International Journal of Research
Available at https://pen2print.org/index.php/ijr/
e-ISSN: 2348-6848
p-ISSN: 2348-795X
Volume 05 Issue 20
September 2018

Sedimentation Future Prediction for Aswan High Dam Reservoir Using Mathematical Model Delft3D

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ABSTRACT:
The High Aswan Dam has been constructed during the 1960's to protect Egypt from high flood hazards and to provide the required water demand during low flood years. Due to the dam construction and lake formation, the flow downstream the dam has become more controlled and the suspended sediment concentration peaks have been reduced significantly and deposited upstream the dam. These deposited sediments are reducing the storage capacity of the lake. This paper is an attempt to predict the future deposition in the Aswan High Dam Reservoir, using a numerical model (Delft3D). During the course of this study, the calibration of the model for flow and sediment deposition was applied during the period 2010–2012. A good agreement, between the observed and modeled results for the whole domain, was obvious. Confident with the obtained results, the model was further used to predict the sediment deposition in the reservoir for fifteen years.

Keywords: *Aswan High Dam reservoir; Aswan High Dam; Reservoir sedimentation; Lake modeling; Delft3D*

1. INTRODUCTION:

Many dams exist along the Nile River for various purposes. The sedimentation, within their reservoirs, reduces their capacity and their practical life span. The Sennar Dam was constructed on the Blue Nile (Sudan) for irrigation purposes. Due to the sediment deposition over a span of 61

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years, the reservoir had lost 71% of its original capacity. The Roseires Dam was constructed on the Blue Nile (Sudan) to store water for irrigation. It lost 36% of its original capacity in a span of 28 years, **[1]**

As for the Aswan High Dam, it created a reservoir on upstream which is the Aswan High Dam Reservoir (AHDR). The AHDR is the second largest man-made reservoir in the world it extends from the southern part of Egypt to the northern part of Sudan with total length of about 500 km (350 km belongs to Egypt and 150 km belongs to Sudan). The Aswan High Dam was created (1964–1968). The width depending on the water level, averages about 12 km. The water level varies between 152 and 182 m above the sea mean level.

It has storage capacity about 162 billion m^3 distributed as follows:

90 BCM: live storage capacity between level 147 m and 175 m.

31 BCM: dead storage.

41 BCM: storage for high flood waters between levels of 175 m and 182 m.

This study was thus initiated with the objective of predicting the deposition volume in the Aswan High Dam Reservoir in order to estimate its effective life span.

2. LITERATURE REVIEW:

Based on the reviewed literature it had been found that the investigations that were executed to simulate and predict the sediment deposition in the Aswan High Dam Reservoir (AHDR), were concerned about two periods (i.e. pre-1985 period and post-1985 period). During the pre-1985 period, investigators concentrated on collecting and analyzing field data to study the characteristics of the reservoir and to deduce relationships between flow and sediment load. While in the post-1985 period, researchers started to develop mathematical models to describe the motion of both water and sediment flow to simulate the water surface and bed profile in the longitudinal direction. Among the researchers, that were concerned with reservoirs, were Hurst, Shalash, EL-Moattassem, Abdel-Aziz, and El-Manadely, and the following table 1 summarize their results.

[2] found that no coarse sand was present in the reservoir. He stated that 30%, of the sediment, by weight was carried as sand fraction, 40% silt, and 30% as clay fraction.

[3] concluded that the average annual rate of sediment inflow was 130 million tons and the average annual rate of outflow was 6 million tons. Therefore, he stated that the average annual sediment deposition was 124 million tons. The deposited sediment was estimated to be 1570 million tons during the 15 year observation.

[4] studied the sediment balance in AHDR during the period of May 1964 to December 1985. They estimated the deposited volume to be 1650 million m3. The calculated deposited volume from the hydrographic survey for the same period was 1657 million m^3.

[5] and **[6]** developed a one-dimensional numerical model based on the continuity equation, the momentum equation, and the sediment continuity equation to estimate the change in the river bed profile in the longitudinal direction. They concluded that the total volume of deposits accumulated inside the reservoir was 2650 BCM for the period 1964 to 1988. This value is nearly equal to the estimated deposited volume based on field measurements which had a value equal to 2760 billion m3. As a result of these two models, it was concluded that the AHDR cross sections are highly irregular, especially in the transverse direction and that the change in the water depth is large. They further recommended that there was a need to develop a new approach based on two-dimensional models in order to predict the sediment deposition in the transverse and longitudinal directions.

3. PROBLEM DEFINITION:

The Aswan High dam reservoir bed level is undergoing continuous changes, such as deposition, erosion and delta formation. This rapid change in bed levels occurred due to the flood suspended sediment load which affects the efficiency and the storage capacity of the lake.

Due to the importance of Aswan high dam reservoir to Egypt this study aims to predict future progress of sediment transport along lake and monitor delta formation progress to determine life span of the lake and side effects of the future dam construction at Nile basin on the lake sedimentation and storage capacity.

4. SITE DESCRIPTION:

Aswan high dam reservoir AHDR is located at the southern part of Egypt (about 350 Km) and northern part of Sudan (about 150 Km) with total length 500 Km and average width 12 Km, this forms a huge surface area about 6500 square km at elevation 182.00 AMSL and has a storage capacity about 162 km^3 of water. The average depth is about 25 m and the maximum depth is 130 m.

4.1. AHDR Bed Levels:

A hydrographic survey of the study area was carried out by the Nile Research Institute "NRI" of the National Water Research Center during year 2010 and 2012. The survey was carried out along the area, between the two banks of the lake; by surveying cross sections spaced with varied intervals depend on the width of the lake at each cross section (ranged from 500m to 2000m spacing between cross sections) as shown in (Figure 1).

In order to calibrate the selected mathematical model, vertical velocity distributions for twenty cross sections were measured. Velocity measurement locations were carefully selected to be expressive of the study area.

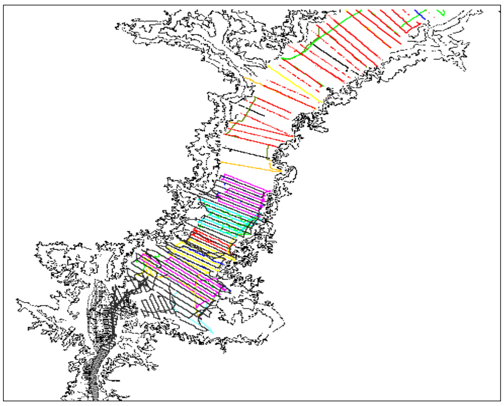

Figure (1): Bathymetry data of study area

Also bed material properties are considered important parameters for calibrating the mathematical models as well as for the verification process. Many factors are interrelated to formulate the value of the roughness, grain size and concentration of suspended materials. Grab Sediment Sampler was used to collect 76 bed material samples from 20 cross sections.

Also for The suspended sediment data available for the period 1966–1982 were used to establish a rising and falling stage rating curves for AHDR allowing for seasonal effects relating to the rising and falling stages.

The following equations were used for estimating the suspended sediment hydrograph at Dongola Station:

(i) For rising stage flow discharge hydrograph:

$$Q_s = 5.753*10^{-6}\ Q^{\ 1.98}$$

(ii) For falling stage flow discharge hydrograph:

$$Q_s = 2.695*10^{-7}\ Q^{\ 2.347}$$

Where Q is the discharge at Dongola Station in million m3/day and Qs is the sediment load in 10^9 kg/day. By applying these equations, the suspended sediment concentration hydrographs at the inlet boundary of the study area of the reservoir (Dongola Station) can be estimated for the period from 2010 to 2012. **[7]**

4.2. Hydrological Data:

It is obvious that flow discharges and the corresponding water levels are essential data to simulate the hydrological characteristics of the study area. For this reason, daily monitoring of the passing discharges through the HAD and the upstream of AHDR and US HAD water levels **[8]**.

To simulate sediment progress scenarios two ways were used the first assumption to simulate an average, maximum and minimum flow a fifteen consecutive years were selected to use these data for simulation, for minimum scenario the data were selected form year 1978 till year 1983, also for maximum were years 1982 till 1997 and for average were selected an average of whole data available all these data were plotted at (Figure 2).

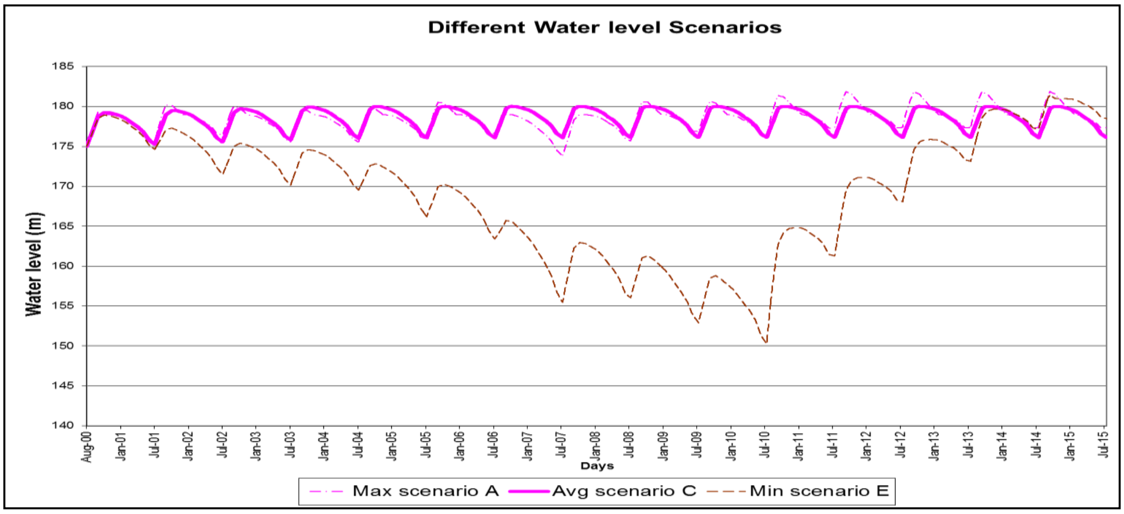

Figure (2): Water levels hydrograph scenarios A, C and E

The second assumption to simulate an average, maximum and minimum flow a five consecutive years were selected from latest 12 years available from year 2000 till year 2012 to use these data for simulation for minimum the data were selected for years 2007 till year 2012, also for maximum were years 2001 till 2006 and for minimum were years 2000 till 2004 all these data were plotted at (Figure 3).

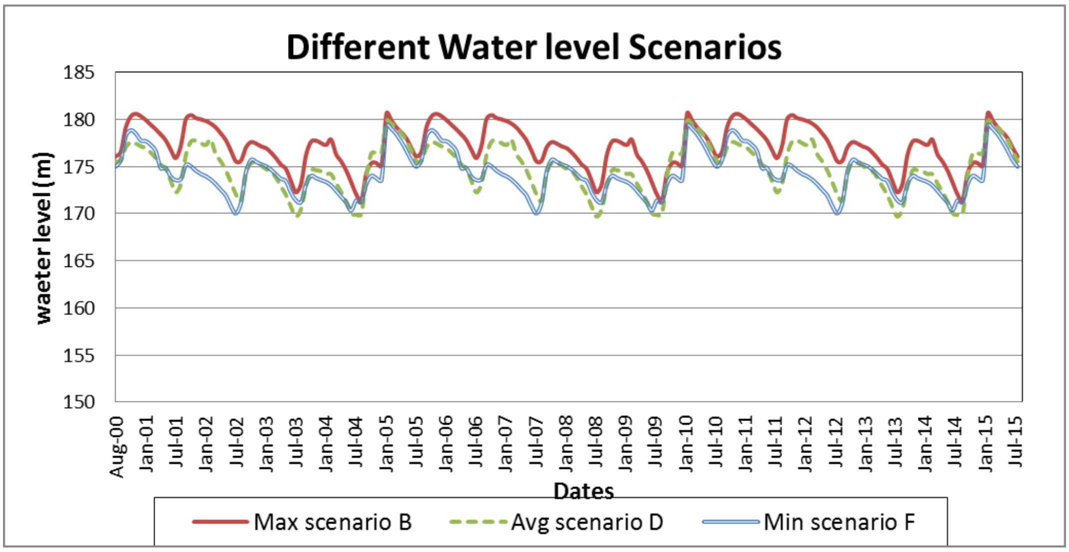

Figure (3): Water levels hydrograph scenarios B, D and F

5. RESEARCH PLAN:

e-ISSN: 2348-6848
p-ISSN: 2348-795X
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1. Compiling of previously published material relevant to the topic of research.
2. Calibrating the model with previous data of the High Aswan Dam Reservoir.
3. Mathematical model (Delft3D) will be applied to many scenarios of sedimentation future progress at the High Aswan Dam Reservoir.
4. Predict of future changes due to future structures on the Nile basin and determine the effect of Sedimentation on Lake Nasser storage capacity.

6. CALIBRATION RESULTS:

Several model runs were made to achieve the best agreement between measured and resulted values from the model. This was carried out by adjusting model coefficients at various locations along the modeled study area till the best results are achieved.

Comparison of the measured field velocities and obtained velocity profiles at the several cross sections are shown in (Figure 4) which representing the accuracy of the velocity calibration results.

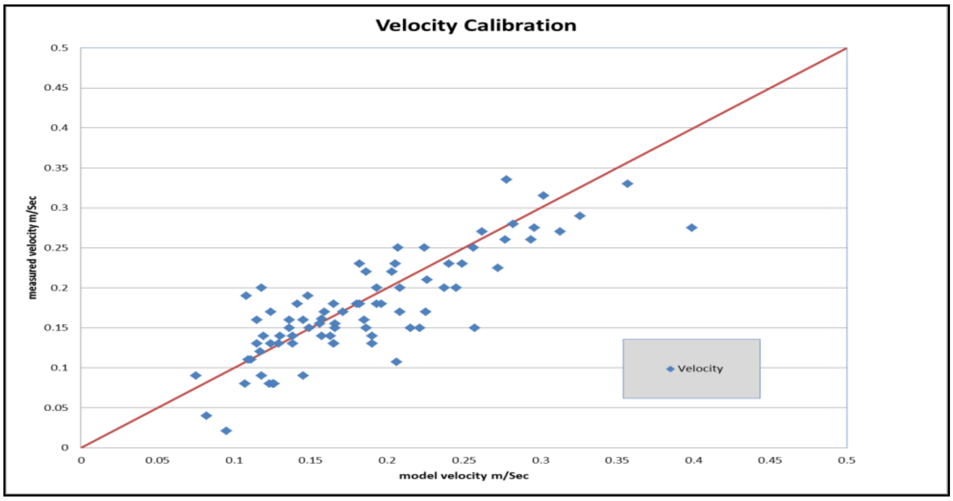


Figure (4): Velocity calibration

A good agreement between the measured and predicted cross-sections was evident although some slight differences are observed at the second cross section but can be neglected. The error in general is less in the channel part than that in the reservoir sides. This might be due to uncertainty of the flow condition of the reservoir. Comparison of the measured field bed levels and obtained bed level profiles at the twenty cross sections are shown in (Figure 5) which representing the accuracy of the morphology calibration results.

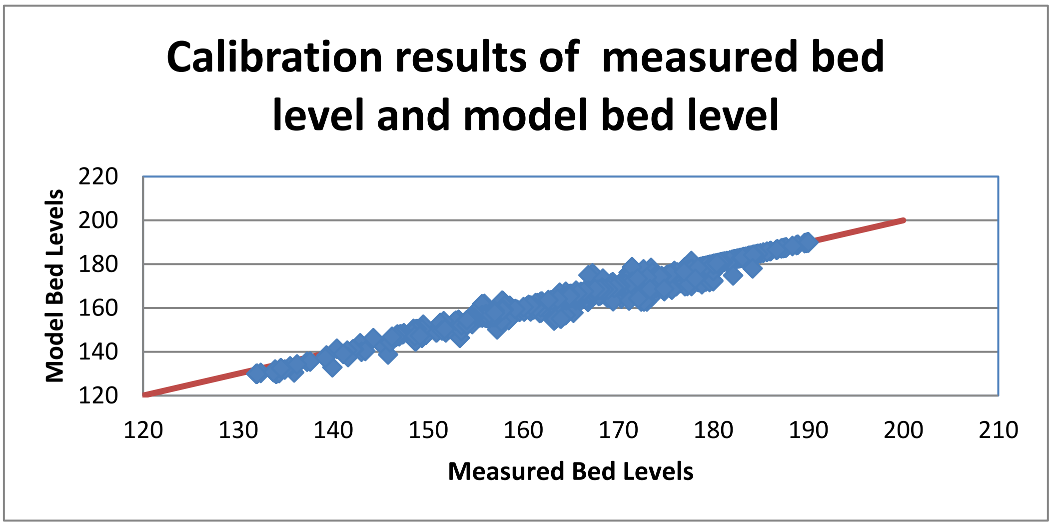


Figure (5): Bed level calibration along study area

A good agreement between the measured and predicted cross-sections was evident although some slight differences are observed at several cross sections but can be neglected. The error in general is very small compared to channel depth and also the figure shows a good comparison between measured and model results this figure represents a comparison between measured bed level and model bed level for the twenty cross sections along reservoir.

7. INPUT DATA FOR DIFFERENT SCENARIOS:

7.1. Discharge and Water Levels Relation during Flow Reduction Scenarios:

due to change of incoming flood flow the resulted water levels would also change, a relationship between the storage capacity and the resulted water level were deduced using HYPACK (hydrographic survey software) software, the calculation started at level 150 m above mean sea level till level 185 m and the resulted data plotted to find out a general updated formula for the latest data available for the AHDR ,which shown at (Figure 6).
A deduced equation was created for easy use and calculates the estimated water level time series

$$WL = 8.9898\ V^{0.1169}$$

Where:

WL is the water level above mean sea level

V is the storage capacity of the AHDR

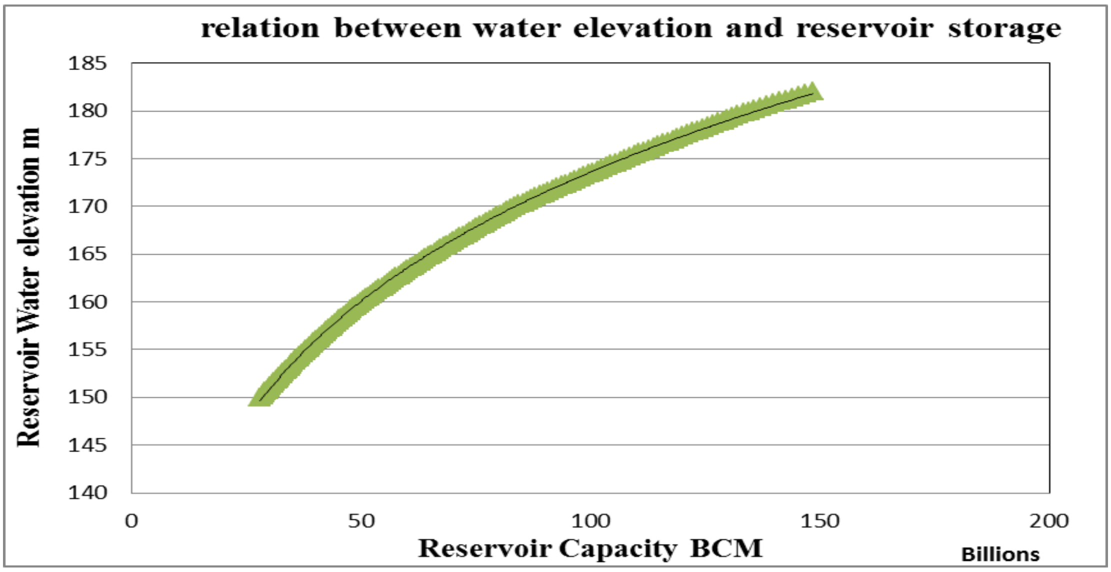


Figure (6): Relationship between storage capacity and water level of the AHDR

7.2. Estimation of Water Levels Time Series Using Deduced Equation:

To estimate time series water levels for AHDR the previous relationship between water levels and storage volume can be used to estimate time series but must take into consideration the evaporation losses which can affect water level in the AHDR.

So to calculate the evaporation loses along the reservoir two variables were needed the surface area of the lake at each water level and also the evaporation rate as a function of time, for surface area it was calculated using HYPACK software the calculation started at level 150 m above mean sea level till level 185 m and the resulted data plotted to find out a general formula for the AHDR, which shown at (Figure 7)

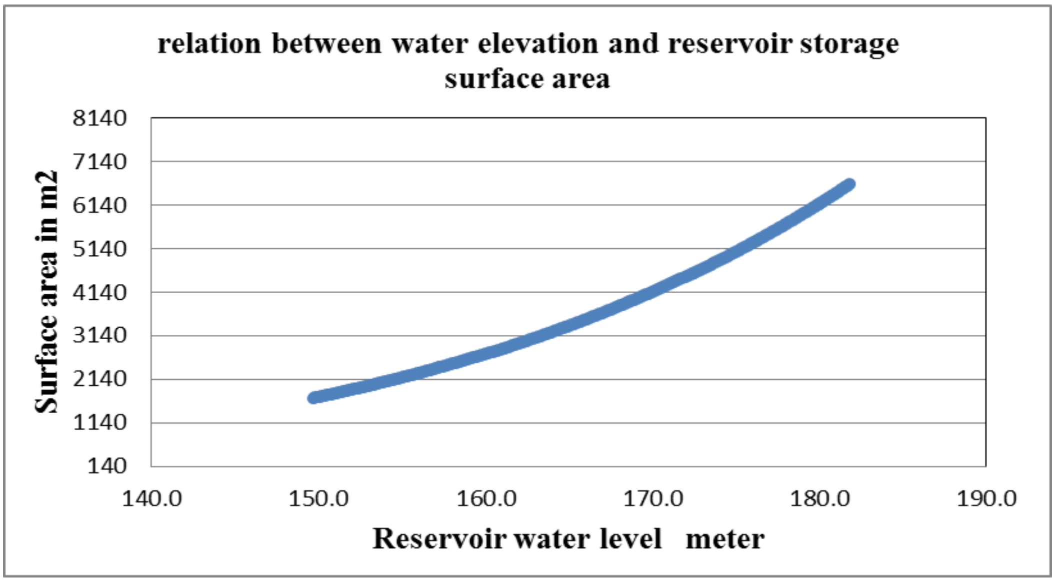


Figure (7): Relation between water elevation and reservoir surface area

A deduced equation was created to calculate the surface area for each water level

$$A = 10^{-12} (WL)^{6.94}$$

Where: WL is the water level above mean sea level in meter (m)

A is the surface area in square meter of the AHDR (m2)

So the average monthly evaporation rate were used to calculate the evaporation volume which can be subtracted from income flow to calculate the water level time series.

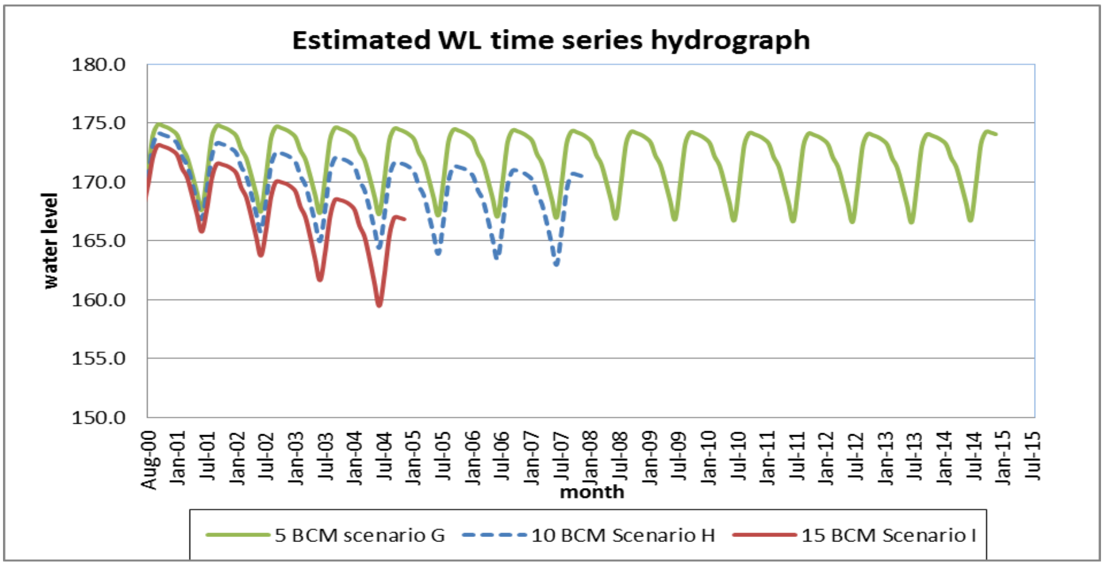


Figure (8): Estimated water levels time series for scenarios G, H and I

These water levels time series were calculated using an average discharge of year 2006 and this can only applied to the flow reduction scenarios 5BCM (G), 10BCM (H) and 15 BCM (I) which shown in (Figure 8)

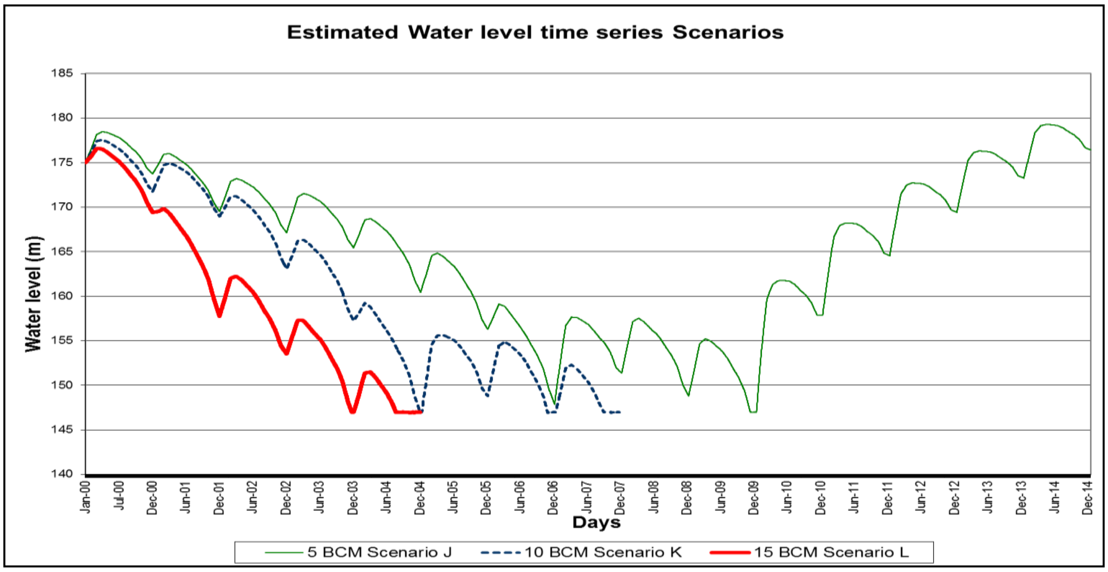


Figure (9): Estimated water levels time series for scenarios J, K and L

These water levels time series were calculated using a minimum flood flow for 15 years which happened at years 1978 till 1993 discharge of these years were reduced by values 5BCM (G), 10BCM (H) and 15 BCM (I) per year which shown in (Figure 9).

8. ANALYSIS AND COMPARISON OF DIFFERENT SCENARIOS:

To predict the sedimentation progress at the future some sets of data were required these time series of data should represent the future which should follow one of three scenarios.

First scenario predicts the sedimentation progress using maximum floods which can be represented by choose maximum flood data from the available data which happened at years from 1982 till year 1997. (Scenario A), Second scenario predicts the sedimentation progress using an average flood which can be represented by choose average flood data from the available data which happened at since HAD start operation. (Scenario C), Third scenario predicts the sedimentation progress using minimum floods which can be represented by choose minimum flood data from the available data which happened at years from 1978 till year 1993. (Scenario E)

All these scenarios summarized at the following figures [10 & 12] which represent a comparison between the three scenarios to clarify the deference in sedimentation between different scenarios the prediction of these scenarios will extended to reach 15 years.

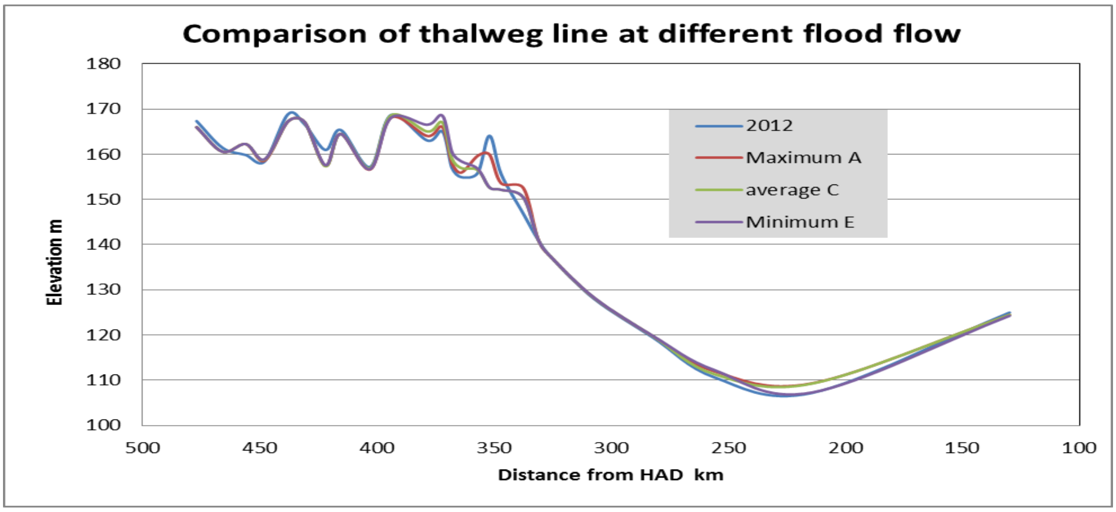
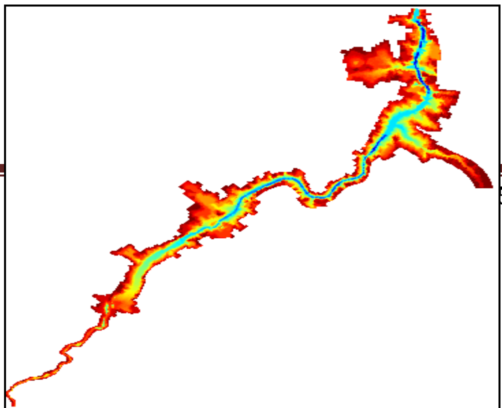


Figure (10): Comparison of thalweg line at different flood flow max A, mini E and average C

The following (Figure 11) representing the sedimentation rapid change zone which the study will focus on the



International Journal of Research
Available at https://pen2print.org/index.php/ijr/
e-ISSN: 2348-6848
p-ISSN: 2348-795X
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following figure to monitor the sedimentation area closely.

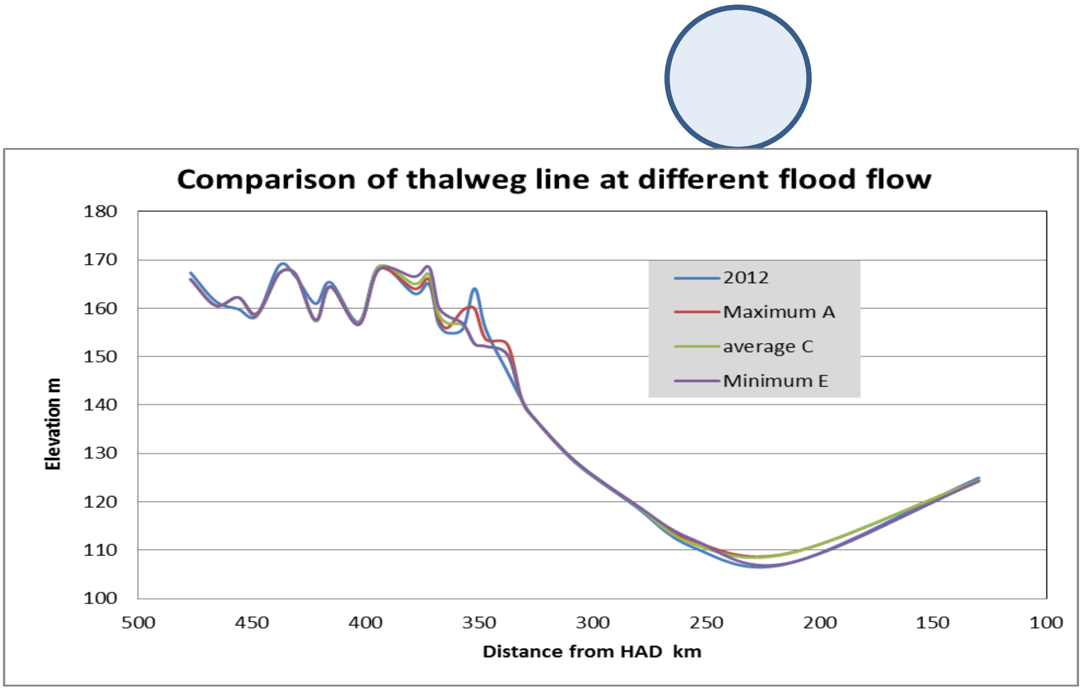

Figure (11): The area of interest for sedimentation progress zone of the study area

Figure (12): Comparison of thalweg line at different flood flow max A, mini E and average C

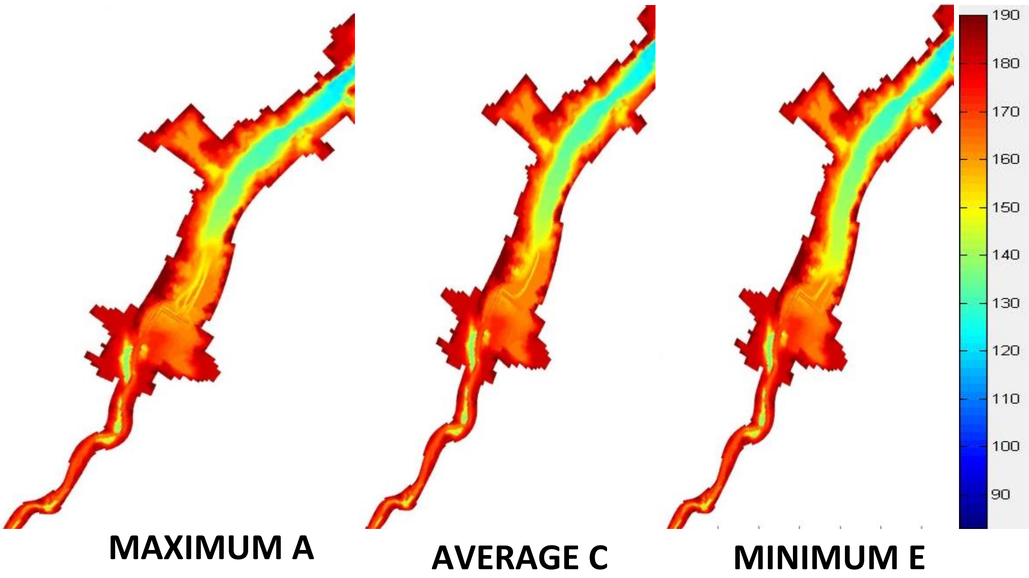

Figure (13): Comparison of bed levels between maximum, average and minimum Scenarios A, C and E

The water level used for these simulations is averaging from 174 to 180 m AMSL for scenarios A and C and from 150 to 178 m AMSL for scenario E which was very low to run scenario E and therefore the resulted deposition affected by these water levels as a result the sedimentation was moving north with the current direction more than other scenarios A and C as shown in (Figures 12, 13). To predict the sedimentation progress at the future some sets of data were required these time series of data should represent the future which should follow one of three scenarios.

First scenario predicts the sedimentation progress using maximum floods which can be represented by choose maximum flood data from the available latest data which happened at years from 2008 till year 2012. (Scenario B), Second scenario predicts the sedimentation progress using average floods which can be represented by choose average flood data from the available latest data which happened at years from 2002 till year 2006. (Scenario D), Third scenario predicts the sedimentation progress using minimum floods which can be represented by choose minimum flood data from the available latest data which happened at years from 2000 till year 2004. (Scenario F) as shown in (Figures 14, 15). All these scenarios summarized at the following (Figures 27 and 28) which represent a comparison between the three scenarios to clarify the deference in sedimentation between different scenarios the prediction of these scenarios will extend to reach 15 years.

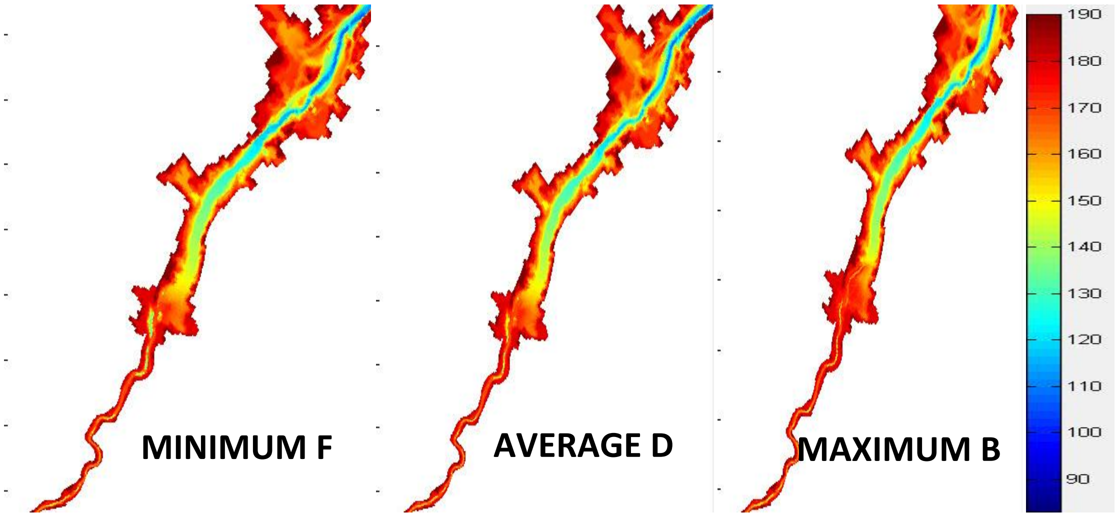

Figure (14): Comparison of bed levels between average, minimum and maximum Scenarios B, D and F

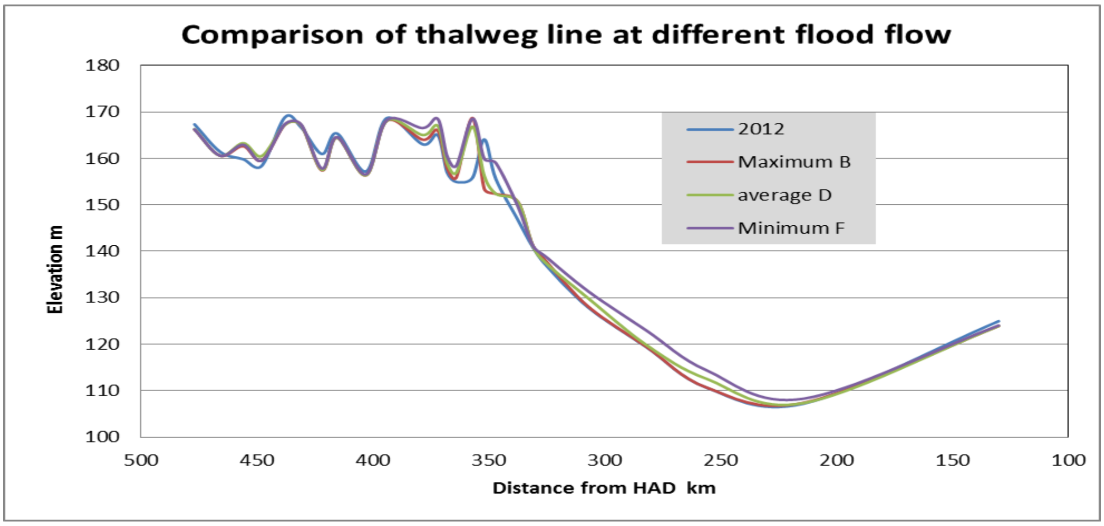

Figure (15): Comparison of thalweg line at different flood flow max B, mini F and average D

The water level used for these simulations is averaging from 172 to 180 m AMSL for scenario B, and from 170 to 179 m AMSL for scenario D and from 169 to 178 m AMSL for scenario F.

9. SEDIMENTATION PROGRESS DUE TO FLOOD FLOW REDUCTION:

First step to simulate the side effect of flow reduction scenarios is to determine the value of flow reduction to reduce this value from the incoming flood, in this study the reduction of flow assumed to be 5 BCM for 15 years, 10 BCM for 8 years and 15 BCM for five years, these flow reduction scenarios had a total reduction value of 75 BCM which may happened in the future due to future construction along Nile Basin and future climate change

Two ways to predict the future time series the first assumption is to choose a minimum flood flow along the available data for 15 years which happened at the period from year 1978 till 1993 and then apply the flow reduction at these years. These simulation were applied for the three scenarios of reduction 5BCM, 10BCM and 15 BCM a thalweg line and three color contour maps were plotted to show the comparison between the three scenarios which shown in (Figures 16 and 17) .

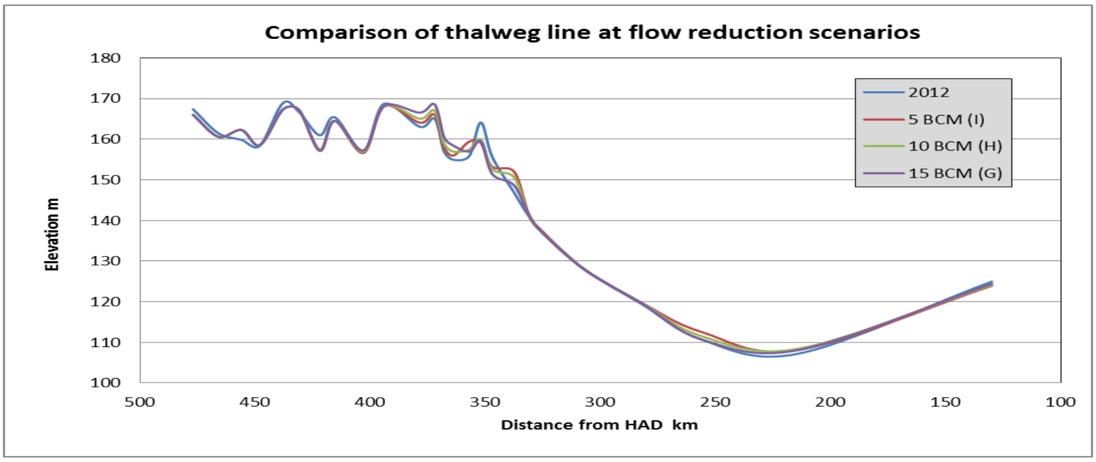

Figure (16): Comparison of thalweg line along AHDR at different flow scenarios G, H and I

e-ISSN: 2348-6848
p-ISSN: 2348-795X
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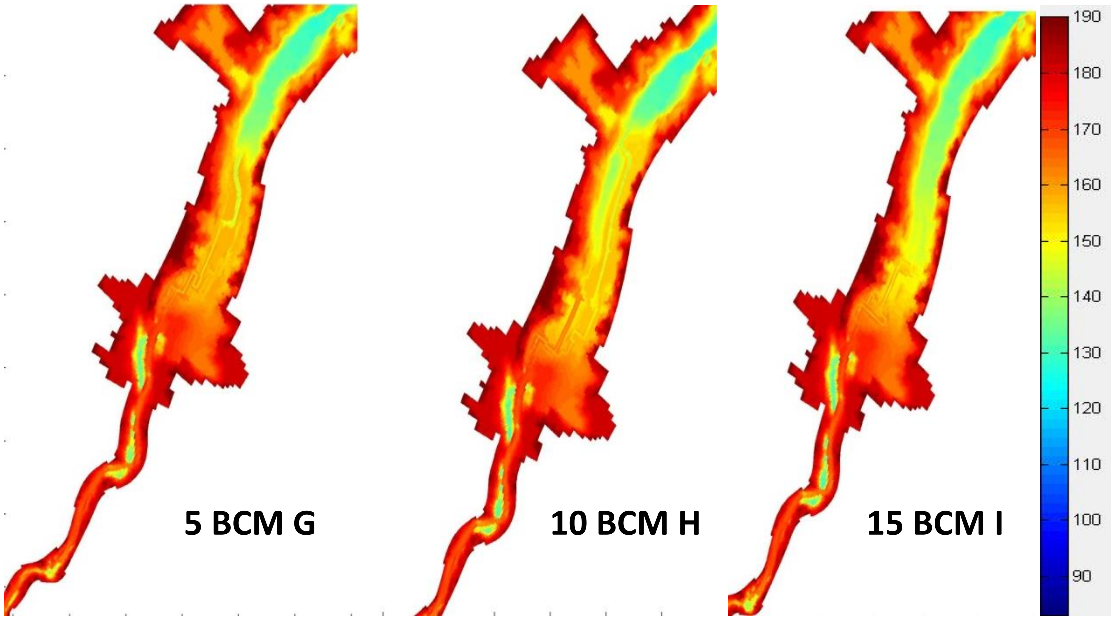

Figure (17): Comparison between different scenarios G, H and I

The water level used for these simulations is averaging from 178 to 147 m and then raise again to 176 m AMSL for scenarios G, from 177 to 147 m AMSL for scenario H and from 176 to 147 m AMSL which was very low to run these scenarios and therefore the resulted deposition affected by these water levels as a result the sedimentation was moving north with the current direction at these scenarios.

As a result to this reduction in water level the water flow will be at a critical situation and the HAD discharge must be reduced to maintain the water level above critical water levels and this will affect the water demand of Egypt.

The second assumption is to choose an average flood flow along the available data which happened in 2006 then apply the flow reduction at this year and repeat the flood for fifteen years but reduce the flow by 5BCM, 10BCM and 15BCM for each year .

These simulation were applied for the three scenarios of reduction 5BCM, 10BCM and 15 BCM a thalweg line and three color contour maps were plotted to show the comparison between the three scenarios which shown in (Figures 18 and 19).

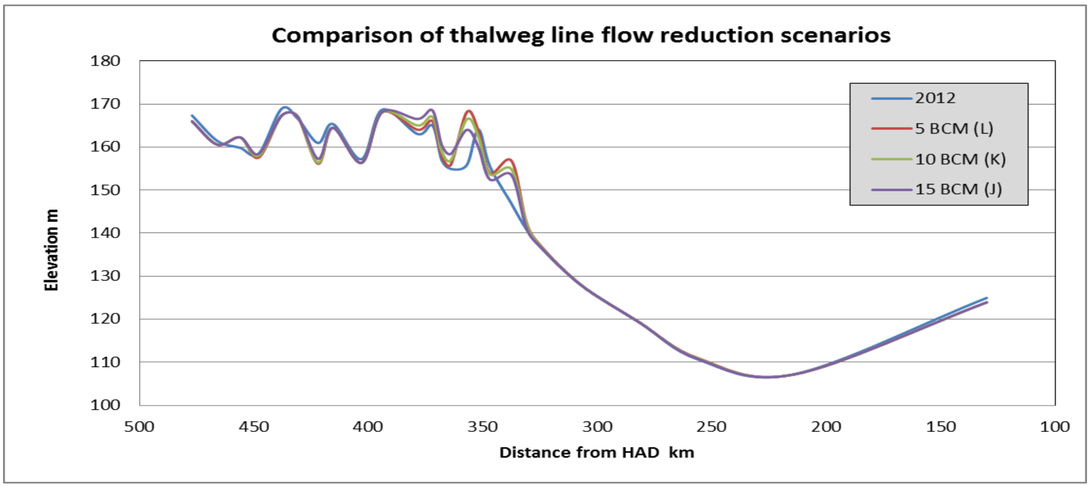

Figure (18): Comparison of thalweg line at different scenarios J, K and L

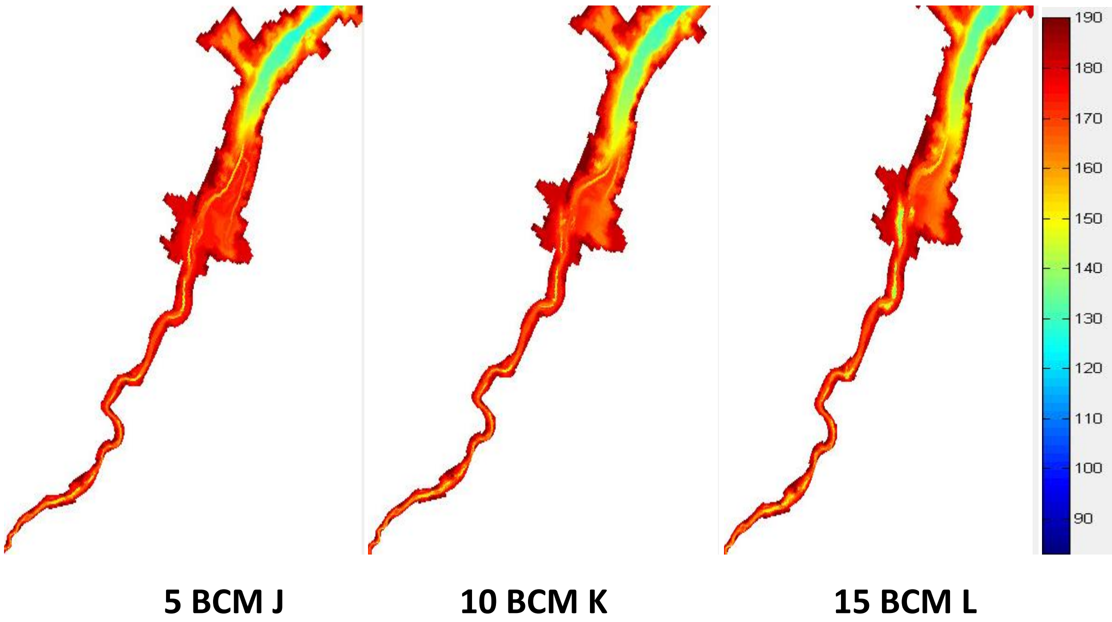

Figure (19): Comparison between different scenarios J, K and L

The water level used for these simulations is averaging from 175 to 167 m AMSL for scenarios J, from 174 to 164 m AMSL for scenario K and from 173 to 154 m AMSL which was higher than levels at scenario G therefore the resulted deposition affected by these water levels as a result the sedimentation was not spreading north like scenario G.

As a result of study these scenarios good estimation of sedimentation volumes achieved by using the resulted digital elevation model for each case and compare each resulted DEM to the last available measured data to find out the difference between each scenario as all these results summarized in table (1)

Table (1): Volume of deposited sediment for all study scenarios

Case	Volume of deposited sediment million m^3	Period of simulation
Maximum flood A	2,523	15 Years
Maximum flood B	2,025	15 Years
Average flood C	1,413	15 Years
Average flood D	1,213	15 Years
Minimum flood E	967	15 Years
Minimum flood F	893	15 Years
5 BCM Flow reduction G	1,533	15 Years
10 BCM Flow reduction H	876	10 Years
15 BCM Flow reduction I	621	5 Years
5 BCM Flow reduction J	1,723	15 Years
10 BCM Flow reduction K	988	10 Years
15 BCM Flow reduction L	662	Years

10. CONCLUSIONS:

In this research work the following conclusions were obtained:

1. The mathematical models like Delft3D are a good tool to simulate reservoirs like AHDR and it was very useful to estimate future progress of reservoirs sedimentation.
2. Van Rijn (1993) equation is the proper equation to simulate the High Aswan Dam Reservoir compared to other equations used by Delft3D.
3. The relationship between storage volume and water level can be used to estimate future time series for water level and discharge which can be used as input data for mathematical simulations to estimate the sedimentation future progress. Also the evaporation losses can be calculated using the relationship between surface area and water level.

4. Using a long term scenarios of flow reduction will reduce the water levels at AHDR which appear clearly in the estimated water levels hydrograph of flow reduction scenarios (G and J) but when using short term reduction scenarios, the water levels will reach critical water levels especially at scenario G which means that the execution of filling of any future reservoir (like Gerd Dam) on Nile basin should use the long term filling scenarios.
5. Using short term flow reduction scenarios "less than eight years" will reduce the storage capacity of the reservoir by 75 BCM through years which will cause lowering water levels by 1.5 meter annually which represent big value of storage reduction which is appear clearly at the estimated water level time series at scenarios I and L.
6. Reducing the water levels of the reservoir due to flow reduction scenarios will reduce the evaporations losses by 1.00 BCM to 4.00 BCM per year through different flow scenarios.

11. RECOMMENDATIONS:

Based on the results and conclusions of this study, the following are recommended:

- Using 3D simulations to simulate the flow reduction scenarios and compare it with 2D simulation of the current study and determine which results are more reliable.
- Update the equations that represent the relationship between the incoming discharges after the operation of Future constructions on Nile river Basin.

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