



INUNDATION HAZARDS ON NILE DOWNSTREAM COUNTRIES DUE TO GERD BREAK

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ABSTRACT

Flood due to Dam break can cause a huge loss to human life and property on the downstream area. This loss to human life and property depended on extent of inundation area, size of population at risk, the propagation of flood waves and the amount of warning time available. This paper presents flood hazards on Sudan and Egypt due to Grand Ethiopian Renaissance Dam (GERD) break. The GERD is located at 20 km upstream of the Ethiopian–Sudaness border on Blue Nile River. GERD break may be occurred due to many different reasons such as structural instability, overtopping and seepage. Earthquakes, landslide and sabotage can be leads to insidious GERD break. Outflow hydrographs due to GERD break were obtained by HEC-RAS model. The Blue Nile and the Nile River downstream of GERD until the AHD is simulated using SOBEK 1D-2D model. The related data were collected to simulate and analyze GERD break hazard. A risk assessment of the GERD break is obtained. The flood wave propagation is found in terms of inundations maps. The flood water levels and arrival time downstream GERD to AHD is achieved. The results of this investigation could be used to help decision makers to prepare an emergency plan and warning systems to rescue the affected downstream area and to put an evacuate plan.

KEYWORDS: Flood hazards, GERD, AHD, numerical modeling, inundation

مخاطر الغرق لدول مصب نهر النيل الناجمة عن انهيار سد النهضة

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المخلص

إنهيار السدود من الممكن أن تتسبب في تولد فيضانات مدمره لما هو خلفها من مساحات، والتي من الممكن أن يتولد عنها خسائر كبيرة في الأرواح والممتلكات. والخسائر في الأرواح والممتلكات قد تتغير طبقا للمساحات المغمورة ومدى انتشار موجة الفيضان وعدد السكان المهددين والزمن المتوفر للإنذار. في هذه الدراسة يتم إيضاح مخاطر الفيضان علي السودان ومصر الناجم عن إنهيار سد النهضة الأثيوبي. يوجد سد النهضة الأثيوبي علي النيل الأزرق علي بعد ٢٠ كم أمام الحدود السودانية الأثيوبية. يوجد عدد من الأسباب لإنهيار سد النهضة الأثيوبي ومنها عدم الاتزان الإنشائي أو تدفق المياه من أعلي جسم السد أو التسريب أو حدوث ظاهرة فوران التربه من خلال جسم السد أو من منطقة الأساسات، وكذلك من الممكن أن يحدث الأنهيار لأسباب فجائية مثل حدوث زلزال أو أنهيار في التربة أو عمل إرهابي. التصرفات الخارجة من بحيرة سد

النهضة نتيجة الانهيار تم حسابها باستخدام برنامج HEC-RAS. تم تمثيل نهر النيل الأزرق ونهر النيل خلف سد النهضة باستخدام برنامج SOBEK 1D-2D. تم تجميع البيانات المطلوبة لتمثيل وتحليل انهيار سد النهضة. تم تقييم المخاطر الناجمة عن انهيار سد النهضة. تم استخراج النتائج المتولدة من انتشار موجة الفيضان علي شكل خرائط غرق وكذلك إيجاد أعماق المياه وزمن الوصل عبر مسار الدراسة من سد النهضة حتي السد العالي. تساعد النتائج المستخلصة من هذه الدراسة متخذي القرار في إعداد خطة طوارئ ونظام إنذار لتقليل المساحات المتأثرة خلف سد النهضة، وكذلك عمل خطة إخلاء بزم من كافي قبل وصول مياه الفيضان.

الكلمات المفتاحية: مخاطر الفيضانات, سد النهضة, السد العالي, النمذجة العددية, الغرق

1. INTRODUCTION

The Nile River is an international river, shared by eleven riparian countries. It has many tributaries as shown in **Fig. 1**. The White Nile is originated from the Kagera, which drains the mountains of Burundi and Rwanda and flows to Victoria Lake. The outflow from Victoria lake is flow through many lakes, swamp, river and tributaries to confluence at Khartoum with the Blue Nile (Sutcliffe & Parks, 1999). The Blue Nile is the major tributary of the Nile River. It begins at Tana Lake in the Ethiopian plateau and flows to Sudan. The Atbara River is one of main tributary of the Nile River system, its flows from the Ethiopian plateau and confluence the Nile River at Atbara, north of Khartoum. The Nile River flow arrive Aswan has contributes about 85% from the Ethiopian headwater, the remaining of 15% coming from the White Nile.

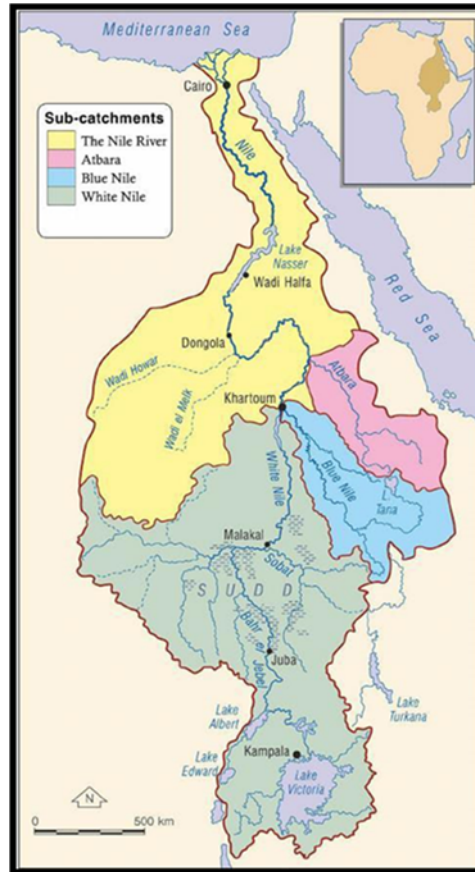


Fig. 1 The Nile River tributaries

The Nile River water is controlled by many dams, such as Rossieres, Sennar, Jebel Aulia, Khashm El Girba, Merowe and AHD. These dams provide water storage and flow regulation, hydropower and protection from severe floods and droughts. The flood due to dam failure causes a huge loss to human life and property. The loss of human life and property occurred due to dam break would vary with size of population at risk, extent of inundation area, and the

amount of warning time available. Planning the emergency and evacuation plan to reduce dam break hazards required many predictions as the dam break floods, the inundated area, propagation of the flood waves, the flow velocity, the flood depth and the travel time of the flood waves along study area. The main objective of this study is to depict the flood hazards due to GERD break on the area bounded by GERD and the AHD.

Soliman et al. (2019) divided the area between GERD and AHD to six separated reaches. The modelling of GERD break shows that, the peak outflow is 2000000 m³/s and occurred within 5 hr from the beginning of break. The peak inflow of AHD reservoir approached 37000 m³/s after 3 weeks from the beginning of GERD break. The Khartoum will be covered by water depth up to 15 m, above the ground level, within 4 days from the beginning of GERD break. AHD affected by GERD failure depends on the water level in its reservoir at the time of GERD break. Khosravi et al. (2019) analysed flood hazards due to Sefied Roud Dam, which is located in Giulan province in Iran. This dam is a buttress gravity dam, with 106 m height, crest length of 425 m, and 8 m width. The reservoir of this dam has a storage capacity of 1.2 billion cubic meters (BCM). The disaster area considered in this study was 21 km downstream of the dam body. The methodology of study consisted of two steps; the first one was to defined the flood hydrograph by using HEC-RAS, and the other one was to estimate a 2D inundation map by RAS-map. Juliastuti & Setyandito (2017) developed a flood modelling to find the inundation map for Krisak dam in Indonesia. The dam type is a homogenous earth dam. The height of Krisak dam is 20 m, 350 m length and the effective reservoir storage is 2.7 BCM. The spillway is free flow ogee and its length is 33 m. A numerical dam break model of Zhong Xing HY-21 was applied. The overtopping and piping failure are assumed as a mode of Krisak dam failure. Asnaashari et al. (2013) applied the combined of HEC-RAS model with Geographic Information System (GIS) to define the breach scenarios for two dams in British Columbia at Canada. The HEC-GeoRAS and ArcGIS were employed to generate the flood inundation maps of the study dam failure. El Bastawesy et al. (2015) simulated the GERD reservoir using SRTM3-DEM. They defined the water level, water depth, reservoir surface area, reservoir storage of GERD. Abdelhaleem et al. (2011) assessed the risk of AHD breaching due to overtopping and piping numerically by using HR BREACH model. They believed that the breach developed progressively in 95 hr and reached a depth of 62.11 m, and a width of 666.30 m at level of 133.89 m+msl. The resulting flood wave propagations downstream of the AHD were also simulated by applying SOBEK 1D-2D model. They stated that the first propagation wave takes about 143 hr to travel a distance of 953 km downstream the AHD. Mahdi (2007) used the National Weather Service breach model (NWS-Breach) to estimate the flood hydrograph of the Bovilla Dam due to the piping failure. This dam is an earth fill dam with 81 m high and located in in Albania, South Eastern Europe.

Assesing the risk hazards due to GERD break is depends on creating inundation maps and defining the flood depth, time arrival and flow velocity at main structure and cities downstream the dam. This paper aims to assess hazards of inundation due to GERD break on Sudan and Egypt, numerically. Many roads, hospital, airport, schools, railway, police and fire station are exepcted to be out of service due to this break. 15 milion of Sudanese live on the bank of Blue Nile River and the Nile River threatening to lose their lives and their homes. Many of Cattle heads will be losed. 600000 km² of Sudan area is expected to be inundated.

2. STUDY AREA AND DATA COLLECTION

The area bounded by the GERD and AHD is considered as the study area to estimate flood hazards due to GERD break, Fig 2. The study area is 640000 km² with 225 km as an average width along the Blue Nile and the Nile River. The area of is loctaed in Sudan and Egypt. The dams in the study area are Roseires dam, which located in Sudan with 6.8 BMC at level 490 m+msl (Shahin, 1985). The dam consists of five sluice gates with 6 m wide and 10.5 m high at an invert level of 438.5 m+msl. It is spillway was constructed using 10 radial gates with 12 m width by 10 m high at a crest level of 466.7 m+msl, (Ali, 2014). Sennar dam is located at 350 km south Khartoum city, with a storage capacity of 0.93 BMC at 420 m+msl. The dam contains eighty low level sluices with 2 m wide and 8.4 m height at an invert level 404 m+msl. It has also 112 spillways at higher level with variable wide ranged from 3 to 5 m at an invert level at 417 m+msl, (Ali, 2014). Merowe dam is located about 350 km north of Khartoum city and the operation of this dam started in 2009. The dam is about 9.2 km long.

Its reservoir has 12.4 BCM storage at level of 300 m+msl. The spillway of this dam consists of two surface gates at 280.50 m+msl and 12 low level sluices at elevation of 264 m+msl. The considered study area ended by the AHD which is located at 6.50 km south of the Aswan Old Dam (AOD) in Aswan city, Egypt. Its reservoir has a maximum capacity of 162 BCM corresponds to water level of 182 m+msl (Abdelhaleem et al. 2011).

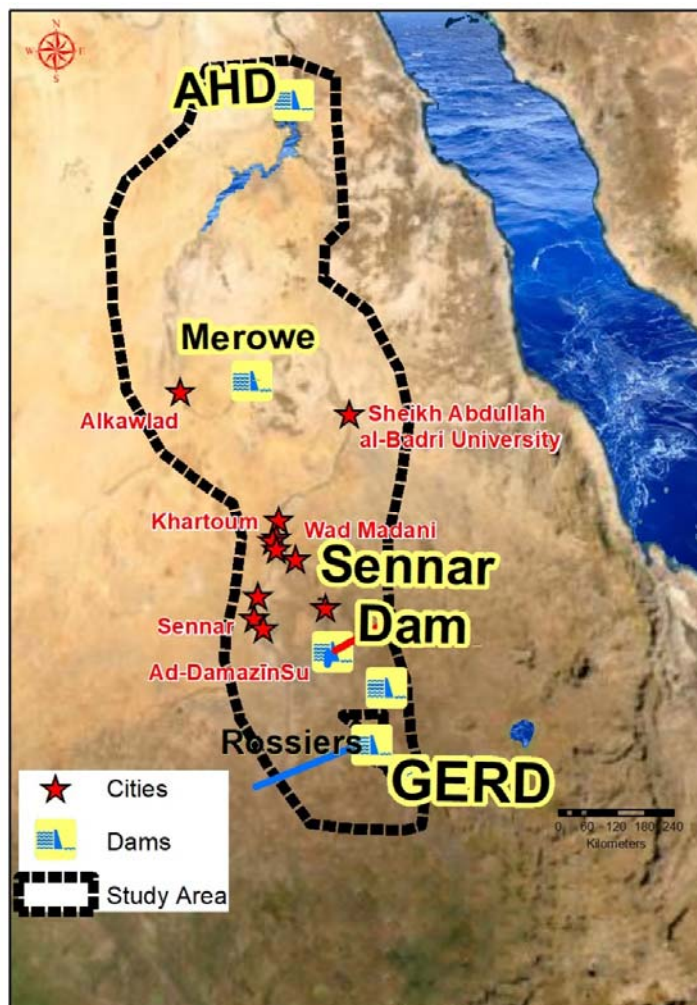


Fig. 2 Study area

The study area starts with the GERD, which is located 20 km upstream Ethiopian-Sudanans borders on the Blue Nile, as shown in Fig 3. GERD is still under construction since 2011, it consists of two dams, a main dam and a saddle dam. The main dam is a roller compacted concrete dam, with 145 m height and 1780 m length. The saddle dam is a Rock fill dam, with a bituminous surface sealing. It has 45 m height and 4800 m long. The crest level of the dam is 644 m+msl. its reservoir has 640 and 590 m+msl as a full and minimum supply level respectively. The total storage of the reservoir is 74 BCM. The reservoir storage is divide into live and dead storages as 59.22 BCM and 14.78 BCM, respectively. The reservoir area at full supply level will cover 1874 km² and 606 km² at minimum level, (Sayed et al., 2013). Based on the available information about GERD, the total power generated by dam turbine is of 6000 MW with 350 MW capacity. The GERD reservoir outflow is ranged between 3600 to 3800 m³/s, depited of the measured inflow of Rosaries reservoir, which ranged between 200 m³/s and 6500 m³/s (Tesfa, 2013).



Fig. 3 GERD location (Soliman et al., 2019)

3. SOBEK Model

SOBEK Rural-1D combined with SOBEK overland-2D were used for simulating the Blue Nile River from GERD to Khartoum and Nile River from Khartoum to AHD as 1D and the study area as 2D. Basic equations used for SOBEK Rural-1D is full Saint-Venant equations. This is based on continuity and momentum equations. Substitute friction slope in momentum equation by discharge, Chezy coefficient, section geometric properties and the Boussinesq leads momentum equation to be written as:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha_B \frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2RA} = 0 \quad (1)$$

where C = Chezy coefficient, ($L^{0.5}T^{-1}$).
 g = gravitational acceleration, (LT^{-2}).
 h = water level relative to reference level, (L).
 Q = discharge, (L^3T^{-1}).
 R = hydraulic radius, (L).
 T = time, (T).
 x = distance along the channel, (L).
 α_B = Boussinesq coefficient, (-).

The flow in SOBEK overland-2D is described by three equations as the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction. The continuity equation can be written as:

$$\frac{\partial \xi}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} \quad (2)$$

For two-dimensional flow, two momentum equations are calculated, together with the continuity equation. The momentum equations can be written as:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial \xi}{\partial x} + g \frac{u|v|}{c^2h} + au|u| = 0 \quad (3)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial \xi}{\partial y} + g \frac{v|v|}{c^2 h} + av|v| = 0 \tag{4}$$

where: u = velocity in x-direction, (LT⁻¹)
 v = velocity in y-direction, (LT⁻¹)
 V = velocity = $(u^2+v^2)^{0.5}$. (LT⁻¹)
 ζ = water level above plane of reference, (L)
 d = depth below plane of reference, (L)
 h = total water depth = $\zeta + d$, (L)

These equations are solved numerically using the Delft-scheme. This scheme solves the De Saint-Venant equations a staggered grid. In this staggered grid the water levels are defined at the connection nodes and calculation points, while the discharges are defined at the intermediate reaches or reach segments.

4. STUDY METHODOLOGY

The hazards due to GERD break on Sudan and Egypt are investigated through a procedure as depicts in Fig 4. To start this study, its required to collect a various forms of data, such as, cross sections along the Blue Nile River and the Nile River, and 30-m Digital Elevation Model, DEM were created. Discharge and water levels were collected at various gauge stations and at the main structures along the study area. After data collection, 1D numerical model is developed and calibrated. Suitable DEM used as grid to couple the 1D with 2D model. Time step and simulation period is selected to process the model. The output results are presented in table, chart and maps.

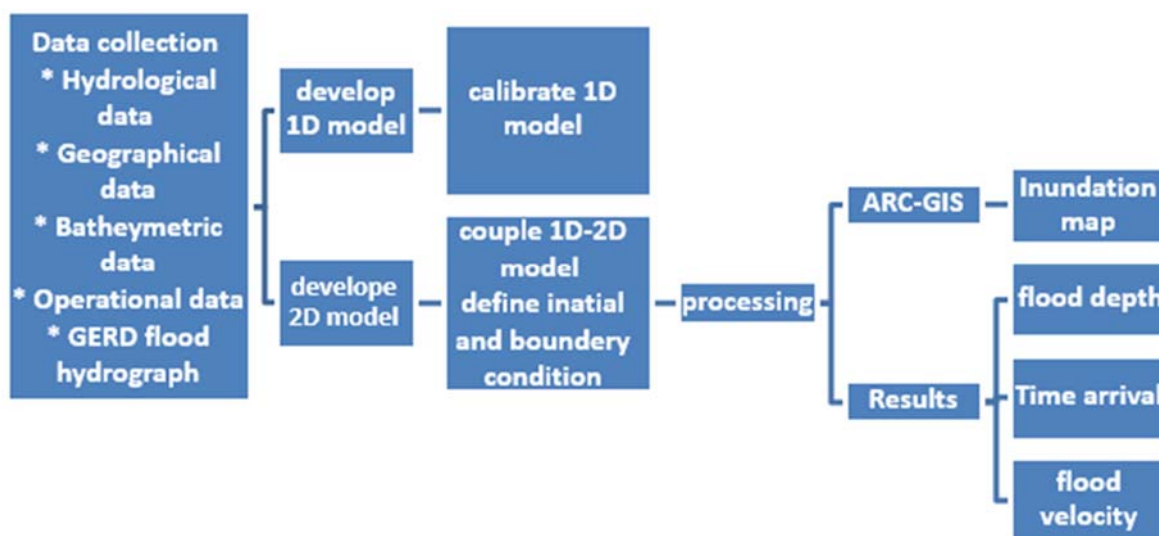


Fig 4 Study methodology

5. MODEL SCHEMATIZATION

The study reach described by 480 cross sections, calculation nodes. the inflow points is used to simulate White Nile and Atbra River, and structure points is used to define Roseires, Sennar and Merowe dams. Also, boundary and inital piont is used to defin the inital and boundary condition. The model schematization is shown in Fig 5.

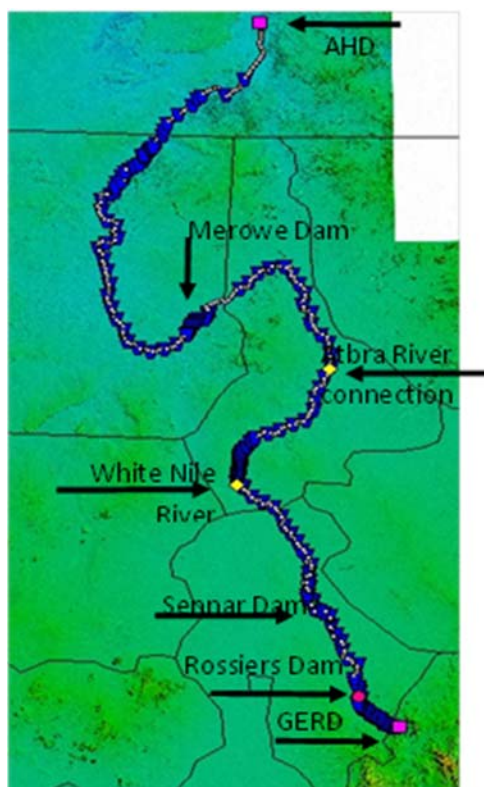


Fig 5 Model schematization

6. CALIBRATION MODEL

Calibrations of the 1D model done based on field measurements of dam reservoirs inflows, outflow, water levels upstream and downstream dams. The calibration were performed by comparing the simulation results with those measured values at the main dam (various gauge stations at study area were recorded). Several model runs were made to achieve the best agreement between measured and computed values from the model. This was carried out by adjusting the roughness coefficients at various locations along the modeled reaches. The opening of Roseires, Sennar River and Merowe dams and the inflow of White Nile and the Atbra River were considered during calibration process.

The comparison between the computed water level and the measured ones is shown in Fig 6, a good agreement between them is observed.

The measured upstream and downstream water levels at Rossiers dam at the third of August 2010 were 469 and 449 m+msl, respectively, and the corresponding simulated water levels upstream and downstream Rossiers dam were 468.6 and 448.3 m+msl, respectively. The difference between the upstream measured and computed water levels were about 0.40 m, for the downstream was 0.70 m. The measured upstream and downstream water level of Sennar dam at the third of August 2010 were 417 and 411 m+msl, respectively. The corresponding computed water levels upstream and downstream Sennar dam were 417 and 410 m+msl. The difference between the upstream measured and the computed water levels were about 0.00 m, for the downstream is 1.00 m. The measured upstream and downstream water levels of Merowe dam at the first of September 2010 were 292 and 252.5 m+msl, respectively. The corresponding simulated water levels upstream and downstream Merowe dam were 292 and 260 m+msl, respectively. The difference between the upstream measured and the computed water levels were about 0.00 m, for the downstream was 7.50 m. The measured upstream water level of AHD at the second of September 2010 were 175 m+msl. the corresponding simulated water levels upstream AHD was 174.8. The difference between the upstream measured and the computed water levels were about 0.20 m. the abovementioned comparison between measured and computed water levels reveal that the numerical model simulates the studied reach well.

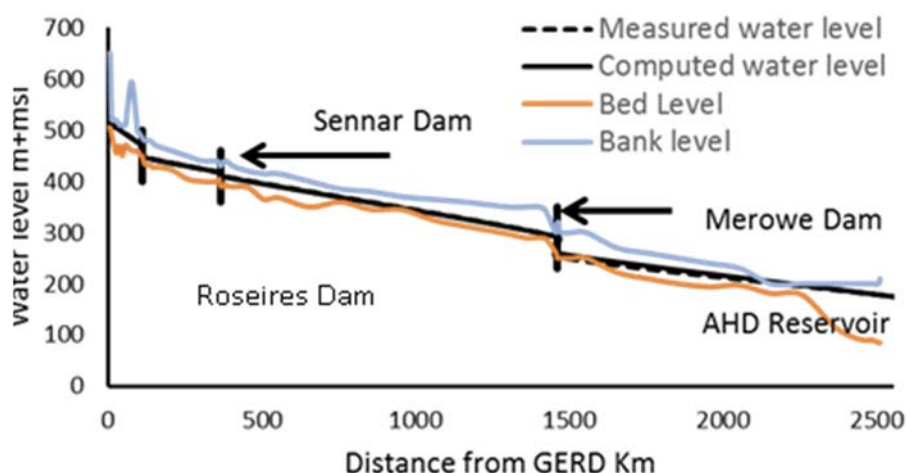


Fig 6 Model calibration

7. INITIAL and BOUNDARY CONDITION

Idress et al. (2018) developed 15 scenarios for the flood hydrograph due to GERD break. The worst flood hydrograph take place in case of 5 hours full formation time. This scenario is selected in this study as an initial condition for the model, Fig 7. Upstream water level of the AHD was considered as downstream boundary condition (174 m+msl). Simulation time is 120 days discretized into a day as incremental time steps. White Nile and Atbara are simulated in this model as lateral inflow to the model with constant discharges as 1000 m³/s and 1530 m³/s, respectively.

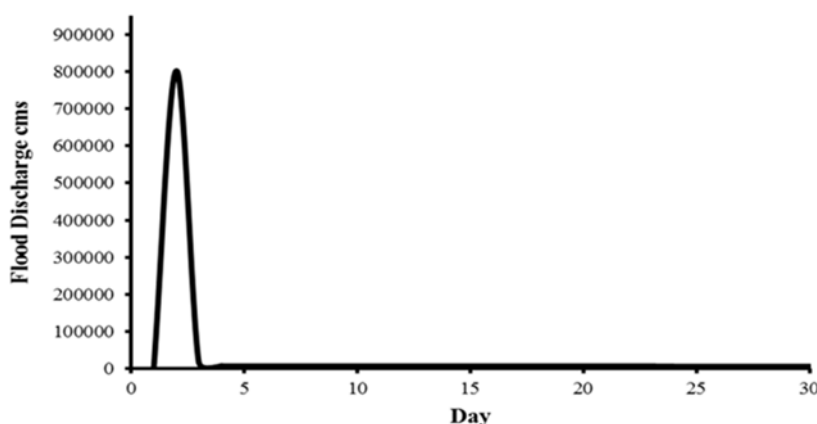


Fig 7 Flood hydrograph due GERD break just D.S. Dam, (Idress et al., 2018)

8. SIMULATION ASSUMPTIONS

The debris presented in the GERD, Rosaries, Sennar and Merowe dams that may obstruct the vents during the passage of the flood wave, are assumed absent. All the gates of dam were opened when the flood wave reaches them. Erosion did not take place during the simulations. The lateral flow-off from White Nile and Atbara River worked with their maximum capacity during the flood.

9. RESULTS AND DISCUSSION

The hypothetical break of GERD caused huge damage along the Blue Nile and the Nile River from Khartoum to AHD. The Rossiers dam flow in operation case is ranged from 8000 to 5000 m³/s and maximum upstream measured water level was 470 m+msl. The GERD break

flood increased the inflow to 54000 m³/s as a peak value and, the water level at upstream Rossiers Dam to 498 m+msl with 28 m over the maximum operation level. The Sennar Dam maximum inflow is between 9900 to 6000 m³/sec with maximum upstream measured water level of 420 m+msl. GERD break increased the inflow to Sennar Reservoir to be 40000 m³/s and upstream water level to 435 m+msl as a peak value. The GERD break flood increased the water level at the Merowe Dam to 281 m+msl as a peak water stage while the operational stage is 270 m+msl. The AHD Reservoir inflow increases to 42000 m³/s after 26 day from start GERD break. Many cities in Sudan faces a catastrophic effect due to GERD break as shown in Fig 8 and tabulated in Table 1. ARC-GIS software was employed to develop inundation maps for the study area as shown in Fig(s) 9, 10, 11 and 12.



Fig 8 Main Sudan cities along study area

Table 1 Flood depth and time arrival due GERD

Name	distance from GERD (Km.)	lag time (day)	initial water level (m+msl)	peak water level (m+msl)	flooded depth (m)
Rossiers	110	1	468.5015	498.0259	29.5244
Galgani	200	1	423.8505	465.6467	41.7962
Barankwah	250	1	417.5677	457.2323	39.6646
Sennar	430	2	413.3019	434.2141	20.9122
Hajj Abd allah	500	3	402.9133	425.8674	22.9541
Wadi Madani	595	4	387.8125	414.8963	27.0838
Ruffa	650	4	380.2402	405.493	25.2528
Wadi Rawah	702	6	378.2999	394.775	16.4751
Khartoum	751	6	378.4842	395.199	16.7148
totti		6	377.4325	394.08	16.6475
Khartoum	800	6	378.1312	394.3866	16.2554
Abd alkader	851	7	372.8307	386.6921	13.8614
Attbra	1100	11	343.8707	360.1598	16.2891
Merowe dam	1550	16	272.8236	281.0992	8.2756
Merowe	1600	17	252.162	267.0162	14.8542
Dongola	1848	21	215.5586	232.8488	17.2902
AHD		26	174.8004	174.8058	0.0054

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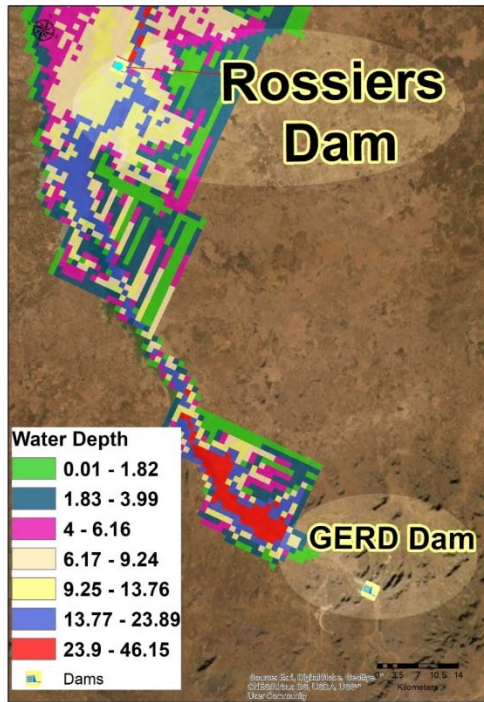


Fig 9 Inundation map from GERD to Rossieres dam

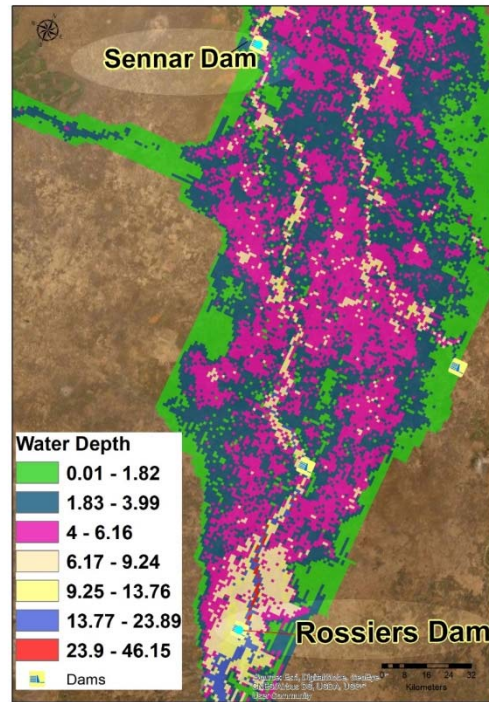


Fig 10 Inundation map from Rossieres Dam to Senar dam

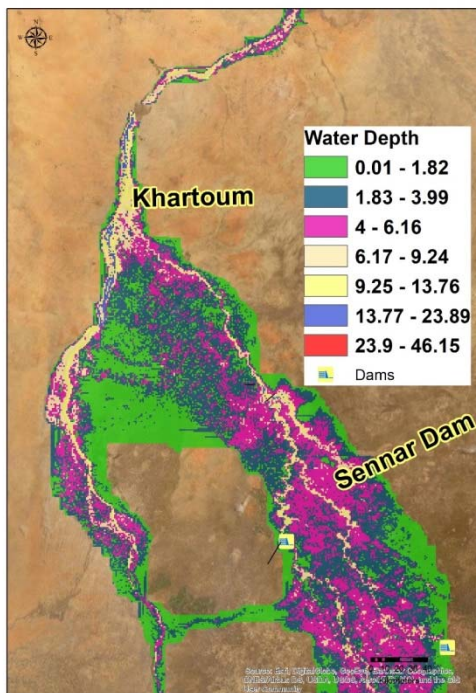


Fig 11 Inundation map from Khartoum to Merowe dam city

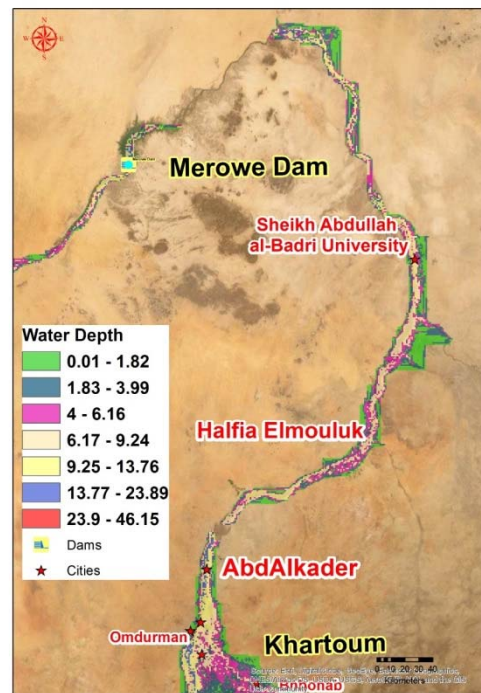


Fig 12 Inundation map from Senar dam to Khartoum city

10. CONCLUSIONS

GERD break simulation revealed that the average hourly peak outflow is about approximately 2300000 m³/s within 5 hr from the beginning of GERD break. In addition, the average daily peak inflow at the entrance of Lake Nasser approaches 42000 m³/s after 26 days from the beginning of GERD break. The inflow to Lake Nasser is about three times of the maximum inflow at wet seasons (maximum recorded peak inflow at wet season was about 13000 m³/s). So, it may be harmful to the AHD without precaution measures like lowering the crest level of touda spillway, and this needs more investigations. Also, the numerical results showed that Rosaries, Sennar, and Merowe dams are covered by GERD break flood. Moreover, Al Khartoum city is flooded by a water depth of about 17 m above the land level. The GERD break floodwater is arrived Al Khartoum city within 6 days from the beginning of dam break. So that, many infrastructures in Sudan like universities, roads, railways, hospitals, airports, schools, farms and factories, etc. are faced catastrophic destruction due to GERD break.

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