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Hydrodynamic Modeling of Flood Wave Propagation in Major Rivers due to Dam Failures. Case Study: The Grand Ethiopian Renaissance Dam (GERD) on Nile River.

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الملخص

سد النهضة الإثيوبي لإنتاج الطاقة الكهرومائية ، تحت الإنشاء على نهر النيل الأزرق علي الحدود الإثيوبية السودانية داخل إثيوبيا. ويبلغ حجم تخزين المياه ٧٤مليار متر مكعب، ومن المتوقع أن تنتج ٦٠٠٠ ميجاوات من الطاقة الكهرومائية ، الهدف الرئيسي من هذا البحث هو وضع نهج للنمذجة الهيدروديناميكية لاستخدامها في محاكاة انتشار موجة الفيضانات الناشئة من انهيار السدود على الأنهار الرئيسية نحو المصب. ولتحقيق هذا الهدف سيتم دراسة حالة استخدام احد برامج النمذجة الهيدروديناميكية (HEC-RAS) والذي سيتم استخدامه لتمثيل انهيار السد واجراء الدراسة للسريان الغير المستقر للموجة الفيضانية باستخدام معادلات تدفق الموجات الفيضانية. وسيتم الاستعانة بنظام المعلومات الجغرافية (GIS) والذي يستخدم على نطاق واسع وذلك خلال مرحلة ما قبل النمذجة وبهدف تجهيز البيانات اللازمة لادخالها على النموذج الهيدروديناميكي وكذلك خلال مرحلة ما بعد اجراء الدراسة الهيدروديناميكية من أجل إنتاج خرائط غمر الفيضانات لمختلف السيناريوهات لإنهيار السد.

1 ABSTRACT

The Grand Ethiopian Renaissance Dam (GERD) is a large-scale hydropower dam under construction on the Blue Nile River, upstream of the Ethiopian-Sudan border inside Ethiopia. The GERD has a reservoir storage capacity 74 billion cubic meters and is expected to produce 6000 MW of hydropower energy. The aim of this study is to develop a hydrodynamic modeling approach to be used in simulating the propagation of flood wave downstream dam failure locations on major rivers. To achieve this objective a case study will be investigated using Hydrologic Engineering Center’s River Analysis System (HEC-RAS) model that will be used to model breach/break formation and to solve the non-uniform/unsteady flow equations of flood wave propagation. Geographic Information System (GIS) shall be extensively implemented for pre-processing of the input data required for hydrodynamic modeling and post-processing of the hydrodynamic output to produce flood inundation maps for various dam failure scenarios.

2 INTRODUCTION

Dam break study becomes a major component of dam safety program, and for preparing emergency action. As for the Grand Ethiopian Renaissance Dam (GERD), it has raised several questions about its safety and impacts on downstream countries in case of its failure.

The Blue Nile and the Nile River Upstream the High Aswan Dam is taken as a case study in the proposed research where the failure of the GERD and the downstream corresponding impacts are to be simulated.

The Grand Ethiopian Renaissance Dam (GERD) has raised several questions about its safety and impacts on downstream countries in case of its failure. The Nile River (the longest river worldwide) is taken as a case study in the proposed research where the failure of the GERD and the downstream corresponding impacts are to be simulated.

3 RESEARCH OBJECTIVES

The main objective of this research is to develop a hydrodynamic modeling approach to be used in simulating the propagation of flood wave downstream dam failure locations on major rivers.

4 CASE OF STUDY: Grand Ethiopian Renaissance Dam (GERD)

The Grand Ethiopian Renaissance Dam figure (1), is technically named as the Millennium Dam, is under construction upstream of the Ethiopian-Sudan border inside Ethiopia, on the Blue Nile River, which is located about 40 km east of Sudan. The project is owned by Ethiopian Electric Power Corporation (EEPC). Construction of the Dam started in April 2011, should be expected to be finished in July 2017.

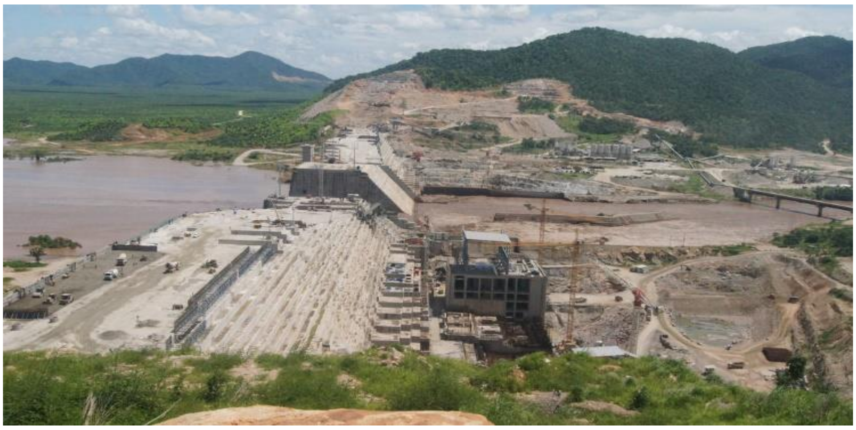

Figure (1) Shows the Grand Ethiopian Renaissance Dam

4.3 Construction of the Dam

The construction of the dam will be a roller-compacted concrete (RCC) gravity type, comprising of two power stations, three spillways and a saddle dam. The main dam will be 145 m high and 1,780 m long. The reservoir's surface area is 1,680 km^2 at Full Storage Level (FSL), the dam will serve as a bridge across the Blue Nile.Gated spillways fitted with six radial gates will be located on the left side of the main dam. Each gate capacity discharge is 2,450 m^3/s at probable maximum flood occurrence.

The Saddle dam supporting the main dam will be 4,800 m long and 45 m high. It will have emergency spillway to discharge water directly into the Roseires reservoir. The two outdoor power stations, there capacitates are 3,500 MW and 2,250 MW, will be located on either bank of the river. The powerhouses include 16 generating units of 375MW each.

4.4 Dam power and water capabilities

The Dam will generate power with an expecting capacity of 6,000 MW, the main and saddle dams will impound a reservoir with capacity of 74 billion cubic meters. It's capability of handling flood will be 19,730 cubic meters per second, will reduce alluvium in Sudan by 100 million cubic meters and facilitate irrigation of around

500,000 ha of new agricultural lands, it will also reduce approximately 40 km of flooding in Sudan, upon its completion.

The regulated flow of water from the dam will improve agriculture and impact from evaporation of water from the dam will be minimal compared to other dams in Ethiopia, which will help in water conservation.

Water evaporation in Aswan High Dam, as well as other dams in Ethiopia, equates to around 19 billion cubic meters. Grand Ethiopian Renaissance Dam will reduce the capacity of Aswan High Dam.

5 DATA PREPROCESSING

Preprocessing data is processing the raw data and preparing them to another processing procedure, the following figure (2) shows the flow chart stages of the dam break simulation by preparing the data of reservoir, River cross- sections, the breach parameters, then computing the analysis and evaluating the effect on downstream channel, Presenting these Data by preparing the flood inundation maps.

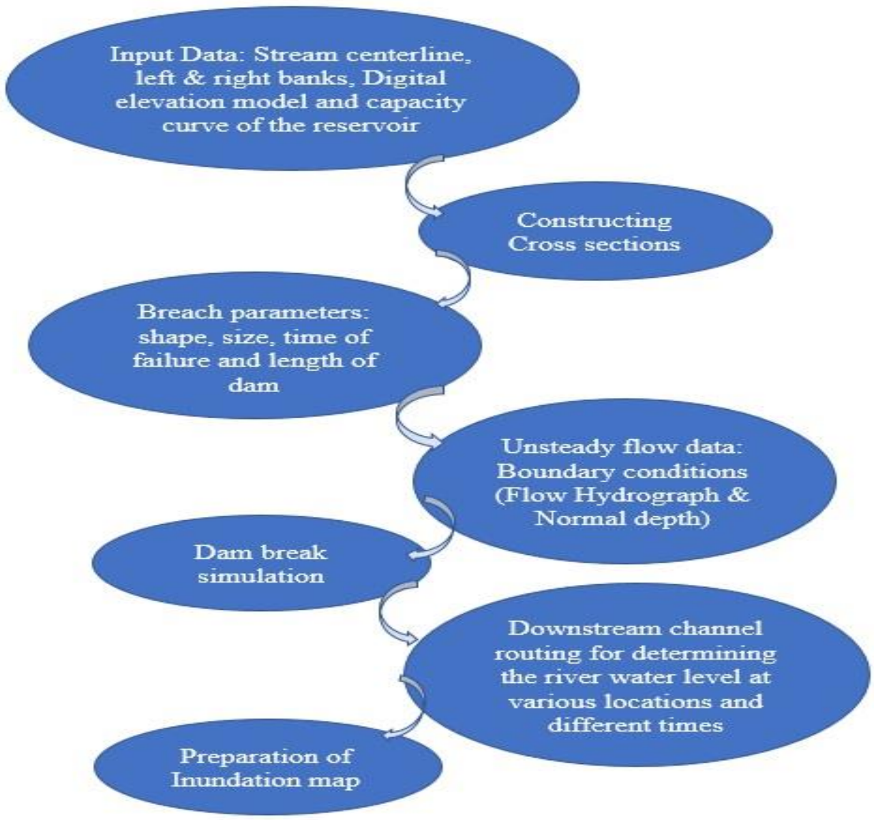

Figure (2) The Dam Break Simulation stages

5.1 Stream Flow Data

The case of analyzing GERD is the impounding stage and the downstream impacts, especially flow from the Blue Nile and on AHD operation, considered an average sequence of years regarding AHD inflows. Figure (3) shows the low, average and peak through the year.

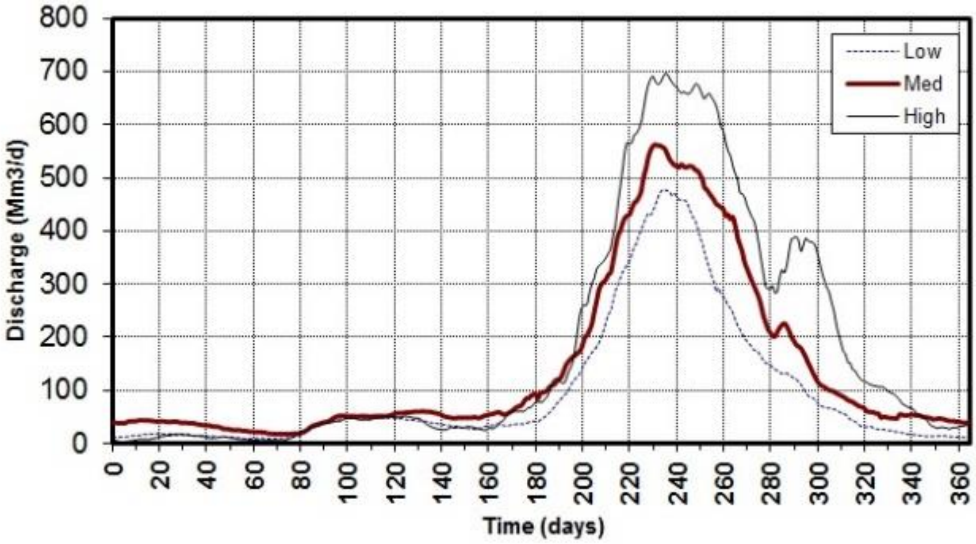

Figure (3) The calculated flow of Blue Nile

5.2 The Capacity Curve of the Dam

The capacity curve is necessary for defining the storage capacity of the reservoir. it is obtained by planimetering the area enclosed to the dam within a contour line in the reservoir area, as shown in figure (4).

The contour's level as shown in the figure is 645 m, the volume of reservoir's dam will be approximately 70,000,000,000 m^3.

Table (1) shows capacity curve that relates the storage of the reservoir to the elevation of the water surface, and showed in the graphical plotting of capacity curve as shown in figure (5).

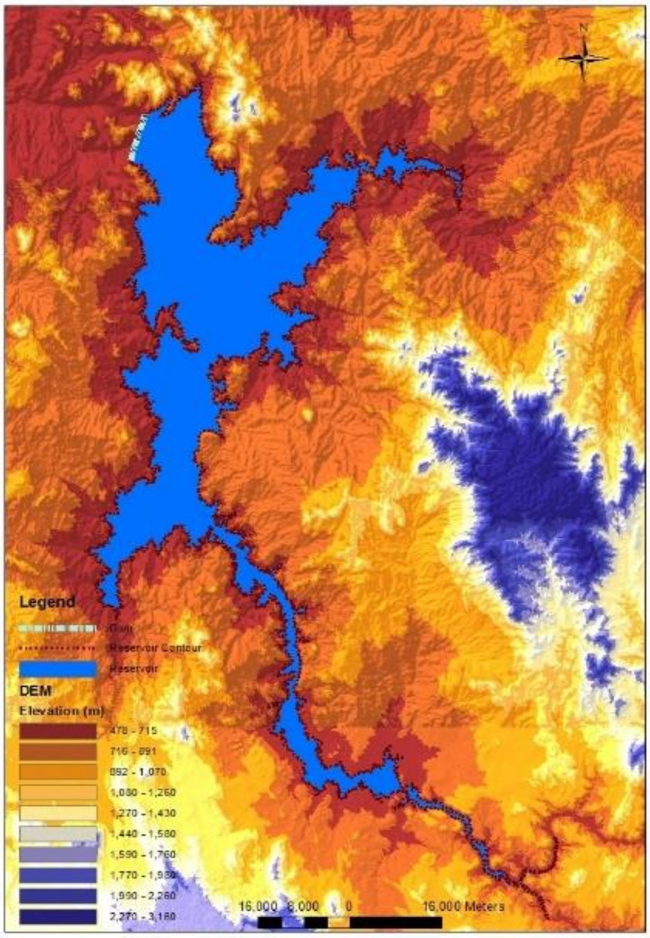

Figure (4) The contour line of the reservoir area of GERD

Elevation (m)	**496**	**500**	**505**	**510**	**515**	**520**	**525**	**530**
Volume (Mm^3)	0.0	0.2	2.0	8.6	22.4	48.8	103.8	194.4
Elevation (m)	**535**	**540**	**545**	**550**	**555**	**560**	**565**	**570**
Volume (Mm^3)	333.6	542.1	837.9	1,241.4	1,778.7	2,478.2	3,350.9	4,432.1
Elevation (m)	**575**	**580**	**585**	**590**	**595**	**600**	**605**	**610**
Volume (Mm^3)	5,770.2	7,394.1	9,326.7	11,609.9	14,276.2	17,368.3	20,918.9	24,969.6
Elevation (m)	**615**	**620**	**625**	**630**	**635**	**640**	**645**	
Volume (Mm^3)	29,556.1	34,763.5	40,623.9	4,7173.3	54,399.6	62,293.86	70,775.59	

Table (1) Capacity curve table that relates the storage of the reservoir to the elevation of the water surface

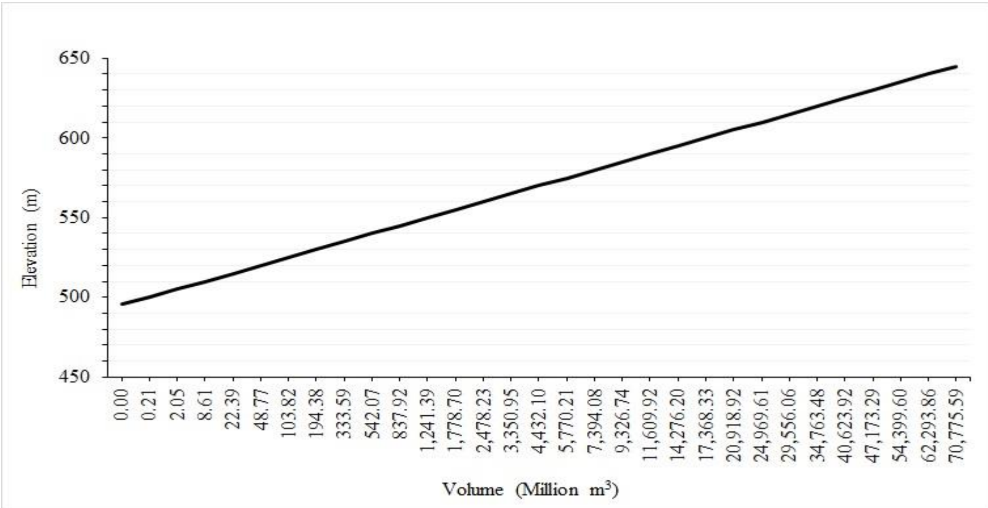

Figure (5) Capacity curve that relates the storage of the Reservoir to the elevation of the water surface

5.3 Digital Elevation Model

As shown in figure (6) is the prepared DEM representing the continuous elevation values over a topographic surface by a regular varieties of z value, referenced to a common vertical datum. It is used for exporting the elevation in GIS.

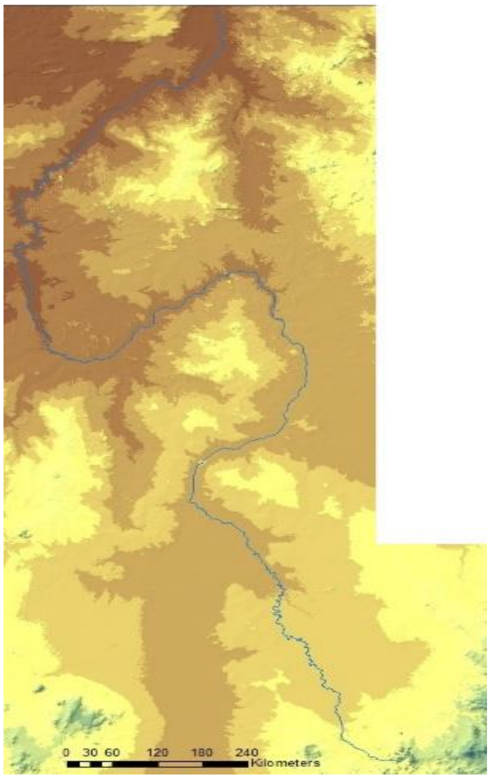

Figure (6) DEM of the Nile

6 METHODOLOGY

6.1 Dam Break Simulation

The stages of the Dam Break Simulation can be summarized in the following steps;

- Preparing the reservir data, and River cross-sections,
- Defining the breach parameters,
- Processing the dam break analysis,
- Study the effect on downstream channel, then
- Presenting these Data by preparing the flood inundation maps.

6.1.1 Geometric Data

Geometric data are to create the river system, entering the cross-section data, adding hydraulic structure data for the dam.

Geometric data consist of creating the connectivity of the river system, entering cross section data and hydraulic structure data.The geometric data will be exported from Arcmap GIS, the procedure for applying the geometric data to HEC-RAS can be summerized by locating the area under scope on the globe to define the coordinates, this was done using the Google Earth application, as shown in figure (7).

Figure (7) The path of the Blue and Nile river on Satellite Image

The location of Nile River is drawn by asistance of Arcmap GIS, as shown in the below figure (8); will be used for adding the elevations from upstream to downstream of the constructed cross section of the Nile River, by the assistance of Arcmap GIS as shown in figure (9).

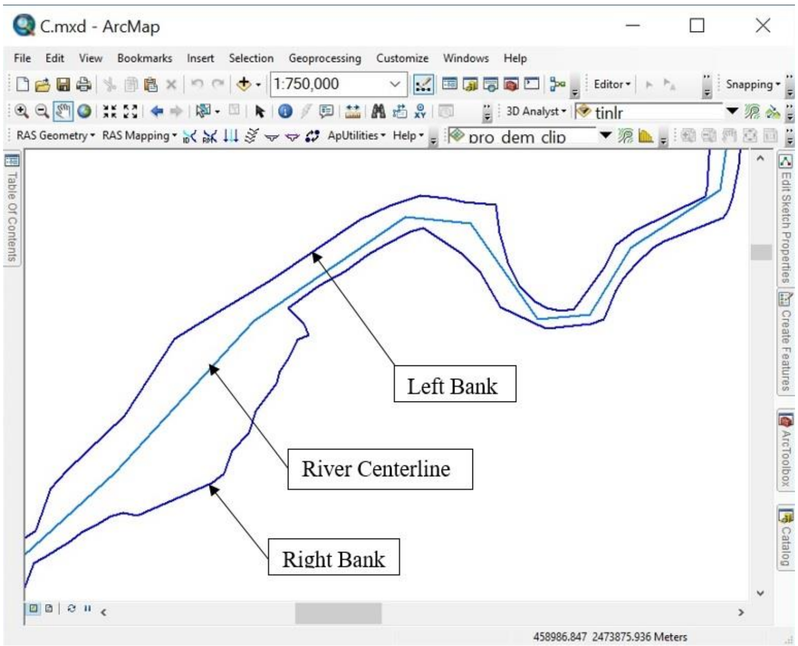

Figure (8) The centerline of the Nile river, left and right banks in Arcmap

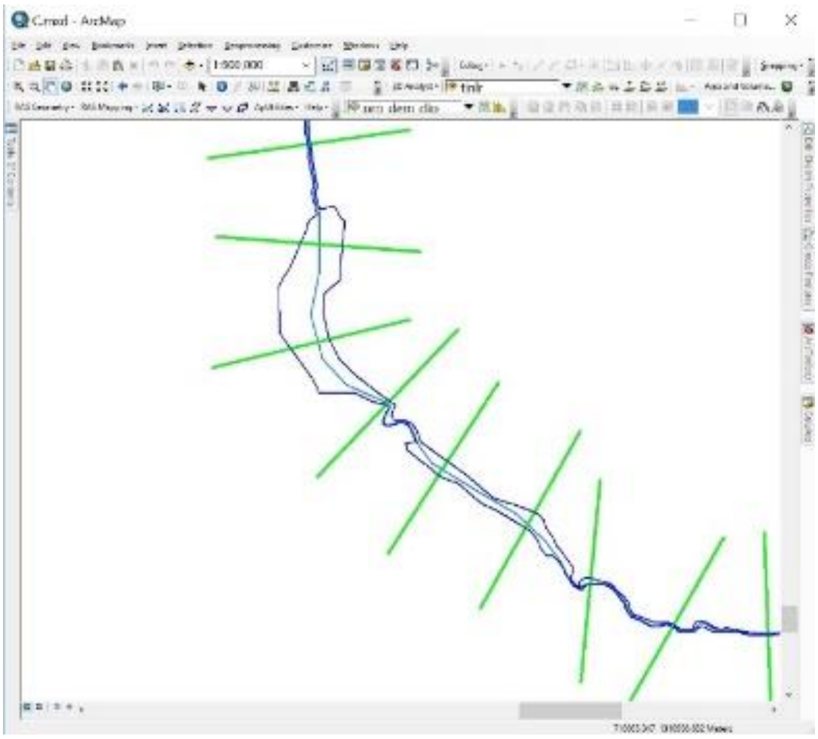

Figure (9) The Constructed cross section along the stream

To apply the data to HEC-RAS, the data will be ready by creating Topology, Lengths/Stations, and assign Elevations to the River, by importing the exported file from Arcmap GIS, figure (10) & (11).

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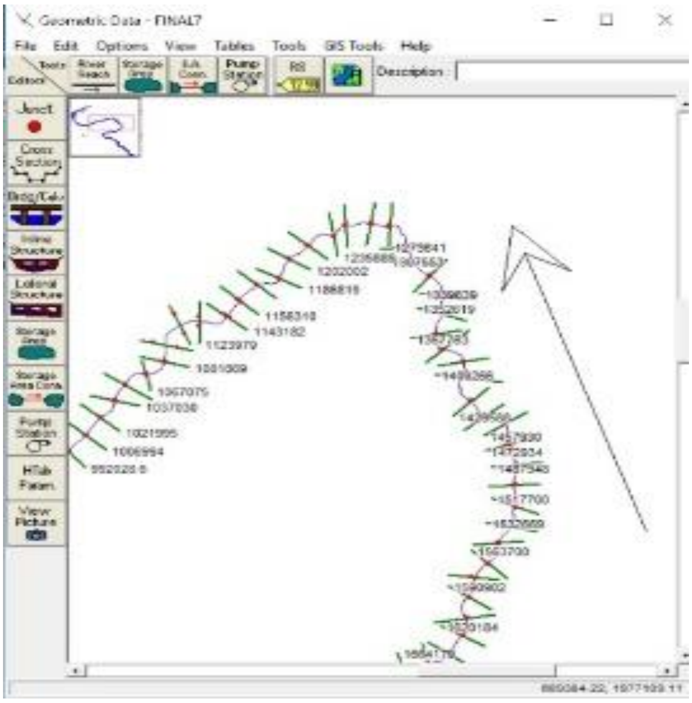


Figure (10) Cross section along the stream imported to HEC-RAS

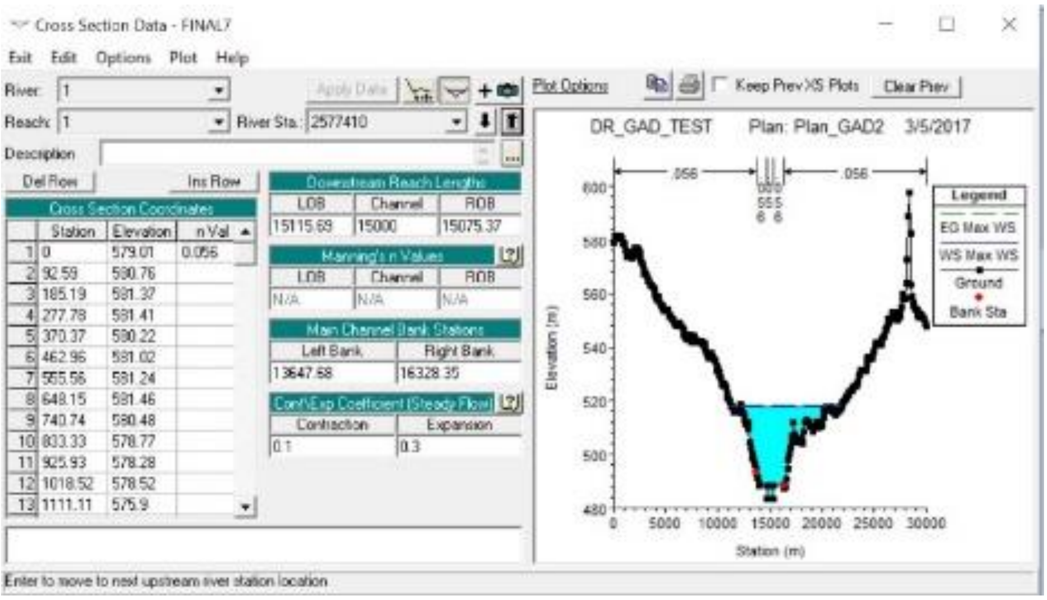


Figure (11) Cross section data input

6.1.2 Unsteady Flow Analysis

After entering all geometric data, to compute the unsteady flow water surface profiles, there are two steps prior starting the unsteady simulation. First entering the unsteady flow data and boundary conditions, second develop a plan to perform the calculations.

Unsteady Flow Data

The required data is the boundary condition of the external bounds of the river. There are several types of boundaries depends on the location of the cross section, from these types the Flow Hydrograph boundary was selected for the upstream boundary condition. Another type is normal depth, usually selected for the downstream boundary condition.

Flow hydrograph boundary conditions:

Flow hydrograph is calculated by the reservoir routing method to predict the changes of outflow due to the occurrence of the breach.

The reservoir routing equation is;

$$\Delta S = (\sum I - \sum Q)\,\Delta t \tag{1}$$

where,

ΔS = change in storage, (m^3)

$\sum I$ = Inflow, (m^3/sec)

$\sum Q$ = outflow, (m^3/sec)

Δt = time, (hr)

The inflow is assumed to be the peak flow of the Blue Nile is approximately 8000 m^3/sec.

The breach type is assumed to be piping failure, the mechanism of the failure start at any elevation, location and grow to maximum extents. The ultimate breach size and breach formation time are critical in the estimation of the outflow hydrograph, then the actual failure initiation mode.

The outflow discharge will be calculated by the orifice equation, added to it the assumed turbines flow of the dam is 5000 m^3/sec.

The orifice equation is;

$$Q = Cd * A * \sqrt{2gh} \quad (2)$$

where,

Q = Outflow discharge, m^3/sec

C_d = Coefficient of discharge, 0.5

A = Area of breaching

g = acceleration from gravity, 9.81 m/sec^2

h = centerline head.

By calculating the inflow breach hydrograph at upstream cross section, assuming the breach start time will be 10 hours, it showed that the peak of outflow discharge will be 396,162 m^3/sec at hour 15. By increasing the breach start time the outflow discharge will be increased too, figure (12)

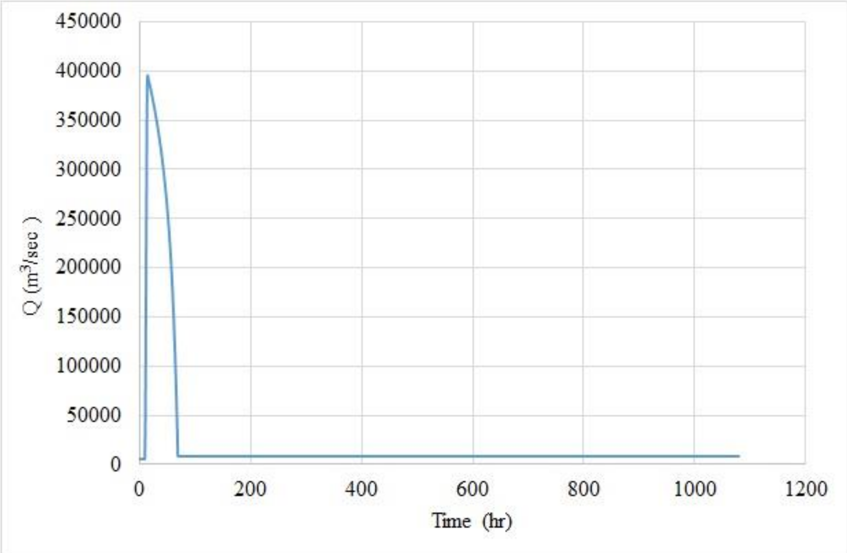


Figure (12) Breach flow hydrograph

Normal depth boundary condition

Will be at the downstream open channel water cross section before Lake Nasser by entering the friction slope, which will help in simulating the depth of flows by manning's equation.

6.1.3 Unsteady Flow Calculations

After entering all the geometric data and unsteady flow data, we can compute the unsteady flow simulation, before performing a simulation we should put a plan, the plan describes both the geometry and unsteady flow data are used. Also, includes simulation time, computation settings and the simulation options.

7 RESULTS

After entering the breach parameter, doing a plan for the breach, and performing the unsteady flow calculation; once all these data are entered and computing a window appears HEC-RAS finished computations shows the progress of the computational.

Our case of study is assuming the full maximum storage of GERD reservoir with the peak flow from the Blue Nile, assuming the breach type is orifice, with breach start time 10 hours. The output data were disaster, the result of flood wave from the breaching consequences were massive destruction through the downstream of the dam.The output will be viewed in cross sections and water profile for the main channel, water extent and cross section table output.

The water extent shows the reaching of the water extent from both left and right banks, in our case some the cross sections the water extents in few meters and after that it gets wider along the cross section, which means the flood wave propagation damage some lands, the below figure (13) shows the full water extent along the stream, figure (14) shows the water extent from the upstream cross section at the dam, where the width is few meters then gets wider along the cross section which means the flooded water is damaging through the area.

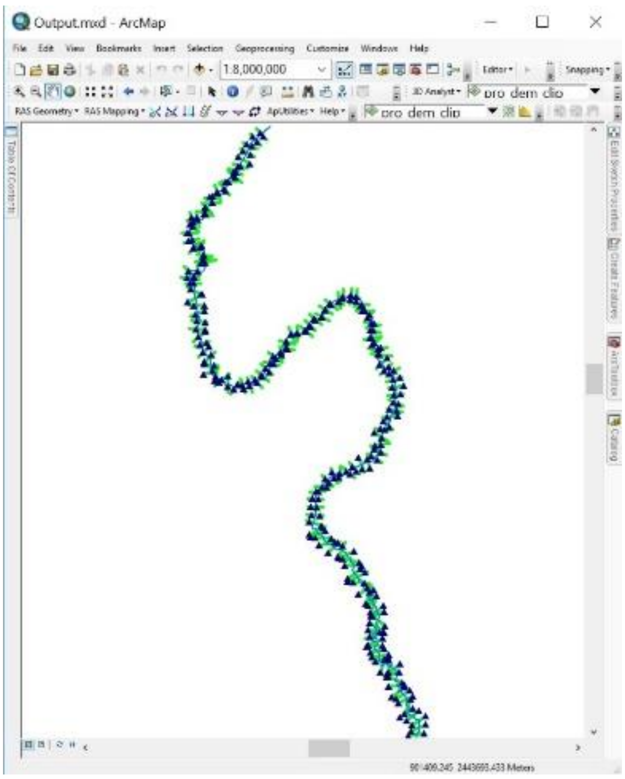


Figure (13) Full water extent along the river

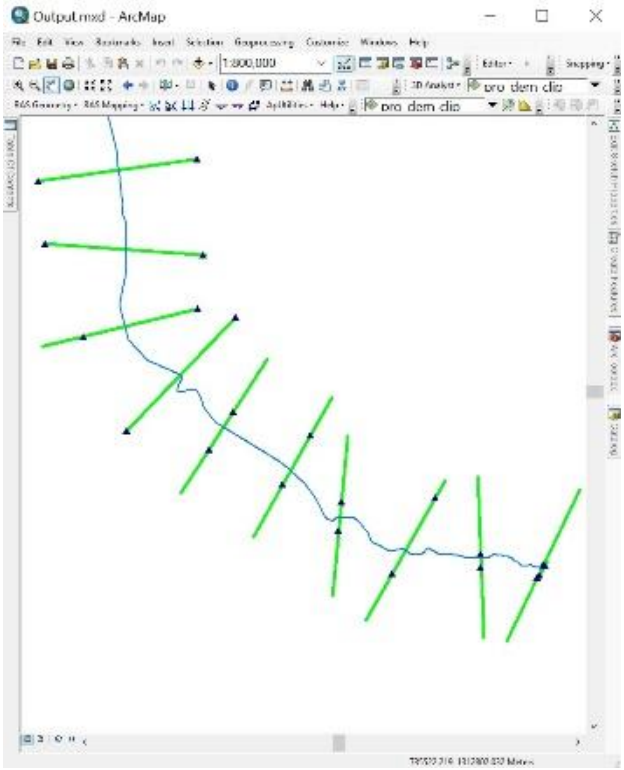


Figure (14) Water extent at the upstream cross section

As given shown by the water extent plan, the cross sections will show the flooded water in various locations on the Nile, as shown in the following figures (15) and (16) are random cross sections along the Nile showing the level of flooded water due to the breach that occurred.

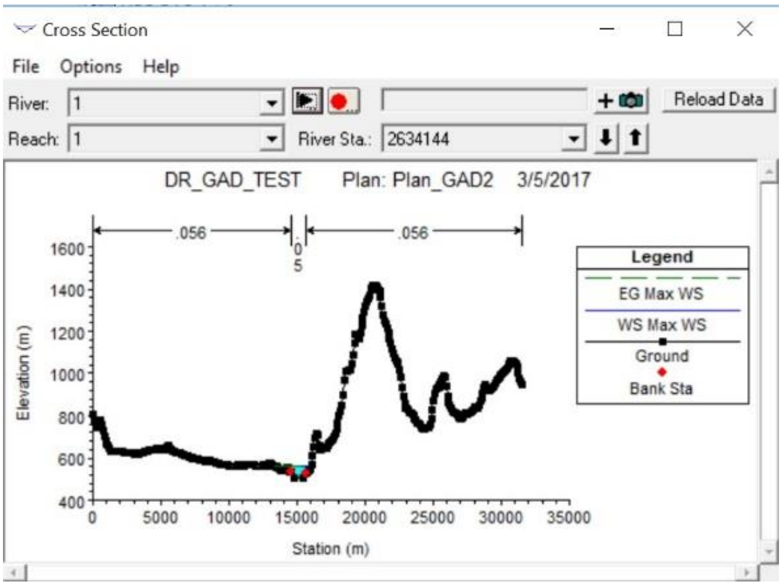


Figure (15) Random cross sections along the Nile

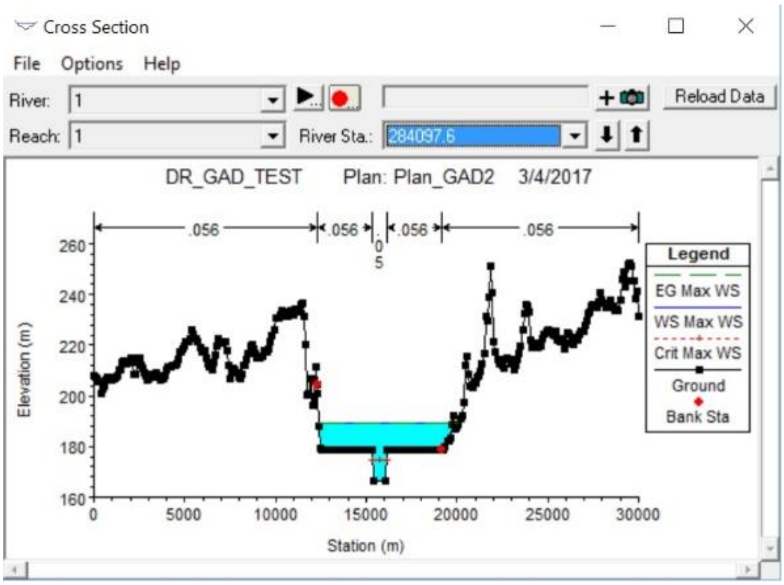


Figure (16) Random cross sections along the Nile

The profile plot shows the water surface along the Nile, starting from the GERD location to the cross section before Lake Nasser, the below figure shows that the maximum water starts at 560 m with velocity 6.10 m/sec, as the bed channel is steep, water is flowing with high velocity leading to damage on the way, then the bed channel becomes mild the maximum water surface reduced to 455 m and velocity to 1.19 m/sec; meaning that the water floods across the width of cross sections flooding the lands beside the Nile, ending to Lake Nasser with maximum water surface 177.68m, critical water surface 168.10 m with velocity 0.59 m/sec.

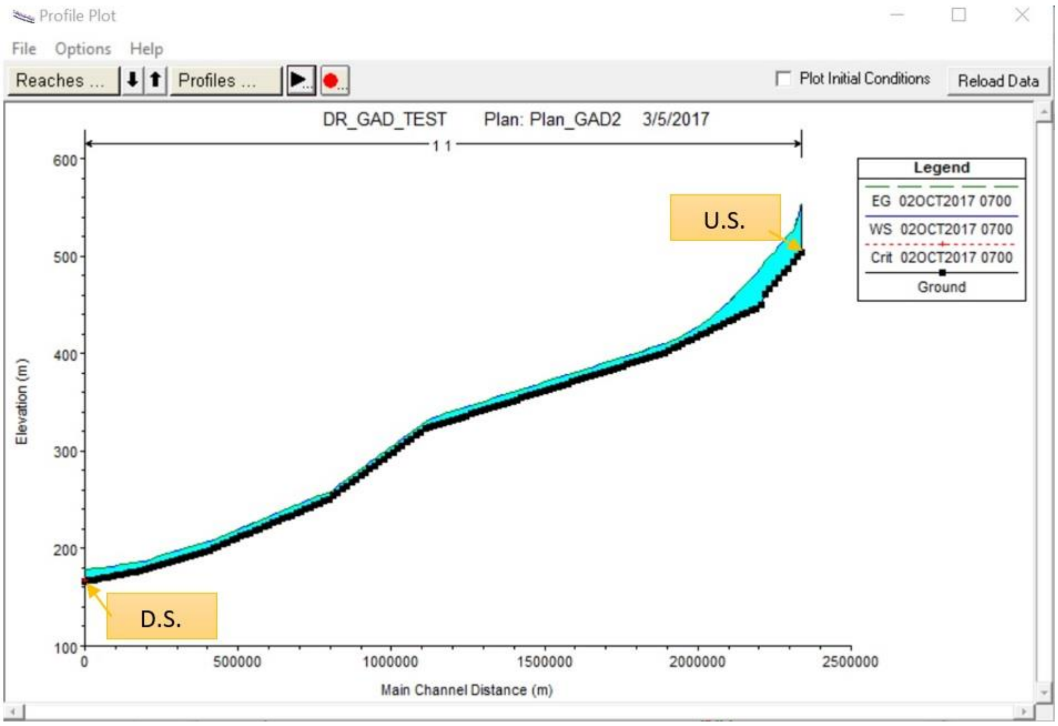


Figure (17) Profile plot along the stream showing the upstream and downstream cross sections

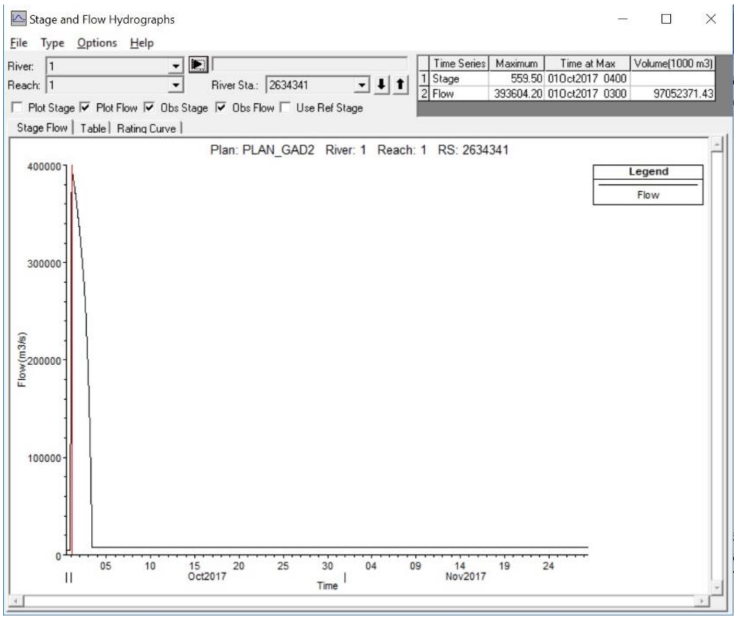


Figure (18) The upstream time peak at the flow hydrograph

The following figures shows that the flow hydrograph at upstream with the time peak 15 hr's and flow peak 393,604.20 m^3/sec of cross section; while in downstream shows the time peak 766 hr's with flow peak 50,010.64 m^3/sec. Meaning that the time of flood movement is 751 hr's.

The wave propagation velocity at the upstream is extremely high 7.63 m/sec, where the bed channel is steep; afterwards the velocity reduced to 3.77 m/sec as the bed channel get moderate, and as will the flooded wave is moving in all areas around while it arrives to Lake Nasser with 0.63 m/sec, the below figure (20) shows the velocity of wave propagation along the whole stream.

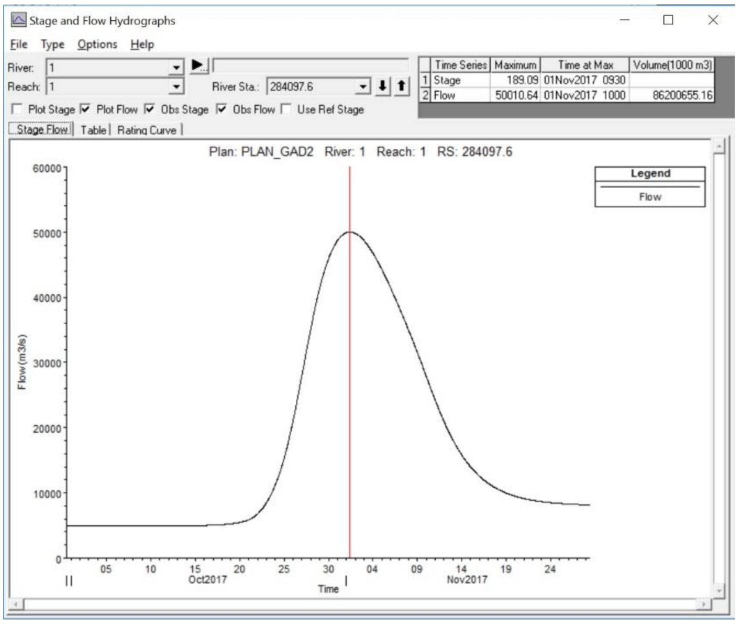


Figure (19) The downstream stream time peak at the flow hydrograph

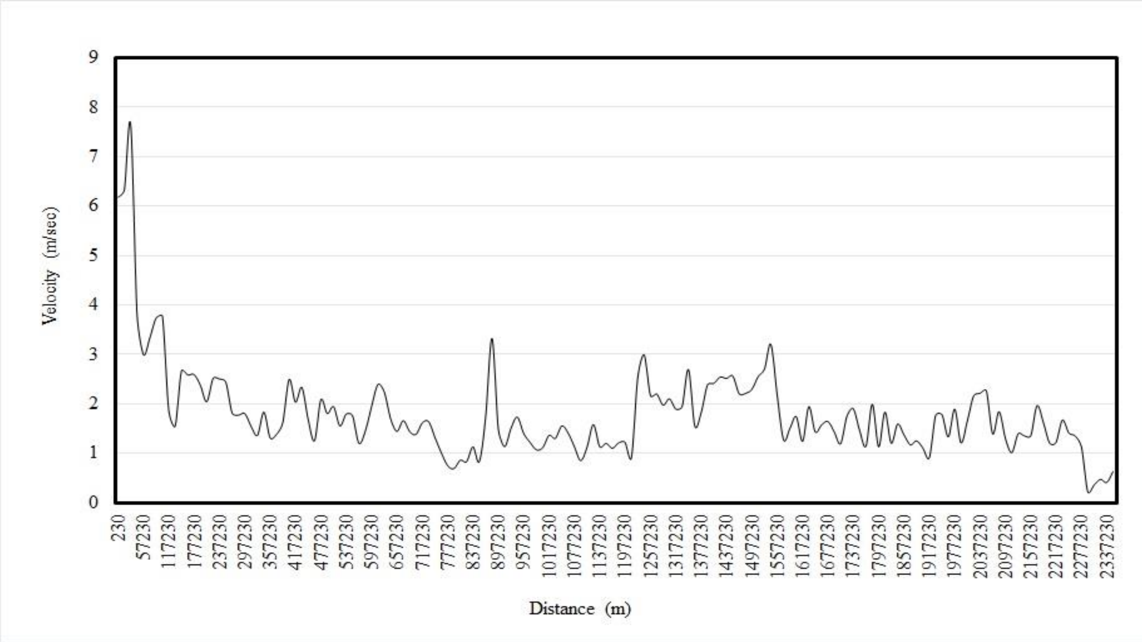


Figure (20) The velocity wave propagation along the stream

At the downstream cross-section, the results showed many action and possibilities could happen to AHD and the downstream of the dam.

The stage and flow hydrograph shows that the wave propagation will sensed after 20 days of the dam breach occurs at the upstream with maximum discharge 50,010.64 m^3/sec with elevation 189.09 m, happens after 32 days, the following figure (21) shows the stage and hydrograph of downstream.

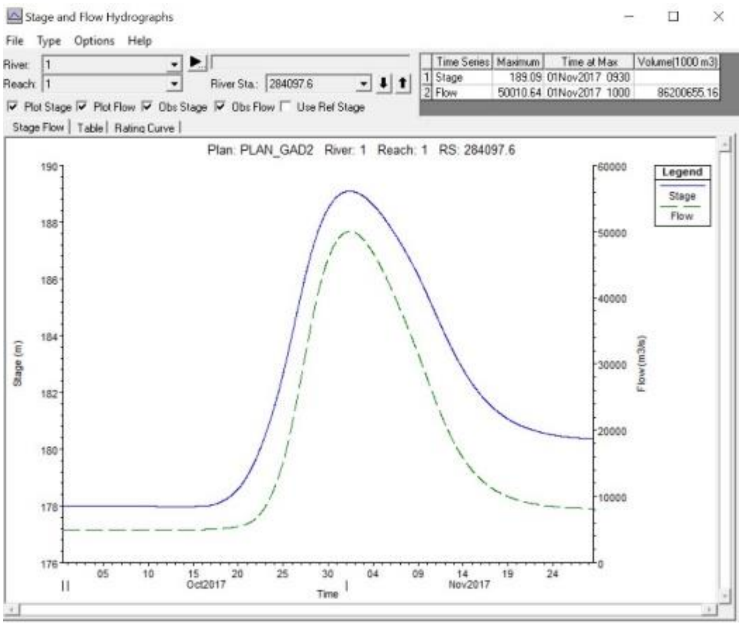


Figure (21) Stage and Flow Hydrograph of downstream cross section

To prepare AHDR for the dam breach occurred at the upstream there's three cases of possibilities could happen at the time of breach; cases are:

1. At summer peak discharge 250,000,000 m^3/day.
2. Future extension maximum downstream discharge 350,000,000 m^3/day.
3. Maximum turbines capacity 950,400,000 m^3/day.

It's very important to have an emergency plan to avoid overtopping or any damage to the downstream of AHD, the following will show each case what the probabilities will occur at the AHD and downstream of it.

The AHDR level through the three cases with the time as shown in the above figure, when the flow of AHDR is bigger the level of reservoir get decreased which will help in overcoming the overtopping that could occur.

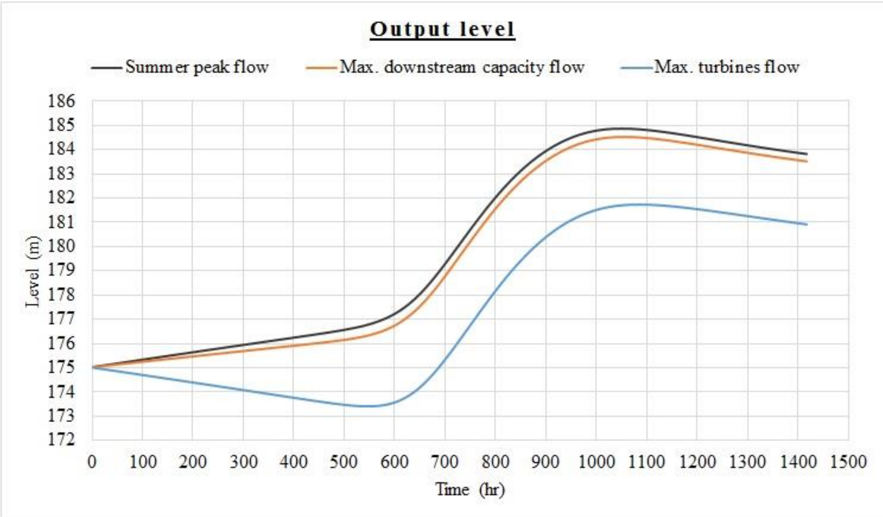


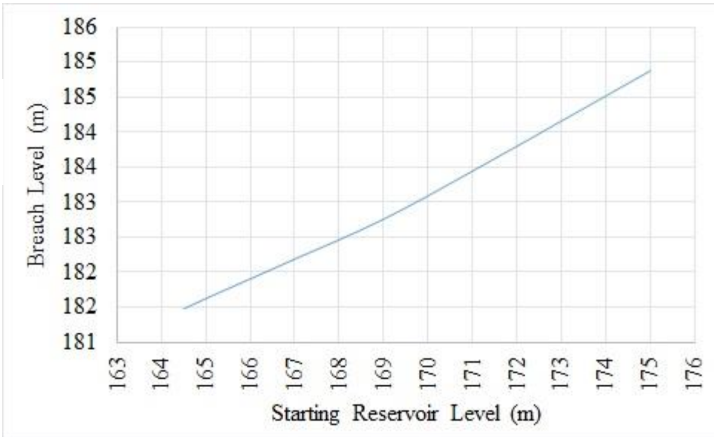
Figure (22) shows the ADHR level in three cases

After the breaching occurred, the wave propagation is sensed; at the summer peak flow, the AHDR live storage level 175 m, the volume will be increased to 3.74*109 m^3, while at the maximum downstream capacity flow the volume will be 3.03*109 m^3.

<u>In case AHD at Summer peak discharge 250,000,000 m^3/day</u>

The level of reservoir should be reduced to 164.5 m as to avoid overtopping, in this case nothing will be harmed but if the reservoir couldn't empty till this level then overtopping will occur, downstream will be harmed depends on the level of reservoir will be, the below figures shows charts of reservoir level should be and the flow overtopping on each level of reservoir.

Figure (23) The starting reservoir level



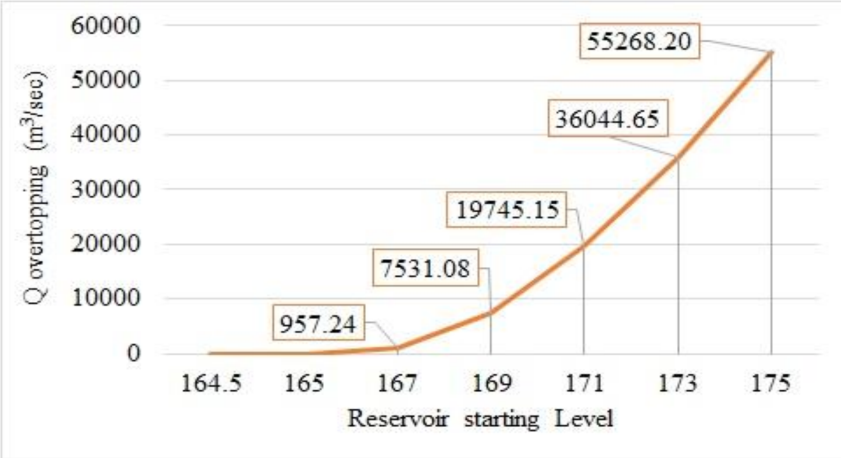


Figure (24) The overtopping flow

<u>In case AHD at Maximum Downstream Capacity discharge 350,000,000 m^3/day</u>

The level of reservoir should be reduced to 166.5 m as to avoid overtopping, in this case nothing will be harmed but if the reservoir couldn't empty till this level then overtopping will occur, downstream will be more harmed compared to summer peak, the below figures shows charts of reservoir level should be and the flow overtopping on each level of reservoir.

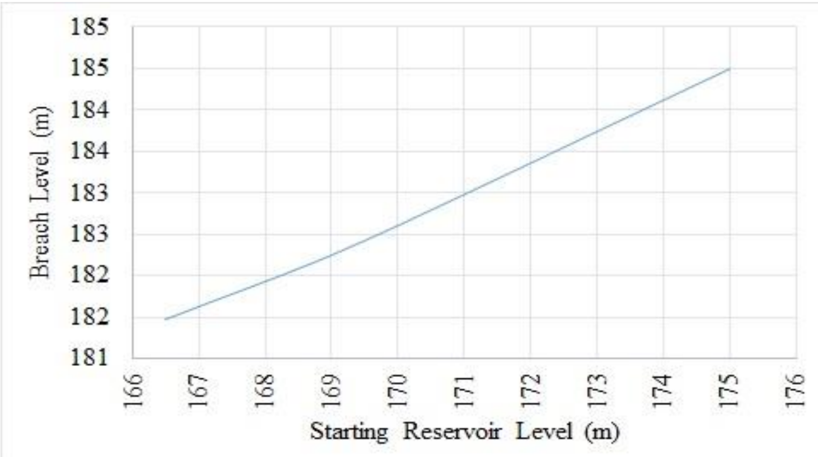


Figure (25) The starting reservoir level

Figure (26) The overtopping flow

In case AHD at Maximum Capacity discharge 950,400,000 m^3/day

At maximum capacity, the downstream will be ruined but at least the dam will be saved from overtopping which could lead to failure, the reservoir should be emptied to level 174.5 m, the below figures show charts of reservoir level should be and the flow overtopping on each level of reservoir.

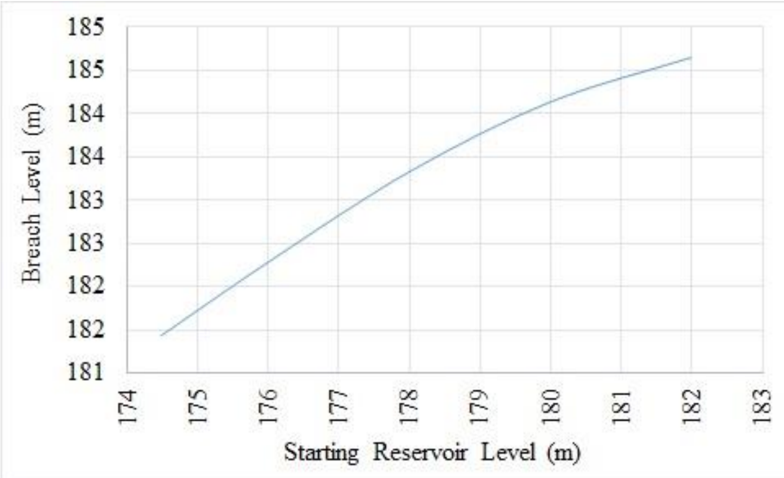


Figure (27) The starting reservoir level

Figure (28) The overtopping flow

From three cases, reducing the AHDR level is a must to avoid overtopping and saving the downstream of the dam, but the maximum turbines case even when the AHDR level is reduced to the needed level the downstream will be ruined due to the maximum capacity of the downstream is more less.

8 CONCLUSION & RECOMMENDATIONS

8.1 Conclusion

The detailed results of the study are considerably risky for constructing another dam on the Blue Nile is a challenge for the downstream countries in case of dam failure occurred.

The simulation showed the following results:

1. In case of the breach occurs, a massive flood will occur by flooding Sennar Dam and the areas between the dam and until it reaches Khartoum to Aswan High Dam.
2. If the failure occurred giving notice to downstream, with peak summer flow, AHD should reduce its level to 164.5 m to avoid overtopping.
3. For further plan, if the failure occurred giving notice to downstream, with the maximum downstream capacity flow, AHD should reduce its level to 166.5 m to avoid overtopping.
4. If the failure occurred giving notice to downstream, with maximum turbines capacity, AHD should reduce its level to 174 m to avoid overtopping.
5. At AHD, overtopping could happen if no emergency plan followed by reducing the level of reservoir and could affect the dam.
6. In case of occurrence of the failure; AHDR level is less than 166.5 m, in the three cases of discharge the dam can overcome the failure wave by discharging the excess to the downstream without minimum damages.
7. In case of occurrence of the failure; AHDR level is 182 m, in the summer peak and the maximum downstream discharge the dam won’t overcome the failure wave, overtopping will occur while with the maximum turbines discharge there will be an excess of flow that overtop the dam and downstream is already being ruined by the maximum turbines flow.
8. The velocity along the main channel of the Nile with average 1.80 m/sec fluctuates according to the cross sections that pass by.

8.2 Recommendations and proposed future studies

Based on the results of the present study,

- Future studies should be conducted to check each area will be affected by the flood wave propagation.
- Studies should be conducted to check each dam on the downstream of GERD will be affected by the failure or not.
- AHD should have a precise emergency plan to avoid overtopping which could lead to another catastrophic damage.
- Future studies should be conducted with 2D modelling, to be more accurate with the flood routing along the cross sections.

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