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Retrogressive Implications of Reservoir Sedimentation and Siltation on Water Storage and Other Socio-Economic Activities in Arid and Semi-Arid Regions of Nigeria

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ABSTRACT

Sedimentation and siltation are jeopardizing water resources in Nigeria's arid regions, threatening livelihoods and ecosystem. Sediment deposit is one of the principal and most serious technical challenge facing reservoirs today. Year-in, year-out, various dams are gradually losing their ability to store water for the purpose for which they were built, due to sedimentation and siltation. It is against this background that the National Water Resources Institute (NWRI), Kaduna, embarked on the study of reservoir sedimentation and siltation situated within the Arid and Semi-arid regions of Nigeria by the use of bathymetric surveys to ascertain their siltation levels. The study also looked at reported research findings from published works in the area of sedimentation and siltation to complement the findings from the field. The results indicated a substantial reduction in the storage capacities (i.e., original design depths) of all the reservoirs assessed by NWRI from 2012 to 2021 due to siltation and sediment transportation, and further supported by reported research findings from published works. This is not unconnected to their susceptibility to erosional features within and along the course of the main rivers and the tributaries feeding them, including climate change phenomenon. This decrease in storage capacity has also affected the diverse socio-economic activities which these reservoirs offer in these regions. This study intensifies the urgency of adopting sediment management strategies, including dredging, and erosion control, as this would improve water conservation, preserve reservoir functionality and sustain their diverse socio-economic benefits.

1. INTRODUCTION

Reservoir sedimentation is a global challenge, but its impacts are particularly acute in Nigeria's arid regions, where water scarcity and socio-economic dependence on reservoirs amplify the consequences.

Naturally, sediment inflow and outflow approximately balance silt deposits in most flowing rivers. This is because reservoirs formed in such basins are characterized by extremely low flow velocities and efficient sediment trapping capability. Gradually, as time goes by, these reservoirs accumulate sediments and lose storage capacity until the entire impoundment becomes fully silted, thereby eliminating all the environmental and socio-economic benefits provided (Ezugwu, 2013; Kondolf *et al.,* 2014; Obialor *et al.,* 2019; Ren *et al.,* 2021; Lee *et al.,* 2022).

Water flowing in streams or rivers has the ability to scour channel bed, to carry component part and to deposit materials. This phenomenon of sediment transport can affect considerably the design of reservoirs. Many cases have been documented where reservoir siltation reduced water storage structures unusable in less than 25 years. Sedimentation problems were observed mainly with small to medium size reservoirs (catchment area less than 100 km^2) (Mama and Okafor, 2011; Morris, 2020; Vázquez-Tarrío *et al.,* 2024).

Reservoirs formed by dams on rivers, get silt through river water. A significant part of the sediments settles down in the reservoir, thus reducing the space accessible for water storage and also produces structural damages to the dam and causing substantial damage to any power generating turbine situated within the area. Studies have shown that silts get deposited in both the dead and live storage (Petkovsek and Roca, 2014; Obialor *et al.,* 2019; Mama and Okafor, 2011; Morris, 2020).

Water is a critical natural resource. Without it, life could not exist and people could not survive (Okoye, 2004). For more than 5000 years, dams have provided people with reliable sources of water for their survival. A dam is a barrier across flowing water that obstructs, directs or slows down the flow, often creating a reservoir, lake or impoundments (Ezugwu, 2013). Most dams have a section called a spillway or a weir over which, or through which, water flows either intermittently or continuously, and some have hydroelectric power generating systems installed. A dam- reservoir facility provides numerous benefits including generating electricity, direct water from rivers to canals, and irrigation and water supply systems, increase river depths for navigational purposes, to control water flow during times of flood and droughts, create artificial lakes for fisheries and recreational use, ground water recharge, etc. Many dams are multipurpose and fulfil several of these reasons.

Due to the significance of sedimentation to ecosystems and humans, various methods to determine sedimentation rate have been developed and used depending on conditions such as data accessibility, measurement purpose, and budget and time available (Szmytkiewicz and Zalewska, 2014; Gonzalez Rodriguez *et al.,* 2023). Measurement of bathymetry is one of the most common and accurate methods to determine sedimentation rates. This method uses acoustic signals and geolocation technologies to reproduce the underwater topography (Gonzalez-Rodriguez *et al.,* 2023; Li *et al.,* 2023). Core chronology is another typical technique to measure sediment deposition with high temporal resolution over periods of up to 100–150 years (Xiang *et al.,* 2002; Rose *et al.,* 2011). Additionally, hydrological data can be used in mathematical formulae to calculate sedimentation and trap efficiency, where equations and models are selected according to the type, quality and frequency of the data available (Efthimiou *et al.,* 2022; Avgeris *et al.,* 2024; Molina *et al.,* 2024). In recent times, satellite imaging and remote sensing techniques have been projected as substitute methods to monitor sedimentation (Darama *et al.,* 2019; Mbatya *et al.,* 2019).

Effective management of sediment in rivers is becoming increasingly important from an economic, social and environmental perspective. Sediment carried by rivers is a vital constituent of the world-wide geochemical cycle (Aldrees *et al.,* 2022). A recent study of 145 major rivers with longer-term records of annual sediment loads and runoff showed that around 50 % of river records demonstrated a statistically significant upward or downward trend (Walling and Fang, 2003; Zhang *et al.,* 2019). The majority of these rivers confirmed decreasing sediment loads due to dams and other river control structures trapping sediment.

There is also a growing body of evidence that climate change will influence the sediment loads of rivers around the world. This is by no means a new trend, with records revealing fluxes in sediment yields due to historical climate change and associated changes in rainfall and runoff (Zhou *et al.,* 2017; Nkwasa *et al.,* 2024). Some areas are expected to become wetter under current climate change scenarios which may increase sediment transport through erosion and runoff. Climate change impacts may also interact with other anthropogenic causes of sedimentation in rivers, such as agricultural production (Dash and Maity, 2023; Szalińska *et al.,* 2024).

In recent years, the National Water Resources Institute under its Reservoir Monitoring Unit has conducted an appraisal on a number of reservoirs across the Nation through bathymetry studies and the results obtained revealed an alarming rate at which these reservoirs are losing their design storage capacity to siltation. Despite numerous studies on sedimentation in Nigeria, there is limited understanding of its cumulative socio-economic impacts in arid and semi-arid regions, necessitating a comprehensive evaluation.

2. MATERIALS AND METHODS

2.1. Conduct of the Bathymetry Survey

Bathymetric surveys were chosen for their accuracy in estimating sediment volumes, complemented by secondary data from historical records to ensure robustness.

2.1.1. Bathymetry surveys equipment

The bathymetry survey of the reservoirs was conducted using the Garmin GPSMAP 546s Chart plotter Echo Sounder. The Garmin GPSMAP 546s Chart plotter Echo Sounder is a high precision compact Chart plotter that features a high-resolution, super-bright 5" (12.7 cm) VGA colour display (Horta *et al.,* 2014; Chukwu Fidelis and Badejo, 2015; Shuaibu, 2024). The GPSMAP 546s also comes with standard high-sensitivity GPS receiver for superior satellite tracking and quicker acquisition times. The GPSMAP 546s comes with a powerful dual-frequency transducer that clearly illustrates depth contours, fish targets and underwater structures in freshwater or ocean hydrographic applications (Sepúlveda Steiner, 2020).

2.1.2. Bathymetry surveys procedures

The bathymetry survey of the reservoirs was conducted using high precision acoustic instruments, Garmin GPSMAP 546S Chart plotter Echo. The Echo Sounder has inbuilt Global Positioning System (GPS) and thus the Echo data collected during the bathymetry surveys were synchronized automatically with GPS (Odhiambo and Boss, 2004; Samaila-Ija *et al.,* 2014; Kim *et al.,* 2020). The bathymetric data over the reservoirs were collected along track lines sufficiently spaced apart to ensure that the reservoir bed topography was captured adequately (Olubukola *et al.,* 2019; Cooper *et al.,* 2020). Both the team and hydrographic survey equipment were carried on a 6 m long 12 persons capacity fiber boat powered by a 60 hp Yamaha outboard engine while a 12-volt battery provided the power for the equipment. Boat navigation is also controlled by the hydrographer via the display on the echo sounder so that boat tracks the grid line accurately.

The echo sounder receiver units were by default sets to World Geodetic System of 1984 projection system (WGS84). Prior to commencement of depth sounding each day and at the end of sounding, the reservoir water level is read on the reservoir water level gauge marked on the hydropower Intake Tower (Mdee *et al.,* 2018). The reservoir depth sounding is preceded by a bar check run whereby the accuracies of the reservoir depths continuously displayed on the display unit of the echo sounder were checked and verified by physical depth measurements using sounding line (Furnans and Austin, 2008). This operation is repeated from time to time during the survey to ensure the accuracies of the displayed depth on the display unit of the echo sounder (Tuno *et al.,* 2024).

The echo sounder measured the depth to the reservoir bed from a transducer operating at dual frequencies of (50/200 kHz) to the bed of the reservoir (Freitas *et al.,* 2008). Depths were measured at a fixed distance, otherwise referred to as draft which in the case of this study was set at 0.25m below the water surface i.e. the transducer was mounted at a distance of 0.25m from the surface of the water. The measuring time was also preset at five (5) seconds interval. The depth to the reservoir bed and the horizontal position of the points measured are streamed to the storage unit of the echo sounder by the transducer where the data recorded and stored automatically in the memory of the echo sounder receiver unit. Garmin GPS Map 78 was also connected to the echo sounder via the NMEA0183 port to provide backup record of depths and horizontal coordinates of the depths measured.

2.1.3. Bathymetry data processing and presentation

The data obtained was analysed on Microsoft Excel to remove false echo data and subsequently reduced to mean sea level datum using the reservoir water level recorded corresponding to the date of data capture (Kim *et al.,* 2020). The data were further adjusted for the reservoir water level at the time of the bathymetry surveys and finally exported into Ersi ArcMap 10.1 (Endalew, and Mulu, 2022).

2.1.4. Development of reservoir surface topographic layers

The reservoir surface topography was captured by the reservoir area contour map and which proceeded with further analysis of the vectorized pre-construction reservoir area contour map and the discreet x, y, and z data points collected during the bathymetry surveys within ArcMap 10.1 using the 3D-Analyst Modules (Ceylan and Ekizoglu, 2014). Each dataset i.e. pre-construction and bathymetry data were converted to raster and the raster file used to create the Triangular Irregular Network (TIN), a digital representation of the underwater surface topography of the reservoirs (Hell and Jakobsson, 2011). The triangular irregular networks layers were used to generate the water surface elevation, three-dimensional area and volume at different operating elevations of the reservoir.

2.1.5. Development of longitudinal and cross-sectional profiles

The triangular irregular network (TIN), a digital representation of the underwater surface topography of the reservoir was created and used to generate the longitudinal and cross-sectional profiles of the reservoir bed as captured by the bathymetry surveys (Jaballah *et al.,* 2019; Ibrahim *et al.,* 2023). The cross-section profile lines were generated and extended between both banks at 20 m interval for the first 100 m; 50 m interval for the next 500 m; 100 m interval for the next 1000 m and 250 m interval for the next 14.5 km.

2.1.6. Development of revised area-elevation-capacity curves

The pre-construction and existing reservoir surface extent and volume at every one (1) metre interval over the range of operating elevations of the reservoir were computed using the Triangular Irregular Network (Khaba and Griffiths, 2017; Ibrahim *et al.,* 2023).

2.2. Bathymetric Survey Studies Conducted on Some Reservoirs in Arid and Semi-Arid Regions sourced from Recently Published Articles

Reviews are significant in synthesizing state-of-the-art information and understanding built on peer-reviewed papers (Arksey and O'Malley, 2005; Owusu *et al.,* 2022). The systematic review method uses a transparent, objective and systematic process to comprehensively search studies and synthesize findings around a specific research question (Armstrong *et al.,* 2011; Parris and Peachey, 2013; Owusu *et al.,* 2022). Recent Journal publications on dams and reservoir siltation and sedimentation studies using the bathymetry surveys and other global best practices methods was deployed. The systematic review was complemented by highlighting the contributions of specific research studies from Arid and Semi-Arid Regions of Nigeria.

3. RESULTS AND DISCUSSION

3.1. Findings from the Bathymetric Survey Studies Conducted by the National Water Resources Institute (NWRI), Kaduna in Arid and Semi-Arid Regions

Findings from the bathymetric survey studies carried out on some reservoirs in arid and semi-arid regions of Nigeria by the National Water Resources Institute (NWRI), Kaduna, from 2012 to 2021, lend credence to sedimentation and siltation of reservoirs in Arid and Semi-Arid Regions. The results of these findings are presented as follows;

In 2012, the Kangimi reservoir, Kaduna State, capacity was estimated at the spillway crest level at 40.946 MCM and reservoir loss to sediment at 17.563 MCM at sedimentation rate 501,820.8 m^3/year or 30 % of the designed capacity over a period of 35years. The results also indicated that the Kangimi reservoir capability to sustain the designed draft for Kaduna water supply has reduced from 386.46 days in 1971 to 270.45 days in 2012 and by 2037, the reservoir will not be able to meet the raw water demand of the Kaduna Water Supply for six months' continuous dry season for which it was designed for (Bathymetric Survey of Kangimi Reservoir, 2012).

In 2014, the bathymetry surveys of the Bakolori reservoir, Zamfara State established the revised reservoir capacity at spillway crest level of 334 m amsl as 269.18 MCM against the designed capacity of 443.00 MCM. This translates to a total storage capacity loss of 156.66 MCM over the thirty-one (31) years of service by the reservoir or an annual storage loss of 5.05 MCM/year. The loss of 156.66 MCM or 36.79 % of the designed storage capacity is appreciable and what is helping the reservoir is the fact that the six ungated sections of the spillway equalize or regulates the outflow from the reservoir in a manner that the water level does not rise significantly upstream the dam beyond the designed maximum water level (Bathymetric Survey of Bakolori Reservoir, 2014).

In 2016, the results of the bathymetry surveys of the Sabke dam reservoir, in Katsina State, indicated that available potential storage capacity has reduced from the designed capacity of 31.6 MCM to 21.895 MCM which is the 60.65 % of the designed capacity or a capacity loss of 39.35 %. Upstream dams and reservoir constructed on the main Sabke River channel and its tributary numbering about ten (10) numbers are greatly affecting the potential runoff arriving at the Sabke reservoir so much so that the reservoir rarely attained its full potentials each year. This study also concluded that even if the reservoir attained its existing potential capacity of 21.895 MCM, the available water can only irrigate 100 ha of irrigated land along with full supply for other purposes it was designed for. If on the other hand, the existing capacity is dedicated for irrigation water sully, the reservoir could only irrigate 750 ha of irrigated land (Bathymetric Survey of Sabke Dam Reservoir, 2016).

In 2017, the bathymetry surveys of the Gurara dam reservoir in Abuja - FCT indicated that the pre-construction reservoir capacity at the Normal Water Level of 624 m amsl was 954.19 MCM as against the designed 880 MCM at the same elevation for which the 2017 bathymetry surveys estimated at 971.96 MCM. The study indicated that the dam reservoir has sufficient capacity and the hydrology of the basin's potential runoff could meet adequately the designed water demand over the designed period adequately. The basin has not suffered degradation and the runoff from it is clean (Bathymetric Survey of Gurara Dam Reservoir in Abuja, 2017).

The Oyan dam reservoir in Abeokuta, Ogun State and Lower Usuma dam in in Abuja - FCT, were surveyed in 2017 and 2018 respectively. The studies indicated that Oyan dam reservoir had lost 8.47 % of its designed capacity in 34 years of operation. The low level of siltation over the operational period was due to the fact that the bottom outlet valve of the reservoir was opened for the flushing of sediment during the rainy season by the Ogun Osun River Basin Development Authority. The loss was concentrated in the inlet areas of the tributaries into the reservoir (Bathymetric Survey of Oyan Dam Reservoir in Abeokuta, 2017).

In the Lower Usuma dam reservoir in Abuja - FCT, a loss of 6.33 % of the designed capacity was recorded over 34 years of its operation. This low-level loss was attributed to the clean nature of Usuma River catchment of which the headwaters and its tributaries were hilly and the catchment urbanized with lots of green areas as part of the FCT development (Lower Usuma dam in in Abuja, 2018).

The 2019 revised capacity of the Ruwan Kanya reservoir in Kano State at the spillway crest level of 511 m amsl as 49.26 MCM against the designed capacity of 58.00 MCM in forty-three (43) years; In over forty-three (43) years of service the Ruwan kanya reservoir lost 8.74 MCM or 15.06 % of its designed storage capacity (Bathymetric Survey of Ruwan Kanya Reservoir, 2019).

The 2019 revised capacity of the Tiga reservoir in Kano State at the spillway crest level of 527.61 m, above mean sea level (AMSL) as 1954.24 MCM against the designed capacity of 1974.00 MCM in forty-four (44) years; In over forty-four (44) years of service the Tiga reservoir lost 19.76 MCM or 1.00 % of its designed storage capacity (Bathymetric Survey of Tiga Reservoir, 2019).

The estimated available capacity of the Hadejia barrage reservoir in Jigawa State at minimum supply elevation of 37.46 m from the 2019 bathymetry data set was 5.58 MCM against the designed capacity of 11.4 MCM (TRIMING, 2017). The available capacity estimated at minimum supply elevation of 37.46 m from the April 1982 pre-construction data set was estimated at 12.73 MCM against the 11.4M CM quoted in the "Environmental and Social Impact Assessment Final Report (TRIMING, 2017)". This is 1.33 MCM or 11.67 % error above the quoted designed capacity of 11.4 MCM. The results translate to a capacity difference of 5.82 MCM or 51.01 % of the designed capacity over thirty-seven (37) years of operations. Although the extent of the bathymetry survey was limited to 9.97 Sqkm (30 %) out of the 33.78 Sqkm of the total extent area of the Hadejia barrage, the overgrown surfaces of the barrage reservoir were under pool of water submerging the Typha grass stem at absolute depths ranging between 0.51 m and 10.24 m as indicated by the statistical characteristics of the 2019 bathymetry data. The implication of this is that the estimated capacity could be much higher than estimated (Bathymetric Survey of Hadejia Barrage Reservoir, 2019).

The 2020 revised capacity of the Dadinkowa reservoir in the village of Yamaltu in Deba Local Government Area of Gombe State at the spillway crest level of 247.00 amsl as 2631 against the designed capacity of 2800.00 MCM in thirty-three (33) years; In over thirty-three (33) years of service the Dadinkowa reservoir lost 265.12 MCM or 9.15 % of its designed storage capacity (Bathymetric Survey of Dadinkowa Reservoir, 2020).

The 2020 revised capacity of the Challawa reservoir in Kano State at the spillway crest level of 524.00 amsl as 765.92 against the designed capacity of 930.00 MCM in twenty-eight (28) years; In over twenty-eight (28) years of service the Challawa reservoir lost 172.15 MCM or 18.35 % of its designed storage capacity (Bathymetric Survey of Challawa Reservoir, 2020).

The 2020 revised capacity of the Goronyo reservoir in Sokoto State at the spillway crest level of 288.00 amsl as 825.74 against the designed capacity of 942.00 MCM in thirty-seven (37) years; In over thirty-seven (37) years of service the Goronyo reservoir lost 116.26 MCM or 12.34 % of its designed storage capacity (Bathymetric Survey of Goronyo Reservoir, 2020).

The 2020 revised capacity of the Zobe reservoir in Dutsin-Ma Local Government Area of Katsina State at the spillway crest level of 493.00 amsl as 165.07 against the designed capacity of 177.00 MCM in thirty-seven (37) years; In over thirty-seven (37) years of service the Zobe reservoir lost 11.93 MCM or 6.74 % of its designed storage capacity (Bathymetric Survey of Zobe Reservoir, 2020).

In 2021, the bathymetric survey of river Galma in Kaduna State at locations adjoining proposed sugarcane project areas in Kaduna State and the results showed that the existing river water can only irrigate 7000 ha instead of proposed 20000 ha where additional boreholes were suggested to supplement the available water after the bathymetric survey was carried out (Bathymetric Survey of River Galma, 2021).

3.2. Sediment Transport and Bathymetric Survey Studies from Literatures and Recently Published Reports

Numerous scholars have carried out sedimentation studies on lakes and reservoirs using various methods including mathematical modelling, bathymetric surveys, remote-sensing, sediment coring, and multi-frequency acoustic systems (Oke *et al.,* 2019; Iradukunda *et al.,* 2021; Endalew and Mulu, 2022; Gonzalez Rodriguez *et al.,* 2023).

3.2.1. Sedimentation study of the Kubanni watershed area - Ahmadu Bello University reservoir

The Kubanni Watershed has an area of 57.6 km^2 and drains two rivers – Samaru River and Goruba River – into the Kubanni River downstream of Kubanni Reservoir (that is Ahmadu Bello University Reservoir. It was reported that Samaru River conveys higher sediment concentrations than Goruba River from the Kubanni watershed as shown in Table 1. Based on the measurement technique, the US Army Corps of Engineers (1995) categorized total sediment loads into measured and unmeasured loads. The measured load is mainly the suspended sediments that can be sampled with depth integrated hand-held samplers while the unmeasured load includes some of the unaccounted suspended load, within the 0.15 m depth of a sampled water column and the whole bed load (US Army Corps of Engineers, 1995: Adeogun, 2008; Otun and Adeogun, 2012). Since the bed materials solely represent the unmeasured loads, it is suitable that the bed materials be fragmented into its components.

Table 1: Seasonal sediment load (in kg/annum) transport in Kubanni watershed (Otun and Adeogun, 2010)

Months	Samaru River		Goruba River		Total ($x10^2$) (kg/annum)
	Measured sediment load x 10^3 (kg/month)	Unmeasured sediment load x 10^3 (kg/month)	Measured sediment load x 10^3 (kg/month)	Unmeasured sediment load x 10^3 (kg/month)	
June	44	10	8	2	64
July	929	97	210	22	1258
August	3137	243	816	101	4297
September	5339	349	1346	152	7186
October	4369	307	1183	134	5993
November	1062	107	285	41	1495
December	62	12	15	3	94
Total	14944	1125	3863	455	20387

3.2.2. Forecast of hydrological processes, transport mechanism and yield of sediments in Kaduna watershed

Over the years, sedimentation has posed a great danger to the storage capacity of hydropower reservoirs. Good understanding of the transport system and hydrological processes in the dam is very crucial to its sustainability (Daramola *et al.,*2019). Under optimal functionality, the Shiroro dam in Northern Nigeria can generate ~600 MW, which is ideally sufficient to power about 404,000 households. Unfortunately, there have not been dependable monitoring measures to assess yield in the upstream, where sediments are sourced into the dam (Daramola *et al.,*2019).

In this study, Daramola *et al.* (2019) applied the Soil and Water Assessment Tool (SWAT) to forecast the hydrological processes, the sediment transport mechanism and sediment yield between 1990 and 2018 in Kaduna watershed (32,124 km2) located upstream of the dam. The model was calibrated and authenticated using observed flow and suspended sediment concentration (SSC) data. Performance evaluation of the model was achieved statistically using Nash-Sutcliffe (NS), coefficient of determination (r2) and percentage of observed data (p-factor). SWAT model evaluation using NS (0.71), r2 (0.80) and p-factors of 0.86 suggests that the model performed satisfactorily for streamflow and sediment yield predictions. The model recognized the threshold depth of water (GWQMN.gw) and base flow (ALPHA_BF.gw) as the most delicate parameters for streamflow and sediment yield estimation in the watershed. Our finding showed that an estimated suspended sediment yield of about

84.1 t/ha/yr was deposited within the period under study. Basins 67, 71 and 62 have erosion prone area with the highest sediment values of 79.4, 75.1 and 73.8 t/h respectively.

3.2.3. Study on the rate of sedimentation in the conveyance canals of Kano River irrigation project (Phase I)

Tukur *et al.* (2013) examined the rate of sedimentation in the conveyance canals of Kano River Irrigation Project (Phase I). Five canals were sampled from the total number of canals using systematic sampling technique. The base lines of the canals were taken to be the transect line, and all the samples were taken with reference to the transect line using simple random sampling. The method adopted was a combination of volumetric analysis and filtration method for field and laboratory work respectively. Variables investigated include canal discharge at pre and post siltation period, sediment texture, and sedimentation of the canals. Descriptive statistics with the use of tables (as means total and percentages) was used for the analysis and presentation of data collected on canals discharge, sediment texture and suspended and dissolved sediments. The deposit consists of a fine sand fraction (76.3 %) with a small amount of clay and silt of about 12.04 % and 11.66 % respectively. The average canal concentration for the suspended sediment concentration was found to be 8474.4 ton per annum. Although result of student t-test revealed no difference between the present and potential discharge the canals discharge has reduced by 47 %. And this in turn affected the farms by reducing the total designed irrigable hectares of land. Many factors are believed to have contributed to the increase of sediments in the canals which include movement of farm tractors across the canals, poor irrigation practice by the farmers, and lack of adequate maintenance.

3.2.4. Sedimentation assessment of a small reservoir at the Afaka Forest reserve, Kaduna, Nigeria

Onwuegbunam *et al.* (2013) conducted the sedimentation assessment of a small reservoir constructed in 1987 at the Afaka Forest Reserve, Kaduna, Nigeria between 2004 and 2013. The procedure for the assessment involved the peripheral survey as well as bathymetric survey of the reservoir to determine its water surface area and mean water depths, by means of a hand-held Global Positioning System, GPS (Model: GPSmap76CSGARMIN) and a 4 m leveling staff, respectively. The study showed that the reservoir storage capacity has decreased, due to sediment build-up, from its initial design capacity 16400 m^3 to 10665 m^3, implying a storage loss of about 35 %. A linear relationship was established between the reservoir storage capacity and the age of the reservoir and the result shows a rate of change (decrease) in the reservoir storage capacity of 221 m^3 $yr\text{-}^1$. This implies that the reservoir storage capacity would eventually reduce to zero at reservoir age of 76.5, if desilting is not carried out.

3.2.5 Siltation level of the Lugu Dam reservoir, Sokoto State, Nigeria

Ugwu *et al.* (2021) determined the siltation level of the Lugu dam reservoir, Sokoto State, Nigeria, using the bathymetric survey method. A total of eleven (11) ground control points were established over the study area using Hi-Target Global Navigation Satellite (GNS) Real-time Kinematic (RTK) System. The base station was set- up over the reference Bench Mark, while the Rover station was moved around to predetermine locations of the ground control points. The depths to the Lugu dam reservoir bed, as well as its underwater topographic mapping with a section of the River Rima on the right flank of the reservoir area, across the collapsed spillway were conducted using Garmin Global Positioning System Map. This was mounted on a nine feet fibre boat to enhance the echo sounding. The result of the study was used to produce a digital elevation model, topographic contours and the area-elevation-capacity curve for the reservoir. This indicates that between elevations 260.5 m and 262 m, the available minimum and maximum designed storage capacities of Lugu dam reservoir ranges from 21.24 MCM and 34.25 MCM respectively. The Lugu dam reservoir maximum storage capacity at breached level stands at 25 MCM, while its active storage capacity is 20 MCM. This is to conclude that the amount of siltation at the reservoir is 9.25 MCM representing 27.01 % indicating the difference between the maximum designed capacity and the current storage capacity.

3.2.6. Volume of sediment accumulated in Tagwai Reservoir Basin, Minna

Oladosu *et al.* (2019) examined the threat by siltation and land use activities within the corridors of the reservoir area using Leica TC1201 (total station) was used for perimeter survey, while Raytheon DE-119 (echo sounder) was adopted for depth measurement. Data collected from fieldwork to investigate the volume of sediment accumulated in Tagwai reservoir basin over a period of 31 years since the dam was constructed in 1978. Sediment accumulation study in a dam is one of the useful methods of gathering information needed for its monitoring, maintenance, and sustainability. A comparison was made between the designed reservoir volume (28.3×10^6 m^3) and the computed volume (20.4×10^6 m^3). A loss of about (7.9×10^6 m^3) was recorded. Sediment accumulation gave 0.25 Mm^3, a spread of about (0.80 %) annually. Prediction and error analysis was done using geostatistical methods of Kriging/Co-kriging and Empirical Bayesian Kriging in ArcGIS software. The predicted root mean square errors are 0.0963 and 0.1189 for both methods which presented a good representation while testing with other available methods. It can be concluded that the storage capacity of the reservoir is depleting which has further exacerbated the shortage of water experienced in Minna metropolis.

3.3. The Impact of Sedimentation and Siltation on Socio-Economic Activities in the Arid and Semi-Arid Zones

The sedimentation and siltation of dams in Nigeria can have significant impacts on socioeconomic activities in diverse ways, including:

(i). Sedimentation can cause abridged water storage capacity, affecting irrigation and agricultural productivity in the nearby areas.

(ii). Sedimentation can change fish habitats, affect fish populations, and impact fishing and aquaculture activities in the dam.

(iii). Sedimentation can lessen the effectiveness of the hydroelectric power plant, affecting energy production and supply to immediate communities. Over the years, sedimentation has posed a great danger to the storage capacity of hydropower reservoirs. Good understanding of the transport system and hydrological processes in the dam is very crucial to its sustainability. A study by Daramola *et al.* (2019) reported that under optimal functionality, the Shiroro dam in Northern Nigeria can generate ~600 MW, which is ideally sufficient to power about 404,000 households. but unfortunately, there have not been dependable monitoring measures to assess yield in the upstream, where sediments are sourced into the dam. Their findings showed that an estimated suspended sediment yield of about 84.1 t/ha/yr was deposited in Shiroro dam within the period under study.

(iv). Sedimentation can affect water treatment and supply, impacting domestic, industrial, and commercial activities in neighbouring towns.

(v). Sedimentation can make the dam less navigable, upsetting water transportation and trade in general.

(vi). Sedimentation can make the dam less appropriate for boating, fishing, and other recreational activities. Water experts warn that the River Niger is threatened by drought, silting up, industrial waste and population. A Nigeria fisherman said that the River Niger had become shallower, making it harder to catch fish. As, most of the place are covered by sand band. If there is no rigorous action, there is the risk of River Niger drying up (Gusikit, 2008; Gusikit and Lar, 2014)

(vii). Sedimentation can upsurge the dangers of flooding downstream, affecting homes, businesses, and infrastructure. This was witnessed from the results of 2020 flood in Goronyo Local Government Area, which resulted in the loss of building infrastructure and agricultural products such as millet, rice, maize and other legumes such as beans to the flood including properties worth millions of naira was lost to the flood. It was also obvious that waterborne diseases are prevalent after the flood in the study area. It is therefore recommended that Goronyo Dam be desilted to restore the original depth and carrying capacity of the dam in order to reduce the vulnerability of the dam to flooding when there is heavy rainfall (Lawal and Shehu, 2024). Sahabi *et al,* (2023) posited that Goronyo dam was constructed to control flood and boost water supply but due to changing regime and flow pattern of River Rima the communities downstream are affected and as a result the outbreak of diseases like cholera, typhoid, bilharzias among others were predominant. The study was also discovered that the dam project has created many environmental challenges including high incidence of floods, soil erosion, deterioration of water quality and quantity, disruption of plants and animal species, loss of historical/cultural sites among others.

(viii). Sedimentation can lead to the dislocation of communities due to reduced water storage capacity or increased flood risk. Sedimentation in reservoirs has serious impacts on the reservoir capacity since it depletes the available water storage capacity. Ezugwu (2013) reported that sedimentation leads to reduction in the reservoir life and benefits in the area of power generation, irrigation, water supply, flood control, navigation, wild life development, recreation and sanitation, ground water recharge, etc

(ix). Sedimentation can result in significant economic losses for nearby communities, affecting their livelihoods and well-being, as witnessed during the 2020 Goronyo dam flood event which resulted to decreased in crop yield, decrease in animal production, reduction in fishing activities, displacement of people, loss of jobs

(x). Sedimentation can lead to reduced agricultural productivity, affecting food security and availability in the region, as recorded during the 2020 Goronyo dam flood event which resulted to decreased in crop yield, decrease in animal production, reduction in fishing activities

(xi). Sedimentation can lead to conflict over water rights and usage riparian communities.

3.4. Collaboration with Stakeholders in Nigeria to Manage Dams and Reservoir Sedimentation

Effective collaboration with stakeholders is crucial to manage dams and reservoir sedimentation in Nigeria, through the:

(i). Involvement of government agencies, local communities, farmers, fishermen, hydroelectric power companies, and environmental organizations.

(ii). Creation of a forum for stakeholders to share knowledge, concerns, and ideas on sedimentation management.

(iii). Collaboration on sedimentation monitoring, impact assessments, and research studies.

(iv). Creation of an all-inclusive plan integrating stakeholders' inputs and addressing socio-economic and environmental concerns.

(v). Engagement of stakeholders in implementing actions to decrease erosion and sedimentation, such as reforestation and sustainable agriculture.

(vi). Organization of workshops and training programs for stakeholders on sedimentation management and its impacts.

(vii). Involvement of stakeholders in decision-making procedures to guarantee their worries and interests are taken into consideration.

(viii). Reassurance of local communities to take possession of sedimentation management through awareness campaigns and participatory creativities.

(ix). Collaboration with stakeholders to access funding, expertise, and resources for sedimentation management.

(x). Regularly assessing the effectiveness of collaborative efforts and adapt strategies as required.

By working together, stakeholders in Nigeria can effectively manage dams and reservoir sedimentation, ensuring sustainable water resource management and minimizing negative impacts.

4. CONCLUSION

Reservoirs offer critical services and signify large fiscal reserves from earlier generations, with often inadequate locations to develop new reservoirs, it is imperative that current reservoirs are maintained and managed sustainably. In Nigeria, there are many dams that were built and utilized for various purposes particularly in the arid and semi-arid regions of Northern Nigeria. These dams are vital resources as they improve the socioeconomic life of the people of the areas where they were established. Based on the studies carried out in some of the reservoirs as earlier stated, in the arid and semi-arid regions of Nigeria, it is most likely that the reservoirs are susceptible to sedimentation and siltation and therefore in an attempt to saving the reservoir and to revitalize their capacities for sustainable livelihood, security and development, adequate considerations should be given to sedimentation and siltation issues in order to ensure the success and sustainability of the entire reservoirs in Nigeria. This study presents an outlook of sediment and siltation issues, depicting the research conducted in the arid and semi-arid regions of the country by NWRI and those reported from published works. It was found out that all the reservoirs assessed had a decreased in water storage capacity as against their originally designed depths. This calls for urgent attentions as most of these dams had lost the socio-economic value inherent in them. There is the need for immediate assessment of all reservoirs to determine their capacity through the conduct of bathymetry study. The dredging or desilting of the reservoirs should be done, if sediments are found to accumulate from the findings of the bathymetry study, in order to return them to their designed capacities. Sediment from the reservoirs bottom is normally endowed with rich varieties of macro and micro nutrients – biologically active ingredients that can be used in natural organic fertilizers known as Bio-deposit Agro used in agriculture, which can also be deployed for the Great Green Wall Project. There is need for policy maker’s commitment to holistically implement the integrated water resources management and integrated watershed management concepts for all dams and reservoirs in Nigeria for sustainability. Adequate attention must be given to weeds control over the reservoir surface area and traps of sediments should be removed in order not to increase the rate of sedimentation in the reservoirs. Fit the activity to the soil, climate, and terrain, maximize vegetative cover and infiltration, manage slopes and drainage ways to prevent or take care of flow concentration, protect and preserve vegetation in natural riparian buffers, plan, monitor, and maintain control measures, and provide sediment trapping structures and sediment bypass. Engaging the local communities and stakeholders in the planning and decision-making process, which is crucial to addressing the socioeconomic impacts of sedimentation and siltation.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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