Extraction of Water Depth and Surface Water Area Variations Analysis using Landsat Satellite Imageries and Statistical tools: A case of Zobe Dam, Nigeria

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Abstract
A repeatable and reliable procedure to determine the water depth, surface water area, and storage capacity of a Dam's reservoir is needed for effective utilization and sustainable management of a Dam. The conventional approaches to mapping bathymetry are labor-intensive, time-consuming, and require huge capital investment. These problems constitute a setback, particularly in low-budget and low-accuracy projects, especially in developing countries like Nigeria. The conventional hydrography survey methods can now be determined using the emerging Satellite Remote Sensing techniques. Lamentably most of the models developed for this approach are based on tidal waters environs, and the comprehensive use of the approach to study Nigeria's Dams and inland water bodies remains less explored. This paper attempts to use a modified rotation transformation matrix model of Van Hengel and Spitzer (1991) in a non-tidal environment to study the water depth and surface water area variation of the Zobe Dam from 1986 to 2022. This study demonstrated that, with a few modifications, it is possible to use the model in a non-tidal water environment. The study also confirmed the alarming decreasing trends of the water depth and the overtime surface ware area variations of Zobe Dam. The study's results have some policy, operational, and managerial implications. Therefore, the government and organizations responsible for water resource management are encouraged to take advantage of the remote sensing technology as an alternate window for monitoring the water status of the Dams.

Key Words: Surface water area, Water Depth, Remotes Sensing, Bathymetry Survey, Satellite imageries, Landsat and Zobe Dam

1.0 Introduction

Zobe Dam was constructed and impounded in 1987 by the Federal Government of Nigeria as part of its River Basin Development policy and in an attempt to address challenges of water availability for domestic water supply and irrigation needs of the Dam's immediate environs. The construction Dam has altered the nature of the environment, the ecology, and the river hydrology at both the upstream and downstream sides of the Karaduwa River system upon which it was located.

Since its impoundment, the Zobe Dam has yet to be fully utilized for its intended purposes. Often poor funding, shortage of skilled personnel, and lack of suitable monitoring equipment are cited as the principal factors. The up-to-date status of the Dam's water availability is poorly known. Poor data acquisition and record-keeping procedures, uncoordinated competing water uses, and inadequate maintenance of the reservoir and other related water infrastructures are among the many challenges. These problems have continually represented challenges to the Dam's management.

Because of the aforementioned challenges, seeking ways to achieve results sustainably becomes imperative. As Time is a limited and costly factor in the planning and management of water resources, a repeatable and reliable procedure to determine the bathymetry and capacity of the Dam's reservoir is needed for effective utilization and sustainable management of the Dam.

Two main issues are addressed in this paper. The first is determining the 2022 spatiotemporal conditions of the Surface water area and water depth of the Dam reservoir as extracted from Satellite image data, and the second is to compare this with the 2016 results of extracted image data and the field measurement. The preliminary analyses were carried out to collaborate with the earlier works of Abdulkadir, I. F. (2019), and Funtua et al (2020) in the same study area.

2.0 Materials and Method

2.1 Description of Study Area

Zobe Dam (Figure 1) is under the auspices of the Sokoto Rima Basin Development Authority (SRRBDA). It lies between 12°20′23″N, 7°26′52″E, and 12°28′40″N, 7°41′ 03″E. It is situated near Garhi Village, Dutsin-Ma Local Government Area, of Katsina State, Nigeria. The Dam closed the Karaduwa valley after the confluence point of Bunsuru where the road bridge leads the main Funtua- Dutsin-Ma road over the Karaduwa River near Garhi Village, Dutsin-Ma Local Government Area, of Katsina State, Nigeria. It was commissioned in the year 1983 for irrigation and domestic water supply (Funtua et al, 2020).

Figure1. Map of Katsina State Nigeria Showing Zobe Dam
(Source: Adekola and Terdoo, (2014) Modified),

The Zobe Dam catchment area and sub-basins lie in the Sahel region of Northern Nigeria. The Topography of the area is a generally flat and gently undulating surface with an elevation of about 450-500m above Mean sea level (ANGYU, 2010). The inflow into the reservoir depends mostly on the runoff from rainfall. The major source of rainfall in the area is the monsoon weather system with August/September being the most active months. The hydrogeology of the Study area comprises some major water bodies (Figure 2) which include; Karaduwa, Kasanya, Kurechin-dutsi, Dogon ruwa, Unguwar Mangoro, and Kwari. Of these, only the Karaduwa flows during the dry season.

The area has two groundwater flow directions namely from the north to east and from west to East. The Northeast flow direction is the Dam's reservoir recharge direction.ANGYU (2010), identified two major aquifer systems within the area namely, the upper unconfined and lower confined. The upper aquifer has a thickness that varies from 0-90m whereas the depth to static water level varies from 14.3 to 19.6m.

The area belongs to the geological region of the south and central parts of Katsina State, which are underlain by crystalline rocks of the basement complex. The soil type is commonly sandy in nature with low nutrients and low water retention capacities.

2.2 The in-situ bathymetry Survey and Gauged water level Analysis

The in-situ bathymetry field survey aimed to determine the average depth of the reservoir, and use it to validate the Satellite-derived bathymetric data. The fieldwork was carried out following the basic Survey principles of working from whole to part, and the application of the principles, and technology of GPS ECHO sounding. Some of the results of the field surveys and the obtained gauged water level records are used here to help compare and further analysis. Reference was made to the procedures and results obtained by Funtua et al, (2020). The summaries of methods are highlighted in the following paragraphs.

The available daily water level records from 1988 to 2016 from the installed gauge in the intake tower of the Dam were obtained from the Dutsin ma office of the SRRBDA. These were integrated and used to provide a reference surface for both the field depth and Satellite-derived measurements.

To isolate the Surface Water Area (SWA) of the Dam Image masking was done, this was by masking the image that gives a zero value for the object and not the water surface. The masking is achieved using the UNESCO Bilko Ver.3.4 (64-bit) software environment.
The selected area of interest (AOI) covered the whole Surface Water Area (SWA) of the Dam and its immediate environs as defined by the following UTM (32N) coordinates; 330784.75m E & 356930.63mE and 1373092.37m N & 1362578.99m N. The developed masked portions of 1986, 2001, and 2016 Landsat imagery of the study area were imported to ArcMap 10.1 for further processing.

For the production of the Digital Elevation Model (DEM), the water bodies' extent was delineated and evaluated based on the values obtained during fieldwork. Global Mapper software was used to generate DEM of the AOI and the ArcMap GIS 10.1 was used for analysis. Table 1 is the spatial and spectral properties of the selected Landsat imageries.

Table 1. Spatial and Spectral Properties of the Selected Landsat Imageries

Landsat Scene ID	Image and File Date	Band Number	Spatial Resolution	Spectral Band Range
LT51890511986008XXX03	1986-01-08 & 2014-06-18T13:25:03Z	1 (Blue), 2 (Green), 5 (Middle IR)	30 meter 30 meter 30 meter	0.45 to 0.52 µm 0.52 to 0.60 µm 1.55 to1.75 µm
LE71890512001025EDC00	2001-01-25 & 2015-07-25T12:06:44Z	1 (Blue), 2 (Green), 5 (Middle IR)	30 meter 30 meter 30 meter	0.45 to 0.52 µm 0.52 to 0.60 µm 1.55 to 1.75 µm
LC81890512016107LGN00	2016-01-11 & 2016-05-18T12:55:11Z	1 (Blue), 2 (Green), 5 (Middle IR)	30 meter 30 meter 30 meter	0.45 to 0.52 µm 0.52 to 0.60 µm 1.55 to 1.75 µm

2.0 **Derived Bathymetry and Surface Water Area Delineation.**

The fundamental principle behind using remote sensing in bathymetry is that different wavelengths of light will penetrate water to varying depths (Deidda and Sanna, 2012).
According to (Haibin et al, 2008), increasing depth induces a faster decrease in radiance for spectral bands with stronger attenuation.
The study has attempted, the use of a combination of STRM data obtained from the USGS website, the results from the field survey, and the extracted depth from the Landsat Imageries also obtained from the USGS website of a study area to evaluate reasonably the changes occurring around the Dam environs.
The method of Van Hengel and Spitzer (1991) in short V-S (1991), which was developed and used in shallow tidal water environments was modified, employed, and validated for use in a non-tidal environment. The model is in the form of a rotation transformation matrix for the transformation of Satellite imagery to produce relative water depth or depth index, Y1 value from the image. The model provides an elaboration on the idea that the reality of computed water depth depends to a considerable extent on the accuracy of known water depth data used to calibrate the algorithm. It utilizes three multi-temporal images as input data to get relative water depths from LANDSAT ETM+. This enables the relative water depth map to be acquired without prior knowledge of the actual value of the water depth (Setiawan, 2013).
Landsat Imageries of 1986, 2016, and 2022, of the Zobe Dam environment, downloaded from the USGS website were used. The images were subjected to Radiometric Correction, Computing the radiance values, Atmospheric reflectance, etc. The AOI extracted from each of the respective selected Imageries and subsets of the images were developed and further processed using UNESCO Bilko Ver.3.4 (64-bit) software. A combination of band 5, 2 1 was used. Details were discussed in Funtua et al, (2020).
To extract water surfaces, digital numbers of the randomly selected points from each respective spectral band were converted to surface reflectance using the calibration

coefficients provided in the image's metadata, The raw DN (Digital Number) extraction process was carried out using UNESCO BILKO (64Bits) Software which automatically displays DN Value of a selected pixel.

For the water surface reflectance, it was assumed that the illumination, atmospheric transmission, water attenuation per unit water depth, water surface state, surface reflectance, bottom reflectance, and water body radiance per unit volume were all constant over the imagery. Any changes present in the recorded radiance in each band were assumed to be due to changes in water depth.

The required three input bands, of the V-S (1991) model are defined in equations nos. 1.0 to 1.4a as follows:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix} = \begin{bmatrix} \cos(r)Sin(s) & \sin(r)\cos(s) & \sin(s) \\ -\sin(r) & \cos(r) & 0 \\ -\cos(r)\sin(s) & -\sin(r)\sin(s) & \cos(s) \end{bmatrix} \times \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad \text{.................1. 0}$$

This can be expressed in a linear equation format as follows,

$Y_i = (\cos(r) \times \sin(s) \times X_1) + (\sin(r) \times \cos(s) X_2) + (\sin(s) \times X_3)$ ……………………1.1

Where:

Y_i: Relative depth obtained from the image (Depth Index), for value, i (i = 1, 2, 3),

Xi: Reflectance in spectral band, i (i = 1, 2, 3),

r and s: Rotation Parameters

Value of rotation angle (r and s) in the algorithm is a constant obtained from the calculation with the following formulas (Equation 1.2 and 1.2a):

$$r = \arctan\left(U_r + \sqrt{U_r^2 + 1}\right) \quad \text{……………………………………1.2}$$

$$S = \arctan\left(U_s + \sqrt{U_s^2 + 1}\right) \quad \text{…………………………………1.2a}$$

While U_r and U_s are obtained respectively from (equation 1.3 and 1.3a)

$$U_r = \frac{\operatorname{var} X_2 + varX_1}{2\operatorname{cov} X_1 X_2} \quad \text{……………………………………..1.3}$$

$$U_s = \frac{\operatorname{var} X_3 + varX_1}{2\operatorname{cov} X_1 X_2} \quad \text{...........………………………………1.3a}$$

Where:

Var X_i: variant values of band I and

Cov $X_i X_j$: covariant band i and band j

Depth value is the result of rotation on the relative depth values shown by the variable Y_1.

While the result of the rotation Y_2 and Y_3 is the effect produced by this matrix.The resulting depth of Y_1 is a relative depth from the image.

Therefore the relative depth should be changed to the absolute depths to obtain the actual depth value. This is achieved by regression analysis.

The regression equation obtained is use to convert water depths (Equation1.4) as shown below;

a Y1,i + b = Sti ……………………………………… (1.4)

Where:

a and b : Regression constants
I : Pixel number
Sti : Water depth.

According to Setiawan, (2013), the discrepancy between the in situ measurement and those obtained from the images can be determined using error model algorithm described by Equation 1.4a.

$$\varepsilon_a = \frac{A_1 - A_o}{A_o} \times 100\% \qquad \text{.................................. (1.4a)}$$

Where;
 : Error value
A1: Depth measurement using remote sensing data
A0: In situ data.
The water bodies' extent was delineated and evaluated based on the values obtained during fieldwork. Global Mapper software was used to generate DEM of the AOI and the ArcMap GIS 10.1 was used for analysis.
The bathymetric maps were produced by the composite integration method. This entailed the combination of results of processed bathymetry from Landsat Imageries and corrected for errors and processed using the V-S(1991) model and those obtained from in situ data obtained from field measurements. The clarity of the reservoir's water and the availability of clouds free Satellite images provide the basis for the choice of the method of the study.

3.0 Results and Discussions

The results indicated that over the period of the study, the average surface water level was highest in 2010 at an elevation of 493.778m and Lowest in 2012, with an average elevation of 491.087 above MSL. This lowest average water elevation can be attributed to the safety measures taken by opening the gates to release stored water to avert the dangers posed by excessive rainfalls and flood disasters that occur due to heavy rainfalls that year.
The results of in-situ bathymetry carried out in 2016 were analyzed and compared to those obtained using the remote sensing method of the same period, the variations of the depth range between a minimum of + 0.112m to a maximum of +2.7 m for the selected sounded points. Figure 2 is the 2016 bottom profile of the Dam as a result of the in-situ measurements while Figure 3 is the 3D view of the underwater topography of the Dam.

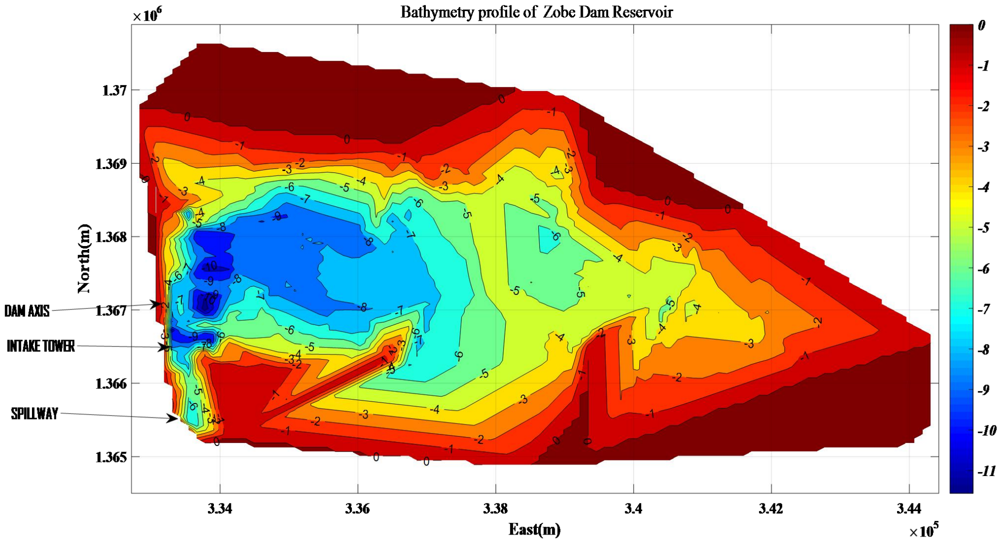

Figure 2. 2016 Bottom profile of Zobe Dam (Adopted from Funtua et al (2020)

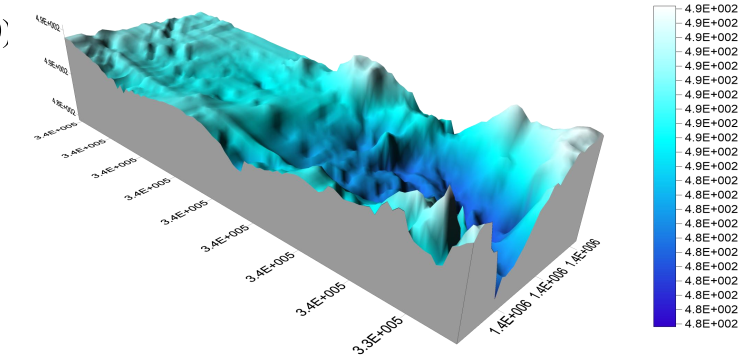

Figure 3. 3D view the underwater topography of Zobe Dam

Figure 4 is the 1986 superimposed DTM of Zobe Dam with SWA fully delineated and

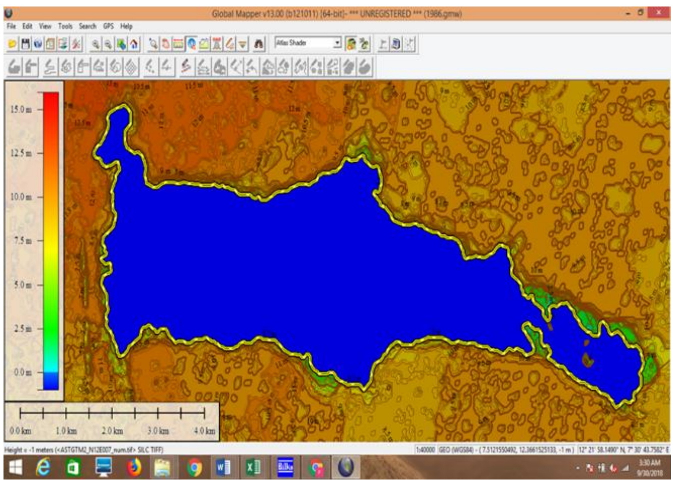

Figure 4 **1986 Superimposed DTM of Zobe Dam with SWA fully delineated**

Figure 5 is the 2016 composite map of Zobe Dam showing the different land cover.

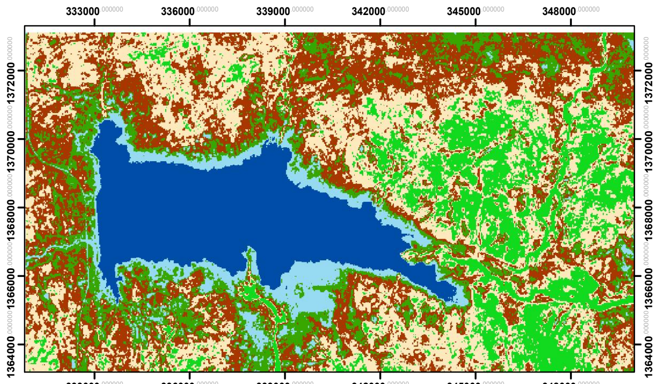

Figure 5 2016 Composite map of Zobe Dam

The 2022 SWA profile of the Dam (Figure 6) was generated using Global Mapper software. The SWA was obtained from the results of the contours generated using downloaded ASTER GDEM v2 Worldwide Elevation Data (1 arc-second Resolution) imagery SRTM Worldwide Elevation Data (1-arc-second Resolution, and SRTM plus V3) from the USGS website.

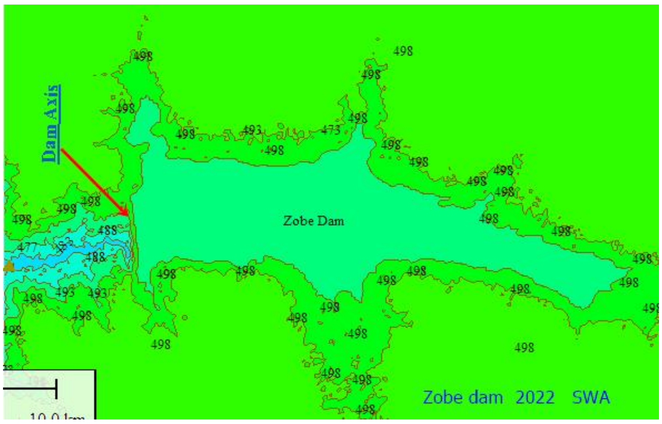

Figure 6 2022 Generated Contour map of Zobe Dam

The results of the application of the V-S (1991) model on Landsat imagery was found at a 95% confidence level, to be within the minimum (0.3m) standard of the International Hydrographic Organization (IHO) (S-44, 5), 2008 edition. This is adequate for research and low-accuracy projects. However, the result shows that the V-S (1991) model transformation parameters are a time dependent as the values of r and s obtained for the year 1986 the values are 74° 50' 51.03" and 80°48'26" while it was 68° 30’28.6’’and 77°29’16’’ respectively for 2016

The results of the comparison of the three (1986, 2016, 2022) epochs, show a continuous decrease in the overall SWA and volumetric capacity reduction of the Dam. The approximate 1986 perimeter coverage of the Dam was 57.875km with 32.411 sq. Km SWA.

For 2016, these were 54.977 km and 29.088 sq. km and for 2022, it was 40,181 km and 27.745 sq, km respectively. The surface area and storage capacity plans (Figure.7 and Figure 8) were respectively prepared using the design records and the generated data of the Dam.

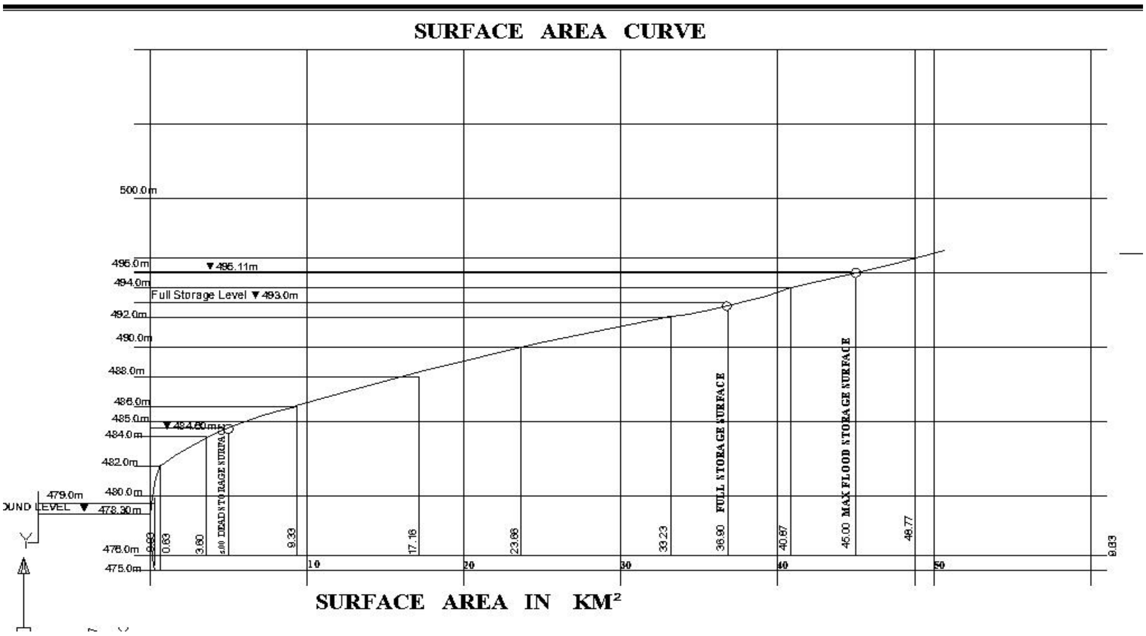

Figure 7 Surface area Curve of Zobe Dam reservoir

The developed SWA Curve is shown in Figure 8.

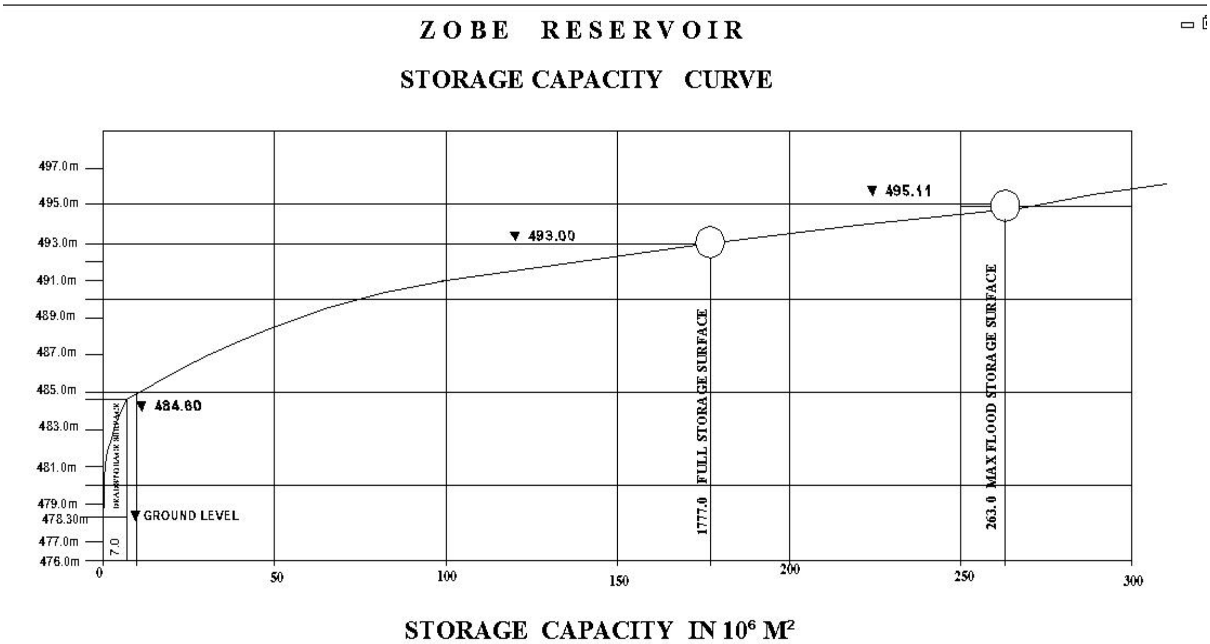

Figure 8. Storage capacity Map

The water depth has shrunk from its designed 17 m maximum The initial surface water area was 39.6 sq km at full storage level (Elevation of 493.00m above MSL). The current elevation is 493 m above MSL contours covering a surface water area of 26.593 sq. km. The estimated designed active full volumetric capacity of the Dam was 177.0 x106 m3depth to about of 11m maximum depth. The study established there is an alarming volumetric/storage capacity loss (about 60%) of its designed estimated capacity.

4.0 Conclusion and Recommendations

It is possible to use Satellite imagery as an alternative window for the determination and evaluation of water depth and surface water area variations for planning and management of a Dam and its environment. As most of the existing models for the extraction of water depth from Satellite Imageries were based on tidal waters environs, knowledge of their efficacy of the potential in non-tidal water environs is emerging spheres. However, this study demonstrated that with some modifications, it is possible to use the V- S (1991) method and the freely available Landsat Satellite Imageries in a non-tidal water environment such as Zobe Dam. The results of the 1986 t0 2016 study was compared with those of 2022 for validation.

It is shown that a modified form of the V- S (1991) model could provide suitable pixel information that could be employed for water depth extraction in a non-tidal water environment, especially in a Dam reservoir area. This is achieved by neglecting the tidal corrections components of the model, however, the accuracy depends on a number of factors. These factors include the water clarity, the accuracy of the Satellite data, the band's combination used to form the image composite and to generate atmospheric correction necessary to obtain reflectance values, and the accuracy of the in-situ bathymetry survey data.

The study also confirmed the continuing decreasing trends of the water depth and the overtime variations SWA of the Zobe Dam. The 60% loss in the volumetric capacity of the Zobe Dam in the last 30 years is of serious concern. Thus the findings of the study have some policy and operational and managerial implications for the sustainable use of the Dam. It is important for the operators and managers of such resources to know at any given time, the status especially the bathymetric conditions and any variations in the volumetric capacity of their water facilities. Therefore, the government and organizations responsible for water resource management are encouraged to take the advantages of the remote sensing approach and make use of freely available Landsat Satellite images and especially of Nigeria2 for the study and monitor all the water resources in the country..

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