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Satellite Derived Bathymetry of Kainji Dam, Niger State, Nigeria

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Abstract

Satellite-Derived Bathymetry (SDB) has emerged as a cost-effective and efficient technique for mapping shallow water bodies. This study investigated the application of SDB using Landsat 8 imagery for Kainji Dam (in Borgu local government area of Niger State), a deep-water reservoir. The methodology involved radiometric correction, Top of Atmosphere (TOA) reflectance, floating, and low-pass filtering to enhance image quality. Land-water separation and application of the Stumpf algorithm implemented using the band ratio technique, enabled bathymetric mapping. Validation using 35, 75, and 150 in-situ points varying from 1m to 71m depth revealed an optimal R^2 value of 0.4 with 35 points, indicating moderate accuracy. The results showed a depth range of approximately 30 meters with 27.92 meters being the deepest result from SDB, highlighting SDB's potential for mapping shallow to moderate depths. However, the study exposed limitations in using Landsat 8 imagery for deep water bathymetry, as it failed to accurately capture depths beyond 30 meters threshold. This limitation is attributed to the sensor's spectral and spatial resolution. Future research will focus on developing an algorithm for deep water SDB using high-resolution satellite imagery. This study contributes to the understanding of SDB's potential and limitations in freshwater environments, emphasizing the need for sensor-specific evaluations and algorithm development.

Keywords: Bathymetric mapping, band ratio, in-situ, Landsat 8, TOA, SDB.

1. Introduction

According to the International Hydrographic Organization (IHO), hydrography encompasses the measurement and description of marine feature and coastal areas, primarily for navigation and various other purposes, including offshore activities, research, environmental protection, and prediction services (IHO, 2005). Hydrographic surveys involve collecting, analysing, visualizing, and managing spatial data related to marine features, processes, and properties in four dimensions i.e. x, y, z and t (Samaila-Ija *et al.,* 2014). This includes studying lakes, dams, oceans, and rivers. Hydrography encompasses all measurement and analysis operations in the marine environment. Bathymetry, the marine equivalent of topography, involves measuring water body depths from the surface. Traditional bathymetric survey methods include shipboard echo sounding and airborne Lidar, which provide accurate depth measurements but are limited by high costs, operational inefficiencies, and restrictions in shallow waters (Prayogo and Basith, 2021).

Satellite-derived bathymetry (SDB) addresses the limitations of traditional bathymetry methods in shallow water bathymetry, filling gaps and updating existing data. Since the 1970s, SDB approaches have used multispectral satellite images to extract depth information. A pioneering University of Michigan for the Spacecraft Project of U.S. Naval Oceanographic Office study demonstrated remote shallow water depth determination using wave refraction and Fourier transform plane analysis with data obtained at a Lake Michigan test site. The technique requires suitable water waves and has been improved with advancements in technology, algorithms, and satellite sensors. SDB applications now span multiple sectors, including oil and gas, coastal engineering, aquaculture, ports, and infrastructure development (Muzirafuti *et al*., 2020).

Satellite-derived bathymetry (SDB) relies on the principle that the amount of electromagnetic radiation, such as visible light, reflected from the seafloor is depth-dependent. As light travels through water, it is attenuated, with greater attenuation occurring at increased (Westley, 2021). This is why shallow water appears bright when viewed from above, as light reaches and reflects off the seafloor, whereas deep water appears dark due to absorption of light before it reaches the seafloor. Other factors like suspended sediment and atmospheric scattering can also impact light reflection and absorption. The wavelength of light is crucial; as longer wavelengths are absorbed faster by water. Consequently, the blue (0.45-0.52 μm) and green (0.52-0.6 μm) parts of the spectrum are commonly used for SDB due to their greater water penetration. In theory, once water column and atmospheric effects are accounted for, the energy reflected back to a satellite should be inversely proportional to water depth. (Westley, 2021).

1.1 Study Area

Kainji Dam is a hydroelectric dam located on River Niger in Nigeria, near the town of New Bussa in Borgu local government area of Niger State**.** It is positioned between latitudes 09°51′00″N and 10°40′00″N, and longitudes 04°22′30″E and 04°42′20″E as shown in Figure 1 below. Its construction began in 1964 and was completed in 1968, creating Kainji Lake, one of Nigeria's largest man-made lakes. The dam rises to about 65 meters (213 feet) and spans approximately 550 meters (1,800 feet). Kainji Lake covers a surface area of about 1,200 square kilometers (460 square miles) and has a storage capacity exceeding 12 billion cubic meters (9.7 million acre-feet) of water (Ibrahim *et al*., 2024). The dam's hydroelectric power station boasts an installed capacity of 760 megawatts, making it a key contributor to Nigeria's electricity generation. In addition to its energy production role, Kainji Dam helps regulate the Niger River's flow, aiding in flood control downstream and supporting irrigation for agriculture in the region. Kainji Dam is owned by the Federal Government of Nigeria and operated by Mainstream Energy.

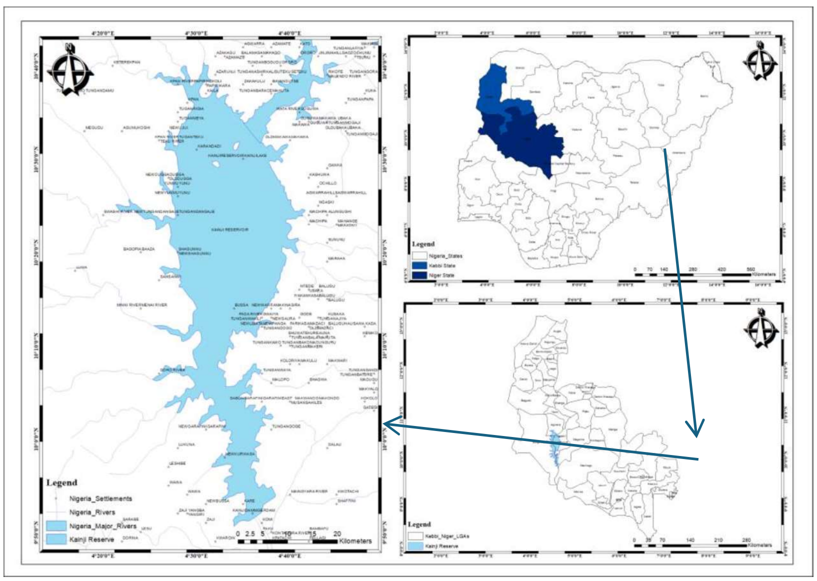


Figure 1: Map of the Study Area

2. Dataset

Landsat 8 (Launched 2013) extends a 40+ year Earth land surface record, orbiting every 8 days, with data processed and distributed by USGS. The Landsat satellites carry a variety of components, including remote sensing systems, data relay systems, attitude-control and orbit-adjustment subsystems, a power supply, and receivers and transmitters for ground station communications. Landsat 8 Operational Land Imager (OLI) -Thermal Infrared Sensor (TIRS) Collection 2 Level 1 (L1) captured on 25th November, 2022 and 15th January, 2024 was used for the project research. Landsat's most important tasks are observation and exploration of the Earth's surface, which has a wide range of applications. Landsat 8 carries two push-broom instruments: The Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI sensor acquires a total of 9 bands: eight multispectral bands with 30 m, and one panchromatic band with 15 m spatial resolution. The TIRS instrument collects two spectral bands for the thermal infrared wavelength. The temporal resolution of this mission is 16 days.

3. Methodology

It includes the methods, procedures and techniques employed in the execution of this satellite derived bathymetry research. The methodology involves data selection or choice, data acquisition, data preprocessing up to Bathymetry derivation.

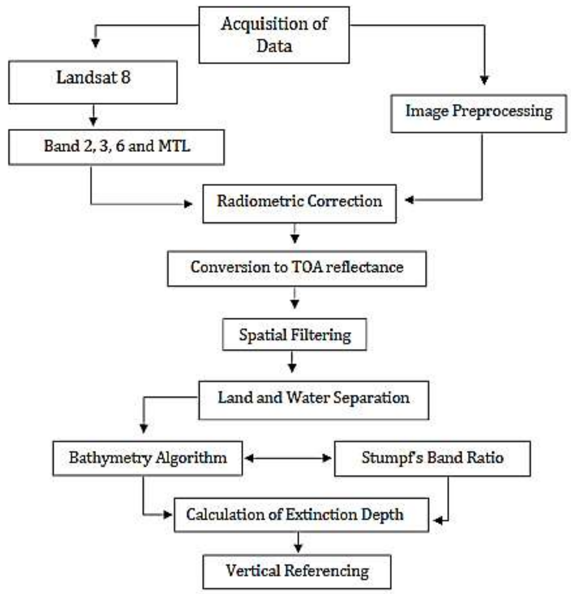


Figure 2: Satellite-Derived Bathymetry Flow Chart

3.1 Data preprocessing

Raw remotely sensed images always have error in values recorded for the pixels, known as radiometric errors. High-resolution optical data were converted to Top of Atmosphere (ToA) radiance and reflectance. Digital number values were converted to ToA radiance using the absolute radiometric calibration factor and effective bandwidth values specific to the individual scene. Reflective band Digital Number, DN were converted to Top of Atmosphere, TOA reflectance using the rescaling coefficients given in the MTL file using Arc Toolbox (i.e. Raster calculator of map algebra contained in spatial analysis tools) in ArcMap 10.8 software and the formula:

$$\rho\lambda' = M\rho Qcal + A\rho \quad (1)$$

where:

$\rho\lambda'$ = TOA planetary reflectance, without correction for solar angle.

Note that ρλ' does not contain a correction for the sun angle**.**

$M\rho$= Band-specific multiplicative rescaling factor from the metadata (REFLECTANCE_MULT_BAND_x, where x is the band number) = 2.0000E-05 (for Band 2,3 and 6)

$A\rho$ = Band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_x, where x is the band number) = -0.100000 (for Band 2,3 and 6)

$Qcal$ = Quantized and calibrated standard product pixel values (DN)

TOA reflectance with a correction for the sun angle is then:

$$\rho\lambda = \rho\lambda'/\cos(\theta SZ) = \rho\lambda'/\sin(\theta SE) \quad (2)$$

where:

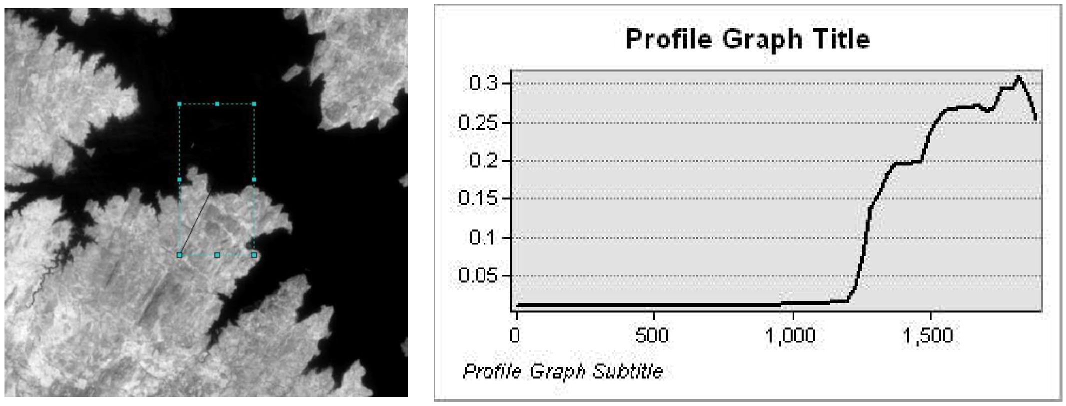
$\rho\lambda$ = TOA planetary reflectance

θSE = Local sun elevation angle. The scene center sun elevation angle in degrees is provided in the metadata SUN_ELEVATION = 48.51234300 and 52.25869692 for 2022 and 2024 image used respectively)

θSZ =Local solar zenith angle; θSZ = 90° - θSE

3.2 Spatial Filtering

Speckle noise in the Landsat imagery was removed using spatial filtering. The threshold value was identified to separate land and water using the Near Infrared band which reflects the water body (and appears dark) and the land area (appears bright). The threshold value of water and land separation on the satellite imagery was calculated using profile option of the 3D Analyst tool of the Arc Toolbox. In the 3D Analyst tools, the infrared band (Band 6) was selected and then Interpolate Line icon (3D Analyst tool/Interpolate line).



(a) (b)

Figure 3: (a) Water and Land interpolate (b) Threshold graph

3.3 Bathymetry Algorithm application (Band Ratio Model)

Bathymetry calculations were performed using the Stumpf *et al*. (2003) algorithm, leveraging the blue and green spectral bands. Research by Chénier *et al*. (2018) suggests that the optimal band ratio for bathymetry estimation varies with water depth. In shallow waters (0-4m), the blue-to-yellow band ratio (ln(B)/ln(Y)) yields the most accurate results, while in deeper waters (>6m), the blue-to-green band ratio (ln(B)/ln(G)) is more effective. The coastal-to-green band ratio (ln(C)/ln(G)) did not offer any advantages. The choice of band ratio depends on site-specific characteristics, such as water depth and turbidity. The bathymetry algorithm application of blue-to-green band ratio gives the satellite-derived bathymetry as shown in Figure 4 below.

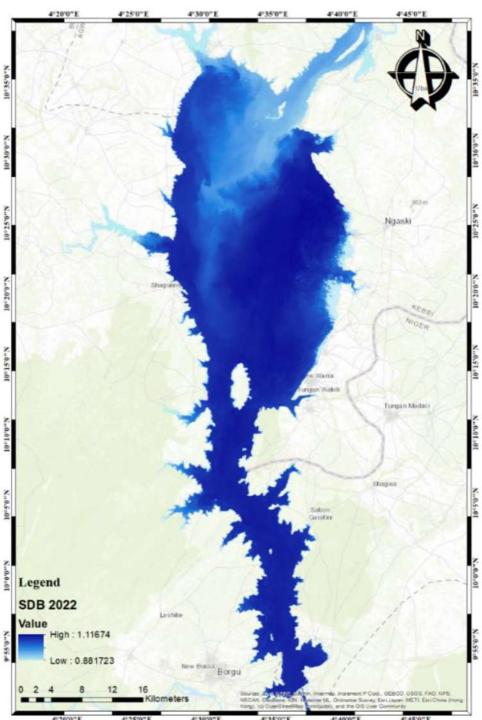


Figure 4: Relative SDB $(ln(blue)/ln(green))$

The optic depth limit for inferring bathymetry (also known as, the extinction depth) was calculated. In order to obtain absolute bathymetry, the relative bathymetry was referenced to the local datum. The in-situ data was acquired during a field survey previously conducted on the reserve. 35 points on the basis of the location of field data isobaths and the optical variation (bright and dark areas) of the water was used. These training points were homogeneously chosen on in situ data with water depth ranging from 0.1 to 71m, and with some points having the same water depth values. Table 1 and Figure 5 below represents the estimation of vertical reference parameters for the points average values computed and relative SDB (ln(blue)/ln(green)).

Table 1: In-situ depth and relative SDB

DEPTH	RASTERVALUE	DEPTH	RASTERVALUE
2.64000000000	1.08579000000	22.43510000000	1.10398000000
6.61140000000	1.04259000000	23.31400000000	1.02666000000
7.91610000000	1.08868000000	24.54590000000	1.10723000000
8.19660000000	1.10252000000	26.19540000000	1.10507000000
9.91060000000	1.08349000000	29.23780000000	1.10471000000
10.82050000000	1.09006000000	30.28200000000	1.10161000000
12.55570000000	1.04747000000	31.89490000000	1.10634000000
13.25810000000	1.09975000000	36.98000000000	1.10136000000
14.42620000000	1.10235000000	41.13400000000	1.10191000000
15.34000000000	1.10362000000	43.81000000000	1.10455000000
16.51960000000	1.10682000000	49.15000000000	1.10299000000
17.52380000000	1.10463000000	51.35000000000	1.10299000000
18.59000000000	1.10183000000	55.23000000000	1.10203000000
19.99000000000	1.02699000000	59.06000000000	1.10440000000
20.69820000000	1.11182000000	63.90600000000	1.10320000000
21.47200000000	1.10737000000	66.17200000000	1.10367000000
		69.83000000000	1.10477000000

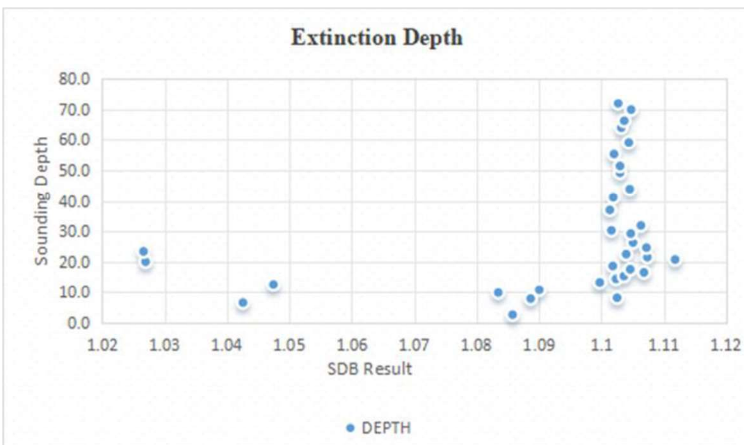


Figure 5: In-situ data and relative SDB

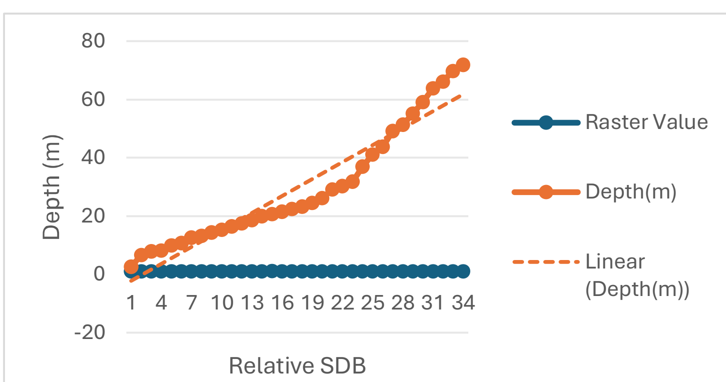


Figure 6: In-Situ Data and Relative SDB Trend

This process was executed in Microsoft Excel, where the constant used to scale the ratio to the depth (m1 = -95.735) and the offset for the depth of z = 0 (m0 = 99.473) were determined obtained as shown in Figure 5 below. These values were integrated into relative SDB in ArcMap 10.8 to compute the absolute water depth, as mathematically described in equation (3) below.

$$y = 99.473x - 95.735 \qquad (3)$$

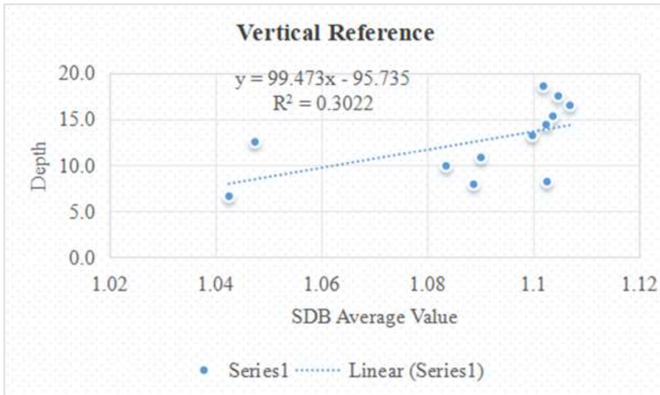
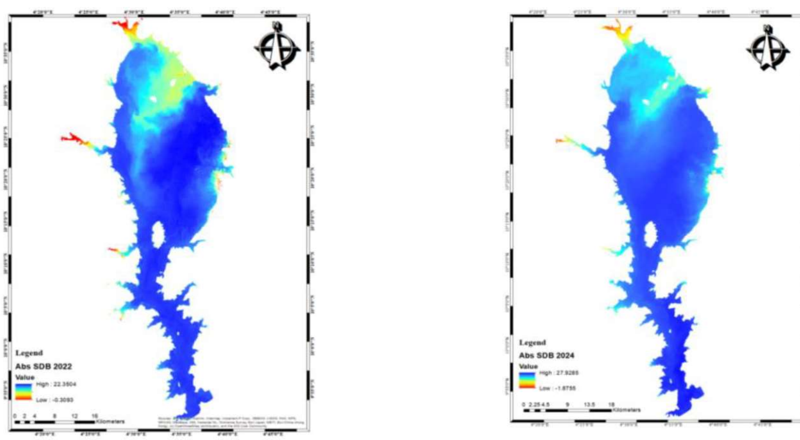


Figure 7: In-Situ Data and Relative SDB Trend

4. Result and Analysis

Equation (3) was applied to the bathymetry algorithm derived earlier by band ratio in ESRI ArcMap 10.8 in order to obtain absolute water depth reflecting the depth of the water as determined using the control points or existing sounding data and the raster value derived from the relative satellite derived bathymetry as shown in Figure 8 below.



(a) *(b)*

Figure 8: SDB (a) 2022 (b) 2024

5. Discussions

In the determination of the depth of Kainji Dam using satellite imagery (Landsat 8) and band ratio algorithm, it was noted that area with depth over 20m are not well determined and has very low correlation coefficient with the application while areas with depth lower than 19m have high correlation coefficient with the Insitu depth and well determined as shown in table 1 below. It was confirmed that the typical extinction depth of multispectral sensors such as Landsat8 is between 5 to 15m. also, the process was carried out on several other Landsat 8 images from which best performance was chosen. To obtain higher degree of correlation, the Insitu depth was increased from 35 points to 75 points and 150 points due to the extent of Kainji reserve and the extinction depth was also neglected in some cases to observe the algorithm difference all yielding the result given a table 2 below.

Table 2: Result analysis

Landsat 8		R² value	
Year	No of Insitu Points	With Extinction Depth	Without Extinction Depth
	35	0.3022 (22)	0.1097 (67)
2022	75	0.250	0.0919
	150	0.0016	0.0782
	35	0.4848 (30)	0.3327 (74)
2024	75	0.3866	0.2542
	150	0.0908	0.2332

6. Conclusions

Statistical indices obtained in this project work indicate that the band ratio algorithm can determine accurate depths up to 20 m using Landsat 8 imagery. The procedure used for deriving the satellite bathymetry is convenient as a tool for examining coastal areas in such a depth range and even updating the existing data of such areas. Currently, the SDB algorithm cannot be applied to Landsat 8 in very deep waters such as the Kainji Dam with the highest depth of approximately 72m as observed in a 2022 survey carried on it and oceans as it has been experimented with in this project. By using the results of this tool, surveyors and hydrographers can assess the current amount of change in depth and if a weaker R2 value is observed, it necessitates the update of sounding data and high-resolution hydrographic chart to the existing one. To derive the bathymetry using satellite imagery, environmental conditions such as water clarity, cloud cover, a sunlight need to be considered depending on the resolution of the image because they could degrade the accuracy of estimated depth. SDB is a promising method for remote mapping of shallow water zones, offering a cost-effective and wide-coverage solution for various applications.

7. Acknowledgments

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