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Estimation of Sediments and Volumetric Analyses of Shiroro Dam Using Geospatial Technique

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Abstract: To effectively manage reservoirs, there is need to routinely check the rate of sediment accumulation as it effects the capacity of the reservoir. Remote sensing technique provides useful alternative for extracting depth information and a fast, repetitive and low-cost mapping over large areas which optimize and minimize intensive field works. This study seeks to estimate the sediment accumulation of Shiroro reservoir in Niger state, Nigeria using Satellite-Derived Bathymetric (SDB) models (python script algorithm). Landsat8 image data (30 m resolution) was used for the research, the preprocessing and post processing stage was carried out aimed at increasing the reflectance of the image data. The sequence involves the derivation of depth using band ratio technique and the volume of the suspended sediment was estimated using python script on ArcGIS software. The estimated volume obtained was about 5365.47 Mm^3 as against the reservoir designed volume of 7000 Mm^3, it indicates a loss of about 1635 Mm^3. The rate of sediment accumulation was estimated to be 70.02 Mm^3/year which translate to be about 0.65% per year. The study recommend that further investigation should be carried out using different means of data acquisition to ascertain the outcome of the results obtained. However, routine checkup should be carried out to preserve the lifespan of the reservoir.

Keywords: Sediment Accumulation, Reservoir, Satellite Derived Bathymetric, Sediment Volume, weighted staff depth measurement

I. Introduction

Lake, reservoir, and wetland distribution is important in many scientific fields. It is important in large-scale studies of the environment, biodiversity, health, agricultural suitability, climate change modeling, and for assessments of present and future water resources [1]. Many have considered continental waters to be a minor part of the biosphere so much so until recently, the activity of inland waters was ignored in global estimates of ecosystem processes [2]. A lot of important attributes ranging from physical, chemical and biological features to depth, area and volume of inland waters are still not well accounted for [3].

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A reservoir is a man-made lake built for the purpose of storing water. Reservoirs are mostly formed by constructing barriers known as dams across rivers to impound its water. A reservoir can also be formed from a natural lake whose outlet has been dammed to control the water level. The dam controls water flow quantity out of the reservoir. For thousands of years, people have been making reservoirs. Jawa Dam in Jordan is the oldest known dam in the world built about 3000 years BC to store water for irrigation [4]. The water stored is the reservoir and it can be used for many purposes including residential and industrial water supply, irrigation, flood control, hydro-electric power generation, recreation, and for navigation [5]. Dam built across river channel impound water upstream and the natural flow of sediments pattern downstream are altered in the process giving rise to sediments accumulation at the bottom of the reservoir [6], the amount and volume of which can be determined using different approaches like water sampling analysis, reservoir sediment probing, integrated bathymetry, geostatistical analysis, GIS and remote sensing. The formation of these sediments may be as a result of poor maintenance culture, indiscriminate disposition of wastes, excessive flooding and many more. Water supply and water resources management are not possible without reservoirs. They offer water for a variety of uses, including drinking, agricultural, industrial, and recreational use. However, many reservoirs are experiencing a number of issues as a result of the strain from population increase causing the rise in demand for water. The loss of volume caused by silt buildup in reservoirs is one of the key issues they encounter. The water in the reservoir becomes shallower as sediment builds up. This causes the reservoir's surface area to shrink and lowers the reservoir's capacity [7].

Lakes are experiencing sustainability threats globally, encroachment and anthropogenic activities altered region's hydrology [8]. Dam built across river channel impound water upstream and the natural flow of sediments pattern downstream are altered in the process giving rise to sediments accumulation at the bottom of the reservoir basin [6,9]. When it rains, bare earth (topsoil) is washed into reservoir and takes different time to settle down below the reservoir basin [10]. Runoff from land-based activities is the primary factor that reservoirs and lakes accumulate debris. Biomaterials from industrial, urban, and agricultural sources are carried in this runoff. These substances, often known as non-point source pollutants, can be challenging to control and contain because of their diffuse nature[11].

Globally, an average of 0.5 to 1% of the volume capacities of small and large reservoirs is lost because of sediment accumulation annually [12]. The accumulation of sediments causes reduction in volume of the reservoir leading. When the volume of a reservoir is reduced, its productivity is also low causing reduction in the required water supply for agricultural and residential use. The issue of sediment accumulation in reservoirs is complicated. It is brought about by a number of things, such as erosion from upstream sources, variations to water flow patterns, the operation of dams, and changes in land use [13]. Sediment accumulation can result in lower water storage, decreasing water quality, and deterioration of aquatic habitat [14]. The location and size of the reservoir also influence the rate of sediment accumulation, larger reservoirs are more prone to silt collection [15]. Although there isn't a single answer to the sediment accumulation problem, there are a number of approaches that can be taken, including dredging, sediment trapping, and sediment bypassing [16].

The availability and management of water, one of the most important resources in the world, are of utmost significance. In order to help preserve the long-term sustainability of these important resources, it is crucial to first determine the water volume and sediment buildup of reservoirs and other inland waters [17]. The demand for reservoirs to store water for later use is rising as populations continue to rise. Knowing how much water is available and the amount of sediment accumulated in the reservoir is crucial for the sustainable management of the water the reservoir. This information can be used to standardize the reservoir's water volume, thereby ensuring its sustainability [11].

Additionally, research on reservoir volume and sediment accumulation can aid scientists in improving their knowledge of water use and sediment. Scientists can develop models to assist predict and plan for future water needs and sediment levels by understanding the dynamics of a reservoir. Utilizing this information will enable reservoir management to be more viable [18]. Also the analysis of reservoir water volume and sediment accumulation is critical for identifying potential water pollution issues. For example, large quantities of silt in a reservoir might cause water pollution issues such as low level of water oxygen or higher levels of hazardous compounds. Researchers can identify possible water contamination issues and help to avert them by understanding reservoir volume and sediment accumulation [19]. An essential step in the water management cycle is the requirement to precisely monitor the volume of water in reservoirs. Information regarding the many characteristics of water resources, such as water volume, evaporation, and infiltration, is increasingly being gathered via remote sensing techniques [20]. The standardization of water volume in reservoirs is the main topic of this study, which focuses on the application of remote sensing techniques. These techniques enables the precise measurement of water volume which can further be used in detection of trends in the usage of water resources. This can aid in enhancing the management of water resources and guarantee that they are used sustainably.

A suitable and precise measurement of water levels and extents is very important for monitoring its volume and sediment accumulation. Unfortunately, it is difficult to use in-situ hydrographic measurements to estimate long-term dynamic information of lake volume, especially in some remote regions [21]. Hence, this research seeks estimate the volume of sediment materials present in shiroro dam using multispectral image data.

II. Materials and Methods

A. Study Area

Shiroro dam is situated in Shiroro local Government Area (LGA) of Niger state. The dam was created in May, 1984 by damming Kaduna River at Shiroro village. The reservoir has an estimated surface area of 312 km^2 and a mean depth of 22.4 meters[22]. The dam is bordered in the northeast by Munya LGA while at the west by Rafi LGA. It has a distance of about 55km from Minna metropolis, the capital of Niger State. It is geographically located between latitude 9 50'N to 10 05'N and longitude 6 50'E to 6 55'E of the Greenwich. The climate condition of Shiroro LGA is viable for cereals and perennial crops. It has maximum average temperature of about 26.45 Celsius and average rainfall of about 4.7mm per annum [23].

B. Data Acquisition

The Landsat 8 Operational Land Imager Level-1, 16-bit, relatively cloud-free multispectral imagery was downloaded from USGS Earth Explorer in geo-referenced GeoTIFF format in Universal Transverse Mercator (UTM) Zone 32 North projection (U.S. Geological Survey, 2016b). Table 1, depicts the image data characteristics

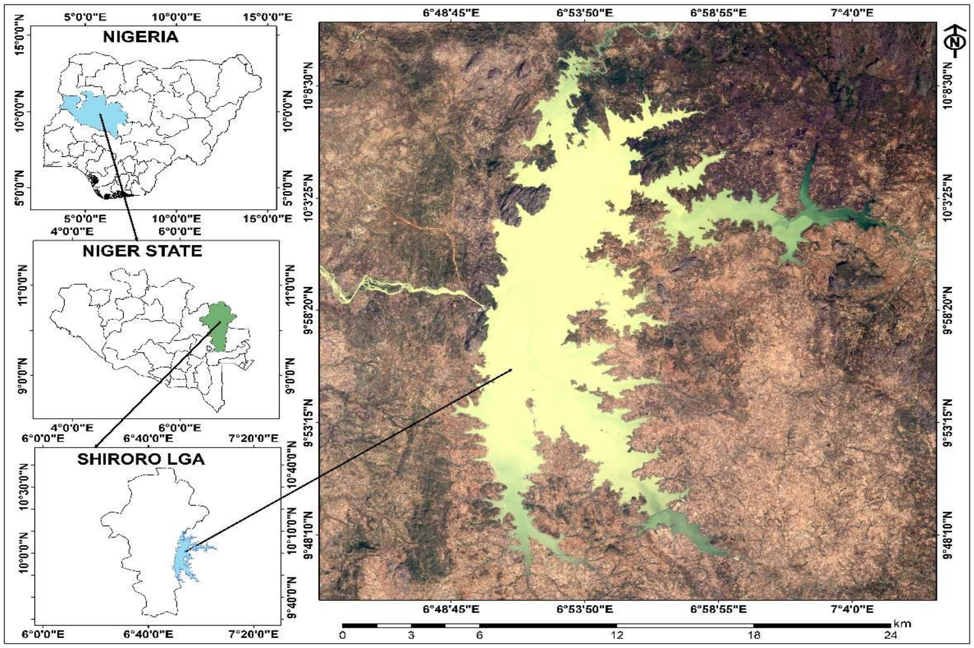

Figure 1: Shiroro Dam in shirora LGA of Niger State

Table 1: Characteristics of Landsat 8; Spectral, Spatial and Temporal Resolution

`	**Bands**	**Wavelengths (µm)**	**Spatial resolution (m)**	**Swath width**	**Revisit time**
3 Operational Land Imager (OLI)	Coastal/Aerosol	0.43-0.45	30	185 km	16 days
	Blue	0.45-0.51	30		
	Green	0.53-0.59	30		
	Red	0.64-0.67	30		
	NIR	0.85-0.88	30		
	SWIR 1	1.57-1.65	30		
	SWIR 2	2.11-2.29	30		
	Panchromatic	0.50-0.68	15		
	Cirrus	1.36-1.38	30		
Thermal Infrared Sensor (TIRS)	TIR 1	10.60-11.19	100		
	TIR 2	11.50-12.51	100		

unavailability of underwater topography data (chart data) for inland waters in Nigeria, this research assigned assumed depth value by utilizing information about its designed depth. According to [22], the mean depth of the study area is about 22.4 meters. This information was used in the derivation of SDB points across the study area using in Esri ArcMap 10.8 software. Figure 2 shows the conceptual flow of the research.

This model uses a log-transformed ratio of the reflectance of bands with different absorption strength which is a function of it band combination and its resultant (wavelength) which off course, will influenced the predicted SDB depth. In this way, one band will have arithmetically lower values than another. As the reflectance of both bands decreases with increasing depth, the $\ln(L_{obs}(\lambda_i))$ of the band with greater absorption (green) will decrease proportionally faster than the ln $(L_{obs}(\lambda_j))$ of the band with less absorption (blue) [27]. Thus, the greater the depth, the greater the value of this ratio [26, 28].

This ratio of natural logarithms method, as shown in equation 1a and 1b, was used to approximate relative vertical profile by using multispectral satellite bands from which the diffuse attenuation coefficients are computed [25, 26, 27]. Depth estimates are derived using this equation as in the Stumpf and Pe'eri approach:

$$\rho_{SDB} = \frac{\ln\left(L_{obs\,(\lambda_i)}\right)}{\ln\left(L_{obs(\lambda_j)}\right)} \qquad 1a$$

$$Z = m_i * (\rho_{SDB}) - m_0 \qquad 1b$$

Where

z: relative vertical profile depth estimates;

pSDB: SDB attenuation coefficient or the "pseudo" depth by satellite (dimensionless);

m_i and m_0: gain (tangent of the slope angle) and offset (intercept), respectively, that are empirically determined;

l_n: Natural logarithm ratio of the attenuation between observed radiance estimated;

Lobs (*λi*): observed radiance of the Landsat blue band;

Lobs (*λj*): observed radiance of the Landsat green band.

The derived SDB depth was obtained from the combination of bands, the most correlated band combination result was selected as the predicted SDB depth. The validation was ensured using weighted calibrated staff, to determine the depth measurement across the dam. The Calibrated staff was position at longitudinal direction at 25m inters points across the study area. This approach of depth estimation happens to be one of the earliest method and it known for its high accuracy for ocean depth determination less than 250m [29]. This is aimed to validate the remotely sensed (SDB) method derived from the image data. The predicted SDB variation map was sorted relative to its geo-position at longitudinal direction along with the referenced observation (weighted depth). SDB observation was analyses using correlation analyses index, mean square error (RMSE) and correlation analysis index (CAI).

$$RMSE = \sqrt{\sum(Z_{sat} - Z_{obs})^2} \qquad 2$$

Where: Z_{sat}, predicted observation and Z_{obs}: Referenced observation

This is intend to determine the average mean deviation of the predicted point from the referenced observation and also, to identify the ratio of closeness of the referenced (weighted) observation to the predicted (SDB) depth measurement. The Surface Volume (3D analyst) tool of Esri ArcMap 10.8 software was used to estimate the volume of the study area. This was done using the result raster of the derived SDB. The volume of the reservoir was estimated using a set of python script exported to the ArcGIS software environment

C. Volume of Sediment Accumulated

Sediment Accumulated Volume (SAV) was computed by subtracting the Designed Reservoir Volume (DRV) from the Estimated Volume of the reservoir (EV) from this study. This method was previously utilized by [5, 6, 30] in finding the volume of timeline sediment accumulation in their respective research. Equations 2a and 2b were used for the determination of the reservoir volume losses and the estimation of the percentage of annual loss of the Shiroro reservoir volume capacity.

$$R_{annual} = \frac{v_i - v_f}{t} \qquad 3a$$

$$R\% = \frac{(R_{annual}) * 100}{v_i} \qquad 3b$$

R_{Annual}; is the mean annual actual sedimentation volume in (Mm^3/year);

V_i ; Initial reservoir volume in (Mm^3);

V_f: Final reservoir volume in (Mm^3);

t : Number of years (year) under consideration.

III. Results and Discussion

A. Results

This section covers results obtained from the study, in line with the study targets. Figure 3 depicts the Dam reservoir before and after extraction

From Figure 3, the extracted water pixels were converted to polygon for the purpose of area calculation. The result of the area calculation was 320 km^2 showing remarkable increase of about 8 km^2 when compared with its original designed stage area by [22] as 312 km^2 in the year 1984. Figures 4, 5 and 6 depicts the regression combination of bands for the depth estimation.

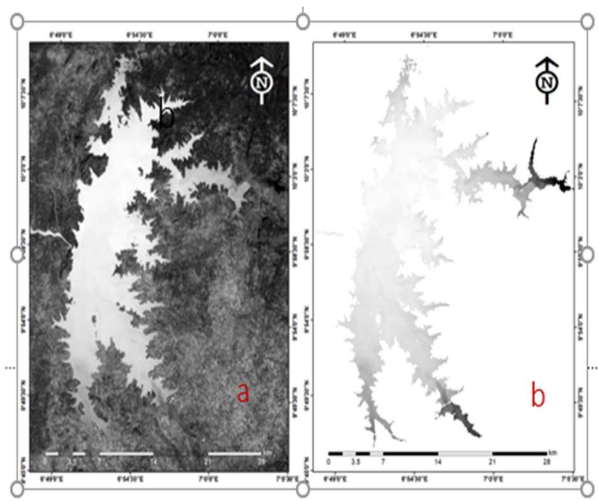

Figure 3: Study Area before (a) and after (b) Water Extraction.

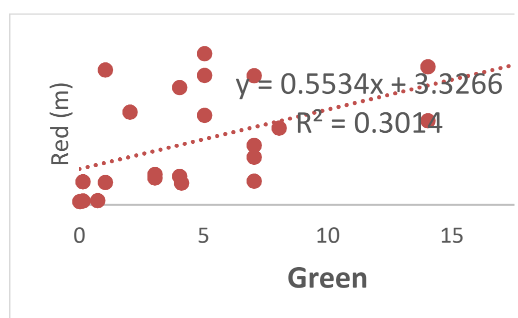

Figure 4: Regression Combination of

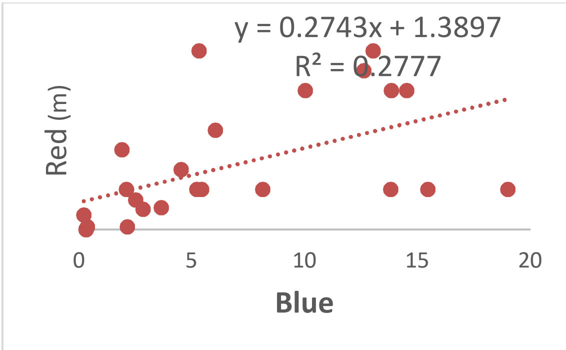

Figure 5: Regression Combination of Blue/Red Band

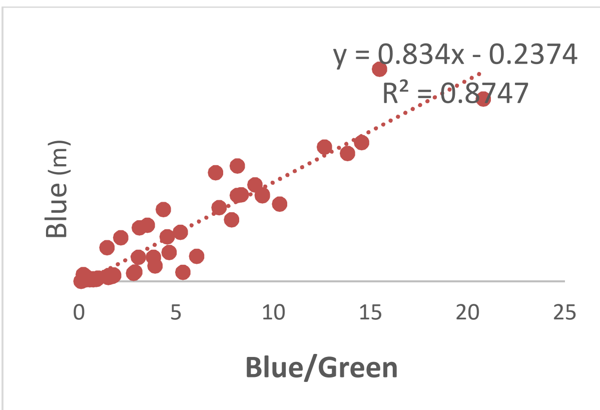

Figure 6: Regression Combination of Blue/Red Band

The band combination for the three bands clearly suggested the most correlated band combination for the predicted SDB depth. Green/red band indicates a correlation index of 54.9%, Blue/red recorded about 52.7% correlation index. Blue/Green recorded about 93.5% correlation. Table 2 shows the correlation level of each band combination and slope. The red band combination indicates weak wavelength in clean water, this can be seen in table 4.1 while the combination of Blue and green band shows strong penetration wavelength on clean water, it corroborate [31]. Figure 7 depict the depth variation of Shiroro dam.

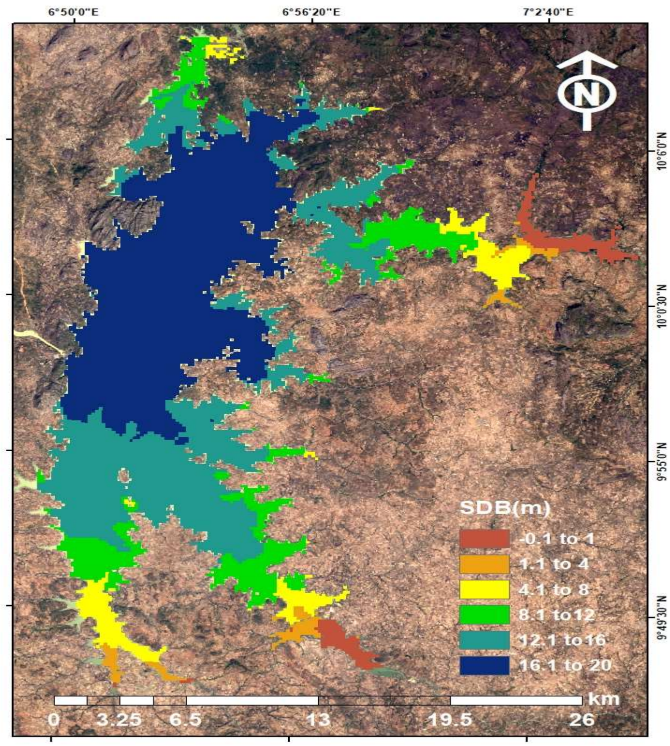

Figure 7: Depth Variation of Shiroro Dam

From the predicted SDB measurement, the highest depth recorded was 16.170m while the lowest was -0.13m. The dark blue areas of the map depicts areas of high depth while the green area is the average depth and the red areas depicts low depth. The validation of the predicted SDB was actualized using calibrated weighted staff instrument. Figure 8 depicts the line graph of both measurement.

The highest depth recorded from the referenced observation was 18.453m as against 16.170m. The difference of about 2.283m was observed when compared with both measurement. . Figure 9 depicts the scattered regression plot for both observation. The computed mean square error was 2.677m from the referenced observation.

Table 3: Variables Derived From Band Ratio and Weighted Staff Approach

`Methods	Correlation index analyses (CIA)	Root Mean Standard Error(RMSR)
Band ratio	0.9241	2.6777
Weight staff	1	

This is within the threshold when compared with the number of depth point considered

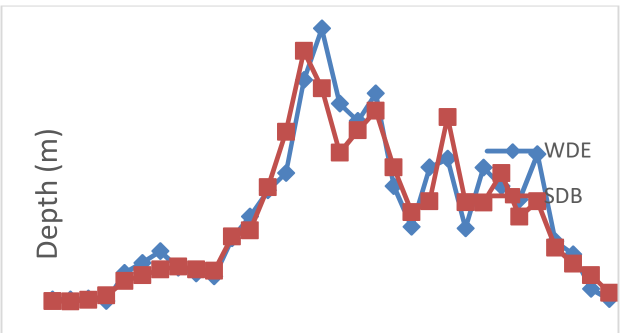

Figure 8: Depth Pattern from the Referenced (Weighted) Depth Estimation and Predicted (Satellite Derived Depth) Observation

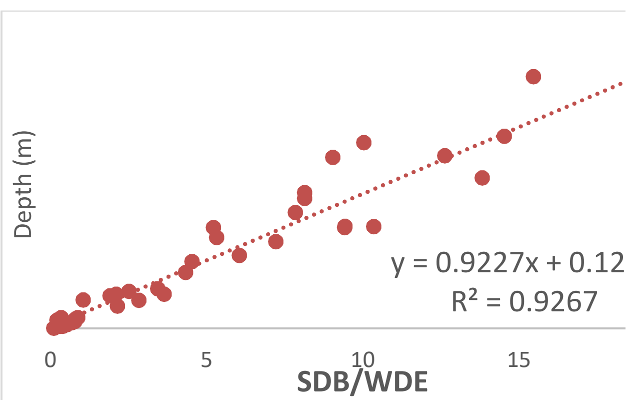

Figure 9: Predicted SDB and the Referenced (Weighted) Depth Estimation

From Table 3, it shows that the SDB depth deviated from its reference depth (weighted staff depth) by about 0.76%. The degree of correlation obtained when the SDB depth was compared with weighted depth was about 92.4%. This indicates that there is high correlation level between the weighted staff method of depth measurement and SDB (band ratio) approach. However, the means error variance at each point was computed to be at 2.6777.

The estimated volume of the reservoir obtained was 5365.47Mm³ as against the original designed volume of 7000Mm³. The reduction in volume could be a function of sediment that must have settle at the bottom of the dam which could be as a result of carelessness from the authority responsible [31]. Hence, it indicate that about 1635Mm³ of the dam capacity is engulf with sediments for the period of about 36 years. It also indicates that about 23.35% of the original volume capacity of the dam is loss as a result of sediments. The rate of sediment accumulation for this study was calculated to be 70.02Mm³/year which is about 0.65% yearly

IV. Conclusion

The study demonstrated the use of remote sensing technique to assess sediment accumulation of inland waters by depth extraction using satellite image data. Satellite Derived bathymetry offers an alternative to basic hydrographic Method. The combination of band ration methods have shown high sustainability in the method, the blue and green band spectrum combination have demonstrated high correlation and wavelength penetration in clean water. The result of the satellite derived bathymetry of Shiroro reservoir in this study revealed a loss in water volume to be about 1635Mm³ for the period of 36 years considering the original designed capacity of 7000Mm³ due to sediment accumulation. In addition, the average rate of sediment accumulation estimated is 70.02Mm³/year and the percentage loss of the reservoir capacity is 23.35% between the volumes considered, which means the reservoir is losing its capacity by 0.65% annually. The use of remote sensing in such estimations for reservoir sedimentation is not only rapid and less laborious but also low-cost and affordable in the long run which gives time to time systematic information about the fluctuations in the water level (live storage capacity) and the aggregate of sediments deposited in the reservoir.

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