Sedimentation Assessment of a Small Reservoir at Afaka Forest Reserve, Kaduna, Nigeria

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Abstract

The sedimentation assessment of a small reservoir constructed in 1987 at the Afaka Forest Reserve, Kaduna, Nigeria was carried out 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 4m leveling staff, respectively. The study showed that the reservoir storage capacity has decreased, due to sediment build-up, from its initial design capacity 16400m^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 221m^{3}yr^{-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. For economic justification, it is recommended that the reservoir be desilted, at least, every 15 years by a capacity of 3280m^3 (which is equal to reservoir depth of 0.66m), equivalent to 20% of the design capacity, to ensure continuous life span of the reservoir. Results of reservoir sedimentation assessment are necessary tools that serve as guide for safe design of reservoirs for various catchments.

Key Words: Reservoir sedimentation, Storage capacity, Assessment, Catchment, Afaka Kaduna

1. Introduction

Small reservoir (small earth-fill dam or micro-dam) has been defined as a barrier constructed across a river or a natural stream to impound water, the dam height measured from lowest point of natural ground level being less than 15m or up to 25m provided the capacity is less than 2 million cubic meters and does not cause significant damage in life and properties to downstream environment in case of breach (NBCBN 2005). An understanding of the quantity of sediment deposit in a reservoir is necessary for effective reservoir and basin management. Sedimentation affects both the useful life and aesthetic quality of a reservoir. Most reservoirs are designed to be usable for 50 to 100 years, before they are rendered useless by sedimentation (Hotchkiss 1995). The rate of reservoir sedimentation can be accelerated by natural or human modifications to the watershed (Ongkosongo *et al*. 1992; Renwick 1996).

Water being a scarce or limited resource, its efficient use is necessary for increased agricultural production per unit volume of water, per unit area of cropped land. Hence, following rainfall events, the enormous amount of water that is often wasted annually as runoff discharged into rivers far away from farm areas can be harnessed and stored in reservoirs. Depending on the quality, the water can be useful for domestic purposes, irrigation, potable water for livestock and fish rearing during the dry seasons. Runoff water harvesting and storage into small reservoirs is a common practice in many rural communities in Africa like Kenya, Uganda, Ethiopia, Egypt and Uganda (McCartney *et al.* 2002; NBCBN 2005).

The reservoir under study (Fig. 1) was designed and constructed in 1987 to be able to store 16400m^3 of runoff at full capacity. It is a micro-dam, having capacity less than 2 million cubic meters as defined by NBCBN (2005). The water source is a runoff stream which drains all storm flow from within the catchment. The annual runoff volume which can be stored in the reservoir has been evaluated to be in excess of the reservoir; implying that the reservoir could be dredged to harness more runoff. The reservoir inflow persists even after rainy season to January when base-flow ceases (Onwuegbunam 2008). Thereafter, the reservoir volume reduces continuously as a result of use, as well as losses due to evaporation. Presently, the minimum reservoir capacity before recharge in the following rainy season is at dead storage.

Reservoirs serve a number of different functions but one of the largest is to maintain an area’s water supply. As means of conserving water for useful purposes during the dry or scarce periods in Kaduna State, Nigeria, the government has constructed several dams among which are Kufana, Sabon Sarki, Pambegua, Fatika, Matari, Likarbu and Kuzuntu earthdams; Gimbawa, Kangimi, Shika, Kubani and Bagoma dams (DIS 2013). These dams are constructed mainly for irrigation, community water supply and recreation purposes. So far, massive siltation has been reported at Bagoma and Gimbawa dams as well as Matari earthdam (DIS 2013). Inefficient reservoir and watershed management often lead to massive reservoir sedimentation.

The construction of dams or reservoir blocks the flow of sediments downstream recharging streams. This leads to downstream erosion of the sedimentary depositional environment and increased sediment build-up in the reservoir. While the rate of sedimentation varies for each dam and each river, eventually all reservoirs develop reduced water storage capacity due to the exchange of storage space for sediment (McCully 1996). Diminished storage capacity results in decrease ability to produce hydroelectric power, reduced availability of water for irrigation, and if left unaddressed, may ultimately result in the expiration of the dam or river (Gregory & Jiahua 1998).

Siltation study for Afaka reservoir was not carried out since construction in 1987, until 2004. The sedimentation study became necessary because of the continued reduction in the reservoir storage capacity. Accumulation of sediment from upstream agricultural land may shorten the lifetime of a reservoir and reduce its long-term benefits (Lee *et al*. 2013). Progressive monitoring of reservoir siltation is necessary information for the prediction of storage losses and the probable economic life of reservoirs. The main objectives of this study were: (i) to evaluate the annual rate of siltation in a small reservoir at the FRIN-JICA afforestation project of Afaka, Kaduna, Nigeria using bathymetric surveys, (ii) to predict the life span of the reservoir based on observed parameters.

2. Materials and Methods

2.1 Description of the Study Area

This study was carried out on a small reservoir constructed in 1987 at Sabon Afaka, Kaduna, Nigeria, by the Japanese International Corporation Agency (JICA) in collaboration with the Trial Afforestation Project (TAP) of the Forestry Research Institute of Nigeria (FRIN). The reservoir was constructed primarily for the purpose of nursery plantation irrigation and forest fire fighting. The study area is located between latitude $10^0\,33^/$ N - $10^0\,41^/$ N and $07^0\,26^/$ E - $07^0\,28^/$ E.

The climate of Sabon Afaka is characterized by a clear distinction between dry and rainy seasons. The rainy season lasts from mid-April to early October. The climate of this area can be categorized into three main seasons: the warm rainy season, the cool dry season and the hot dry season (FAO 1971). The mean annual rainfall is 1266.0mm based on annual rainfall record of forty three years (1969 – 2012) (NIMET 2012). The general vegetation of the area is classified under the Isoberlinia Savannah or the Northern Guinea Savannah vegetation characterized by woodland consisting of different layers rather less distinct than those of the forest (Barbour *et al*. 1982).

The reservoir catchment has been evaluated to be 25.5ha, with a maximum travelling distance of 762.5m over the catchment. The elevation over the maximum distance is 21.6m, corresponding to a slope 0.028 (Onwuegbunam *et al.* 2008).

The reservoir catchment is part of the FRIN-JICA afforestation project, with dominantly sandy clay loam soil textural classification based on 1987 survey by the Afforestation project (FRIN-JICA 1991). Up to 25cm depth of the top soil profile has been eroded by surface runoff leaving sandstone outcrops protruding in some parts of the reservoir catchment (Sobowale 2006).

2.2 Bathymetric Surveys

The reservoir storage capacity for each of the observation years was estimated as a function of the water surface area and the corresponding mean depth of water. The reservoir perimeter at full storage, just before spilling, was traversed with the aid of a hand-held Geographical Positioning System, GPS (Model: GPSmap76CSGARMIN) and plotted using AUTOCAD software. The reservoir surface area was subsequently obtained from the plotting of the peripheral coordinates. The depth of the reservoir was measured at grid intervals of 20m by 20m along and across its surface respectively, using floats, anchor and a 4m leveling staff. Hence a mean value was determined for all the grid points.

2.3 Reservoir and Siltation Parameters

The reservoir and siltation parameters were computed using the formulae presented in Table 1 (Adwubi *et al.*, 2009; Aynekulu *et al.*, 2009).

Table 1
Formulae used for calculating the sedimentation parameters

Parameter	Equation	Equation Number
Reservoir storage capacity (RSC)	$RSC = A_r \times h$	(1)
Sediment volume (m^3)	$SV = RSC_i - RSC_{i+n}$	(2)
Sedimentation rate (tyr^{-1})	$SR = \frac{SV \times \rho_b}{Y}$	(3)
Sediment yield (tyr^{-1})	$SY = \frac{100 \times SV \times \rho_b}{TE \times Y}$	(4)
Area specific sediment yield ($tha^{-1}yr^{-1}$)	$ASY = \frac{SY}{A}$	(5)

Where,

Ar = water surface area (m^2), h = mean depth of reservoir (m), RSC_i = reservoir storage capacity at an initial year, i (m^3), RSC_{i+n} = reservoir storage capacity n years after i, (m^3), SV = sediment volume (m^3), SR = Sedimentation rate (tyr^{-1}), ρ_b = Bulk density (tm^{-3}), TE = Trap efficiency (%), AR = Age of reservoir (yr), ASY = Area-specific sediment yield ($tha^{-1}yr^{-1}$), SY = Sediment yield tyr^{-1}, A = Reservoir catchment area (ha)

2.4 Estimation of reservoir trap efficiency

Trap efficiency (TE) is the proportion of the incoming sediment that is deposited, or trapped, in a reservoir or pond (Verstraeten and Poesen, 2000). To determine the average sediment yield from the contributing watersheds, the weight of deposited sediment must be adjusted for the reservoir sediment TE. The calculation proposed by Brown (1943) was used to estimate the TE of the reservoir, as follows:

$$TE = 100[1 - \frac{1}{1+0.0021D\frac{C}{W}}] \qquad (6)$$

D is a coefficient with values ranging from 0.046 to 1 and a mean value of 0.1 (Brown 1943). The value of TE depends on D, which also depends on a reservoir's characteristics. The D value for this study was estimated to be 1 based on the curve developed by Brown (1943) which relates TE to a capacity–watershed area ratio (C/W). Brown (1943) suggested that values for *D* are close to 1 for reservoirs in regions with smaller and more variable runoff and for those that hold back and store flood flows.

3. Results and Discussion

The perimeter view of the reservoir shown in Fig. 1 is an irregular shape. The irregularity has been as a result of reservoir bank erosion by contributing runoff streams as well as deposition of silts on the banks of the reservoir. Fig. 2 shows a portion of the reservoir embankment worn out by the erosive force of incoming runoff stream. Non-uniformity of reservoir depth was also observed, showing that the extent of siltation is not the same throughout the reservoir volume.

The reservoir storage capacities, sediment volumes, loss in reservoir storage, bulk density of sediments, age of reservoir, sedimentation rates, sediment yield and the catchment area-specific yield were determined (Table 2). No sedimentation data existed for the reservoir between 1987 and 2004. It was ascertained from the Project authority that desiltation of the reservoir had not been carried out since the time of construction.

The area-specific sediment yield varied over the years with maximum value of 14.0 $tha^{-1}yr^{-1}$ occurring in 2013 while the minimum, 4.6 $tha^{-1}yr^{-1}$ occurred in 2010. The main factors that contributed to the variation are the annual rainfall in terms of amount and intensity as well as catchment vegetation and land use over each period of observation. The catchment land use has been mainly for woodlot development, cultivation of arable crops and free range grazing by the Fulani cattle.

Table 3 shows the variation of SR and ASY with the periodical annual rainfall. It was observed that SR and ASY increased with the periodical mean annual rainfall. However, the relationship is not defined as there are other factors that affect siltation rates, including the intensity of the rainfall, catchment slope, catchment soil characteristics and nature of the deposited sediments. High intensity rainfall is more effective to cause sediment yield from watershed because detachment susceptibility of soil particles from ground surface is severely affected by the impacting force of falling raindrop during rainfall. The available rainfall data of the catchment was in terms of total rainfall amount; rather than intensity.

The reservoir catchment comprised Eucalyptus woodlot of about 70% canopy density (Fig. 3a) and cultivated areas (Fig. 3b). Sheet and rill erosion have been predominant within the exposed parts of the catchment. Bank erosion has led to the exposure of the upper zone root system of the Eucalyptus trees along the reservoir bank.

The ASY values are within the range of 3 to 49tha^{-1}yr^{-1} with a mean value of 19tha^{-1}year^{-1} as obtained by Tamene (2005) in related studies in Tigray, Ethiopia. The mean global and mean African yields have been estimated to be 15tha^{-1}yr^{-1} and 9tha^{-1}yr^{-1}, respectively (Adwubi *et al.* 2009), while SY ranges between 1.4 to 33tha^{-1}year^{-1} for different basin sizes ranging from 15 km^2 to 70,000km^2 (NEDECO 1997).
Fig. 4 shows a linear relationship between the reservoir storage capacity and age, with R^2 value of 0.994. The equation of the line is expressed as:

$$RSC = -221AR + 16401.4 \tag{7}$$

Where,

RSC = Reservoir storage capacity (m^3), AR = Age of reservoir (year)

Hence, the rate of change (decrease) of reservoir storage, RSC with age, AR is given by the slope, 221m^{3}yr^{-1}. One implication of this relationship is that the reservoir would have been completely silted up (zero storage capacity) when its life span is 76.5 years. According to (IJPR, 1988), the useful life of a reservoir is terminated when its capacity is reduced to 20% of the design capacity. This also implies that the reservoir useful life could terminate in the next 15 years.

4. Conclusions and Recommendations

The study shows that about 35% of the reservoir storage capacity has been covered with sediments within a period of 26 years, and an eventual total sedimentation at 76.5 years, which is a serious problem that undermines the economic life of reservoirs and the associated water uses. Sediment accumulation from the upstream agricultural and woodlot land may shorten the lifetime of the reservoir thus reducing its long-term benefits. The rate of sedimentation was found to increase with periodical mean annual rainfall, though other factors affecting sedimentation were not precisely considered. The study was conducted for only FRIN-JICA reservoir in Afaka. However, it has been ascertained that there are several similar micro-dams within Kaduna State, some of which are almost completely silted up. Since dams are constructed for their economic usefulness, progressive reservoir sedimentation eventually amounts to total economic loss when the reservoirs can no longer perform. Soil erosion control measures within catchments should be undertaken regularly as erosion has been identified as the basic means of sediment detachment and transportation into the reservoir. Adequate data on reservoir sedimentation should be taken as means to guide designers on proper working design of reservoirs for long-term benefits.

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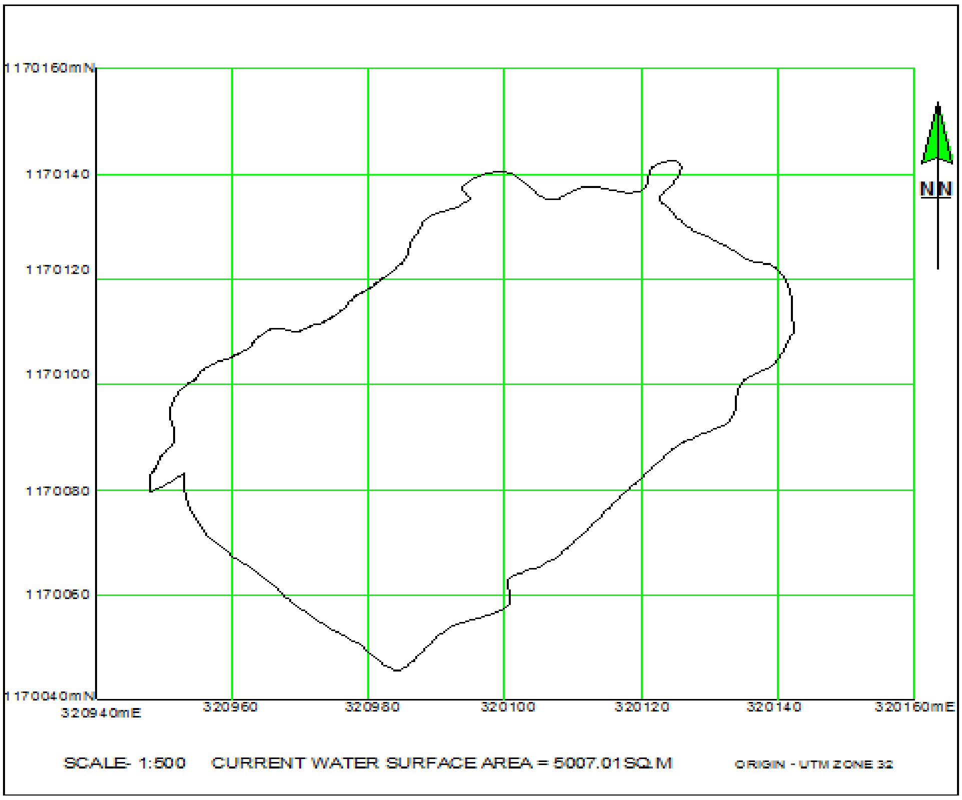

Fig. 1 Perimeter survey of FRIN-JICA Reservoir at Sabon Afaka, Kaduna, Nigeria

Fig. 2. A portion of eroded reservoir embankment showing shape irregularities

Fig. 3a. Part of the reservoir catchment comprising Eucalyptus woodlot

Fig. 3b. Cultivated portions of the reservoir catchment

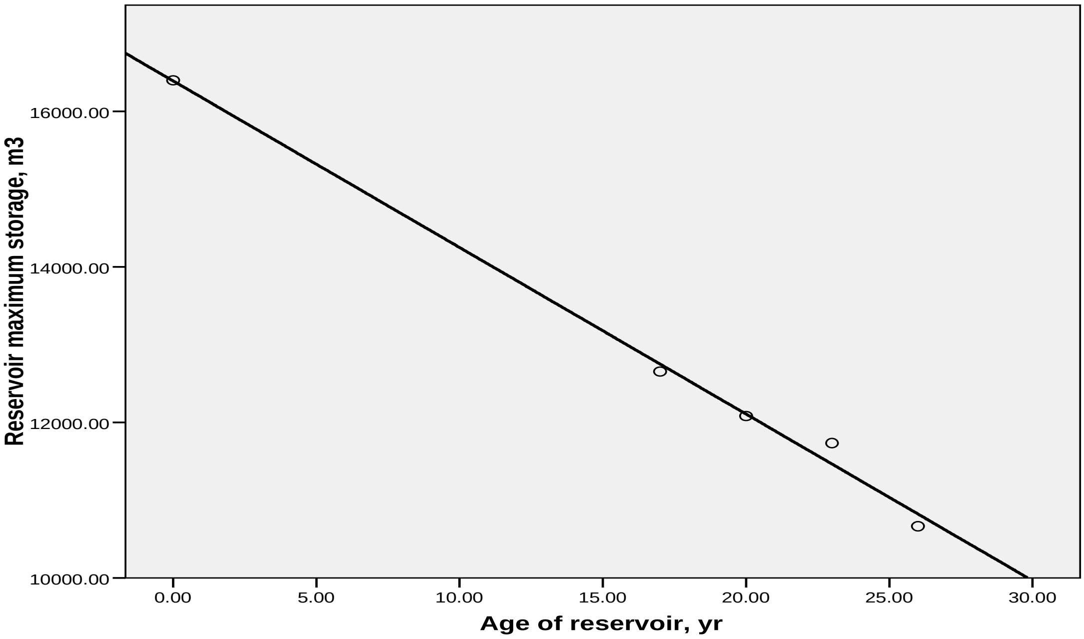

Fig.4: Reservoir maximum storage over time as affected by sedimentation

Table 2

Estimated reservoir storage and sediment parameters

Year	RSC (m^3)	SV (m^3)	SL (%)	ρ_b (tm^{-3})	AR (yr)	SR (tyr^{-1})	SY (tyr^{-1})	ASY ($tha^{-1}yr^{-1}$)
1987	16400	-	-	-	0	-	-	-
2004	12654	3746	22.8	1.20	17	264.0	264.0	10.4
2007	12083	4317	26.3	1.04	20	197.9	197.9	7.8
2010	11734	4666	28.5	0.97	23	116.3	116.3	4.6
2013	10665	5735	35.0	0.96	26	356.3	356.3	14.0

Table 3

Mean periodical annual catchment rainfall and sedimentation rates

Year	**1987-2004**	**2004-2007**	**2007-2010**	**2010-2013**
R (mm)	1211.6	1093.0	972.9	2081.6
SR (tyr^{-1})	264.0	197.9	116.3	356.3
ASY ($tha^{-1}yr^{-1}$)	10.4	7.8	4.6	14.0

R = Mean periodical annual rainfall (mm)

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