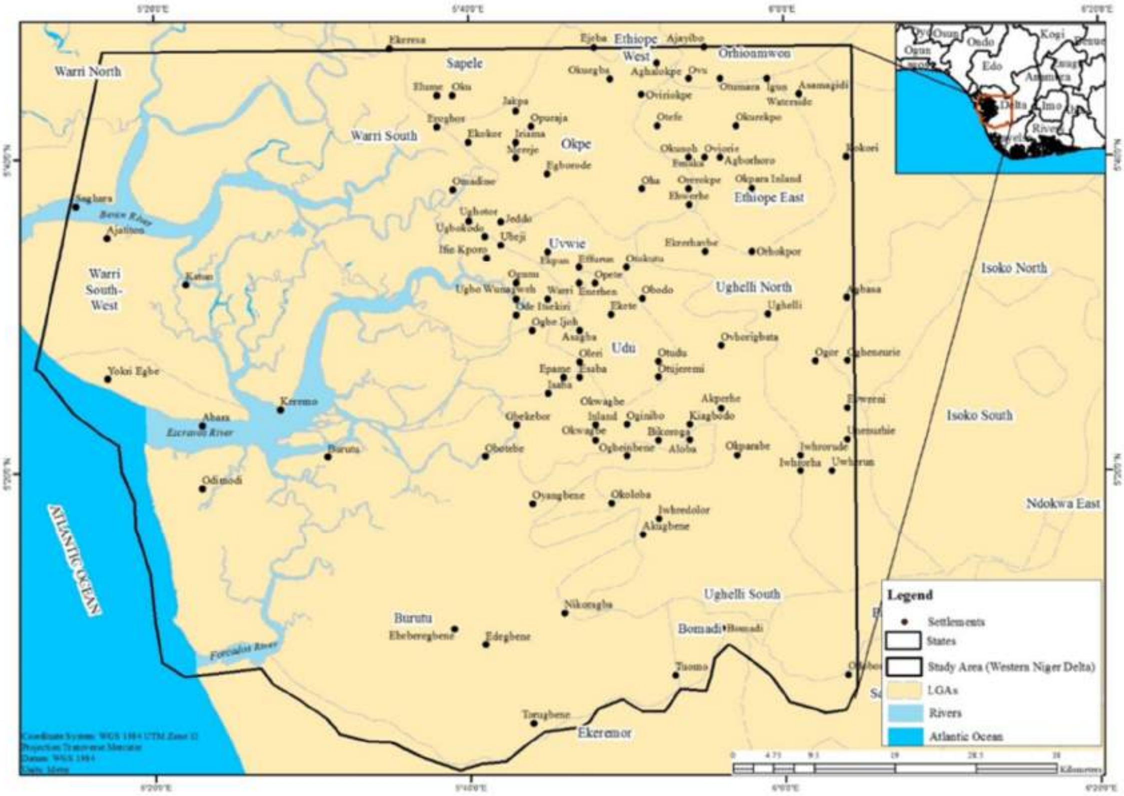

Fig. 1b: The study area with indexed map of southern Nigeria. This includes dominant river networks and the local administrative. The depositional and the expansive nature of the delta can be seen with series of interconnected streams and other fluvial systems predominates the area. The delta ends its fluvial products and processes into the expansive Atlantic Ocean.

The Western Delta flank is typified by an active hydrographic regime with quasi-constant tidal, waves and current actions contributing to the nature of landforms in the area. Often, tides are semi-diurnal with a mean wave height above 1 metre. Tidal actions are often pushed inland affecting connecting streams, creeks, and rivers in terms of the increasing water level. Wave actions are also seasonal with longer wave periods observed in the rainy season and short periods in dry season. Landforms observed in the study area include wide intertidal beaches, which are very wide, and greater than 175 metres mostly composed of fine to very fine-grained, moderately well-sorted sand. Beach slopes range between 1:50 to 1:90. This encourages the formation of anti-dunes along the beach range. Rivers Benin, Escravos and Forcados interrupt the beaches leading to the formation of different tidal inlets, mudflats and sinuous creeks inland and at the coastal banks (Sexton & Murday, 1994).

These geomorphic varieties are dominated and described by the geological origin of the entire Niger Delta region traceable to the Cretaceous epoch (Short & Staeuble, 2004). This formation further progressed, as dictated by transgressive and regressive cycles of divergent durations in response to abutting sea level dynamics (Kuenzer, van Beijma, Gessner, & Dech, 2014). The sediment structure of the Niger Delta is determined fundamentally by the two dominant landform processes of fluvial and marine composition, which leads to the emergence of deposited layers of sand, silt and clay (Abam, 1997). Reijers (2011) has provided a detailed and most novel stratigraphy and sedimentology of the Niger Delta detailing the rock profile and related surficial and bedrock geological formations.

These definite relationship defined by the geological and geomorphological endowments of the Niger Delta have contributed immensely to the traditional and modern anthropogenic activities observed in the area. Traditionally, the indigenous tribes and ethnic groups are engaged in fishing, boat making, net making, and small-scale agriculture; hence they are highly dependent on the localised ecosystem services. The mangrove and its associated swamps provide excellent grounds for localised fishing and breeding of fish breeds such as catfish and other species. The closely connected streams, creeks and rivers present a medium for small-scale retail fishing and boat making. All these are noted among the Ijaw, Urhobo, Itsekiri, and Isoko communities in the study area. Crop farmers cultivate a bit inland with banana, plantain, and oil palm being the most notable. These activities are obviously aided by the prevailing geomorphic flat surface, fertile soil, wetlands, surface water and marine resources and biodiversity, which is typical of most global river deltas (Kuenzer *et al*., 2014). Also, these deltas often rely on ecosystem services which dictate to a great extent, the source of livelihood and the nature and structure of the indigenous economy.

With the discovery of oil and gas in huge quantities by mid-20th century, the prevailing local economy have been severely affected. Exploration activities of most multinational oil corporations have altered the prevailing socio-ecology of the entire Niger Delta. It has shaped the nature of the demography of the region leading to urbanization of several places. Labour migration from several parts of the country has led to the divergent ethnography, localised rural – urban migration and several other demographic changes. However, the distortion of the predominant environmental system has been the most profound impact of the oil and gas activities. Oil spillages (Baird, 2010), and gas flaring (Anejionu, Blackburn, & Whyatt, 2012; Anejionu, Blackburn, & Whyatt, 2013) have been researched and noted to be the key environmental pollutions in the area. Notwithstanding, water, air and soil pollution are also widespread leading to a series of health issues. Destruction of oil and gas infrastructure owing to resource-driven social conflicts and militancy have also been noted to impair the environmental quality of the area.

MATERIALS AND METHOD

Data Sources

Geology maps, Landsat ETM+ imagery, pre-georeferenced digital elevation model (DEM), and vegetation and land use and cover map provided the sources from which the mapping of the geomorphological units of the area was carried out. This, therefore, provides the basis upon which subsequent geostructures can be mapped with their respective morphology. The characteristics of these datasets are indicated in Table 1.

Table 1: Data used for the study

Data	Year	Scale / Resolution	Source	Remarks
Soils Maps of Nigeria	1990	1:650,000	Soil Survey Division, Federal Department of Agricultural Land Resources, Kaduna.	Surface geology were extracted
Landsat ETM+ satellite image for Warri Region	2015	30m spatial resolution Bands 174 for wet season	Earth Explorer Portal of USGS www.earthexplorer.usgs.gov.us	Bands 715 was selected for June 2015 data for wet season data and Bands 741 December 2015 for dry season data
SPOT DEM (Digital Elevation Model)	2013	20 metre horizontal resolution and 12 metres vertical accuracy.	Office of the Surveyor General of the Federation (OSGOF), Nigeria Association of Hydrological Sciences (NAHS) Flood Outlook DataBank	Orthorectified hence errors arising from vegetation, buildings and others likely distortions have been resolved from source.
Vegetation and Land Use and Cover Map Sheet NB 31 –12/1	1977	1:250,000	Federal Department of Forestry, Abuja	Acquired in hardcopy and scanned to match software requirements.
Infrastructure and Utility Map Guide of Delta State	1998	1:300,000	Published for Delta State Government by Pace Int'l Ltd.	Rivers and Creeks data and gazettes of places were extracted

Source: Authors' Analysis

A systematic approach was designed for this study, which details the data extraction from DEM and layer extraction from the satellite imagery to generate individual landforms and geostructures. A similar approach to this was designed by Temovski & Milevski (2015) which sought to explore and analyse the geomorphic structures within the Karst region of Macedonia. The overall process is displayed in Fig. 2. The satellite image was geo-rectified and ortho-rectified from the source hence, there is no need to repeat these steps. Image compositing was done in two batches. First, bands 7, 1, and 5 were combined for wet season satellite data collected in June 2015 as the colour composite depicted water-bearing features. Second, bands 7, 4 and 1 were combined for dry season satellite data collected in December 2015, as this is appropriate for dry ephemeral features that become visible during the dry season.

The existing soil map 1:650,000 and land cover (vegetation) map were used as the base for preliminary geomorphologic unit mapping. This is based on direct interpretation mode using selected elements including association, site, size and pattern (Odunuga & Oyebande, 2007, Odunuga *et al*., 2011; Odunuga *et al*., 2013). These base maps were scanned and imported into GIS for the extraction of applicable data layers. The semi-automatic approach, which involves the detection, recognition, identification and classification of landforms and features using heads-up onscreen digitization, was adopted from the data layer extraction from these base maps. The zooming facility of the ArcGIS 10.2 allows for an in-depth visual expression at reasonably large scale.

DEM Examination and Accuracy Assessment

The DEM data was geometrically corrected from source with inherent 20 metres by 12 metres horizontal and vertical resolution respectively, yielding a cell size of 20*20 on the horizontal plane. The DEM was validated using the Geostatistical Tool of ArcGIS 10.2 using the Diffusion Kernel assessment (defined further as Epanechnikov's function), defined below.

$$1-\left(\frac{r}{h}\right)^2, for\ every \frac{r}{h} < 1 \qquad [1]$$

For this function, *r* is a radius centred at point *s* and *h* is the bandwidth within the cells. This function was cross validated cell by cell. Flow barrier cost formula was selected based on the morphological cum geomorphic mapping application of the DEM along a deltaic plain. The validation algorithm was implemented with the bandwidths that corresponds to the cell size and permitted to run with 100 iterations that lasted for two hours of spatial statistical processing. The assessment criterion for acceptance is set on regression output with a root mean square error of ≤ 0.001, hence it follows the procedure elucidated by Yan & Su (2009).

Landform detection and extraction from Landsat ETM+ imagery

Subsequent to the seasonal band acquisition in June and December 2015 as explained under data sources, the extraction of the identified landforms and features were based on a semi-automation method, in which features were manually digitised and digitally registered as vector layers in the GIS environment. At this level, feature identification was non-topographic; hence, the visual analysis of the geometry, site, situation, colour, and season of the year were the elements used in feature landform identification. For further verification of the identified landform, virtual fieldwork was designed in which geobrowser Google Earth Professional was used as a mapping guide for features.

This was assisted with the use of existing geomorphologic information extracted from the Infrastructure and Utility Map of Delta State and the soil and land cover (vegetation) map earlier generated for the study area.

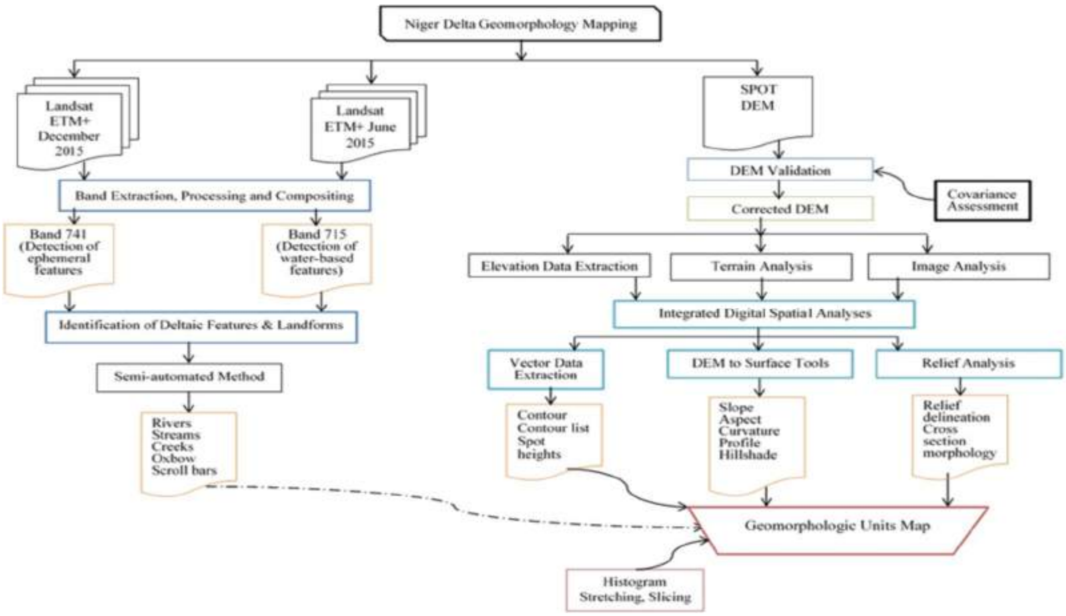

Figure 2: The study research framework

Direct Elevation Analysis

First-order elevation data were extracted as vector data from DEM raster format. The Contour Tool rooted in Surface Analysis Tools suite of ArcToolBox of ArcGIS 10.2 software package was used to extract the contour polylines, contour list and spot heights (points). The algorithm design for this was based on a simple extraction of lines from crenelated elevation values in the DEM. However, the extracted contour values were observed to be roughed and highly tessellated. These were smoothened using the Focal Statistics entrenched in the same software.

The Focal Statistics tool executes a neighbourhood procedure that calculates an output raster where the value for each output cell is related to the values of all the input cells that are in a specified neighbourhood around that location. The function performed on the input is a simple statistic, such as the range, mean or sum of all values noticed in that neighbourhood.

Terrain Analysis and Morphometry Measures

The terrain and relief morphometry of any landform is defined by the slope, aspect, curvature, profile, surface roughness, landform classification, and topographic position index (Schillaci *et al*., 2015). These are placed-based and context-specific as their relativity define the apt geo-indicators to use. Mathematically, these are second-level derivatives of contour and elevation values hence are defined as such in this study.

Second level elevation derivative were extracted using DEM to Surface Tools – a set of tools domiciled in the ArcToolbox suite embedded in the ArcGIS 10.2 software package, specifically designed to extract slope, aspect (orientation and direction), curvature and mathematically exaggerated shaded relief. These pixel-based neighbourhood analyses parameters ascertain relationship between a pixel and its adjoining neighbours. Slope is quantitatively computed as the maximum rate of change in the value of a cell (pixel) to its neighbours expressed as angles in this study. For a large area, the average slope is used and implemented across the entire image. The algorithm embedded in ArcGIS software is defined mathematically as

$$Slope\ (degrees) = ATAN\left(\sqrt{([dz/dx]\ 2 + [dz/dy]\ 2)}\right) * 57.29578 \qquad [2]$$

$$[dz/dx] = ((c + 2f + i) - (a + 2d + g)) / 8 \qquad [3]$$

In an image of values *a* to *i*, the rate of change in the *y* direction for cell *e* is calculated with the following algorithm:

$$[dz/dy] = ((g + 2h + i) - (a + 2b + c)) / 8 \qquad [4]$$

Taking the rate of change in both the *x* and *y* direction for cell *e*, aspect is calculated using:

$$aspect = 57.29578 * atan2\ ([dz/dy], -[dz/dx]) \qquad [5]$$

If aspect < 0; cell = 90.0 – aspect, else if aspect > 90.0; cell = 360.0 - aspect + 90.0; else cell = 90.0 - aspect.

This is implemented in this study, with the use of the Rose histograms embedded in the OA Tools ArcGIS 10.2 extension.

Shaded relief has been used for geomorphological mapping and it was based on hillshade method in which sun angle or hypothetical solar illumination is computed from the raster values in a cell (Marston and Jenny, 2015). Shadow and light ranges were set from 0 to 255 representing black and white shades respectively. Azimuth (angular solar direction) and altitude as detected from the pixel values were used as parameters. The hillshade algorithm used in computing the following software is embedded in the mathematical expression;

Hillshade = 255.0 * ((cos(Zenith_rad) * cos(Slope_rad)) + (sin(Zenith_rad) * sin (Slope_rad) * cos(Azimuth_rad - Aspect_rad)))

Exaggerated shade of 10 was selected as appropriate for a plain or an area with low elevation. This was effected using the GeoWEPP software. These analyses were based on a (3x3) cell neighbourhood analysis window. It is most appropriate for the size and elevation characteristics of the western Niger Delta.

Relief Analysis, Cross Sections and Geomorphologic Unit Mapping

Land surface analysis and geomorphologic unit identification is multidimensional hence any singular mode of relief or landform detection is erroneously inadequate (Minár *et al*., 2013). Relief classification was based on the average elevation differences. To achieve this, the Raster Math Tool was used for differentiating areas of elevation differences thus establishing the main areas of low elevation and higher elevation within the study area. Hillshade, slope, and stratified/classified aspect were also used as variables of correlation to define the land configuration. The outcome of the relief classification was used as the basis for geomorphologic unit classification in conjunction with slope and aspect analysis. It is expected that the elevation based differences will coupled with the proximity to the Atlantic Ocean generate the differences in local geomorphic processes. Landforms associated with the various geomorphic processes and tidal effects were employed in this taxonomy.

The cross sectional analysis was based on land morphological change with respect to elevation. Relief profile was thus drawn based on software using the Profile Graph function of 3D Analyst in ArcGIS software. Averagely, a 60 km horizontal scale was adopted for profile analysis.

RESULTS AND DISCUSSION

DEM Assessment and Validation

The iteration procedure generated 70,029 points of the DEM image. The root mean square error estimate (RMSE) from the regression computation is put as 0.000142329 and the error plot is displayed in Fig. 3. Hence, the image is deemed fit for the study as the RMSE estimate falls within the acceptable limits for geomorphological mapping (Odunuga *et al*., 2013; Yan & Su, 2009).

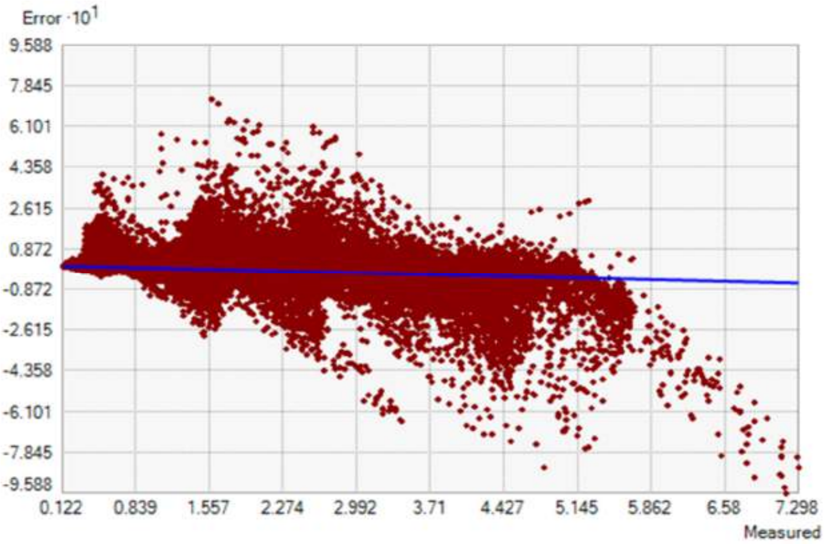

Fig. 3: Error plot of the DEM image validation procedure; horizontal axis plots measured points of the image pixels while the vertical axis plots the predicted points.

Source: generated from ArcGIS 10.2

Non-topographic Landforms identified from Satellite Images

Within the coastal environment, the dominant processes such as morphodynamics, sediment mobility, tidal, wave action and related hydrodynamics are dictated mainly by littoral factors and the consequent landforms detected ashore. This background makes the features that were less topographic in nature basically understandable.

All the features identified within this category are entirely hydrologically related or controlled by water-related natural actions. The extents of seasonality of these features were thus tested with seasonal procedures of bi-annual mapping. However, virtually all the features that fall within 30 metres minimum mapping unit (MMU) are perennially active. Evidently, these are driven by quasi-constant availability of water via precipitation and streamflow from bifurcated streams of the River Niger. Three main features were detected on image interpretation in the areas. The permanent rivers with stable meanders are of stream order 8^{th}. These could be further divided into three – main river channels; connecting creeks; and meandering streams. Rivers Benin, Escravos and Forcados are the main river channels within the study area (Fig. 4). These are hydrologically active fluvial systems that convey load into the Bight of Benin, thus establishing a fluvio-marine complex while providing the platform for tidal incursions into the fluvial system into the main delta channel. Connected to these river systems are perennially active systems of creeks and rivers. These creeks are inlet channels usually smaller in length and connect either directly to the main river channels or via lower-order Rivers. A list of some of these is documented in Table 2.

Other detected landforms within the fluvial systems include scroll bars and oxbows. Scroll bars were detected as along river bends which usually results from lateral accretion within alluvial zones. Usually these manifest in soil–vegetation contrasting morphostructural complexes in which secondary vegetation are interspersed by dense vegetation leading to curvilinear landforms on the surface (Jordan, Meijninger, van Hinsbergen, Meulenkamp, & van Dijk, 2005). Oxbows are previous meanders that were structurally cut off from the dominant river under the influence of fluvial forces. These were still filled with water or marsh establishing an almost continuous river system.

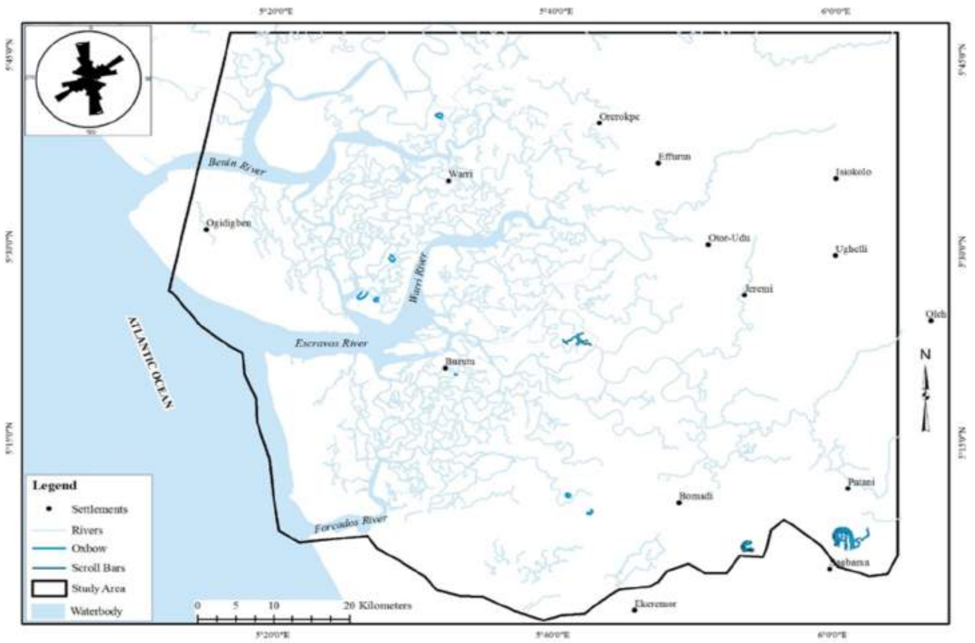

Fig. 4: The fluvial system of the western Niger Delta indicating the interconnecting river channels, streams, creeks and other waterbodies. These were extracted based on the minimum mapping unit of 30 metres as of Landsat data. Oxbows and scroll bars were detected and mapped.

Table 2: List of identified rivers, creeks and streams within the study area

Main river channel	Connecting River	Creeks and streams
Benin River	Unnamed	Dele Creek Adagbarassa Creek Gwafa Creek Robbins Creek
Escravos River	Unnamed	Nana Creek Jones Creek Kpokpoilele Creek Benin Creek Ogidigbo Stream
Forcados River	Warri River Chanami River	Galpin Creek Okpori Creek Alajiko Creek Odube Creek Chikoko Creek Orugbene Creek

Source: Interpreted from the Infrastructure and Utility Map of Delta State (1998)

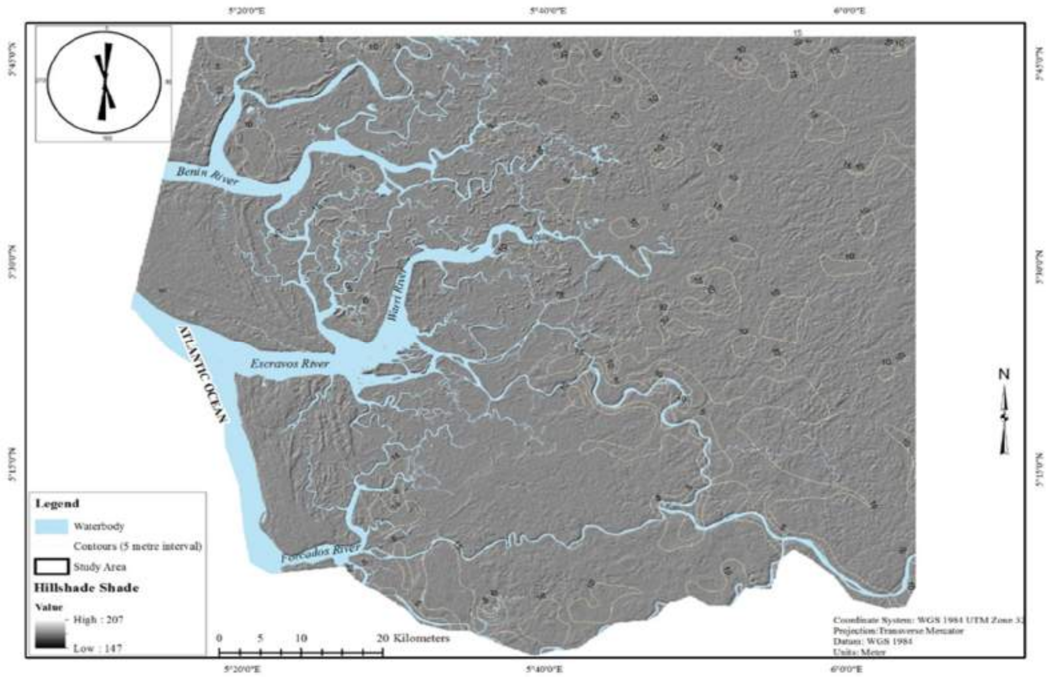

Fig. 5: Shaded relief indicating the general outlook of the land configuration

Most part of the area is low-lying with the exception of the higher elevation values towards the north-western fringe. Contour values with specified spot heights depict low elevation that ranges between the mean sea level and 1 metre above sea level, thus, establishing a somewhat flat terrain. These areas are filled with meandering streams, sinuous creeks and streams flanked by mangrove vegetation. Increasing elevation values were observed at the central zone which extends to the northwestern direction. Averagely land rises close to about 5 metres in some places that are traversed by rivers and even up to 10 and 15 metres at the extremes. Similarly, the rose histogram that provides the orientation of watercourses and river functionality hypothesises the direction of flow.

In order to understand the elevation changes in an image, the main cell and the adjoining members are considered for slope computation and analysis. Consequently, the first-order measure of land configuration was tested and analysed with slope in this study. On such a quasi-flat terrain as that of the study area, a gentle slope is not unexpected. An assessment of the contour arrangement and orientation depicts a generally uniform slope (Fig. 6). This was tested via the observation of the equidistance arrangement of contours. The cumulative area-slope analysis yields a plain (a deltaic plain) with generalised slope $\leq 2^0$ (Connallon & Schaetzl, 2017). Areas with lower values are mainly water surfaces or are dominated by watercourses. Three classes of distinct slope classes can be identified from the slope map in Fig 6. The upper slopes with spots of yellow and red colours are slope values within built-up areas, including areas of oil infrastructure installations. Conversely, the lower slope denoted by the blue colour depicts the influence of water surfaces close areas of higher slope values. These are directly proportional to the influence of water surface upon the overall plain landscape. The green colour indicates the extent of the flat terrain leading to the nomenclature deltaic plain. A slope map of the Niger Delta displaying these landform and its traits is displayed in Fig. 5. Overall, the entire area is a flat terrain and dominated by deltaic plain accretion.

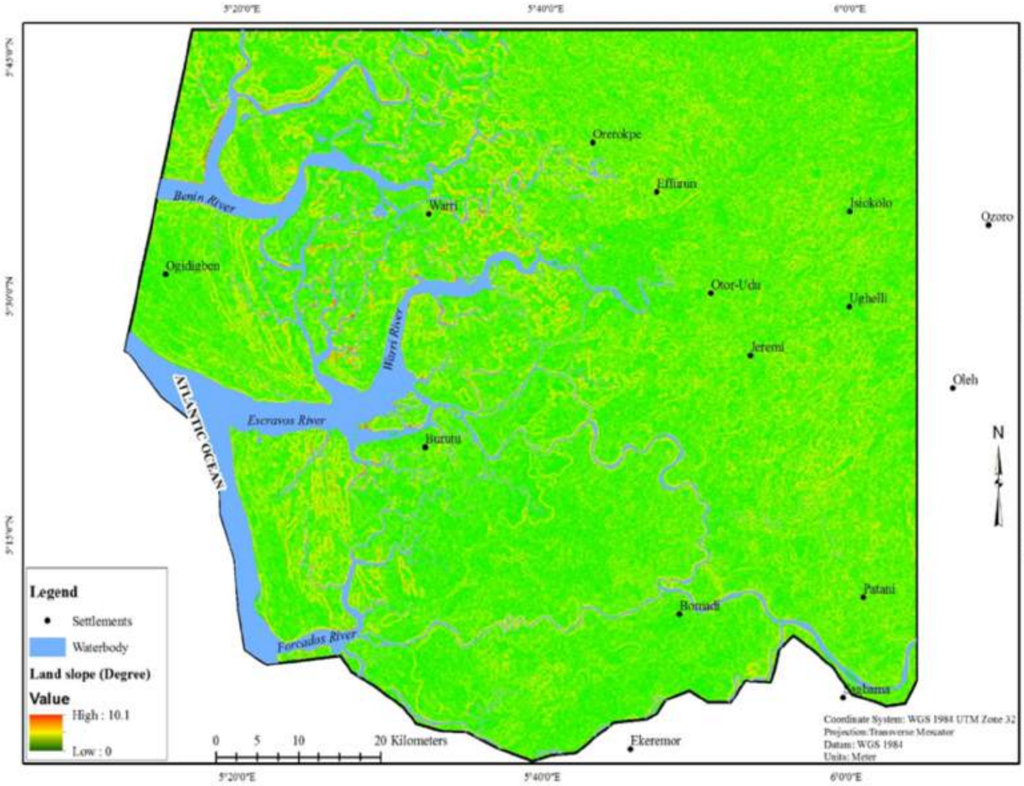

Fig. 6: Slope map of the western Niger Delta depicting a low gradient terrain hence its deltaic configuration

Terrain morphostructural differences can also be measured via aspect analysis across differentiated image analysis, filtering and yielding different landforms depending on the subject of morphological investigations (Jordan, Meijninger, van Hinsbergen, Meulenkamp, & van Dijk, 2005). The uniform aspect aids the geometrics of planar surfaces with a quasi-uniform terrain characteristics. The fitness of this methodology calls for the adoption of a uniform smoothening and high majority filtering, which was conducted to produce the stratified aspect map displayed in Fig. 7. Aspect as a function of slope is a second-order topographic analysis indicating overall direction, illumination and flat surfaces as governed by the geomorphic processes of either erosion, denudation or deposition.

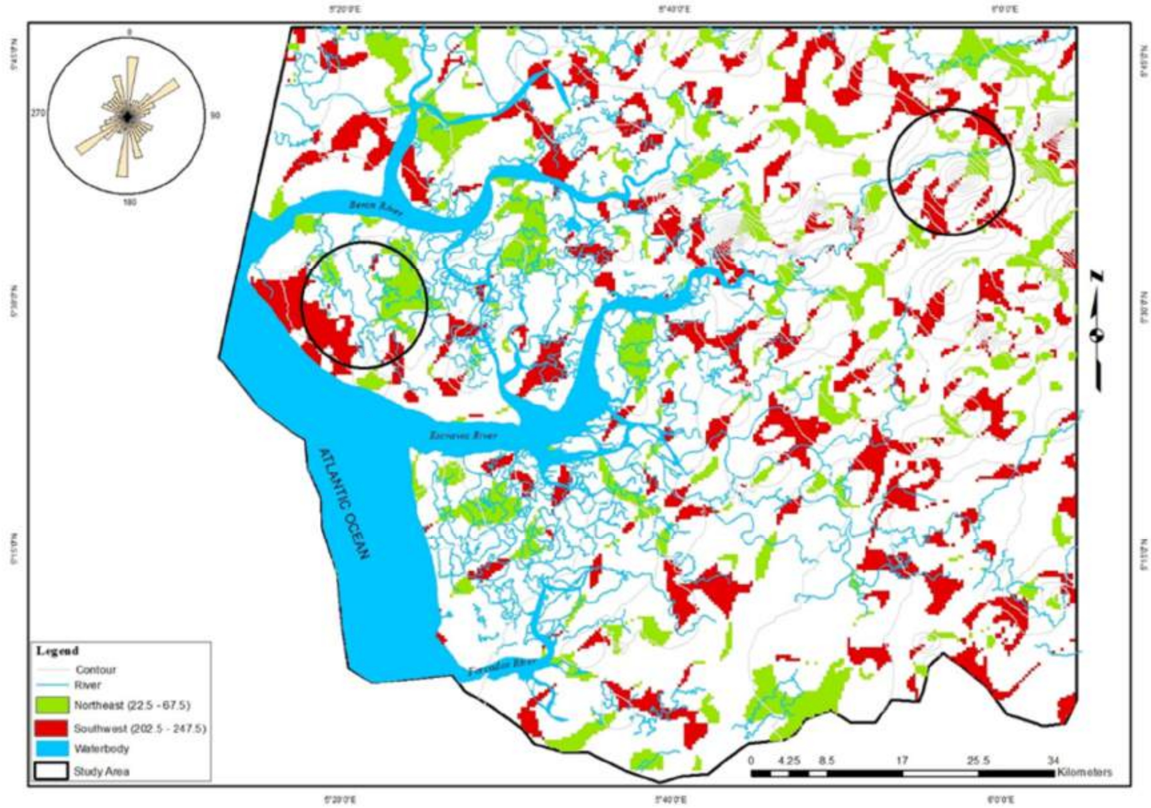

Fig. 7: Stratified aspect map for the northeast – southwest direction with average angle 45^0 and 225^0.

Geomorphologic units

From the terrain characterisation and the associated morphostructural characteristics explained by the spatial differences in elevation, slope range and the stratified aspect, two elevation-based geographically differentiated morphological units that are genetically homogeneous and produced by a definite constructional or destruction geomorphic process (Faniran *et al*., 1976; Odunuga *et al*., 2013) can be identified - tidal mudflats and saltmarshes.

Tidal mudflats

The tidal mudflats are dominated by the mangrove ecosystem but under the influence of tidal fluctuations as the area is separated by the active anti-dune beaches and small-scale ripple bedding beach to the ocean. This indicates that the area is mostly under depositional processes as the river mouths run at low streamflow when compared to the upstream feeding rivers, hence the development of anti-dunes within the broad flat beaches. Within this geomorphic unit, the occurrence of quasi-horizontal laminae, which are found in the trenches of sedimentary morphostructural origin, is seemingly ubiquitous (Sexton & Murday, 1991; Isola *et al*., 2017; Zhang *et al*., 2017).

On the basis of average elevation change and proximity to the marine influence, the tidal mudflats can be further classified into intertidal mudflats and supratidal mudflats. The former defines the beachfront characterisation of the area while the latter is much more dominated by the mangrove ecosystem and affected by tidal influence through the river connecting on the trough. The average elevation of the intertidal zone (B1) as depicted by the cross section profile of the horizontal scale of 160 kilometres as derived from the map in Fig (Fig. 8) is one metre (1m) above the mean sea level. Wave action and tidal amplitude contributes to the morphological processes and landforms. Coastal and submarine landforms influenced by gravity, in-washing of seawaters, sandy beach with minor traces of pebbles are observed within the intertidal zone (Zhang *et al*., 2017). The supratidal zone (Fig. 9) is directly influenced mainly by littoral drift with depositional low velocity rivers, streams and creeks. It is mainly typified by the mangrove ecosystem influenced by tidal fluctuations. Similar coastal and fluviomarine landforms as the intertidal zone are observed in this zone but are differentiated by increasing elevation and proximity to built-up areas. A cross section profile of the area labelled as B2 in the geomorphic unit map depicts an average elevation of 2 metres with possibility of exposure to open water particularly during the rainy season of the year.

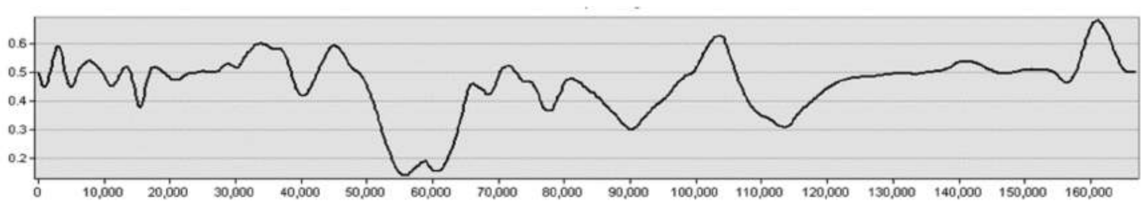

Fig. 8: Morphological cross section profile of the Intertidal Zone as defined spatially by B1 on Fig. 10. Arrows indicate slope and aspect orientations towards water levels and flat terrain geometry.

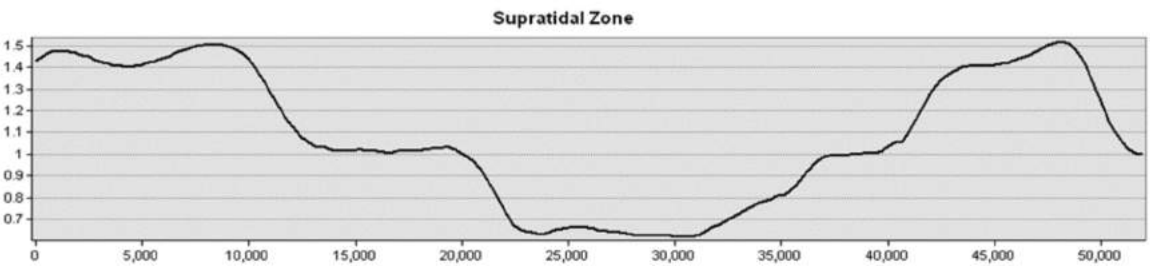

Fig. 9: Morphological cross section profile of the Supratidal Zone (B2) on Fig. 10, t he scale is defined in meters and the horizontal scale is slightly exaggerated to depict form changes. Arrows point towards slope changes and possibilities of water surfaces.

Saltmarsh Zone

The saltmarsh zone is entirely of higher elevation when compared with the tidal mudflats and the change in elevation as depicted by the slope is higher. Elevation is roughly 3 metres above the mean sea level. However, there are possibilities of lower elevation within the areas of wetlands, shallow rivers and swamps. As a coastal plain phenomenon, tidal influence is observable and associated features are also typified by seasonality. Spatial expression of sandflats, sand ridges, and tidal ripple deposits based on upstream alluvial materials are observed in varying quantities especially during the low tide periods. Expectedly, the landforms are shaped in respect to the surficial geology through curvilinearity, sinuous river courses with loads of sedimentary origin (Sivakumar, 2015), thus, defining the geometry of landforms within such an environment. There are evidences to suggest that transverse and pyramidal sand deposits, which could be covered by natural vegetation at the pristine stage or exposed by human action, are possible within the zone. Possibility of mud progradation with sand deposits which aids saltmarsh development starts upstream and manifest alongside the sparse vegetation.

Geographically, two saltmarsh zones can be identified regarding the elevation and geomorphic landforms. The outer saltmarsh zone is characterised by lower elevation averaging 2 metres above the mean sea level and is at the fringes of the supratidal zone (Fig. 10 and Fig.11). In some cases, there are proximate overlaps in between the zone but these are differentiated on elevation basis (Isola *et al*, 2017; Zhang *et al*., 2017). Slopes are roughly gentle over the plain and are very close to some rivers and streams within the area.

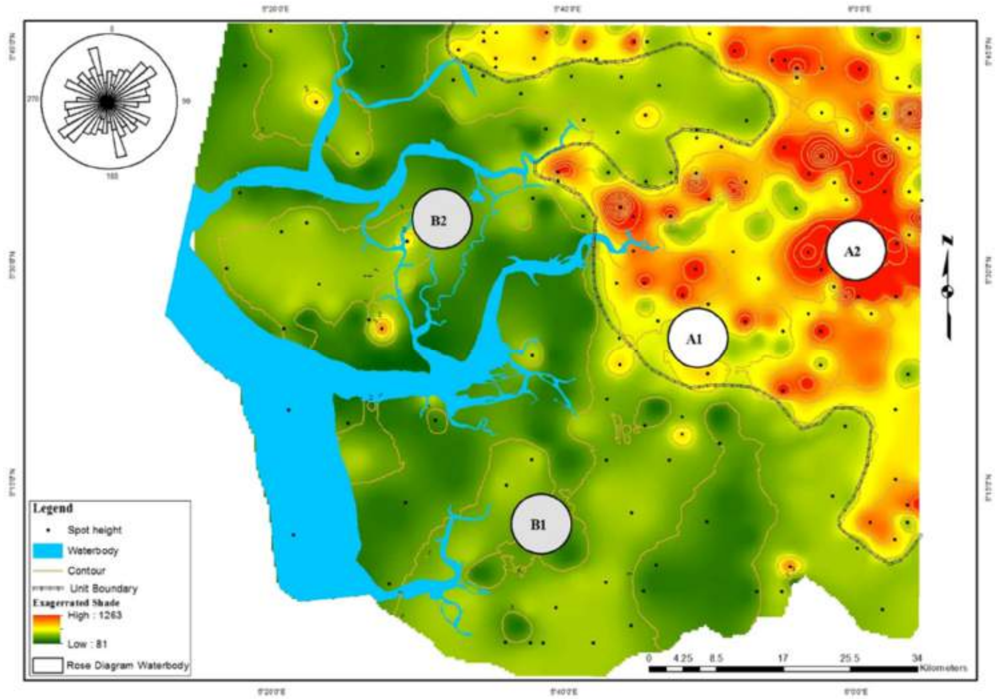

Figure 10: Geomorphologic units of the Western Niger Delta as indicated by the imaginary delineation line between the tidal mudflats (denoted B1 and B2) and saltmarsh zones (denoted A1 and A2). These are terrain heights differentiated as indicated by the contours and the exaggerated hillshade. Rose histogram depicts orientation of flow of denudational and depositional action of the main river channels with respect to these units and differentiated by littoral processes and landforms

Lacustrine swamplands (Fig. 12) that are tangential to rivers are noted in the area (denoted A1). Tidal fluctuations, the appearance of sandy shoals is flooded frequently during the rainy season. Sandy-mud deposition is also typically a seasonal geomorphic phenomenon.

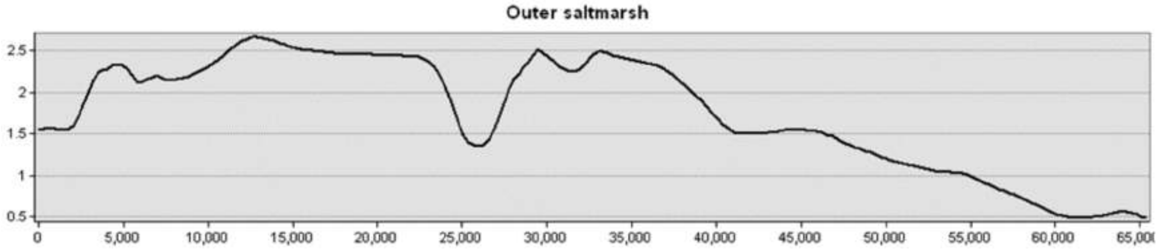

Figure 11: Morphological cross section profile of the Outer Saltmarsh zone (A1), the scale is representatively defined in meters and exaggerated horizontally. Arrows indicate direction of flow towards the adjoining supratidal zone and water surfaces. It also defines the geometry of the terrain and slope characterisation and orientation.

Fig. 12 Pictographical display of a section of the Outer Saltmarsh Zone indicating the lacustrine swamplands which is mostly filled with water all-year-round. The historical palms indicating the paleobotany – a good geomorphic marker of migrating creeks impact on the area at time in the past. This end leads to tidal mudflats which is mostly influenced by the tidal fluctuations.

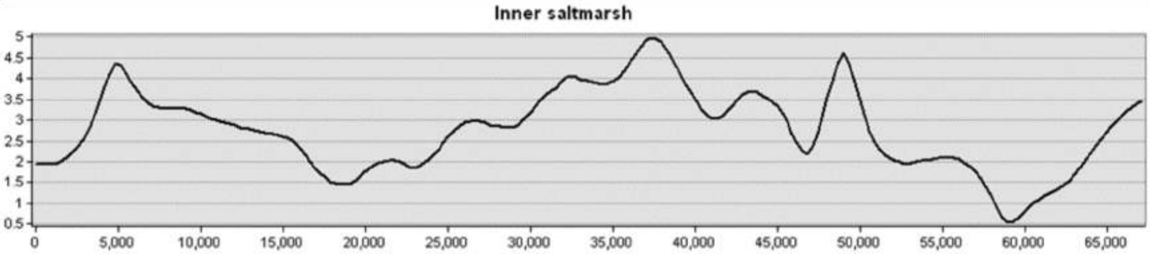

Figure 13: Morphological cross section silhouette of the Inner Saltmarsh zone (A2), the scale is expressed in meters and exaggerated horizontally. Arrows are indicators of terrain configurations of slope, aspect and change in landforms. The rising profile indicates the presence of built structures, roads and pavement along the northeastern fringe of the Niger Delta.

Figure 14: Pictographical description of the Inner Saltmarsh Zone of a part of the Warri City, a grassy field with the depiction of soil layers at the horizon. The soil layers coupled with the annually fluctuating hydrophytes indicate the impact of fluctuating water level as well as quasi-flat topography of the city hence flooding is a perennial geo-problem in the area. This area falls within the lower elevations of this section with drastic seasonal changes. During the wet season the grassy field are covered with floodwaters.

Conversely, the inner saltmarsh occurs towards the higher elevation of over 3 metres extending to as high as 10 metres within the built-up areas of the north-eastern fringe (Fig. 13 and Fig. 14). The zone (denoted A2) is characterised by combined erosional and depositional processes. Rivers have less tidal influence and there are spots of lacustrine wetlands under tidal influence. Geometrically, fine sand lenses interposed by mud that characterise unfussy lenticular bedding are observed. Accumulations are more of sandy loads being further transported along the waterlines defined by stream action. Littoral drift is stealthily active at this stage as it gravitates along the stream action and as influenced by the geological bedrock.

Overall, the map displayed as Fig. 10 shows the spatial relationship between these morphological features and their morphostructural discontinuities. The tidal mudflats and saltmarshes, therefore, typify the fundamental geomorphic units within the Western Delta flank. These units have differentiated landforms under the influence of fluvial erosional, depositional and denudational geomorphic processes.

CONCLUSION

The study shows the application of geoinformation technology to monitor, model and characterize factors of the geomorphic change in difficult and inaccessible environment such as the core of the Niger Delta. Detection and mapping of morphological features using the DEM and raster-based GIS approach has been demonstrated in this study. The detection and mapping involve the systematic digital terrain analysis combined with satellite image interpretation using a mixture of software tools and semi-automated landform of the western part of the Niger Delta as case study. Histogram analysis, exaggerated shade, slope and stratified aspect were used as the basic parameters for landform identification. Relief analysis was used as a basis for the geomorphologic unit delineation. The satellite image analysis was based on bi-annual seasonal approach in which landforms in both dry and wet season were synchronized and mapped synoptically.
Expectedly, fluvial landforms dominate the detected landforms which include various river systems including the main channel, tributaries and distributaries with creeks, and streams. Scroll bars and oxbows with water and marsh were also detected. In addition, alluvial systems under accretion processes and landforms were detected. Beaches with shoreline progradation within the extensive deltaic were identified. Two distinct geomorphologic units/zones were detected based on the terrain characterisation. The tidal zone, delineated into intertidal and supratidal zone, was detected within the lower elevation relief (about 1 metres mean elevation). Equally, the saltmarsh zone, delineated into inner and outer saltmarsh zones, was identified. The average elevation of this unit is above 5 metres. Terrain characterisation, tidal influences, mangrove vegetation, sandy loads, fluvial and wave action were identified as the fundamental active geomorphic agents of the region in this study.

This study has however provided the platform for further morphostructural and geomorphometric studies of the study area. Such a study should consider modeling the changes in the ecological and geomorphological changes for the entire Niger Delta. This would provide a holistic information for planning that will also ensure environmental sustainability of the oil rich region. Such studies should be carried out using the emerging tools and approaches with regards to earth observation satellite and geoinformation technology on a continuous basis. This will support future planning and mitigate the adverse effects of continuous global environmental changes issues as well curtailing disaster risk issues related to sea level rise, flooding and coastal erosion. Also, the establishment of a dedicated and fully resourced authority to practically deal with coastal environmental problems and monitor coastal resources and anthropogenic activities changing the oil rich fragile environment might be desirable. This is fundamental as most of the geohazards along the shore are better understood using the integrated methodologies of remotely sensed data and GIS.

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