REMOTE EVALUATION OF SEDIMENTATION OF ELEYELE RESERVIOR, IBADAN, OYO STATE, NIGERIA: THE SATELLITE DERIVED BATHYMETRIC APPROACH

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ABSTRACT

The availability of water in adequate quantity is fundamental to sustainability of the environment thus artificial impoundments called dams are constructed to conserve water resources for a variety of purposes ranging from domestic to industrial uses. Eleyele reservoir, constructed in 1942, has been subjected to severe sedimentation since its construction thus unable to cater to water demands of users in Ibadan and environ. This study adopted Satellite-Derived Bathymetric (SDB) approach to evaluate the rate and volume of sediments deposit in the reservoir between 2001 and 2020. Landsat imagery constitute the main input data while other ancillary data utilised include SRTM, rainfall, Goggle Earth imagery, digitised map, etc. The methodology involves a comparative analysis of depths of shallow water body derived through the processing of satellite imagery at different epochs. The satellite derived bathymetry was calibrated with ground truth data. The obtained bathymetric data showed that the deposited sediment between 2001 and 2006 was 66.05%, 29.62% between 2006 and 2011, 66.08% between 2011 and 2016 and between 2016 and 2020 sediment deposited was 35.81%. The result analysis showed that remote sensing data can be used in determining the depth of water, total sediment thickness, sediment removal systems, catchment management practices, and periodic desilting.

Keywords: Satellite imageries, sedimentation, digital image processing, satellite derived bathymetry, spatial analysis.

INTRODUCTION

Water is connected to every form of life on earth and it is one of our most precious resources (Dinka, 2018). Nothing can live without it. However, there has to be the right amount of water in the right place at the right time. Access to water is one of the main goal of Millennium Development Goals (UN-MDGs) and it is also one of the main goal of the Sustainable Development Goals (SDGs) (Dinka, 2018; Ki-moon & General, 2010). The UN-SDG goal states that "Water sustains life, but safe clean drinking water defines civilization". Despite these facts, there are inequalities in access to safe drinking water in the world. In some countries, sufficient freshwater is not available (physical scarcity); while in other countries, abundant freshwater is available, but it is expensive to use (economic scarcity) (Dinka, 2018).

Dams are constructed to provide communities and individuals with great benefits because of their multipurpose uses however these dams are mostly affected by sedimentation as a result of both natural and anthropogenic factors which reduces their energy production, storage, discharge capacity and flood attenuation capabilities. (Ezugwu, 2013). Reservoir sedimentation is filling of the reservoir behind a dam with sediment carried into the reservoir by streams. The deposition of sediment will automatically reduce the water storing capacity of the reservoir, and if the process of deposition continues longer, a stage is likely to reach when the whole reservoir may get silted up and become useless (Garg, 1973; Obialor *et al.*, 2019). A study was carried out on the world's 145 major rivers with consistency long term sediment records and the results show that about 50% of the rivers have statistically a significantly downward flow trend due to sedimentation (Walling & Fang, 2003). Sumi and Hirose (2009) reported that the global reservoir gross storage capacity is about 6000 km3 and annual reservoir sedimentation rates are about 31 km3 (0.52 %). This suggests that at this sedimentation rate, the global reservoir storage capacity will be reduced to 50% by year 2100.

Eleyele reservoir with the total length of embankment of 244 meters, surface area of 160ha, maximum height of foundations of 185.4m (above sea level) and capacity of 7 $mm^{3,}$ is the source of drinking water for the part of the city of Ibadan (Elufioye, 2017). It was constructed in 1942 and commissioned in 1943 to supply raw water for treatment at the Eleyele Waterworks and for flood controls during high flow periods through its reservoir holding capacity. Thus, there is a recurring scenario every year that large volumes of torrential rainfall water which supports the dam with its needed water source equally carry along with them a considerable quantity silts as they travel and finally deposited in the dam, this continuous process then resulted in siltation of the reservoir hence reducing its capacity to hold water. Due to lack of regular dredging activities on the reservoir, it had become overly silted, thus reducing the capacity of the reservoir to hold and provide sufficient water supply for a varied user community for an array of uses. In 2011, due to persistent torrential rainfalls, the reservoir became flooded causing colossal damage to the spillway and a resultant massive flooding of the surrounding settlements In order to ensure that the dam is utilized to optimal capacity, there is a pressing need to execute bathymetric survey as well as the usage of satellite images which will aid depth determination at different spots within the dam to determine the current capacity of the dam and to ascertain the volume of silts that have to be dredged off in order to bring it back to its initial designed capacity. This research is aimed at carrying out a simplified remotely sensed bathymetric technique to determine the rate and volume of sedimentation for selected timeline to create awareness as well to assist its sustainable maintenance and this was achieved by carried out satellite-derived bathymetry of the study area, evaluate the volume of sediment deposits in the reservoir and determine the rate of sedimentation in the reservoir.

The Study Area

The Eleyele waterworks (Figure 1 and 2) is situated upstream on River Ona, in the city of Ibadan at an altitude of 125m above sea-level within geographical coordinates:7°25’00’ and 7°26’30’N latitudes and 3°51’00’ and 3°52’30’E longitudes (Adeleru, 2017). It falls within Ido Local Government Area and was constructed along the Ona River (part of a dense network of inland waterways that flow southward into the Lagos Lagoon) at Eleyele community in 1942; Otaru, Awba, Yemoja and Alapo streams also empty into it. The reservoir is surrounded by a variable margin of woodland, beyond which is urban development on all sides of the reservoir and mostly dominated with the rural fishing communities by Ilaje and Yorubas. Eleyele reservoir is located to the north-west of the Ibadan City centre bounded by Eleyele urbanisation in the south, the areas of Apete in the east, Awotan izn the north and Ologuneru in the north-west. Eleyele reservoir is a vital resource for fishery, domestic water supply and flood control; the reservoir is fast being degraded due to various anthropogenic activities around its catchments (Bolaji, 2010; Olanrewaju *et al.*, 2017). Eleyele Dam is exposed to flooding, notable among which was the flood event which took place after a heavy downpour of 187.5 mm in about 4-5 hours on August 26, 2011. This flooding occasion was induced by the overflow from Eleyele reservoir, causing the death of over 120 people and serious damages to infrastructure, with many bridges collapsed, roads washed away, and substantial property lost (Adeleru, 2017).

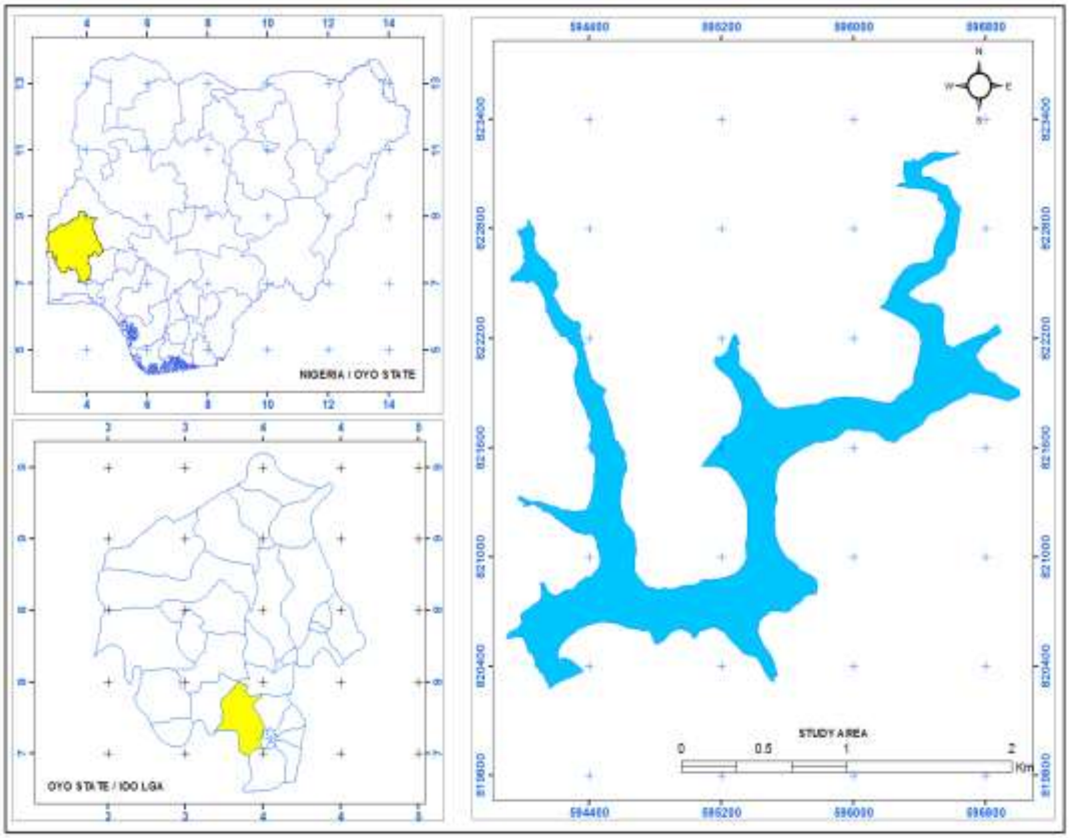


Figure 1: Study Area Location Map

Figure 2: Pictorial view of Eleyele reservoir

METHOD AND MATERIALS

For the quantification of the volume of sediment deposited in the reservoir, satellite data was used for basic information extraction, i.e. water spread area at different water surface elevations. The selection of water year for analysis is from consideration of maximum variation in reservoir levels and availability of images. Remote sensing based reservoir. The material used in this research are divided into three major classes namely; data, software and hardware. They were all used during data acquisition, data processing and data analysis. The data encompasses all the relevant datasets needed for successful execution of this study and the sources for each. Several sets of Landsat satellite images over a period of years are the main datasets.

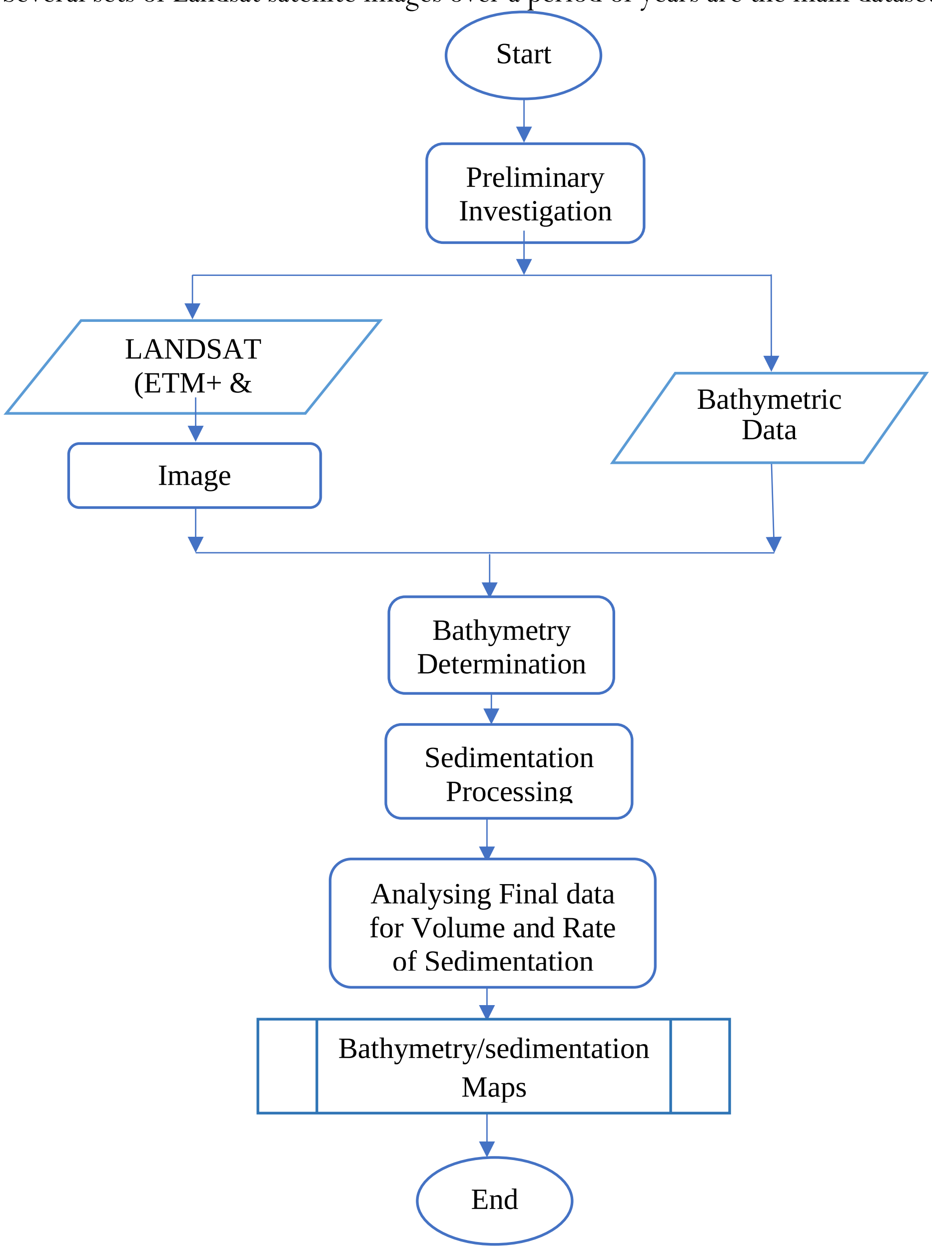


Figure 3: Research Methodology Flowchart

Table 1: Datasets Used (Source: Author)

S/N	DATA TYPE	SOURCE	DATE
1	Eleyele bathymetric data	Darts Geomatics Consulting Limited.	2016
2	Google Earth imagery	Google	
3	Digitized map of the study area	Researcher	
4	Landsat 7 ETM+ satellite imagery with 30.0m resolution	U.S. Geological Surveys (U.S.G.S).	2001, 2006, 2011.
5	Landsat 8 OLI satellite imagery with 30.0m resolution	U.S. Geological Surveys (U.S.G.S).	2016, 2020
6	Shuttle Radar Topography Mission (SRTM)	http://srtm.csi.cgiar.org/	2001-2020

Table 3: Landsat Imagery Datasets Details (Source: Author)

Year	Sensor	Scene ID #	Date Acquired	Acquisition Time (GMT +1)	Resolution
2001	ETM+	LE71910552001343SGS00	09-12-2001	10:51:32 am	30m
2006	ETM+	LE71910552006341ASN00	07-12-2006	10:53:04 am	30m
2011	ETM+	LE71910552011003ASN00	03-01-2011	10:56:08 am	30m
2016	OLI / TIRS	LC81910552016344LGN01	10-12-2016	11:02:55 am	30m
2020	OLI / TIRS	LC81910552020020LGN00	20-01-2020	11:03:05 am	30m

The software used during various project phases included ENVI 5.3 for study area boundary delineation using spectral index Modified Normalized Difference Water Index (MNDWI), image pre-processing (radiometric correction, atmospheric correction and noise reduction) and image classification. ArcGIS 10.5 was used for both GIS work (editing, clipping, area calculation, volume calculation, data conversion, database creation, geometric correction and elevation model creation.), raster creations and bathymetry creation (or determination). Surfer 16 was used for plotting 3D Wireframe, 3D Surface and flow direction. Google Earth was used to obtain pictorial view and time series images of the study area and as a supplement to 1 arc seconds SRTM elevation data of the land surrounding the study area. The hardware include personal computers, GPS receivers, Printers, Scanner, Survey boat, life jackets, etc.

Data Processing

The boundary map of reservoir was extracted from satellite imagery using Modified Normalised Difference Water index (MNDWI) spectral index formulae in equation 2 with the aid of ENVI 5.3 software.

$$MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR} \quad \text{(eqn. 2)}$$

Green = pixel values from the green band
SWIR = pixel values from the short-wave infrared band
The Modified Normalized difference water index is a tool to delineate open water features and enhance their presence in satellite images.

Table 4: Values for Land/Water threshold

Landsat Data	Path/Row (WRS-2)	Acquisition Date (DD-MM-YYYY)	Water Threshold Values (Surface Reflectance)
Landsat 7 ETM+	191/55	09-12-2001	60
	191/55	07-12-2006	30
	191/55	03-01-2011	60
Landsat Data	Path/Row (WRS-2)	Acquisition Date (DD-MM-YYYY)	Water Threshold Values (Digital No.)
Landsat 8 OLI	191/55	10-12-2016	12,500
	191/55	20-01-2020	12,500

a) Generating a water subset

All the NIR bands were converted into float format through conversion of each integer cell value of the raster into a floating-point representation. This was also done for the green and blue bands of each Landsat data acquired. Then, a low-pass focal filter was performed on the raster by traversing a low pass filter over the raster. Next, the Set Null tool was used to assign No Data values to cells/pixels with values higher than the previously calculated water threshold values. The land was removed from the blue and green bands by filling the *Set Null* window for the blue and green bands with the threshold value calculated from the IR band.

b) Applying the bathymetry algorithm

The bathymetry was calculated using the Stumpf et al. (2003) algorithm on the blue and green bands. The S.D.B algorithm was applied as shown below (Figure 8).

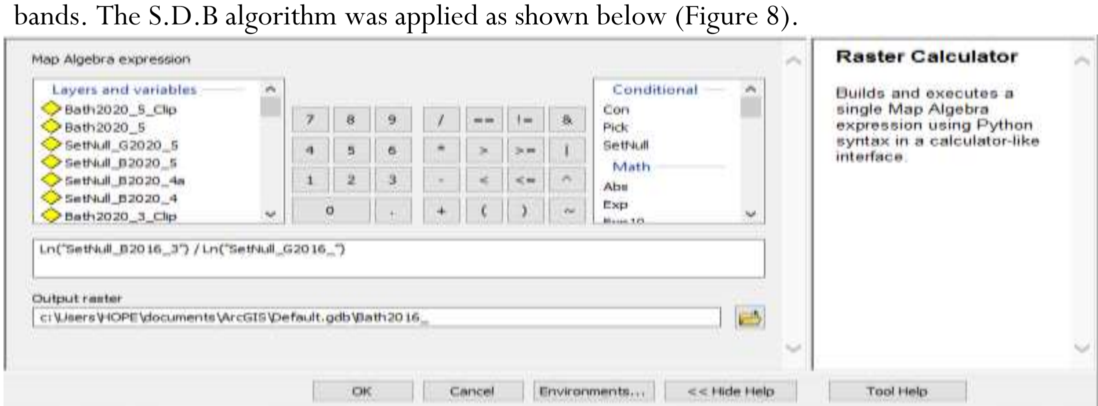


Figure 8: Calculation of SDB algorithm with the Raster Calculator

c) Vertical referencing

This is the final step in the procedure and it involves statistical analysis for calculating the gain and offset for referencing the algorithm result/value to the sounding/chart datum. *Extract Values to Points tool* was then used to extract from the used algorithm at known points

d) Identifying the extinction depth

The optic depth limit for inferring bathymetry (also known as, the extinction depth) was calculated. After the depth of extinction was determined (Table 3.6), further tuning of the Algorithm values in this range was done to delete erroneous values that could undermine the integrity of the gain and offset values.

Table 5: Depth of Extinction values for all Landsat scenes

Landsat Data	Path/Row (WRS-2)	Acquisition Date (DD-MM-YYYY)	Depth of Extinction, DoE (m)
Landsat 7 ETM+	191/55	09-12-2001	6
	191/55	07-12-2006	5.7
	191/55	03-01-2011	5.3
Landsat 8 OLI	191/55	10-12-2016	6.4
	191/55	20-01-2020	6.9

The sedimentation process was carried out using the S.D.B data generated from multispectral satellite imageries, the differences between the depth data for each two different epochs was used to calculate the volume of sediment deposits and the rate will be calculated by consider the year interval between the two epochs in addition to already calculated volume.

3D Surface is one of the important terrain parameters which are explained by horizontal spacing of the contours. In general, in the vector form closely spaced contours represent steeper slopes and sparse contours exhibit gentle slope whereas in the elevation output raster every cell has a value. The lower values indicate the flatter terrain (gentle slope) and higher values correspond to steeper terrain. The 3D Surface and its aspect information were derived from one second arc S.R.T.M data downloaded and imported into the ArcGIS environment. Eleyele vectorised boundary was imported to clip out the boundary from the DEM map. After clipping, the 3D surface of the study area was generated.

Data Quality

Quality control of SDB results was carried out to compare the SDB product against any and all in situ data for the study area and assign an uncertainty level (10, 20 or 30%) to the SDB output. Root mean square error was also calculated to check the proximity of the SDB data to real data. In a practical sense, the procedure is best used as a reconnaissance tool for investigating coastal areas before a high-resolution hydrographic survey (e.g. MBES) is conducted. The accuracy assessment for the sedimentation was based on the accuracy of the SDB results after the SDB results were well checked and rest assured

RESULTS AND DISCUSSIONS

Presentation of Results

After cleaning, filtering and elimination of redundancies, numbers of depths were obtained during the satellite derived bathymetry survey. The obtained bathymetric data of the sampling points as well as other ancillary / field data were used to generate maps needed for analysis of volume and rate of sediment deposit. After importing the depths into the GIS environment, cartographic enhancement was done to produce the bathymetric chart shown in Figure 9.

The plotted satellite derived bathymetric data of the study area for each epoch were compared and surface difference map were generated (Figure 10) from successive epochs to calculate the change in volume and the rate of sediment deposition. The areas where deposition/siltation occur in in the study area were depicted in blue (above), most likely erosion areas were depicted in red (below) and the stable region are depicted in yellow although it is negligible.

Analysis of Results

The analysis performed on the processed data include calculation of volume and rate of sediment deposited by comparing satellite derived bathymetric data for all epochs; analysis and justification of the results and also the quality control analysis of the results.

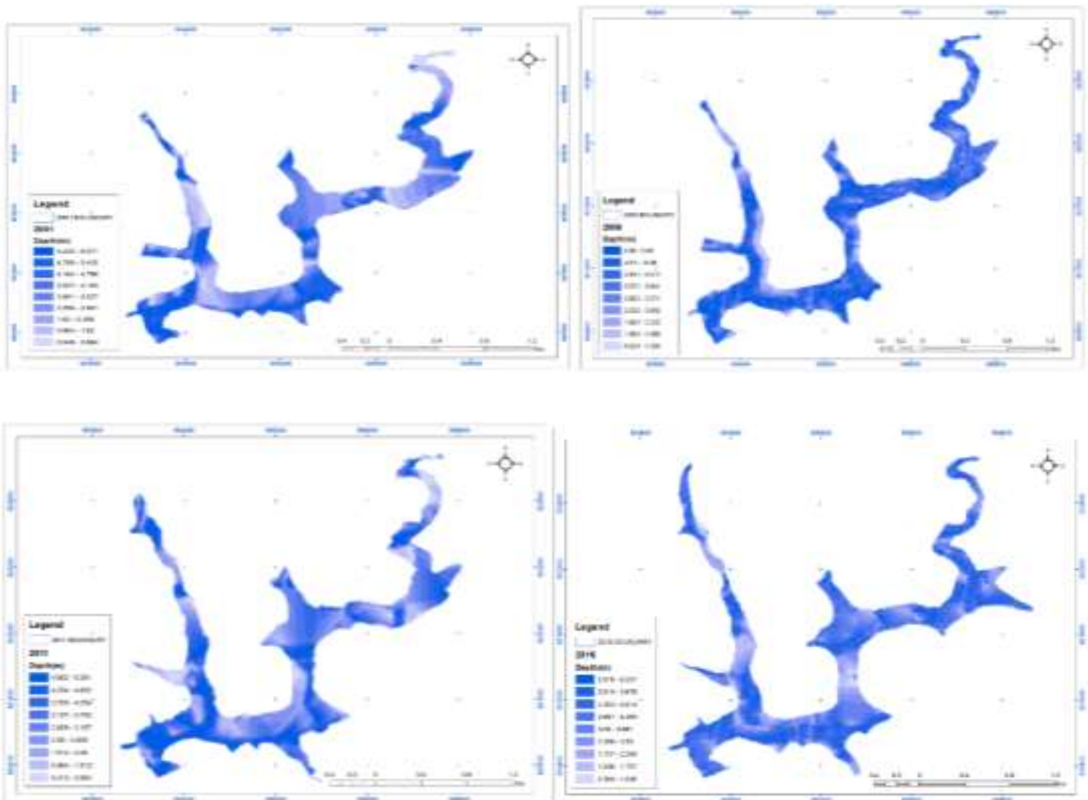
SDB Based Volumes, Areas and Percentages

Sedimentation of Eleyele reservoir was determined by using satellite derived bathymetric survey and GIS and remote sensing techniques. Analysis of bathymetric map (Table 7) in those specified years indicated that there was loss in volume between 2006 – 2011 and 2016 –2020, as a result of this it can be said that sediments were really deposited thus reduce the volume of the water. However, in order to depict where sediments were really deposited, a surface difference analysis was run not only to show the pictorial view but also the percentage of sediment deposited.

From Table 8, it was observed that between 2001─2006, there are more of sedimentation than erosion as a result of human activities around the area as well as contributions from vegetation surrounding the area. However in 2006─2011 the erosion or washing away of the seabed is quite large compare to that of siltation and this may be as a result of activities such as fishing in the area and also attempted dredging work before being stopped. Between 2011─2016, the volume of siltation is quite large compare to erosion and not balanced with, this may be as a result of flooding that happened in 2011 and the effect of occurrence still remain till 2016. In 2016─2020, siltation is less than that of erosion/washing away of the seabed and this can be tied to the activities of the people on the waterbody and also possible precautionary measure being put there by the people.

From Table 9, the percentage of sediment deposit is highest between 2011—2016, followed by the year 2001 – 2006 then 2016-2020 and lastly between 2006 —2011. The difference is represented graphically as shown in Figure 10.

Note: The surface difference works with the difference between depth(s) between two planes and it can recognise the difference between data to any length. So where erosion (below) or siltation (above) occurs sometimes does not mean the place has the higher or highest depth difference than others.



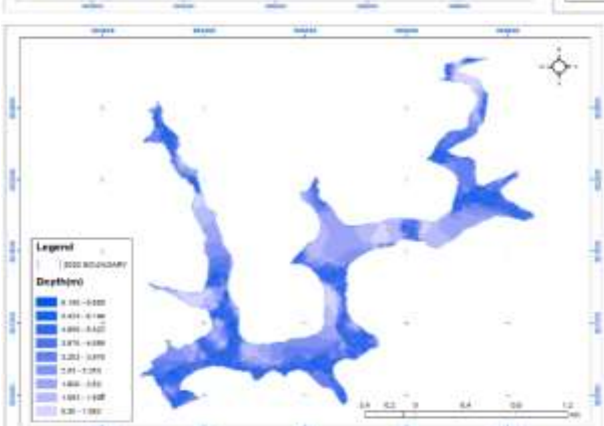


Figure 9: Eleyele Satellite Derived Bathymetry (SDB) Maps for the Years 2001, 2006, 2011, 2016 and 2020.

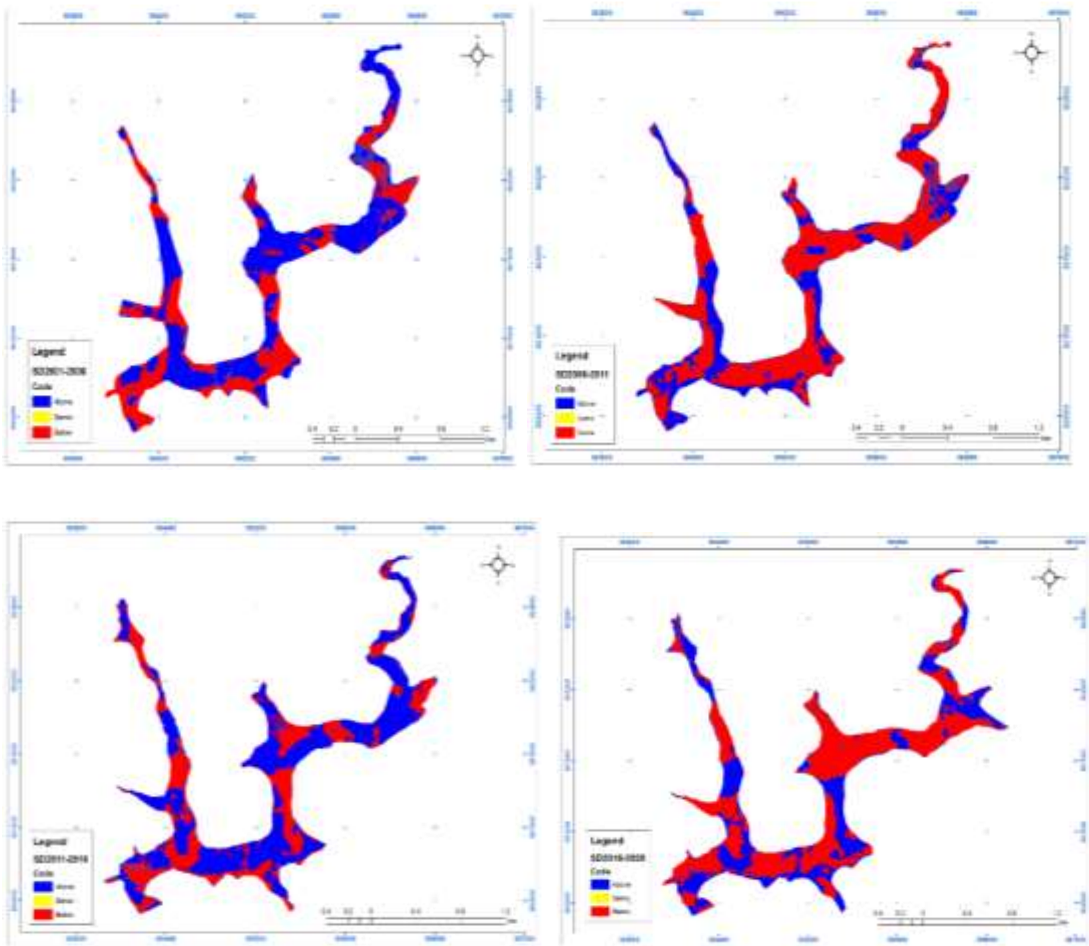


Figure 10: Eleyele SDB Surface Difference Maps for 2001-2006, 2006-2011, 2011-2016 and 2016-2020 Epoch.

Table 6: S.D.B derived surface volumes of the area for all the epochs

Year	Volume (m^3)
2001	4,600,773.608
2006	5,302,318.014
2011	5,030,738.149
2016	5,913,691.005
2020	5,182,212.894
Volume = A × h (depth(s))	

Table 7: Volume lost (-) or gain (+) between two each epoch

Year	Gain (+)	Loss (-)
2001 - 2006	701,544.41	
2006 - 2011		271,579.87
2011 - 2016	882,952.86	

2016 - 2020	731,478.11

Table 8: Volumes and areas of Erosion and Deposition

VOLUME (m^3)			AREA (m^2)	
Year	Below	Above	Below	Above
2001 - 2006	741,898.484	1,443,442.888	596,053.443	863,569.788
2006 - 2011	1,467,509.676	617,482.471	912,830.096	498,120.654
2011 - 2016	766,892.185	1,493,715.994	582,364.237	985,896.278
2016 - 2020	1,548,312.526	863,778.344	981,519.574	596,285.127

Note: Above (siltation) indicate the surface above a reference plain while below (erosion) indicates the surface below a reference surface.

Table 9: Volume, rates and percentages of Sediment deposits

Year	VOLUME (m^3)	RATE ($m^3/yr.$)	Percentage (%)
2001 – 2006	1,443,442.888	288,688.578	66.05114
2006 – 2011	617,482.471	123,496.494	29.61558
2011 – 2016	1,493,715.994	298,743.199	66.07585
2016 – 2020	863,778.344	215,944.586	35.81036

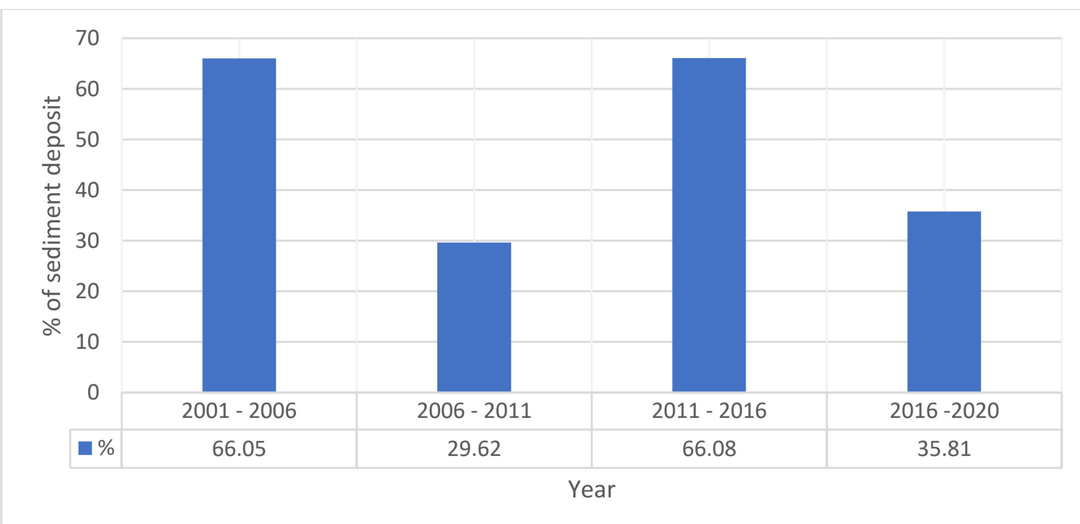


Figure 11: Percentage of sediment deposit.

Accuracy Assessment

The assessment of accuracy was made by comparing random S.D.B 2016-point data generated with the real bathymetric data obtained by SBES for the same year. The accuracy level of both algorithms was assessed using the simple statistic models, the Root Mean Square Error (R.M.S.E). The R.M.S.E equations used is shown in Equation 3.

$$RMSE_{(DepthRangeX)} = \sum \sqrt{\frac{(d_{sdb} - d_t)^2}{N}}$$

(eqn. 3)

Where,

$d_{sdb} =$ Predicted depths (SDB data);

$d_t =$ Reference depths (SBES data);

N = number of samples

The result of the analysis shows that the Stumpf model delivered the R.M.S.E value of 3.149m. This was as a result of Landsat Imagery being low resolution image though this does not affect the change detection analysis, even some researches where high resolution images were used, were having RMSE of 1-2 meters, example of this was a research carried out by Said *et al* (2017) whereby a RMSE of 1.624m was obtained. Therefore, this result can be improved marginally by adopting Least Square Equation (LSE) adjustments during the calibration process.

Summary of Findings

The study was made to determine the deposit caused by sedimentation of the Eleyele reservoir by using bathymetric surveys obtained in 2001, 2006, 2011, 2016 and 2020 and by using GIS and remote sensing techniques. Analysis of the bathymetric data obtained from the Eleyele reservoir showed that sediment deposited between 2001 and 2006 was 66.05%; from 2006 to 2011, it was 29.62%, for 2011−2016 it was 66.08% and lastly from 2016 to 2020 the total sediment deposited was 35.81%. Analysis of the bathymetric maps also showed that sediment accumulation is severe near and around the reservoir. The use of satellites to estimate bathymetry is an effective tool in areas otherwise difficult to survey. For Eleyele reservoir the maximum extinction depth that could be obtained was 6.9 meters and the uncertainty in the data was up to 3.149 m. The majority of the SDB does not meet the requirements of S-44 orders, but can be accurate enough for a rough estimation of the waterbed.

CONCLUSION

An increasing number of studies has shown that bathymetric information can be derived from optical satellite multispectral imagery at the spatial resolution of the source image. Various models have been developed to convert image pixel values into depth estimates. Stumpf‘s method addresses several issues that have considerable relevance to using passive multispectral imagery to map shallow-water bathymetry. First, it has fewer empirical coefficients required for the solution, which makes the method easier to use and more stable over broader geographic areas. Secondly, the ratio method can be tuned using available (reliable) soundings. Thirdly, it works well over variable bottom types. This study applied the Stumpf et al (2003) ratio transform model to estimate depths from Landsat imageries. Depths were not estimated for regions beyond the optic depth limit for the study site. Evaluation of bathymetry changes was used for sedimentation processes and the results were considerably good although S.D.B cannot give perfect result but it can be used for change detection. Although in theory, Stumpf‘s model accounts for spatial variations in bottom reflectance, the analysis suggests that much of the model estimate error is caused by reflectance attenuation due to spatial heterogeneity in bottom substrates such as algae or seagrass, high turbidity of Nigerian coastal waters and other extraneous variables acting underwater. Depth estimates were significantly overestimated or underestimated for some points. The sedimentation rate obtained using remote sensing data can be explained on the basis of accuracy in the determination of water spread area and the mixing of water pixels with the land around the periphery of the reservoir. However, the use of better (spatial and temporal) resolution satellite data maybe a remedy for these problems to some extent. The use of remote sensing technique therefore enables a fast and reasonably accurate estimation of storage capacity due to sedimentation.

RECOMMENDATIONS

Keeping in view the time and cost involved in hydrographic surveys, it is recommended that hydrographic surveys may be conducted at longer intervals and the remote sensing based sedimentation surveys may be carried out at shorter intervals, so that both surveys complement one another. However, there are some limitations in the remote sensing data collection method. For example, remote sensing techniques give the information on the capacities only in the water level fluctuation zone, which generally lies in the live zone of the reservoir. Below this zone, i.e. in the dead load zone, the information on the capacity could be taken from the most recently conducted hydrographic survey.

Also further extensive assessments of Stumpf‘s model with various benthic environments are needed in order to determine its robustness.

Other empirical models to account for turbidity and other extraneous variables underwater which could explain the outcomes of erroneous and outlier depth estimates should be incorporated.

Lastly, the results can be used for change detection analysis and/or reconnaissance prior the time a classical bathymetric survey (using Dual Frequency Echo sounder) will be carried out.

CONTRIBUTION TO KNOWLEGDE

The results of this study prove that this remote sensing method can augment existing hydrographic datasets in the country and is a useful reconnaissance tool for hydrographic surveying offices. It also offers a viable interim solution for areas where there is inadequate hydrographic data and scarce resources for extensive surveys using other methods. S.D.B cannot give perfect result, therefore, this result can be improved marginally by using Least Square Equation (L.S.E) adjustments during the calibration process.

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