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EVALUATION OF USEFUL LIFE OF GURARA DAM RESERVOIR USING TRAP EFFICIENCY

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ABSTRACT
Sediment inflow and deposition depletes much required storage capacity, decreases the useful life, and alters the beneficial uses of dam reservoirs. This research was carried out to estimate the useful life of the Gurara dam reservoir to improve the effective operation and management of the Gurara dam reservoir. The results of 2018 total annual fluvial sediment inflow into Gurara dam reservoir, trap efficiency, Capacity Inflow ratio (C/I), Capacity sediment density and other empirical approaches were used. The Gurara dam started operating in 2007. No detailed study was yet carried out to assess its useful life. The result shows approximately that the useful life of the Gurara dam reservoir is about 165 years. The estimated useful life of 165 years is feasible since the watershed has good vegetation cover, plenty of rocks on its upper watershed. Integrated watershed management, good environmental practices in agriculture are the Engineering measures recommended as actions to be taken for the sustainability of the Gurara watershed.

KEYWORDS: *Useful life of reservoir; Reservoir sedimentation; Trap efficiency; Capacity inflow ratio (C/I); Gurara Dam reservoir.*

1.0 INTRODUCTION

Reservoirs primary purposes are water supply, irrigation, flood control, hydropower and navigation. Hence, reservoirs are vital infrastructures for survival and well-being of mankind. Reservoir sedimentation is the process of sediment deposition into a lake formed after dam construction (Garg & Jothiprakash, 2008), which in turn affects the useful life of the reservoir. The period up to which the reservoir can serve the defined purpose is called usable life, the period after which the cost of operating the reservoir exceeds the additional benefits expected from its continuation is called economic life, design life is generally the useful life, full life period is that when no capacity is available in the reservoir for useful purpose (Murthy, 1980; Kulkarni et al. 1994).

The useful life of a reservoir is a period in which the sediments deposited do not influence the economic feasibility and sustainability of water resources demand (Issa et al, 2013). It is the period when the reservoirs are depleted 50% of their storage capacity or the dead storage is filled with sediment (Gill, 1979); (Pirzada, 1978). Thus, provisions should continuously be made to guarantee the total design reservoir storage capacity for the existing useful life as a result of reservoir sedimentation. To estimate the rate of sediment deposition and the time at which the sediment would interfere with the useful functioning of a reservoir is the problem to be addressed. Several methods and models are usable for the estimation, analysis and prediction of the reservoir sedimentation process (Garg & Jothiprakash, 2008). However, these methods and models differ greatly in terms of their input parameters, complicacy, and computational prerequisite. Reservoirs are constructed for beneficial purposes like water supply, irrigation, hydropower generation, flood control, navigation, etc. Sedimentation is one of the most crucial problems that affect the performance of reservoirs directly. Reservoir sedimentation causes loss of storage capacity, influences the performance and operation of reservoirs. Thus periodic estimation of the useful life is an important issue for the operation and management of the reservoirs (Campos, 2001).

The assessment of sedimentation rate in the reservoirs to ascertain actual storage capacities is among these operations (Al-Ansari & Knutsson, 2011). Gurara Dam Reservoir is one of the strategic projects and its storage capacity needs to be evaluated periodically. The reservoir was operated in 2007 and no detailed studies had been carried out to know its useful life. They are several causes of reservoir sedimentation; yet, the largest natural contributing factors are watershed, sediment and river characteristics. The prevalent factors that influence the rate of silting in a reservoir are: (a) Capacity to Inflow Ratio (C/I), (b) sediment content in the water flowing in, (c) texture and size of the sediment, (d) trap efficiency of the reservoir, and (e) the method of reservoir operation (Arora and Goel, 1994). The most important application of the sediment quantification study in a reservoir is the estimation of the useful life of the reservoir. The estimation of the useful life of dam reservoir requires knowledge of the sediment discharge inflow, the Brune curve of trap efficiency of sediments, the value of the specific weight, reservoir characteristics, etc. Once the volume of sediment inflow to a reservoir has been determined, effects of the sedimentation process over the life span and the daily operation of the reservoir must be evaluated (Farhad Imanshoar et al, 2014)

2.0 Materials and methods

2. 1 Study Area: Gurara Dam Reservoir

Gurara dam is one of the most important hydraulic structures in Nigeria which has been built on the Gurara River, Northern Nigeria. The Dam is located on the Gurara River at Latitudes 9°13'N and 9°39' and Longitudes 7°26'E and 7°42'E as shown in Figure 1. Some basic parameters and information of the Gurara dam reservoir are summarized in Table 1. Land use of the study area in km^2 and percentage are clearly shown in Figure 2 and Table 2. Reservoirs having C/I ratio of more than 50% may be considered hydrologically large (Morris and Fan, 1998), therefore, the Gurara dam reservoir is categorized as a large reservoir. The reservoir is fed by the flow from rainfall.

Table 1: Parameters of Gurara Dam Reservoir

Dam Parameters	Parameter Values
Catchment Area: Catchment Area at Izom Catchment Area at Jere Total catchment Area	 16,650km ^{2} 4,016km ^{2} 20,666km ^{2}
Catchment Area at Dam Site	2,150km ^{2}
Average yearly inflow into reservoir	1,730Mm ^{3} (55m ^{3}/sec)
Average Rainfall	1,415mm
Reservoir Area	62.8km ^{2}
Storage Capacity (Volume)	800 million m ^{3}
Volume of fill	7,335,000m ^{3}
Probable maximum flood	4200m $^3/s$
Height and length of the Dam	53m and 3.1 km respectively
Normal Water Level (NML)	624.9m amsl
Maximum Water Level (MWL)	627.5m amsl
Minimum Operating Level (MOL)	605m amsl
Dam Crest Level	624m
Dam Crest Width	6m
Height	55m
Crest Length	3040m
Altitude	290
Dam type	Earth fill + Rockfill dam
Category	Large
River	Gurara
Purpose	Irrigation, water supply and Hydro power
Hydrological zone	2
Embankment	8.2 million m ^{3} of embarkment
Lake surface area	61km ^{2}
Right bank of lake	1.16km ^{2}
Intake	42m high intake tower equipped with hydraulic valves that transfers raw water through a 75km long conveyance pipeli ne of 3m diameter to Lower Usma dam, Abuja
Spillway	Located on left bank at the and consists of 34,000m ^{3} concrete lined ogee and rocky channel
Stilling basin	USBR Type III
Discharge	2,715m ^{3}/ seconds
Power house	Equipped with 3x10 Megawatts of turbine
Comments (Irrigation)	2000 ha irrigation

Source: Gurara Dam Pamphlet (2007)

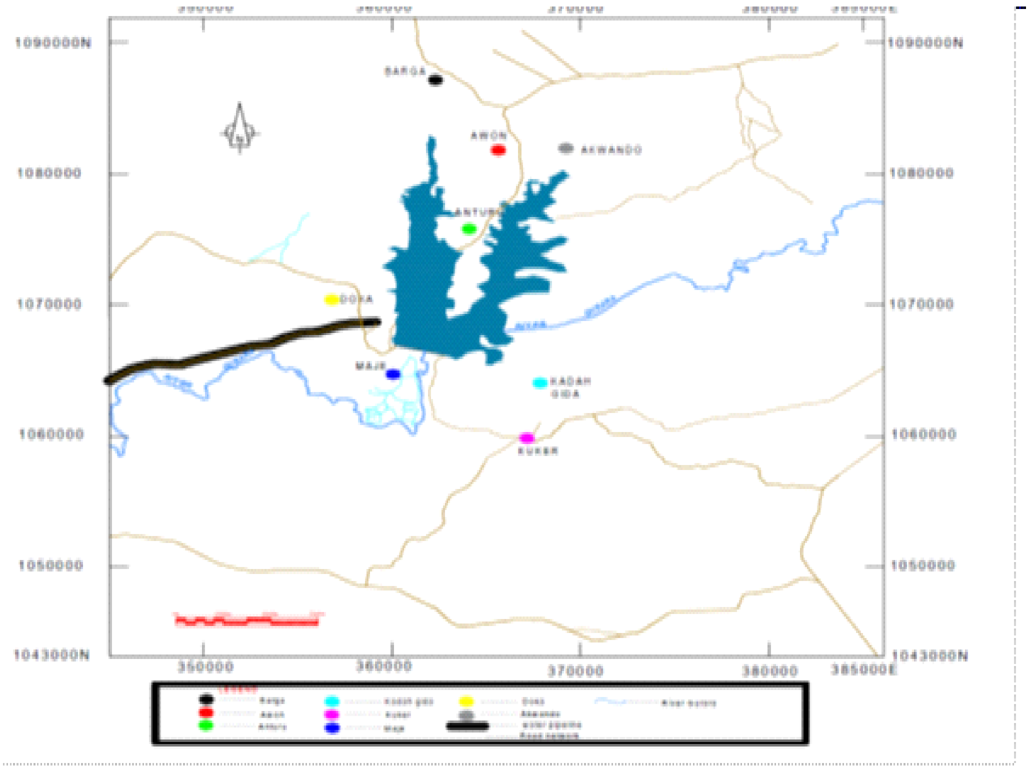

Figure 1: Location of Gurara Dam reservoir (Ugbala, 2021)

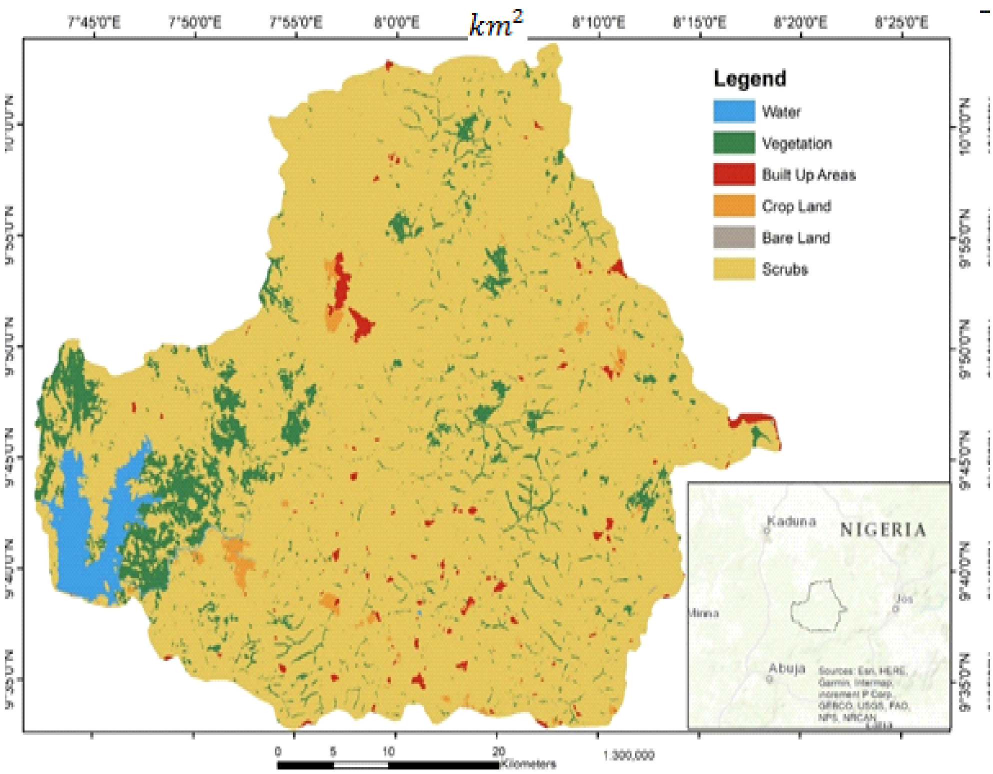

Figure 2: Land use and Land cover of the study area (Ugbala, 2021)

Table 2: Landuse of the study Area in km^2 and their percentages

Landuse	Area (km^2)	Percentage
Water	60.652534	2.6%
Vegetation	182.979848	7.8%
Crop Land	19.872146	0.9%
Scrubs	2043.574228	87%
Built Up Areas	26.634684	1.1%
Bare Land	0.217745	0.01%

Reservoir Trap Efficiency

Trap efficiency is defined as the capability of the reservoir to settle or entrap sediments and is also the ratio of settled or trapped sediments to incoming sediments in percentage. It is usually a function of the sediment characteristics, and the ratio of reservoir volume to average annual runoff volume. Methods for estimating reservoir trap efficiency are empirically based upon measured sediment deposits in reservoirs. The commonly used are those by G. Brune and A. Churchill (Strand, 1974). Trap efficiency is dependent on several parameters, including sediment size, distribution; the time and rate of water inflow to the reservoir; the reservoir size and shape; the location of the outlet structure and water discharge schedules (Morris and Fan, 1998); (Campos, 2001). Several empirical research showing the relation between reservoir storage capacity, water inflow, and Trap efficiency have been carried out (Brune, 1953). From the research, the (Brune, 1953) is likely the most generally used method for estimating the sediment retention in reservoirs (Garg and Jothiprakash, 2008). Churchill method, which accounts for sediment received from an upstream reservoir, provides a more realistic estimate of sediment yields than the Brune method (Garg and Jothiprakash, 2008). Although the use of the Churchill curves may give a better prediction than the Brune curves, but it is very difficult to obtain the input data for computing the sedimentation index (Garg and Jothiprakash, 2008). This is probably the reason why Brune's approach is used so extensively as opposed to that of Churchill (Garg and Jothiprakash, 2008). The Brown curves are indisputably, the easiest to use, indeed if runoff data are lacking. In this research Equation 3 was used to compute the trap efficiency.

Evaluation of Gurara Dam Reservoir Useful life

The useful life for the Gurara dam reservoir was computed using algebraic equations that were proposed by Gill (Gill, 1979). The equations represent the relationship between initial storage capacity of the reservoir, water and sediment inflow into the reservoir and specific weight of sediment deposited as shown in Equations (3-6). Type 2 reservoir operation was assumed from Table 3. The assumption of this reservoir operation type was made through the operation study and engineering judgment carried out which is based on hydraulic conditions of the intake and sediment trap coefficient of the reservoir (Farhad Imanshoar et al, 2014).

2.4 Unit Weight of deposited Sediment

The main factors that affect the value of the unit weight of the deposited sediment in a reservoir are the way the reservoir is operated and the size of the sediment particles. The sediment deposition was computed in terms of weight per time. Conversion was made to obtain the volume of deposited sediment. Once the reservoir operation type has been selected, the density of the sediment deposit was computed using Equation 1.

Table 3: Classification of Reservoir operations, constant and percentages of clay, silt, and sand,

Type	Reservoir Operation	Sediment Deposit					
		Sand		Silt		Clay	
		W_s	K	W_{si}	K	W_{si}	K
1	Sediment always submerged or nearly submerged	97	0	70	5.7	26	16
2	Normally moderate to considerable reservoir drawdown	97	0	71	1.8	30	8.4
3	Normally considerable reservoir drawdown	97	0	72	0	35	0
4	Reservoir normally empty	97	0	73	0	60	0

Source: (Otun and Adeogun, 2010)

$W = W_{C,}P_{c,} + W_{st,}P_{st,} + W_{s,}P_{s,}$ .... (1)

Where, W = Unit weight in pounds per cubic foot (density in kilograms per cubic meter),

Where, W = Unit weight in pounds per cubic foot (density in kilograms per cubic meter), P_c, P_{st}, P_s = Percentages of clay, silt, and sand, respectively, of the incoming sediment W_c, W_{st}, W_s = Coefficients of clay, silt, and sand, respectively, which is obtained from the Table 3. An approximation of the integral for determining the average density of all sediment deposited in n-years of operation [3] as shown in Equation 2 was used.

$W_T = W_1 + 0.4343K\left[\frac{T}{T-1}(\log_e T) - 1\right]$.................. (2)

Where, W_T = average density after n-years of reservoir operation, W_1= initial unit weight (density) as derived from Equation 1K = constant based on type of reservoir operation i.e. type 2 was assumed and sediment size analysis as obtained. This value was then applied to convert the initial weights (initial masses) of incoming sediment to the volume it will occupy in the reservoir after 100 years.

Sediment Trapped (m^3) for a period is $S_{trap}(i) = EI_{sp}$ ....(3), where E = Trap efficiency from Dendy relation (Adeogun, 2008); (Otun and Adeogun, 2010) and (Ugbala, 2021)

$E = 0.97\left[0.19^{\log \frac{C_i}{I_i}}\right]$..............................(4), Where C = reservoir storage capacity (m^3) from Table 1, I = Average annual inflow (m^3). The average annual inflow was constant throughout the computation. The initial reservoir storage capacity value was obtained from records. The subsequent interval values of initial reservoir storage capacity were computed using Equation (5) below:

$C_{i+1} = C_i ! S_{trap}$ (i) ....(5), The storage depleted by the sediment trapped during a period is obtained in percentage by using equation (6) below.

$\%C_i = \% C_{i!1} = \left(\frac{S_{trap(i-1)}}{C_i}\right) 100\}$............(6)Where C_i = the initial storage capacity at the beginning of computation. The computational procedure above continued till the reservoir storage capacity remains half against a certain period of operation which is considered the useful life of the reservoir. 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 proposed by Brown (Pirzada, 1978). The method above was used to compute the useful life of the Gurara Dam Reservoir.

To ascertain the rate at which reservoirs will fill with sediments, is always important to estimate the weight per unit volume of the deposited sediment since the quantity of sediment transported by a stream is normally expressed to weight rather than volume. The computation of sediment deposits in the reservoir is carried out usually at a interval of 5 years of operation [10]. The computations are explained as follows (Adeogun, 2008); (Otun and Adeogun, 2010) and (Ugbala, 2021).

(1) Period of operation in any convenient interval generally, five years is written.
(2) Initial storage capacity is written in the first line and subsequent storage capacities are worked out by subtracting volume of sediment trapped for a period from the storage capacity at the beginning of the period.
(3) From available records, the average annual inflow is written which is kept constant throughout the computation.
(4) Capacity- inflow ratio is found by the constant average annual inflow.
(5) Trap efficiency corresponding to the capacity –inflow ratio above is read from brume figure.
(6)Average annual total sediment inflow as calculated is Written is also considered constant throughout the computation. Composite specific weight as delineated before is used to convert weight of sediment in volume in hectare foot.
(7)Total sediment inflow is worked out for the period of operation in consideration by multiplying the average annual total sediment inflow in the previous step by the period of operation i.e. by 5 years.
(8) Total trapped sediment in the reservoir is worked out by multiplying the trap efficiency obtained in step 5 by the total sediment inflow for the period.

However, the inflowing sediment size analysis shows 70% sand, 16% silt and 13% clay which was used to calculate the average unit weight for each of the sediment sizes of the Gurara dam

2.5 Calculation of Average unit weight of Sediments of Gurara Reservior operation

Using Equation 2, the average unit weight for each of the sediments are calculated below

$$W_T = W_1 - 0.434K + \left(\frac{KT}{T-1}\right) LogT$$

For clay, W_c (10) = 35 – (0.434*8.4) + ($\frac{8.4*10}{10-1}$) Log10 = 41

For silt, W_{si} (10) = 71 – (0.434*1.8) + ($\frac{1.8*10}{10-1}$) Log10 = 72

For sand W_s (10) 97 – (0.434*0) + ($\frac{0*10}{10-1}$) Log10 = 97

2.6 Calculation of composite specific weight of Gurara reservoir sediment mixture

The composite specific weight of the Gurara reservoir sediment mixture is calculated using Eqn 7 below

$$W_c = \frac{1}{(Fp_c/W_c)\,\text{clay} + (Fp_{si}/W_{si})\,\text{silt} + (Fp_s/W_s)\,\text{sand},}$$

.................................(7) Where F_{FI} is the fraction of each of the sediment.

$$W_c = \frac{1}{\left(\frac{0.7}{97}\right) + \left(\frac{0.16}{72}\right) + \left(\frac{0.14}{41}\right)} = 78.125 Ib/ft^3$$

(12,516N/m^3)

Average annual sediment inflow

$$I_{SA}\ (m^3)\ \frac{\text{Average sediment inflow in metric}\frac{\text{kg}}{\text{annum}}(\text{weight unit}), I_S}{\text{Composite specific weight of sediment}, W_C}$$

$$I_{SA} \quad \frac{Is}{Wc} = \frac{25{,}725{,}000}{12{,}516} = 20,553.69$$

Again, these percentage values of the incoming sediment and average unit weight of each sediment were used to calculate the composite specific weight of the sediment mixture as 78.125 lb/ft^3 (12, 516N/m^3), which was necessary to estimate the useful life of the reservoir and it is usually important to estimate the weight per unit volume of the deposited sediment since the quantity of sediment transported by a stream is normally expressed in terms of weight rather than volume. Therefore, the total sediment deposit (25,725, 000 kg/year) was converted from weight unit to volumetric unit in hectare foot using the composite specific weight above. An equivalent volumetric value of 5.2hectare foot was obtained, from which the sediment trapped and the useful life of the reservoir was obtained. The Gurara dam Reservoir is estimated to have a useful life of 165 years based on the estimated annual sediment inflow of 25,725,000 kg/year as shown in Table 4.

3.0 Results

Table 4: Results Evaluation of Gurara dam Reservoir Useful Life

Period (years) (1)	Storage Capacity,(C)H 10^6 (m^3)= $C_{i+1}=C_i-S_{trap\ (I)}$ (2)	Av. Annual Inflow,(I) H 10^6 (m^3) (3)	$C\ I$ Ratio =(2)/(3) (4)	Trap Efficiency E (%) (5)	Av. Annual sediment inflow, I_{SA} (m^3) (6)	Sed. Inflow for period, I_{sp} (m^3) =(1)*(6) (7)	Sed.Trapped $S_{trap(1)}$ H 10^6 (m^3) =(5)*(7) (8)	% of initial capacity (9)	Remarks (10)
1-5	808.00	54.62	14.79	99.56	20553.69	102768.45	10.23	100	
5-10	796.73	54.62	14.59	99.56	20553.69	102768.45	10.23	98.73	
10-15	785.46	54.62	14.36	99.55	20553.69	102768.45	10.23	97.44	
15-20	774.19	54.62	14.17	99.55	20553.69	102768.45	10.23	96.13	
20-25	762.92	54.62	13.96	99.54	20553.69	102768.45	10.23	94.80	
25-30	751.65	54.62	13.74	99.54	20553.69	102768.45	10.23	93.45	
30-35	740.38	54.62	13.53	99.53	20553.69	102768.45	10.23	92.08	
35-40	729.11	54.62	13.33	98.53	20553.69	102768.45	10.23	90.69	
40-45	717.84	54.62	13.14	99.52	20553.69	102768.45	10.23	89.28	
45-50	706.57	54.62	12.92	99.52	20553.69	102768.45	10.23	87.85	
50-55	695.30	54.62	12.71	99.51	20553.69	102768.45	10.23	86.40	
55-60	684.04	54.62	12.52	99.50	20553.69	102768.45	10.23	84.92	
60-65	672.78	54.62	12.31	99.50	20553.69	102768.45	10.23	83.42	
65-70	661.52	54.62	12.11	99.50	20553.69	102768.45	10.23	81.89	
70-75	650.26	54.62	11.91	99.49	20553.69	102768.45	10.22	80.34	
75-80	639.00	54.62	11.69	99.48	20553.69	102768.45	10.22	78.76	
80-85	627.74	54.62	11.49	99.48	20553.69	102768.45	10.22	77.16	
85-90	616.48	54.62	11.08	99.47	20553.69	102768.45	10.22	75.53	
90-95	605.22	54.62	11.08	99.46	20553.69	102768.45	10.22	73.87	
95-100	593.96	54.62	10.87	99.46	20553.69	102768.45	10.22	72.18	
100-105	582.70	54.62	10.67	99.45	20553.69	102768.45	10.22	70.45	
105-110	571.44	54.62	10.46	99.44	20553.69	102768.45	10.21	68.69	
110- 115	560.18	54.62	10.26	99.43	20553.69	102768.45	10.21	66.90	
115-120	548.92	54.62	10.05	99.43	20553.69	102768.45	10.21	65.07	

120-125	537.67	54.62	9.84	99.42	20553.69	102768.45	10.21	63.21	
125-130	526.42	54.62	9.64	99.41	20553.69	102768.45	10.21	61.31	
130-135	515.17	54.62	9.43	99.40	20553.69	102768.45	10.21	59.37	
135-140	503.92	54.62	9.27	99.39	20553.69	102768.45	10.21	57.38	
140-145	492.67	54.62	9.02	99.38	20553.69	102768.45	10.21	55.35	
145-155	481.42	54.62	8.81	99.37	20553.69	102768.45	10.21	53.28	
145-155	481.42	54.62	8.81	99.37	20553.69	102768.45	10.21	53.28	
155-160	470.17	54.62	8.61	99.36	20553.69	102768.45	10.21	51.15	
160-165	458.92	54.62	8.40	99.35	20553.69	102768.45	10.21	48.97	End of useful life

4.0 Conclusion

The estimated 165 years useful life of the Gurara Dam Reservoir is feasible since the watershed has good vegetation cover and many rocks on its upper watershed as shown in Figure 2 resulting in a small sediment yield and a longer useful life time for the reservoir. The results will be improved with more sediment discharge measurements in the future. However, this result does not nullify the inevitability for coming maintenance to protect the conditions that yield a low sediment load in the reservoir. It is feasible that deforestation in the watershed can lead to alteration of the current results. Watershed management is recommended, to minimize regular activities that encourage hydrosedimentologic instability on the watershed. Government at all levels should work to adopt efficacious operations to surmount the sediment related issues.

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