Estimating the Sediment and Water Capacity in the Aswan High Dam Lake Using Remote Sensing and GIS Techniques

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Abstract Egypt's Ministry of Water Resources and Irrigation (MWRI) is responsible for monitoring the changes in the Aswan High Dam Lake's (AHDL) capacity, which is of special importance after the construction of the Grand Ethiopian Renaissance Dam (GERD). The AHDL capacity is affected directly by the changes in the lake's bed surface. Thus, it is of the utmost importance for Egypt to properly understand these changes (sedimentation and erosion), to monitor the decrease in the storage capacity of the lake. Consequently, the main focus of this paper is to detect the changes in AHDL bed surface (practically sediment accumulation) during the period 2000–2012 using remote sensing (RS) and Geographic Information Systems (GIS) techniques by building a 3D profile of the lake. Moreover, this study is concerned with developing relationships between water volume or capacity/surface area/water level for the active sedimentation zone of AHDL for the years from 2000 to 2012; both individually and collectively. These relationships are estimated by establishing the developed rating curves (volume/level) and (area/level). The present computations are compared by the method of cross sections that was adopted by the Aswan High Dam Authority (AHDA) to detect the amount of sedimentation in the study area. The results indicate that the present approach

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overestimates the sedimentation capacity by about 4.3% compared to the results of the method used by AHDA. The measured velocity patterns are mapped, analyzed, and 2-D profiles are correlated to the erosion and sedimentation patterns. Moreover, the accuracy of the developed relationships is assessed by comparing the results with the observed data and the existing rating curves for the lake. The root mean square error is found to range between 5–10% and 2–4% for (a) the relationship between the lake capacity and the level, and (b) the lake surface area and the level relationship, respectively.

Keywords Aswan High Dam Lake, GIS, Lake capacity, Nubia Lake, Rating curve, Remote sensing, Sudan

Contents

1 Introduction

Large reservoirs are used for many purposes, which include flood control, water storage for irrigation, generation of electricity, industrial or domestic use, and regulation of flow for navigation. Many man-made reservoirs have been constructed all over the world; among those are the Volta reservoir [1], Ghana, Lake Kainji on River Niger [1], Lake Kariba on Zambia River, Zambia [1, 2], Bratsk reservoir on Anga River, Russia [3, 4], Williston Lake on the Peace River, Canada, Zeya reservoir on the Zeya River in Russia [5], Lake Guri in Venezuela [6], and the Aswan High Dam Lake (AHDL) on the River Nile in Egypt [1] and through Sudan.

The High Dam differs from other dams in a number of characteristics. It is the biggest rockfill dam in the world. It has an impervious core, with a grout curtain that extends 180 m under the core to meet the rock, and a horizontal upstream impervious blanket. The length of the dam at the top is 3,600 m, while the width is 980 m at the bottom and 40 m at the top and its height above the river bed level is 111 m.

Before the construction of Aswan High Dam (AHD), around 125 million tons of mud was transported annually through flooding. The sedimentation consists of fine sand, silt, and clay, which contributes to soil fertility. About 15% of this mud has been deposited in irrigated areas of Upper Egypt and in the Nile bed upstream Cairo; roughly, the same amount or more was spread in the agricultural lands of the Nile Delta. Most of the mud quantity brought down to the Delta coast was deposited through the Rosetta and Damietta estuaries. The remaining amount of mud was deposited in the continental shelf at the Mediterranean Sea.

The situation has changed after the construction of the Aswan High Dam in 1964, and the formation of a large reservoir, named the High Dam Lake (Nasser/Nubia). This was largely due to the increasing rate of mud storage in the dead zone in Nasser Lake and the lesser chance for mud to travel in the River Nile through its journey to Mediterranean Sea.

Since sedimentation in this lake is dominant, the problem arises that storage capacity is decreasing over the years yielding the reservoir useless after some decades [7]. Adding to the above, it was found that the storage of mud in the dead zone caused the formation of a new delta in the lake inside the Sudanese region (Nubia Lake). This formation of a new delta will decrease the life of the reservoir since the volume of storage in the dead zone is about 31.6 billion cubic meters, and the life of reservoir is defined by scientists as the time required for sediment to fully fill the dead zone of the lake. This sedimentation can in turn adversely affect the working turbines and operation of the High Dam. The trapping of sediment by the dam has been the reason for the increase of coastline erosion surrounding the River Nile Delta.

Based on the above discussion, it is necessary to carry out a study to estimate the amount of sediment in the AHDL, and to optimize the utilization of this sediment accurately in order to manage its removal in a better, more efficient, and economic manner. The trapped sediment can be used effectively in many fields to gain an optimum benefit, such as increasing the soil fertility by spreading the lake sediment over desert lands, contributing to duplicating the production of the land, and decreasing the risk on the Aswan High Dam.

The AHDL is vital to Egypt; as it stores and regulates Nile water; the main source of fresh water for about 85% of its population [8]. Therefore, it is of the utmost importance for Egypt to understand properly the changes which occur in the AHDL bed surface (the morphological changes related to erosion/sedimentation processes). This will help in monitoring the variation in the storage capacity of the lake, improving the knowledge on the water mass balance, and consequently enabling this lake to fulfill its purpose efficiently [9].

Many studies have been carried out on the Lake as well as changes in progress over time. Many of these studies were issued in the form of reports, papers, books, dissertations, as well as seminars and workshops. Most of these publications, especially reports, dissertations, seminars, and workshops, are either of limited distribution or unavailable to research workers. The authors tried to obtain these studies in the present work. In situ measurements and satellite observations data have been used to estimate and analyze changes in lake bed surfaces, with successful applications in different parts of the world. An example includes the morphological changes related to erosion and sedimentation processes which occurred in San Giuliano Lake which is located in the Basilicata Region (Southern Italy). This phenomenon was examined during the period 1984–2004, and was analyzed using RS data integrated GIS technique [10]. Schultz [7] detected the changes in sediment and erosion in the upper region of Lake Kemnade in the Ruhr River valley in Germany using remote sensing techniques and echo sounding data for a period of 8 years. El-Sammany and El-Moustafa [11] proposed a method for calculating the changes in the AHDL bed from the year 1953 to the year 2004 depending on the processing of the field measurements (bathymetric data) only using GIS tools, such as geo-spatial analysis and 3D analysis tools in order to analyze the Digital Elevation Models (DEMs) for the study area. Negm et al. [12] studied the scouring and silting processes in the AHDR by applying a two-dimensional numerical model. Concerning the flow velocity characteristics and distribution in the AHDL to indicate its effect on sedimentation and erosion processes in the lake, limited research was conducted; these include [11, 13, 14]. Furthermore, many investigations estimating the water storage quantity and variations in lakes and reservoirs were carried out in other parts of the world, including: Roseires reservoir in Sudan [15], Lake La Bure in the south – west of France [16], Lake Izabal in Guatemala [17], Lake Tana in Ethiopia and Lake Mead (U.S.A) [18], Lake Dongting in China [19], and Randy Poynter Lake in Georgia [20]. Concerning the Aswan High Dam Lake (AHDL), several studies were conducted including those of [15, 21, 22].

The main aims of the present study are:

(a) detecting the changes in the AHDL active sedimentation of the bed surface (sediment and erosion) and the quantitative amounts from year 2000 to 2012 using GIS and RS techniques
(b) detecting the effect of inflow velocity on sediment and erosion patterns via the comparison between changes of the lake bed profiles and the corresponding 2-D inflow velocity profiles
(c) developing the rating curves for the Lake Nubia active zone for the period from 2000 to 2012 through a combination of remotely sensed data and in situ measurements, in order to detect the variations in the water capacity
(d) a comparison between the results of the method used by the Aswan High Dam Authority (AHDA) based on the complementary cross sections in estimating

the amounts of sediment, the water capacity in the study area and the results of the present study using RS/GIS.

It is hoped that the current study will contribute to the knowledge foundation of the AHDL and help those who are responsible for sustainable development, management, and protection in their decision making and planning.

2 Study Area and Data Collection

2.1 The Study Area

AHDL is considered one of the largest man-made lakes in Africa, and extends for 500 km south of the dam. The majority of this lake lies in Egypt with a length of about 350 km and is known as Lake Nasser. On the Sudanese side, it is referred to as Lake Nubia (LN) [23] with a length of 150 km. The study area extends between latitudes 21°44′30″ and 22°00′00″N (upstream AHD) within the Sudanese part (LN) where most of the sediments are accumulated. It contains six cross sections (22, 24, 25, 26, 27, and 28) from North to South as indicated in Fig. 1.

In addition, from the studies and observations done by field survey missions, which were successfully carried out through the joint efforts of the Aswan High Dam Authority (AHDA) and the Nile Research Institute (NRI), it was concluded that the cross sections have been enlarged due to excessive erosion and the water velocity has decreased in this portion [24]. The study area considers the lake portion with most intensive sediment deposition. Moreover, the total amount of the accumulated sediment in this part of the AHDL is about 50–70% of the total amount of sediment in the AHDL as indicated in the foregoing estimations by AHDA [24]; although this portion represents only about 5.96% of the total area of the AHDL [26]. This reach is called the active sedimentation portion.

The geometric characteristics of the AHDL (large area, high depth, and bed relief) make the detection of the lake bed surface changes and estimation of the lake volume difficult to be examined by traditional methods and therefore, need to be as accurate as possible for operational purposes by applying new techniques such as remote sensing and GIS.

2.2 In Situ Data

2.2.1 Hydrographic Survey Data

The hydrographic survey data, which is described by the geometry of the AHDL, were collected by using the eco-sounder via field trips performed by AHDA and NRI. The lake geometry presented by Easting, Northing, and Elevation

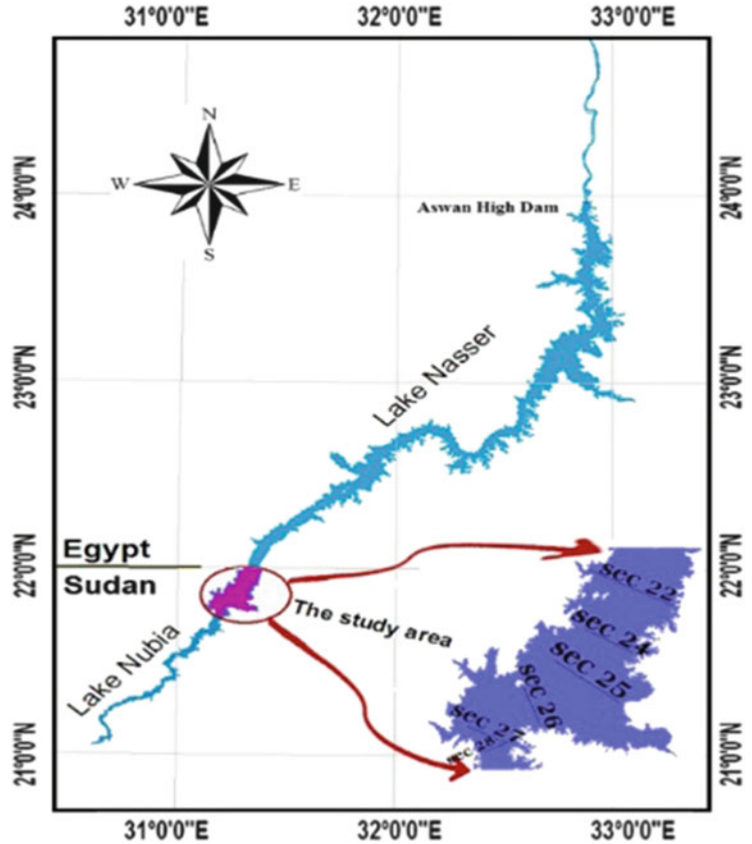

Fig. 1 Location of the study area in AHDL

(E, N, and Z) was used for the 3D bed surface generation. In this study, the hydrographic survey data for years 2000, 2004, 2006, 2008, 2010, and 2012 for the study area were used [24].

2.2.2 Water Levels Data

The water levels upstream AHD, which were recorded by AHDA gauge stations at different times of the year [25], were collected to help in detecting the water surface levels at the dates of acquiring the satellite images.

2.2.3 Inflow Velocity Data

The inflow velocity data, which represents the velocity magnitudes, were measured by using the Vale Port velocity meter device via the AHDA and NRI field trips.

These data were obtained at the locations of the cross sections shown in Fig. 1. In this study, the inflow velocity magnitudes data for the years 2006, 2008, and 2010 were used [24].

2.2.4 Inflow Quantity Data

The total amounts of discharge (inflow) which arrives at Aswan (enters Egypt) for the last 20 years, as recorded by AHDA and according to the Dongola gauge station [26], are used to detect the effect of this charge on the lake bed.

2.3 Satellite Images (Remote Sensing Data)

Three Landsat ETM+ images (Path/Row = 175/045) were used in this research. The three images were acquired on different dates (September 2000, March 2006, and March 2009) from the GLCF website in GeoTIFF (systematic correction) products [27]. The acquired images are used to extract the lake boundaries. The satellite images were taken in September 2000 when the water level of the lake was 178 m amsl; in March 2006 when the water level was 173 m, and in March 2009 when the water level was 176.60 m.

3 Methodology

To achieve the objective of the present work, the adopted methodology is provided in Fig. 2, and is explained in the following subsections.

3.1 Water Surface Areas Extraction

Many investigations of water area estimation have been carried out worldwide [29–33]. Considering the AHDL, many water surface extraction studies have been carried out on Lake Nasser [11, 15, 28], while few studies concentrated on Lake Nubia [11].

Remotely sensed imagery has many applications in water resource assessment and management. These applications involved the extraction of water information by various techniques [30].

In this study, the unsupervised classification technique of Landsat images to obtain the water body class of the AHDL was performed; it is considered the best technique for water texture recognition [8, 34].

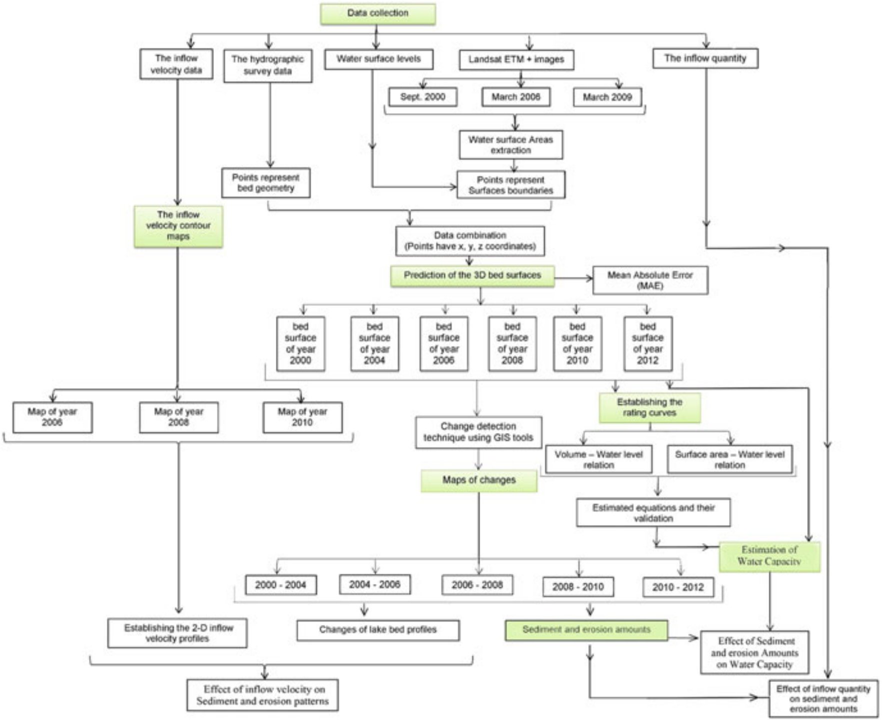

Fig. 2 Flowchart of the procedures adopted in this study to achieve its goals

The applied procedures for extraction of water boundaries in this study (using unsupervised image classification technique) are explained below and summarized in Fig. 3.

(1) Detecting the Landsat scene of the study area by making a clip from the original image.
(2) Making unsupervised classification, then converting the final classified image (contain four classes) into features (vector layers).
(3) Separating the water feature from the other features as a polyline.
(4) Converting the polyline boundaries into a water points layer which has (x, y) coordinates and z coordinates from the water levels recorded by the AHDA which were synchronized with the acquired dates of the satellite images.
(5) Converting the water polyline layer into polygon layer.
(6) Finally, converting the polygon layer to raster water scene (water raster) to help in the interpolation method (predicting the 3D bed surface).

The extracted lake boundaries, obtained from the satellite images, were used to form the shape of surface and also to form a group of scatter points (x, y, z) using the WGS84, UTM Z36N as defined in the projected coordinate system. These points were used, combined together with the hydrographic survey points in the generation

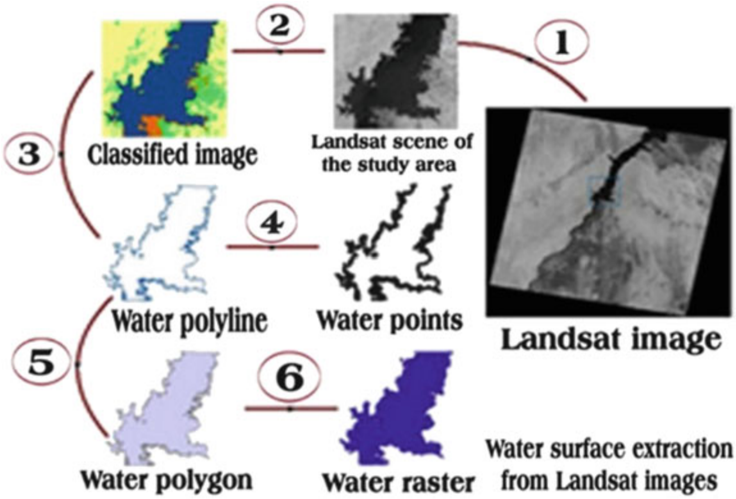

Fig. 3 Extraction of water boundaries from Landsat images

of the 3D bed surfaces of the study area for all available years (2000, 2004, 2006, 2008, 2010, and 2012).

3.2 Prediction of the 3D Bed Surfaces

In order to predict the original lake 3D bed surfaces from the year 2000 to the year 2012, the available hydrographic survey data combined with the points that represent the water surface areas which were derived from Landsat satellite images were used in the interpolation process. In addition, the water surface, which represents the highest surface for all predicted bed surfaces, was from the 2000 Landsat image. The interpolation process is performed with the Radial Base Functions (RBF) method [35].

To assess the accuracy of the interpolation methods, the Mean Absolute Error (MAE) is estimated. For accurate interpolation, the MAE should be as close to zero as possible, as the error here represents the difference between measured and predicted values.

3.3 Change Detection Technique

This technique is a digital overlaying technique which depends on detecting the changes in the lake bed levels by overlaying every two sequential predicted bed surface images using the cut/fill tool in the ArcGIS Software [36].

3.4 Establishing Maps of Changes

The maps of changes were derived using the change detection technique and represent the changes in sediment and erosion zones. These maps were generated in order to quantify the changes in sediment and erosion in the study area during the period from 2000 to 2012.

3.5 Generation of the Inflow Velocity Contour Maps

In order to establish the inflow velocity contour maps for years 2006, 2008, and 2010, the available inflow velocity magnitude data were used in the interpolation process. This process was performed by using ArcGIS software. These contour maps were produced in order to explain the effect of the velocity magnitudes on erosion and sedimentation patterns [37].

3.6 Establishing the Rating Curves

The relationships between the three parameters of the lake (water volume/surface area/level changes) are estimated by using ArcGIS software v9.3 [35]. These relationships are generated in order to establish the rating curves for the years from 2000 to 2012.

3.7 Rating Curves Equations and Their Validation

The equations of the developed rating curves (volume/level), (area/level), and (volume/area) are estimated by using Microsoft Excel [38].

Table 1 presents the statistical indicators including Root Mean Square Error (RMSE) and R^2 (coefficient of determination) that are used to assess the accuracy of the developed rating curves equations.

Table 1 Statistics indicators for the equations of the developed rating curves [9]

Concept	Name	Formula
Root M. square error	RMSE	$\sqrt{\sum (\text{Mes} - \text{calc.})^2 / N}$
Deter. coefficient	R^2	$\sum(\text{calc.} - \text{avg.Mes})^2 / \sum(\text{Mes} - \text{avg.Mes})^2$
Percent. of root M. square error	RMSE (%)	$(\text{RMSE}/\text{avg.Mes}) \times 100$

4 Results

4.1 Creation of the 3D Bed Profiles

The extracted water surfaces built using the unsupervised technique from all available Landsat images (see Fig. 4) are used in the creation of the 3D bed surfaces.

In order to predict the 3D bed surfaces, the Radial Base Functions (RBF) method for interpolation is used as it produces good results for gently varying surfaces such as elevations [34].

To assess the accuracy of the used RBF method, MAE was computed and is found to be close to zero for all studied years. The MAE for year 2010 equals 0.003281 indicating a high level of accuracy of the interpolation process as shown in Fig. 5.

The 3D bed surfaces are predicted for the years 2000, 2004, 2006, 2008, 2010, and 2012. Sample results are presented in Fig. 6 for the years 2006 and 2008.

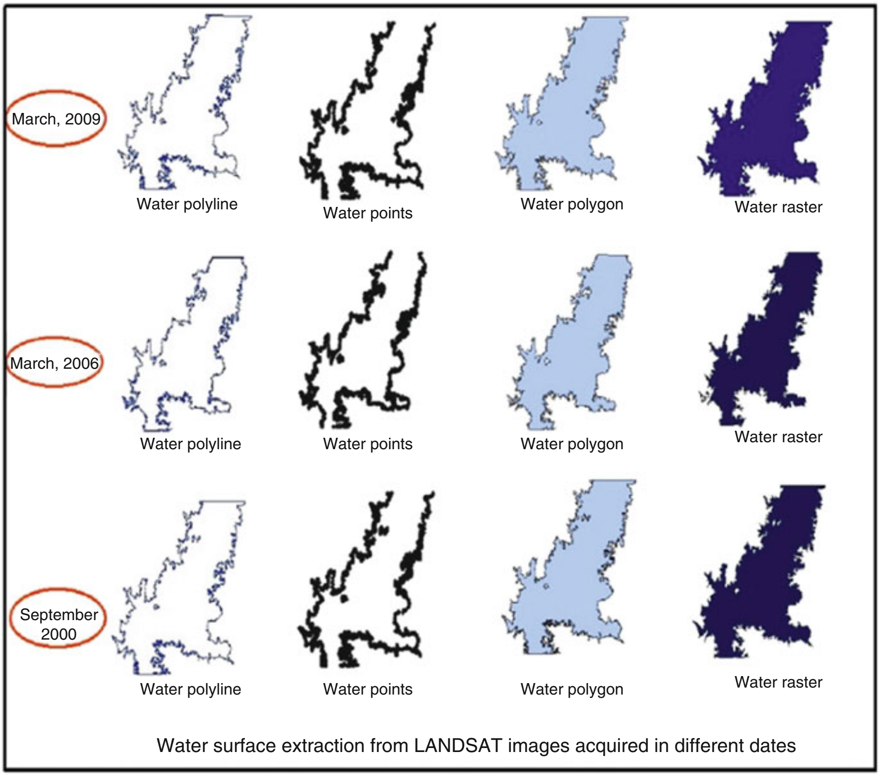

Fig. 4 The extracted water boundaries from Landsat images

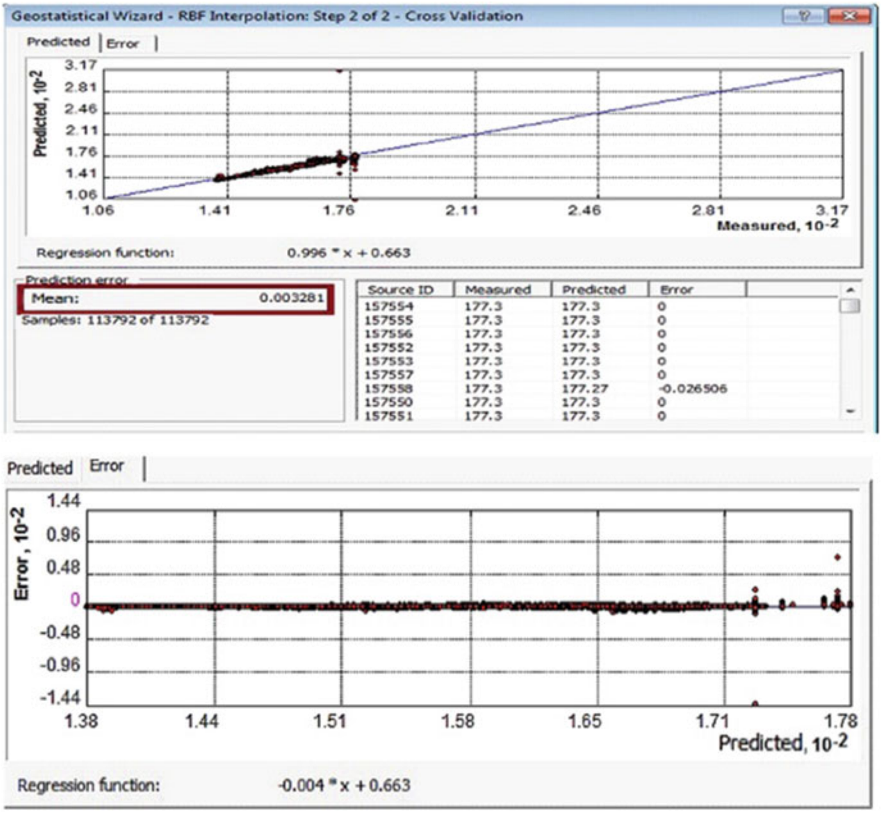

Fig. 5 Errors in the predicted values for year 2010

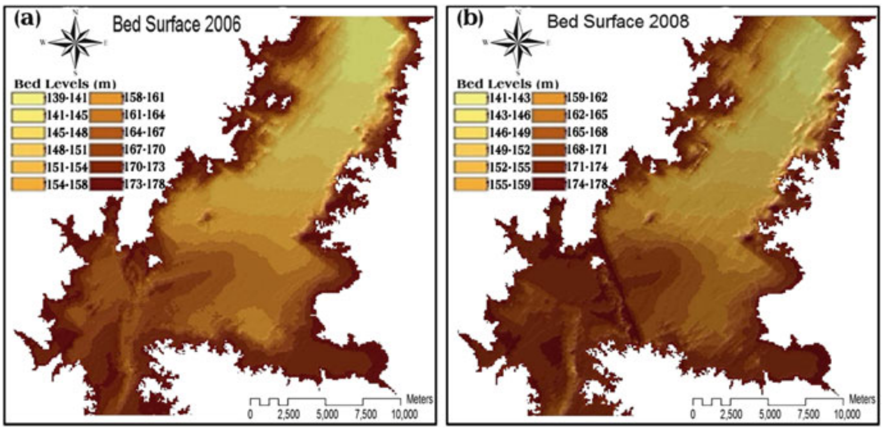

Fig. 6 Sample results of the predicted bed surfaces for the years (**a**) 2006 and (**b**) 2008

4.2 Maps of Changes

To infer the changes in bed levels between every two sequential predicted bed, surfaces were generalized by three broad change categories:

- No change: the levels that have the same values in both the old and new bed surface
- Sedimentation: the old bed surface levels were increased in the new bed surface
- Erosion: the old bed surface levels were decreased in the new bed surface

Maps of changes for the years 2004–2006, 2006–2008, and 2008–2010 are produced. Samples for the years 2006–2008 and 2008–2010 are presented in Fig. 7.

4.3 Velocity Maps

The collected field data about the inflow velocity values for years 2006, 2008, and 2010 were interpolated by using ArcGIS software. Afterwards, the velocity contour maps were produced.

Figure 8 shows sample results for years 2006 and 2010, respectively.

5 Discussion

5.1 Sediment and Erosion Changes

Figures 9 and 10 show the change in sediment and erosion amounts, respectively, from year 2000 to 2012, that were estimated by using the statistics of the change categories (classes) in the maps. It is obvious from these figures that there is an increase in the amount of sediment from the years 2000–2004, 2006–2008, and 2010–2012 accompanied with decrease in the amount of erosion in the same periods.

There is a decrease in the amount of sediment from year 2008 to 2010 accompanied with an increase in the amount of erosion in the same period. From the years 2004 to 2006, the amount of sediment is nearly equal to the amount of erosion.

Table 2 shows the change in sediment and erosion 2D surface areas, respectively, from the years 2000 to 2012; it is obvious from this table that the values of the 2D areas of sediment and erosion are approximately proportional to the amounts of sediment and erosion, as the amount of erosion increase leads to increase in its 2D area and vice versa, and the same manner for sedimentation.

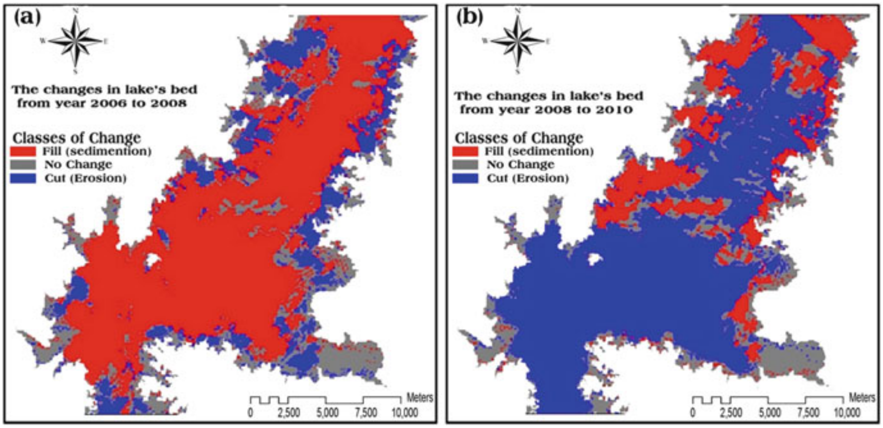

Fig. 7 Sample for maps of changes for the years 2006–2008 and 2008–2010

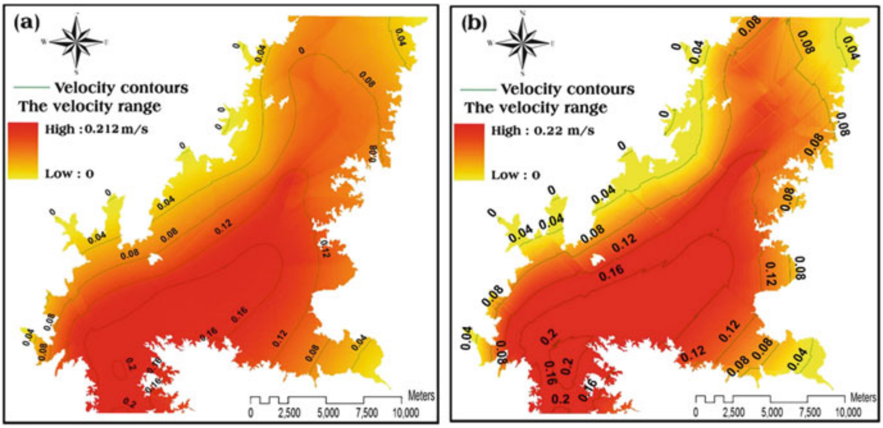

Fig. 8 Sample for the inflow velocity contour maps for the years 2006 and 2010

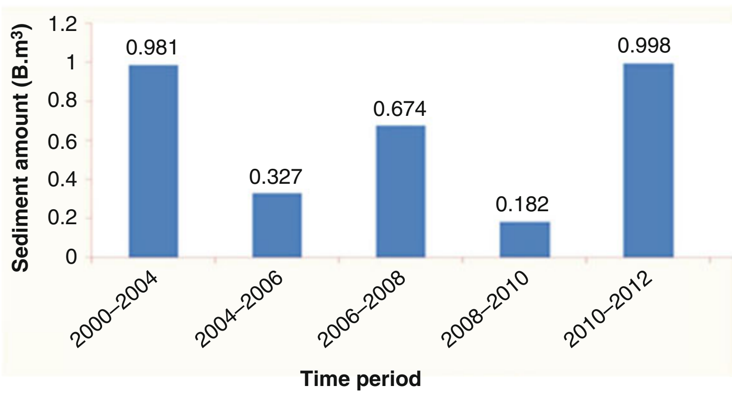

Fig. 9 Sediment amount in the study area

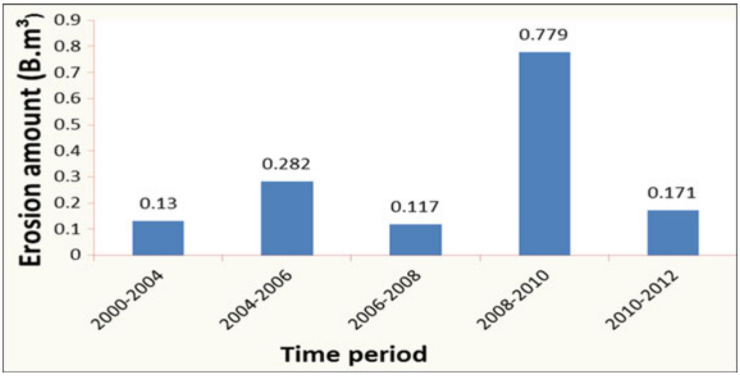

Fig. 10 Erosion amount in the study area

Table 2 2D surface area of sedimentation and erosion from year 2000 to 2012

Time period	2D area of sediment (km^2)	2D area of erosion (km^2)
2000–2004	227.45	47.06
2004–2006	145.70	91.38
2006–2008	216.05	48.84
2008–2010	59.93	205.81
2010–2012	222.28	50.19

5.2 *Effect of Inflow Quantity on Sediment and Erosion Amounts*

Table 3 shows the difference in the annual inflow quantity (discharge) in the study area, which is recorded at Aswan at the end of July [26]. By comparing this table with Fig. 8, we can realize that the amount of erosion is directly affected by the amounts of inflow, as a decrease in the inflow quantity leads to an increase in the amount of erosion and vice versa. This explains the change in the amount of erosion from the year 2000 to the year 2012. From Table 3 and Fig. 9, it is obvious that there is an increase in sedimentation amounts between the years 2000–2004, 2006–2008, and 2010–2012 due to the increase in the inflow amount. There is a decrease in sediment during the period 2008–2010 due to the decrease in inflow. In spite of this, a direct relationship between the sediment amount and the incoming flow to the lake cannot be detected, as sediment amount depends not only on the quantity of inflow but also on some other parameters such as the particles size of sediment, the inflow velocities, and shape and size of the lake's cross sections which are perpendicular to the incoming flow of the lake. Thus, it is recommended to study the effects of these parameters on the amount of sediment in future research.

Table 3 Quantity of inflow from 2000 to 2012

Year	Inflow (Bm^3)	Average (Bm^3)
2000–2001	69,512	59,678
2001–2002	70,878	
002–2003	41,794	
2003–2004	56,528	
2004–2005	47,287	50,403
2005–2006	53,518	
2006–2007	80,420	78,170
2007–2008	75,920	
2008–2009	55,130	48,635
2009–2010	42,139	
2010–2011	63,314	56,700
2011–2012	50,085	

5.3 *Effect of Inflow Velocity on Sediment and Erosion in the Lake Bed Surface*

Flowing water erodes or deposits particles depending mainly on how fast the water is moving. The following examples are considered as indicators on the effect of the inflow velocity values on the lake bed surface relief. These examples illustrate the relationships between (a) the 2-D velocity profiles and (b) the bed change profiles which are deduced from the predicted bed surfaces and the generated velocity contour maps, respectively.

The first example that illustrates the relationship between the inflow velocity and the changes of lake bed surfaces profiles is shown in Figs. 11 and 12, and indicates the bed surfaces cross sections at sections 22 and 26 (see Fig. 1) and the corresponding 2-D inflow velocity profiles. It can be noticed that the increment in the velocity rates is associated with decrement in bed surface levels (high amounts of erosion), as occurred during 2008–2010. On the other hand; the decrement in the velocity rates is accompanied with incremental changes in bed surface levels (high amounts of sedimentation), as occurred during 2006–2008.

The second example for indicating the effect of the inflow velocity magnitude on the sediment and erosion pattern is shown in Fig. 13, which illustrates the comparison between changes of the bed profiles (longitudinal sections that pass through the lowest points in the study area bed surface) and the corresponding 2-D inflow velocity profiles for the years; 2006, 2008, and 2010. The analysis of this figure confirmed the velocity effect on sedimentation and erosion patterns through the achieved comparisons in Figs. 11 and 12.

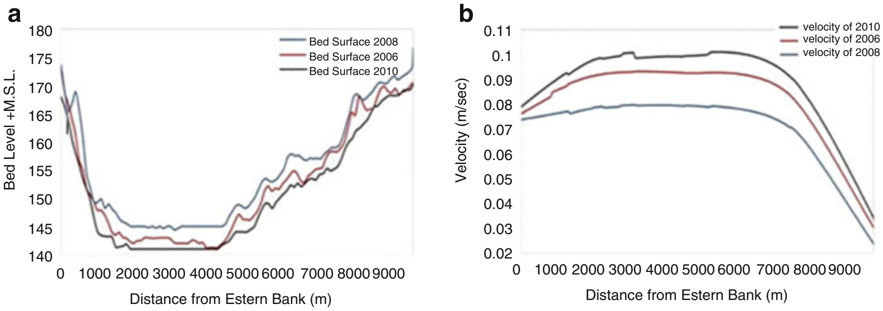

Fig. 11 Comparison between bed surfaces and velocity profiles at section 22 (337.5 km U.S AHD): (**a**) bed surfaces cross sections; (**b**) velocity distribution

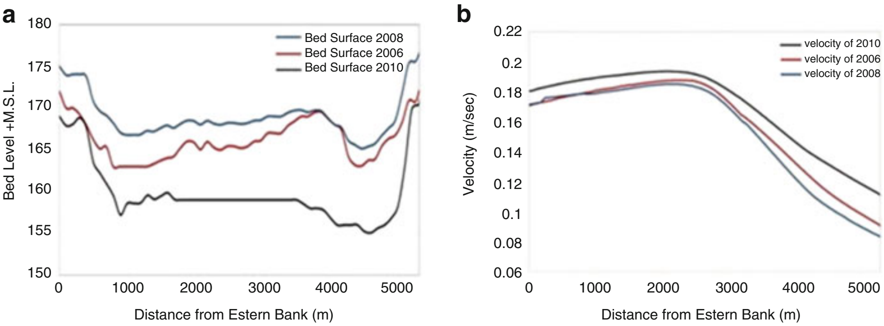

Fig. 12 Comparison between bed surfaces and 2-D velocity profiles at section 26 (357 km U.S AHD): (**a**) bed surfaces cross sections; (**b**) velocity distribution

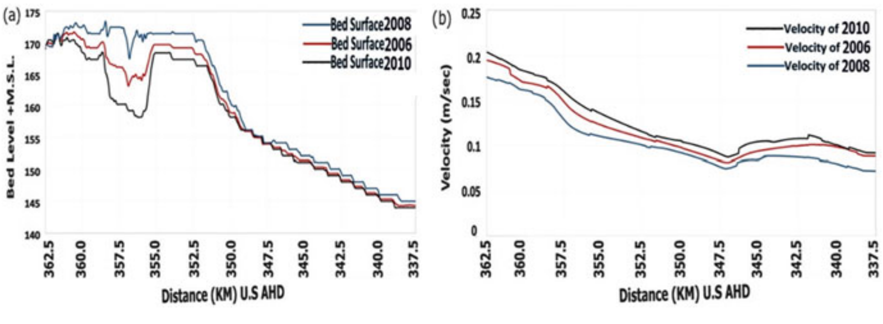

Fig. 13 Comparison between bed surfaces and 2-D velocity profiles: (**a**) bed surfaces longitudinal sections; (**b**) velocity distribution

5.4 Rating Curves and Their Validation

To infer the water capacity (volume) variations in the study area, we developed various rating curves between volume or capacity, surface area, level changes, which are closely connected with the lake remotely sensed data and hydrographic survey data.

5.4.1 Volume/Level Relation

Figure 14a, b shows samples of established rating curves that represent the relationships between volume/level for the year 2010 and collectively for the whole period from 2000 to 2012. It is noticed from these graphs that the volume changes as a function of level change and expressed a third polynomial relationship.

Table 4 presents the eight developed equations for the years (2000, 2004, 2006, 2008, 2010, and 2012), for 2 years (2010 and 2012), and for all years (2000–2012) for the relationship between volume/level. From this table it is clear that the computed volumes are in a good agreement with measured volumes with R^2 varied from 0.94 to 0.99 and RMSE varied from 5 to 10% only.

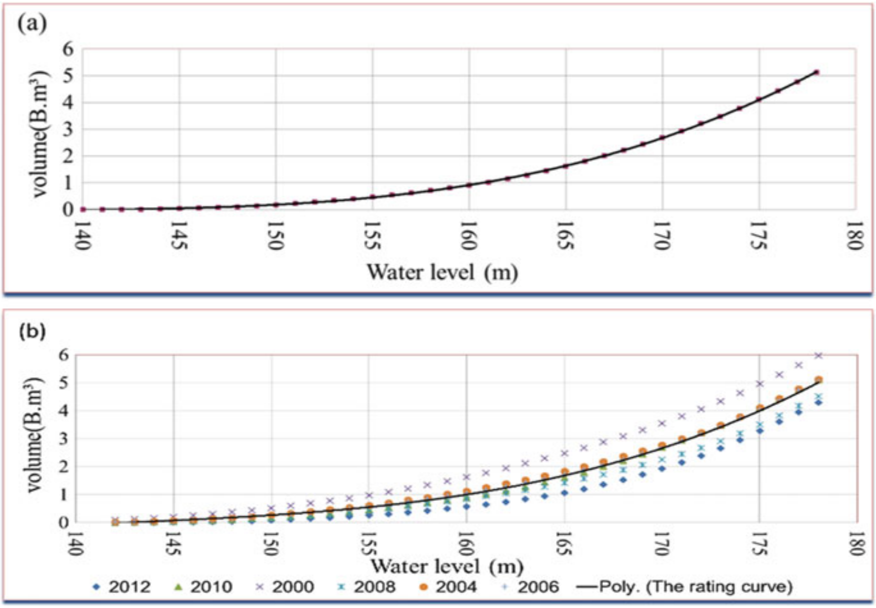

Fig. 14 Sample results of the rating curves (volume/level): (**a**) 2010 rating curve and (**b**) collective rating curve for the years (2000–2012)

Table 4 Developed relationships between volume and water depth for the period from 2000 to 2012, individually and collectively

Period of the estimated rating curve	Number of points	R^2	RMSE (Bm^3)	RMSE (%)	Rating curve equation (y = volume in Bm^3 and x = water level in m)
2000	45	0.99	0.091	5.2	$y = 4\,E-05\,x^3 - 0.0148\,x^2 + 1.817\,x - 74.04$
2004	40	0.99	0.084	5.6	$y = 7\,E-05\,x^3 - 0.0292\,x^2 + 4.0817\,x - 191.2$
2006	40	0.99	0.078	5.4	$y = 8\,E-05\,x^3 - 0.0337\,x^2 + 4.7562\,x - 224.92$
2008	38	0.99	0.070	5.5	$y = 9\,E-05\,x^3 - 0.0388\,x^2 + 5.6086\,x - 271.85$
2010	39	0.99	0.069	4.9	$y = 8\,E-05\,x^3 - 0.0332\,x^2 + 4.6016\,x - 213.06$
2012	37	0.99	0.058	5.3	$y = 0.0001\,x^3 - 0.0431\,x^2 + 6.1978\,x - 297.355$
2010 and 2012	74	0.97	0.099	7.6	$y = 0.0001\,x^3 - 0.043\,x^2 + 6.1793\,x - 296.7$
2000–2012	222	0.94	0.164	10.7	$y = 9\,E-05\,x^3 - 0.0386\,x^2 + 5.5358\,x - 265.35$

5.4.2 Area/Level Relation

The relationship between area/level is clearly nonlinear (a second-order polynomial function). A sample of the obtained results is presented in Fig. 15a, b for the years 2010 and for all years from 2010 to 2012.

Similarly, Table 5 presents the eight developed equations for the relationship between area and level for the active sedimentation zone of Lake Nubia for the years (2000, 2004, 2006, 2008, 2010, and 2012), (2010 and 2012) and collectively for the period from 2000 to 2012. The value of R^2 is more than 0.97 while RMSE ranged between 2.7 and 5.4 m. The predicted surface area values using the developed equations are compared with the measured values as shown in Fig. 16 for the lake water level of 175 m.

5.5 *Water Capacity of the Study Area*

As a quantitative indicator for the above results, Fig. 17a, b shows the difference between measured water capacities via the created 3D bed profiles and the calculated water volumes from the derived rating curve equations at water level 178 and 175 m, respectively. These figures illustrate that the computed and the measured volume values are nearly equal for individual studied years. In contrast, there is a difference in the volume values collectively for years from 2000 to 2012.

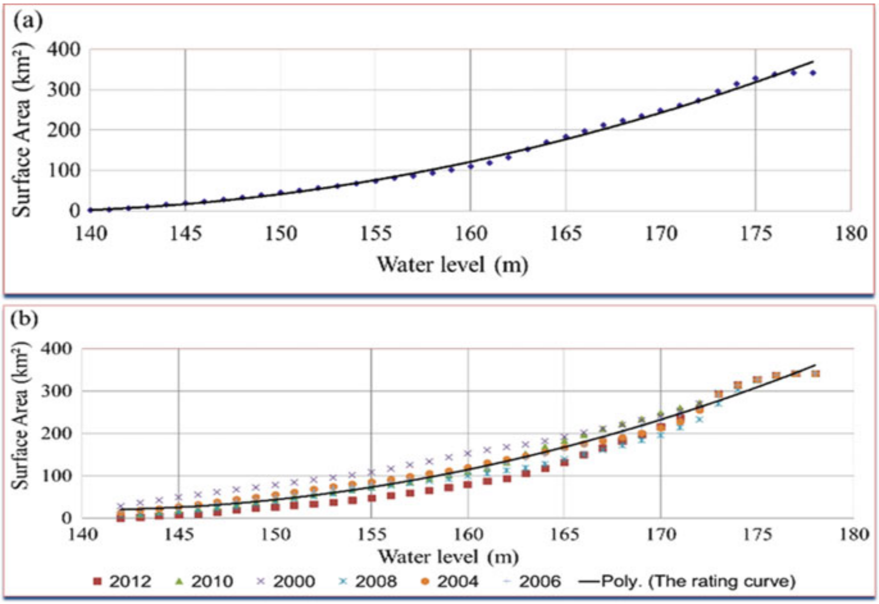

Fig. 15 Sample results of the rating curves (area/level): (**a**) 2010 rating curve and (**b**) collective rating curve for the years (2000–2012)

Table 5 Developed equations for the rating curves of the area/level for the years from 2000 to 2012

Period of the estimated rating curve	Number of points	R^2	RMSE (km^2)	RMSE (%)	Rating curve equation (y = surface area and x = water level)
2000	45	0.99	2.76	2.1	$y = 0.1249\ x^2 - 31.068\ x + 1923$
2004	40	0.99	3.70	2.8	$y = 0.1972\ x^2 - 53.803\ x + 3682.3$
2006	40	0.99	3.06	2.3	$y = 0.2203\ x^2 - 60.939\ x + 4229$
2008	38	0.99	3.32	2.7	$y = 0.2642\ x^2 - 75.287\ x + 5379.2$
2010	39	0.99	3.03	2.2	$y = 0.2054\ x^2 - 55.65\ x + 3766.8$
2012	37	0.99	3.07	2.5	$y = 0.33\ x^2 - 95.598\ x + 6932.7$
2010 and 2012	74	0.98	4.52	3.4	$y = 0.2683\ x^2 - 75.816\ x + 5365.4$
2000–2012	222	0.97	5.38	3.8	$y = 0.2348\ x^2 - 65.673\ x + 4612.5$

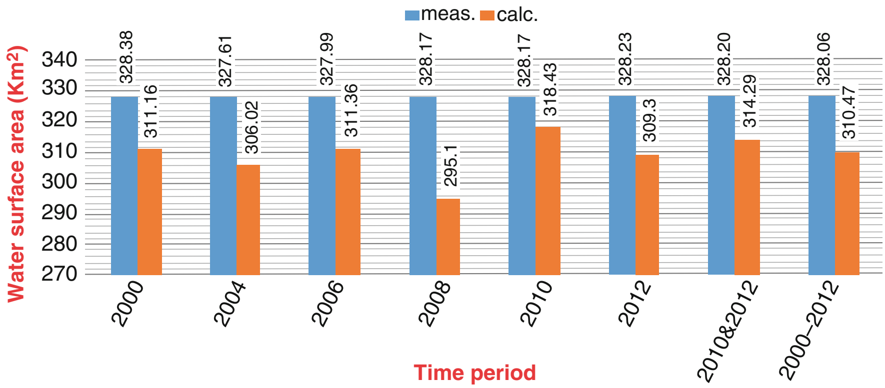

Fig. 16 Water surface area computed from the individual and collective rating curves at water level (175 m amsl)

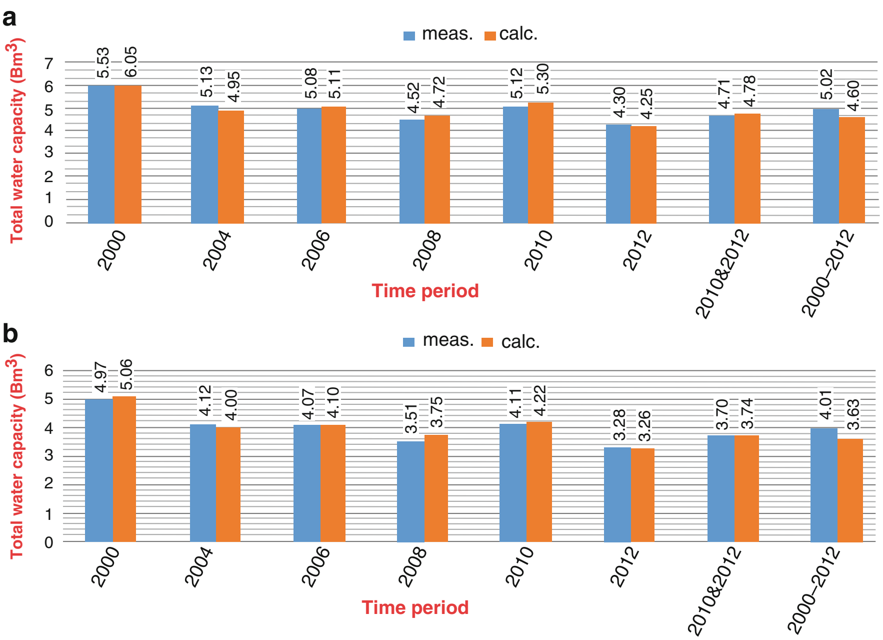

Fig. 17 Total water capacity computed from the individual and collective rating curves: (**a**) at water level (178 m amsl), (**b**) at water level (175 m amsl)

5.6 Effect of Sediment and Erosion Amounts on Water Capacity of the Study Area

Table 6 illustrates the effect of sediment and erosion change amounts on the measured water capacity from the years 2000 to 2012. It is obvious from this table that there is a decrease in the water capacity from the year 2000 to 2008 and from year 2010 to 2012 due to sediment accumulation (the amount of sediment is higher than the amount of erosion). Otherwise, there was an increase in the water capacity by 0.60 Bm^3 from year 2008 to 2010, because of the higher amount of erosion than the amount of sedimentation.

The previous results showed that by increasing the sediment amount more than the erosion amount, the water capacity decreases and vice versa.

5.7 Application and Comparisons

Table 7 illustrates that the sum of water volume of the AHDL active sedimentation portion that was estimated by AHDA and NRI (the traditional methods) was about

Table 6 Effect of sediment and erosion amounts on the water capacity

Year	Time period	Water capacity (Bm^3)	Difference between sediment and erosion = Total change amount (Bm^3)	Case	Type of total change
2000		4.97			
	2000–2004		0.85	Decrease in water capacity	Sedimentation
2004		4.12			
	2004–2006		0.05	Decrease in water capacity	Sedimentation
2006		4.07			
	2006–2008		0.56	Decrease in water capacity	Sedimentation
2008		3.51			
	2008–2010		−0.60	Increase in water capacity	Erosion
2010		4.11			
	2010–2012		0.83	Decrease in water capacity	Sedimentation
2012		3.28			

Table 7 Calculated water volumes of the study area by AHDA at water level (175 m amsl) at year 2012

Sec. code	Area (m^2)	Served length (km)	Volume (Bm^3)
22	190515.91	7.95	1.514
24	95818.63	7.25	0.695
25	98114.46	8.00	0.785
26	19233.31	6.00	0.115
27	8947.32	8.50	0.076
28	11884.96	4.00	0.047
			$\sum = 3.232$

Table 8 Comparison of results between the present and traditional methods of estimating sediment amount area from year 2000 to 2012

Time period	Amount of sediment by GIS/RS method (Bm^3)	Amount of sediment by AHDA method (Bm^3)
2000–2012	1.69	1.62

3.232 billion m^3 [24]. These values are nearly equal to the computed volume in this study using the RS/GIS approach at the same water level (175 m amsl) which has a value 3.26 billion m^3 as shown previously in Fig. 17b. This means that the present method overestimates the water capacity by less than 1%. Consequently, the developed equations can be used to estimate the water volume (capacity) of this part of the lake as an alternative to extensive costly measurements. However, field measurements by AHDA and NRI are necessary from time to time in order to update such equations and for monitoring purposes as well.

Table 8 illustrates that the total amount of sediment from year 2000 to 2012 was about 1.69 billion m^3 (sum of total change amount – between 2000 and 2012 – from Table 4), and the estimated sediment amount by the AHDA (the traditional method) was equal to 1.62 billion m^3 in the same period [24]. This means that the present approach overestimated the sedimentation capacity by about 4.3% compared to the method used by AHDA. This percent indicates that the AHDA and NRI sediment data are trustful and reliable.

6 Conclusions and Recommendations

This study presents and discusses the results of change detection in bed surface (sedimentation/erosion) of the active portion of Aswan High Dam Lake based on using RS/GIS techniques. The results indicate that sedimentation is dominant in years with high flood while erosion occurs when the incoming flow to the lake is low. The computed water capacities show an increase during the periods where erosion amounts exceed sediment amounts and vice versa. Moreover, results indicate that the present approach overestimates the sedimentation capacity by about 4.3% from year 2000 to 2012 compared to the results of the method used by AHDA. The measured velocity patterns are mapped, analyzed, and its 2-D profiles are correlated to changes of the study area bed profiles. According to this correlation, it can be concluded that the increment in the inflow velocity rate is associated with the erosion phenomenon. On the other hand, the decrement in the inflow velocity rate is accompanied with the sedimentation phenomenon. In addition, this study developed several relationships between water volume or capacity/ surface area/water level for the active sedimentation zone of Nubia Lake for the years from 2000 to 2012 individually and collectively. The accuracy of the developed relationships was assessed by comparing the results with the field measurements and the existing rating curves for the Lake. The RMSE was found to range between 5–10% and 2–4% for the relationships (volume/water level) and (surface area/water level), respectively. Also, the correlation coefficients ranged from 0.94 to 0.99 (volume/water level) and from 0.97 to 0.99 (area/water level). The authors highly recommend the use of the same tested method in this paper in studying the change detection of the entire AHDL. Also, it is recommended to jointly use the remote sensing and in situ data to provide an accurate estimate of water capacity (volume) variations and sediment amounts of the whole AHDL.

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