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ANALYSIS OF SEDIMENT ACCUMULATION EFFECTS ON HYDRAULIC STRUCTURE OPERATION AND MAINTENANCE IN AGBA DAM RESERVOIR

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Abstract

Sedimentation in dam reservoirs across the globe is a significant issue that affects the performance, longevity, and operational efficiency of hydraulic structures and Agba dam reservoir is not exempted. This study investigates the impact and sediment accumulation on the functionality and safety of Agba dam reservoir in kwara state. Through computational modeling, the research quantifies the rate of sedimentation, estimated the sediment accumulation and assesses its implications on the reservoir's storage capacity, flood control abilities, and downstream water quality. The results indicated that Agba dam reservoir current storage capacity was 2,326,884.56 m^3 and the reservoir was constructed in 1949 with a design capacity of 3,000,000 m^3. From the inception to the time of the present study, 73 years had elapsed. This shows that within 73 years, the reservoir lost 0.67m^3 of its original capacity to sediment. The average rate of sediment accumulation for the 73- year period was estimated to be 1743.06349 m^3/year. This indicates a progressive reduction in the effective storage volume of the reservoir due to sediment deposition and accumulation, which in turn reduces its capacity to manage flood events and supply water during drought period. To mitigate these effects, the study suggests implementing regular sediment management practices, in addition to this; the research highlights the significance of continuous monitoring and adaptive management strategies to maintaining the structural integrity and operational effectiveness of dam reservoirs in the face of ongoing sedimentation challenges.
Keywords: Sedimentation, Dam reservoir, Efficiency, Longevity, Impact, Capacity, Flood control, Mitigate, Management, Maintenance, Strategies.

1.0 Introduction

The reservoir has the potential to be used for a variety of purposes, including domestic, water supply, irrigation, flood control, and hydropower; however, it is vulnerable to sediment buildup due to erosion in the watersheds. Reservoir sedimentation is the process of sediment being transported into a dam reservoir by streams, and it is a worldwide occurrence that has been seen as a major environmental hazard in recent years (Adongo et al., 2020; Ayele et al., 2021). Sediment deposition in reservoirs is a significant downstream consequence of soil erosion that endangers the long-term viability of dams built for various purposes (Froehlich et al., 2017; Iradukunda and Bwambale, 2021). Currently, the global loss of storage capacity in surface water reservoirs due to sedimentation is greater than the increase in storage volume achieved through new reservoir buildings (Ayele et al. 2017; Kondolf et al., 2017). Reservoir sedimentation is a major issue all over the world since it decreased the original capacity of the reservoir which affect drinking, water supply, agriculture, hydropower, flood management, and recreational activities. The sedimentation of reservoirs is unavoidable due to a lack of reservoir management measures such as reservoir sediment routing, periodic sediment flushing, and catchment management to decrease soil erosion, and it has steadily become a major issue for many countries across the world (Adongo et al., 2021; Michalec and Cupak, 2021). As a result of this, evaluating the sedimentation rate and the time period before silt accumulation interferes with the reservoir's effective operation is critical. Estimating catchment erosion and sediment delivery processes can be done in a variety of ways. Physically based models that predict watershed erosion are becoming increasingly prevalent (Abbasi et al., 2019; Sultana and Naik, 2016).

Dams and reservoirs are some of the main storage structures around the world. They are constructed to serve one or more purposes: the storage of water for water supply, the creation of a water head for hydropower plants, and flood control. In dry and semi-dry regions, where there is a significant difference in the river flow between the wet and dry seasons, storage and multipurpose dams are considered the sources of reliable water release. Usually, the flow regime in a river balances the sediment transportation between the flow transport capacity, and the sediment load concentration. The construction of different hydraulic structures, such as dams, barrages, and weirs, change this balance and disturb the sediment transport balance. These structures trap a significant part of the carried sediment upstream of the hydraulic structures. In dam reservoirs, the gradual expansion of the flow section when the flow approaches the reservoir inlet leads to a reduction of the flow velocity and transport capacity. This causes the deposition of coarse sediment in the upper part of the reservoir and the formation of a delta. Then, the fine sediment is deposited along the stream wise flow up to the upstream of the dam axis where the finest sediment is deposited (Ezz-Aldeen, 2020). This situation is one of the most common and major problems in all storage dams around the world. Without efficient sediment management plans, after years of dam operation, sediment deposition leads to a reduction in storage capacity and the reservoir's ability to reliably supply of different water demands. However, it exerts effects on the operational efficiency of the different hydraulic structures attached to the project, such as the bottom outlet gates, hydropower plants, and water intakes for different purposes (Ezz-Aldeen, 2020.). The aim of the study is to assess the effects of sediments on the performance of hydraulic structures, understand how sediment accumulation and transport can impact the efficiency of the structures, and develop strategies for mitigating these effects and the specific objectives include; to determine the present volume of water in the reservoir over time, estimate the sediment transport phenomena and morphological changes in the reservoir in the vicinity of the hydraulic structures, assess the effects of sediment on the performance of the reservoir, such as changes in storage capacity and develop strategies for mitigating the effects of sediment on the performance of the hydraulic structures.

1.1 Sediment distribution in reservoirs

The study of sediment distribution within the reservoir is useful to designers and planners of most hydraulic structures (Issa *et al*., 2013a). However, most studies on reservoir sedimentation have focused on predicting and reducing sediment infilling rate using models but little has been done to determine the sediment distribution and pattern within the reservoir or lake. The pattern of sediment distribution is controlled by either primary or secondary processes. The primary process refers to initial sediment deposition while secondary process refers to sedimentation that takes place after resuspension and redistribution of the previously deposited sediment (Shotbolt *et al*., 2005). In some cases, deltas act as depositional or erosional zones to reservoirs and are sources of sediment reworking in reservoirs. According to Shotbolt et al., (2005) reservoirs are subject to alternating periods of deposition and erosion due to changes in stream inputs and reservoirs water levels. Sediment deposition pattern depends on factors such as; characteristics of the sediments plus quantity of moving sediment and stream flow (Issa *et al.*, 2013a). The coarse particles usually settle first thus forming the delta while the fine sediment is transported by turbid density currents or non-stratified flow resulting to bottom set beds (Issa *et al*., 2013a). Furthemore, hydrodynamics play an important role in sediment redistribution and contaminant movement in shallow lakes (Ndungu *et al.*, 2015). This can be achieved using various techniques such as the use of spud bar or bathymetry survey. According to Shotbolt et al., (2005) assessment of sediment distribution within a reservoir is also paramount prior to the collection and selection of suitable cores for environmental analysis.

1.2 Determining reservoir sedimentation

In assessing sedimentation status of a lake or reservoir, past and current bathymetric surveys can be compared and the actual sedimentation rate be determined (Zarris and Lykoudi, 2017). According to Rakhmatullaev et al., (2011), volume and surface area differences derived from results of multiple surveys for individual reservoirs provide estimates of the capacity loss over time due to sedimentation. According to Jakubauskas and DeNoyelles (2008), sediment thickness and volume can be estimated using topographic maps, sediment coring, spud bar and multifrequency acoustic systems. Some approaches such as the use of sediment coring and spud bar method provide a limited representation of actual sedimentation rates, distributions and patterns since they are limited to a few point samples (Bennett *et al.*, 2013). Hence, acoustics have been used in bathymetric surveys to establish water depth and in some cases both water depth and sediment thickness. To establish information on sediment thickness using acoustics the bathymetric survey findings are compared with the topography at the time of dam construction or with the previous bathymetric surveys conducted for the reservoir or lake. However, according to Dunbar et al., (2015) for proper comparison of bathymetric survey results, a 10 years span between the surveys is paramount. Bathymetric surveys are also used in quantifying the magnitude of bottom sediment erosion, deposition and redistribution processes resulting from storm events. This is usually possible by comparing results of bathymetric surveys conducted before and after the storm events (McAlister *et al.*, 2013; Lachhab *et al.*, 2015). However, for proper comparison of different bathymetric survey results, there is need to use the same survey lines, equipment and procedures, otherwise the computed volume loss may not be comparable (Solis *et al.*, 2012; McAlister *et al.*, 2013). According to Dunbar et al., (2015), overstated pre-impoundment reservoir capacity leads to inaccurate estimation of reservoir sedimentation rates. Odhiambo and Boss (2015) also reported that the estimated reservoir sedimentation rates are affected by over-reliance on Universal Soil Loss Equation. Thus, to accurately predict reservoirs and/or lakes sedimentation rate, there is need for a methodology that can aid in establishment of sediment thickness throughout the lake or reservoir.

2.0 Materials and Methodology

2.1 Description of the Study Area

The reservoir of study is located at Agba dam, off Ahmadu Bello way, behind kwara state Government House, Ilorin south Local Government Area of kwara state. The reservoir is between Latitude 80 30' 38" and 80 30' 49" N and Longitude 40 35' 18" and 40 35' 52" E. The dam was completed in 1949. (Source: CONLD) It is an earth dam with crest length of 570m. The height is about 17.8m. The capacity at inception was 1344 Million litres and the diameter of the bell-mouth is 2m (Kwara State Water Corporation, 2013). The reservoir is approximately 1km long with a breadth of 0.3km at its widest point. It is the first dam constructed in the state. According to the Kwara State Water corperation (2013), the dam supplies raw water through an intake to a treatment plant where the water is treated and distributed to some parts of Ilorin such as Governmrnt House, the whole of Government Reserved Area (GRA), Gaa-Akanbi, Olunlade, Offa Garage and part of Ibrahim Taiwo road. The overhead tank of the fire service at the Ibrahim Taiwo road and the areas around Unity road are also supplied by Agba reservoir. The reservoir location falls within the Southern Guinea Savannah coogical zone of Nigeria (Ejieji, 2011).

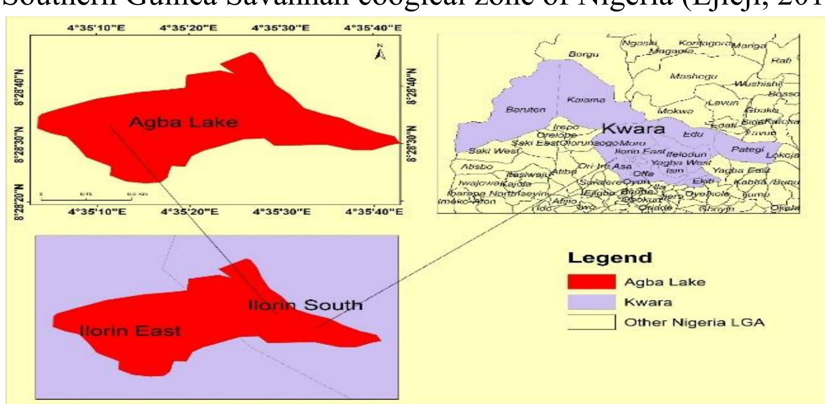

Figure 1 Map of the study area

Source: Wikipedia

2.2 Materials

The following sets of data such as hydrological data such as precipitation or rainfall data, evaporation, infiltration, groundwater levels, watershed characteristics, hydraulic data such as cross sectional area, velocity, water level, streamflow, channel slope and bathymetry data such as sediment load, sediment grain size distribution, settling velocity, bedload transport were used during the analysis of sediment transport on the performance of hydraulic structures on Agba dam reservoir.

2.3 Methodology

The methodology for used for this study includes; the use of hydrographic survey remote sensing technique such as ArcGIS was employed to determine the volume of water in the reservoir and to measure the depth and area of the reservoir. The hydrodynamic modeling software such as ArcGIS will be used to simulate the flow and sediment transport in the reservoir under different hydraulic conditions to estimate the sediment transport and the morphological changes. Sediment sampling and analysis, bathymetric survey data was used to measure the changes in storage capacity to assess the effects of sediments on the reservoir's performance. To develop mitigation strategies, options that could be considered are to explore innovative sediment management techniques and as well as to refine existing methods.

3.0 Result and Discussion

3.1 Hydrological condition of the dam and parameters that influence sediment deposition

3.1.1 Temperature

From the temperature analysis result the temperature of the reservoir falls within range (33.78 – 34.077) which shows that the temperature is moderate (Figure 3.1). Moderate temperature may not directly influence sediment transport, while moderate temperatures may not have a direct and pronounced effect on sediment deposition in a dam, they can indirectly influence sediment-related processes through their impact on weather, vegetation, water temperature, and hydrology.

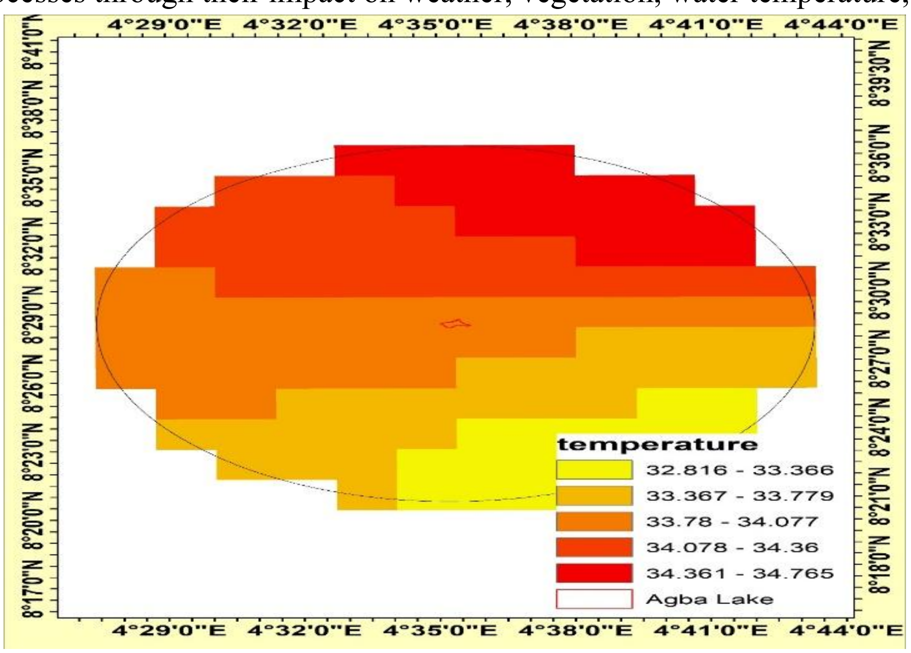

Fig 3.1: The temperature map of the study area.

3.1.2 Contour Map

From figure 3.1, the contour shown the steep slope and less steep slope, area with compacted contour lines indicate steep slope, which is high elevation while area with non-compacted contour lines indicate depression. The area with less steep slope is depressed topography which accommodate water and retain water while steep area elevated topography will experience runoff.

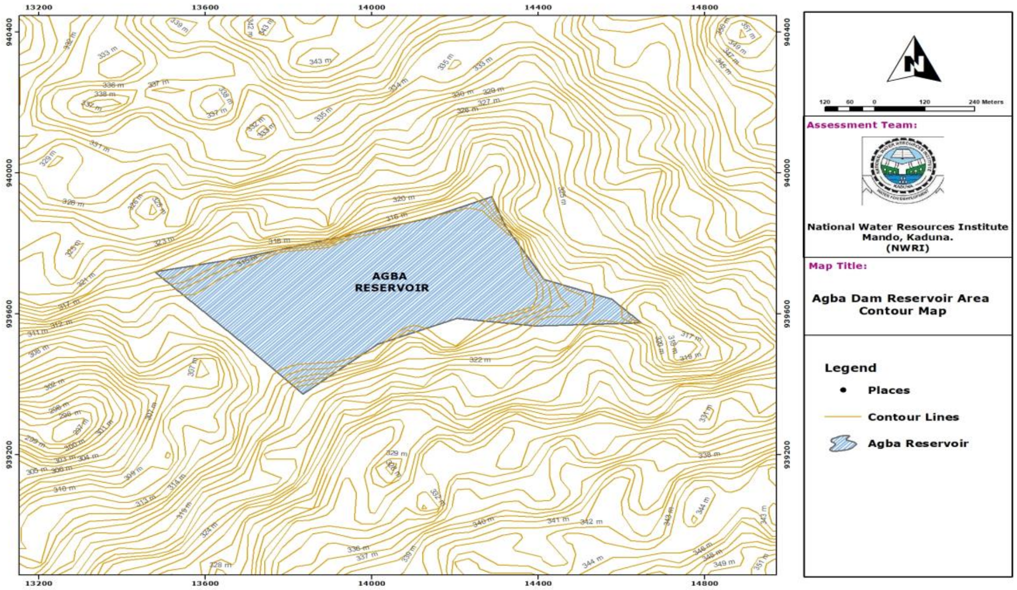

Fig 3.2: The contour map of the study area

Source: NWRI 2022 Agba dam Progress Report

3.1.3 Flow Rate

This is a flow rate map, showing the intensity of the water flow and from the analysis result, the flow rate falls within the range (151-249) which brings us to the conclusion that the flow rate is moderate (Figure 3.3). This implies that moderate flow rate can help maintain sediment transport and prevent excessive deposition; they can also contribute to gradual sediment accumulation within the reservoir.

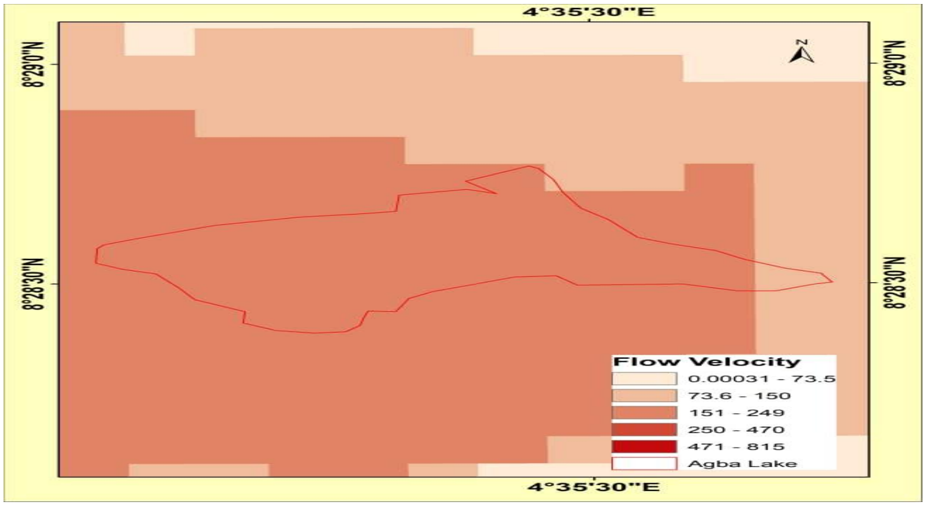

Fig 3.3: The Flow rate map of the study area.

3.1.4 Precipitation

Figure 3.4 shows the down pour rate of the study area, the darker area indicates area of high precipitation with 4.26 rate while the lighter area indicates case precipitation with 3.56 rate, this shows that larger area of the map experience high precipitation.

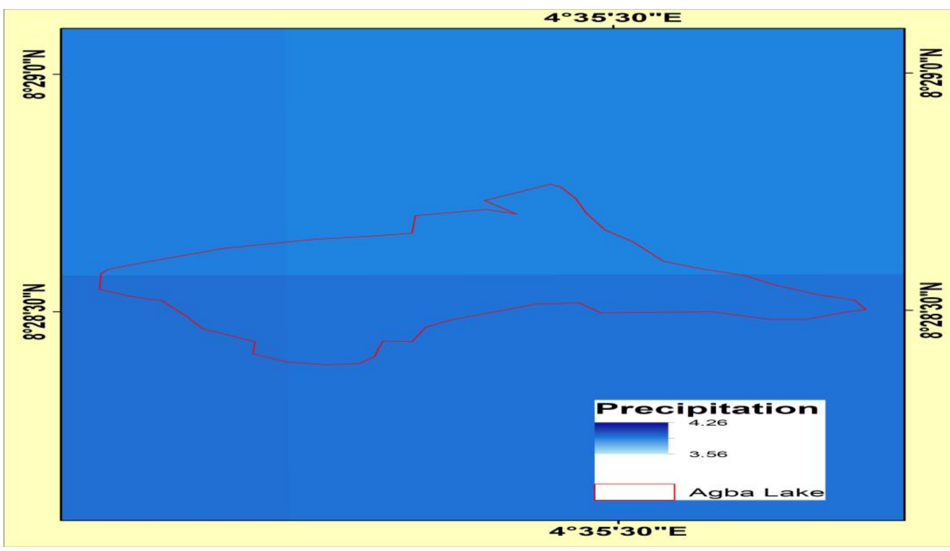

Fig 3.4: The Precipitation map of the study area.

3.1.5 Stream Order.

Figure 3.5 shows the stream order analysis and stream order 1 connecting to form stream order 2 within the dam. This is to say we have two major recharge sources and some other minor channels recharging this reservoir from the surface, so we can deduce that it's connected to an aquifer as a result, the reservoir will experience less inflow from the surface rather it will experience subsurface recharge from the aquifer.

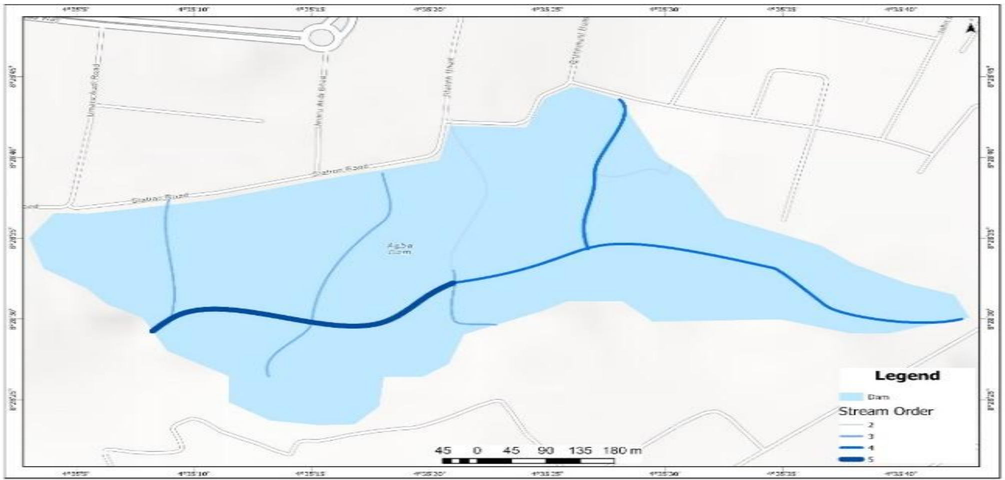

Fig 3.5: The stream order map of the study area.

3.1.6 Soil Type

After analysing the shape file of the soil in GIS, the general soil type of the study area is categorized as sandy clay soil as shown in the map (Figure 3.6). Sandy clay is a type of soil which has high runoff potential due to very slow infiltration rates. Due to the presence of clay, it has high swelling potential, high permanently water tables, and it is shallow over nearly impervious parent material.

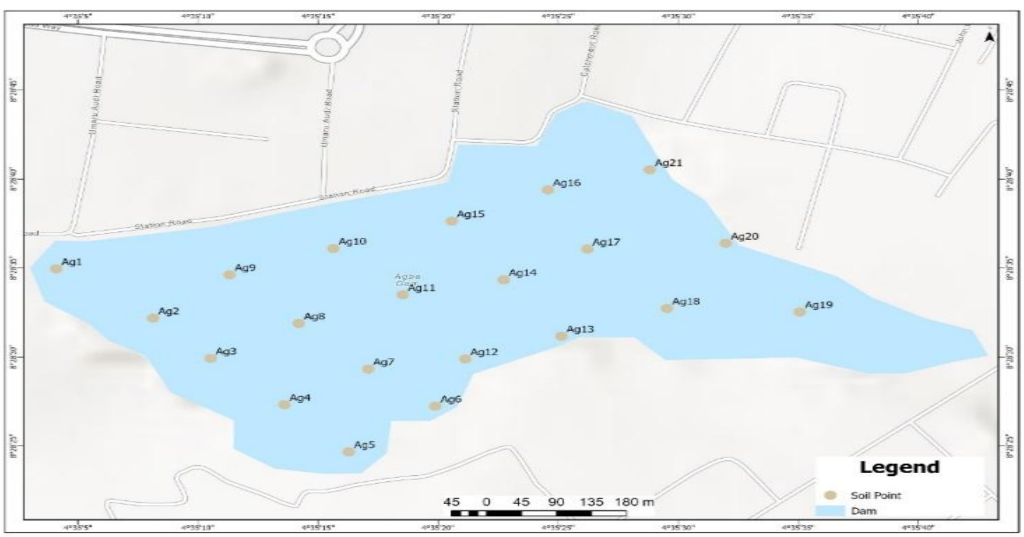

Fig 3.6: The Soil Type map showing the study area.

3.2 Volume Computation

Using the TIN model, the volume of water present in the reservoir was calculated. The Surface Volume tool in ArcGIS was employed to determine the volume of water displaced by sediments, providing an estimate of the total volume of water present in the reservoir.

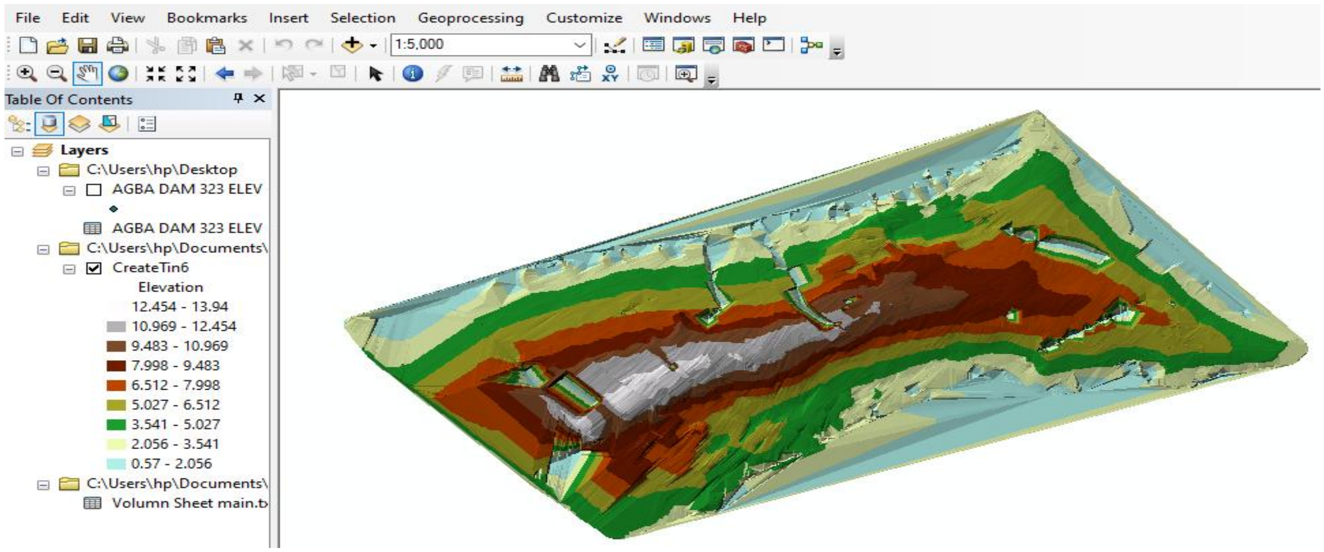

Fig 3.7: The snip showing the surface volume of water present in the Agba reservoir

	A	B	C	D	E	F	G
1	Dataset	Plane_Height	Reference	Z_Factor	Area_2D	Area_3D	Volume
2	..hp\Documents\ArcGIS\createtin	13.94	BELOW	1	262066.786	271445.7656	2326884.531
3							
4							

Fig 3.8: The snip showing the result of the present volume computation table

3.3 Estimation of Sediment Accumulation

3.3.1 Bathymetry Map

The contour data used for this analysis was acquired from USGS earth explorer, which was further embellished. The processed bathymetric data was integrated with the contour data to create a comprehensive representation of the reservoir's boundary as shown in Figure 3.9.

The integration involved aligning the bathymetric data with the contour data, ensuring consistency and accuracy in the combined dataset. The reservoir boundary was digitized using Google Earth Engine. The digitized boundary was saved as a shapefile, providing a precise outline of the reservoir for further analysis.

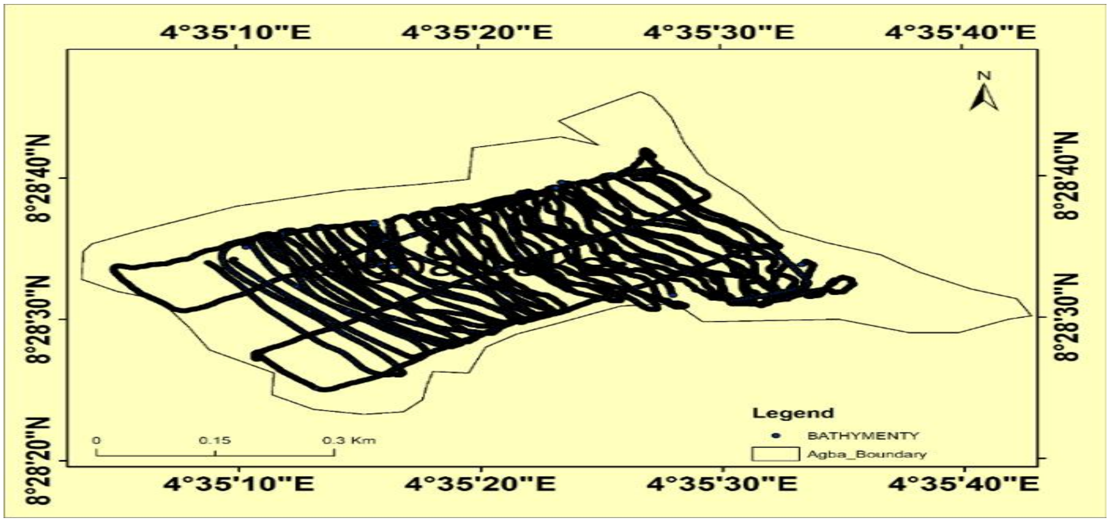

Fig 3.9: The bathymetry map showing the shapefile of the study area.

3.3.2 Contour to Raster Map.

The contour data that was downloaded from USGS earth explorer was exported to ArcGIS, then the contour data was interpolated to raster using contour to raster tool under the conversion tools in the ArcGIS software. The interpolation is necessary because contour data is in a shapefile and we need to interpolate it to raster to provide a continuous surface representation of elevation and to carry out further spatial analysis. Figure 3.10 is the result of the interpolation.

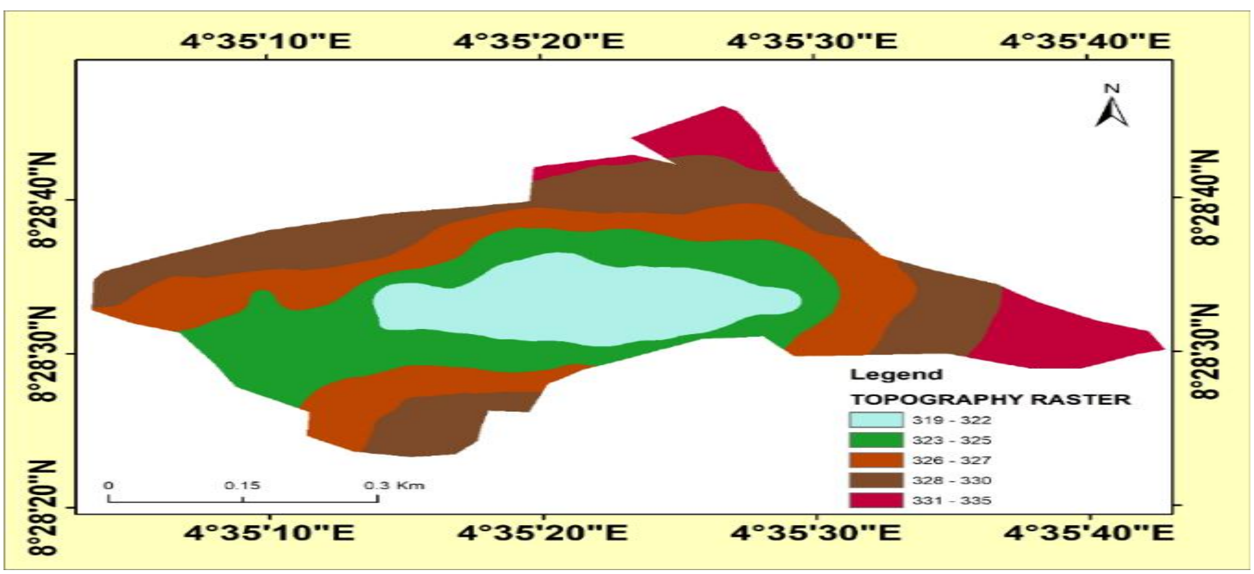

Fig 3.10: Contour to raster map showing the surface representation of elevation of the study area

3.3.3 Bathymetry to Raster Map

The bathymetry point data was also interpolated to raster map using the inverse distance weighting (IDW) tool in the ArcGIS software. Figure 3.11 shows the interpolation result;

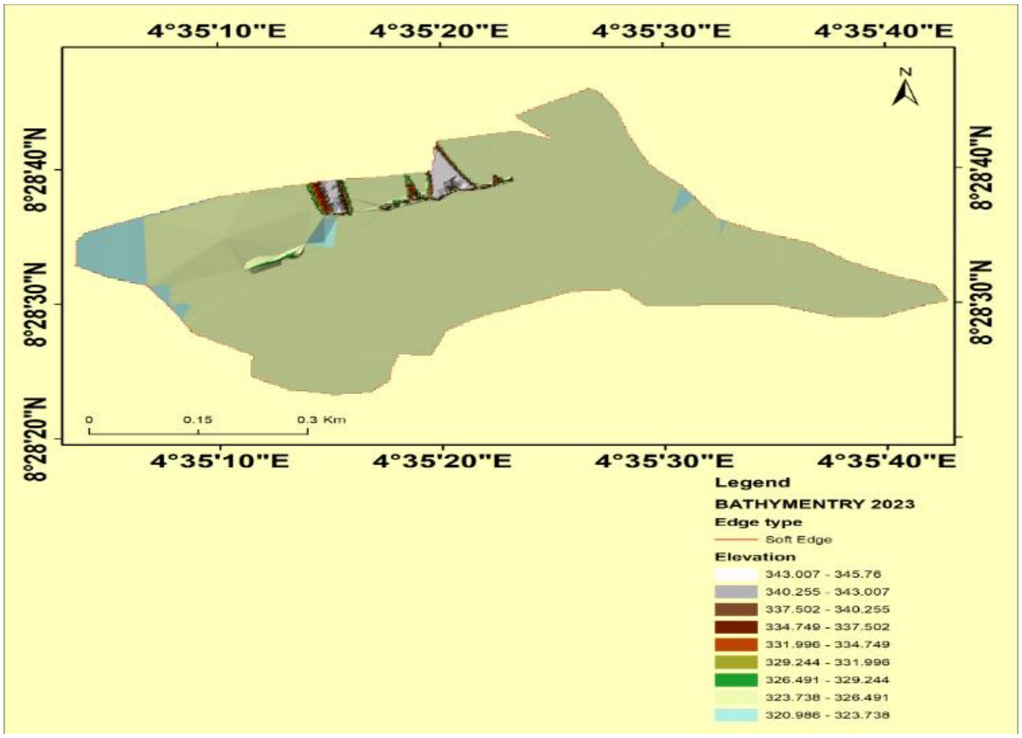

Fig 3.11: The bathymetry to raster map showing

3.3.4 Sediment Deposition Map.

To further with the analysis, the converted files was extracted from the general file so as to maintain the study area (Dam) boundary. Hence, the converted bathymetry data and contour data was extracted. The results of the extracted data after processed and prepared is discussed; The two-raster data (bathymetry raster and contour raster data) was converted to triangular irregular network (TIN). Afterwards, the surface difference analysis using the 3D Arc GIS tool was carried out, which systematically classified the reservoir sediment deposition condition into to 3 classes (Above, Same and below). The blue region indicate area that carries the major deposition which is classified as above, while area with no difference is classified as same and the eroded area is classified as below. Figure 3.12 shows the result of the surface difference analysis.

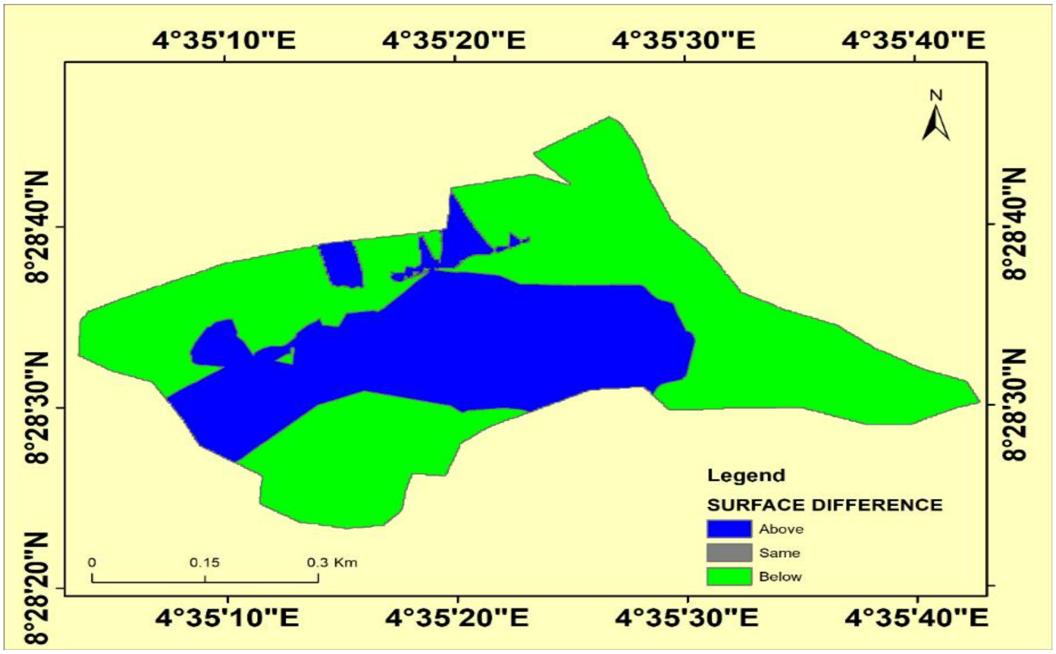

Fig 3.12: The Sediment deposition map showing the sediment deposition condition of the study area.

3.4 Sediment accumulation analysis

Table 3.1 shows the attribute table of the surface difference analysis contains, dam area, volume, square area, which was exported to MS excel for further analysis. This was used in estimation of sediment deposition.

Table 3.1: Sediment Accumulation Analysis Result

	A	B	C	D	E
1	FID	Shape *	Volume (m3)	SArea	
2	0	Polygon	120577.2607	48908.39	
3	1	Polygon	36896.18073	5981.947	
4	2	Polygon	142668.079	58052.69	
5	3	Polygon	278387.6898	135641.8	
6	4	Polygon	581866.4277	120796.5	
7	5	Polygon	2366.347599	1297.427	
8	6	Polygon	53.133558	299.7792	

3.4.1 Sediment Accumulation Estimation

The last stage of the analysis was completed on excel using the attribute table of the surface difference analysis; Reservoir sediment accumulation estimation; volume * code ; The Excel auto sum was used to find the accumulation and the result obtained was: 636218.1726 m^3

The result is as follows;

In m^3 per year;

$$\frac{\text{Accumulation}}{365} = \frac{636218.1726}{365} = 1743.06349$$

Tonne estimation;

In tonne

$$\frac{Accumulation}{1000} = \frac{636218.1726}{1000} = 636.2181726$$

In tonnes per year

$$\frac{Tonnes}{Year\ interval} = \frac{636.2181726}{73} = 8.71531743$$

Table 3.2: The snip showing the estimated sediment accumulation

	A	B	C	D	E	F	G	H	I	J
1	FID	Shape *	Volume (m3)	SArea	Code	Accumulation				
2	0	Polygon	120577.2607	48908.39	-1	-120577.2607				
3	1	Polygon	36896.18073	5981.947	1	36896.18073				
4	2	Polygon	142668.079	58052.69	-1	-142668.079				
5	3	Polygon	278387.6898	135641.8	1	278387.6898				
6	4	Polygon	581866.4277	120796.5	1	581866.4277				
7	5	Polygon	2366.347599	1297.427	1	2366.347599				
8	6	Polygon	53.133558	299.7792	-1	-53.133558		m3/year	Tonnes	Tonne/year
9						636218.1726	m3	1743.06349	636.2181726	8.71531743
10						Accumulation				

4.0 Conclusion

Different strategies can relatively control the amount of sediment movement and sustain the structure life with the help of monitoring systems. Fund schedule monitoring of the sediments effects is essential to achieve the cost benefit analysis of the project. The computation of the present volume of the Agba dam reservoir was successfully conducted using GIS techniques and hydrological analysis tools. This study provided a comprehensive assessment of the current volume capacity of the reservoir, incorporating both topographic data and sedimentation patterns. The integration of Digital Elevation Models (DEMs) and bathymetric data in ArcGIS allowed for precise calculation of the reservoir's current volume. By creating a detailed representation of the reservoir basin, the analysis accurately reflected the true storage capacity. Sediment accumulation was mapped, quantified and estimated, showing that sediment management practices need to be implemented to restore and maintain the reservoir's capacity. The use of ArcGIS facilitated the visualization of sediment deposition patterns. The spatial analysis provided clear insights into the areas most affected by sedimentation, enabling targeted

management strategies. Contour and surface maps generated during the study illustrated the changes in reservoir topography over time, underscoring the dynamic nature of sediment deposition. This study shows that Agba dam reservoir current storage capacity as computed was 2,326,884.56 m^3. The reservoir which was constructed in 1949 had a capacity of 3,000,000 m^3. From the inception to the time of the present study, 73 years had elapsed. This means that within 73 years, the reservoir lost 0.67m^3 of its original capacity to sediment. The average rate of sediment accumulation for the 73- year period was estimated to be 1743.06349 m^3/year. Morphological changes in the reservoir i.e sediment accumulation upstream and scouring downstream were mapped and analyzed. These changes have implications for the reservoir's storage capacity and structural integrity. The hydrological analyses carried out indicated a progressive infilling of the reservoir, reducing its effective volume and potentially compromising its operational efficiency. The ArcGIS software used provided predictive insights of the sedimentation patterns and morphological changes, including different flow conditions and sediment loads deposited. The software was calibrated and validated using bathymetry data, ensuring its accuracy and reliability, emphasizing the need for robust management strategies. Flow variation under varying hydraulic conditions, the impact of the reservoir on flow regimes becomes more pronounced. The ArcGIS software used demonstrated that the operational protocols of the reservoir play a crucial role in managing flow regimes.
The presence of the reservoir induces morphological changes in the river system, such as altered sediment deposition patterns and modified channel shapes. Upstream areas are prone to aggradation, while downstream reaches may experience degradation and channel incision. The impacts of dam reservoir on flow regime can depend on the size of dams and the purposes of dam construction. Agba dam was constructed to work for single water purposes for municipal water supply. In general, the resulting impacts can affect any of the three main characteristics of monthly hydrographs: i) magnitude, ii) variability and iii) timing of flow. Water supply dams for domestic needs consume water and can therefore have significant effects on the magnitude of flow and can also change the variability of flow. The study revealed that sediment deposition upstream of hydraulic structure can lead to reduced water storage capacity, increased flood risk, and potential damage to infrastructure. The use of ArcGIS in conjunction with hydrological models allowed for the simulation of various scenarios, including different flow conditions and sediment loads. This predictive capability is invaluable for planning and managing the hydraulic structure.

Lastly, from the analysis carried out, it revealed that there is a continuous increase of sediment deposition of the study area (Agba dam), the deposition of sediment is influenced by two major factors which are the physical factors and the anthropogenic factors. Physical factors that bring about sediment deposition in the dam are, surface topography of the dam, soil type, force at which water flows. Anthropogenic factors are as a result of human activities carried out within the environment of the study area such as vegetation clearance and burning.

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