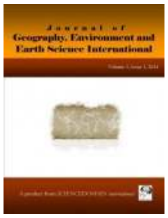

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Time-lapse Analysis of the Effects of Oil and Gas Exploitation Using Remote Sensing and GPS in Parts of the Niger Delta, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Geophysics Department of SPDC designed the study originally for reservoir compaction quantification resulting in the present work as one of the outcomes. Author EDU wrote the protocol, and wrote the first draft of the manuscript. Authors EDU and VNO managed the literature searches. Geomatics Department of SPDC performed change analysis. Both authors read and approved the final manuscript.

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ABSTRACT

Changes due oil exploration and production have occurred within Cawthorne Channel area from 1986 to 2003. Three satellite image datasets consisting of Landat TM acquired On 19th of December 1986; SPOT 4 of 16th December 1998 and Landsat ETM of 8th January 2003 were used for the study. The satellite image datasets were processed using ISOclass unsupervised classification to generate the various landcover classes. Baseline information was extracted from Natural Colour Composites, LandCover Classification and Normalized Difference Vegetation Index (NDVI) composites, for the three epochs. The statistics of the various classes were then generated for each processed dataset. These statistics were further analyzed to identify the change patterns.

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Change analysis also involved processing and graphically identifying various landcover types and the changes that have occurred over the years. Normalized Difference Vegetation Index was performed using NDVI processing algorithm for the three epochs to adduce the possible reasons for such changes. From the analysis carried out, it is evident that the landcover classes changed across the three epochs. The water class covered an area of 80.12 km^2 in 1986: 85.05 km^2 in 1999 and 76.64 km^2 in 2003. High mangrove covered an area of about 32.64 km^2 in 1986, 77.72 km^2 in 1998 and 110.41 km^2 in 2003. This could be due to the decrease in low mangrove. Low mangrove covered an area of about 146.96 km^2 in 1986, 100.66 km^2 in 1998 and 75.41 km^2 in 2003. Wet mangrove covered an area of about 25.46 km^2 in 1986, 18.57 km^2 in 1998 and 19.71 km^2 in 2003. The increase in 2003 could be due to the presence of water within the mangrove. Settlements, sand and cloudcover covered an area of about 1.85 km^2 in 1986, 5.03 km^2 in 1998 and 4.86 km^2 in 2003. The decrease in 2003 after the increase in 1998 might be attributed to sand reduction and vegetation growth. Also, orthometric elevation changes are carried out using Global Positioning System (GPS) to ascertain areas where elevation changes (land subsidence) have occurred. The rate of elevation changes (land subsidence) in the study area is at each location of levelling. It varies from 66.67 mm yr^{-1} to 200.00 mmyr^{-1}, and an average of 86.00 mmyr^{-1}. The elevation changes in this Field are localized only where the measurements are located, and are mainly in river and drenched channels and slopes caused by erosion. This conclusion regarding minimal impacts of hydrocarbon production on elevation changes is based only on orthometric height difference, and not on the reservoir stress changes. Knowledge of the present distribution and area of landcover, elevation changes, as well as information on their changing proportions, is needed by legislators, planners, and State and local governmental officials to determine better land use policy, to project transportation and utility demand, to identify future development pressure points and areas, and to implement effective plans for regional development.

Keywords: Landcover; landuse; elevation changes; petroleum exploitation; change detection; remote sensing; global positioning system; Niger Delta basin.

1. INTRODUCTION

Land use and landcover changes (LULC) are some of the most sensitive indicators of environmental change as it reflects the impacts of human activities on the biophysical environment. Land cover refers to the physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures [1,2]. Land use describes how human activities such as agriculture, forestry, oil and gas exploitation and building construction alter land surface processes including biogeochemistry, hydrology and biodiversity [3]. While land cover may be observed directly in the field or by remote sensing, observations of land use and its changes generally require the integration of natural and social scientific methods to determine which human activities are occurring in different parts of the landscape, even when land cover appears to be the same. The impact of the activities relating to oil and gas generate some significant effects on the environment, such as loss of wildlife habitat, changes in surface and topsoil hydrology that may lead to accelerated soil erosion and land degradation, vegetation changes, air pollution and changes in coastline geomorphology and land surface subsidence [4,5]. The application of satellite remote sensing and GIS data has proved useful in mapping land cover and land use patterns over space and time [2]. Knowledge of the present distribution and area of landcover, as well as information on their changing proportions, is needed by legislators, planners, and State and local governmental officials to determine better land use policy, to project transportation and utility demand, to identify future development pressure points and areas, and to implement effective plans for regional development [6-10]. The use of remote sensing and Global Positioning System (GPS) facilitates observations across larger extents of Earth's surface than is possible by ground-based observations.

The aim of this paper is to use remote sensing and GPS in three epochs to determine the effect of oil and gas exploration and production (E&P) on landcover and elevation changes in the study area, Cawthorne Channel (CAWC) in the Niger Delta, Nigeria (Fig. 1). This time lapse remote sensing monitoring is to track oil and gas exploration and production related changes on water body, high-, low-, and wet-mangrove, surface topography and human settlement environments. The oil and gas production activities involved vegetation clearing (deforestation) and dredging of existent river channels and creation of new channels which provide access to the study area, and migration of human population thus creating infrastructural developments and increased population settlements.

A settlement is a community in which people live. A settlement can range in size from a small number of dwellings grouped together to the largest of cities with surrounding urbanized areas. Settlements may include hamlets, villages, towns and cities. In the field of geospatial predictive modelling, settlements are "a city, town, village, or other agglomeration of buildings where people live and work" [11]. A settlement conventionally includes its constructed facilities such as roads, enclosures, field systems, boundary banks and ditches, ponds, parks and woods, wind and water mills, manor houses, moats and churches.

Time lapse remote sensing and GPS monitoring accomplished through the comparison of remote sensing surveys that have been recorded in 1986, 1998 and 2003 time over the life of the CAWC Field. It is recognized here that the changes in the study area environment may be more and more prominent after 2003, but the scope of this present work focuses on data availability of 1986, 1998 and 2003.

The study area comprises mainly the New Calabar, Cawthorne Channel Rivers, and populated with a lot of creeks, rivers and tributaries (Fig. 1). Land-surface subsidence induced by hydrocarbon production has been recognized as a potential problem in many areas which have undergone oil and gas exploitation. The production of oil in Venezuala, where subsidence above a number of important oil reservoirs boarding Lake Maracaibo is a constant phenomenon, and huge dykes have been built to protect the coastal area from flooding [12]. In the Houston-Galveston area, land subsidence induced by large-scale groundwater withdrawal since 1906 has been up to 3 m [13]. The implication of elevation changes in coastal wetlands can have dramatic impact on the wetland ecosystem; a slight decrease in elevation can lead to frequent flooding that can deteriorate, and eventually destroy, vegetation [14]. Erosion followed by the loss of vegetation could further accelerate the loss of wetland in these areas [15]. Geodetic measurement of surface deformation with dense spatial coverage is essential for assessing the magnitude, distribution and spatial pattern of land subsidence at oil field basins. This paper uses geodetic measurements (GPS) in levelling to provide magnitude and spatial extent of elevation changes (land subsidence) associated with hydrocarbon exploration and production in the study area in the Niger Delta.

2. AREA OF STUDY

The Cawthorne Channel is a navigation channel in the Niger Delta region of Nigeria. It covers an area of approximately 287.27 km^2. The area of interest is south of Port Harcourt. The study area is defined by 490800E 69500N and 515000E 50820N (Fig. 1).

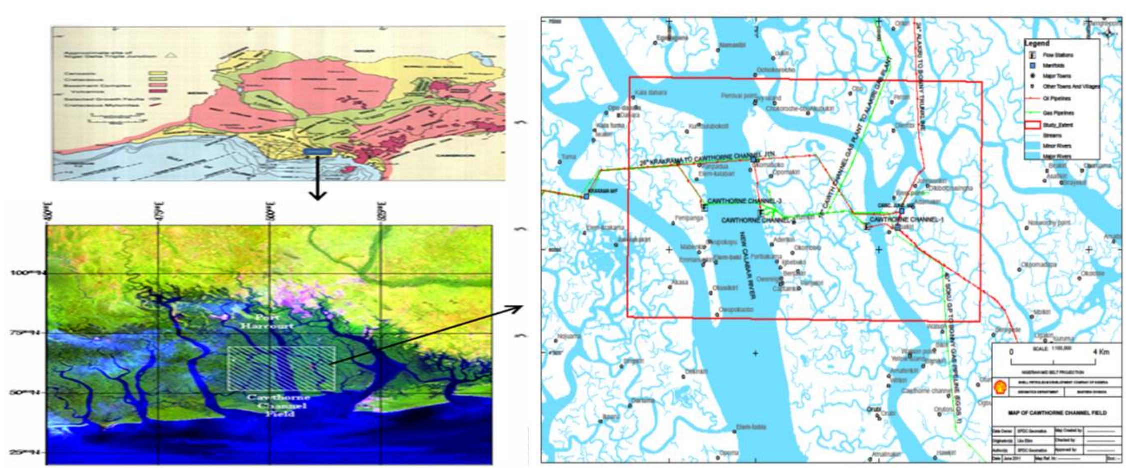


Fig. 1. The map of the Niger Delta showing the study area [16]

The area is dominated by mangrove swamps and river channels. The mangroves have been divided into 4 types – wet mangrove, sparse mangrove, low mangrove and high mangrove. The wet mangrove occurs in low-lying swampy areas in the western part of the areas and is surrounded by a large area of sparse mangrove. Low mangrove is widespread throughout the area whilst high mangrove occurs on the banks of some minor river channels. Stands of forest occur in the South-Eastern part of the area. These are interpreted to be on low sandy ridges that correspond to strand lines or old beach deposits. Drainage in the area of study comprises mainly the New Calabar and Cawthorne Channel Rivers. They empty into the Atlantic Ocean. Quite a lot of tributaries are found within the area of interest. This area is really populated with creeks and rivers [17].

3. MATERIALS AND METHODS

3.1 Land Cover Classification

Data were extracted from the multi-temporal satellite images and topographic maps. A number of processing algorithms are used to process the Natural Colour Composite Image, LandCover-Classification, Normalized Difference Vegetation Index (NDVI), orthometric elevation model, using Earth Resource (ER) Mapper software. Further processing was carried out to delineate areas of vegetative growth and landcover types in the area of interest. These satellite images were processed and the different land cover types are obtained for the analysis.

A Landcover classification was carried out over the Cawthorne Channel, for three epochs using the Baseline information Landsat TM, acquired on 19th of December, 1986; SPOT 4 of 16th December, 1998 and Landsat ETM of 8th January, 2003 were used for the study. The imagery multi-spectral and geodetic schemes used are presented in Tables 1 and 2. The data from Landsat ETM, Landsat TM and SPOT 4 were reclassified and downgraded to the same level of pixel size and 25 m resolution; three bands of red, blue and green colours were used throughout. All the images were captured in the dry season to avoid seasonal variation effects which can arise in rainy season due to thick cloud cover. As the results are spatially compared, the datasets used were subsets of the original images kept in the Remote Sensing archives. The images were geo-referenced to MINNA datum projection and TMNIGM. Normally, there are two types of classification in remote sensing: unsupervised and supervised [18-20]. We preferred the unsupervised classification to enable us evaluate areas where there is little or no knowledge of the site. Unsupervised classification is unbiased in its geographical assessment of pixels. Moreover, unsupervised classification relies purely on image statistics and brightness levels to identify natural groups of pixels, without requiring any prior knowledge of the scene. Supervised classification, on the other hand, is a process where the analyst has some prior knowledge about the surface materials within the study area and can use samples of known identity called training data to classify pixels of unknown identity.

NDVI was used in highlighting the different levels of vegetation health. This objective was achieved by applying the vegetation formula to the image. A normalized difference vegetation index is a ratio of Near Infrared (NIR) and Red bands. The formula is presented below:

DN (out) = (band 1 – band 4)/ (band 1 + band 4)

Table 1. Landsat TM imagery (Multispectral)

	Baseline 1986 Landsat TM imagery (Multispectral)	Monitor 1998 SPOT 4 imagery (Multi spectral)	Monitor 2003 Landsat ETM imagery (Multispectral)
Date acquired	19 December, 1986	16 December, 1998	8 January, 2003
Ground pixel dimension, GPD	25 m x 25 m	20 m x 20 m	30 m x 30 m
Band 1	0.45-0.52 µm	0.50 – 0.59 µm	0.45-0.52 µm
Band 2	0.52-0.60 µm	0.61 – 0.68 µm	0.52-0.60 µm
Band 3	0.63-0.69 µm	NIR: 0.79 – 0.89 µm	0.63-0.69 µm
Band 4	NIR:0.76-0.90 µm	SWIR: 1.58 – 1.75 µm	NIR:0.76-0.90 µm
Band 5	SWIR: 1.55-1.75 µm		SWIR: 1.55-1.75 µm
Band 7	SWIR: 2.08-2.05 µm		SWIR: 2.08-2.35 µm

Key: NIR = Near Infra-Red and SWIR = Short Wave Infra-Red

3.2 Determination of Changes in Orthometric Elevation

To determine changes in orthometric heights in two epochs, the heights from 1986 (baseline) and 2003 (monitor) surveys are compared at each measurement point, and the differences in the heights are used to determine the magnitude of any vertical land-surface changes. The vertical land-surface changes, between the 1986 baseline and 2003 monitor surveys, were calculated by differencing the orthometric heights of the levelling determined for the two surveys, and are presented Table 3, which is used to contour orthometric heights over baseline and monitor maps.

Table 2. Geodetic parameters

Geodetic parameter	Geo-reference
Coordinate system name	Nigerian Mid Belt
Projection	Transverse Mercator
Ellipsoid	Clarke 1880
Datum	MINNA
Semi major axis	6378249.145 metres
Longitude of origin	8deg 30 min East
Scale factor at central Meridian	0.99975
Latitude of origin	4deg 00 min North
False easting	670553.98 metres
False northing	0.00 meters

(The images were geo-referenced in MINNA datum projection and TMNIGM)

Table 3. Orthometric heights using GPS

Site	Eastings	Northings	Leveling-derived orthometric height for base survey (1986) (m)	Leveling-derived orthometric height for monitor survey (2003) (m)	Difference (Base – Monitor) = Subsidence (m)	Annual subsidence rate (cm/year)
1	499127.00	64120.00	2	1	1	6.67
2	499128.00	64170.00	2	1	1	6.67
3	499129.00	64270.00	2	1	1	6.67
4	499130.00	64320.00	2	1	1	6.67
5	499171.00	67322.00	1	1	0	0
6	499171.00	67372.00	1	1	0	0
7	499171.00	67422.00	2	1	1	6.67
8	500562.00	66703.00	-10	-9	-1	-6.67
9	500564.00	66804.00	-9	-7	-2	-13.33
10	500564.00	66854.00	-8	-7	-1	-6.67
11	509707.00	64415.00	2	2	0	0
12	509807.00	64413.00	2	2	0	0
13	504405.00	66556.00	-5	-5	0	0
14	504410.00	66657.00	-2	-2	0	0
15	504416.00	67156.00	2	2	0	0
16	504417.00	67206.00	2	2	0	0
17	504417.00	67256.00	2	2	0	0
18	504418.00	67306.00	2	2	0	0
19	504419.00	67356.00	2	2	0	0
20	509657.00	64415.00	2	1	1	6.67
21	509707.00	64415.00	2	2	0	0
22	510014.00	66986.00	2	1	1	6.67
23	510016.00	67136.00	2	2	0	0
24	510016.00	67186.00	2	1	1	6.67
25	510017.00	67236.00	2	1	1	6.67
26	510017.00	67286.00	2	1	1	6.67
27	513514.00	66943.00	2	2	0	0
28	513516.00	67043.00	2	2	0	0
29	513517.00	67143.00	2	2	0	0
30	513518.00	67193.00	2	1	1	6.67
31	514193.00	65434.00	-10	-8	-2	-13.33
32	514198.00	65484.00	2	1	1	6.67
33	514198.00	65534.00	2	2	0	0
34	514199.00	65584.00	2	2	0	0
35	499470.00	63566.00	2	1	1	6.67
36	499787.00	60616.00	-6	-5	-1	-6.67

Site	Eastings	Northings	Leveling-derived orthometric height for base survey (1986) (m)	Leveling-derived orthometric height for monitor survey (2003) (m)	Difference (Base – Monitor) = Subsidence (m)	Annual subsidence rate (cm/year)
37	499787.00	60662.00	-6	-6	0	0
38	499788.00	60712.00	-7	-6	-1	-6.67
39	499814.00	63061.00	2	1	1	6.67
40	499815.00	63111.00	2	1	1	6.67
41	499819.00	63412.00	2	1	1	6.67
42	504369.00	63406.00	2	2	0	0
43	504370.00	63456.00	2	2	0	0
44	504371.00	63506.00	2	2	0	0
45	504371.00	63556.00	2	2	0	0
46	507158.00	62421.00	2	2	0	0
47	507158.00	62471.00	2	1	1	6.67
48	507159.00	62521.00	2	1	1	6.67
49	509234.00	60594.00	2	1	1	6.67
50	509234.00	60644.00	2	2	0	0
51	509236.00	60745.00	2	2	0	0
52	509236.00	60795.00	1	-3	4	26.67
53	509237.00	60845.00	2	1	1	6.67
54	510245.00	63408.00	2	1	1	6.67
55	510295.00	63407.00	2	1	1	6.67
56	510345.00	63407.00	2	1	1	6.67
57	510395.00	63406.00	2	2	0	0
58	510320.00	63382.00	2	2	0	0
59	510320.00	63432.00	2	2	0	0
60	512058.00	62257.00	-8	-5	-3	-20.00
61	512058.00	62308.00	-2	1	-3	-20.00
62	512058.00	62360.00	2	1	1	6.67
63	514134.00	60485.00	2	2	0	0
64	514135.00	60535.00	2	2	0	0
65	514136.00	60585.00	2	2	0	0
66	514136.00	60635.00	2	2	0	0
67	499465.00	57042.00	2	2	0	0
68	499515.00	57041.00	2	2	0	0
69	499564.00	57041.00	2	2	0	0
70	499614.00	57040.00	2	2	0	0
71	502639.00	59001.00	-10	-9	-1	-6.67
72	498402.00	60055.00	1	1	0	0
73	498452.00	60054.00	1	1	0	0
74	498502.00	60054.00	1	1	0	0
75	498551.00	60053.00	1	1	0	0
76	507289.00	58944.00	2	2	0	0
77	507339.00	58944.00	2	2	0	0
78	507389.00	58943.00	2	2	0	0
79	504105.00	59984.00	-7	-7	0	0
80	504203.00	59985.00	-6	-6	0	0
81	509541.00	57091.00	-9	-8	-1	-6.67
82	509542.00	57141.00	2	1	1	6.67
83	509543.00	57191.00	2	2	0	0
84	509543.00	57241.00	2	2	0	0
85	512783.00	58376.00	2	2	0	0
86	512883.00	58375.00	2	2	0	0
88	510280.00	60033.00	-8	-8	0	0
89	510276.00	60082.00	-8	-8	0	0
90	510279.00	60133.00	-8	-8	0	0
91	510942.00	57174.00	-10	-9	-1	-6.67
92	510947.00	57224.00	-10	-10	0	0
93	510944.00	57273.00	-11	-11	0	0
Average						0.860

4. RESULTS AND DISCUSSION

4.1 Landcover Types

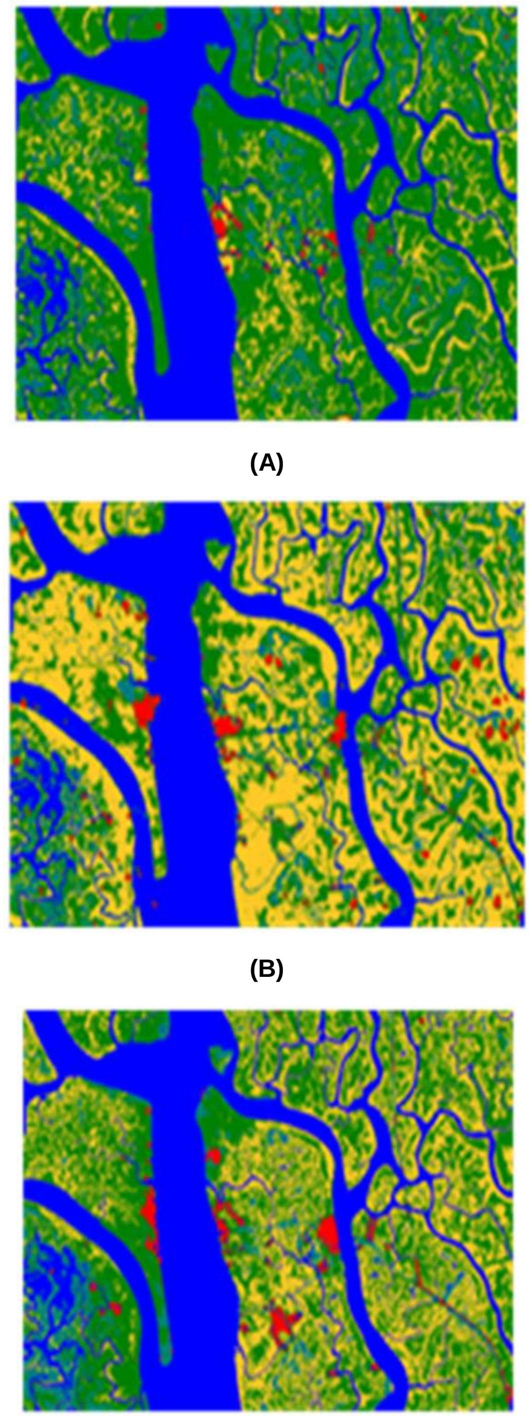
The landcover types found in the area of interest are: water, forest I (i.e. Mature Forest), forest II (i.e. Secondary Forest), farmland, stressed vegetation, high mangrove, low mangrove, wet mangrove and settlements/sand. Numerous settlements are seen within the area of interest. High Mangrove is mainly found around the edges of the major rivers and the tributaries. Low Mangrove is found within the area in close proximity to high and wet mangroves. They could easily be submerged in water. Wet Mangrove is the low mangrove that has been submerged or over run by water. When these occur, the low mangroves appear wet. Settlements/Sand/Cloud Cover is the combination of settlements, sand and cloud cover.

The sand deposits found within the area were possibly brought about by dredging. The image representations could be seen in Figs. 2 and 3.

A Normalized difference vegetation index (NDVI) was applied to the images (Fig. 4). It was observed that the areas with high NDVI values for the entire epochs are High mangrove, Wet Mangrove and Low Mangrove. These are shown in green, yellow and orange colours respectively. The water and settlements/sand/cloud cover are in blue and purple showing low NDVI.

Time-lapse analysis is for assessing changes in an area within a period of time. For the case of this study, it was carried out on Cawthorne Channel Area of Interest using the Landsat ETM 2003, SPOT 4 of 1998 and Landsat TM 1986 landuse/landcover images were equally compared. A breakdown of the various landcover types as a percentage of totals is shown in Table 4 and Fig. 5 pictorially.

Areas of mud occur dominantly in the east of the area. Much of the mud areas are associated with and interpreted to be due to E&P activity although there do appear to be some naturally occurring areas of mud in the south and west. Areas of soil are found on the banks of dredged slots and are interpreted to be the dredge spoils which are now grassy areas surrounding the slots (Fig. 6). A large sandy area occurs in the NW part of the area which is the only urban area of significant size in the Cawthorne Channel Area. Other smaller settlements do occur but these are not spectrally distinguishable from clearings of soil or mud.



(A)

(B)

(C)

Fig. 2. Landcover maps from (a) Landsdat TM of 1986, (b) SPOT 4 of 1998 and (c) Landsat ETM 2003

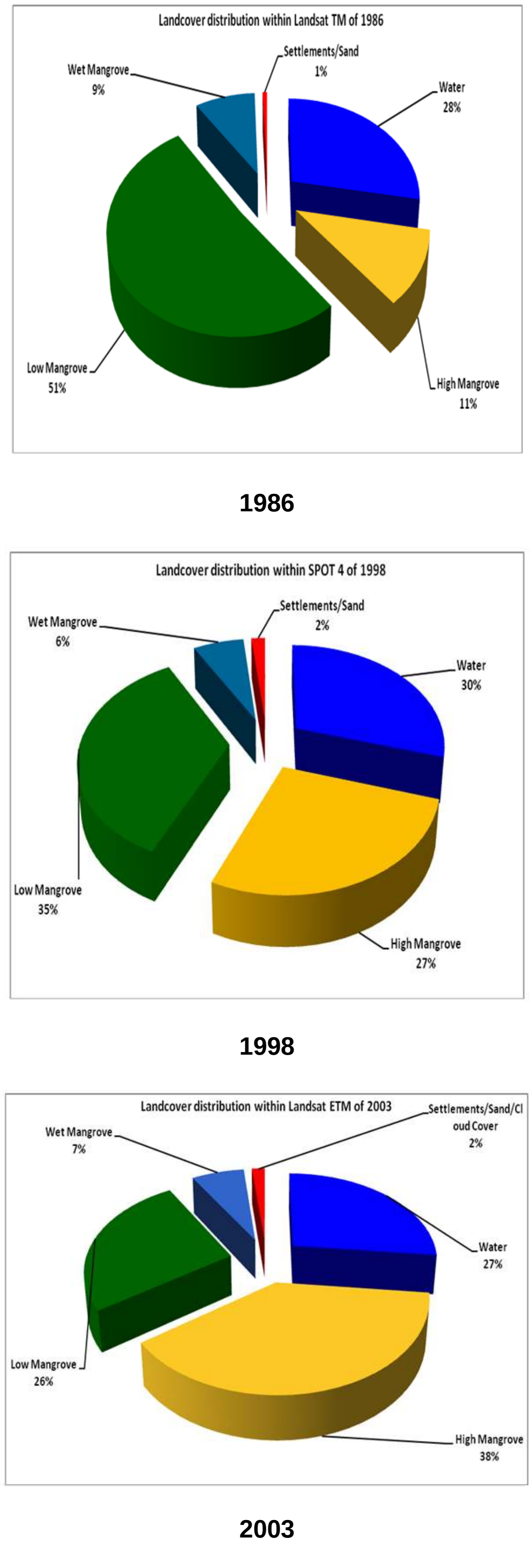


Fig. 3. Pictorial representation of the landcovers in 1986, 1998 and 2003

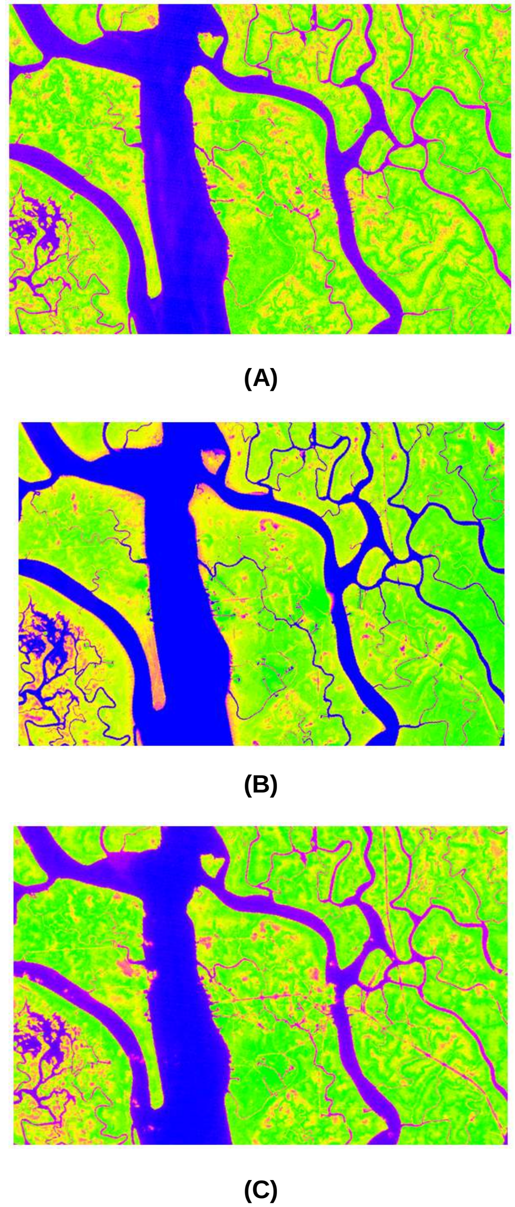


Fig. 4. NDVI Map of (a) Landsat TM for 1986, (b) Landsat ETM for 1998 and (c) Landsat ETM for 2003

4.2 Elevation Changes

The 1986 (baseline) elevation contour map over baseline map of 1986 is presented in Fig. 7. The 2003 (monitor) contour map over monitor map of 2003 is presented Fig. 8, while the difference (Baseline minus Monitor) elevation map over monitor map of 2003 showing the elevation changes as presented in Fig. 9. The rate of elevation changes (land subsidence) contour map is plotted over baseline map of 1986 to show the rate of land subsidence over time, and is presented in Fig. 10. The average rate of ground surface subsidence in the study area is 0.860 cm/year. Land subsidence can be caused by the removal of fluids (water, gas, or oil) when fluid production is voluminous, and the standing fluid levels in the wells exhibit large drops [21]. They further said that for land subsidence to take place, producing formations are located at shallow depth, 300 – 1000 m. In our research, the reservoir is not shallow but deeply-seated at a depth of more than 2400 mss. Another criterion for land subsidence is that the reservoir beds should have flat or gentle dips at the structure crest [21]. The reservoirs in the Niger Delta Basin are generally steep complex collapsed-crest roll-over anticline [22]. In addition to the above and other factors, reservoir compaction and land surface subsidence take place when the reservoir pore-fluid pressure is lowered by thousands of psi [23]. The reservoir pore-fluid pressure depletion in the Field of study is only 674 psi [24].

Subsidence caused by hydrocarbon production in the study area is therefore negligible due to the depth of the reservoir (2410 mss), and the subsidence affects only the immediate area and do not affect the entire Field of study on a regional scale. The minimal impacts of hydrocarbon production on land subsidence are based only on orthometric height difference. It is neither on subsurface data from the producing field nor from any numerical or analytical models that incorporate the physical changes of the reservoir formations associated with stress changes. Surface deformation data can only be explained by a combination of reservoir compaction [12,24].

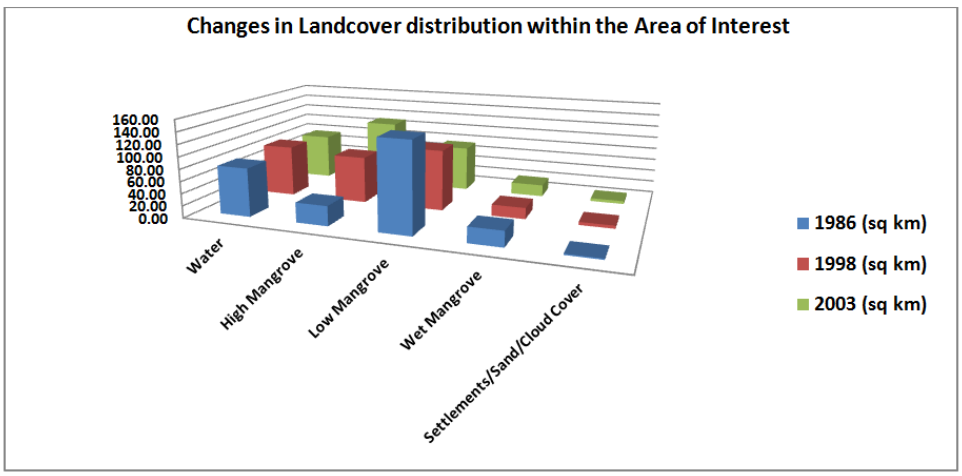


Fig. 5. Pictorial representation of the three Epochs

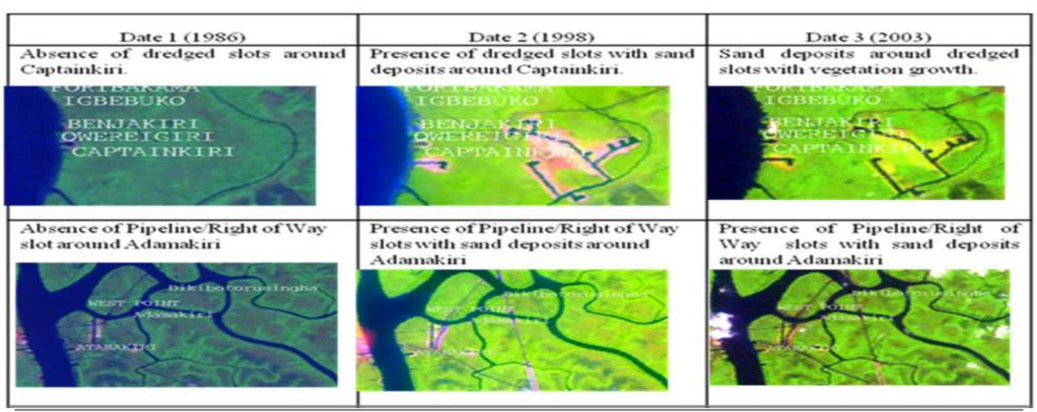


Fig. 6. Pictorial representation of landcover changes in 1986, 1998 and 2003

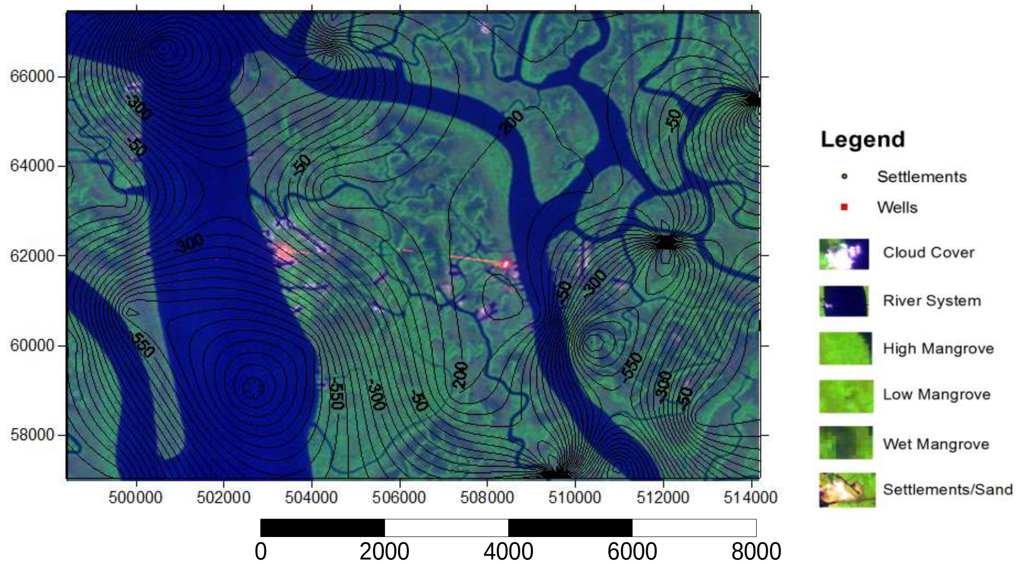


Fig. 7. Baseline elevation contour map over baseline map of 1986

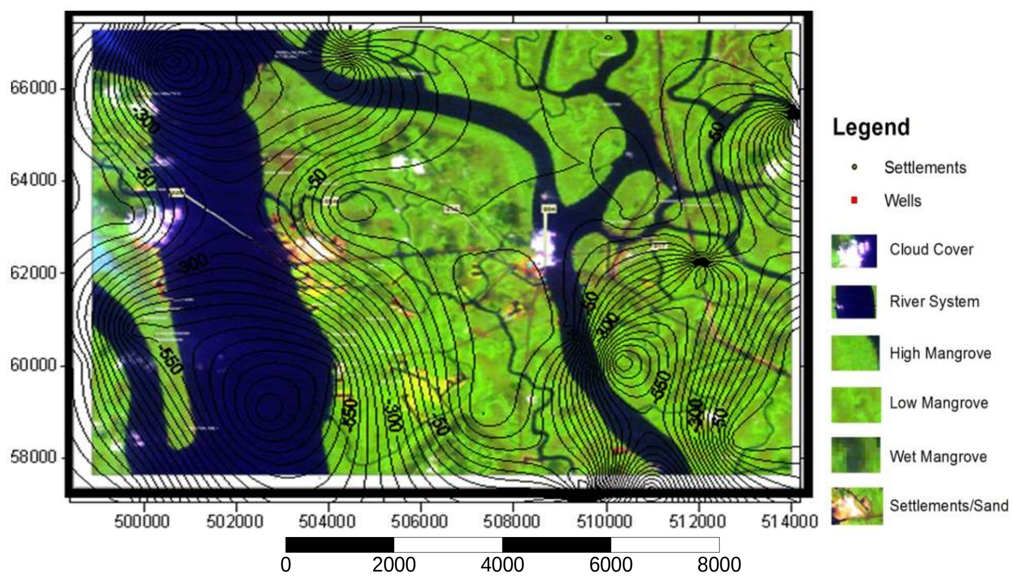


Fig. 8. Monitor contour map over monitor map of 2003

Table 4. Landcover summary for the three epochs

Landcover types	1986 (%)	1998 (%)	2003 (%)	1986 (sq km)	1998 (sq km)	2003 (sq km)
Water	27.91	29.63	26.70	80.12	85.05	76.64
High Mangrove	11.37	27.08	38.47	32.64	77.72	110.41
Low Mangrove	51.20	35.07	26.27	146.96	100.66	75.41
Wet Mangrove	8.87	6.47	6.87	25.46	18.57	19.71
Settlements/Sand/Cloud Cover	0.64	1.75	1.69	1.85	5.03	4.86

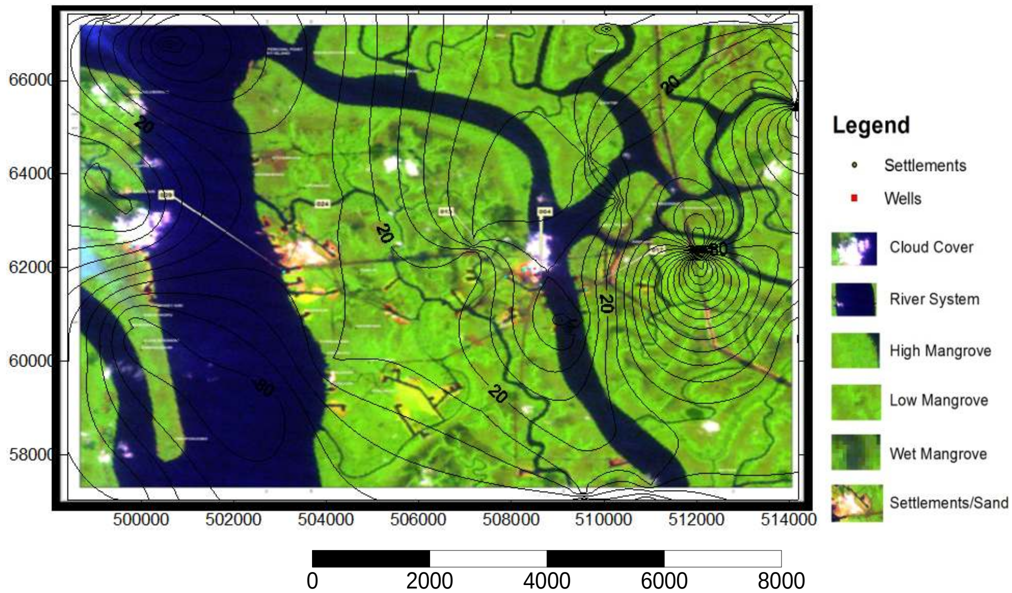


Fig. 9. Difference (Baseline minus Monitor) elevation map over monitor map of 2003

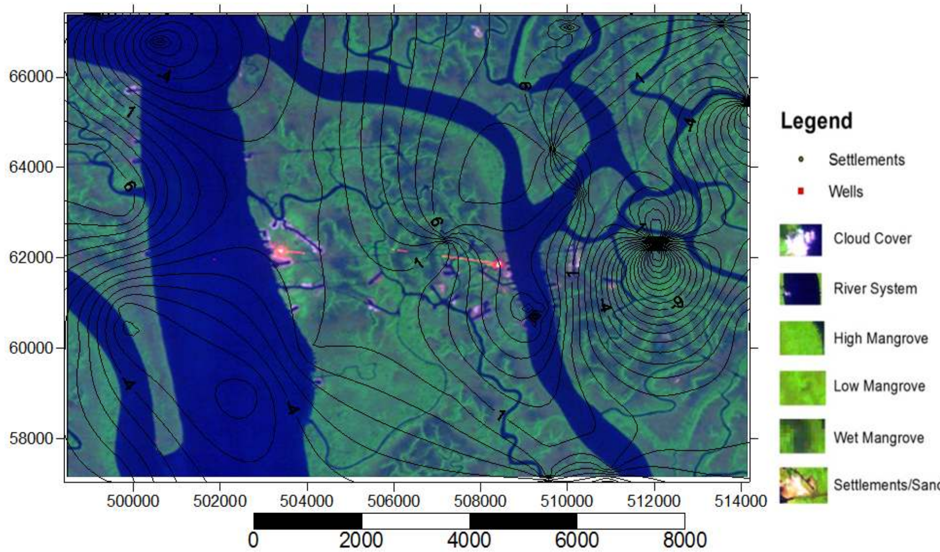


Fig. 10. Rate of elevation changes (land subsidence) over baseline map of 1986

5. CONCLUSION

The landcover change detection within Cawthorne Channel operational area between 1986, 1998 and 2003 was carried out in this study. The Cawthorne Channel Field consisted dominantly of water, mangrove and forest. Between 1986 and 1998 water increased from 80.12 km^2 to 85.05 km^2 respectively. This might be due to the upward surge in the water bodies. By 2003 it had decreased to 76.64 km^2. Also, since the acquisition was done during the dry season, the decrease could be due to increase in sand deposit along the river channel. High Mangrove vegetation is mainly found in close proximity to the river channel. It covered an area of 32.64 km^2 in 1986; 77.72 km^2 in 1998 and 110.41 km^2 in 2003. Low Mangrove vegetation is mainly found around the high mangrove. It decreased from 146.96 km^2 in 1986 to 77.72 km^2 in 1998 and to 75.41 km^2 2003. The reason may be the activity of water on the vegetation. Wet

Mangrove is mainly found within the low mangrove. This low mangrove is submersed in water. It decreased from 25.46 km^2 in 1986 to 18.57 km^2 in 1998 and made a slight increase to 19.71 km^2 in 2003. The reason may be the activity of water on the vegetation which depends on the water content.

For Settlements/Sands, in 1986 it was 1.85 km^2 and by 1998 it increased to 5.03 km^2 which appears to be due to clearing of mangrove through E&P activities while in 2003 it decreased to 4.86 km^2. Some areas of sands may be due to natural processes. For instance, dredging of slots could have increased the sand deposit in 1998 the area was heavily affected by human activities – these include urban/industrial, sand, soil, heat, affected areas and infrastructure most of which is directly related to E&P activities. There is little evidence, from the Remote Sensing data, of widespread settlements in the area. However, ground-truths show fishing settlements are widespread. These are dominantly too small to be resolved on the satellite data. While in 2003, vegetation could have started to grow on the sand. Also, the presence of cloud cover in 2003 could have obscured the sand and/or settlement bringing about the decrease.

The rate of elevation changes (land subsidence) at each location of levelling points varies from 66.67 mm yr^{-1} to 200.00 mmyr^{-1}, and an average of 86.00 mmyr^{-1}. The elevation changes in this Field are localized only where the measurements are located. Localized elevation changes associated with this Field are mainly in river and drenched channels and slopes caused by erosion. This minimal impacts of hydrocarbon production on elevation changes is based only on orthometric height difference, and not on the reservoir stress changes.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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