

Mitigating the Impact of Climate Change by Reducing Evaporation Losses: Sediment Removal from the High Aswan Dam Reservoir

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Abstract

Scientists in Egypt are particularly interested in the sustainable management of water and land resources. Global climate change will have a dramatic impact on the Egyptian water and land resources as well as its coastline and agriculture. Egypt is likely to become one of the most vulnerable countries in the world in the next several decades. Many climate scenarios predict that climate change will severely affect rainfall in the Nile basin and the flow of the Nile River in general and the High Aswan Dam Reservoir (HADR) in particular. Global warming and the higher temperatures will lead to higher evaporation rates, which, in turn, will result in less water availability at the HADR. Egypt's Ministry of Water Resources and Irrigation predicts that the evaporation losses will, compared to the mean annual evaporation rates for the last 30 years, be approximately 3% to 10% higher by the year 2100. Since the construction of the High Aswan Dam fifty years ago, high sediment loads are a tremendous problem. 6.6 Billion Cubic Meter (km³) of sediments were deposited in the HADR during this period. The sediment has raised the lakebed level as well as the water level and caused a larger surface area. These developments have decreased the storage capacity of HADR and have increased the evaporation rate. The presented paper investigates the impact of lowering the lakebed by removing sediments from the HADR with a distinct emphasis on evaporation losses. A digital elevation model for the HADR was developed to describe the hydrological characteristics and to assess the consequences of removing sediment deposits. The results show that the removal of sediments will reduce evaporation losses by about 1.1 km³ projected for 2100, which represents 6.5% of the total projected evaporation losses.

Keywords

Bathymetric Survey, Climate Change, DEM, Evaporation Losses,

1. Introduction

Dams and their reservoirs play an essential role in people's lives and the development of countries. The purposes of dams are manifold: They are in use for water supply or irrigation, hydropower as well as for flood control, navigation, water quality, sediment control ... These multipurpose dams provide domestic and economic benefits to the people in industrial, developing, and rural countries [1] [2]. In general, artificial reservoirs formed by dams on natural waterways cause problems with regard to sediment inflow and deposition. Sediments consist of mineral and organic material transported by water [2] [3]. The mean annual sediment loads vary considerably from river to river and from reservoir to reservoir depending on their respective morphological and hydrological characteristics [4] [5].

The accumulation of sediments in reservoirs can lead to several problems, such as the loss of storage capacity, which, in turn, reduces the functional efficiency of the reservoir in the long run and increases spillway flows and risk of flooding in downstream waterways. Furthermore, sediments may clog reservoir intakes and outlet structures and scour hydraulic machines. An increase of sedimentation load is likely to cause the loss or impairment of fish, macro-invertebrates, and other aquatic organisms, to reduce water quality due to turbidity in the water, to lower dissolved oxygen levels, and to lead to higher water temperatures [3] [5] [6] [7] [8] [9].

In the period between 1964 and 1971, Egypt constructed the High Aswan Dam (HAD) to overcome the great variability between water supply from the Nile River and Egyptian needs of water quantity and seasonal availability. The Nile River presents the main source of Egyptian water supply. The HAD forms a large man-made reservoir called High Aswan Dam Reservoir (HADR). The reservoir is divided into Lake Nasser in Egypt (approximately 350 km long) and Lake Nubia (approximately 150 km long) to the south in Sudan. The HADR is one of the biggest artificial lakes in Africa and the world. Worldwide, it is the third largest artificial reservoir in terms of storage capacity and the second largest artificial reservoir in terms of surface area [2] [10] [11] [12] [13] [14]. Although enormous benefits are gained from the HAD, it causes a broad variety of problems that are commonly associated with large reservoirs, especially with regard to sediment transport and deposition. 6.6 km³ of sediments have been deposited since 1970 [15].

The Nile's average annual inflow in the HADR of 84 km³ contains approximately 134 million tons of suspended matter, mostly silt. The suspended matter is heavily loaded with inorganic clay, silt, sand, as well as other organic debris (detritus). 98% of the annual sediment load is moved during flood season [16]. Almost all of the clay, sand, and detritus brought by the Nile River are deposited

in Lake Nubia. Most of these are deposited south of Halfa, where a new delta is currently being formed, and only the fine silt enters the HADR. 97% of the sediment load entering the HADR is from the Ethiopian Highlands, with 72% from the Blue Nile and 25% from the Atbara. Only 3% of the sediment load comes from the White Nile [15]. This breakdown and concentration levels vary according to seasonal boundary conditions.

Deposition in the reservoir is governed by a number of factors: The most important one is the sudden decrease of flow velocity as soon as the river reaches the open area of Lake Nubia [15]. As a result, new delta has emerged in the entrance reach of Lake Nubia [15] [17]. The maximum sediment thickness of 60 m was recorded in Lake Nubia approximately 394 km upstream from the HAD in 2008 [18]. The deposits do not only fill the dead storage, but also the life storage of the reservoir, particularly in Lake Nubia. The High Dam Authority (HDA) has repeatedly claimed that the life storage will be recovered if inflows are high. The results of the survey by the HDA indicated, however, that the high inflows in recent years simply have expanded the delta and reduced the live storage of the reservoir [18].

The life time span of the HADR has been predicted several times before and after operations began at the HAD. In 1964, Russian engineers estimated that the life time span of the dead zone would be 500 years. The German company Hochtief, in 1970, expected that the dead zone will be filled in 750 years, and, in the same year, the American Building Authority calculated the life time span of the dead zone to 1000 years [16] [19]. In contrast, [16] estimated that the life time span of the dead zone would be 440 years. Recent studies, however, have painted an even grimmer picture, as they predict that the dead zone will be filled already in 200 to 254 years, that is, even less than 50% of the intended life time span of the original design. [17] used a two-dimensional numerical model (CCHE-2D) to study the scouring and silting processes in the HADR. The results showed that the life time span of the dead zone is only 254 years, while the life time span of the life zone is 985 years. [20] Ahmed and Ismail (2008) released the results of a report entitled “the sediment in the Nile River system,” which was funded by the International Sediment Initiative, a UNESCO International Hydrological Program. Using data available for the HADR, they found out that the suspended sediment dominates the total sediment in transport. This study shows that approximately 90% of the total sediment load is suspended load and less than 10% is bed load. Based on these results the dead storage is likely to be filled in about 200 years. Unfortunately, most of the sediment is deposited in the live storage, which slightly reduces the function of the dam.

With its limited water resources, Egypt will be significantly affected by climate change [21] [22]. Climate change will reduce Egypt’s share of water from the Nile by causing flow fluctuations and higher evaporation losses from the HADR, which can reach up to 20 km³ per year [23]. These losses are expected to gradually increase due to global warming [24]. As the flow of the Nile River is likely to change considerably, it will also greatly affect water management in Egypt. Cur-

rent water management strategies, which are used to secure the water supply in Egypt, may not be sufficient to meet these demands in the future. Both, water supply and demand are expected to change in response to climate change, population and industrial growth, as well as the upstream development projects in other Nile Basin countries [23]. In light of these developments, the Ministry of Water Resources and Irrigation (MWRI) of Egypt developed climatic scenarios (low, medium, high) based on the results generated with eleven Global Circulation Models (GCM) for B2 emission scenario (IPCC, 2007), which is included in the Special Report on Emissions Scenarios (SRES) [24]. In these GCM models, the effects of climate change on air temperature and evaporation losses were studied. Based on the Climate Model ECHAM5, developed by the Max Planck Institute for Meteorology in Hamburg, it is predicted that the mean annual evaporation losses at the lake's surface area of 6500 km² will increase by about 0.47 km³, 0.88 km³, and 1.66 km³ for the years 2030, 2050, and 2100, respectively. Using the Climate Models HadCM3, developed by the UK Hadley Centre for Climate Prediction and Research, it is estimated that the annual evaporation losses will increase by about 0.52 km³, 0.80 km³, and 1.46 km³ for the same years. That means that evaporation losses will be about 3% to 10% higher by the year 2100, compared to the mean annual evaporation rates for the last 30 years [23].

Recent researches focused on the HADR and investigated options for the reduction of the high evaporation losses. Since the construction of the HAD, many studies have offered methods for estimating evaporation losses. In contrast, only few recent projects have discussed about tools for reducing them. [25] assessed tools for reducing the evaporation from Lake Nasser using new and environmentally safe techniques. Their empirical study showed that the annual average of the daily evaporation rate from Lake Nasser is 6.3 mm per day and that the average annual water lost by evaporation is about 12.5 km³. They designed a system to cover a part of the lake surface by using small artificial circular foam sheets between big ones. This system had a coverage efficiency of about 90%, and prevented the passage of sunlight to the water body. Despite this shortcoming, the system can save more than one million cubic meters (Mm³) of water from Lake Nasser by covering 0.50 km² with circular foam sheets.

[26] also evaluated tools that could be used to reduce evaporation at Lake Nasser by disconnecting fully or partially some of embayments, have been named locally as khors, of the HADR. They used Landsat 7 ETM+ images to calculate the surface temperature from Landsat's thermal band in March and, applying aerodynamic principles, thereby evaporation depth and approximate evaporation volume for the entire lake. The study showed that there were evaporation losses between 2.73 mm per day at the center of the reservoir and 9.58 mm per day along the shores, which leads to a total loss of approximately 0.86 km³ per month in March. They recommended disconnecting two khors from the HADR with dams with approximate heights of 8 m and 15 m to save 2.4 km³ annually. It is important to consider these and other tools, as climate change will have a severe impact on Egypt in general and the region around the HADR in

particular.

Using an up-to-date digital elevation model (DEM) of the HADR, [27] assessed options for reducing evaporation losses. The DEM was developed using recent satellite images for water levels above 154 m above mean sea level (AMSL) and the data collected during a bathymetric survey of the lakebed in 2010. The hydrological characteristics for the HADR (surface area, water volume) for different water levels were computed based on this DEM, and new equations were generated to model the relationship between all variables. Several alternatives for reducing the evaporation losses of two large khors, Kalabsha and El-Alaky, and two small khors, Korosko and Sara, were investigated. The study recommended several measures to eliminate these khors to save up to 3 km³ of water by 2100. The results of this study are relevant due to the fact that lowering the lakebed will decrease the surface area and, subsequently, will reduce evaporation losses.

Further on, the accumulation of sediment reduces the water volume which, shortens the life time span of the HAD [15] [18] [19]. Therefore, it is important to develop a plan to mitigate these serious consequences, to prevent blockages in Egypt's vital waterway, the Nile River, reduce evaporation losses, and make use of the sediments. This paper will assess the impact of removing the sediment deposits from HADR on its hydrological characteristics and evaporation losses with a distinct emphasis on climate change.

2. Material and Methods

2.1. Study Area

The HADR is located upstream of the HAD, 17 km south of the old Aswan Dam. The HADR is approximately 500 km long and 3.5 km wide at its widest point. It covers a surface area of 6514 km² at an altitude of 182 m AMSL and has a storage capacity of 162 km³ of water. This is about twice the average annual yield of the Nile at Aswan, which is estimated at approximately 84 km³ [18]. It is located between latitudes 23°58'N at the High Dam and 20°27'N at the Dal Cataract in Sudan and between longitudes 30°07'E and 33°15'E, as shown in **Figure 1** [28].

The morphology of the HADR is characterized by the presence of numerous side extensions (embayments), locally known as khors, which are considered the key feature of the reservoir. There are over 100 khors, 48 of which are located on the eastern side of the reservoir [29]. The existence of the khors greatly increases the length of the shore, which is estimated to be 12,000 km at an altitude of 182 AMSL. These khors cover approximately 3000 km² or 50% of the total surface area [27]. The large surface area of these shallow khors is one of the major reasons for high evaporation losses [18].

There are basically four storage zones in the HADR. The dead storage zone is the storage below the level of 147 m AMSL and a storage capacity of 31 km³. This zone is reserved to be filled with sediment; as discussed above, this process may take up to 500 years. The live storage zone between 147 m and 175 m AMSL is the active storage, with a storage capacity of 90 km³. The zone between 175 m and 182 m AMSL is the flood storage, with a storage capacity of 41 km³. This

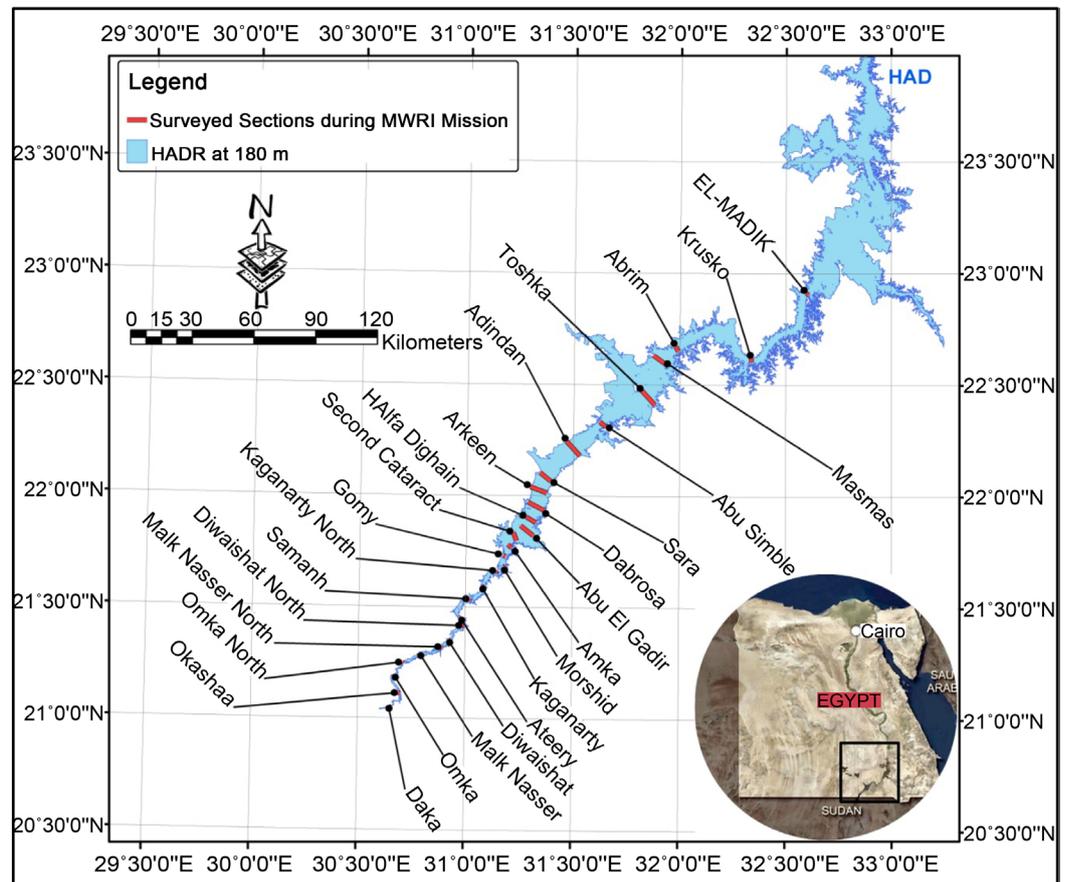


Figure 1. Map of HADR with location of cross section by the MWRI mission in 2007.

zone is divided into two zones: the flood control zone between 175 m and 178 m AMSL, which is used to contain water from the annual flood and which needs to be emptied at the beginning of the water year (August 1), and the surcharge storage zone between 178 m and 182 m AMSL, where excess water can spill over the top of the dam in a spillway. The maximum upper limit is 183 m AMSL [16].

2.2. Methodology

Between 1973 and 1999, the MWRI conducted bathymetric surveys for only a few cross sections because it was very difficult to measure the reservoir's morphology and sedimentation processes in the HADR with traditional survey methods. However, since 1999, the MWRI has used a hydro-acoustic system with a Differential Global Positioning System (DGPS) and Echo Sounder to collect data on depth and location as an alternate method of mapping the bottom of the reservoir. This technology provides bathymetric data in a format that can be used to create digital maps. In general, survey data has been collected along cross sections of the reservoir, as shown in **Figure 1**. The number of sections increased from 18 cross sections in 1999 to about 29 cross sections in 2006.

The bathymetric survey of the HADR has been conducted on a regular basis by the MWRI. Due to the analysis of these cross sections, it became clear that the sedimentation rate was extremely high in Lake Nubia across the border to Su-

dan. Therefore, the MWRI has usually conducted comprehensive surveys for Lake Nubia in its entirety and for the sections in Egypt's part of Lake Nasser that are characterized by high erosion or sedimentation rates, as shown in **Figure 2**. Since 2006, the entire Lake Nubia has been surveyed to investigate sediment problems. Lake Nasser was only surveyed in certain sections except the conduct survey in 2010 when the reservoir was comprehensively surveyed up to the El-Madik section. It has to be noted that some parts of Lake Nubia were not surveyed due to navigation problems.

In addition to a small percentage of small-size gravel, the main river's sediment load includes sand, silt, and clay. During a bathymetric survey, the MWRI also monitors the soil at the bed of the HADR. These samples have been collected to determine the properties of the deposits in these cross-sections. The samples have been collected from eastern and western parts of the cross section as well as from the middle. Sieve analyses and sedimentation analyses were applied to the samples to determine their characteristics and distributions. There are three main categorizes: clay and silt, sand, and gravel.

This study uses the data that have been generated by the MWRI since 2007, to analyze and identify the characteristic features of the soil at the bottom of the HADR. The average distribution of clay and silt, sand, and gravel were stored in data files. A point shape file was created including the soil classification data for each section along the HADR using a GIS-system. **Figure 3** shows, in a flow chart, how the data from the bathymetric surveys was processed. The data on water depths was saved as text files, which included the coordinates of each point and the water depth. Water depths were subtracted from the lake surface water level, measured during this phase to determine the lakebed altitudes above

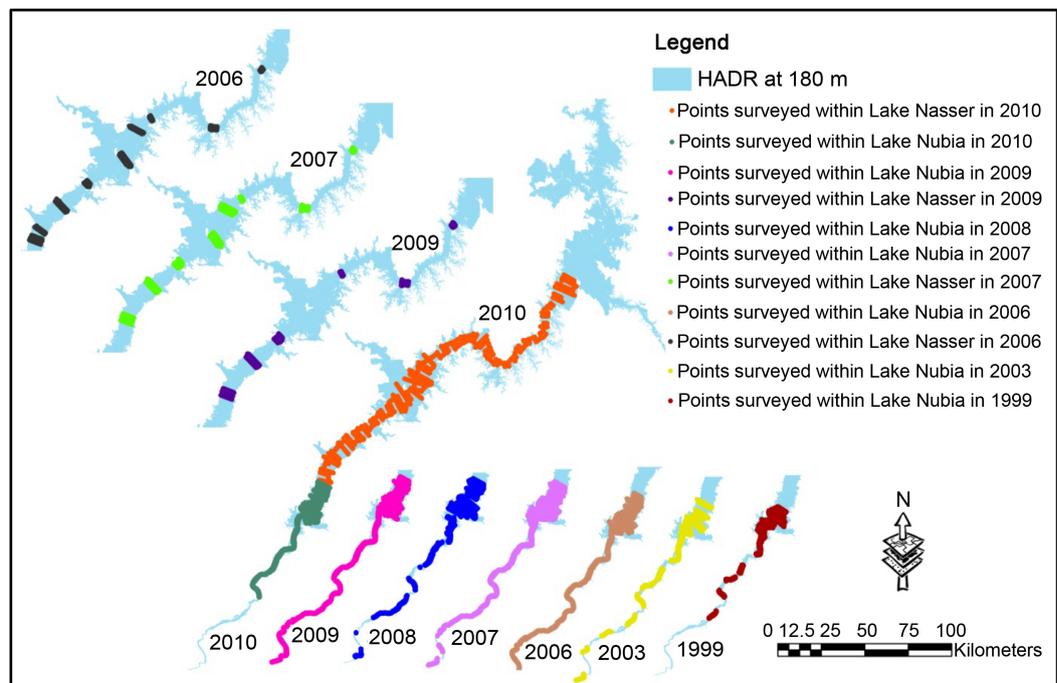


Figure 2. Points surveyed on Lake Nasser and Lake Nubia between 1999 and 2010.

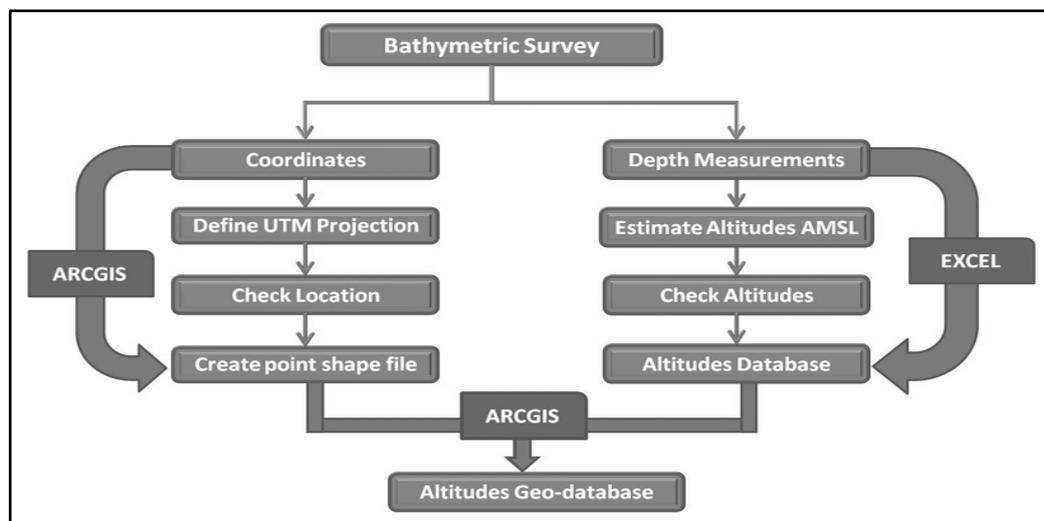


Figure 3. Flow chart depicting the processing of the bathymetric survey measurements.

mean sea level. The data was checked to eliminate wrong altitudes or coordinates outside the HADR. The data was created as a point shape file. The surveyed points reached up to 300,000 points for one mission. In this paper, the data collected for the missions executed in 1999, 2003, 2006, 2007, 2008, 2009, and 2010 was used to generate point shape files, as shown in **Figure 3**. The bathymetric surveys usually covered the Lake Nubia in its entirety. Therefore, the point shape files were used to generate DEMs for the bed of Lake Nubia during the above mentioned years. These DEMs were used to monitor sediment events in Lake Nubia because this part of the HADR usually undergoes high sedimentation rates. The annual amount of sediment deposited in this area for those particular years was computed by estimating the difference between the altitude values in the DEMs, as shown in **Figure 4**. The volumes of sediment and erosion events were estimated.

[27] produced an up-to-date DEM for the HADR and built mathematical models for the relationship among hydrological characteristics of the HADR (water level, surface area, water volume). The impact of removing deposits from the reservoir was calculated as follows: Assuming that the sediments were removed from the HADR, the volume of these sediments in the HADR was subtracted from the current water volume, and new equations were generated to simulate the hydrological characteristics of the HADR after a potential removal of sediment deposits. The differences between the surface areas, before and after the removal of the sediment deposit at different water volumes, were computed. These differences were used to estimate the potential reduction in evaporation losses.

3. Results and Discussions

3.1. HADR Bed Soil Sedimentary Categories Database (HADRBSDB)

The HADR Bed Soil Sediment Categories Database (HADRBSDB) was created

to record the sediment categories of the bed soil data of the HADR, which has been collected by the MWRI since 2007. **Figure 5** shows a chart with percentages of the HADR's bed soil categories in 2007. The 410-kilometer-long section starting at the southern end of the HADR has been characterized by higher sedimentation rates of sand while in the other part, more silt and clay sediments, particularly in the section from kilometer 350 to kilometer 400 upstream of the HAD, were deposited. However, strong winds from the eastern desert also brought sand to the reservoir, and these sands were deposited from kilometer 100 to kilometer 350 upstream of the HAD [15] [18]. In few sections, a very small percentage of gravel was found.

Figure 6 shows the distribution of bed soil sediments along the cross sections of the HADR in 2007. There are thick layers of silt and clay sediments in the cross-section between the HAD and the Ateery cross section, which is located 415 km upstream of the HAD. Sand sediments increased from the Ateery cross

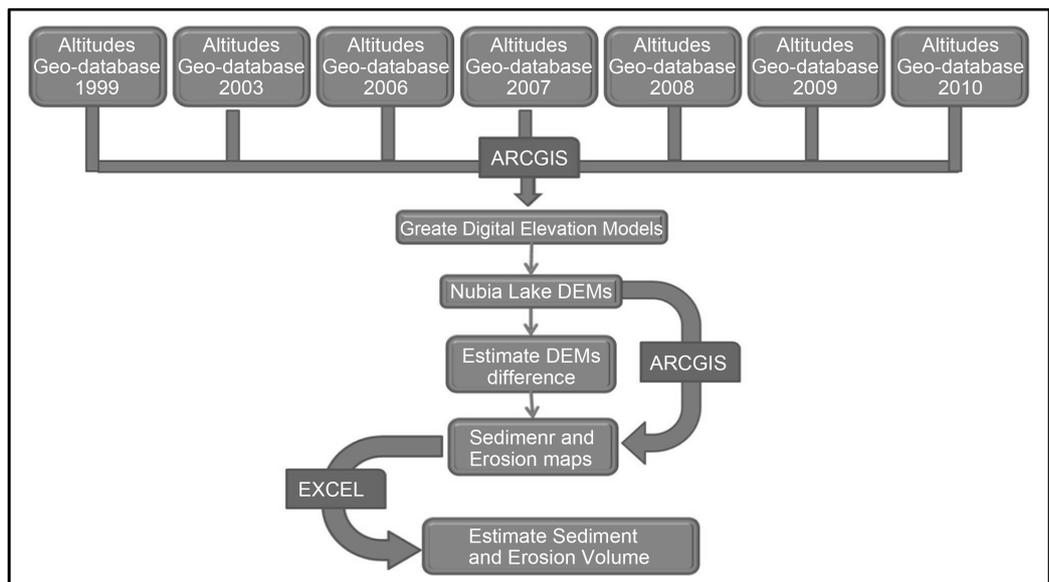


Figure 4. Flow chart depicting the method for estimating sediment and erosion events.

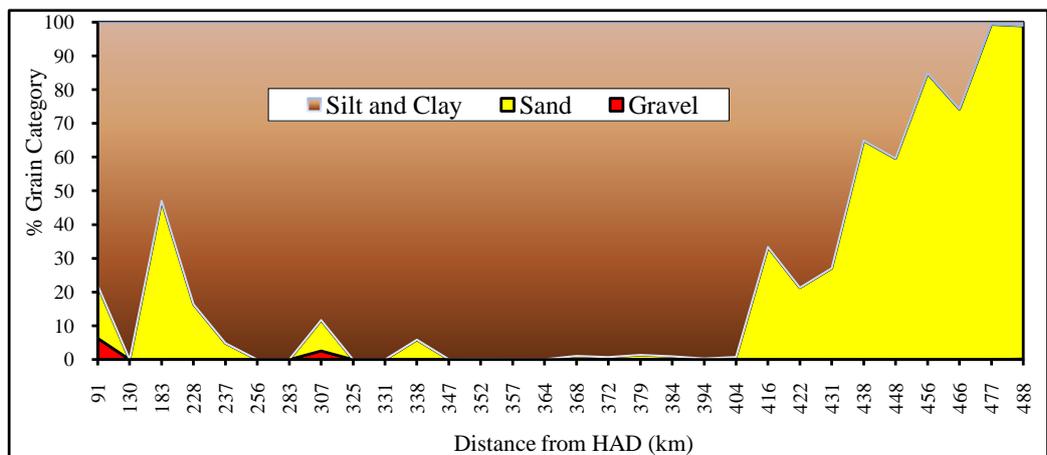


Figure 5. Chart depicting percentages of the HADR's bed soil sediment categories in 2007.

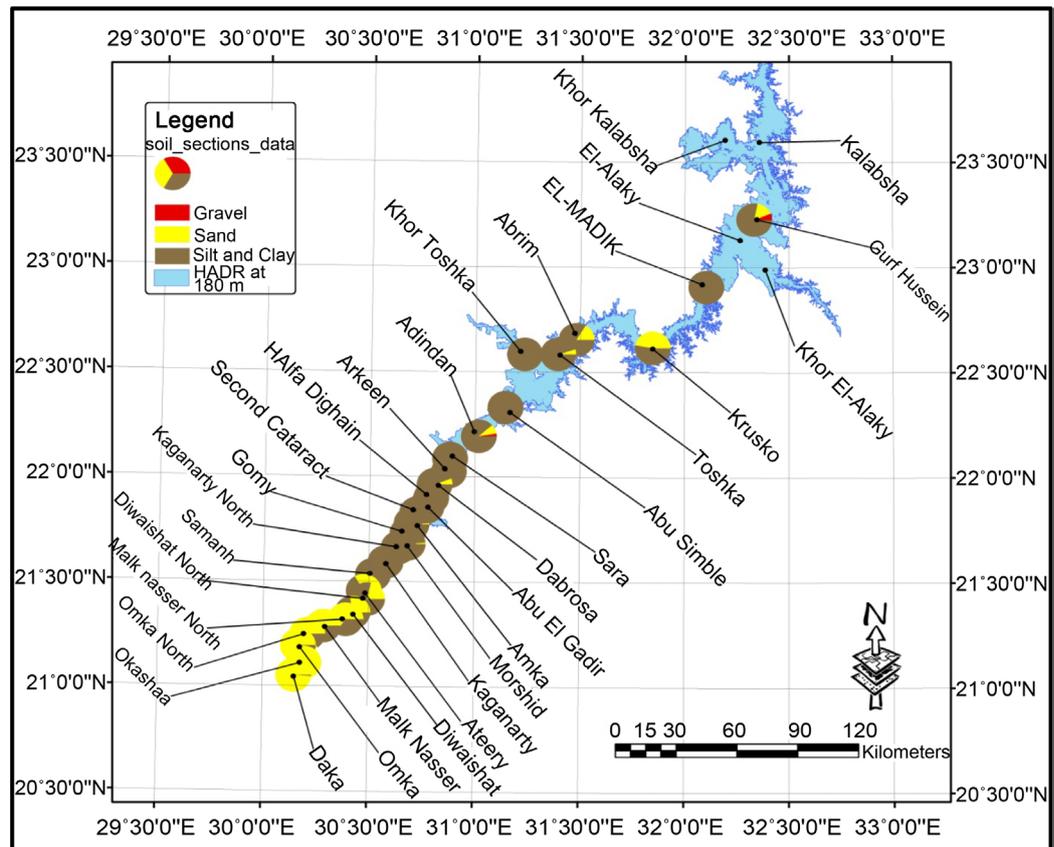


Figure 6. Distribution of bed soil sediments along the HADR's cross sections in 2007.

section to the Daka cross section, which is located 478.5 km upstream of the HAD, and they reached almost 100% at the southern end of the reservoir.

3.2. Exploring the Sediment Conditions in the HADR

The DEMs of Lake Nubia for the years 1999, 2003, 2006, 2007, 2009, and 2010 were compared to monitor changes at the bottom of the HADR due to sediment and erosion events. **Figure 7** shows the longitudinal section along the HADR's deepest points from 1964 to 2010. The longitudinal section of 1964 was taken from the main Nile regime before the construction of the HAD. The section of 1977 was taken from an old survey of the HADR. A new delta has developed between the Samanh section, approximately 403 km upstream of the HAD, and the Gomy section, 378 km upstream of the HAD [15] [18] [20]. **Figure 8** shows the changes in terms of altitude due to successive sedimentation and erosion events during the past 50 years.

In the period from 1964 to 1977, successive sediment events occurred, particularly in Lake Nubia, whereas the El-Madik section at 130 km in Lake Nasser experienced minor erosion problems. There were minor sediment problems in Lake Nasser, particularly between the Sara and Apreem sections from 325 km to 331 km, while the reach between Korosko and El-Madik from 182 km and 130 km did not experience any major changes. In the period from 1964 to 1977, the Madik Amka section at 368 km experienced the largest increase of sediment

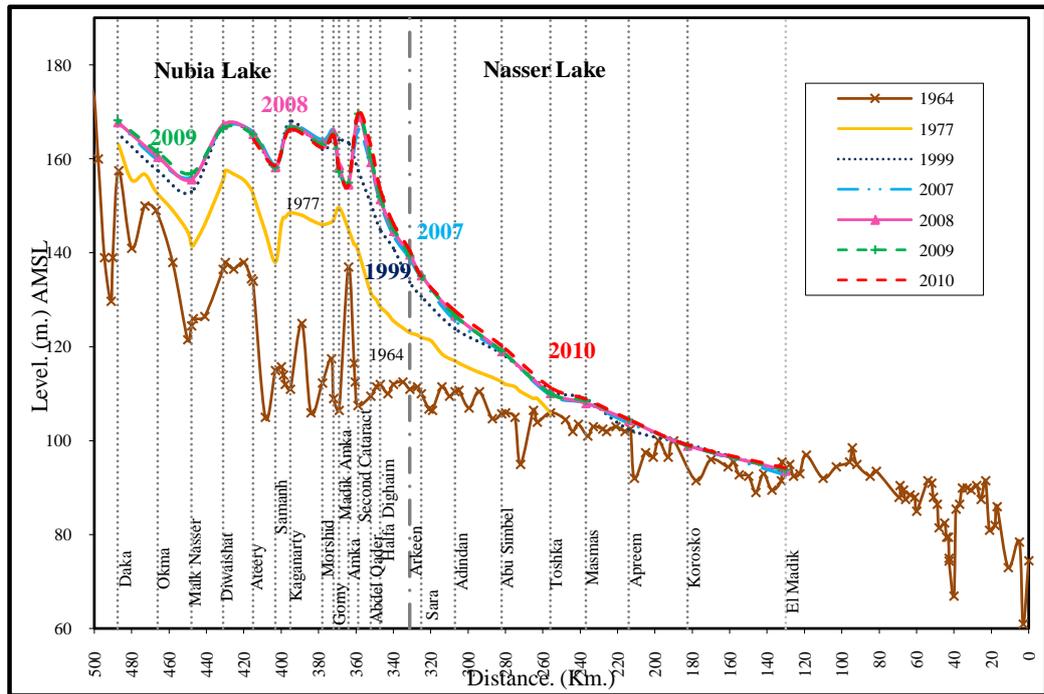


Figure 7. Longitudinal section along the deepest points of the HADR from 1964 to 2010.

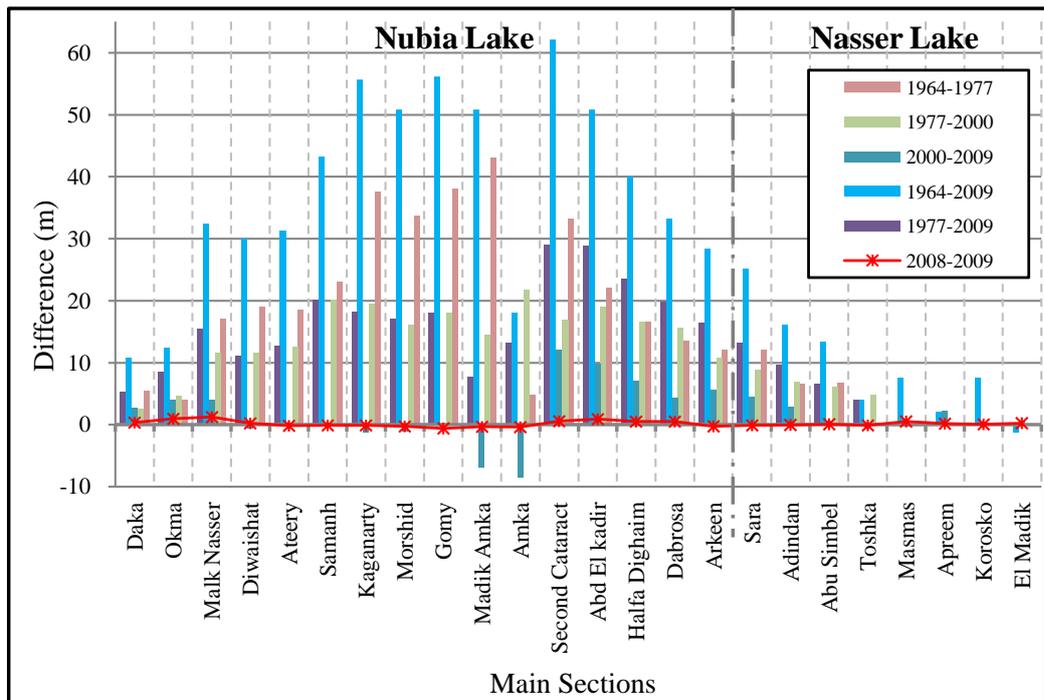


Figure 8. Sedimentation and erosion in Lake Nubia and Lake Nasser reflected by changes in altitudes from 1964 to 2009.

deposition of about 43 m. The Second Cataract section at 357 km experienced the overall largest increase in the amount of sediment, which reached over 60 m. In the period from 1977 to 1999, the largest sediment layers were found between the Samanh and Abd El kadir sections from 403 km to 352 km. The bed level in-

crease gives a value of 20 m, which is equivalent to approximately one meter of sediment deposition per year. During the past decade, the Second Cataract section was characterized by a sediment deposition of over 12 m and an annual sedimentation rate of 1.2 meter.

The sections between Second Cataract and Dabarosa (from 357 km to 338 km) experienced high sedimentation as well. In the other direction, the sections north of Second Cataract all the way up to Diwaishat at 431 km, experienced major erosion problems. The highest erosion rate was measured at Amka section (364 km) up to approximately 80 cm per year. Therefore, the area between Second Cataract section and Dabarosa section was isolated to study the changes in the lakebed during the past decade. **Figure 9** shows the HADRDEMs of Lake Nubia for 1999 and 2010 and the changes in terms of altitude to the lakebed for the same period as well as the annual change between 2007 and 2008. The sediment deposits increased from Section Daka to Section Second Cataract and then decreased to Section Dabarosa. This pattern is caused by the increase in cross

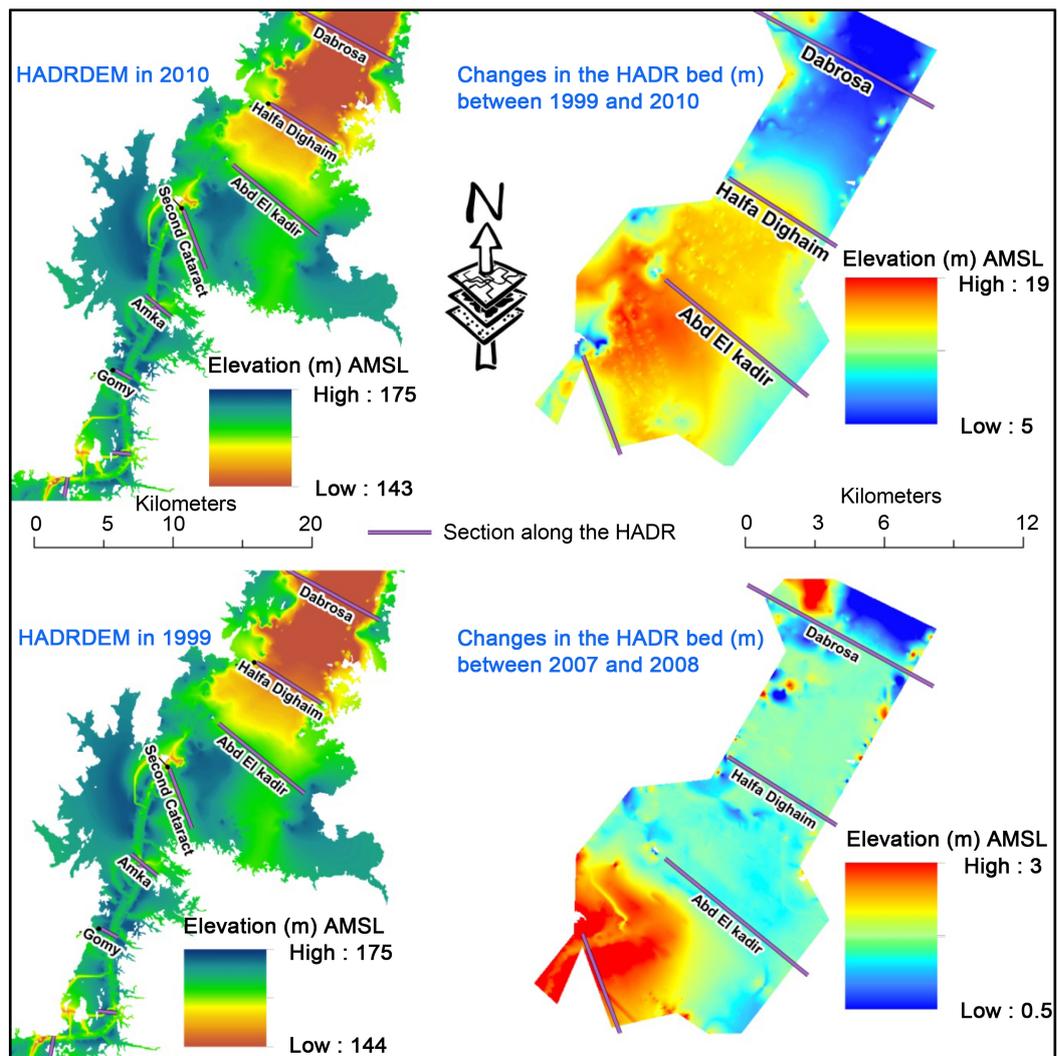


Figure 9. Digital elevation models of the HADR (HADRDEM) for 1999 and 2010 as well as the respective changes of the lakebed and, lakebed changes between 2007 and 2008.

section width (12.4 km) at Section Second Cataract, which follows the narrow sections upstream, which have a maximum width of 3.7 km. The accumulated sediments are decreasing gradually to Section Dabrosa, where the width of cross sections decreases slightly.

From 1964 to 2010, the total erosion volume was approximately 126 Mm³ while the total volume of sediment reached over 6.6 km³. Approximately 5.5 km³ of sediments were deposited in Lake Nubia in the past five decades, whereas the total change in terms of sedimentation in Lake Nasser was approximately 1.1 km³. Changes to the HADR's total water volume were usually positive due to the small volumes caused by erosion in different years, which account for only 2% of the changes to the bed level of the HADR. The total annual mean sediment volume deposited in the reservoir was approximately 140 Mm³ whereas the total annual mean volume that was removed from the bed by erosion was approximately 4 Mm³. The sections between Second Cataract and Dabarosa have shown the majority of these extensive changes in sediment volume during the last 15 to 20 years.

The deposits accumulated at major sections in Lake Nubia from 1977 to 2010 due to successive sediment and erosion events are shown in **Figure 10**. Section Daka suffered from successive erosion events until 1996 and then had successive sediment events that led to minor changes. Until 2006, Section Okma suffered from successive sediment events leading to minor changes. The period from 2006 to 2008 was characterized by minor erosion events; after 2008, more sediment was deposited than eroded. Section Ateery, Section Amka, and Section Dabarosa showed successive moderate sediment events until 2010. At Section Second Cataract, there were successive and massive sediment events, while Section

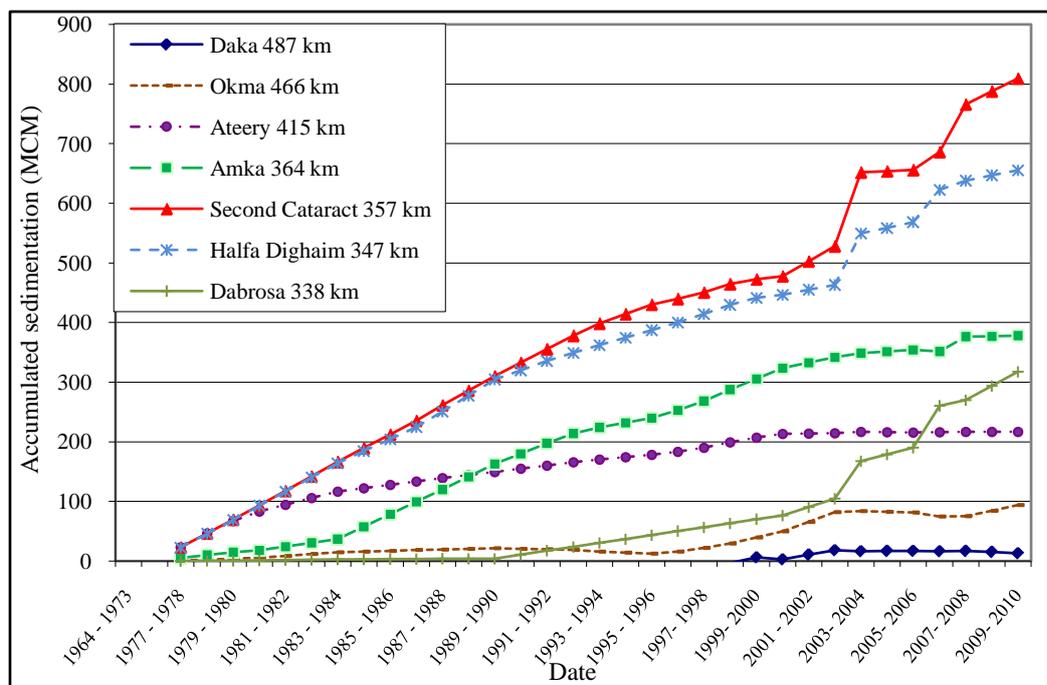


Figure 10. Sediments accumulated at major sections in Lake Nubia from 1977 to 2010.

Halfa Dighaim experienced successive major sediment events. The sediment deposits increased from Section Daka to Section Second Cataract and then decreased to Section Dabarosa. The largest amount of accumulated sediments with 800 Mm^3 , which represents 17% of the total sediments deposited in Lake Nubia till 2010, were deposited at Section Second Cataract. Furthermore, the 2.8 km^3 of sediment deposited between Sections Amka and Dabrosa, a distance of approximately 26 km, account for approximately 60% of the total sediments in Lake Nubia and 50% of the total sediments in the HADR during the period from 1977 to 2010.

3.3. Removing Sediments from the HADR to Reduce Evaporation Losses and to Mitigate the Impact of Climate Change

The effects of removing sediment deposits from the HADR and lowering the lakebed were investigated. The water level and the surface area before and after the potential removal of the sediments were computed using new equations developed for both cases, as shown in **Figure 11**. The removal of sediments will lower the lakebed, increase storage capacity, and reduce water levels. Mean water level will lower by 0.90 m to 2.90 m, with an average value of 1.80 m. The maximum potential reduction in terms of surface area is approximately 355 km^2 at an altitude of 178 m AMSL. The minimum reduction in surface area is approximately 180 km^2 at an altitude of 181 m AMSL. The average reduction in surface

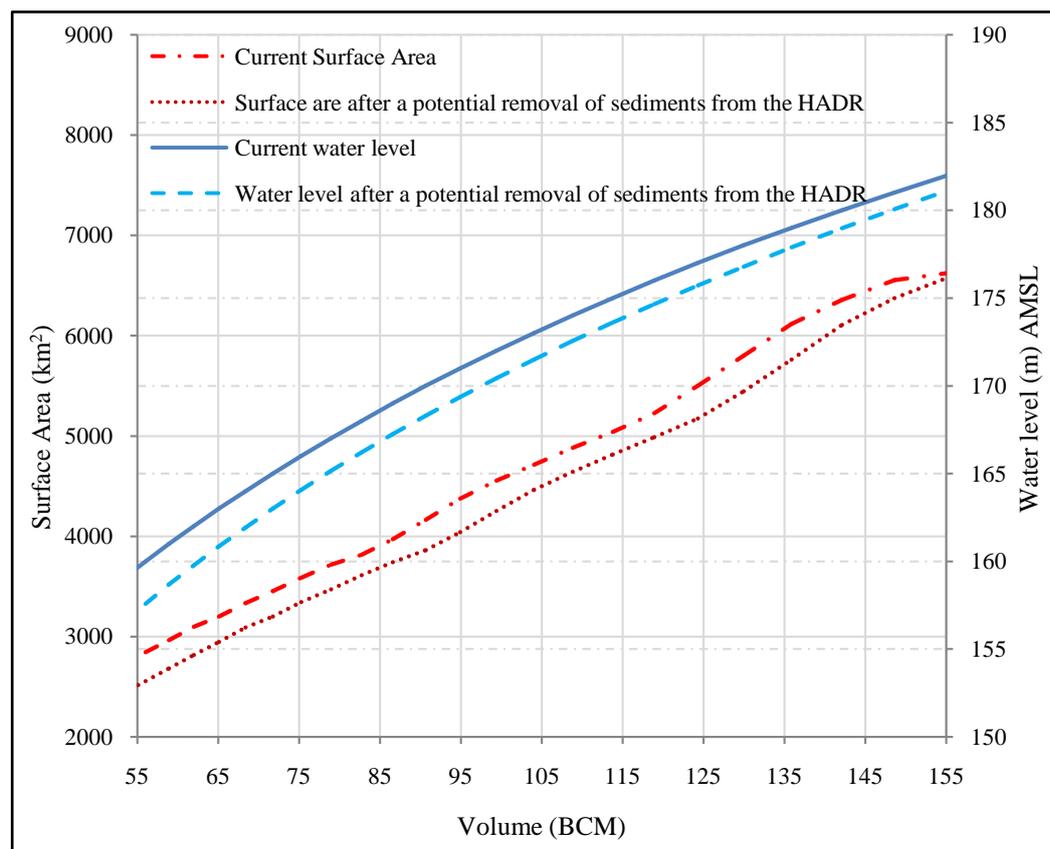


Figure 11. The effect of removing sediment deposits from the HADR on its hydrological characteristics.

area is approximately 270 km², which accounts for over 6% of the surface area of the HADR. Based on a mean annual evaporation rate of 2700 mm, the maximum water savings could be up to approximately one km³ under current climatic conditions. By 2100, the maximum reduction with regard to annual evaporation losses could reach approximately 1.1 km³, based on the results of ECHAM5 and HadCM3 models.

4. Conclusion and Recommendations

The paper shows that the Nile's average annual inflow contains approximately 134 million tons of suspended particles such as clay, silt, sand, and organic debris. Most of these sediment particles were deposited south of Halfa in Lake Nubia, where a new delta had formed. Sedimentation processes in the reservoir are governed by a number of factors. The most important one is the sudden decrease in flow velocity as soon as the inflow reaches the open area of Lake Nubia. 6.6 km³ of sediments as total amount of deposits in the HADR during the past five decades, 5.5 km³ were deposited in Lake Nubia and 1.1 km³ in Lake Nasser. 2.8 km³ of sediments were deposited in the reach between the Amka to Dabrosa sections, which are located approximately 26 km apart. This amount represents approximately 60% of the total sediment load in Lake Nubia, which, in turn, represents 50% of the total sediment deposits in the HADR during the period from 1977 to 2010. In contrast, in Lake Nasser between Korosko and El-Madik, there were only minor changes of the bottom level during the past two decades. Erosion in the bed of HADR is very limited; 126 Mm³ was the total volume removed from the bed by erosion during the past five decades. The HADR is characterized by primarily silt and clay sediments in Lake Nasser. Deposition of sandy sediments increased in Lake Nubia and reached almost 100% at southern end of the HADR.

The paper recommends the removal of 6.6 km³ sediment deposits from the HADR to reduce its surface area by 355 km² and, consequently, to reduce evaporation losses by approximately 1.1 km³ by 2100. Removing the deposits and lowering the lakebed would not only reduce evaporation losses, but it would also prevent the formation of blockages in the waterway of the Nile in general and at new delta emerging at the southern tip of Lake Nubia. These valuable sediments could be used to reclaim and develop new arable land in Egypt and to protect the socially and economically significant areas in the Nile delta from the rising sea level. Although Lake Nubia is comprehensively and regularly surveyed, there is not enough data on Lake Nasser, in part because neither Egypt nor Sudan has enough resources to survey this large area on a regular basis. A comprehensive bathymetric survey of the entire reservoir, including its khors, is needed to update digital elevation models of the HADR and to build new mathematical models that can be used to compute its hydrological characteristics (water level, surface area, water volume). A feasibility study of the most appropriate methods for removing sediment deposits from HADR needs to be conducted as well. Furthermore, a feasibility study that evaluates the possibilities for using sediment

from the HADR has to be conducted, and a pilot project needs to be completed to evaluate the characteristics of sediment for its potential use in agricultural land reclamation and to identify how these sediments affect crop yields.

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