Sediment Accumulation in Roseires Reservoir

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Abstract
Sedimentation is a serious problem that faces natural and manmade reservoirs. It is the major problem which endangers and threatens the performance and sustainability of reservoirs. It reduces the effective flood control volume, presents hazards to navigation, changes water stage and groundwater conditions, affects operation of low-level outlet gates and valves and reduces stability, water quality, and recreational benefits.
Reservoirs are often threatened, by loss of capacity due to sedimentation. While causes of reservoir sedimentation are many; watershed, sediment and river characteristics are among the main natural contributing factors. Other important ones are reservoir size, shape and reservoir operation strategy. Manmade activities play also a significant role particularly in land use pattern.
This paper is an attempt to assess the sediment accumulated as well as the rate of sedimentation in the Roseires reservoir. The basis for the study is the previous bathymetric surveys carried out on the reservoir in the years 1976, 1981, 1985, 1992, 2005 and 2007.
Analysis and comparative studies were carried out between the different surveys to quantify the amount of sediment deposited as well as the rate at which sedimentation took place. The design storage capacity of 1967 for the different reservoir levels was taken as base line. The sediment accumulation rates for the different bathymetric surveys are obtained as the difference between base line capacity and the computed capacity at the respective levels during the specific survey.
It was found that sedimentation in Roseires reservoir resulted in the reduction of the reservoir capacity from design storage of 3.0 milliard m^3 in 1966 to 1.9 milliard m3 in 2007 i.e. a loss of about 1.1 milliard m^3 in 41 years of operation. The sedimentation rate varies both with time and levels in the reservoir.

***Key words*:** Sedimentation, Reservoir sedimentation, Roseires reservoirs, sediment accumulation

1. INTRODUCTION

Reservoirs are often threatened, by loss of capacity due to sedimentation. Causes of reservoir sedimentation are many however; watershed, sediment and river characteristics are among the main natural contributing factors. Other important ones are reservoir size, shape and reservoir operation strategy. Manmade activities also play significant role particularly inland use pattern (Nazr, 2006).

Sedimentation is a complex hydro-morphological process which is difficult to predict. It has been underestimated in the past and perceived as a minor problem which can be controlled by sacrificing certain volume of the reservoir for accumulation of the sediment (dead storage). However, today's experience revealed that it is of paramount importance in design and implementation of sediment control measures as well as in the planning, operation and maintenance phases of the reservoirs (Siyam, 2005).

Considering Reservoir sediment problem, surveys are necessary to get more realistic data regarding the rate of siltation to provide reliable criteria for studying the implications of annual loss of storage over a definite period of time. This loss should be associated with particular reference of intended benefits in the form of irrigation potential, hydropower, flood absorption capacity and water supply for domestic and industrial uses including periodic reallocation of available storage for various pool levels. It will also help in proper estimation of loss of storage at the planning stage itself besides evaluating the effectiveness of soil conservation measures carried out in the catchments area of Blue Nile River (Agarwal, K.K. 2000).

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Since the major cause of storage capacity change is sediment deposition, the monitoring program can determine depletion caused by sediment deposition since closure of storage dam, annual sediment yield rates, current location of sediment deposition, sediment densities, lateral and longitudinal distribution of deposited sediment and reservoir trap efficiencies.

2. THE STUDY AREA

Roseires reservoir is located in Sudan and situated along the Blue Nile reach between the dam site and the Ethiopian border. The dam is located in the vicinity of the formerly Damazin Rapids, approximately 6 km upstream the Roseires and some 500 km south of Khartoum. This dam was built in the year 1966 for multi-propose irrigation, fisheries and hydropower (Gibb, 1996).

The watershed of the Roseires reservoir is located within latitude lines (11°--14°) north and longitude lines (33°--35°) east. The soil properties of the study area are clay layers covered with hilly forest at Eldeim then surround by poor Savanna in Roseires and Damazin.

The climate is hot in summer with rains but is cold in winter. The temperature is between (27°—46°C). The annual average rainfall is 700 mm in Damazin and 1500 mm in Eldeim and usually falls between June and October. Rainfall increases gradually upon going South and decreases towards the North till it is almost dry (Ministry of agriculture in Blue Nile State, 2008). Figure (1) shows the location of the reservoir within the Blue Nile system. In figure (2) the Roseires reservoir is shown with a longitudinal and three transverse cross sections (one near the dam axis, one in the middle and one near the end back water)

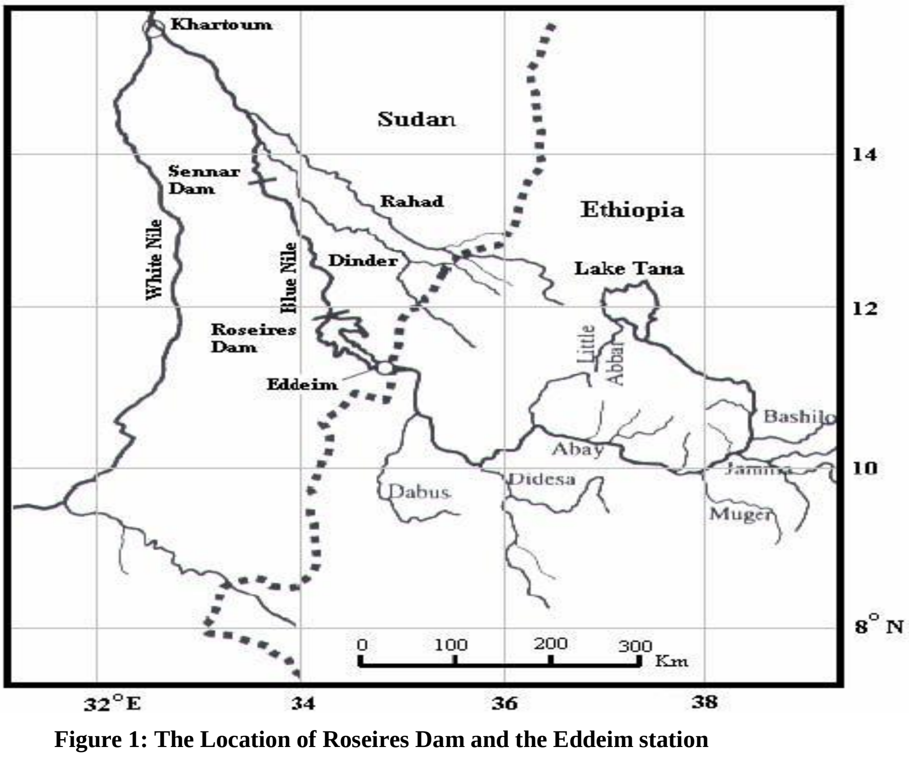

Figure 1: The Location of Roseires Dam and the Eddeim station within the Blue Nile in Ethiopia and Sudan

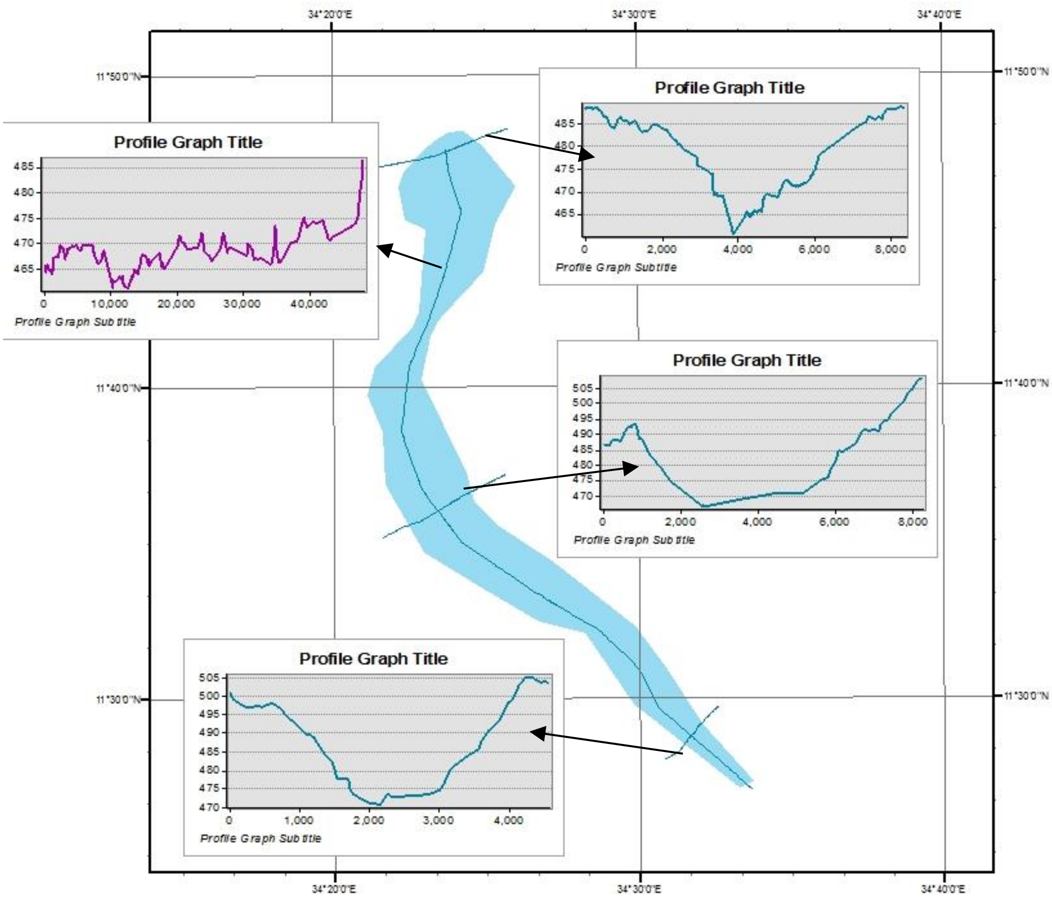

Figure 2: Roseires reservoir with a longitudinal and three transverse cross sections

2.1. The Data

This study uses secondary data available from the dams' operation unit in the Ministry of Irrigation and Water Resources. The bathymetric surveys carried at Roseires reservoir (1976, 1981, 1985, 1992, 2005 and 2007) were collected and used to estimate the sediment accumulation, sedimentation rate and trap efficiency. The 1966 data was used as the base line information and all other surveys were compared to it for storage and sedimentation estimation.

2.2. Roseires Reservoir Operation

Since the trap efficiency is influenced by reservoir operation, it is important to closely examine the reservoirs in order to make judgment on their impact on trap efficiency. The Roseires reservoir filling period commences after the flood peak has passed. According to the reservoir operation rules, filling may start any time between the 1st and the 26th of September each year depending on the magnitude of the flow at El Deim gauging station. From past experience, filling normally starts within the first ten days of September when the suspended sediment concentration is still relatively high at about 2500 mg/l. The filling period usually continues for nearly two months.

There are four main operation periods for Roseires reservoir. During the rising flood, the reservoir drawdown attains the level of 467 R.L which is the lowest operating level. Over this operation period, minimum sediment deposition is expected despite the large quantities of sediment inflow which may approach 3 M ton/day. This is particularly true after many years of continuous operation of the reservoir where a well defined channel, capable of transporting almost the whole sediment inflow past the reservoir during the drawdown period, was developed naturally (Siyam, 2005).

Due to the gradually rising water level and the relatively high suspended sediment inflow, significant sediment deposition is expected during the second filling operation period. In contrast, during the third and fourth operation stages (maintaining full retention level and reservoir emptying), sediment deposition is insignificant due to the exceedingly small sediment and inflow quantities.

From the above description, only operation filling period is of importance as far as reservoir sedimentation and trap efficiency are concerned in Roseires reservoir. Therefore this is taken in consideration when estimating the trap efficiency using either Brune or Churchill method. Over the filling period, the water level at 474 m R.L is considered for the computation. The reservoir content at this mean level is used together with an annual water inflow of $50x10^9$ m^3 to estimate the trap efficiency using both methods. The results are compared with measured values for the years when reservoir surveys were made.

3. METHODS

3.1. Sediment Accumulation

Sediment accumulation in the reservoir is calculated using the bathymetric survey data collected from the Dams Directorate of the Ministry of Irrigation and Water Resources. The base line was taken as the design storage capacity of the reservoir at the different levels in 1966. The storage capacity in the different bathymetric surveys compared to that of 1966 at different levels enables estimation of sediment accumulation rates. Thus, the comparison between accumulated silt volumes deposited between the different surveys is obtained. This work is done using spreadsheet analysis in excel.

The accumulated volume of deposited sediment V_d can also be calculated Empirically from the following formula

$$V_d = (\text{T.E}/100) * (140x10^6 * T)/\gamma$$

Where V_d = accumulative volume of deposited sediment, m^3

T.E = trap efficiency after T years of operation (%)

T = years of operation

γ = average specific weight of deposited sediment over T years (t/m^3) calculated from Miller, 1953 formula (given below)

The constant $140x10^6$ is a site specific term with dimensions t/year derived from Brune's curves.

3.2. Siltation Rate

The average silt deposit per year for the different reduced levels is calculated by dividing the sediment accumulated by the corresponding number of years of operation.

The fraction of reservoir volume silted is obtained by the following calculation:

Average fraction of reservoir depth between two reduced levels silted per year = $\frac{v}{A.d.N}$

Where:

v = Volume of silt accumulated in the given range between any two successive reservoir levels in m^3

A = Average surface area of the reservoir at the middle of given two successive levels in m^2

d = difference between given two successive levels in m.

N = number of years of operation.

3.3. Trap Efficiency

Reservoir trap efficiency is defined as the ratio of deposited sediment to total sediment inflow for a given period within the reservoir economic life. Trap efficiency is influenced by many factors but primarily is dependent upon the sediment fall velocity, the detention-storage time, flow rate through the reservoir and reservoir operation. The relative influence of each of these factors on the trap efficiency has not been evaluated to the extent that quantitative values could be assigned to individual factors. The detention-storage time in respect to character of sediment appears to be the most significant controlling factor in most reservoirs (Siyam, 2005).

Trap efficiency estimates are empirically based upon measured sediment deposits in large number of reservoirs mainly in U.S.A. Brune (1953) and Churchill (1948) methods are the best known ones.

For a given reservoir experiencing sediment deposition, its trap efficiency decreases progressively with time due to the continued reduction in its capacity. Thus trap efficiency is related to the reservoir remaining capacity after a given elapsed time (usually considered from the reservoir commissioning date).

The measured trap efficiency is computed from the following equation:

$$\mathrm{T.E}(\%) = \frac{(V_0 - V)\gamma}{\mathrm{T} * 140 * 10^6}$$

Where, T.E. = trap efficiency after T years of operation
V_0 = original reservoir capacity, m^3
V = capacity remaining after T year of operation
(i.e $V_o - V = V_d = \Sigma v$)
γ = average specific weight of deposited sediment over T years (t/m^3)

γ is calculated from the following equation (Miller, 1953)

$$\gamma = \gamma_i + 0.434\kappa\left[\left(\mathrm{T}/(\mathrm{T}-1)\right)*\left(Ln\mathrm{T}\right)-1\right]$$

with $$\gamma_i = \gamma_{cl}\mathrm{P}_{cl} + \gamma_{sl}\mathrm{P}_{sl} + \gamma_{sa}\mathrm{P}_{sa}$$

Where γ_i is the initial value of γ, while P_{cl}, P_{sl} and P_{sa} are fractions of clay, silt and sand respectively of the incoming sediment and γ_{cl}, γ_{sl} and γ_{sa} are specific weights of clay, silt and sand respectively which can be obtained from the tables prepared by USPR, 1982 for normally moderate to considerable reservoir drawdown (reservoir operation 2) which is the case for Roseires reservoir. The consolidation factor k in lb/ft^3 should be used to calculate γ in lb/ft^3. k depends on the type of sediment (sand, clay, silt) and operational conditions of the reservoir (continuously submerged, periodical drawdown, predominantly dry). Miller provided values for combinations of these variables, ranging between 0 and 256 kg/m^3 (0 and 16 lb/ft^3). In composite sediments, a weighed value should be used.

The essence of Churchill's method is contained in a graph relating the percentage of sediment that passes through a reservoir to a so-called sedimentation index SI. (Taher, A., 1999).

Brune's method is certainly the most widely used one to estimate reservoir's trap efficiency. Siyam (2000) has shown that Brune's curve is a special case of a more general trap efficiency function given by the following equation:

$$\mathrm{T.E}(\%) = 100\exp(-\beta V / \mathrm{I})$$

Where, in addition to the already defined terms, β is a sedimentation parameter that reflects the reduction in the reservoir storage capacity due to the sedimentation processes and I is the average annual inflow of sediments in m^3/y (V/I is the reservoir capacity-Inflow ratio).

Siyam (2000) demonstrated that the above equation with values of β = 0.0055, 0.0079 and 0.015 describes well the upper, median and lower Brune's curves respectively. Brune's semi-dry reservoirs (β = 0.75), and in the case of a mixer tank where all the sediment is kept in suspension (β = 1). The Roseires Reservoir data was fitted with β = 0.056 which was the mean of the individual β values resulting from fitting the observed trap efficiency data.

4. RESULTS AND DISCUSSIONS

The variations of the reservoir storage capacity and silt contents with elevations calculated from the bathymetric surveys of the years, 1976, 1981, 1985, 1992, 2005 and 2007 are shown in the following subsections.

Table 1: Storage capacity at different Reduced Levels (RL)

R.L	1966 (Mm³)	1976 (Mm³)	1981 (Mm³)	1985 (Mm³)	1992 (Mm³)	2005 (Mm³)	2007 (Mm³)
465	454	68	36	26	23	4.5	6.21
467	638	152	91	80	60	13.71	13.98
470	992	444	350	342	235	72.46	72.38
475	1821	1271	1156	1088	932	517.46	566.85
480	3024	2474	2384	2020	1886	1658.38	1637.56
481	3329	2778	2689	2227	2104	1934.73	1920.89

Table (1) shows the decrease in the storage capacities with time at all levels. Figures 3a and b show the variation of storage with reduce level in the specific survey years and the variation of the same with time at specific reduce level. It can be seen that after fourty one years of operation (1966-2007), the total capacity of the reservoir (as computed at reduced level R.L = 481 m) have been reduced to 1920.89 million cubic meters and 13.84 million cubic meters have been lost in the last two years (2005 – 2007).

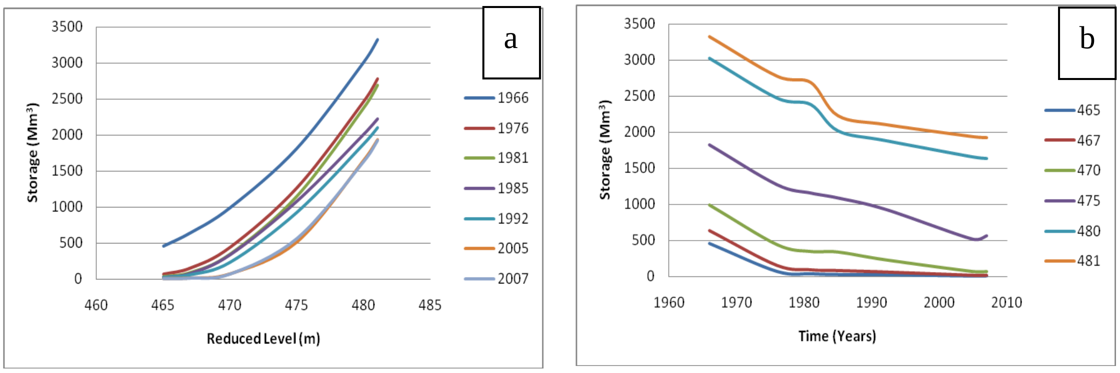

Figure 3: Variation of storage with time and reservoir level

As the initial capacity below reduced level 467 was established to be 638 million cubic meters the loss of capacity below this level was 97.8% of the initial storage. The expected total capacity at design stage of the reservoir at level 490 m was $7.4*10^3$ Mm^3. However, due to the loss of capacity found now at level 481 m, the remaining reservoir capacity at this level amounts to $1.92*10^3$ Mm^3, the expected capacity after the heightening project implementation will be $5.99*10^3$ Mm^3.

Table 2: Accumulated Silt volume deposit for different surveys

R.L	**1976 (Mm³)**	**1981 (Mm³)**	**1985 (Mm³)**	**1992 (Mm³)**	**2005 (Mm³)**	**2007 (Mm³)**
465	386	418	428	431	449.5	447.79
467	486	547	558	578	624.29	624.02
470	548	642	650	757	919.54	919.62
475	550	665	733	889	1303.5	1254.2
480		640	1004	1138	1365.6	1386.4
481		640	1102	1225	1394.3	1408.1

Table (2) Shows the accumulated silt deposited at the different water levels in the different years of survey. It can be seen that there is an increase in the silt deposit with time at all reduced levels. After forty one years of operation (1966-2007), the accumulated silt volume deposit of the reservoir has amounted to 1408.1 million cubic meters. About 14 million cubic meters have been added in the last two years (2005 – 2007) i.e. about 1%. Figure (4) depicts the variation of silt deposited with time and reduced level.

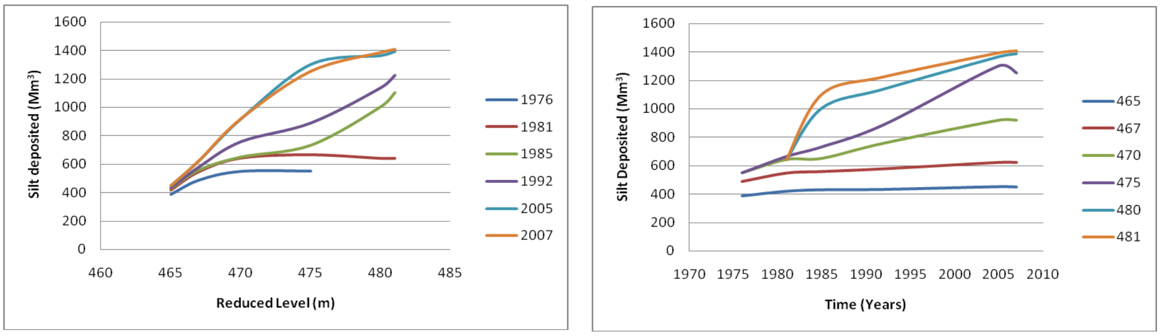

Figure 4: Variation of storage with time and reservoir level

From Roseires reservoir resurveys summarized above, the observed and computed trap efficiency values with Brune's and Churchill's methods are given in table (3). Figure (5) shows graphically the variation of the trap efficiency with time.

Table 3 : Roseires Reservoir Trap efficiency %

Years of re-survey	**1976**	**1981**	**1985**	**1992**	**1995**
T (Years)	10	15	20	27	29
Observed	45.5	36	33.2	28	26.2
Brune's methods	51	49	46	45	45
Churchill's methods	67.7	66	64.4	63.5	62.8

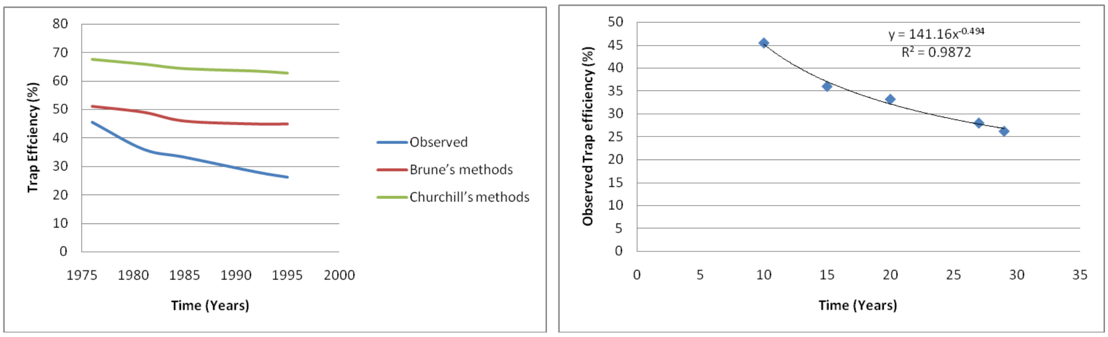

Figure 5: Variation of trap efficiency of the reservoir with years of operation

From Figure (5) it can be seen that the observed trap effeceincy is invesely propotional to the square root of operation time. This figure may be used to estimate subsequent trap efficiency of Roseires reservoir. From the figure, the projected trap efficiency after 100 years of continuous operation will be about 14% if conditions remain the same in the mean time.

It is generally believed that the volume of deposited Sediment from the 1992 resurvey as given in Tables (1, 2) was over estimated. Making use of the results of the later resurvey in 1995, it is expected that the trap efficiency in 1992 to be close but higher than its observed value in 1995 due to the relatively short time in between the two resurveys.

From Table (3) both Brune's and Churchill's methods overestimated the trap efficiency values. The failure of these methods may be attributed to their structures as they consider only few factors. In the earlier years of the reservoir life, the rate of sediment deposited was high as reflected in the relatively high observed trap efficiency values. The deposition rate, however, decreased progressively with time as witnessed from the gradual drop in observed trap efficiency from 45.5% in 1976 to 26.2% in 1995. This trend was not reflected in the computed trap efficiency values using both Brune's and Churchill's methods which remained fairly constant over the years of observations.

Accumulation rate

Table (4) contains the average silt deposited per year for the different reduced levels. As depicted in figure (6) it can be seen that there is a decrease in siltation rate with time at all reduced levels. This phenomenon can be explained by the fact that as time passes a decrease in the reservoir storage capacity occurs; flow velocities for the same discharges are increased; the sediment carrying capacity of the flow being the limiting factor of sediment transport is in turn increased. Between year 2005 and 2007, the siltation rate has dropped from 16.01 million cubic meters per year to 15.22 million cubic meters per year at 467 Reduced Level and from 35.75 million cubic meters per year to 34.34 million cubic meters per year at 481 Reduced Level.

Table 4: Siltation Rate for different surveys (Mm^3/Year)

R.L (m)	1966-1976 (Mm^3/Year)	1966-1981 (Mm^3/Year)	1966-1985 (Mm^3/Year)	1966-1992 (Mm^3/Year)	1966-2005 (Mm^3/Year)	1966-2007 (Mm^3/Year)
Years	10	15	19	26	39	41
465	38.60	27.87	22.53	16.58	11.53	10.92
467	48.60	36.47	29.37	22.23	16.01	15.22
470	54.80	42.80	34.21	29.12	23.58	22.43
475	55.00	44.33	38.58	34.19	33.42	30.59
480	-	42.67	52.84	43.77	35.02	33.82
481	-	42.67	58.00	47.12	35.75	34.34

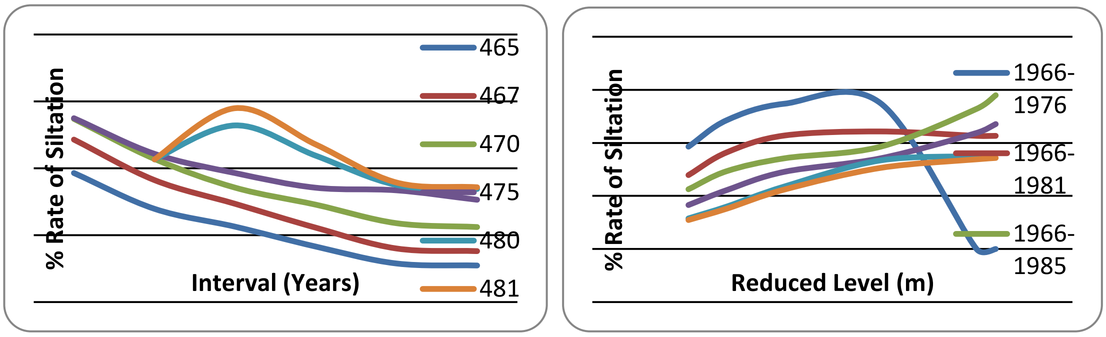

Figure 6: Variation of % siltation rate with time and reservoir level

The accumulated volume of silt deposited in the area impounded by the given intervals of reduced levels (*v*), the average surface area of the reservoir at given intervals of reduced levels (A), corresponding depth increment (d) and the corresponding estimate of % silt; for years 2005 and 2007 are shown in table (5). The value of the average silt deposited per year per depth increment as a percentage of its storage capacity is calculated as given before: % of Silt = *v/AdN*, where N is the number of years of operation.

Table 5: Average silt deposited per year per depth increment as a percentage of its storage capacity (2005, 2007)

Years		**2005**			**2007**		
Level (m)	Depth increment D (m)	Accumulated Silt Volume since start = v (Mm^3)	Area A ($x10^6 m^2$)	%age of Silt $\frac{v}{A.d.N}$	Accumulated Silt Volume since start = v (Mm^3)	Area A ($x10^6 m^2$)	%age of Silt $\frac{v}{A.d.N}$
465-467	2	175	4.5	50	176	3.46	62
467-470	3	295	17.6	14	296	18.11	13.3
470-475	5	384	84.1	2.3	335	102.9	1.6
475-480	5	62	236.1	0.1	132	216.14	0.3
480-481	1	29	273.4	0.3	22	281.62	0.2

As expected, siltation rate is generally heavy below the minimum draw-down R.L maintained during the flood period which is 467. Siltation rate is relatively small above this minimum draw-down level. There is no increase in the percentage silt deposited in the ranges 475- 481. Figure (7) shows the variation of the siltation rate for a given area in the reservoir in 2005 and 2007.

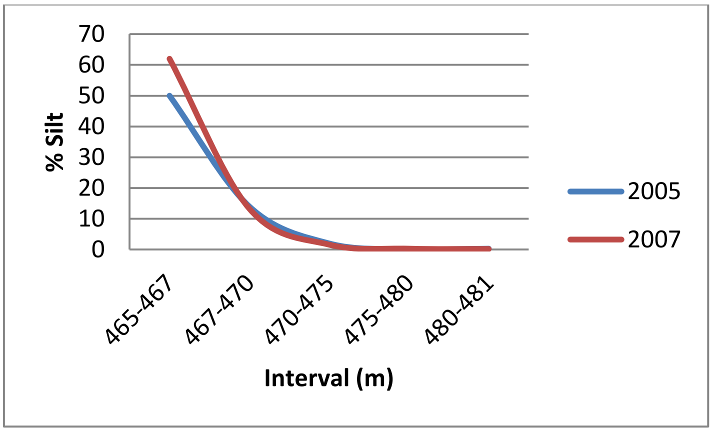

Figure 7: Variation of the siltation rate with area in 2005 and 2007

5. CONCLUSIONS AND RECOMMENDATIONS

About 30% of the reservoir storage capacity is silted up. The rate of siltation at all levels is continually decreasing with time which is an indicator of decrease in storage capacity.

Siltation rate below reduced level 467 dropped from 16 million m^3/year in the period 1966-2005, to 15.22 million m^3/year in the period 2005-2007. While below 481 R.L the siltation rate was dropped from 35.75 million m^3/year in the period 1966-2005 to 34.34 million m^3/year in the period 2005-2007. The present reservoir capacity at reduce level 481 is 1920.89 million m^3 of which 6.21 million m^3 is a dead storage below R.L 465.

A relationship between observed trap efficiency and years of operation was found. The trap efficiency for the reservoir follows linearly the square root of time and is inversely proportional to it. It is projected that the trap efficiency of Roseires reservoir after 100 tears will be in the order of 14%.

It is recommended that a well-planned program for sediment data collection be established especially on the characteristics and movement of sediment in the reservoir, and Blue Nile near the Ethiopian border to monitor the effect of changes and interventions on the upstream site.

Also regular bathymetric surveys, monitoring of sediment accumulation and reservoir trap efficiency is recommended to assess the effects of the interventions.

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