Adaptation of Surface Water Modeling System for Sediment Transport Investigations in Lake Nasser

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Abstract

The Nile River presents the main source of Egypt's water supply where it currently supplies most of the total demands. Due to the great variability between water supply and demands in quantity and timing, it was decided to construct a century dam. In the period between 1964 and 1971, Egypt constructed the Aswan High Dam. The construction of the dam entailed the development of an extensive reservoir, known as Lake Nasser, which is considered the second largest man-made lake all over the world. Optimum management of Lake Nasser requires a better understanding of the influence of the hydrologic system of the lake. Hydrologic budgets that describe the sources and losses of water to lakes are essential to many lake management decisions, for example, to adopt the best management practices and to evaluate lake-restoration projects .However, many available hydrologic budgets lack the necessary accuracy to define cause and effect clearly when lake levels begin to change .Sediment transport and deposition is one of the main problem associated with large reservoirs. This paper describes the process of generating the bathymetry of the lake bed surface and the development steps for a 2-D hydrodynamic model for its flow fields and the application of the hydrodynamic model in the sediment transport studies to explore the sedimentation problem at the lake entrance. The Surface Water Modeling System (SMS), which contains RMA2 2-D hydrodynamic model, shows good calibration and verification results .Hence, it can be utilized in the lake hydrodynamic analysis for different scenarios. These results can be used as the input data into SED2D sediment transport model for the sediment transport and deposition investigations in the lake. In addition, Geographic Information System (GIS) tools, such as geo-spatial analysis tools, have been utilized in data preparation, the analysis and estimation of the sediment deposition volumes and distributions.

Key words: 2-D Hydrodynamic Model, GIS, Lake Nasser, RMA2, Sediment Transport, SED2D, SMS.

1. INTRODUCTION

In 1964, the Nile River was diverted and the construction of the Aswan High Dam (AHD) started resulting in formation of a huge reservoir, formally known as Lake Nasser, which is considered the second largest man-made lake all over the world (ICOLD, 1984). Lake Nasser is considered the strategic water bank of Egypt. The lake is designed to have a maximum water level of 182 m above mean sea level (MSL), a total capacity of 162×10^9 m^3, a length of 500 km, an average width of 12 km, and a surface area of about 6500 km^2 at its maximum water level. The mean depth of the reservoir is 25 m while the maximum depth reaches up to 110 m at water level of 182 m above (MSL). The lake has a shoreline length of 9802 km at its maximum water level. However, the lake morphology is very irregular, its shores have numerous side arms or embayments (Khours) extending in both the Egyptian and Sudanese stretches as shown in Figure 1. Hence, the reservoir is considered dendritic in shape characteristics.

Sediment transport and deposition is one of the major problems associated with large reservoirs. Sediment accumulations, in Lake Nasser, lead to formation of a submerged delta, resulting in decreasing the lake storage capacity, navigation problems and other water quality and environmental problems (EL-Sammany, 1999). The delta is formed where the stream enters into the reservoir pool. The sediments deposit from non-stratified flow when the velocity and the transport capacity decrease. The new submerged delta is divided into two zones, the topset bed and the foreset bed. Coarser particles of bed material size predominate in the delta topset deposits, but finer particles may also present. Fine particles and wash load particles begin to advance downstream the topset deposits. The transition from topset beds to foreset beds in the delta typically coincides with the plunge point of the density currents at which the flow changes from non-stratified to stratified flow as shown in Figure 2.

The location of the plunge point is mobile and sensitive to discharge changes. Because of the density difference between the sediment-laden inflow and the clear water in the reservoir, the heavier current plunges beneath the clear water and moves towards the dam as a submerged underflow. The inflow moves as a density current in the form of overflow if the inflow water is lighter than the surface water of the reservoir. Finally, if the density of inflow is intermediate to that of the top and bottom waters of the reservoir, the inflow will find its own density layer and flow through the reservoir as a density interflow (provided that reservoir water is vertically stratified).

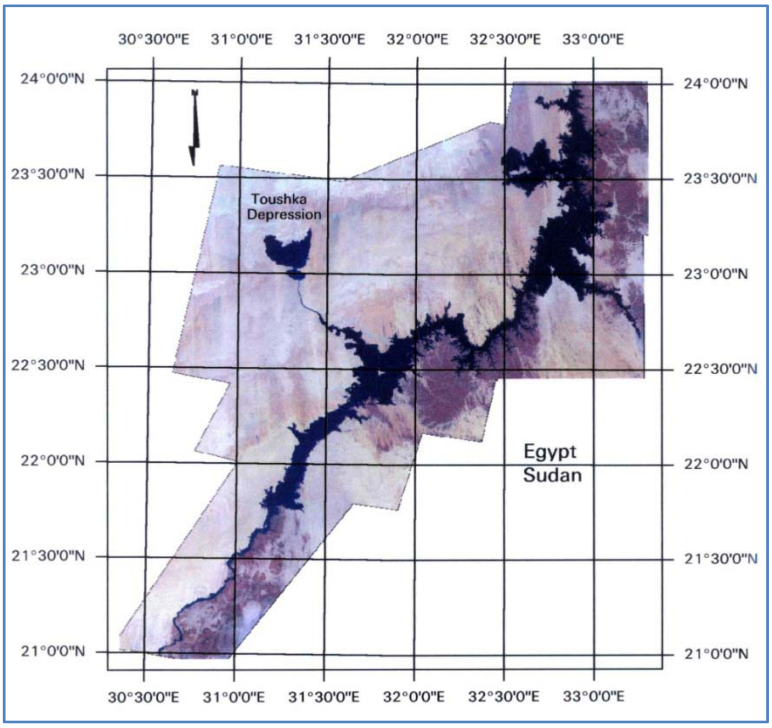


Figure 1: Lake Nasser map (Source: LANDSAT image, November 1998)

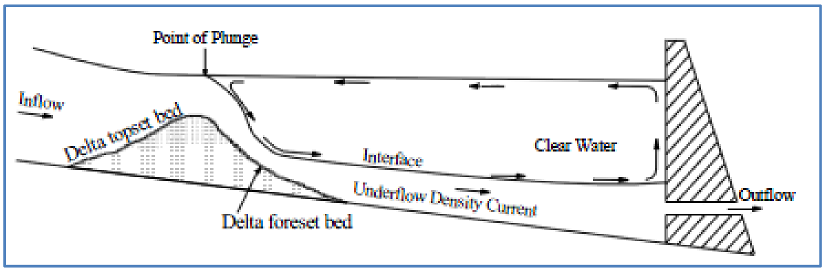


Figure 2: Delta formation process in Lake Nasser (after EL-Sammany, 1999)

Nevertheless, Egypt conducts bathymetric surveys, from year to another, to monitor and follow up the delta formation at the lake entrance to evaluate the sediment depositions and the progress in the delta formation. Bathymetric surveys cost too much and consume many efforts and the personnel may face dangerous situations in the lake while conducting the hydrographic missions. So, looking for a tool to simulate and forecast the sediment transport and depositions is a must. Thus, modeling and geo-spatial analysis approaches will be used in the investigations of sediment deposition in Lake Nasser.

2. MATERIAL AND METHODS

Numerical analysis and modeling techniques are considered good tools to simulate and forecast the sediment transport and depositions at the lake entrance. Hydrodynamic modeling is considered the core of any sediment transport and deposition investigations. The results of the 2-D hydrodynamic model are used as the input data for the sediment transport and deposition model. In this study, the Surface Water Modeling System (SMS) will be used to simulate the 2-D hydrodynamic at the lake entrance and hence, to study the sediment transport and depositions at the lake entrance.

The modeling of the sedimentation process at the lake entrance requires the simulation of the flow fields at the problematic area and using of the available bathymetric survey data for the reservoir beds at this area. The work plan could be summarized as follows;

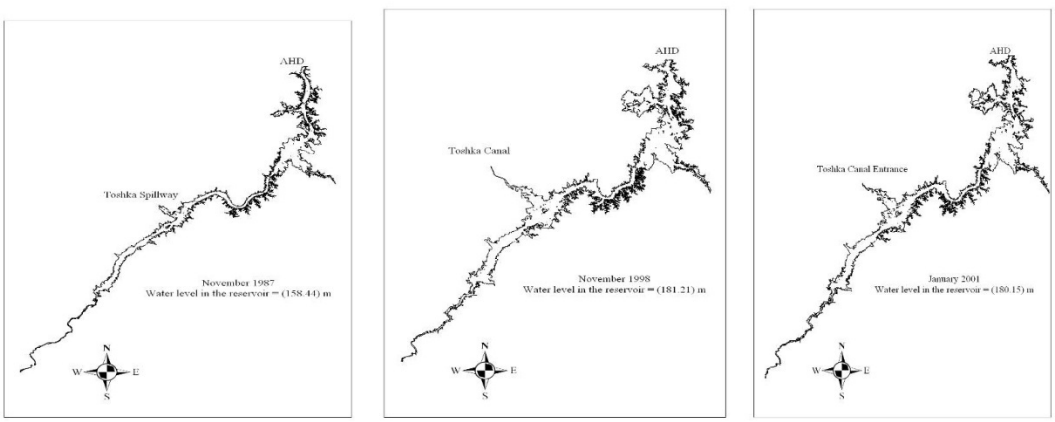
a. Building the geometric map of the reservoir beds using the bathymetric survey data as an input for the 2-D hydrodynamic model.
b. 2-D hydrodynamic model calibration and verification.
c. Study the sedimentation problem at the lake entrance using 2-D sediment transport model.
d. Change detection (spatially and temporally) of the sediment depositions at the study area using Geo-spatial technique to compare both of the lake original beds and the forecasted one.

2.1. Data Presentation

Obtaining an accurate representation of bed topography is likely the most critical, difficult, and time consuming aspect of any 2-D hydrodynamic modeling approach. Simple cross-section surveys are generally inadequate. Conducting Bathymetric surveys by synchronizing Global Positioning Systems (GPS) and depth sounding systems for large water bodies have been found to be efficient technique. Such field data was processed and checked through a quality digital terrain model before being used as input for the 2-D model. Moreover, hydrodynamic models require hydrologic and hydraulic data such as stage and flow hydrographs, velocity measurements, and rating curves to establish initial and boundary conditions and for model calibration and verification. In this study, a discharge boundary condition at the upstream end of the modeled reach of Lake Nasser was represented using a flow hydrograph recorded at Donqola gauging station, water surface elevation at the downstream end was determined using data from upstream the AHD gauge station.

2.2. Geometric Data

Three LANDSAT images for the lake acquired in different dates were used to extract the lake boundaries by image classification techniques as shown in Figure 3. These images were shot in November 1987 (Figure 3; a) where the water level in the reservoir was (158.44 m), November 1998 (Figure 3; b) where the water level was (181.21 m) and in January 2001 (Figure 3; c) where the water level was (180.15 m). The extracted lake boundaries, obtained from the satellite images, were used to form a group of scatter points (x,y,z) using the WGS84 – UTM Z36N as a defined projected coordinate system. These points were used later, combined together with the available bathymetric survey data, in the generation of the bathymetry mesh.



(a): November 1987 **(b): November 1998** **(c): January 2001**

Figure 3: Lake Nasser boundaries extracted from LANDSAT images acquired in different dates

2.3. Water Level and Inflow Data

Figure 4 and Figure 5 illustrate the average monthly water levels U.S. AHD and average monthly discharges hydrographs at Donqola gauging station (750 km U.S. AHD) for the years 1964 till 2005, respectively. The two figures illustrate that the water level in the reservoir reaches the maximum value in November and December every year then decreases gradually till reaches its minimum value in the second half of July. The reservoir reached its lowest storage level of 150.62 m in July 1988, but fortunately, the large flood of 1988-1989 allowed the reservoir to rise again and reach up a level of 168.82 m in December 1988. In the 1990's decade, the reservoir continued its rising until it reached the highest level of 181.60 m in November 1999. After the year 2001, the reservoir water levels slightly decrease again till the year 2005.

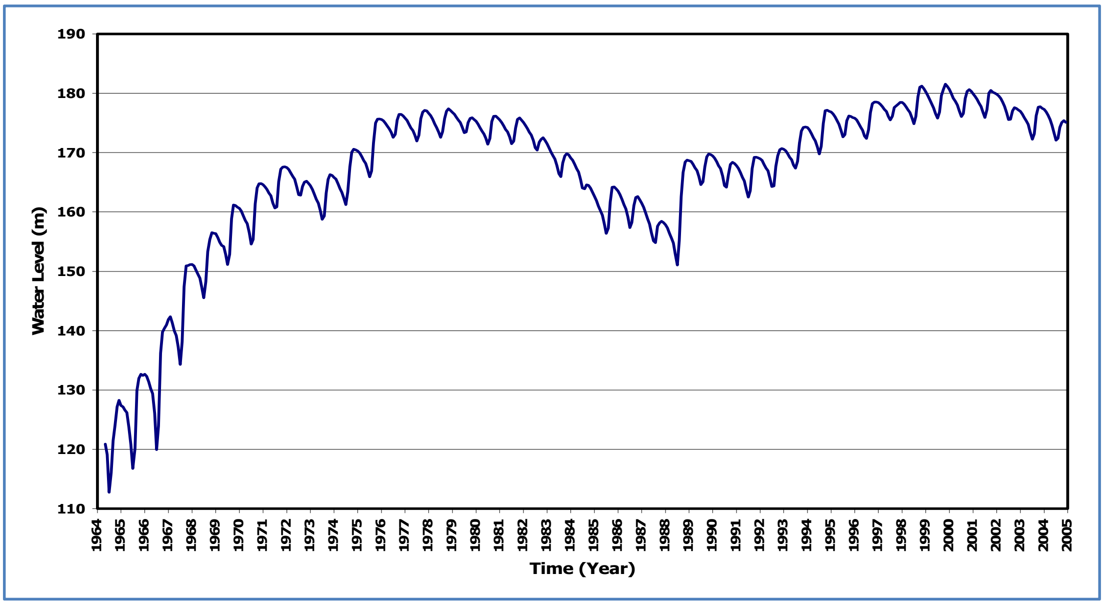


Figure 4: Average monthly water levels hydrograph U.S. AHD for the period 1964-2005

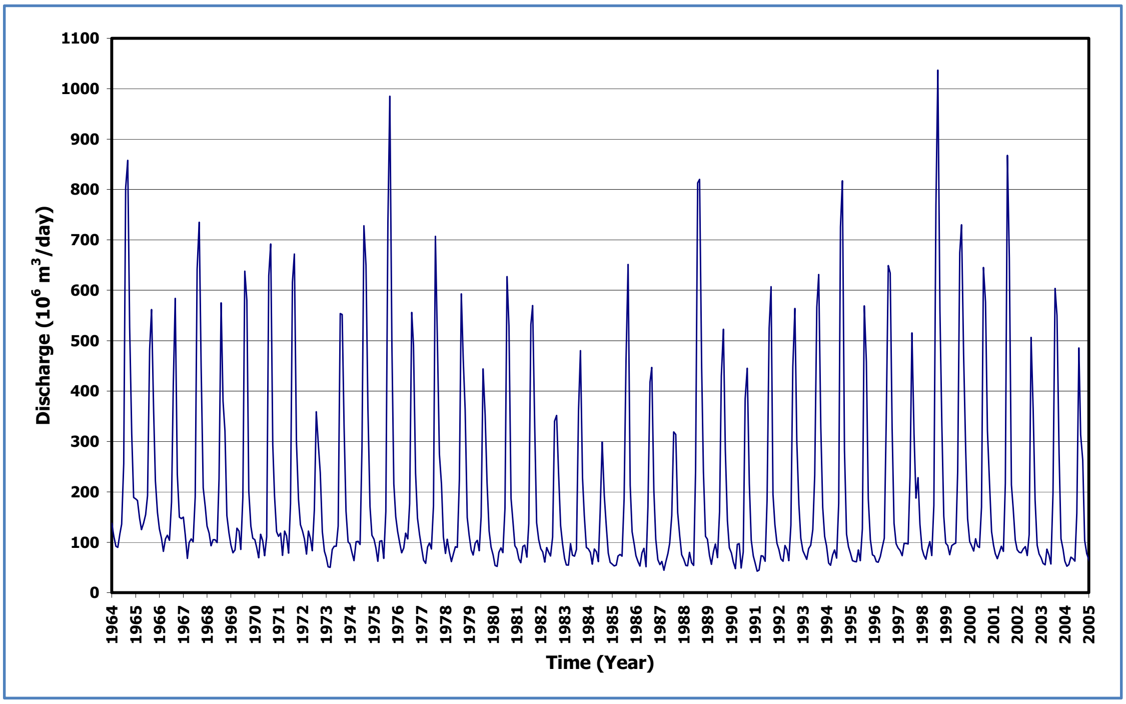


Figure 5: Average monthly discharges hydrograph at Donqola for the period 1964-2005

3. RMA2 HYDRODYNAMIC MODEL

To study the flow fields of the lake, the main objective of the present study was to develop a hydrodynamic model to study the flood routing through the lake and to help in sedimentation and water quality studies.

3.1. Model Selection

The choice of appropriate analytical methods to use during a river hydraulics study is depending on many factors including the objectives, the level of detail being called for, the regime of flow expected, the availability of necessary data, and the availability of time and resources to properly address all essential issues. A Survey was made on the 2-D Hydrodynamic models and the RMA2 model under the SMS interface was selected in the current study case. The original RMA2 was developed by Norton, King and Orlob (1973), of Water Resources Engineers, for the Walla Walla District, USA Corps of Engineers, and delivered in 1973.

3.2. Model Description

RMA2 is a two-dimensional depth averaged finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface two-dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. The Manning's coefficient was used to define friction and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady (dynamic) problems can be analyzed. The program has been applied to calculate water levels and flow distribution around islands, into and out of off-channel hydropower plants, at river junctions, circulation and transport in water bodies with wetlands, and general water levels and flow patterns in rivers, reservoirs, and estuaries.

3.3. Mesh Generation

After creating a polygon, which encloses the study area, a mesh was generated using the adaptive tessellation technique which is a mesh generation technique used to fill the interior of a polygon. This technique uses the existing spacing on the polygon to determine the element sizes on the interior. If a more detailed mesh is used to capture more accurate geometry, the model processing and computation will slow down and consume more time to run the case. Nevertheless, it was found that no noticeable changes occurred. In this study a dense mesh was generated around the islands and near the banks as shown in Figure 6.

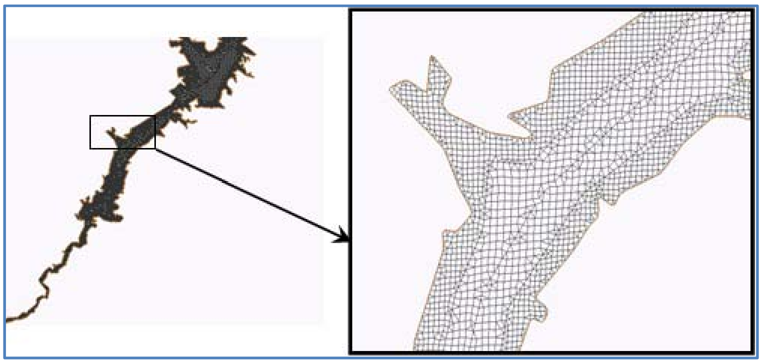


Figure 6: The generated mesh

After the mesh generation, the scatter points obtained from the GIS were used to form a Triangulated Irregular Network (TIN), which was used in the interpolation of the bed levels. After running the model and interpreting the results it was found that this bathymetry should be enhanced especially in the Sudanese part where the stream is narrower than in the Egyptian part at which many areas of the lake were not covered by hydrographical surveys; that may cause the model to converge. Therefore, Shuttle Radar Topography Mission (SRTM) 90m resolution Digital Elevation Model (DEM) of the surrounding area (Figure 7) was used to generate a Triangulated Irregular Network (TIN) using the ArcGIS software. The resulted TIN (Figure 8) was then used in the interpolation process to enhance the bathymetry obtained earlier. The Enhanced Bathymetry (Figure 9) showed better results after running the hydrodynamic model.

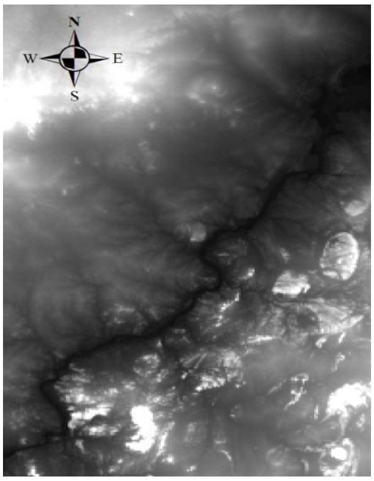


Figure 7: 90m SRTM DEM

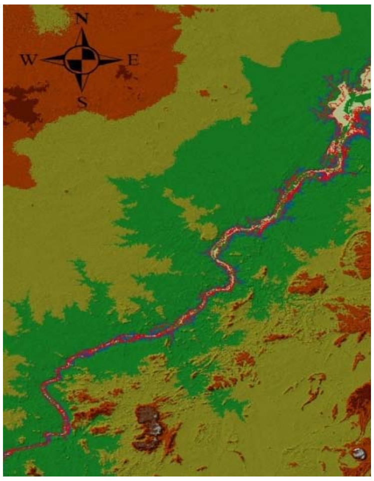


Figure 8: The resulted TIN

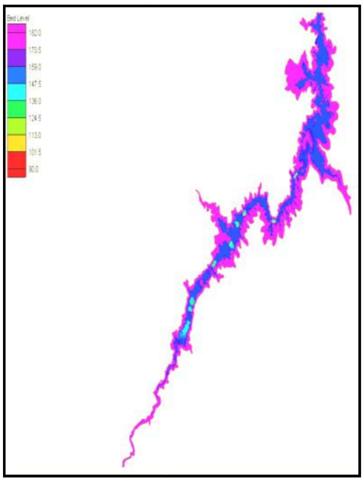


Figure 9: The enhanced bathymetry

3.4. Model Parameters

Hydrodynamic models main parameters can be summarized as: channel bed topography (geometry), roughness, transverse Eddy viscosity distributions, boundary conditions and initial flow conditions. The structure of the geometry and overall study design are the most significant, followed by the boundary condition assignments then the roughness and turbulence factors. The bed friction energy transfer computation, or bottom roughness, is one of the primary calibration parameters. By far, the popular choice is Manning's roughness coefficient (n) value, and these roughness values may be assigned throughout the mesh by material type. The roughness is a function of many variables such as type of bed and bank materials, and river geometry and irregularities. Accurate prediction of the roughness in such case is rather complicated task. In this study, the Manning's coefficient was taken as a constant value over the river part and another constant value on the reservoir part.

Turbulent exchanges are sensitive to changes in the direction of the velocity vector. Conversely, small values of the turbulent exchange coefficients allow the velocity vectors too much freedom to change magnitude and direction in the iterative solution. The result is a numerically unstable problem for which the program will diverge rather than converge to a solution. A possible recourse is to continue increasing the Eddy viscosity (E), until a stable solution is achieved. The time step is dependent on a dimensionless flow parameter called the Courant number. Some hydrodynamic models developers suggest that to maintain numerical stability and produce accurate results, the Courant number should not exceed 1.0 (Westerink et al., 1992).

3.5. Model Calibration

When a model is calibrated, the parameters (primarily Manning's n and reach storage), which control the model's performance, are determined. The key to a successful calibration is to identify the true values of the parameters which control the system and not to use values that compensate for shortcomings in the geometry and/or the boundary conditions.

In our study case, the calibration process was carried out using the recorded water levels at various sections upstream AHD during the mission of the year 2000, for the period between the 10^{th} and the 25^{th} of November 2000 as shown in Figure 10. On the other hand, Figure 11 shows the discharges recorded at Donqola gauging station during the same period.

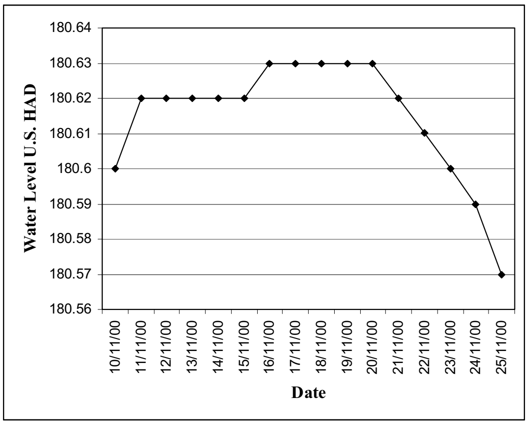


Figure 10: Water levels U.S. AHD

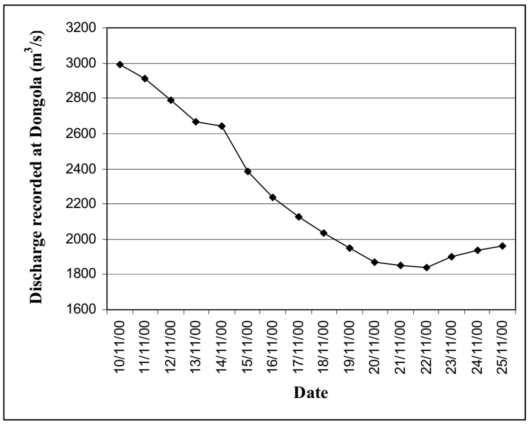


Figure 11: Discharges recorded at Donqola station

The measured water levels were compared with the water levels calculated from the model and the results were plotted as shown in Figure 12. The results show absolute error values ranging from 0.02 cm to 1.28 cm, which is considered a good result.

The model results are plotted in thematic layers illustrating the resulted water levels, water depths and velocity magnitudes at the end of the simulated interval as shown in Figures 13, 14 and 15 respectively.

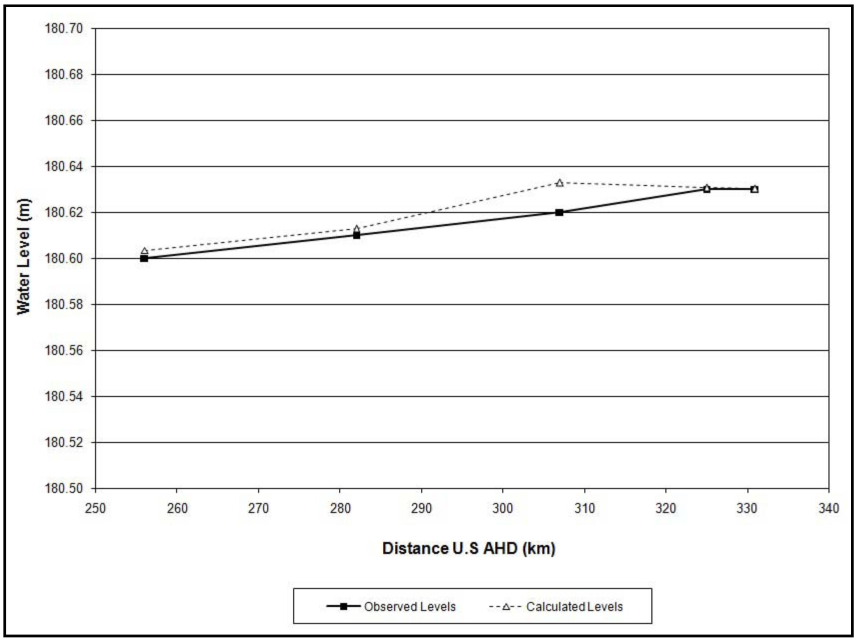


Figure 12: Measured water levels vs. calculated water levels (calibration phase)

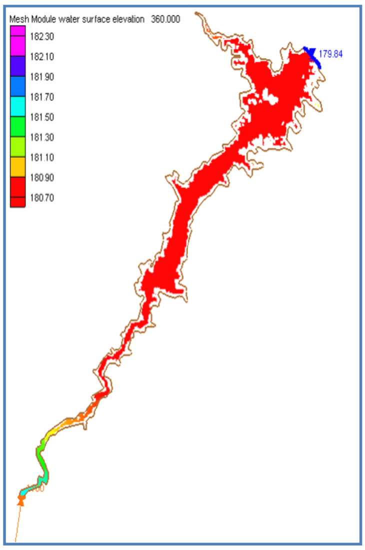


Figure 13: Simulated water surface elevations

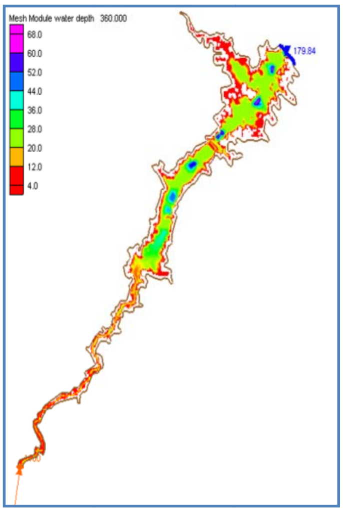


Figure 14: Simulated water depths

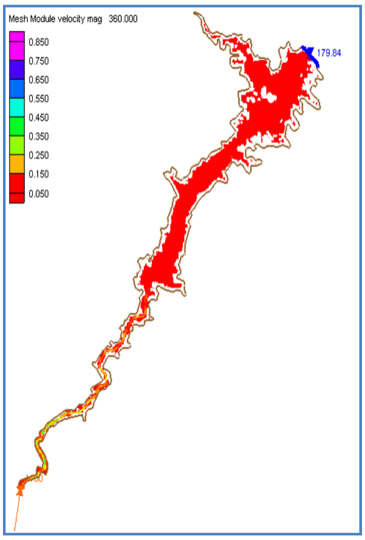


Figure 15: Simulated velocity magnitudes

3.6. Model Verification

Verification is a multi-step process of model adjustments and comparisons, leavened with careful consideration of both the model and the data. It is not a simple two-step (calibration – verification) procedure. The purpose of numerical modeling is to gain insight, not answers.

The verification process was carried out using the recorded water levels at various sections upstream AHD during the mission of the year 2000, for the period between the 1st and the 9th of May, 2000 as shown in Figure 16. On the other hand, Figure 17 shows the discharges recorded at Donqola gauging station during the same period.

The measured water levels were compared with the levels calculated from the model and the results were plotted as shown in Figure 18, which shows absolute error values ranging from 0.83 cm to 8.03 cm. The resulted water levels, water depths and velocity magnitudes at the end of the simulated interval are also presented in thematic layers as shown in Figures 19, 20 and 21 respectively.

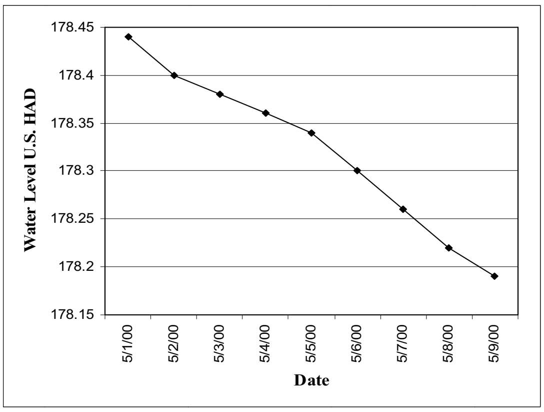


Figure 16: Water levels U.S. AHD

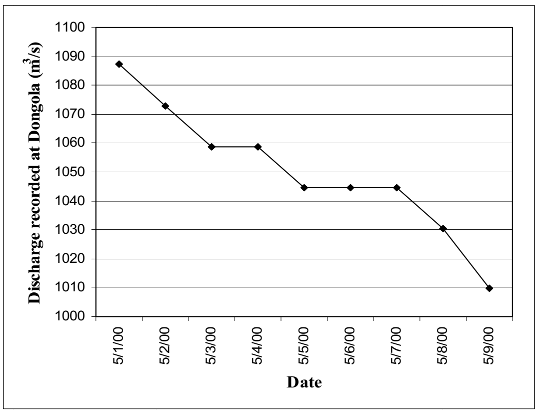


Figure 17: Discharges recorded at Donqola station

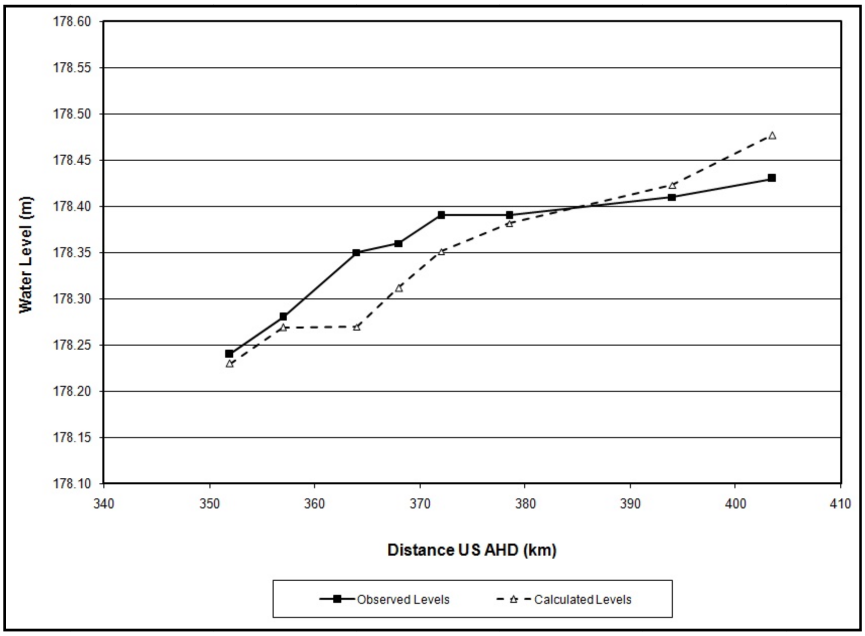


Figure 18: Measured water levels vs. calculated water levels (verification phase)

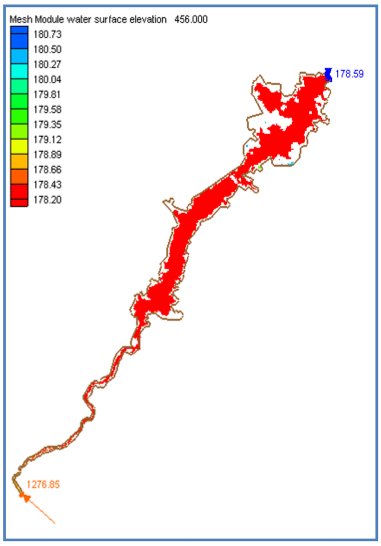


Figure 19: Simulated water surface elevations

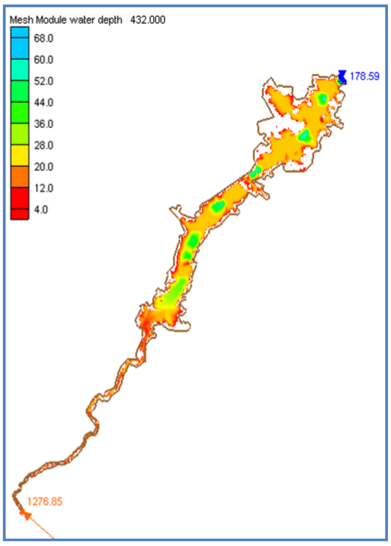


Figure 20: Simulated water depths

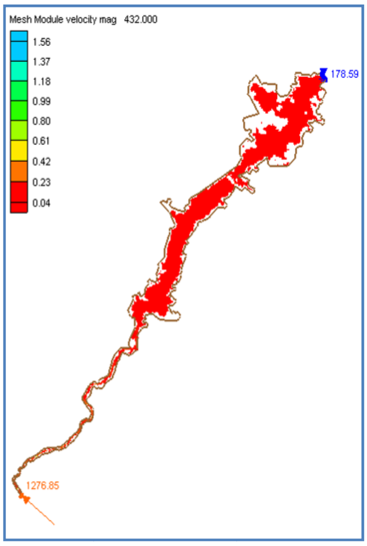


Figure 21: Simulated velocity magnitudes

4. SED2D SEDIMENT TRANSPOT MODEL

4.1. Model Selection

A Survey was made on the 2D sediment transport analysis models. The selection and the comparison between models were based on the following points:

- Availability.
- Compatibility with the RMA2 and the ability to exchange data format.
- Easiness to learn and use. Very good visual representation of the data which helps in the interpretation of the results.
- Availability of documentations.

The SED2D model under the SMS interface was selected in the case study based on the previous choice criteria.

4.2. SED2D Model Origin

The initial code development was accomplished by Dr. Ranjan Ariathurai (l974). The initial code, a 2D model in the horizontal plane, was extended to include the vertical plane by Ariathurai, MacArthur, and Krone (l977) under contract with the US Army Corps of Engineers, Dredged Material Research Program. Modernization and upgrade were undertaken in order to improve model maintenance and to facilitate the addition of new features to the code.

4.3. SED2D Model Assumptions

The SED2D model is based on the following conceptual model:

a. Basic processes in sedimentation can be grouped into erosion, entrainment, transportation, and deposition.
b. Flowing water has the potential to erode, entrain, and transport sediment whether or not sediment particles are present.
c. Sediment on the streambed will remain immobile only as long as the energy forces in the flow field remain less than the critical shear stress threshold for erosion.
d. Even when sand particles become mobile, there may be no net change in the surface elevation of the bed. A net change would result only if the rate of erosion was different from the rate of deposition - two processes which go on continuously and independently.
e. Cohesive sediments in transport will remain in suspension as long as the bed shear stress exceeds the critical value for deposition. In general, simultaneous deposition and erosion of cohesive sediments do not occur.
f. The structure of cohesive sediment beds changes with time and overburden.
g. The major portion of sediment in transport can be characterized as being transported in suspension, even that part of the total load that is transported close to the bed.

4.4. SED2D Applications and Capabilities

SED2D can be applied to clay or sand bed sediments where flow velocities can be considered two-dimensional in the horizontal plane (i.e., the speed and direction can be satisfactorily represented as a depth-averaged velocity). It is useful for both deposition and erosion studies and, to a limited extent, for stream width studies. The program treats two categories of sediment: 1) non-cohesive, which is referred to as sand herein; and 2) cohesive, which is referred to as clay. The derivation of the basic finite element formulation is presented in Ariathurai (1974) and Ariathurai, MacArthur, and Krone (1977). There are four major computations;

a. Convection-diffusion governing equation.
b. Bed shear stress.
c. The bed source/sink.
d. The bed strata discretization.

4.5. SED2D Limitations

The SED2D model does not compute water surface elevations or velocities; these data must be provided from an external calculation of the flow field. For most problems, a numerical model for hydrodynamic computations, RMA2, is used to generate the water surface elevations and velocities. An implicit assumption of the SED2D model is that the changes in the bed elevation due to erosion and/or deposition do not significantly affect the flow field. When the bed change calculated by the model does become significant and the externally calculated flow field supplied by the user is no longer valid, then the SED2D run should be stopped, a new flow field calculation should be made using the new channel bathymetry generated by SED2D, and the SED2D run should be restarted with the new flow field as input.

4.6. SED2D Model Boundary Conditions

In the case of tidally fluctuating flow across a model boundary the specification of an accurate concentration is not simple. In the current model version it is allowed to determine whether to apply the concentration specification or whether to apply a zero concentration gradient boundary condition (BC). The gradient BC allows the concentration to be solved from the interior concentration field of the model. This provides some relief; but strong concentration gradients reaching the boundary can result in abrupt jumps in the concentration as the tide turns to enter the mode. This is the result of not accounting for the concentration history of waters that have crossed the boundary.

4.7. Model Input Files

There are numerous input files required for SED2D that may be summarized as follows;

a. **Geometry File**
   The mesh geometry, which SED2D will use, is normally defined in a binary file produced by the Geometry File Generation program (GFGEN). This mesh geometry file consists of the nodes and elements that define the size, shape, and bathymetry of the study area.
b. **Hydrodynamic File**
   The hydrodynamic input, which SED2D will use, is normally defined in a binary file produced by the RMA2 model, which is a depth averaged hydrodynamic model. This binary solution file consists of the velocity components, water depths, water surface elevations, and wet/dry status at each node within the computational domain. This data set may be either steady state or time varying.

The water levels recorded upstream AHD during the sediment transport simulation interval are plotted along with the recorded inflows at Donqola gauging station as shown in Figure 22.

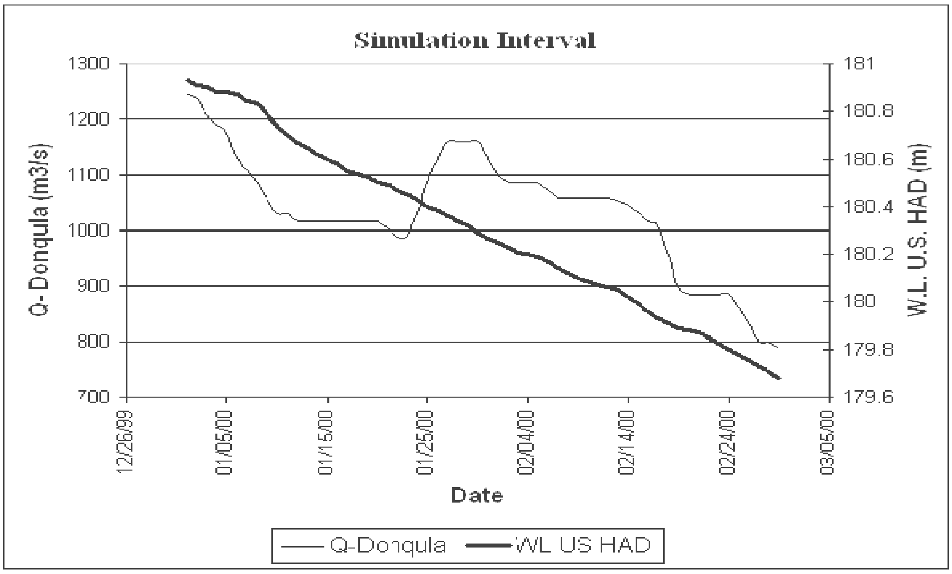
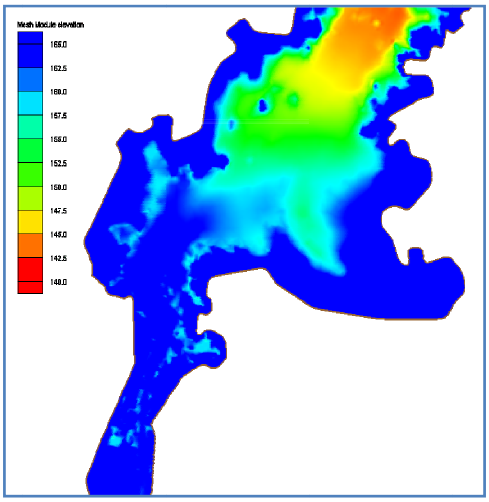


Figure 22: Inflows and water levels during the sediment transport simulation interval

4.8. SED2D Model Results

After the hydrodynamic model was calibrated and verified, it was then used as the source of input files to the SED2D sediment model. The following two figures represent the lake bed surfaces of the study area, i.e., the original one and the forecasted one after the application of the sediment load to a time interval of 5 days as shown in Figures 23 and 24. The results show that there were almost no sediment depositions in the lake beds.



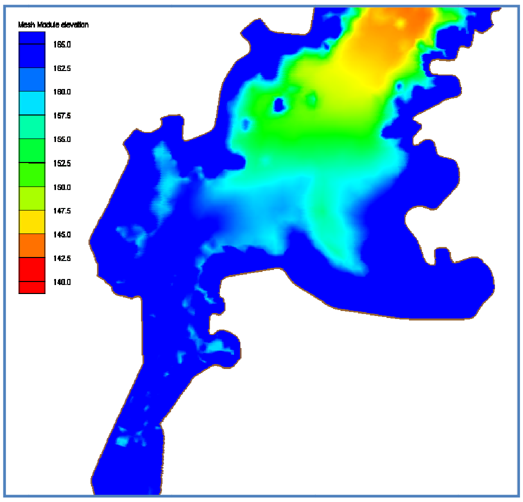


Figure 23: Original lake bed surface **Figure 24: The 5 days forecasted lake bed surface**

Figure 25 illustrates the forecasted lake bed surfaces of the study area after applying the same sediment load to a time interval of 60 days (starting from the 1st of January 2000 to the end of February 2000). The results show that there were distinguished sediment depositions of few millimeters, in this simulation interval, in the lake beds.

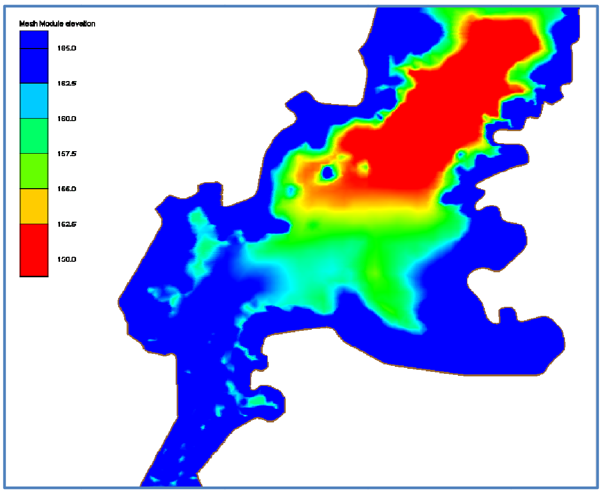


Figure 25: The 60 days forecasted lake bed surface

5. SEDIMENT STUDY USING GEO-SPATIAL ANALYSIS

The spatial analyst and the 3D analyst tools under the ArcGIS software have been utilized to investigate the changes in the lake beds based on quantitative analysis. Both of the original lake beds in 1953 before the construction of AHD and the one surveyed in 2004 have been converted into TINs using the available bathymetric data. Consequently, these TINs have been converted to DEMs as shown in Figure 26.

Both of the 2 DEMs, of the study area, have been overlayed and analyzed to calculate the sediment deposition volumes and to define sediment deposition distributions as shown in Figure 27. ArcGIS proved to be a powerful tool that can be used in sediment investigations in Lake Nasser. Nevertheless, ArcGIS is not able to forecast the lake bed changes unless it is linked to a sediment transport model.

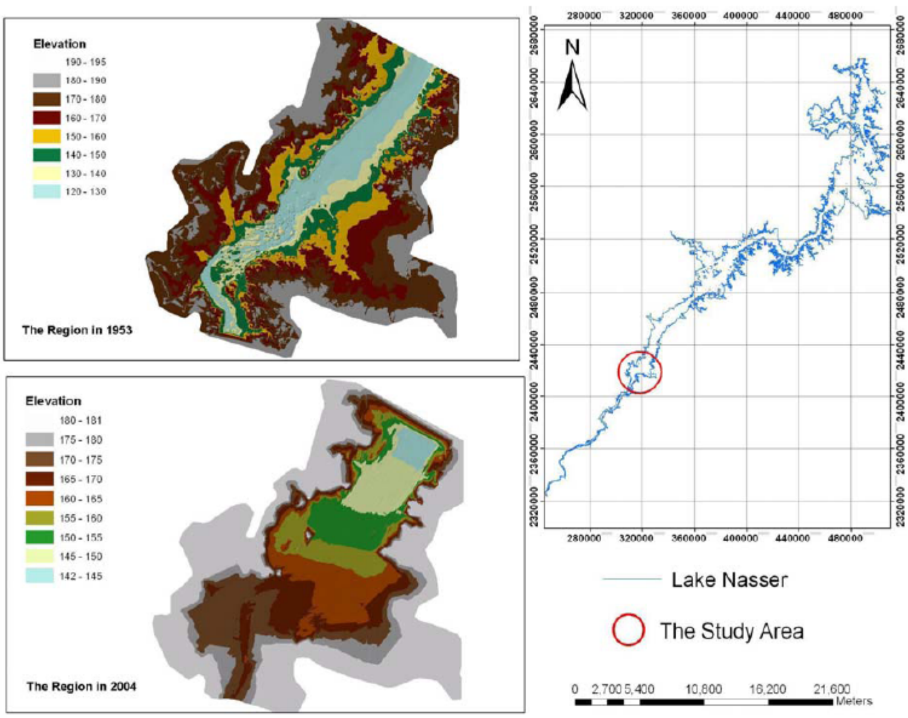
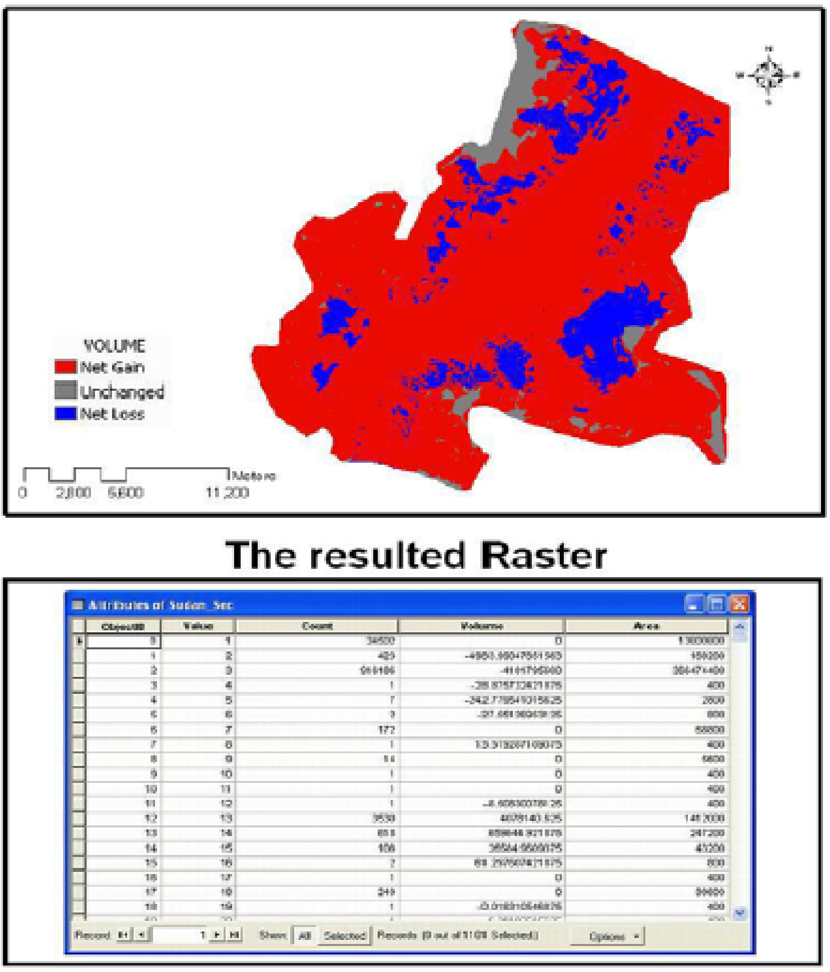


Figure 26: The resulted DEMs for the study area



ObjectID	Value	Count	Volume	Area
0	1	34500	0	13800000
1	2	423	-4950.99047581583	169200
2	3	961186	-4111795080	38447400
3	4	1	-28.875732421875	400
4	5	7	-242.779541015625	2800
5	6	2	-27.461382446	800
6	7	172	0	68800
7	8	1	13.319207109375	400
8	9	14	0	5600
9	10	1	0	400
10	11	1	0	400
11	12	1	-8.60830078125	400
12	13	3530	4078140.625	1412000
13	14	618	658646.921875	247200
14	15	108	38564.5500075	43200
15	16	2	89.2976074871875	800
16	17	1	0	400
17	18	249	0	99600
18	19	1	-5.018310546875	400

Record 1 Show: All Selected Records (0 out of 1108 Selected.) Options

Figure 27: Sediment deposition volumes and distribution in the study area

6. CONCLUSION AND RECOMMENDATIONS

A 3D surface of Lake Nasser beds has been created as the first step for the hydrodynamic modelling. RMA2, which is a 2-D hydrodynamic model, was adopted to simulate the flow fields (steady and unsteady) in the lake. The calibration process showed variability of the calibration parameters, specially the Manning's roughness coefficient, due to the sophisticated shape of the lake boundaries and the irregularity of the bed surfaces. However, the calibration and the verification steps show good results. The RMA2 output results have been used as input data into SED2D which is a sediment transport model. SED2D succeeded to simulate the sediment transport in the study area. The geo-spatial analysis technique was found to be an accurate and much faster approach to estimate lake bed changes. However, it could not be used directly to forecast the future lake bed changes unless it is linked to a sediment transport model.

As the SED2D model succeeded to simulate the sediment depositions in Lake Nasser, it is highly recommended to conduct comprehensive studies, using SED2D model, to forecast the delta formation progress in the lake. Hence, the delta topset shifting up and the delta foreset advancing towards the dam will be forecasted at different future times. As a result, decision makers will decide when and where the desilting of the lake sediment depositions will take place.

Also, it may be recommended that establishing a number of stage gauging stations, along the lake upstream the AHD up to the lake entrance, will enhance the model results. Moreover, establishing flow and sediment load gauging station close to the lake entrance will have accurate and continuous inflow and sediment load measurements entering into the lake. Consequently, that will assist in reducing the modelling effort by minimizing the processing time and the stability problems. Additionally, complete bathymetric survey should be conducted for the entire Egyptian part of the lake.

7. ACKNOWLEDGMENT

The authors gratefully acknowledge all the facilities, the resources and the support offered by the Nile Research Institute (NRI), National Water Research Center (NWRC), Egypt and the High Aswan Dam Authority (HADA), Egypt, to conduct this research.

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