2D Hydrodynamic Model for Reservoirs: Case Study High Aswan Dam Reservoir

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Abstract

High Aswan Dam (HAD) is one of the most important projects in the history of Egypt. The dam, completed in 1968 at a distance of 7 km south of Aswan City, has provided full control on the discharges released to the Egyptian irrigation network system. Nile flow is allowed to pass only through the open-cut channel at the eastern side of the dam, where six tunnel inlets provided with steel gates are constructed for discharge control and water supply to power plants. An escape (spillway) is also provided at the western side of the dam to permit excess water discharge and control the maximum level of the upstream reservoir.

High Aswan Dam Reservoir (HADR) extends for 500 km along the Nile River and covers an area of 6,000 km2, The reservoir is surrounded by rocky desert terrain. To the west is the great Sahara Desert, and the Eastern Desert on the east side extends to the Red Sea. Another, uncontrolled, spillway was constructed at the end of Khor Tushka (on the western side of Lake Nasser at about 256 km upstream the dam). This spillway is connected to Tushka depression by a canal by which the excess flood can be turned to the depression.

The paper presents the development of a 2D simulation model of HADR. The modeling study aims to determine the optimal management policy for the reservoir in flood conditions by modeling the physical problem via a 2D routing model. The hydrodynamic model simulated the flow fields – steady and unsteady- of the Aswan High Dam Reservoir.

The maximum recorded discharge was simulated using the developed hydrodynamic model and the results are presented.

Introduction

The equations that describe the unsteady flow in the three dimensions, the Saint Venant equations, consist of the conservation of mass equation, and the conservation of momentum equation. The solution of these equations defines the propagation of a flood wave with respect to distance along the channel and time.

The full unsteady flow equations have the capability to simulate the widest range of flow situations and channel characteristics. Hydraulic models, in general, are more physically based since they only have one parameter (the roughness coefficient) to estimate or calibrate. Roughness coefficients can be estimated with some degree of accuracy from inspection of the waterway, which makes the hydraulic methods more applicable to ungauged situations.

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The traditional approach to river modeling has been the use of hydrologic routing to determine discharge and steady flow analysis to compute water surface profiles. This method is a simplification of true river hydraulics, which is more correctly represented by unsteady flow. Nevertheless, the traditional analysis provides adequate answers in many cases. Unsteady flow analysis could be used for all streams. On these streams, the loop effect is predominant and peak stage does not coincide with peak flow. Backwater affects the outflow from tributaries and storage or flow dynamics may strongly attenuate flow; thus, the profile of maximum flow may be difficult to determine.

Tefaruk Haktanir and Hatice Ozmen (1997) computed, using the computer program DUFLOW package, the Outflow hydrographs for three dams with long lakes in narrow valleys using both hydrologic routing (level-pool routing) and hydraulic routing. These hydrographs were then compared with three inflow hydrographs of different peaks. The DUFLOW package is based on the one-dimensional partial differential equations to describe unsteady flow in open channels, the continuity and momentum equations. **Francisco J. Rueda and S. Geoffrey Schladow (2003)** examined the internal dynamics of Clear Lake, California-a large, multibasin and polymictic lake-were using simulations conducted with a three-dimensional hydrodynamic model. The model was based on an accurate and efficient semi-implicit finite difference algorithm for the hydrodynamic equations, which has been previously subject to extensive verification with analytical test cases. **M. El-Moattassem et al (2003)** developed an approach for simulating the flow of water in High Aswan Dam Reservoir (HADR) and for predicting the sediment transport and determine solutions to overcome the problems associated with the sediment deposition.

The Problem Definition

The construction of High Aswan Dam (HAD) in Upper Egypt resulted in the formation of a reservoir that trapped almost all of the inflow and hence forms a large reservoir. The length of HAD reservoir is about 500 km with an average width of about 12 km and a surface area of 6540 km^2 at its maximum storage level. Which is (182.00) m. This reservoir is considered to be the second largest man-made lake in the world.

This paper introduces the development of a bathymetry (3 dimensioned bed level profile) of the High Aswan Dam Reservoir from the upstream about 460 kilometers HAD and ending just upstream the dam as the first step in the hydrodynamic modeling process. This bathymetry will be used to interpolate the levels of mesh points used during the modeling process. Then the development of a 2 dimensional hydrodynamic model as the first hydrodynamic model for the whole reservoir that will be the first step for sediment transport studies and water quality studies of the lake.

Methodology

I- Bathymetric surface simulation

Obtaining an accurate representation of bed topography is likely the most critical, difficult, and time consuming aspect of the 2D modeling exercise. Regular trips took place once a year for the measurement of cross sections, velocities, suspended sediment concentration and water levels at fixed locations along the HAD reservoir.

Simple cross-section surveys are generally inadequate. Combined GPS and depth sounding systems for large rivers and distributed total station surveys for smaller streams have been found to be effective. In either event, you should expect to spend a minimum of one week of field data collection per study site. The field data should be processed and checked through a quality digital terrain model before being used as input for the 2D model. The cross sections profiles show the bed level measured from the left bank so in order to obtain the longitude and latitude of these points some calculations should be done first. A sample of those sections is shown in Figure 1

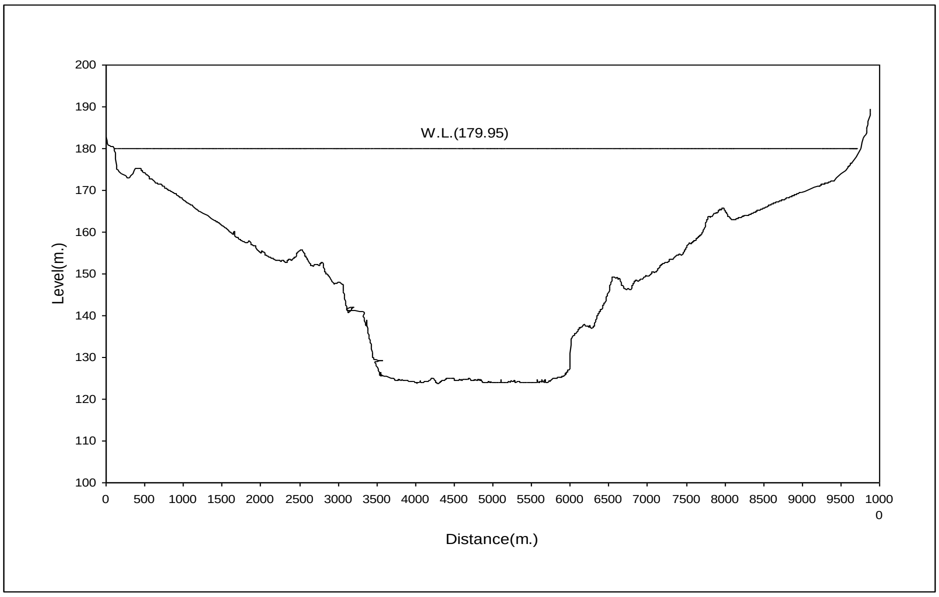

Figure 1: Cross section at Adenean in the year 2000 (307 km US HAD)

The longitudinal section, Figure 2, profile was used to enhance increase the accuracy of the interpolation of the bed level in the area where no cross section data are available.

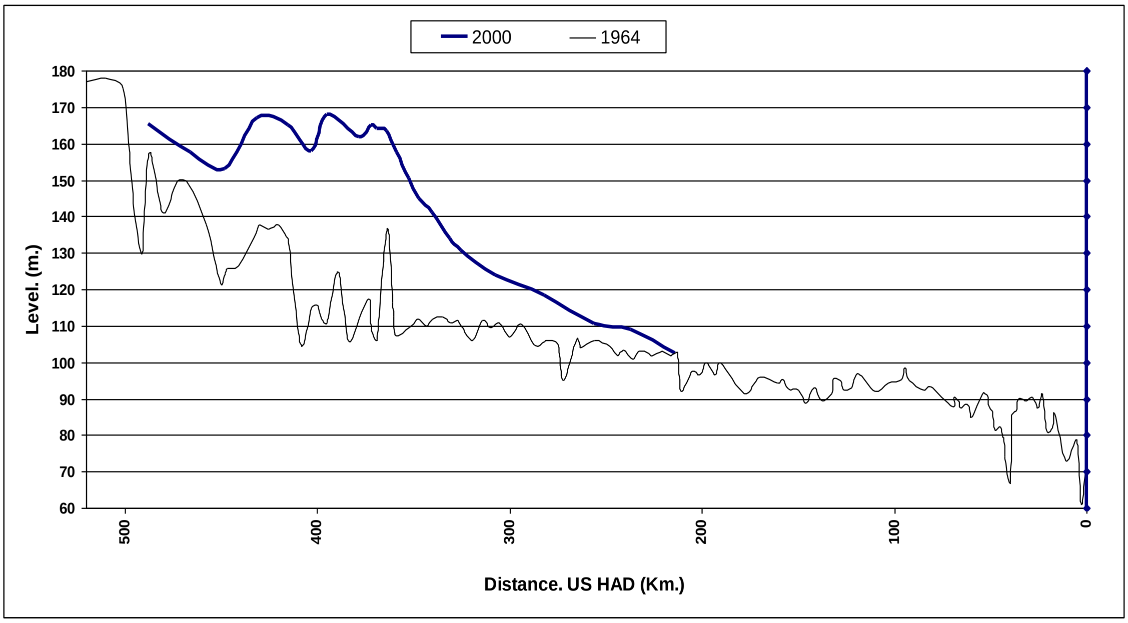

Figure 2: Longitudinal section of the HAD reservoir (1964-2000)

World geode (WGS84) geographical maps for the area of Nasser Lake were digitized from a satellite images to obtain a digital format of the lake **(Source, WRRI)**. These images were taken in;

- November 1987, where the water level in the reservoir was (158.44),
- November 1998, where the water level was (181.21),
- And January 2001, where the water level was (180.15).

These Images shows only the perimeter of the reservoir, it is when the water in the reservoir touches the land. As the water bodies appear in the satellite images as black bodies.

The Geographic Information System (GIS) application has been recognised as a powerful mean to integrate and analyse data from various sources. It was used to project both the High Aswan Dam Reservoir maps and the section points into the Universal Transverse Mercator grid Zone 36 (UTM36) so they all will have the same projected reference.

The cross section points along with the 3 contours of the reservoir perimeter at levels (158.44), (181.21) and (180.15), obtained from the satellite images, were used to form a group of scatter points (x,y,z) with the (UTM36) as a defined projected coordinate system.

The Surface water Modeling System (SMS) interface was used during this stage as it is a graphical aided interface of creating the mesh, and it also can support the file format used by many of hydrodynamic modeling programs.

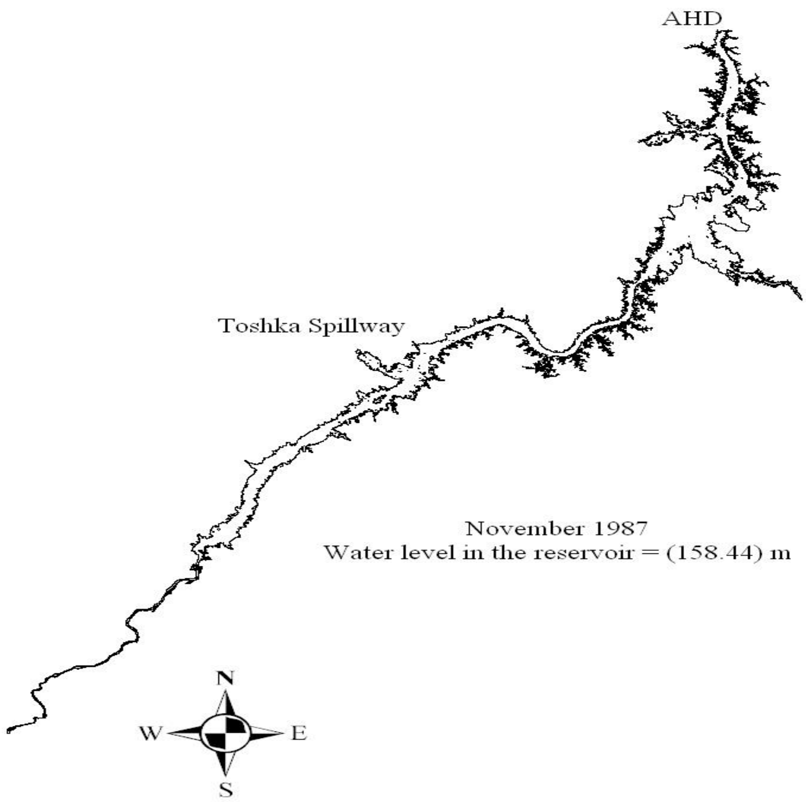

Figure 3: Boundaries of the lake obtained using a LANDSAT image acquired November 1987

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.

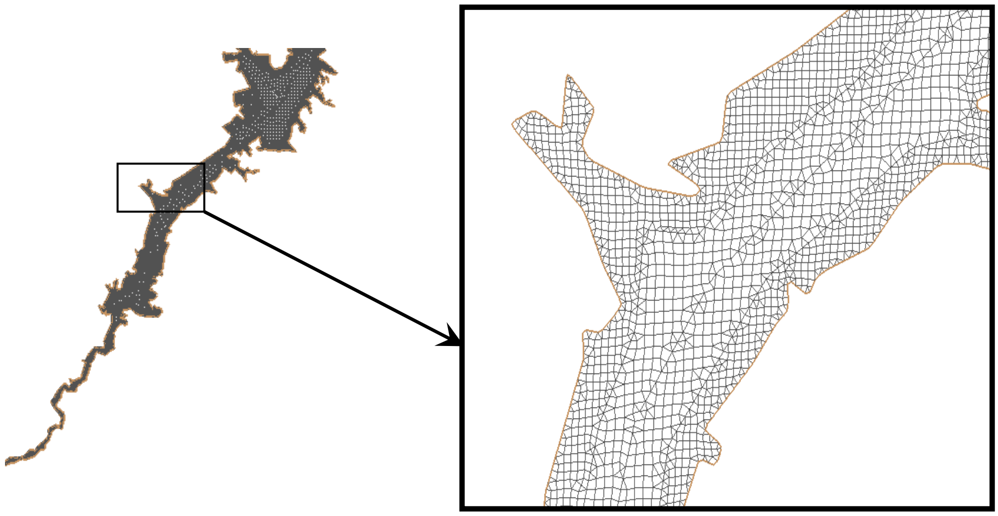

Figure 4: Mesh generation

After the mesh generation, the scatter points obtained from the GIS were used to form a triangles irregular net (TIN) which will be used in the interpolation of the bed levels.

One of the most commonly used techniques for interpolation of scatter points is inverse distance weighted (IDW) interpolation. Inverse distance weighted methods are based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points.

After interpreting the first resulted bathymetric contours it was found that this bathymetry should be enhanced because some parts were not covered by the hydrographical survey may cause errors both in the Sudanese part where the stream is narrower and in the Egyptian part.

Therefore a Digital Elevation Model (DEM) of the surrounding area (Figure 5) was used to generate a Triangulated Irregular Network (TIN) using the GIS software. The DEM is a raster image divided into a group of cells and each cell has a value the represent the elevation of its location. The resulted TIN (Figure 6) was then used in the interpolation process to enhance the bathymetric contours. The Enhanced Bathymetry is shown in Figure 7.

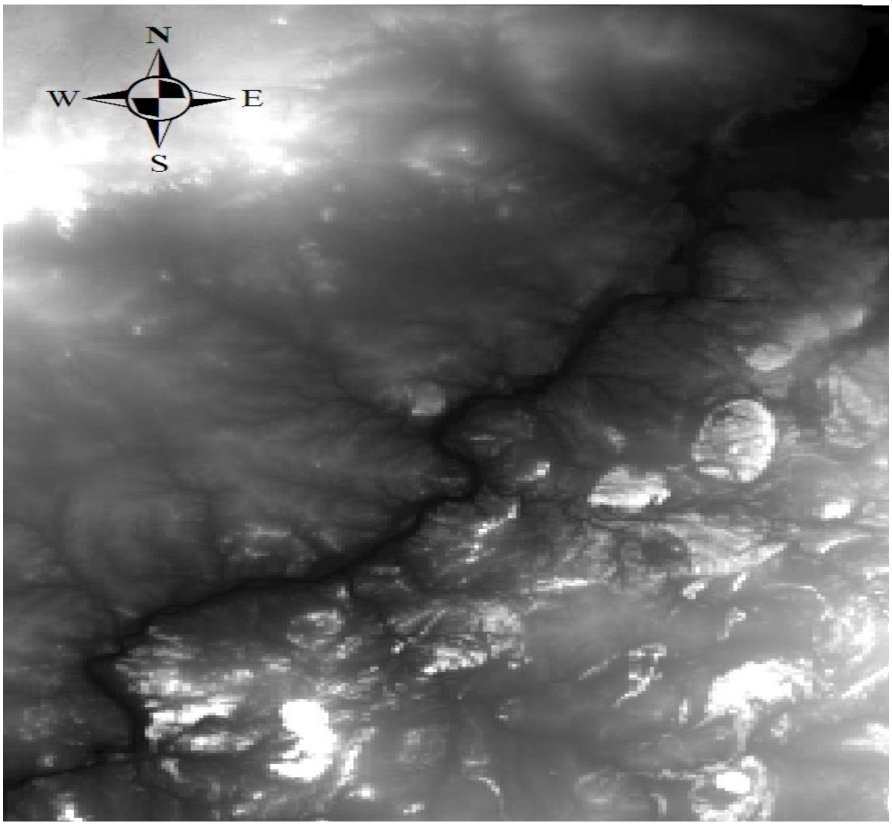

Figure 5: A 90 meters cell size SRTM digital elevation model

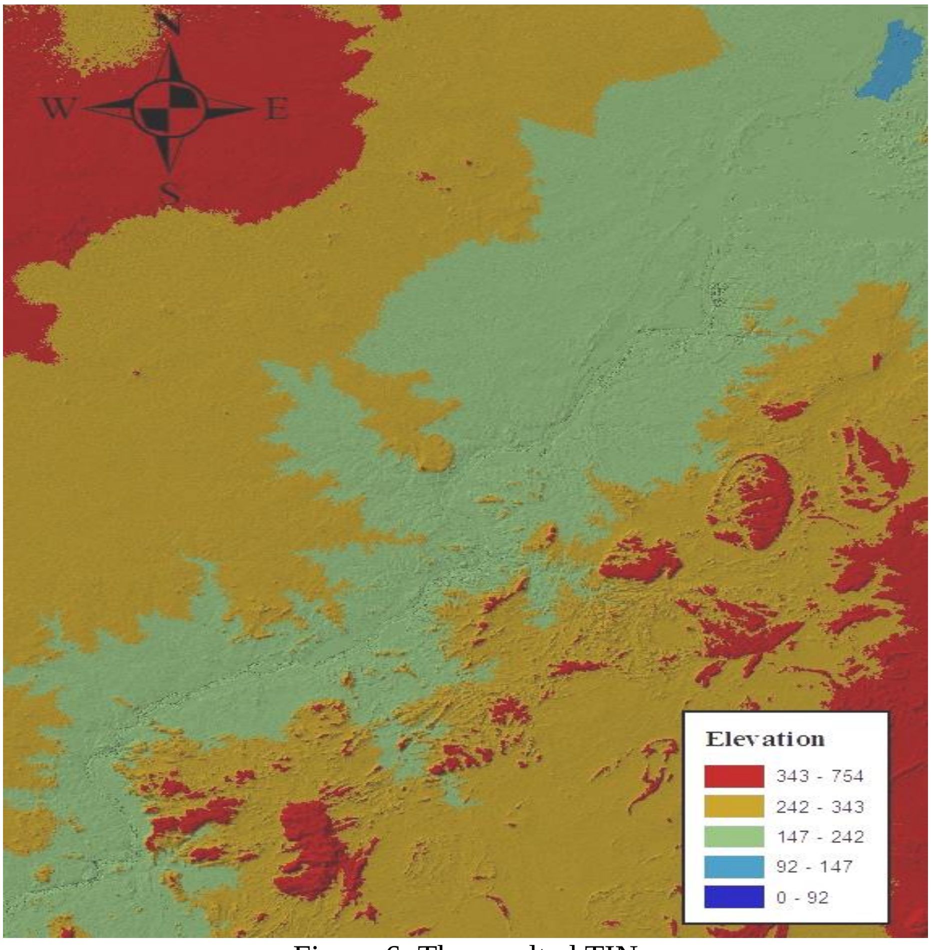

Figure 6: The resulted TIN

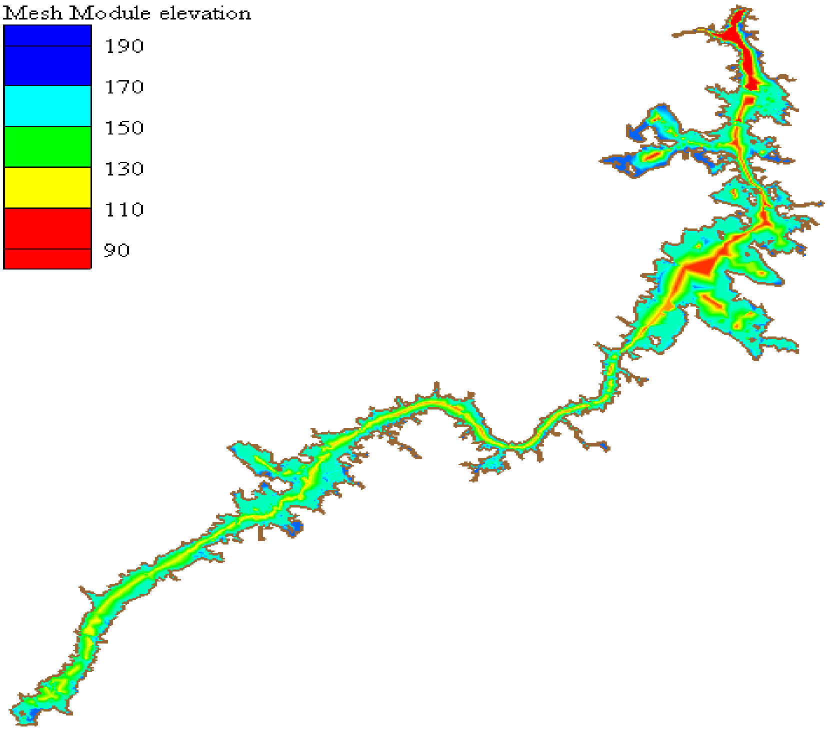

Figure 7: The resulted bathymetry

II- The hydrodynamic model

In addition to topographic data, the model requires hydrologic and hydraulic data such as stage and flow hydrographs, measurement velocities, and rating curves to establish initial and boundary conditions and for model calibration and verification.

The discharge boundary condition at the upstream end of the modeled reach will be represented using the hydrograph recorded at Donqola measuring station about 777 km upstream HAD, water surface elevation at the downstream end was determined using data from level gagging station upstream High Aswan Dam.

The data used in this study were gathered from the files of the High Aswan Dam Authority (HADA), the Nile Research Institute (NRI) and the Water Resources Research Institute (WRRI).

The RMA2 model under the SMS interface was selected in the case study and will be described in the following sections. It is a free-surface calculation model for subcritical flow problems. More complex flows where vertical variations of variables are important should be evaluated using a three-dimensional model.

The generalized computer program RMA2 solves the ***depth-integrated equations of fluid mass*** and ***momentum conservation*** in two horizontal directions by the finite element method using the Galerkin method of weighted residuals.

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left[E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right]+gh\left[\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right]+\frac{gun^2}{h^{1/3}}$$
$$+\sqrt{(u^2+v^2)}=0 \qquad (1)$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left[E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right]+gh\left[\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right]+\frac{gvn^2}{h^{1/3}}$$
$$+\sqrt{(u^2+v^2)}=0 \qquad (2)$$

Where;

h	=	Depth
u, v	=	Velocities in the Cartesian directions
x, y, t	=	Cartesian coordinates and time
ρ	=	Density of fluid
E	=	Eddy viscosity coefficient,
	for *xx* =	normal direction on x axis surface
	for *yy* =	normal direction on y axis surface
	for *xy* and *yx* = shear direction on each surface	
g	=	Acceleration due to gravity
a	=	Elevation of bottom
n	=	Manning's roughness n-value

This pie chart (Figure 8) illustrates the approximate relative importance to the simulation of the different aspects of an RMA2 simulation study. As it can be seen, the structure of the geometry and overall study design are the most significant, followed by the boundary condition assignments. The “other” category includes field data issues, amount of time devoted to the effort, approach chosen to analyze data. Study design includes model choice and boundary placement.

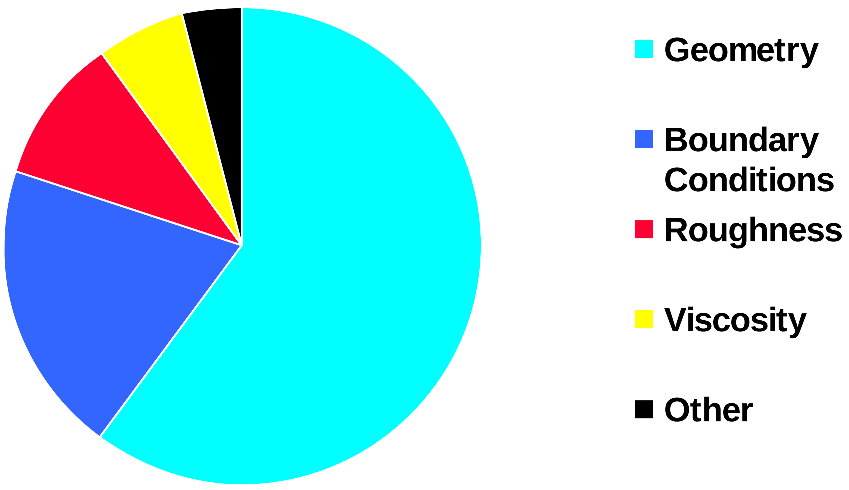

Figure 8: Relative importance to calibration

III- Model parameters calibration and verification

The calibration process where carried out using the recorded water levels at various sections upstream High Aswan Dam during the mission of the year 2000 of the High Aswan Dam Authority in the Sudanese part of the reservoir. The water levels recorded at those sections are presented in Figure 9 along with the date they were recorded on.

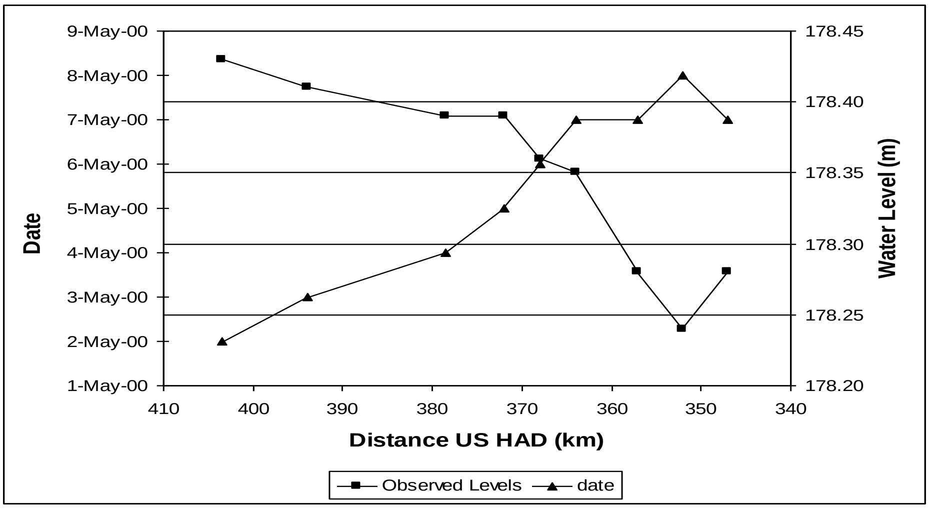

Figure 9: The measured water levels used in calibration process

Figure 10 shows the recorded water levels upstream HAD during the simulation period which begins by the 20th of April 2000 and ends at the 15th of May 2000, and Figure 11 shows the corresponding recorded discharges at Donqola station during the same period.

The travel time was calculated assuming that the flood wave celerity is as 1.5 times as the flow velocity that has an average of 0.25 m/sec in the Sudanese sector of the lake as observed by the HADA. The travel time was calculated from the upstream Station (Donqola) to the entrance of the study reach and was found to be 9 days. So the boundary interval was chosen more than 9 days later than the first recorded level.

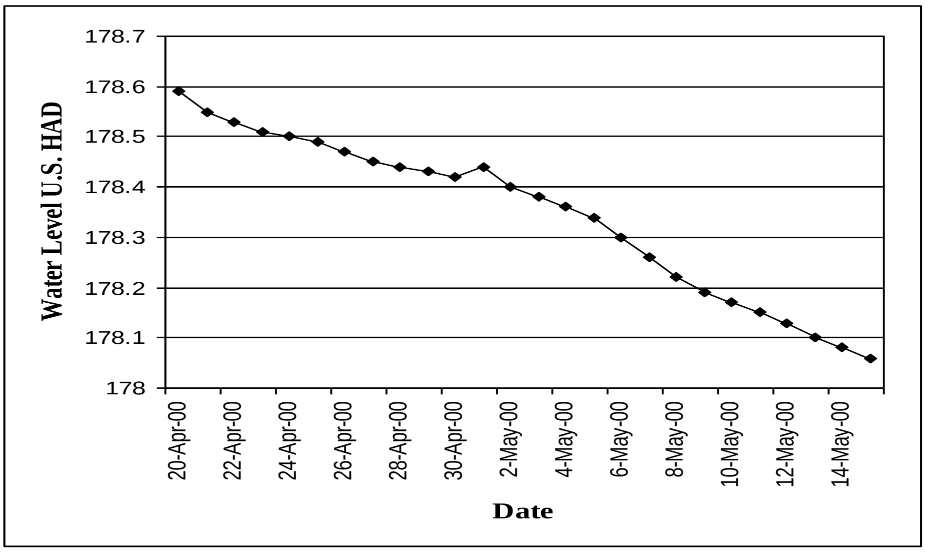

Figure 10: Water level U.S. HAD

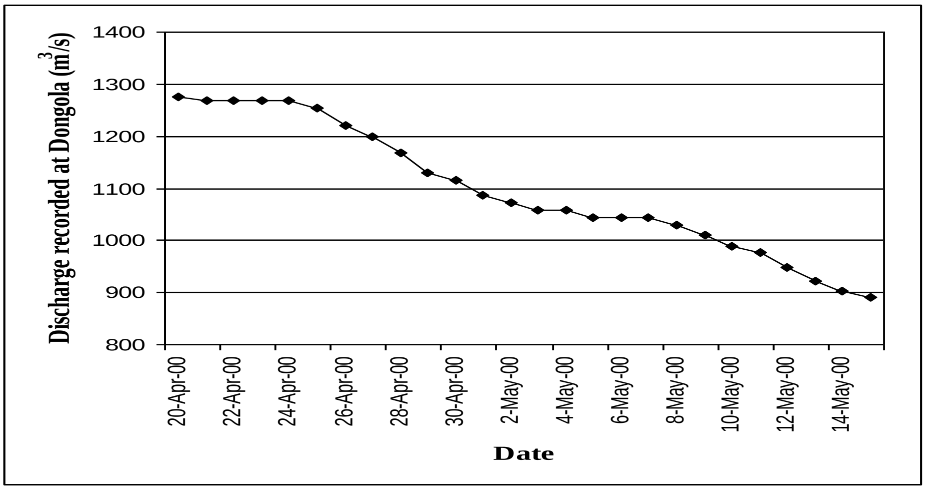

Figure 11: Discharge recorded at Donqola station

The measured levels during the simulation interval were compared with the levels calculated from the model and the results were plotted as shown in Figure 12. The results show an absolute error value ranging from 0.8 cm to 8.01 cm, which is a good result.

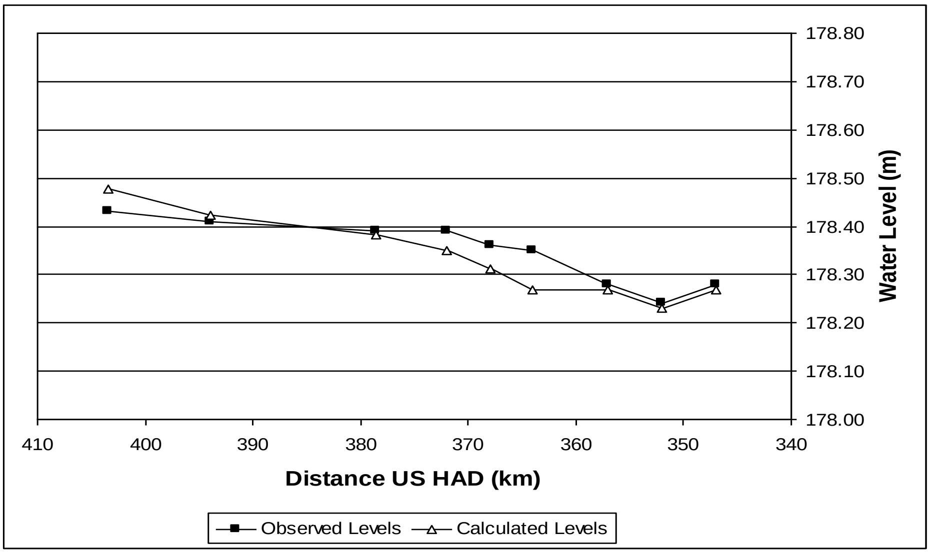

Figure 12: Observed Vs calculated water levels

The model results can be shown in the following figures, which present the resulted water levels and velocity magnitudes at the end of the simulated interval. The difference between the observed and calculated water levels at km 365 is due to uncertainty of geometric data at this zone during data filtering process.

The verification process where carried out using the recorded water levels at various sections upstream High Aswan Dam during the mission of the year 2000 of the High Aswan Dam Authority in the Egyptian part of the reservoir. The water levels recorded at those sections are presented in Figure 13 along with the date they were recorded on.

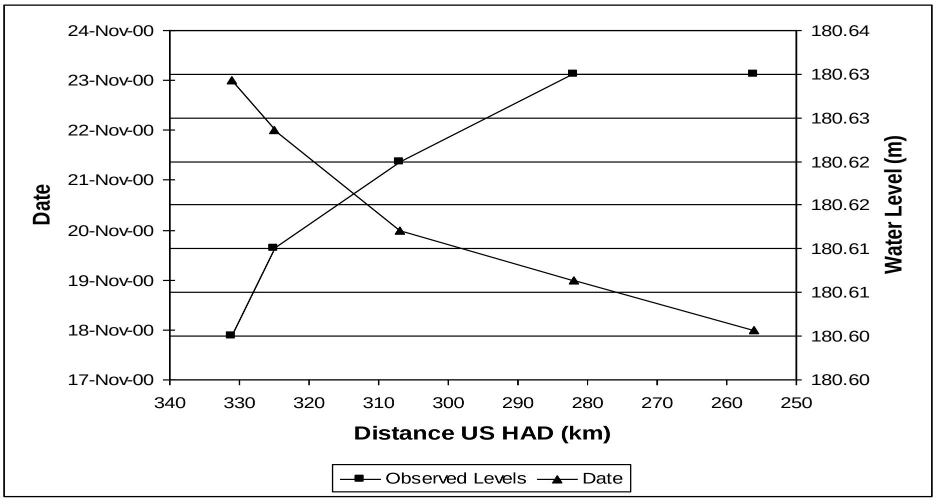

Figure 13: The measured water levels used in verification process

Figure 14 shows the recorded water levels upstream HAD during the simulation period which begins by the 10th of November 2000 and ends at the 25th, and Figure 15 shows the corresponding recorded discharges at Donqola station during the same period.

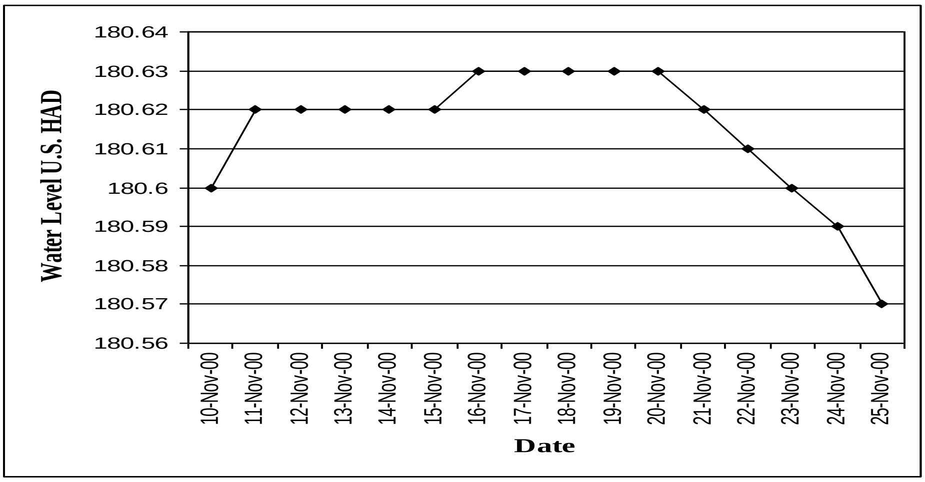

Figure 14: Water level U.S. HAD

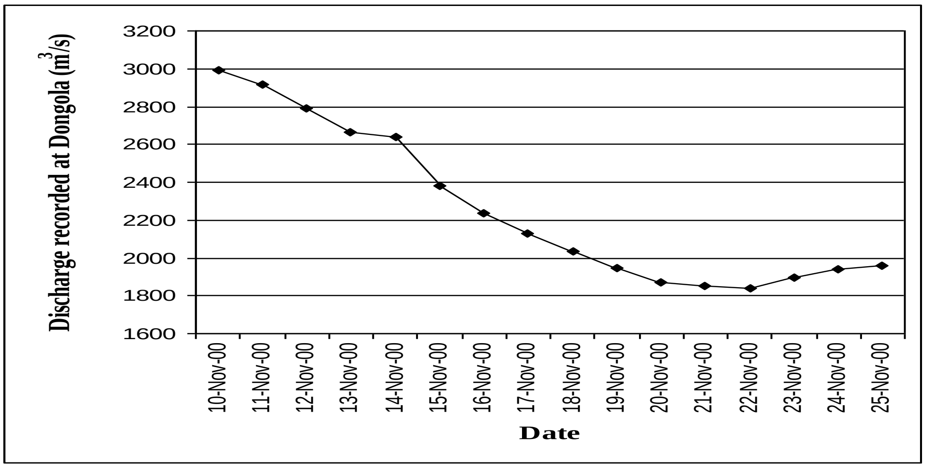

Figure 15: Discharge recorded at Donqola station

Those measured levels where compared with the levels calculated from the model and the results were plotted as shown in Figure 16. The results show an absolute error value ranging from 0.02 cm to 1.28 cm which is a good result.

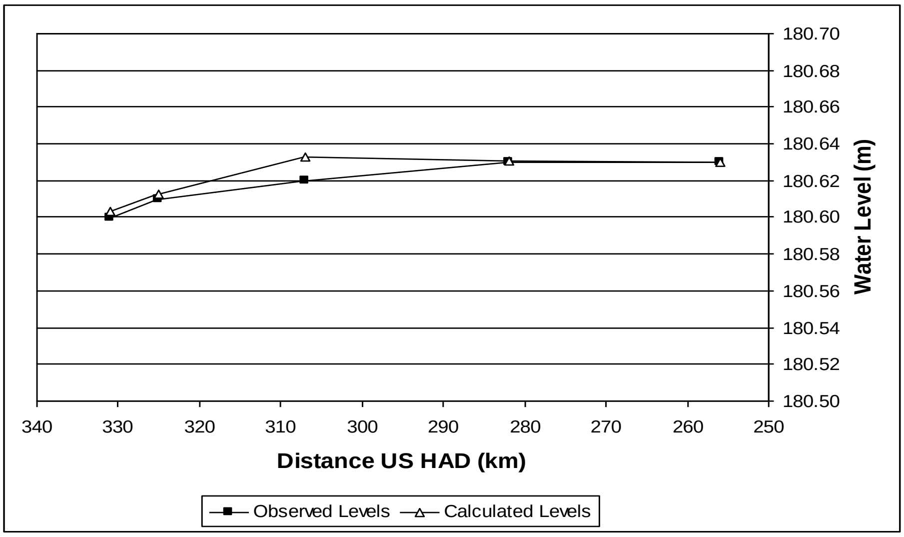

Figure 16: Observed Vs calculated water levels

The model results can be shown in the following figures, which present the resulted water levels and velocity magnitudes at the end of the simulated interval.

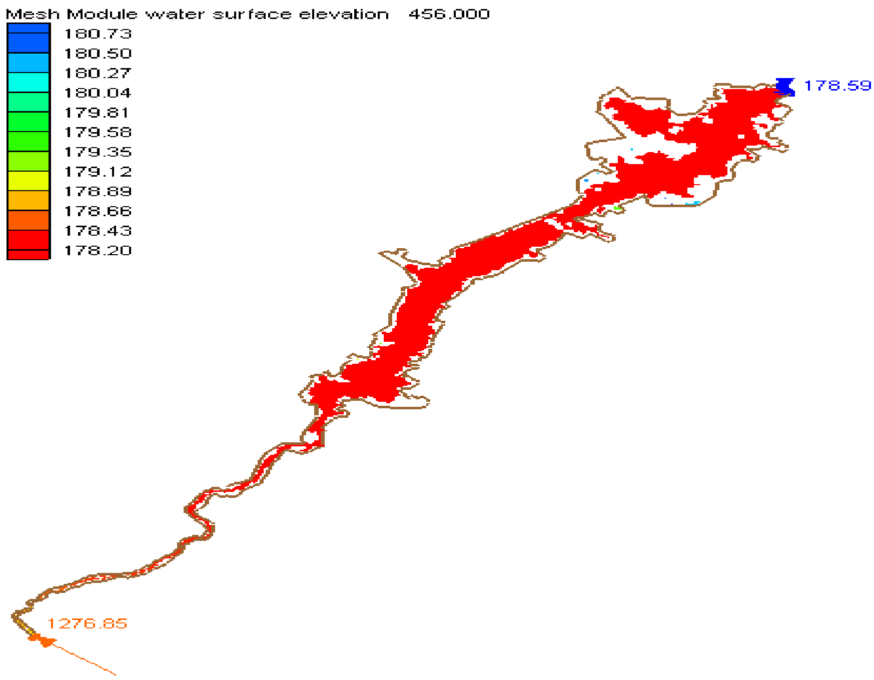

Figure 17: Simulated water surface elevations on 23 Nov. 2000

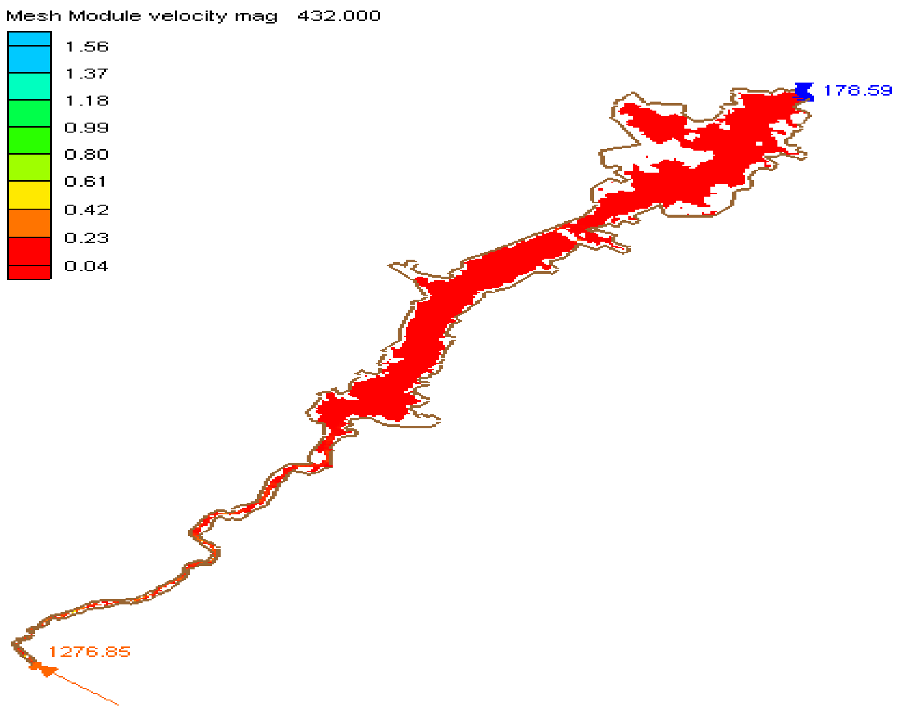

Figure 18: Simulated velocity magnitudes on 23 Nov. 2000

Conclusions and Recommendations

1. A three dimensional surface of the HADR bed was generated as it is a very important step for the hydrodynamic modeling.
2. A two-dimensional hydrodynamic model was developed to simulate the flow fields (steady and unsteady) of the HADR as the first 2D hydrodynamic model for the lake.
3. Further work should be done to update the bathymetry map obtained specially on the Sudanese side because of sedimentation and scouring process.
4. The results of the hydrodynamic model could be used in the sediment transport and water quality studies of the reservoir.

References

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