An Exposition of the Estimation of the Lake Chad Shoreline Dynamics

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Key Words

Shoreline, Lake Chad, Landsat images, DSAS, and GIS

Abstract

Lake Chad in the central part of the Sahel Region is an economically important lake. According to the UN Food and Agriculture Organization (FAO), the Lake Chad basin is one of the world's most important agricultural heritage sites. Due to a number of both anthropogenic and natural factors, the lake is now classified as among the most fragile hydrologic systems exposed to potential modifications of its hydrological conditions. In the last few decades, it has been shown that it has been drastically reduced in size by almost 90 percent (90%) in the last 60 years. The FAO has called the situation an "ecological catastrophe" and predicted that the lake could disappear this century. Despite its political and socio-economic importance, there has been no documented evidence of a specific study relating to the lake’s shoreline, particularly on Nigeria’s border. This paper aims at an exposition of the estimation of the Lake Chad shoreline dynamics on parts of the Nigerian side of the lake. Shoreline by its nature is an ambulatory line, there is a need for a sound understanding of the trends of the phenomena to help set out clearly the locations where safeguard measures are likely to be required and others where alternative options are more sustainable. Landsat 8 operational land imager (OLI) and Landsat 7 enhanced thematic mapper plus (ETM +) images of the study area of the study period, freely obtainable from the USGS website, were compiled and processed in ArcMap Tm. The analysis was based on the concept of the Digital Shoreline Analysis System (DSAS) software (an add-in to the Esri ArcGIS desktop). The software was utilized for the determination of the rate-of-change statistics from multiple historical shoreline positions as well as to assess the dynamics of the rates and for shoreline forecasting. The study covered a thirty-year (1991–2021) period carry out at a 10-year interval. The delineated shoreline of 1991 was used as the baseline for the generation of transects. Baseline maps, shoreline change statistics calculations, tables, charts, and graphs were used to present the results of the intermittent and overall shoreline movement. It shows the time-varying trends of the lake’s shoreline dynamics and identifies the vulnerability extents at specific locations.

The software used includes ArcGIS 10.6.1, ERDAS Imagine 2015, ENVI 5.1, Microsoft Office, and MATLAB R 2016a.

1.0 Introduction

Lake Chad, located in the central part of the Sahel region of Africa, is an economically significant lake. It serves as a major source of water for more than 30 million people living in the four countries (Chad, Cameroon, Niger, and Nigeria) surrounding it. The lake has been a trading hub offering economic opportunities and resources on which people living around it depend.

Lamentably due to a number of anthropogenic and natural factors, the lake is currently exposed to potential modifications of its hydrological conditions especially its shorelines and spatial extents. Sediment supply, climate variability, and geomorphological attributes together with man-made changes are known to be playing significant roles in the lake's shoreline dynamics. Gao *et al.*, (2011) reveal that the lake had shrunk vividly from 24,596.66 km^2 in the 1960s to 2,264.30 km^2 in 2017. The shrinkage was attributed principally to low inflows, the increased water supply demands due to increased population, agricultural activities, climate change phenomena, and persistent drought among other factors.(Yunana D A et al ,(2017), Willibroad and Lee, (2019). FAO (2021) has called the situation an "ecological catastrophe" and predicted that the lake could disappear this century. The myth of the lake's disappearance was earlier discussed in Géraud Magrin, (2016).

Shoreline change is an indicator of the way in which the location of the shoreline changes over time. These changes can have different manifestations over short and long time periods. The profound effects of these are seen when the known shorelines that serve as ambulatory line barriers that distinguish the water feature and land as well as defined the wetland and dry land boundary, keep changing.

Monitoring Shoreline is fundamental to the understanding of the dynamics of the land and water interface for informed decision-making. (Tamassoki E. et al, 2014). Understanding the shoreline changes is therefore essential to provide optimal shoreline management and protection solutions. It helps to identify the nature and processes that triggered these changes. It is also to help assess the human impact and to plan desired management strategies in any specific area.

Much of the regulatory framework initiated by successive governments of the countries surrounding Lake Chad has failed to address the causal factors and mitigate the effects of the spatial changes of the lake. There is an absence of clear identification and recognition of areas of greatest change for prioritizing resource allocation to provide optimal management and protection solutions, especially as affects the changes in the lake's shoreline areas.

As an ambulatory, shorelines move with time, their boundaries position are only the boundaries position on the date of the survey. Hence over time shoreline positions could become outdated due to their natural movement, rendering the recorded positions obsolete for useful decision-making purposes. Therefore it is important to monitor and analyze the shoreline "state" which is its trend at a location regularly (Salghuna and Bharathvaj, 2015).

Shoreline changes draw global attention due to their being among the most important environmental indicators that directly affect economic development and land management (Halls and Costin,(2016);); and Addo,(2008)). Moreover, the International Geographic Data Committee (IGDC) recognized Shorelines as one of the 27 most important earth's surface features to be mapped and monitored.

Although the importance of proper knowledge of shoreline dynamics, especially along administrative boundaries, is clearly recognized, relatively very little effort if any has been made to bring to fore the shorelines 'state', of Lake Chad along the defined international boundaries of the countries surrounding it. Of interest to this study are the physical indicators of the natural dynamics of the spatial extents of Lake Chad, particularly the overtime occurring changes in its shorelines.

Worldwide many methods and approaches have been developed and applied for shoreline change detection, monitoring, and estimating shoreline change. These include the baseline approach, dynamic segmentation approach, area-based approach, and non-linear least squares estimation approach. Several other studies such as Tamassoki et al (2014), Shenbagaraj et al, (2018) Salghuna and Bharathvaj (2015), etc., have shown that Remote sensing and GIS technology approaches can also be used with reasonable accuracy to extract the waters and monitor water body dynamics as an alternative to the labor-intensive conventional terrestrial surveys methods that take more times and requires huge manpower involvements.

Visual interpretation and ISODATA classification were among the remote sensing techniques used to extract the shorelines. These approaches have real-time, macroscopic, and low-cost characteristics and are adjudged as very fast and relatively efficient in monitoring surface changes. The time intervals between the selected images of the studied area help in the detection and quantification of the nature and timing of changes and their impacts. However, the use of Remote Sensing approaches is also saddled with some problems such as noise and missing edge line cues as highlighted by Farizuwana et al (2017).

In this study, Digital Shoreline Analysis System (DSAS) which is an extension tool for Esri ArcGIS desktop software, developed by USGS was used for examining past or present shoreline positions because of its simplicity and user-friendly interface with GIS software. The use of the DSAS tool in Shoreline change analysis enables the computation of the rate-of-change statistics for a time series of shoreline position and the shoreline retreat changes in the area of study. The time intervals between the images studied play an important role in detecting and quantifying the nature and timing of changes associated with anthropogenic impacts by better identifying the timing of major changes and by reconstituting baselines.

Although several past studies on Lake Chad exists, (FAO, (2021). Muhammad, and Nurul, (2016), Ikusemoran, et al (2018), Hussaini et al (2019), and Frederick Policelli et al (2018)), and despite its political and socio-economic importance to date, there is no documented evidence of an attempt to determine its shoreline retreat changes particularly on parts of the Nigerian border side of the Lake Chad, especially studies on the trends and extents of the shoreline. Therefore the major objective of the study is to demarcate the shorelines of 1991, 2001, 2011, and 2021 from the different sensor satellite images. They are used to identify the quantitative and qualitative shoreline changes for the mentioned periods of the study. This would help in setting out clearly the locations where safeguard measures are likely to be required and others where alternative options are more sustainable

This paper is organized as follows. In section 2, the study area, and Dataset used, are described, in section 3, the methodology used is presented, and the results and discussions are briefly highlighted in section 4. Finally, the paper’s conclusion and recommendation are summarized in the last section

2. STUDY AREA AND DATASET

2.1 Study area

The Lake is bounded in the north by the Chad Republic, east by Cameroon, south by Nigeria, and in the northwest by the Niger Republic. It is located within Latitude 12^{0} 30’ and 14^{o} 30’ north of the equator and Longitude 13^{0} 00’ and 16^{o} 00’ East of the Greenwich Meridian (Figure1). The Lake Chad Basin covers almost 8% of the continent and spreads over seven countries; Nigeria, Niger, Chad, Cameroon, Libya, Sudan, Algeria, and the Central Africa Republic. About 20% of the total area of the basin's 427500 km^2 is called the Conventional Basin (42% in Chad, 28% in Niger, 21% in Nigeria, and 9% in Cameroon). Lake Chad serves as a source of fresh water and plays a significant role in the livelihood of over 30 million people in the Sahel region.

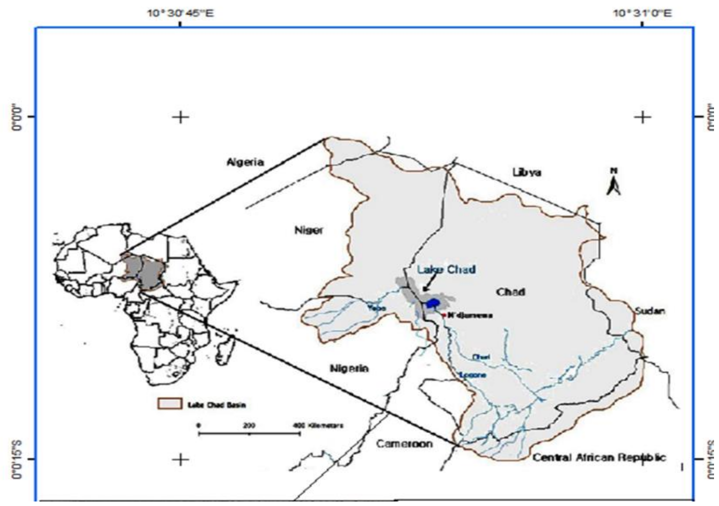


Figure 1. **Study area**

2.2 Materials

The materials used in the study comprised of the freely available satellite images dataset (Landsat 4, 5, 7 ETM+ and Landsat 8 OLI) imageries data respectively of the study area (Table 1) which was downloaded from the United States Geological Survey (USGS) via its website (http://earthexplorer.usgs.gov/). The data temporal coverage is four (4) decades, ranging from 1991-2021, and are of the same seasons (Dry Dec/Jan) at intervals of 10 years(1991-2001, 2001-2011, 2011- 2021) respectively. The software used includes DSAS version: 5.0.20200527.0200, ArcGIS version: 10.5, ERDAS imagine 2015, and Microsoft Office.

Table 1: Satellite Image Dataset

S/N	Data Type	Date	Data Sources	Resolution	Path/Row
1	Landsat 4	Dec/1991	USGS	30 M	185 / 51
2	Landsat 7 ETM	Dec/2001	USGS	30 M	185 / 51
3	Landsat 7 ETM	Dec/2011	USGS	30 M	185 / 51
4	Landsat 8 OLI	Jan/2021	USGS	30 M	185 / 51

3.0 METHODOLOGY

In this study, quantitative changes in shoreline along the Nigeria boundary parts of Lake Chad were interpreted. Figure 2 is the methodology flow chart. The Landsat images (Table 1**)** of 1991, 2001, 2011, and 2021respectively were used to detect the changes in the shoreline in the study area. The Landsat images were freely downloaded from the U.S. Geological Survey and processed. The selected images used were of similar seasons (dated December & January), so they are temporarily comparable. The image elements were analyzed both by visual and digital interpretation.

QGIS 3.14.15 software was used to gap filled the datasets of Landsat 7 ETM+, which has gaps in their data due to Scan Line Corrector (SLC) failure. The software was also used for Layer stacking to combine the multiple images into a single image of the same extent and spatial resolution. Each ETM + and OLI file is comprised of independent single band images.

To enhance the visual quality of the imageries used, Digital Image Processing (DIP) was carried out. An unsupervised classification was performed using the ISODATA clustering method to classify the image. To derive the Shoreline from the satellite image data, the band ratio of the Red band to the IR band is done. The Layer-stack module involved taking band (4, 3, and 2) for Landsat 7 ETM + as color composite and band (5, 4, and 3) for the Landsat 8 OLI respectively. 5 6 4.

Figure 3 is the classified Landsat images of Lake Chad for the years 1991, 2001, 2011, and 2021 respectively.

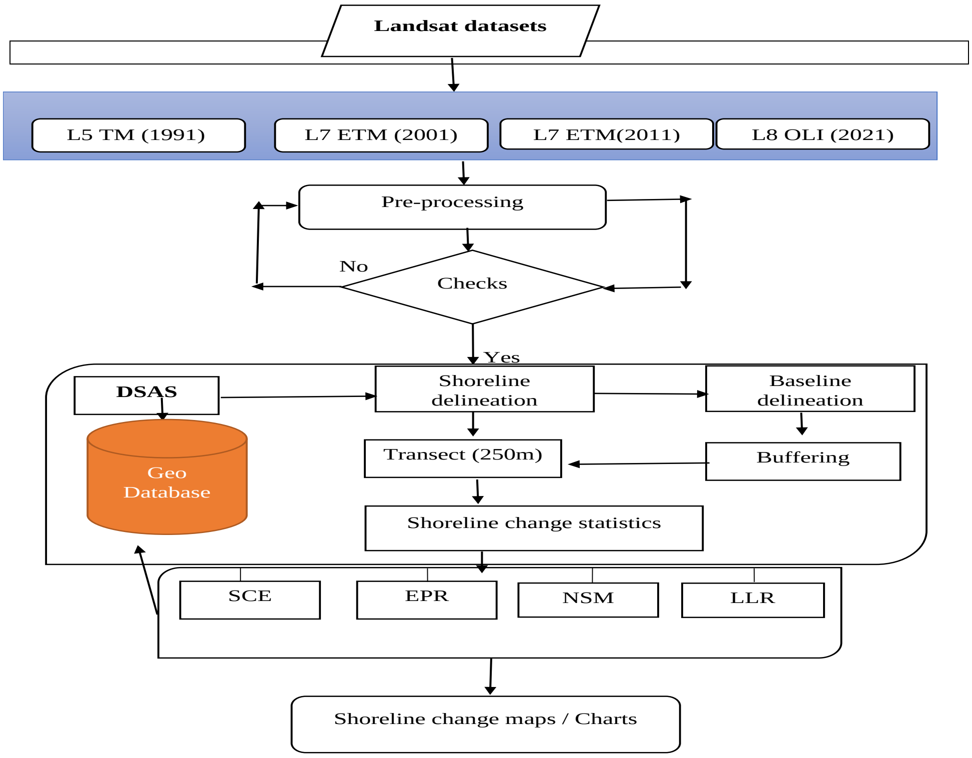


Figure 2. Methodology Flowchart

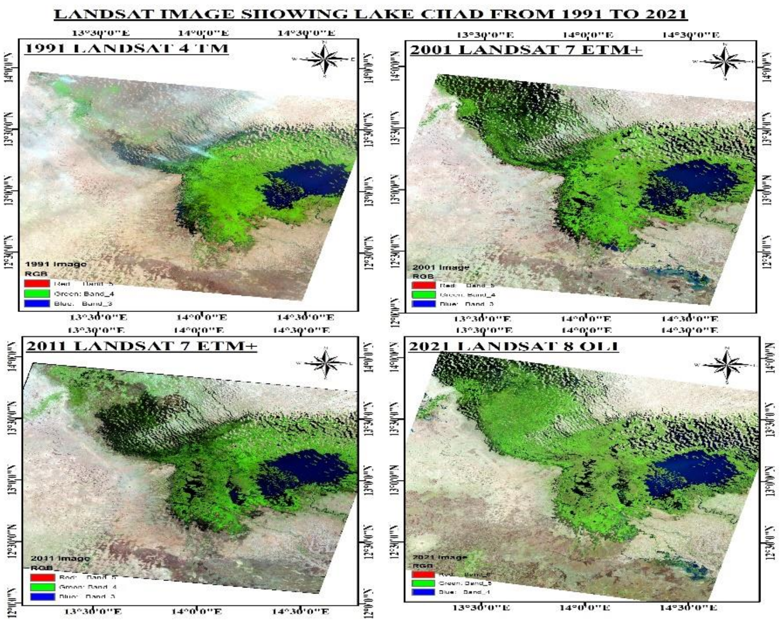


Figure 3 1991, 2001, 2011 &2021 Classified Landsat images of Lake Chad

ArcGIS 10.6.1 was used to digitize, delineate and analyze the shoreline of each of the selected epochs. A geo-database was created for the digitized position and attributes (ID, Shape, and uncertainty) for all of the shorelines. Shapefile of the years 1991, 2001, 2011, and 2021 were each respectively digitized as a single layer. The shoreline for the different epochs was using ArcGIS software. Figure 4 is the map showing the baseline (1991) and the other respective digitized shorelines.

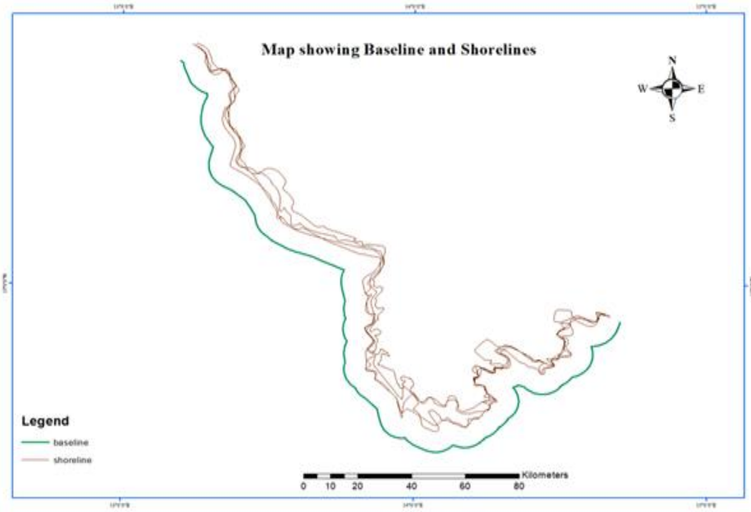


Figure 4; Map showing the baseline (1991) and other digitised shorelines.

The Digital Shoreline Analysis System (DSAS) tool in the ArcGIS environment, was utilized to create transacts along the Nigeria boundary section of the Lake. The generated transects were laid at 250 m intervals using the 1991 shoreline as the baseline. The transact map for 1991- 2021 is shown in Figure 5.

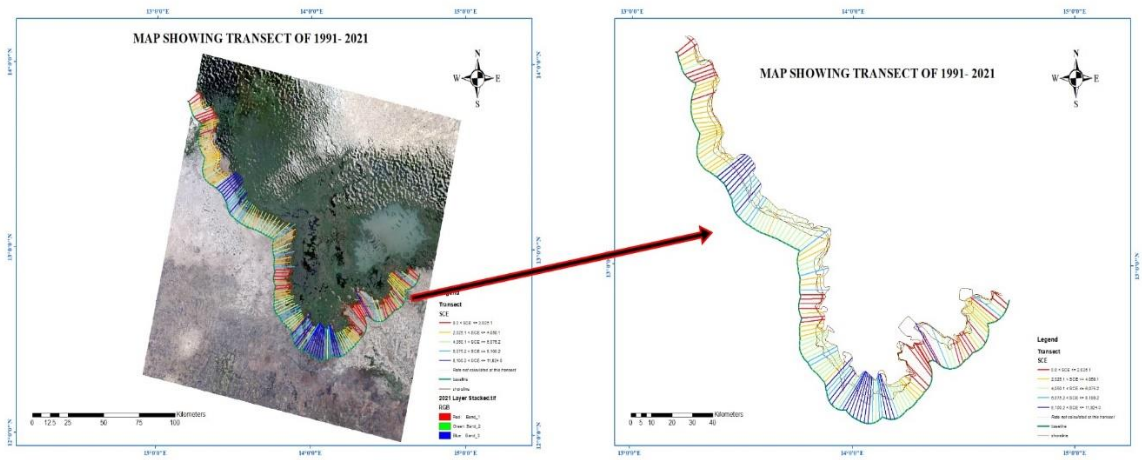


Figure 5: Transact map for the 1901- 2021

Each of these transects intersects the respective shorelines to create a measurement point. The measurement points were used to measure distances and calculate shoreline change rate statistics for each of the selected epochs. These distance measurements and the rates comprise Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), End Point Rate (EPR) Linear Regression Rate (LRR), and Weight Linear Regression (WLR) respectively.
The SCE value represents the greatest distance among all the shorelines that intersect a given transect. The NSM is the distance between the oldest and the youngest shorelines for each transect; therefore, its units are in meters. The EPR is calculated as the ratio of the distances of the shoreline movement by the time that elapses between two shorelines. The LRR is the slope line used to estimate the long-term shoreline change rate for predictive analysis. The horizontal shoreline movement areas were identified, and the Erosion and Accretion, are analyzed,

4.0. RESULTS AND DISCUSSIONS

The overall SCE average transect distances (Table 2) for the period of the study were 3729.77m 3981.22m and 5110.79m for the year (2001 to 2011), (2011 to 2021) and (2001 to 2021) respectively. Transect ID.12 has the maximum transect distance of 16697.2 m in the (2001 to 2011), and (2001 to 2021) periods while transect ID 13, has the maximum transect distance of 16029.41m in the (2011 to 2021) period.

Table2: Shoreline Change Envelope (SCE)

Shoreline Dates used	12/12/1991; 12/31/2001; & 12/12/2011	12/31/2001, 12/27/2011, 1/12/2021	12/12/1991, 12/31/2001, 12/27/2011, 1/12/2021
Total no Transact	117	115	117
Transact Spacing (m)	2500	2500	2500
Ave. Transect Distance (m	3729.77	3981.22	5110.79
Max Transect Distance (m)	16697.2 (ID.12)	16029.41 (ID13)	16697.2 (ID: 12)
Min Transect Distance (m)	49.06 (ID.30)	37.51 (ID29)	56.3 (29)

The NSM rate (Table 3) shows average maximum negative distances of -3786.92m (Transact ID: 114), 2992.31m (Transact ID: 114), and -3142.94m (Transact ID: 109) for the period (2001 to 2011), (2011 to 2021) and (2001 to 2021), respectively, and also respective maximum positive distances of 16697.2m (Transact ID: 12), 14911.38m (Transact ID: 12), 15692.56m (Transact ID: 12) of the same period.

Table 3 Net Shoreline Movement (NSM) Rate Results

Shoreline Dates used	12/12/1991; 12/31/2001; & 12/12/2011	12/31/2001, 12/27/2011, 1/12/2021	12/12/1991, 12/31/2001, 12/27/2011, 1/12/2021
Total nos. transact	117	115	117
Ave. transact distance	2676.24	2912.98	4429.24
Nos. negative trans dist.	24	21	7
% negative trans distance	20.51%	18.26%	5.98%
Max. negative distance	-3786.92 (ID: 114)	2992.31 (ID: 114)	-3142.94 (ID: 109)
Ave negative distance	-801.51	-637.45	-1048.59
Nos, positive trans distance	93	94	110
% positive trans distance	79.49%	81.74%	94.02%
Max. positive trans distance	16697.2 **(ID: 12)**	14911.38 **(ID: 12)**	15692.56 **(ID: 12)**
Ave. positive trans distance	3573.73	3706.16	4777.83

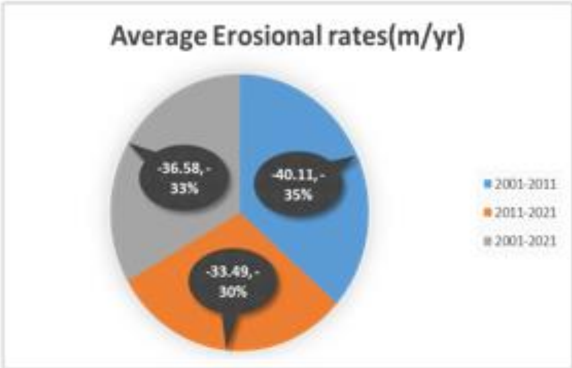
From the EPR overall averages results (Table 4), the total number of erosional transects obtained is 24 for the 2001 to 2011 period. The transect ID: 114 has a maximum erosion value of -188.96 m, and the average of all erosional rates is -40.11 m/yr for this period. While for the years 2011 to 2021 period, the total number of erosional transects obtained is 21, with transect ID: 114 having a maximum erosion value of -157.21m, and the average of all erosional rates is-33.49 m/yr. The cumulative rate for the 20-year (2001 to 2021) period shows that for the total of 7 erosional transacts, the average of all erosional rates is -36.58 m/yr, with transects ID 109 having the maximum erosion value of -108,06 m,

Table 4 End Point Rate, (EPR m/yr) Results

Shoreline Dates used	12/12/1991, 12/31/2001, 12/27/2011	12/31/2001,12/27/2011 , 1/12/2021	12/12/1991,12/31/2001, 12/27/2011, 1/12/2021
Total nos transacs	117	115	117
Ave. rate	133.53	153.04	152.31
Ave. C I rates	0.36	0.37	0.25
Ave. rate n uncertainty	133.53 +/- 0.07	153.04 +/- 0.37	152.31 +/- 0.25
No. erosional trans	24	21	7
% Trans erosional	20.51%	18.26%	5.98%
Max. erosion (Trans ID)	-188.96 **(ID: 114)**	-157.21 **(ID114)**	-108.06 **(ID: 109)**
Ave. erosional rates:	-40.11	-33.49	-36.58
No. Accreation. trans	93	94	110
% Accreation trans:	79.49%	81.74%	94.02%
Max. accretion:	833.15 **(ID: 12)**	783.43 **(ID: 12)**	539.53 **(ID: 12)**
Ave. Accretional rates:	178.35	194.72	164.33

The number of accretional transects for the year 2001 to 2011 period is 93 with average accretional rates of 178.35m/yr. The transect ID 12 has the maximum accretion of 8333.15m. For the year 2011 to 2021 period, the number of accretional transects is 94.

The average of all accretional rates for the period is 194.72m/yr. and it was transect ID 12 has the maximum accretion value of 783.43m. For the year 2001to 2021 period, the total number of accretional transacts is 110. The average of all accretional rates for the period is 164.33 m/yr. with transect ID 12 having the maximum accretion value of 539.53m. Figure 6a and Figure 6b shows the average erosional and accreational rates in meter per year.



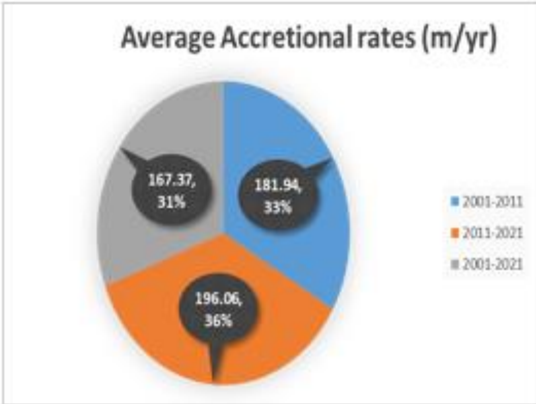


Figure 6a: Average Erosional Rates **Figure 6b Accreational Rates**

The per annum average rate with reduced number of independent transects (n = 1) uncertainty is 133.53m +/- 0.07 for the year 2001 to 2011period, 153.04 m +/- 0.37 for the 2011 to 2021 period and is 152.31m +/- 0.25 for the year 2001 to 2021period respectively

The results include shoreline maps of the years 1991, 2001, 2011, and 2021 with satellite images, baseline map, shoreline change statistics calculation, tables, charts, and graphs

5 CONCLUSIONS

In this study, the Lake Chad Shorelines at different selected epoch was extracted from the freely available Landsat Satellite images downloaded from the USGS website The images, were used to determine the overtime shoreline changes in the Nigeria sector of the Lake. Remote sensing and GIS approaches were applied. The Digital Shoreline Analysis System (DSAS) technique developed by the United States Geological Survey was used to measure distances and calculate the rate of change statistics from multiple historical shoreline positions of Lake Chad extracted from Landsat satellite images, of 1991, 2001, 2011, and 2021. This provide an estimates of the lake shorelines dynamics at specified 2500m intervals over the 37,000m length of Nigeria side of the lake.

The SCE shows that the highest change (transact distance = 16697.2 m) in shoreline happens around the transect ID 12 to ID 13 for the 2001 to 2021 period. While the smallest change ((transact distance =37.51m) happens around transect ID29 to transect

ID30. for the same period. The NSM results show the maximum transact distance of 15692.56m (transact ID: 12). The EPR results show a 94.02% accretion rate, with a maximum accretion of 539.53m (transact ID: 12) and 152.31m/yr +/- 0.25 average rate with reduced n (number of independent transects) uncertainty at 153.04 +/- 0.37. The Linear Regression Rate (LRR) overall averages illustrated a significant positive correlation (0.73) with the EPR results

These results revealed that over the study period 1991-2021, Lake Chad has experienced significant phenomena of erosion and accumulation along its shoreline resulting in varying shoreline movement that impacts the overall reported shrinkage of the lake's spatial extents. The study confirmed the use of the integration of remote sensing and GIS technology for long-term shoreline change studies using multispectral images. It also confirmed the applicability of the overtime Satellite Image dataset to help better understand the shorelines process and recognition of areas of greatest change for prioritizing resource allocation for effective management. Consequently continued monitoring of shoreline changes is important for the understanding of the changes taking place in the shoreline areas. Monitoring changes in shoreline is a requirement to identify the nature and processes that triggered these changes. It is also to help assess the human impact and to plan desired management strategies in any specific area.

The approach used and the results obtained could be valuable to, especially the LCDA's management planning unit, which is required to understand and plan desired management strategies in any specific area and improve the provision of mitigations services, and enhance the resources management for sustainable improvement of the local communities livelihood.

The use of DSAS and Geographic Information Systems techniques employed in this study provides reasonable accuracy, an inexpensive and rapid means for monitoring the shoreline environments, especially for developing countries where funding is challenged. The Government and respective agencies responsible for the monitoring and protection of the shoreline areas of the Lake are encouraged to adopt the approach to help to provide and develop sustainable interventions to protect the environment.

To demarcate the shoreline configuration more accurately, further study may be carried out using high-resolution satellite images or by the use of RTK (real-time kinematic) GPS surveys. The study's results could provide useful information for better and more sustainable shoreline management along the Nigeria side of the lake. These outputs could be more useful for engineers, planners, and other management decision-makers especially the Lake Chad authorities to facilitate suitable management plans and regulations. It would also serve as a baseline for further studies on Lake Chad.

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