AN ASSESSMENT OF SEDIMENT INPUT TO THE LOWER USUMA RESERVOIR, ABUJA, NIGERIA

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ABSTRACT

Many dams and reservoirs have been constructed in Nigeria to provide potable water for municipal consumption, irrigation, industrial among other uses and to address the issues of water management. However, many of the dams and reservoirs are losing their storage capacity as a result of siltation. The goal of this study is to estimate the annual siltation rate for the Lower Usuma reservoir using conventional hydrographic survey and acoustic echo sounding technique (bathymetric method). Lower Usuma reservoir had a gross storage capacity of $100 \times 10^6 m^3$ (100 million cubic metres), a maximum operational level of 587.440m a.s.l., with a maximum depth of 49 metres and a catchment area of $241km^2$ at dam site with a daily designed production capacity of 10,000 cubic metres per hour. The reservoir is 1,300 metres long and became operational in 1986. The result obtained with the conventional hydrographic technique shows a current maximum depth of 35.3m, depth loss of 13.7m (1986-2012), annual siltation rate of 0.53m while the acoustic echo sounding technique records a current maximum depth of 37.0m, depth loss of 12.0m (1986-2012) and 0.46m annual siltation rate. The result of the Z–test statistics indicates that there is no significant difference between reservoir depth measurement by conventional hydrographic technique and integrated acoustic echo sounding technique. The reason for the lower sedimentation depth measurement obtained using the integrated acoustic echo sounding technique can be explained on the basis of accuracy in the depth measurement. The reservoir has lost 12.0m depth to siltation; indicating 24.5% loss in installed storage capacity. The implications of the siltation problem and the consequent loss of depth of the Lower Usuma reservoir is that the dam is gradually losing its function and capacity for controlling flooding and provision of potable drinking water to the FCT inhabitants.

Key-words: Acoustic echo sounding technique, Conventional hydrographic survey, Siltation depth, Storage capacity loss, Dams and Reservoirs.

INTRODUCTION

Sediments originating from erosion processes in the catchment area of the Lower Usuma River are transported by overland flow and stream flow into the reservoir. When the flow of a river is stored in a reservoir, the sediment settles in the reservoir and reduces its capacity. Reduction in the storage capacity of a reservoir beyond a threshold limit hampers the purpose for which it was designed. The sediment input rate into reservoirs is a function of the watershed characteristics such as drainage area, channel slope, soil type and land use. Most earth dams with overflow spillways are designed to impound 5-15% of the average annual streamflow, but about 75-90% of the incoming sediment is entrapped during the process (Mamede, 2008).

Sediment is a naturally occurring material that is broken down by processes of weathering and erosion, and is subsequently transported by the action of wind, water, or ice, and by the force of gravity acting on the particle itself (Alison, 1995). In the context of stream hydrology, sediment is an inorganic and organic material that is transported and deposited in streams, rivers, lakes and reservoirs. Sediment load, which is the quantity of sediment transported by a stream, is a function of stream discharge, soil and land-cover features, weather conditions, land-use activities, and many other factors. Sediment load carried by streams and rivers can be composed either of fine materials, mostly silts and clays, or larger materials such as sand (Troeh *et al*, 2000). Hillslopes control sediment generation in that they represent source areas for water, solute and sediment which are supplied to the fluvial system. The main processes acting on hillslopes, namely raindrop impact, surface water flow and mass wasting (particularly shallow land sliding) have been identified as mechanisms of sediment generation (Rice, 1994). Disintegration of the earth's crust by physical and chemical processes provide much of the material that may become fluvial sediment. Sediment production and transport globally to the oceans is estimated at about 15 to 20×10^9 tonnes per year (UNEP, 2003).

Forest increases soil stability because their roots bind the soil together. When large areas of land are cleared and harvested of trees, the soil becomes vulnerable to erosion as tree roots die and as the land is exposed to direct rainfall. Trees increase the soil's ability to take up water, and as a result there is usually a significant increase in the amount of surface water runoff from the surrounding catchment when trees are felled. Removal of riparian vegetation around river banks is likely to cause banks to become unstable and prone to slips, thereby increasing erosion, especially during floods (Goldsmith and Hildyard, 1982). The importance of extreme events in sediment generation is well illustrated with the example in Tunisia in 1989 where three consecutive floods with a return period of 40, 46 and 60 years respectively carried the equivalent of 20 years of sediment in the Zeroud and Merguellel river in only 13 days (Julien, 1995).

Major floods may also trigger slope instability and lead to input of large quantities of sediment. A 1951 flood produced hillslope erosion in the upper basin of the Kowai River in New Zealand, the resultant increase in sediment supply caused aggradation and channel widening which progressed downstream at an average rate of 1km y^{-1} over 30years (Beschta, 1983). Human activities have had a fundamental and increasing impact on the fluvial system behaviour. Induced land use worldwide has accelerated soil erosion and increased sediment transport by large rivers to 17.8×109 t yr^{-1} (Hooke, 2000; Syvitski *et al*., 2005; Wilkinson, 2005). Landuse changes have significantly altered the runoff regime of many rivers and the pattern of sediment supply (Starkel, 1991). Increased fluxes of sediment are observed almost everywhere catchments have been converted from natural vegetation to agricultural land uses. The consequent effect on the near shore is to foul the marine ecosystem with sediment, and fertilize the waters to the point where eutrophication can be a serious threat to human wellbeing. Where reservoirs have been constructed, fluxes to the oceans have been reduced, in some cases to less than pristine quantities (Phillips, 2003).

The most obvious and significant consequence of reservoir sedimentation is the loss of valuable water storage capacity. Loss of storage capacity in a reservoir has multiple impacts. The nature and severity of these impacts depends largely on the water uses in the affected reservoir. While the water in some reservoirs is used exclusively for agricultural irrigation, municipal and industrial water supply, in many reservoirs the storage capacity is also used for electric power production, flood protection and recreation. Where agriculture is the largest user of water stored in a reservoir, the loss of storage capacity due to reservoir siltation will significantly impact agriculture. Insufficient water to irrigate cultivated lands reduces productivity. Reduced agricultural productivity reduces agricultural revenues and could eventually put local farmers out of business and require importing more products. Industries that support or benefit from agricultural activity would also be impacted. If storage loss is not mitigated, farmers may experience chronic water shortages due to sedimentation and the consequences will become especially apparent during drought – when the water is most needed. There is the potential for permanent loss of productive lands. Such losses will make life in many struggling rural communities even more difficult (Fan and Morris, 1998).

The Usuma reservoir is a homogeneous earth-fill dam which was constructed in 1986 across the Usuma River with the aim of supplying the FCT with potable water for all her needs. The prolonged exploitation of vegetation within the catchment areas of Usuma reservoir has stripped open large areas thereby making the soil susceptible to water erosion at the beginning of the rainy season which is often characterized by high intensity thunderstorms. Sediment generation from the cultivated areas of the catchment is therefore usually high. It is suspected that the initial storage capacity of the reservoir may no longer be obtainable. The research problem of this study is summarized by the following research questions: What is the current depth of the Lower Usuma reservoir? What is the rate of siltation of the reservoir? Is there any significance difference between reservoir depth measured by the conventional hydrographic technique and the integrated acoustic echo sounding technique? What are the prospects of integrated acoustic echo sounding technique for Reservoir sedimentation studies in Nigeria?.The Null Hypothesis (Ho) that was tested is that there is no significant difference between reservoir depth measured by the conventional hydrographic technique and integrated acoustic echo sounding technique.

MATERIALS AND METHODS

The Lower Usuma reservoir was constructed in 1986 and is located in hilly and dissected terrain latitudes $9^{0}05^{1}$N - $9^{0}17^{1}$N and longitudes $7^{0}22^{1}$E -$7^{0}37^{1}$E in the FCT. The highest part of the catchment is the North-eastern ‘pan handle’ where there are many peaks over 760m above sea level. The reservoir has a maximum storage capacity $100 \times 10^{6}m^{3}$ (100 million cubic metres), a maximum operational level of 587.440m a.s.l., a maximum depth of 49m and a catchment area of 241km^{2} at dam site with a daily designed production capacity of 10,000 cubic metres per hour. The reservoir is 1,300m long and feeds the treatment plant mainly by gravity. The reservoir area is 8.5km^{2} and mean annual rainfall total ranges from 1145 mm to 1631 mm. The inflow is provided by the Usuma River that has its headwater near the north-eastern edge of the Jos Plateau (Figure 1). The geology of the catchment is largely dominated by undifferentiated crystal rocks of the Precambrian to early Paleozoic basement complex and cretaceous sedimentary formation (Balogun, 2001).

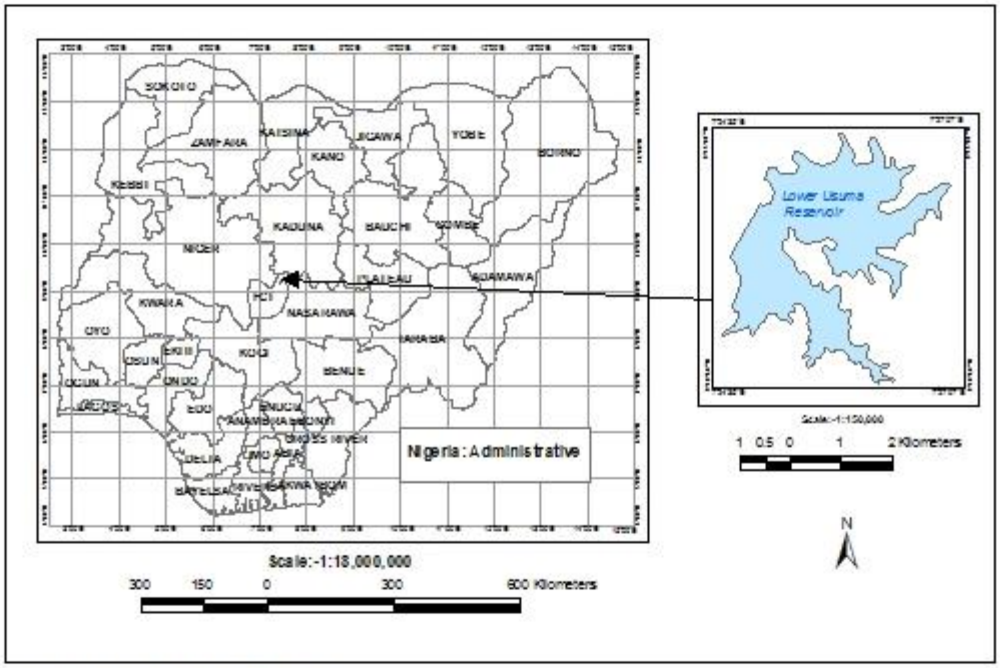

Figure 1: Location of Study Site

Conventional Hydrographic Technique

The conventional hydrographic technique of measuring lake sedimentation (Iguisi, 1997 and Abu, 2009) was adopted for this study. The survey was carried out by using simple land surveying equipments such as a total station, Garmin 12 hand held GPS, ranging poles, 50m steel tape, staff leveling, prism and compass to fix survey points and grid squares over the reservoir area. Grid lines were drawn from the south bank to the north bank and from the embankment to the upstream. Each measurement was accompanied by its coordinate to locate its position within the reservoir. Seven grid lines (i.e traverses) A_1….G_5 were drawn between the two banks at 200m intervals. Seven grid lines (i.e SP1-SP 7) were also drawn between the embankment and the upstream at 200m intervals. The intersection between these two sets of grid lines was designated sampling points (SP). In all, there were 42 sampling points over the reservoir area for the purpose of collecting data on reservoir siltation. A boat was guided from the total station at traverse A_1. At each sampling point along the traverse, the researcher measured the depth from water surface to bottom of reservoir by using a medium weight plumb bob and a rope tied to its end. The plumb bob was lowered down from the boat into the reservoir bed until it sags indicating that the plumb bob has reached the reservoir bed. The rope is drawn up until it is taut and the point of intersection between the rope and the water surface marked by the researcher was measured with a measuring tape and recorded. The same procedure was repeated for all the sampling points over the water surface to determine the depth of the reservoir. The elevation of the reservoir bed (i.e top of sediment) at each sampling point was calculated by deducting the recorded depth from the maximum water surface elevation as measured with the leveling instrument. Reservoir siltation was therefore obtained as the difference between the previous depth and the present depth.

Integrated Acoustic Echo Sounding Technique

The procedures followed by the Usuma Lake bathymetric survey adhere to U.S. Army Corps of Engineers (USACE) standards (USACE, 2002). The Hydro-survey boat was an 18-ft paddled canoe. Equipment used to conduct the survey included a Laptop Computer, Syqwest Bathy 1500 Echo Sounder, Trimble Navigation Fish-finder, Pro XR GPS receiver with differential global positioning system (DGPS) and a12V battery provided power supply to the equipment.

Data collection for Usuma Lake was carried out on November 10, 2012 and bathymetric measurements were conducted on over 4000 points when the reservoir was at full capacity and the water spilling. Integrated acoustic echo sounding technique uses a combination of Geographic Positioning System (GPS) and acoustic depth sounding equipment that are incorporated into a hydrographic survey boat. As the survey boat travels across the surface of the lake, the echo sounder gathers depth measurement readings every five seconds from the lake bottom by emission of sound pulses from the water surface to reservoir bottom to find the depth of siltation. A sound pulse of known frequency and duration (typically around 200 kHz) was transmitted into the water, and the time required for the pulse to travel to and from a target (the bottom of a water body) was measured. The distance between sensor and target is calculated by multiplying half the time from the signal's outgoing pulse to its return by the speed of sound in the water which is approximately 1.5 km/s using the equation

$$D = \frac{1}{2}(S \times T) \tag{1}$$

where D= is the distance between sensor and target, S= is speed of sound in water, and T= is the round-trip time. Reservoir depth sampling points by conventional hydrographic and integrated acoustic echo sounding techniques are presented in Fig. 2. Spatial variation in depth measurement over the reservoir area using data generated from the acoustic echo sounding technique is presented in a triangulated irregular network (TIN) as shown in Fig. 3.

Statistical Analysis

The reservoir depth data generated by conventional hydrographic and integrated acoustic echo sounding techniques were summarized and subjected to statistical analysis using the Z-test statistics in testing the hypothesis formulated. The 95% confidence level corresponding to an alpha value of 0.05 was used in accepting or rejecting the hypothesis.

RESULTS AND DISCUSSION

Results of reservoir depth measurement by conventional hydrographic and acoustic echo sounding techniques are presented in table 1 and 2 respectively while table 3 present the comparison of sedimentation depth data and calculation of the annual siltation rate for the Lower Usuma reservoir. Table 4 shows the Z-test value for the analysis of reservoir depth data.

The results of the reservoir depth measurements shown on table1 revealed that the deepest point in the reservoir is 35.3m. It is also evident from the table that sampling points with depths ≥ 30.0m are only six out of the 42 sampling points. The reservoir is shallower close to the banks and deeper close to the intake tower.

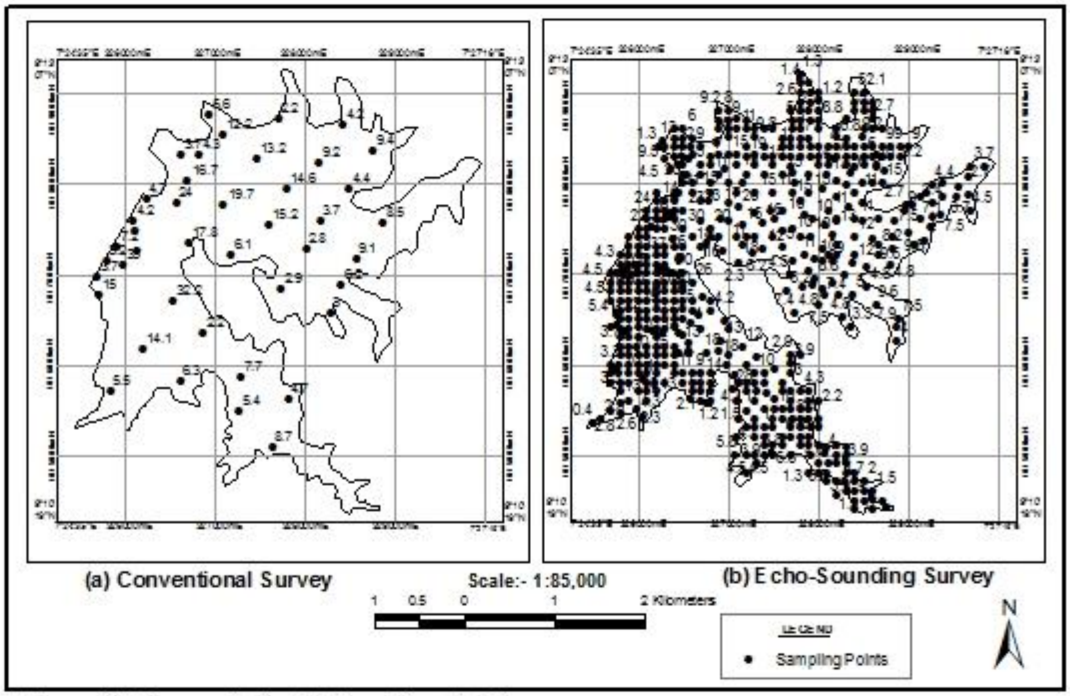

Figure 2: Reservoir Depth Sampling Points
Source: Field Survey, 2012

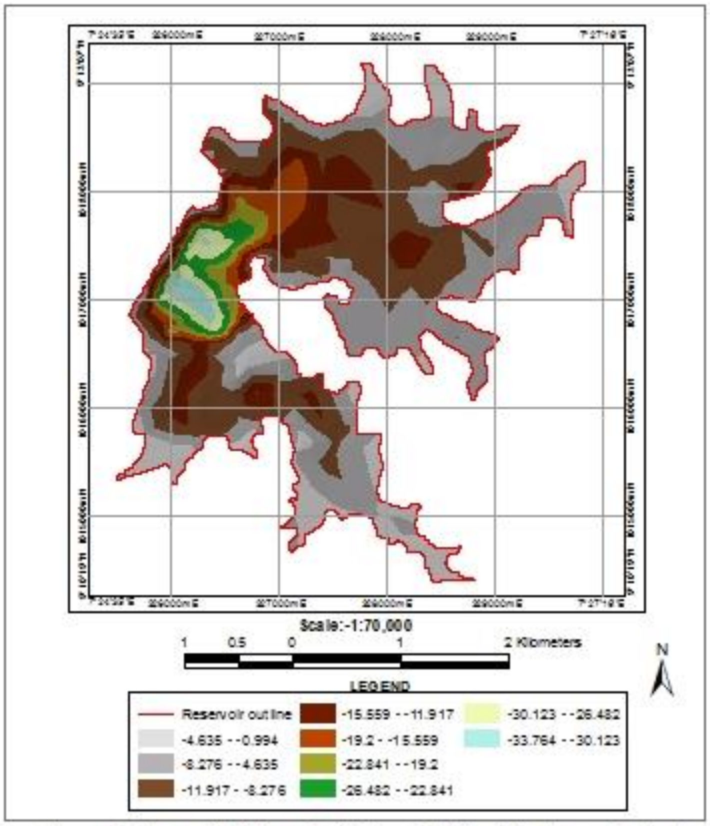

Figure 3: Triangulated Irregular Network (TIN) of the Reservoir Depth
Source: Integrated Acoustic Echo Sounding Survey, 2012

It was also observed from table 2 that the deepest point in the reservoir is 37.0m deep as against the initial depth of 49m. It is also evident from the table that sampling points with depths ≥ 30.0m are fifteen out of the 52 summary sampling points. The integrated acoustic echo sounder has capability for gathering depth measurement readings every five seconds from the lake bottom thereby increasing the number of point measurements at the places not sampled within the lake surface area compared to the conventional hydrographic survey which maintained a fixed traverse distance and few sample points. From this method, it was also observed that the reservoir is shallower close to the banks and deeper close to the intake tower.

The result of the siltation depth estimation in table 3 shows that the maximum depth of the reservoir by conventional hydrographic technique during the 2012 survey was 35.3m as against the 37.0 m recorded by the acoustic echo sounding technique. Also, as calculated above, the results obtained from this study shows that the siltation rate (1986-2012) is 0.53m year^{-1} for conventional hydrographic survey, whereas measurement through acoustic echo sounding technique provided a siltation rate of 0.46m year^{-1} for the same period. The lower sedimentation depth measurement obtained using the acoustic echo sounding technique can be explained on the basis of accuracy in the depth measurement. The potential sources of errors to the observed difference between the conventional hydrographic technique and the acoustic echo sounding technique probably resulted from the few sample points determined by the rigid grid method and possible human induced errors during the depth measurement from the side of the boat with respect to the conventional hydrographic survey.

Table 1 Reservoir depths at each sampling point by conventional hydrogaphic technique

Elevation of Reservoir Bottom (m asl)	Traverse	Depth (m)	Northings	Eastings	Maximum water surface Elevation (m asl)
584.150	A1	3.3	1016826	325682	587.440
572.455	A2	15.0	1016757	325816	587.440
570.915	A3	16.5	1016683	326124	587.440
557.055	A4	30.4	1016607	326490	587.440
578.705	A5	8.7	1016552	326726	587.440
584.755	A6	2.7	1016540	326865	587.440
584.455	A7	3.0	1016732	326819	587.440
575.205	B1	12.2	1016792	326717	587.440
570.335	B2	17.1	1016858	326658	587.440
562.755	B3	24.7	1016957	326517	587.440
557.185	B4	30.3	1017076	326326	587.440
553.355	B5	34.1	1017120	326137	587.440
553.355	B6	34.1	1017069	325923	587.440
583.745	B7	3.7	1016971	325697	587.440
584.205	C1	3.2	1017134	325796	587.440
559.705	C2	27.7	1017141	325961	587.440
555.205	C3	32.2	1017168	326206	587.440
562.205	C4	25.2	1017202	326391	587.440
584.765	C5	2.9	1017199	326757	587.440
584.585	D1	2.8	1017308	326735	587.440
572.205	D2	15.2	1017311	326598	587.440
570.305	D3	17.1	1017300	326474	587.440
562.605	D4	24.8	1017304	326236	587.440
552.155	D5	35.3	1017309	326060	587.440
580.235	D6	7.2	1017305	325915	587.440
583.225	E1	4.2	1017470	326002	587.440
557.225	E2	30.2	1017494	326157	587.440
567.705	E3	19.7	1017519	326396	587.440
564.855	E4	22.6	1017550	326666	587.440
572.055	E5	15.4	1017464	326767	587.440
583.705	E6	3.7	1017335	326809	587.440
583.005	F1	4.4	1017343	326836	587.440
570.965	F2	16.5	1017470	326773	587.440
559.205	F3	28.2	1017625	326638	587.440
558.205	F4	29.2	1017639	326482	587.440
562.205	F5	25.2	1017685	325779	587.440
582.705	F6	4.7	1017681	326126	587.440
583.705	G1	3.7	1017854	326232	587.440
581.805	G2	5.6	1017872	326260	587.440
583.185	G3	4.3	1017794	326361	587.440
561.215	G4	26.2	1017744	326589	587.440
563.225	G5	24.2	1017701	326741	587.440

Source: Field survey 2012

Table 2 Summary results of reservoir depth measurements by acoustic echo sounding technique (bathymetric survey)

Elevation of Reservoir Bottom (m)	Depth (m)	Northings	Eastings
572	1.5	1016836	325613
573	1.6	1016836	325613
576	0.8	1016835	325613
579	3.5	1016828	325622
579	4.6	1016829	325622
579	5.2	1016829	325623
580	5.8	1016831	325625
579	6.6	1016843	325633
579	7.0	1016847	325636
579	7.1	1016851	325639
579	7.9	1016855	325641
580	8.2	1016869	325654
581	8.5	1016871	325656
583	8.7	1016874	325658
585	9.2	1016879	325661
586	9.8	1016883	325664
586	10.0	1016887	325667
577	14.0	1017757	326267
577	15.0	1017751	326265
578	16.0	1017746	326262
578	17.0	1017740	326258
578	18.0	1017734	326255
577	19.0	1017729	326251
579	24.0	1017548	326125
579	23.0	1017543	326122
580	26.0	1017538	326118
580	25.0	1017534	326115
579	31.0	1017079	325894
579	33.0	1017041	325909
579	32.0	1017036	325908
579	29.0	1017030	325902
582	34.0	1017222	326023
582	34.0	1017227	326026
583	35.0	1017233	326030
583	36.0	1017238	326034
583	36.0	1017243	326038
583	36.0	1017249	326041
583	37.0	1017254	326045
583	37.0	1017259	326049
583	37.0	1017265	326052
583	36.0	1017270	326056
583	35.0	1017276	326060
583	35.0	1017281	326063
583	9.6	1017796	326396
583	8.7	1017801	326400
583	7.7	1017806	326403
583	6.1	1017811	326406
583	5.9	1017816	326409
583	4.5	1017825	326415
583	12.0	1017785	326390
583	11.0	1017791	326393
583	9.6	1017796	326396

Source: Field survey 2012

Table 3 Comparison of siltation depth data

Maximum depth at construction (1986)	Maximum depth by conventional hydrographic survey (2012)	Depth loss (1986-2012) by conv. Hydro. Survey	Siltation rate (m $year^{-1}$)	Maximum depth by acoustic echo sounding technique (Bathymetric survey) (2012)	Depth loss (1986-2012) by acoustic echo sounding technique	Siltation rate (m $year^{-1}$)
49.0m	35.3m	13.7m	0.53m	37.0m	12.0m	0.46m

Source: Field survey 2012

Table 4 Z-test for level of significance

$\overline{X}_1$	$\overline{X}_2$	σ_1	σ_2	N_1	N_2	Calculated Z	Tabulated Z
16. 6	17.9	11.2	13.6	42	52	0.5	1.96

The calculated Z value (0.5) is less than the tabulated (1.96)

The Decision rule is that since Z_{cal} is less than Z_{tab} (0.5 < 1.96), H_O is accepted. Hence there is evidence to show that there is no significant difference between sediment depth measurement between conventional hydrographic technique and integrated acoustic echo sounding technique. Although the level of accuracy in depth estimation is higher with the acoustic echo sounding survey, there is no statistical proof to make a generalized statement.

The calculations indicated that within the last 26 year period i.e 1986-2012, the storage capacity of the Lower Usuma reservoir decreased by 24.5% due to siltation. Previous studies on reservoir siltation show that the Lower Usuma reservoir is undergoing similar rate of siltation as other reservoirs studied in the same ecological zone. Iguisi, (1997) in his study of the Kubanni reservoir reported a maximum depth of 5.2m as against the initial 8.5m. This indicates that the reservoir has lost about 1/3 of its installed capacity in about 30 years. Abu (2009) in his study on the Galma reservoir also reported a maximum depth of 7.3m as against the initial 14.9m. This indicates that the reservoir has lost about 51% of its installed capacity in about 32 years. Based on these values, it can be concluded that siltation poses a serious threat to the continued operation and economic sustainability of the Lower Usuma reservoir as well as other dams and reservoirs that have been built for irrigation, water supply, flood retention and production of hydro-electricity in Nigeria.

RECOMMENDATIONS AND CONCLUSION

The siltation rate of 0.46m $year^{-1}$ is an indicator of the annual decrease in storage capacity of the Lower Usuma reservoir. Water resource managers are concerned with the loss of storage caused by sediment accumulation in reservoirs and need a reliable, cost-effective method to determine the degree of storage loss in the reservoirs. The conventional hydrographic technique of sediment depth estimation is still a realistic and reliable method of quantifying the volume of accumulated sediment in dams and reservoirs where other methods are not available. However, advancement in technologies for sediment depth measurement using the integrated acoustic echo sounding technique with GPS (Global Positioning System) and contour mapping software have proved to increase geo-referenced data, improve the accuracy of data collection and most importantly substantially decrease the expenses of bathymetric technique in the long run when compared with the conventional hydrographic technique. This methodology has also shown promise in reducing time and workload for reservoir sedimentation studies.

It is recommended that a well-planned programme for sediment data collection be established especially on the characteristics and movement of sediment into the reservoir. Efforts should be made to monitor changes and interventions on the upstream site of the dam provided. Also regular bathymetric surveys, monitoring of sediment accumulation is recommended to assess the effects of the interventions.

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