Assessment of Sediment Deposition in Aswan High Dam Reservoir During 50 Years (1964–2014)

Ahmed Moustafa A. Moussa

Contents

Abstract During the last century, many dams exist along the Nile River for various purposes. The existing reservoirs especially those on the Blue Nile, Atbara, and the main Nile River are seriously affected by sediment deposition at unexpected rates.

Roseires Dam was constructed on the Blue Nile (Sudan) to store water for irrigation; the dam lost 40% of its original capacity in a span of 43 years. Khashm

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el-Girba Dam was constructed on Atbara River (Sudan); the dam lost 53% of its original capacity in a span of 46 years.

As for the Aswan High Dam (AHD), it created a reservoir behind it which is Aswan High Dam Reservoir (AHDR). The AHDR is the second largest human-made reservoir in the world. The reservoir extends from the southern part of Egypt to the northern part of Sudan. The AHDR has a total length of about 500 km (350 km inside Egypt and 150 km inside Sudan), the average width of the reservoir is about 12 km, and its storage capacity is 162 billion m^3.

This chapter is an attempt to assess and analyzes the deposition in the Aswan High Dam Reservoir during the last 50 years from 1964 to 2014, by using different techniques to estimate the effective life span of the reservoir.

The traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing by GIS method.

Keywords Aswan High Dam, Delta, Deposition, Egypt, GIS, Reservoir, Sedimentation, Sudan

1 Statement of the Problem

Reservoir sedimentation is a worldwide serious problem and considered as a salient enemy. The graduate loss of capacity reduces their effective life span and decreases their irrigation reimbursements, so as the generation of hydropower, water supply, flood control, and navigation clearance under bridges. Also, sediment deposition propagates upstream, up tributaries and ridges. Moreover, it affects water withdrawals and division. Also, they reduce the sediment load downstream, which might result in the channel and tributary degradation, bank erosion, and in changes of the aquatic habits to those more suited to clearer water discharge.

During the last century, many dams exist along the Nile River for various purposes. The existing reservoirs especially those on the Blue Nile, Atbara, and the main Nile River are seriously affected by sediment deposition at unexpected rates. Currently, for some reservoirs, costly sediment control measures are being practiced. The decision of postponing the problem by heightening the dam has been taken, and the unresolved situation is waiting for those in design and planning stage. Also, the Aswan High Dam, though large, is facing the problem of 100% trap efficiency. Further, in Sudan, Ethiopia, and Uganda, new dam projects are underway or have been proposed.

2 Types of Reservoir Sedimentation

Rivers carry sediment particles with different sizes. These particles are transported as a bed or suspended load. Bed load material is of coarse sediment particles that move near the bed and start to deposit at the beginning of the reservoir entrance in the form of the delta as shown in Fig. 1. As for the suspended sediments, they are fine particles with relatively less fall velocity. They are transported deeper into the reservoir either by non-stratified flow forming a uniform deposition at the middle of the reservoir or by stratified flow depositing at the lower part of the reservoir forming a muddy lake. The suspended load is divided into two parts; one comes from the bed of the river, and the other load from the catchments area as wash load.

Batuca and Jordaan [1] have classified the reservoir sedimentation based on the location of deposition into three categories, with the inclusion of the sedimentation in backwater reaches as a part of the reservoir sedimentation. The position of each type of reservoir sedimentation can be seen in the longitudinal profile of the reservoir as presented in Fig. 1 which are classified as backwater deposition, delta deposition, and bottom-set deposition.

2.1 Backwater Deposition

This type of deposition occurs in the river reach before entering the reservoir. After changing the water level in the river by the effect of backwater curve, the velocity of the water will be reduced. Accordingly, a small portion of coarse sediment will settle in this zone and extends into the reservoir to form a delta. Thus forming a transition, separating the riverbed and the delta formation, is evident (Fig. 1). In theory, the backwater deposit should grow progressively, upward and downward. Consequently, bedforms changes occur. However, this growth is limited because the stream adjusts its channel by eliminating meanders, forming a channel having an optimum width-depth ratio, or varying bedform roughness. These factors make the stream transports its sediment load through the reach of evolution done in one direction Nzar [2].

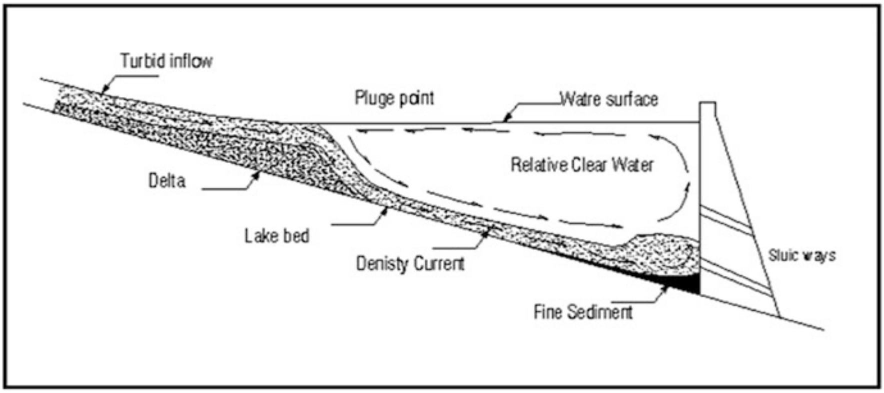

Fig. 1 Longitudinal cross section of reservoir sedimentation

The deposition at the backwater is not stationary, as it fluctuates and advances toward the delta in the reservoir. Accordingly, water surface variation of the reservoir, flow velocity, so as the backwater sediment are carried and transported toward the reservoir and contribute to the formation of the delta.

2.2 Delta Formation

Deltas are formed at reservoir entrances or lake inlets or into the sea. This is achieved by the progressive deposition of large sand sizes (i.e., bed load). This is attributed to the fact that the sediment carrying capacity is reduced.

The water level changes and the expansion of the cross section are the main reasons for water velocity diminishing, and sediment movement is interrupted at the delta zone. Accordingly, deposition occurs at the beginning of the reservoir, where it takes place in the reservoir and basin (i.e., main river zone and over the floodplain) Batuca and Jordaan [1].

Based on the reservoir sedimentation observation, the delta formation contributes to the sedimentation of small reservoirs. On the contrary, large reservoir deltas constitute of a small portion of sedimentation, Morris and Fan [3].

Due to the shallow part small volume at the reservoir entrance, the delta has a relatively smaller volume, which is problematic in terms of upstream aggradation. The cross section of the delta in the longitudinal direction is divided into two zones (i.e., top- and front-set bed) with a different surface slope so as deposition texture as shown by Fig. 2. Strand and Pemberton [4] mentioned that the top-set delta slope ranges between 100 and 20% relative to the original slope that was found at the beginning of the observation. This was the same in 31 observed reservoirs in the States.

For design purposes 50% slope (*S*) is acceptable. Hence:

$$S \text{ top set} = 0.5\, S \text{ river}$$

Based on the same survey data done by Strand and Pemberton [4], the slope of front set can have the relation:

$$S \text{ front set} = 6.5\, S \text{ top set}$$

Under some conditions, the delta forms a major part of the sedimentation of the reservoir (i.e., Glenmore Reservoir – Canada). In this reservoir, 10% of its capacity was lost in 1968 with 70% accumulated in the delta zone, Morris and Fan [3].

The delta advances toward the reservoir in different ways. They are influenced by the reservoir geometric shape at its inlet and its hydraulics. This causes different delta propagation and speed, which have different implications on reservoir sedimentation. Sloff et al. [5] documented the parameters affecting the delta formation shape (i.e., valley slope so as for shape and length, sediment size so as distribution, and reservoir operation so as inflow capacity).

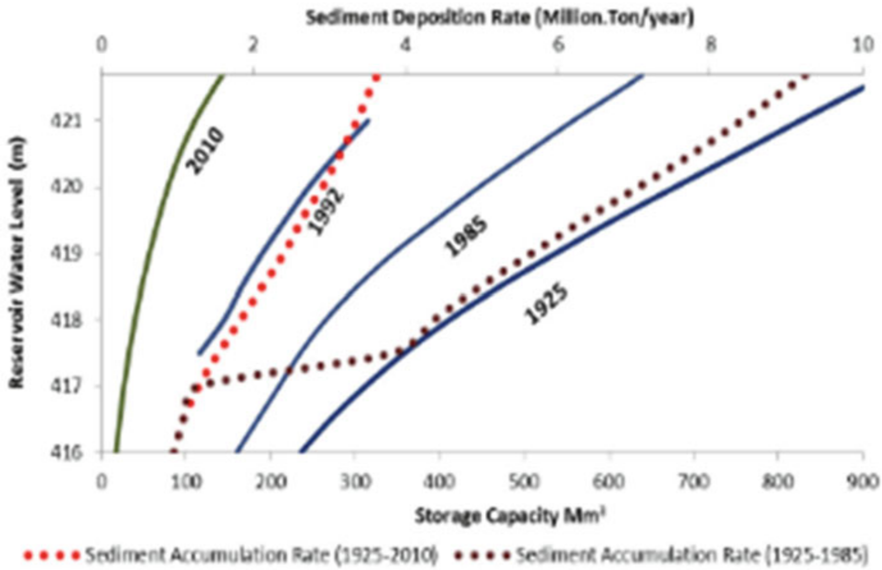

Fig. 2 Reservoir sedimentation and sediment accumulation rate for Sennar Dam Abdallah and Jürgen [8]

The empirical criterion developed by Zhang and Ning [6] mentioned that there are two types of delta formation (i.e., wedge-shaped deposits and delta-shaped deposits). The first has a front that reaches the dam with uniformly distributed sediments, while the second front is away from the dam with nonuniformly distributed sediment.

According to Chang [7] experiments, the delta started with bed load deposition at the mouth. The suspended load is deposited relatively more uniformly over the bottom, Nzar [2].

2.3 Bottom-Set Bed Depositions

Bottom deposition is formed by depositing fine sediment, which is transported by water to the reservoir middle and end. This type of fine sediment is composed of clay and silt, which are transported by turbidity currents or by the turbulent suspension. Its deposition starts beyond the delta upstream the dam wall site.

The shape and configuration of the deposit are affected by the process of transporting and depositing of suspended material. There are two main ways of transporting fine sediment into the reservoir body. First, one is by suspension action of the sediment particle. In this case, they travel toward the reservoir by turbulence of water or by small particles electromagnetically. The second way is by gravity action on the sediment-laden water, which enters to the bottom of the reservoir in the form of a turbidity current.

2.4 Depress Flow

Woods and light material that come with flow cause many troubles and interruption during dam operation. They are quite dangerous to gates and especially to running turbines when the protecting screens are broken under the heavy pressure of the accumulated materials. The best method to get rid of depressing is to direct these floating materials toward the spillways to pass downstream. However, since the depress (wood) comes from the upper catchments, then it would be better to treat the problem, thereby improving and protecting the environment of the wood source. For more information on this topic, consult the reference Nzar [2].

3 Sedimentation in Nile Basin

The reservoir storage is used for water supply, irrigation, power generation, and flood control, but in Sudan, creeping problem of sedimentation causes several implications. First, the lost storage capacity has an opportunity cost in the form of replacement costs for construction of new storage since the present level of supply is to be maintained. Second, there are direct losses in the form of less hydropower production capacity available, less irrigated land to produce food, and reduced flood routing capacity. Finally, the fully silted reservoirs created a decommissioning problem that has both direct and indirect costs.

From Figs. 2, 3, and 4 show reservoir sedimentation and sediment accumulation rate for Sennar, Roseires, and Khashm el-Girba Dam, while Fig. 5 shows the sediment-monitoring network in the Nile Basin. On the other hand, Table 1 shows reservoir sedimentation for some dams in the Nile Basin countries.

From Figs. 2, 3, 4, and 5 and Table 1, it can be seen that the reservoir sedimentation is one of the major challenges in the field of the water resources management in the Nile Basin countries. The process of monitoring and calculation of the reservoir sedimentation is very important for the operation rules of reservoirs.

For example, in Roseires Reservoir, regardless of all efforts done by National Electricity Corporation (NEC) and MOIWR, the sediment problems are still growing. The adverse effects of these problems can be reflected on the socioeconomical part to all users of the dam. The average cost of sediment removal may reach more than 626,000 million US$ per year. Currently, the average annual volume of sediment removed from the hydropower intakes is estimated to be 125 M m^3/year at an average cost of 5 US$ per cubic meter.

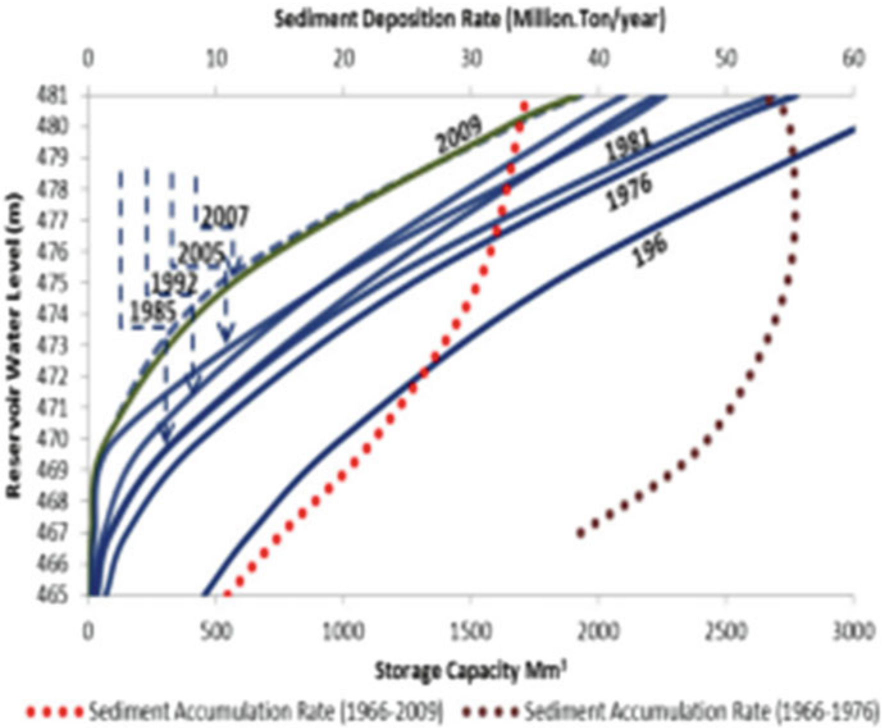

Fig. 3 Reservoir sedimentation and sediment accumulation rate for Roseires Dam Abdallah and Jürgen [8]

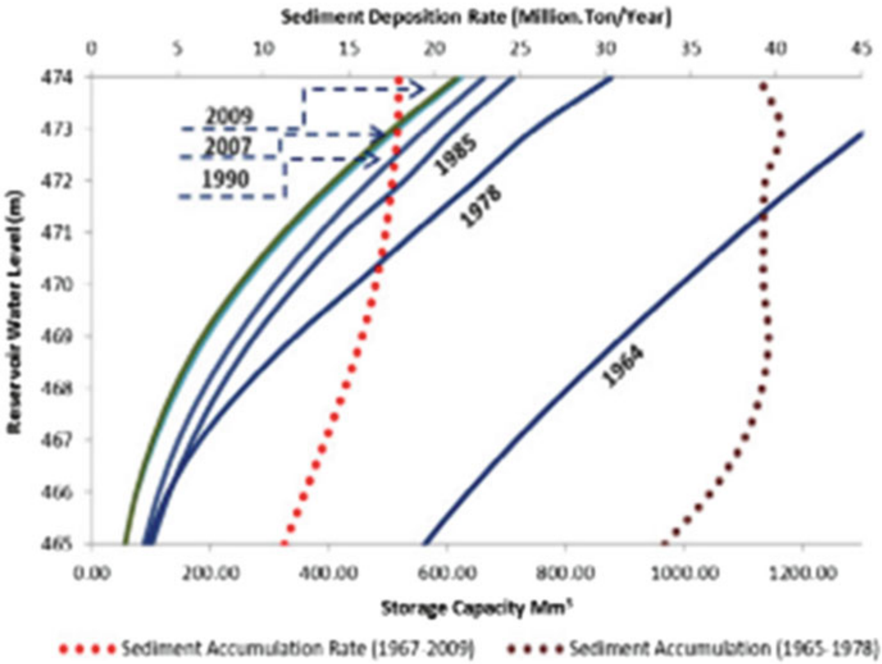

Fig. 4 Reservoir sedimentation and sediment accumulation rate for Khashm el-Girba Dam Abdallah and Jürgen [8]

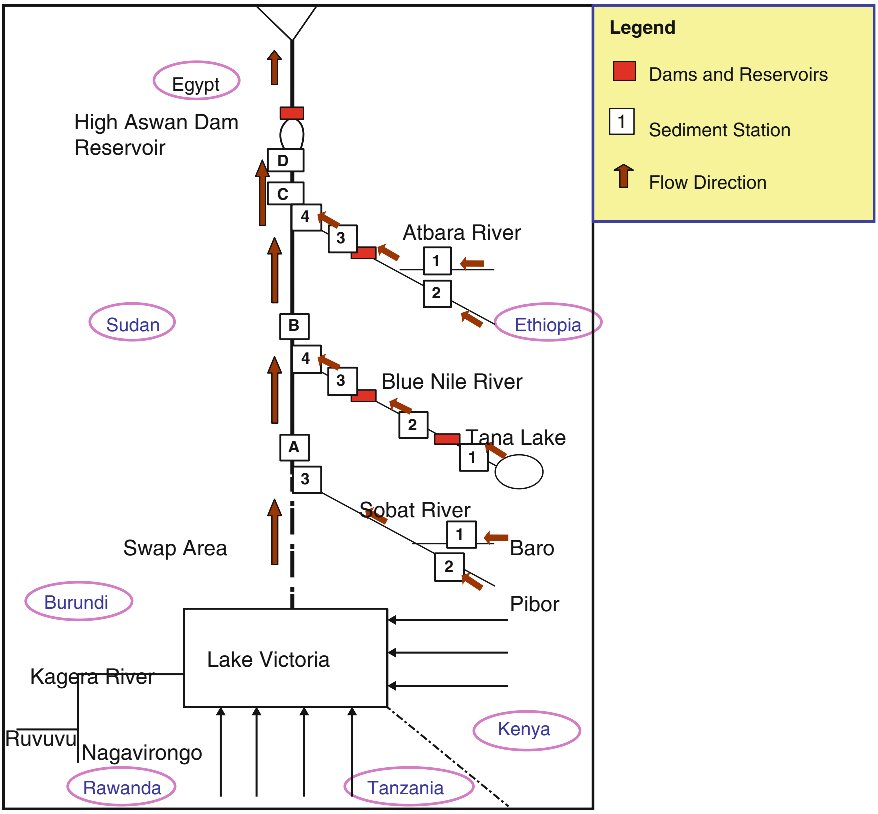

Fig. 5 Layout of the sediment monitoring in the Nile Basin

Table 1 Reservoir sedimentation for some dams in the Nile Basin countries

Reservoir	Country	Name of river	Period considered	Storage losses (%)
Angereb	Ethiopia	Angereb River	1986–2015	46
Koka (Awash R.)	Ethiopia	Awash River	1960–1999	32
Roseires	Sudan	Blue Nile	1966–2009	40
Sennar	Sudan	Blue Nile	1925–2010	85
Khashm el-Girba	Sudan	Atbara River	1964–2010	53
Aswan High Dam	Egypt	Main Nile	1964–2012	4.16

4 The Aswan High Dam Reservoir Sedimentation Rate

The sediment load of White Nile and tributaries is small (i.e., 5% of the annual load of the main river). Meanwhile, 95% of the load is received during the flood and originates from the Ethiopian Plateau.

The Blue Nile system consists of two main tributaries, the Rohad and the Dinder, which join the main stream below Wad Madani (Sudan). These tributaries are fast-

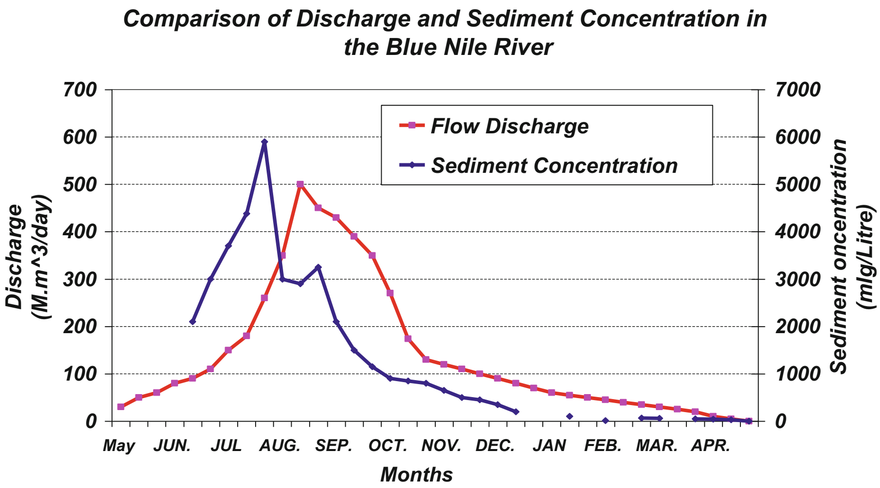

Fig. 6 Comparison of discharge and sediment concentration in the Blue Nile River

flooding stream and drive their water and sediment from the Ethiopian plateau. There are four stations in the Blue Nile, namely, Roseires, Wad Elais, Sennar, and Wad Madani, to measure suspended sediment concentration and flow discharges. The estimated annually suspended load of the Blue Nile was 185 million tons measured at Roseires station (Alexander Gibb 1954). It is noticed that more than 80% of the Blue Nile flow occurs during the period (July–Oct) with a peak in August. The maximum flow may be reached more than 900 M m^3/day; however, during the dry season (Jan–April), the flow may be as low as 10 M m^3/day. The peak of the average discharge comes after the peak of the sediment by about 3 weeks because the sediment is quickly mobilized. This is the characteristic of the Nile Basin catchments. Average sediment concentration is about (4,000 ppm) with maximum values sometimes reaches to (6,000 ppm) as shown in Figs. 6 and 7 [9].

5 Relation Between Discharges and Sedimentation in Aswan High Dam Reservoir

The statistical regression was performed, and the relationship between the flow discharge and sediment discharge can be described by either a linear relationship or a polynomial relationship as follows:

Linear relationship ($R^2 = 0.77$):

$$Y = 0.0011\,X \tag{1}$$

Polynomial relationship ($R^2 = 0.93$):

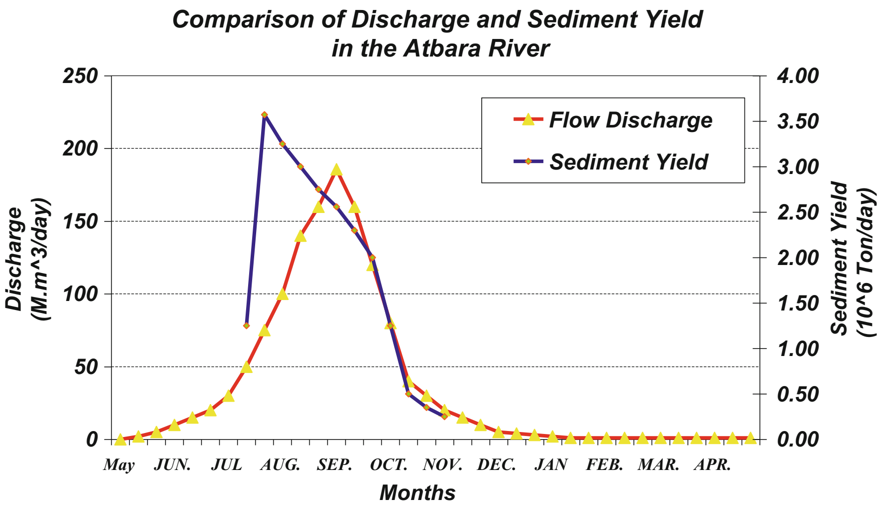

Fig. 7 Comparison of discharge and sediment yield in the Atbara River

$$Y = 6 \times 10^{-10} X^2 - 0.0004X + 70.066 \tag{2}$$

where Y is the total accumulated sedimentation (BCM), X is the total accumulated water discharge (BCM), Aziz and Ismail [10].

6 Previous Sedimentation Studies in AHDR

The literature in the field of reservoir depositions was reviewed. Based on the revision, it was clear that the investigations of sediment deposition in Aswan High Dam Reservoir were concerned with two periods (i.e., pre- and post-1985), e-sciencedirect.

Pre-1985, the investigators were involved in analyzing field data to signpost the reservoir characteristics to designate relationships between sediment and flow. Post-1985, researchers developed mathematical models to the water and sediment to simulate water surface and bed profile (i.e., Hurst [11], Shalash [12], El-Moattasem et al. [13], Abdel-Azez [14], El-Manadely [15], Entz [16], and Smith [17]).

- Hurst [11] found that there was no coarse sand in the reservoir. He documented that 30%, of the sediment, by weight, was transported (i.e., 40% silt and 30% as clay).
- Shalash [12] suggested that the average al rate of sediment was 130×10^6 tons, and the average rate of outflow was 6×10^6 tons. Accordingly, he documented

that the average sediment deposition was 124×10^6 tons. The deposited sediment was $1{,}570 \times 10^6$ tons through 15 years of observation.

- EL-Moattassem and Abdel Aziz [13] considered the sediment balance in Aswan High Dam Reservoir during May 1964 to December 1985. They calculated the volume to be 1650×10^6 m^3, while the deposited volume from hydrographic surveys was $1{,}657 \times 10^6$ m^3 for the same period.
- Abdel Aziz [14] and El Manadely [15] developed 1-D model based on continuity so as momentum equations and the sediment continuity equation. This model could estimate river bed profile change. They determined the deposited volume to be 2,650 BCM during 1964 to 1988. This is equal to estimated volume from field measurements (i.e., 2,760 billion m^3). They concluded that the Aswan High Dam Reservoir cross sections are irregular in the transverse direction. They suggested that developing a new approach to 2-D models is important to predict sediment deposition in transverse and longitudinal directions.
- Entz [16] in 1977 found that sedimentation had been occurring between km 420 and 290 upstream on the dam with its peak at km 350 through echo sounding the lake bottom as early as 1973. He deduced that the sedimentation peak is gradually moving northward. Moreover, he forecasted that the lake would not be completely filled for 1,700 years. In 1980, Entz reinvestigated the sedimentation processes in Lake Nasser during the period from 1965 to 1974. He deduced that the bulk of suspended silt was deposited around the previous second cataract with a layer of 10–25 m thick.
- The wide range of the estimated lifetime differences may be due to many variables including computation method, data input, and theoretical assumptions dealing with the mathematical approach taken Smith [17].

7 Different Techniques for Calculating Sedimentation in AHDR

This section is concerned with the techniques of calculating morphological changes with a new DTM algorithm.

7.1 GIS Method

GIS method will be used for Sudanese part only, which contains 82% of the total sediment deposit in the AHDR.

7.1.1 Algorithm of DTM

Morphological changes calculation could be predicted if the data is available over time steps. By comparing them to the calculated volumetric changes, the changes could be monitored.

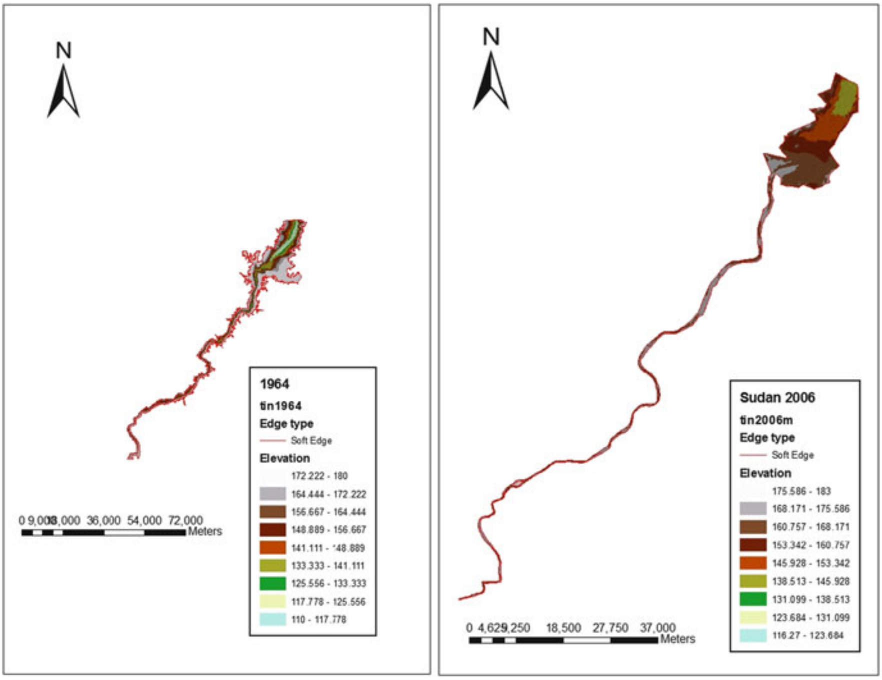

Fig. 8 The interpolated TINs for 1964 and 2006

GIS is obtaining 3-D bathymetry. This is achieved from the collected data of the bed level as scatter points that were interpolated to produce contour lines representing the bed and banks. Three sets were from the Nile Research Institute (NRI). These sets were contour lines and spot level for 1964, 2006, and 2008.

The contour lines of Nile bed level and banks were extracted from data files. They were used to generate scatter points. These will form an irregular triangular net (TIN) by interpolation technique, Fig. 8.

Interpolation technique of scattering points is inverse distance weighted (IDW) method. It is based on interpolating surface that is influenced by nearby points and distant points. The interpolated surface is a weighted average of scatter points and assigned to each point, which diminishes, as the distance from the scatter point increases, Venkatesh [18].

The TIN should be converted to raster files to otain digital terrain model (DTM) representing bathymetry. All DTM files have the same cell size (10 m × 10 m). This type was used in statistical analysis calculations.

7.1.2 Spatial Analysis

The two raster files were used in the logical and mathematical procedure (i.e., algorithm) to calculate deposition volumes. Equation 3 was applied to isolate the topographical surface below the 175 m level which is the water level corresponding to the maximum life span.

$$\text{If } (\mathsf{DTM} \text{ is less or equal than } 175) = \text{logical } \mathsf{DTM} \text{ less than or equal } 175 \quad (3)$$

The logical function on the left-hand side:

If DTM is less or equal 175, it will generate a raster file with the same cells as the original file but with cell values equal to 1 if DTM cell is less than or equal 175 and a cell of 0, if the value is greater than 175.

The logical raster is multiplied by original DTM, such that all values are above 175 m. This will have a zero value, while others will keep original values. The logical and analytical processes were achieved for 2006 and 2008.

To locate the areas where scour and sediment occur, the two bathymetric DTMs of 2006 and 1964 were subtracted from each other and then multiplied by the logical DTM of Eq. 3.

$$\begin{aligned}\text{Morphological raster} = {} & [2006\ \mathsf{DTM} - 1964\ \mathsf{DTM}] \\ & \times [\text{logical } \mathsf{DTM} \text{ less than or equal } 175]\end{aligned} \quad (4)$$

7.1.3 Volumetric Calculations

The resulted raster file, Fig. 9, shows the changes that occurred in the bed during the period from 1964 to 2006 and from 1964 to 2008. Yet, the resulted raster cannot be used to calculate the volume of the scour nor the volume of deposition. However, it can be helpful to locate the locations that were subjected to severe morphological changes.

In order to calculate the volume of bed changes occurred during the period from 1964 to 2006, the following logical and analytical expressions were applied to the resulted morphological changes raster.

$$\begin{aligned}\text{Deposition changes raster} = {} & \text{If (morphological raster greater than 0)} \\ & \times \text{(morphological raster)}\end{aligned} \quad (5)$$

$$\begin{aligned}\text{Scour changes raster} = {} & \text{If (morphological raster less than 0)} \\ & \times \text{(morphological raster)}\end{aligned} \quad (6)$$

The right-hand side of Eq. 5:

If morphological raster is greater than 0, it will generate a raster file with the same number of cells as the original file but with cells equal to 1, whereas depositions occur at a 0, if scour occurs. The logical raster will be multiplied by morphological changes raster. This makes all cell's scour to occur. Deposition occurs and keeps its original value. The logical and analytical procedures are carried to extract deposition and scour, Eqs. 5 and 6.

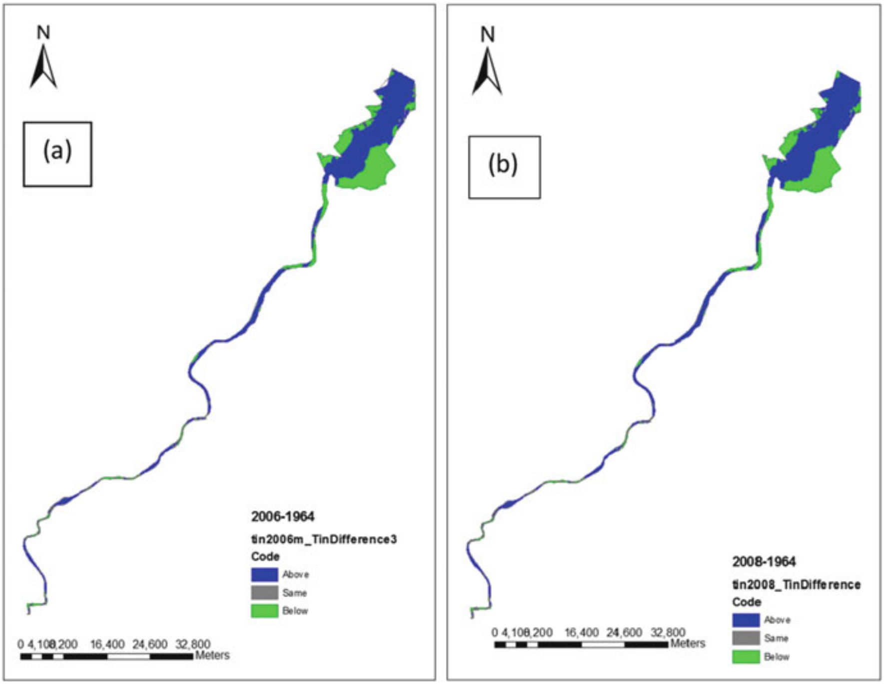

Fig. 9 TINs difference (**a**) 2006 and 1964 and (**b**) 2008 and 1964

The results of Eqs. 5 and 6 are two raster files. One with all the cells, where deposition occurred, is having the deposition depth value, while the rest of the cells have zero values. In addition, the other one shows the scour values for the cells where scour occurred, while the rest of the cells have zero values.

The total volume of scour is calculated by the summation of all cells. Each raster from Eqs. 5 and 6 would be multiplied by 100 m^2 (i.e., area of each cell is 10 m × 10 m), e-cpas.

The same previous steps were repeated for the area for the year 2008.

From Table 2 and Figs. 8 and 9, the total volume at level 175 in 2006 is 4.22 BCM and 4.68 BCM in 2008 for the same level.

7.2 *Traditional Method*

The algorithm is tested against estimated deposition and scour based on the surveyed cross sections to determine the sediment or scour volumes of the river.

The deposited sediment or scour was calculated by assuming distribution to the sediment or scour between cross sections.

The volumes were determined by the area of cross sections and lengths between them. The volume was estimated as the sum of the product of the mean area of two sections and their length e-cpas.

Table 2 The total storage capacity in BCM and surface area km^2 of the AHDR during the period for the year 1964, 2006, and 2008 at different water levels using GIS technique

	1964		2006		2008	
Contour level	Surface area	Volume	Surface area	Volume	Surface area	Volume
110	0	0	0	0	0	0
115	0.07	0	0	0	0	0
120	16.11	0.05	0	0	0	0
125	26.92	0.16	0	0	0	0
130	37.83	0.32	0	0	0.01	0
135	54.61	0.55	0.05	0	0.02	0
140	80.37	0.9	0.21	0	0.1	0
145	108.43	1.38	19.74	0.05	8.72	0.01
150	143.28	2.02	45.08	0.21	34.54	0.12
155	181.24	2.85	74.42	0.5	64.06	0.37
160	214.02	3.84	106.16	0.95	95.11	0.77
165	255.39	5.02	161.12	1.61	138.3	1.34
170	299.77	6.41	239.84	2.6	210.69	2.2
175	368.26	8.11	263.7	3.89	263.12	3.43

In this research, the volumes corresponding to level (175) will be used in the comparison between GIS method and traditional method for 2006 and 2008 in the Sudanese part which contains almost 85% of the total deposited sediment in Aswan High Dam Reservoir.

The total volume at level 175 in 2006 is 4.7 BCM using the traditional method, but GIS method gives 4.22 BCM for the same level.

On the other hand, the total volume at level 175 in 2008 is 5.2 BCM using the traditional method, but GIS method gives 4.68 BCM for the same level.

It can be concluded that the traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing to the traditional method.

8 Percentage of Volume of Sedimentation for Every Cross Section to All Cross Sections of the AHDR

Table 3 represents the volume of sedimentation for every cross section and the percentage of this volume to total volume of sedimentation in AHDR. The maximum percentage of volume is 16.86% in cross section 26 at km 357.0 U.S AHD and the min. Percentage of volume is 2.32% in cross section 19 at km 466.0 U.S AHD. Generally, the average percentage of the most of the cross sections is around 5%.

Table 3 Volume of sedimentation in BCM during the period from 1964 to 2012 and percentage of the volume of sedimentation for every cross section to the total volume of sedimentation of the AHDR

			1964		2012	
Cross section	Km U.S AHD	Repressing length (km)	Volume BCM	Percentage %	Volume BCM	Percentage %
23	487	17	0.121	2.51	0.174	3.08
19	466	19.5	0.15	3.11	0.131	2.32
16	448	17.5	0.204	4.23	0.193	3.41
13	431	16.25	0.287	5.95	0.283	5.01
10	415.5	13.75	0.329	6.82	0.326	5.77
8	403.5	10.75	0.287	5.95	0.269	4.76
6	394	12.5	0.307	6.37	0.298	5.27
3	378.5	11	0.349	7.24	0.353	6.24
D	372	5.25	0.197	4.09	0.197	3.48
28	368	4	0.231	4.79	0.23	4.07
27	364	5.5	0.576	11.95	0.584	10.33
26	357	6	0.725	15.04	0.953	16.86
25	352	5	0.433	8.98	0.785	13.89
24	347	7	0.626	12.98	0.876	15.5
		Sum	4.822		5.653	

9 The Thickness of Sedimentation on the Lowest Point at All Cross Sections During 1964–2012

Table 4 shows the thickness of sedimentation on the lowest point at all cross sections during the period from 1964 to 2012. The maximum thickness of sedimentation on the lowest point is 58.42 m in cross-section D at km 372.0 U.S AHD for the period from the year 1964 (before construction of the AHD) to the year 2012 (the end of the study). These thicknesses varied from 11.04 m in the entrance of AHDR then increasing to the max value 58.42 m in cross-section D at km 372.0 U.S AHD then decreasing the reach around zero in cross-section EL-Madeek at km 130 U.S AHD as shown in Fig. 12.

Figure 10 explains the relation between the storage capacity of the AHDR in billion cubic meters and the years at different water levels from water level 147.0 m (MSL) to water level 180.0 m (MSL) during the period from the year 1964 to the year 2006.

10 Results and Analysis

From Figs. 11 and 12, it is clear that the velocity is decreased in the downstream direction due to the increase of the cross-section area. The d_{50} and TSS also decrease in the downstream direction due to the decrease in the water velocity and their

Table 4 The thickness of sedimentation on the lowest point at all cross sections during period 1964–2012

S. No	C. S. No	Km U.S AHD	Thickness of sedimentation (m)
1	23	487.00	11.04
2	19	466.00	12.42
3	16	448.00	30.82
4	13	431.00	28.06
5	10	415.50	32.66
6	8	403.50	41.86
7	6	394.00	57.5
8	3	378.50	50.6
9	D	372.00	58.42
10	28	368.00	35.42
11	27	364.00	17.02
12	26	357.00	42.32
13	25	352.00	55.2
14	24	347.00	43.7

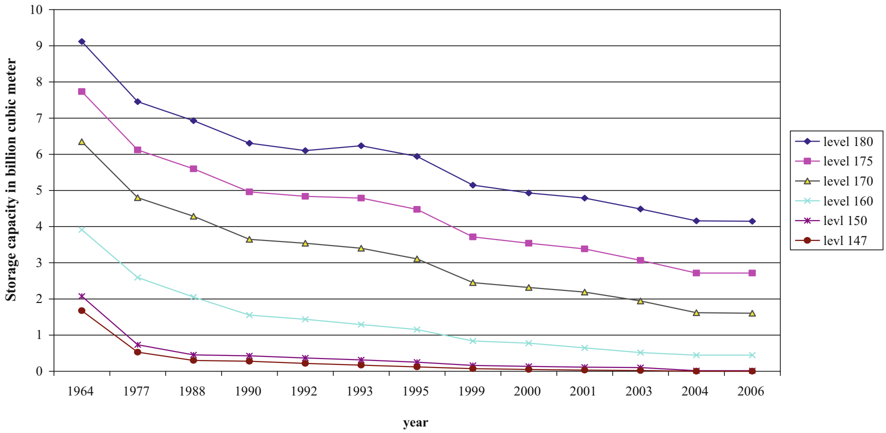

Fig. 10 Storage capacity in M $m^3$of the AHDR at different water levels during the period from the year 1964 to the year 2006

capability to carry up the sediment particles. These explain that almost 82% of the sediment deposit in the first 150 km from 500 km length (the total length of the lake). In addition, almost 18% of the sediment deposit in the last part of the lake 350 km inside the Egyptian border.

Table 5 represents the total storage capacity of the AHDR in Sudanese borders at the year 1964 at different water levels: underwater, level 147.0 m, between the water level 147.0 and 175.0 m, and between water level 175.0 and 180.0 m. It also represents the total storage capacity of the AHDR and sedimentation at the year

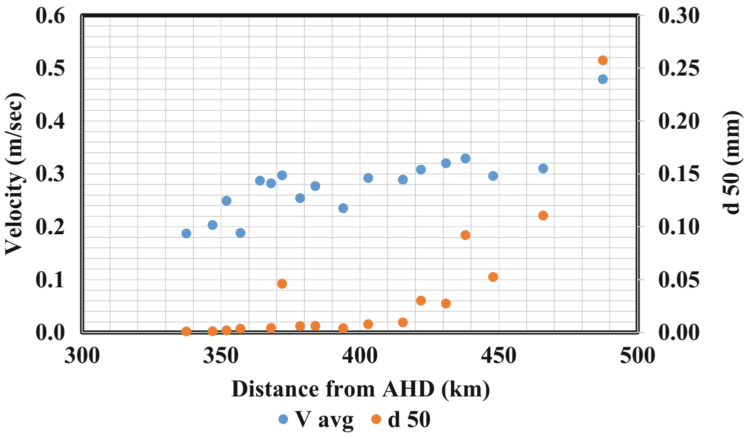

Fig. 11 The relationship between velocity and d_{50} in the Sudanese part in 2006

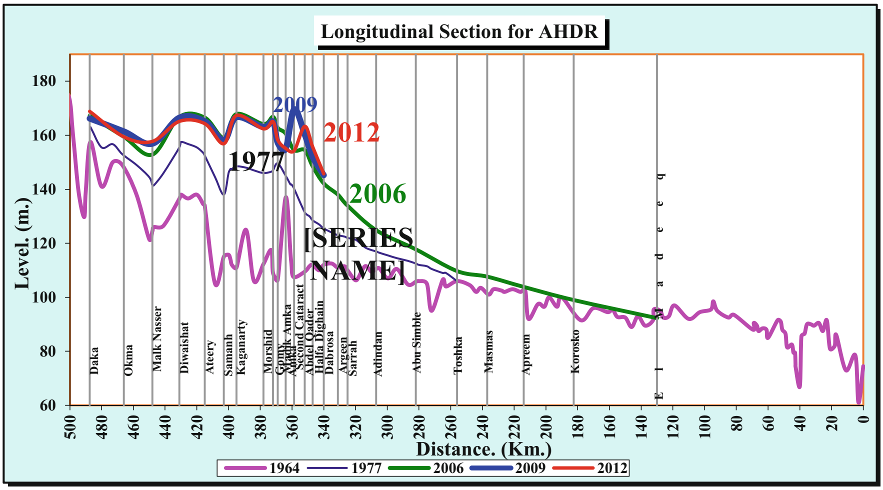

Fig. 12 Longitudinal section of the lowest bed elevation of AHDR from the year 1964 to 2012

2006 at different water levels, at water level 147.0 m, between the water level 147.0 and 175.0 m, and between water level 175.0 and 180.0 m, and the percentage of sedimentation and percentage of the storage capacity of the AHDR at the year 2006 at different water levels. At water level 147.0 m, the storage capacity at the year 1964 equal to 1.673 BCM reduced to zero at the year 2006. At water level between 147.00 and 175.00 m, the storage capacity at the year 1964 equal to 6.06 BCM reduced to 2.715 BCM in the year 2006, and the sedimentation equals to 3.345 BCM. At water level between 175.0 and 180.0 m, the storage capacity at year 1964 equals to 1.380 BCM and still the same value in year 2006 without any sedimentation in this level. At water level under 180.0 m, the storage capacity at the year 1964

Table 5 The volume of sedimentation and storage capacity in B.C.M in Sudanese borders of the HADR at different water levels until 2012

WL	Total storage at 1964	Sedimentation at 2012	Storage at 2012	% Sediment at 2012	% Storage at 2012
<147	1.673	1.673	0	100	0
147–175	6.060	3.862	2.198	63.73	36.27
175–180	1.380	0	1.38	0	100
Sum	9.113	5.535	3.578	60.74	39.26

equal to 9.113 BCM reduced to 4.095 BCM in the year 2006, and the sedimentation equals to 5.018 BCM. The percentages of sedimentation at the year 2006 are 100.0% at water level 147.0 m, 55.20% at water level 147.0 m to 175.0 m, 00.0% at water level 175.0 m to 180.0 m, and 55.06% at water level under 180.0 m.

11 Conclusion

- The total volume at level 175 in 2006 is 4.7 BCM using the traditional method, but GIS method gives 4.22 BCM for the same level.
- On the other hand, the total volume at level 175 in 2008 is 5.2 BCM using the traditional method, but GIS method gives 4.68 BCM for the same level.
- It can be concluded that the traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing to the traditional method.
- The total sediment deposit in the Sudanese border until 2012 is 5.535 BCM.
- The total sediment deposit in the Egyptian border until 2012 is 1.2 BCM.
- The total sediment deposit in the AHDR until 2012 is 6.735 BCM.
- The percentage of losses from the total reservoir capacity until 2012 (162 BCM at level 182 m) is almost 4.135%.

12 Recommendations

The following are also recommendations for future researches:

- Better data should be collected; especially for velocity distribution, wind speed, and bed load.
- It is clear that changes in the watershed and stream management upstream will have a profound impact on the discharge and the sediment load entering AHDR. Watershed models, which link the sediment production and delivery in the upstream catchments to the sediment transport and deposition in the river channels and reservoirs, will allow us to predict the future behavior of AHDR.

- Future upstream engineering projects should be studied for its effects on the amount of water discharge and sediment deposition in the AHDR.
- Using the different technique to estimate the amount of sedimentation such as GIS and remote sensing.

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