ANALYSIS OF FLUVIAL SEDIMENT DISCHARGES INTO KUBANNI RESERVOIR

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ABSTRACT

The sediment discharges into the Kubanni Reservoir (KR) has been measured and analysed in this study. The predominant sandy-clay sediment in the reservoir has an estimated total sediment load of 20,387,000 kg/year. The depth and area coverage of the reservoir was surveyed using a defined distributed grid line configuration. By simple comparative analysis, KR had lost 48% (1.26 H 10^6 m^3) of its initial volume (2.6 H 10^6 m^3) to sedimentation in 33 years of its operation. This implies that the reservoir had experienced severe stacking of sediments over the past years. Fluvial discharge measurements and analytical data required for planning and management of sediment deposition in KR have also been obtained.

Keywords: Fluvial Sediment, Quantification, Sediment Load, Sediment Analysis.

1.0 INTRODUCTION

As water in natural channel flows into a reservoir, so is its energy gradient forced to approach zero, leading to the loss of its transport capacity and eventual deposition of sediments in the reservoir. The accumulations of these fluvial deposits cause reservoirs to lose their capacities and consequently threaten their performances for various water development purposes such as hydropower generation, water supply and recreation activities. Such havocs would continue as long as the reservoir continues to have its storage capacity rapidly depleted unless workable remedial plans and actions are put in place.

To effectively manage this sedimentation problem in any reservoir, relevant and accurate data such as those obtained from various measurements and derived from analysis of fluvial discharges into a reservoir are necessary. This study therefore, carries out some sediment measurements and analysis to provide such information and identify workable actions to forestall the sedimentation in the Kubanni Reservoir (KR) that is currently affecting the available water supplied to Ahmadu Bello University (ABU) Water Treatment Plant (ABU [1]).

1.1 The Study Area

The Kubanni Reservoir (KR), situated in South-West Zaria, Nigeria (11.06N, 7.41E: figure 1), is located at the confluence of Goruba and Samaru rivers, as shown in figure 2. Some basic information and parameters for the KR and dam are summarized in Table 1.

Table 1: Parameters of the Kubanni Dam Reservoir

Reservoir Parameter	Parameter Values
Catchment Area	57.5km^2
Storage Capacity (Volume)	2.6 H $10^6 m^3$
Height and length of the Dam	10.36m & 800m respectively
Top Water Level	644.81m amsl
Dam Crest Level	646.34m amsl
Dam Crest Width	5.5m

(amsl-above mean see level); Source ABU [1]

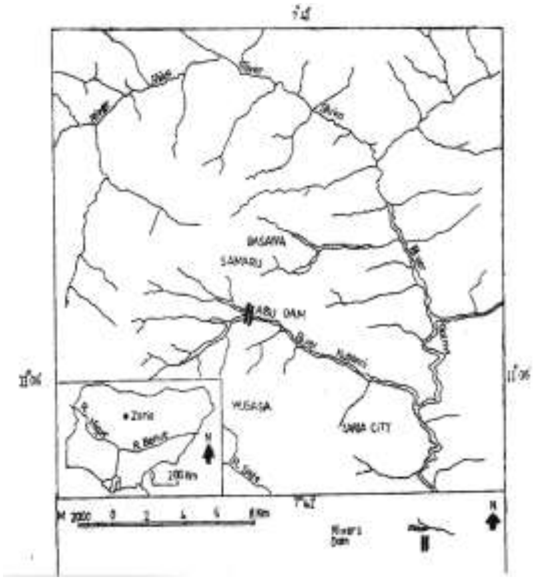

Figure 1 Location of Kubanni Dam Reservoir

Figure 2 Map of Kubanni Reservoir

2.0 STUDY APPROACH

The study is a hydrologic engineering investigation of sediment deposition into Kubanni reservoir. Some fluvial discharge measurements were taken to characterize the fluvial deposits, estimate accumulated sediment deposited over a period, and obtain other related quantities required for effective planning and management of sediment deposition and accumulation in KR.

Methodologically, the study is broadly divided into three major aspects namely; quantifying the total annual sediment discharged into KR, evaluating KR useful life and estimating the KR current storage capacity. In computing the useful life of KR, the assumed consolidation coefficient constants for the specific weight of sediment deposits in KR are chosen from table.

Table 2 Constants for Estimating Specific Weight of Reservoir Sediment Deposit

Type	Reservoir Operation	Sand		Silt		Clay	
		Ws	B	Wsl	B	Wcl	B
1	Sediment always submerged	97	0	70	5.7	26	16
2	Normally moderate to considerable reservoir drawdown	97	0	71	1.8	35	8.4
3	Reservoir normally empty	97	0	72	0	40	0
4	River Bed Sediment	97	0	73	0	60	0

Source: US Army Corps of Engineers [2]

2.1 Quantifying Total Annual Sediment Discharged into Kubanni Reservoir

Based on measurement technique, US Army Corps of Engineers [3] stated that the total sediment load comprises of measured and unmeasured sediment loads. The measured load is mainly the suspended sediments while the unmeasured loads include some of the unaccounted suspended load, within the lower O.15m depth portion of a sampled water column and the entire bed load. The conventional methods used to measure suspended sediment concentration in a river are sampling by point or depth integration in the verticals of the selected river and/or in-situ measurements using apparatus such as nuclear gauges, photoelectric turbidity meter and vibration device, Xlaoqing [4].

The in situ measurement apparatus have their inherent limitations, for instance, the nuclear gauge shows greater relative error at lower sediment concentration, {Berke and Rakoczi, [5]; and Lu Zhi, [6]} while photoelectric effect can only be adopted in rivers where variation in grain size is very small and the concentration is fairly low as the upper limit of application is 1-5gl$^{!1}$ {Brabben [7]; Grobler [8]. Ho Kyung [9] reported that vibration devices like acoustics are still at developing stage and have disadvantage of signal attenuation at high concentration. However, the isokinetic suspended sediment integrating samplers measure the actual amount of sediments in the samples taken although, the samplers disturb flow, Ho Kyung [9]. The latter method was used to sample suspended sediments in this study after dividing the river cross-section into three equal verticals of ¼, ½, and ¾ width in accordance with the procedures in the Guide to Hydrologic Practices, {WMO [10]}. The three samples from the three verticals were mixed thoroughly to obtain a representative sample for laboratory analysis to determine the sediment concentration in the sample.

The US Army Corps of Engineers [3] and Ongley [11] established equation (1) for estimating the measured suspended sediment load Q_s in kg/day, from sediment concentration.

$$Q_s = Kcq \tag{1}$$

where Q_s = sediment discharged (kg/day), c = sediment concentration (mg/l), q = water discharge (m^3/s) and, K= 86.4.

The value of c is obtained as the concentration of the sampled sediments using a standard lightweight handheld US DH-48 sediment sampler, q is obtained from an established stage-streamflow relationships (rating curve) for the gauge station.

In practice, it is more difficult to measure the bed load discharged accurately than it is to measure suspended load. Total sediment load is underestimated if measurement is based on both the measured suspended sediments and bed loads because certain percentage of the suspended sediments closed to the bed are not sampled as stated earlier. This is why the approach adopted in estimating total loads in this research is based on the addition of both measured and unmeasured sediment discharges.

Xlaoqing (4), Gottschalk (12) and Chien (13) showed that several empirical equations and models exist over the years that are used for estimating the unmeasured loads at the lower water column. They include those of Blench, Colby, Duboys, Einstein, Brown-Einstein Engelund-Hansen, Inglis-Lacey, Laursen, Modified Einstein Procedure, Meyer-Peter, Meyer-Peter-Muller, Schoklitsch, Shields and Toffaleti. These mathematical models whose details are in Xlaoqing (4) shows the different divergence opinion on the mechanics of sediment transport. One obvious difficulty in the application of any of these models in a developing nation like Nigeria is the complexities and constraints involved in obtaining some of their parameters by field measurements. Based on these limitations, the study intends to apply the Colby's equation as presented by Daryl et al (14) and simplified with the use of figures 3, 4 and 5. The steps involved are as followed:

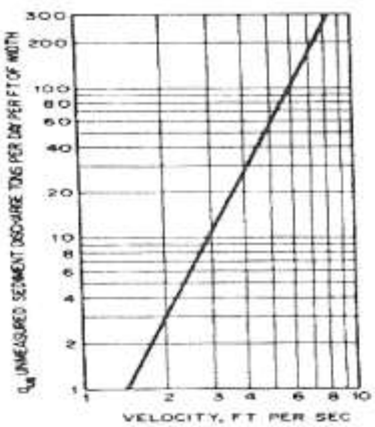

Figure 3: Relationship between Unmeasured sediment discharge and mean velocity; Source: Daryl et al., [14].

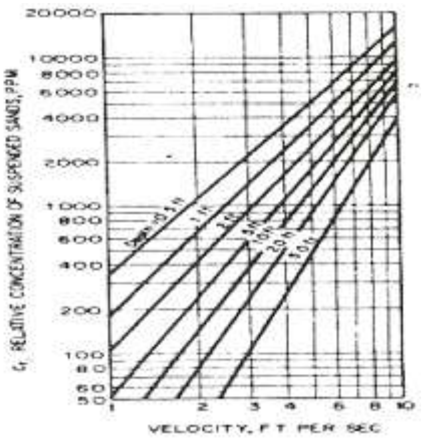

Figure 4: Relative concentrations of suspended sands for different depths and mean velocity; Source: Daryl et al., [14].

(i) From Figure 3 read the unmeasured sediment discharge per unit of width (q_{uv}) for the given mean velocity.

(ii) From Figure 4 read the relative concentration of suspended sand Cr for the given depth and velocity.

(iii) Calculate the availability ratio from C's/Cr, where C's is the measured mean suspended sediment discharge concentration and, use Figure 5 to determine the correction factor, Cf.

(iv) The unmeasured sediment discharge is then the product of the unmeasured sediment discharge in step 1, the correction factor in step (iii), and the stream width B. This is expressed mathematically in equation (2) as:

$$Q_{uv} = k_1 q_{uv} \text{ H } Cf \text{ H } B \qquad (2)$$

where, Q_{uv} = unmeasured sediment load (kg/day) across the stream, q_{uv} = unmeasured sediment load per unit width, Cf = correction factor and B = breadth of the cross section, k_1 = 907.18. The total annual sediment discharged (Q_{tot}) into the reservoir is estimated by equation (3)

$$Q_{tot} = \sum_{i=1}^{n} (Q_{si} + Q_{uvi}) \qquad (3)$$

where Q_s = measured suspended sediment load (kg/day) across the stream and n is the total number of days water flow in a year.

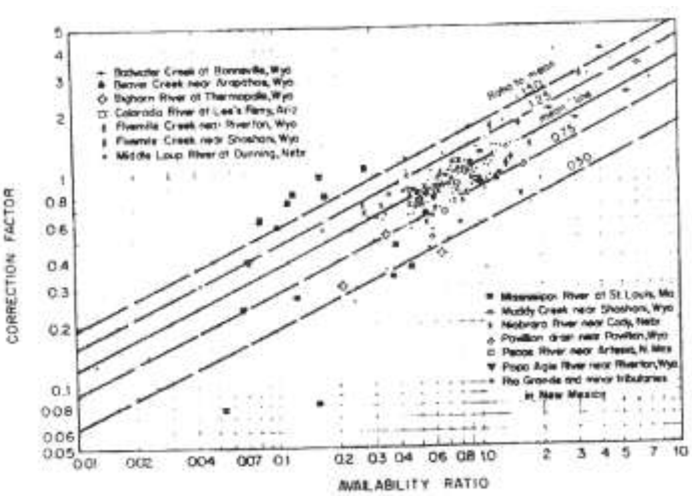

Figure 5: Variation of unmeasured sediment discharge adjusted for mean velocity with a measure of the availability of sands; Source: Daryl et al., [14].

2.2 Evaluation of Kubanni Reservoir Useful Life

The computation of useful life of a reservoir entails the estimation of sediment deposited in the reservoir over a number of years when the reservoir is not able to serve its established purpose, The computation of accumulated sediments in the reservoir is usually carried out in tabular form, at interval of 5 years of operation, For an interval (Δt), sediment inflow for the period (m^2-m) is as expressed in equation (4).

$$I_{SP} = I_{SA}\Delta t \quad (4)$$

where I_{SA} = the average annual sediment inflow (m^2-m) which is considered constant throughout the computation and, it is further expressed in equation 5

$$I_{SA} = \frac{I_S}{W_C} \quad (5)$$

where I_s = Average Annual sediment inflow in metric kg/annum (weight unit), obtained from records; W_C = composite specific weight of sediment, which is necessary for converting sediment quantities from weight unit to volumetric unit, [Adeogun (15)].

US Army Corps of Engineers [2], found equation (6) suitable for determining the composite specific weight of sediments,

$$W_C = \left\{ \frac{1}{(P_s / W_s) + (P_{sl} / W_{sl}) + (P_{cl} / W_{cl})} \right\} \quad (6)$$

where W_c = composite specific weight of the mixture, P_s= percent sand in mixture express as decimal; P_{sl}= similar quantity for silt; P_{cl}= similar quantity for clay; P_s, P_{sl} and P_{cl} are obtained from sediment size analysis curve. W_s = average unit weight for sand over years of reservoir operation; W_{sl}= similar quantity for silt; and W_{cl}= similar quantity for clay.

US Army Corps of Engineers [2] expressed each sediment component average unit weight(x), after T years of operation as:

$$W_x(T) = w_i + B\left\{ \frac{T}{(T-1)\log(T)} - 0.4343 \right\} \quad (7)$$

where W(T) = average unit weight over T years of operation; W_i = specific weight of the initial deposit, obtained from table 2, B = the consolidation coefficient from Table 2 assuming type 2 reservoir operation and, T= age of deposit in years.

Sediment Trapped (m^2-m) for a period is $S_{trap\ (i)}$ = EI_{sp}; where E = trap efficiency, obtained from Dendy [16] relation:

$$E = 100\left(0.97^{0.19^{\log\left(\frac{C_i}{I_i}\right)}} \right) \quad (8)$$

where C = reservoir storage capacity (m^2-m), I = Average annual inflow (m^2-m). The value is obtained from records. The average annual inflow is taken as a constant throughout the computation.

The initial reservoir storage capacity value is obtained from records. The subsequent interval values are found using the expression:

$$C_{i+1} = C_i \; ! \; S_{trap(1)} \quad (9)$$

The storage depleted by the sediment trapped during a period is obtained in percentage by using the relation:

$$\%C_{(i)} = \%C_{(i!1)} - \left\{ \left(\frac{S_{trap(i-1)}}{C_{(1)}} \right) 100 \right\} \quad (10)$$

where $C_{(1)}$= the initial storage capacity at the beginning of computation.

The above computational procedure is continued till the reservoir storage capacity remains half against certain period of operation which is considered the useful life of the reservoir. Pirzada [17] stated that the computation could be continued up to any desired depletion of reservoir capacity if there are circumstances which warrant a different ceiling as against 50% depletion as proposed by Brown[18]. The method above is used to compute the useful life of Kubanni Reservoir.

2.3 Estimation of Kubani Reservoir Current Capacity

The first expression for the estimation of the remaining storage capacity of reservoir was presented as follows, [Xlaoqing (4)]:

$$V_t = V_0 \left(1 - \frac{W_s}{V_0} \right)^t \quad (11)$$

where V_t = storage capacity at t years of reservoirs' operation in m^3, V_0 = initial storage capacity in m^3 , W_s = annual sediment load in m^3.

At present, there are other empirical and graphical methods for estimating process of depletion of storage capacity. The graphical method entails surveying the reservoir to estimate the level of sedimentation over the years and this approach is adopted in this investigation.

The reservoir was mapped out to establish grid lines perpendicular and parallel to the dam using the Grid-technique in land surveying. The intersections between two sets of grid lines were designated as sampling points and in all, 36 sampling points over the reservoir area were established. Sounding was performed at each of the sampling by using an inelastic weighted line from a boat, whose submerged length was measured with a measuring tape. The pier, with gauge marks, near the conical spillway close to the dam was observed before and after each day's survey operation to get the average stage of water which was found to be 643.44m NSD (Nigerian Survey Datum). The crest level of the conical spillway was estimated to be 644.66m NSD that is, at an elevation of 1.22m above the water surface. This value was added to each measured depth to get the total depth at each sounding point.

The US Army Corps of Engineers [2], stated that the most commonly used method for calculating volume of sediment deposits is by subtracting the surveyed capacity from the original capacity and that the surveyed capacity can be obtained from a plot of cross sectional areas (ordinate) versus distances from the dam (abscissa). This implies that the area under the curve represents the current capacity of the reservoir. The plotted curve using the computed cross-sectional areas and their respective distances from the KR dam is presented in Figure 13.

3.0 RESULTS

3.1 Stage, Discharge and Sediment Concentration

Figures 6 and 7 shows the plots of some of the hydrological data obtained in this study. The stage records for Samaru and Goruba rivers respectively ranged between 0.31m to 1.91m and 0.27m to 1.66m. Similar patterns were observed for the discharge measurements obtained for these two rivers. The observed discharge values for Samaru station ranging from 0.074 to 2.172m^3/s and 0.047 to 1.193m^3/s for Goruba station. The plot of the sediment concentrations (mg/l) against the water discharge (m^3/s) for each of these rivers are respectively shown in figures 8 and 9.

As shown in figures 6 and 7, Goruba River has a lower peak discharge value of 1.193m^3/s whereas Samaru has higher peak discharged value of 2. 172m^3/s. This implies that Samaru River is the major tributary of Kubanni Reservoir. Similarly, a lower maximum sediment concentration of 730 mg/l for Goruba station is reflected in figure 8 while a higher maximum value of 1230 mg/l for Samaru station is shown in figure 9. This is an indication that Samaru River is the major source of sediment load into Kubanni Reservoir.

3.2 Total Sediment loads of Samaru and Goruba Rivers Depositing into Kubanni Reservoir

The sediment loads of Samaru and Goruba rivers depositing into the Kubanni reservoir are as given in Table 3. As clearly indicated in this table, the measured sediment loads for Samaru River and Goruba River are 14,944,000 kg/year and 3,863,000kg/year respectively. This confirms that Samaru river is the major source of sediment load deposited into Kubanni Reservoir.

The sediment rating curves (for the unmeasured sediment discharges i.e. the bed loads) for both Samaru and Goruba rivers are respectively shown in figures 10 and 11. These sediment rating curves were further used to compute daily sediment load for the obtained daily discharge values, and their summation gave the monthly values and then consequently the annual sediment load. As shown in table 3, the annual unmeasured sediment loads (theoretically estimated) for Samaru and Goruba rivers were respectively found to be 1,125,000 kg/year and 455,000 kg/year. The respective values for the measured sediment load are 14,944,000 kg/year and 3,863,000 kg/year. This cumulates into a total sediment load of 20,387,000 kg/year since both rivers deposits into the Kubanni reservoir.

In addition, table 4 presents the monthly inflow for the two stations. The highest inflow was 7,960,637m^3 in September while the lowest inflow was 640,569m^3 in June. The seasonal inflow into Kubanni reservoir totals 30,116,793m^3/year.

3.3 Estimation of Kubanni Reservoir Useful Life

The inflow sediment size curve shown in figure 12, indicates that the sediments are characterized as 71 % sand (P_s), 16% silt (P_{sl}) and 13% clay (P_{cl}). The values were used to compute the useful life of the reservoir as outlined in section 2.2. As presented in table 7, a useful life of 107 years was obtained for the Kubanni reservoir. A much more recent approach using remote sensing data and techniques may be a better approach that can considered in the subsequent future works to improve this data obtained.

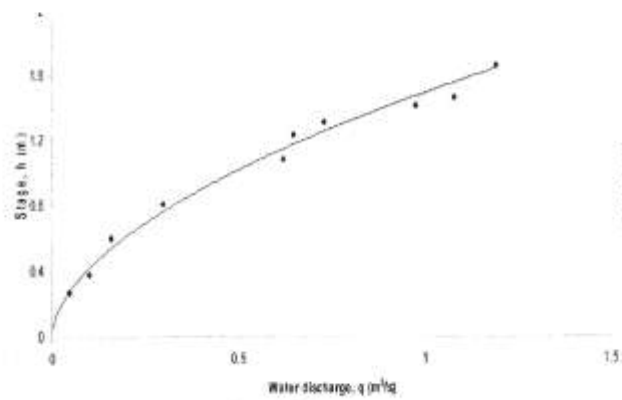

Figure 6: Rating Curve at Goruba Station

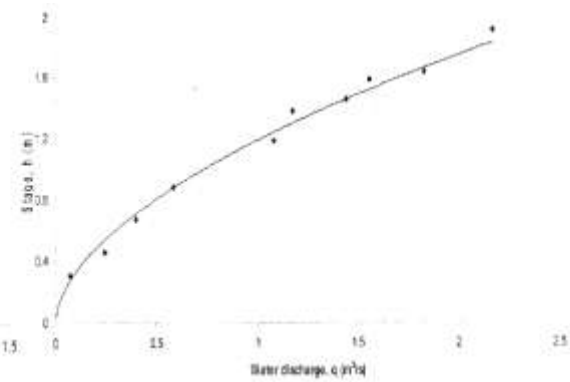

Figure 7: Rating Curve at Kubanni Station

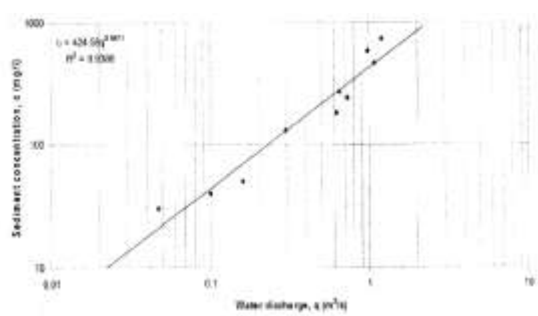

Figure 8: Sediment and Flow Characteristics at Goruba Station

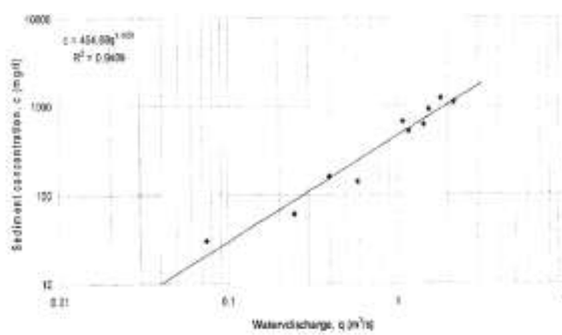

Figure 9: Sediment and Flow Characteristics at Kubanni Station

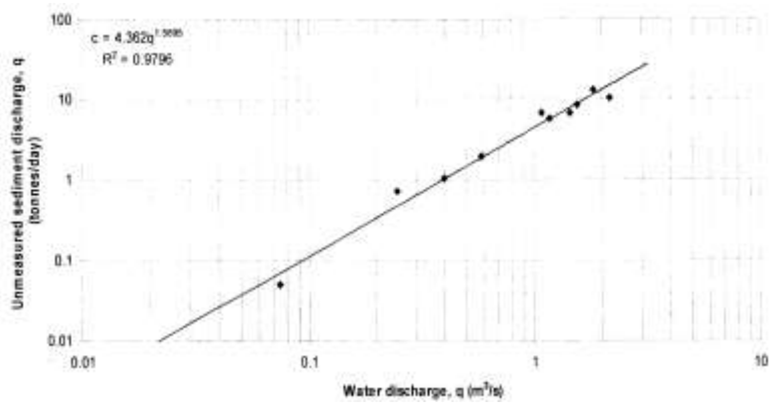

Figure 10: Unmeasured sediment load vs. discharge at Samaru Station

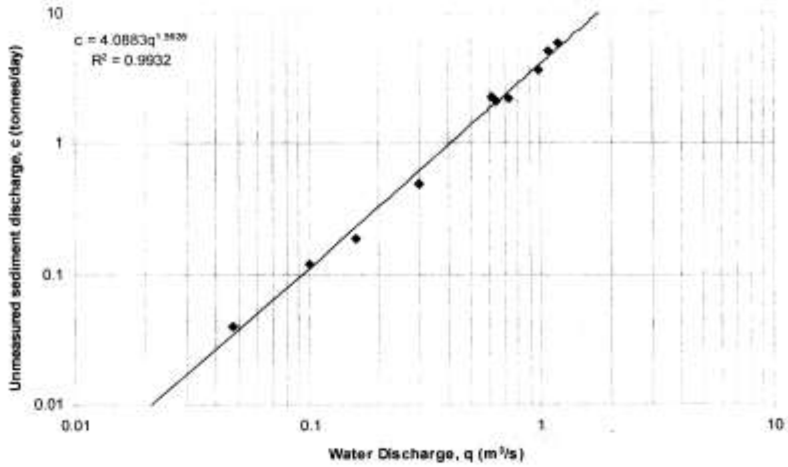

Figure 11: Unmeasured sediment load vs. discharge at Garuba Station

Table 3: Seasonal Sediment Load (in kg/annum) Discharged into Kubanni Reservoir

Month	Samaru River		Goruba River		Total ($H10^3$)(kg/annum)
	Measured Sed. Load H 10^3(kg/month)	Unmeasured Sed. Load H 10^3(kg/month)	Measured Sed. Load H 10^3(kg/month)	Unmeasured Sed. Load H 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	64	12	15	3	94
	14944	**1125**	**3863**	**455**	**20387**

Table 4: Seasonal Inflow into Kubanni Reservoir

Month	Total monthly Inflow (m^3/month)		Total
	Samaru River	Goruba River	
June	456451	184118	640569
July	2243376	1075507	3318883
August	4118688	2245104	6363792
September	5149872	2810765	7960637
October	4784400	2695939	7480339
November	2384640	1258848	3643488
December	494208	214877	709085
Total	**19631635**	**10485158**	**30116793**

3.4 Estimation of Kubanni Reservoir Current Storage Capacity and Storage Loss

The area under the curve shown in figure 13 reflects the current storage capacity of the reservoir. As shown in this figure, the current storage capacity of the reservoir is estimated to be 1.34 H $10^6 m^3$. By a simple comparison with the initial storage capacity of 2.6 H $10^6 m^3$, it is clear that the reservoir has a loss of 1.26 H 10^6 m^3 in storage capacity due to sedimentation since 19973 when the KR was constructed. This translates to a loss of 48.5% in storage volume and reflects an average annual loss of 1.5% per year since 1993.

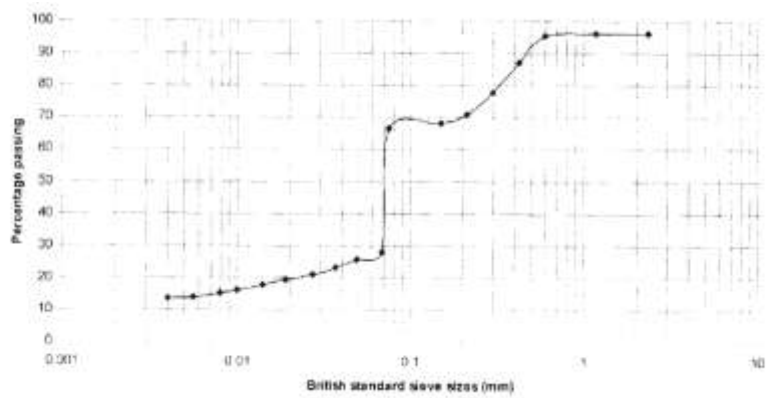

Figure 12: Particle size curve for Kubanni Reservoir bed material

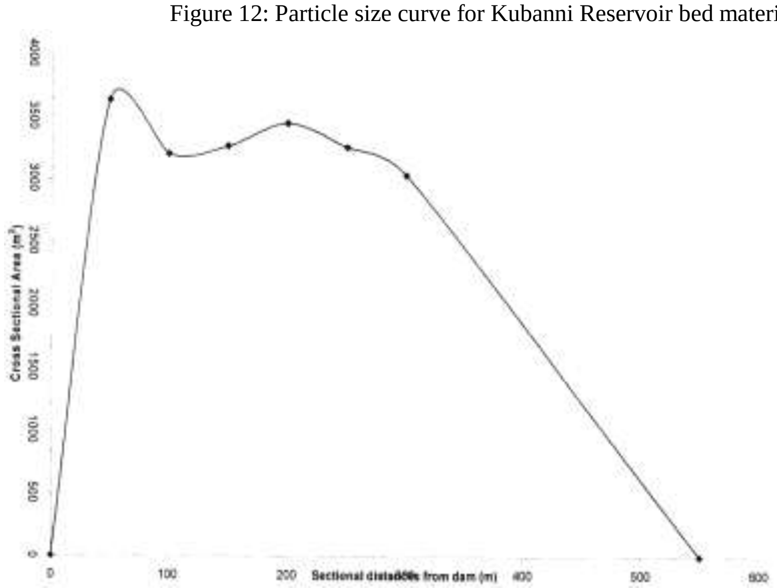

Figure 13: Cross-sectional Areas of Kubanni Reservoir versus Distance from the Dam

Table 5: Estimated Useful Life of Kubanni Reservoir

Period (years)	Storage Capacity H 10^6 (m^2!m)	Av. Annual Inflow (I) H 10^6 (m^2!m)	C/l Ratio	Trap Efficiency E(%)	Av. Annual Sed. Inflow (I_{SA})(m^2!m)	Sed. Inflow for Period (I_{SP}) (m^2!m)	Sed. Trapped {$S_{trap(i)}$} H 10^6 (m^2!m)	% of initial Capacity %$C_{(1)}$	Remarks
1-5	2.600	30.12	0.086	83.63	15712.28	78561.40	0.0657	100.00	
5-10	2.534	30.12	0.084	83.38	15712.28	78561.40	0.0655	97.47	
10-15	2.468	30.12	0.082	83.11	15712.28	78561.40	0.0653	94.95	
15-20	2.403	30.12	0.080	82.84	15712.28	78561.40	0.0651	92.45	
20-25	2.338	30.12	0.077	82.40	15712.28	78561.40	0.0647	89.96	
25-30	2.273	30.12	0.075	82.10	15712.28	78561.40	0.0645	87.47	
30-35	2.209	30.12	0.073	81.78	15712.28	78561.40	0.0642	84.99	
35-40	2.145	30.12	0.071	81.45	15712.28	78561.40	0.0640	82.52	
40-45	2.081	30.12	0.069	81.10	15712.28	78561.40	0.0637	80.06	
45-50	2.017	30.12	0.067	80.74	15712.28	78561.40	0.0634	77.61	
50-55	1.954	30.12	0.065	80.35	15712.28	78561.40	0.0631	75.17	
55-60	1.891	30.12	0.063	79.95	15712.28	78561.40	0.0628	72.74	
60-65	1.828	30.12	0.061	79.53	15712.28	78561.40	0.0625	70.32	
65-70	1.766	30.12	0.058	78.86	15712.28	78561.40	0.0620	67.92	
70-75	1.704	30.12	0.056	78.38	15712.28	78561.40	0.0616	65.54	
75-80	1.642	30.12	0.054	77.88	15712.28	78561.40	0.0612	63.17	
80-85	1.581	30.12	0.052	77.34	15712.28	78561.40	0.0608	60.82	
85-90	1.520	30.12	0.050	76.78	15712.28	78561.40	0.0603	58.48	
90-95	1.460	30.12	0.048	76.17	15712.28	78561.40	0.0598	56.16	
95-100	1.400	30.12	0.046	75.53	15712.28	78561.40	0.0593	54.46	
100-105	1.341	30.12	0.044	74.84	15712.28	78561.40	0.0588	52.18	
105-110	1.282	30.12	0.042	74.10	15712.28	78561.40	0.0582	49.92	End of Useful life

4.0 Discussion of Results

The presence of 71% sand in the deposited sediments into KR implies that the planting of grasses or vegetative cover plants on the watershed can be used as a sediment control action to prevent the detachment and transporting of these sediments, especially the sand component, into the reservoir. This planned action if properly implemented could reduce the observed sand component of the transported sediments by two-third. The proportion of the rest finer sediments deposited into the reservoir will remain in suspension in the reservoir and can either be removed by flushing or abstraction. Its further reduction can be by trapping and localizing them away from the KR by constructing debris or sediment retention basins along the route of the two feeding rivers especially Samaru River that is carrying the higher proportion of these sediments.

The observed reservoir storage capacity loss of 1.47% per annum is considered high when compared to an average annual loss of 1% of reservoirs investigated by Mahmood [19] and Sloff [20]. This rate of siltation in KR is however similar with the rate presented by JICA (21) for other similar reservoirs in northern Nigeria. The consequence of the 48.5% loss of reservoir volume by KR in its 33 years of operation is that the quantity of fresh available for treatment at the ABU treatment plant is seriously affected and the immediate short term action plan should be towards sediment dredging so as to reclaim the storage lost to reservoir sedimentation.

5.0 CONCLUSIONS

This study has examined the sedimentation in Kubanni Reservoir and the following conclusions were deduced from the study:

(a) The total sediment load discharged into Kubanni Reservoir was estimated at 20,387,000 kg/year for the year of study.
(b) Samaru River is the major source of sediment into Kubanni Reservoir with an annual sediment load of 16,069,000 kg while Goruba River annual sediment load totalled 4,318,000 kg.
(c) The current storage capacity of Kubanni Reservoir is estimated to be 1.34 H 10^6 m^3. The difference between the initial storage capacity of 2.6 H 10^6 m^3 after constructing the reservoir and the present available storage capacity shows a storage loss of 1.26 H 10^6 m^3. This shows that the reservoir had lost 48% of its storage volume to sedimentation in 33 years of operation. Hence, an estimated useful life of 107 years is no more feasible.
(d) An estimated annual loss of 1.47% in storage capacity is considered high compared to an average annual loss of 1% of reservoirs investigated by Mahmood [19] and Sloff [20].
(e) The control of sedimentation in Kubanni Reservoir requires a radical approach than ever before.

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