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Potential impacts of failure of the Grand Ethiopian Renaissance Dam on downstream countries

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Abstract

This study assesses the potential downstream impacts in the event of a flood due to failure, either structural or operational, of the Grand Ethiopian renaissance dam (GERD). The following two failure scenarios were modeled as part of this study: Dam Break (DB) and MisGuided Dam Operation (MGDO) as a result of a false flood signature. The DB scenario shows that 40% of the intensively cultivated Gezira Plain would be inundated with average water depths of more than 10 m, resulting in catastrophic loss of highly productive farmlands, livestock, inhabitants, and infrastructure. This scenario did not model damage further downstream since for this magnitude flood it will require another flood routing model given the more complex geometry downstream of the Gezira Plain. In the MGDO scenario flood flows are lower and would have no impact on the Gezira Plain but would reach the High Aswan Dam (HAD) and fill it to its maximum allowable capacity for two and a half months and it would require emergency releases for more than 5 months. The required emergency releases from the HAD are expected to create significant flooding downstream. To accommodate the potential of extra releases from the GERD during flood events the operational rules for the HAD should be modified. However, providing more flood buffer at the HAD will limit the live capacity that is currently used for securing downstream flow requirements during drought periods. One of the expected impacts of increasing the flood buffer would be a reduction of the HAD's contribution to Egypt's GDP. Based on the results of this study the operational rules for the GERD and the HAD should be evaluated and possibly modified.

KEYWORDS

Dam Break, flood management, Grand Ethiopian Renaissance Dam, High Aswan Dam, reservoir operation

1 | INTRODUCTION

Contrary to popular belief, dams built across major waterways are not always as safe and reliable as they might be portrayed. In 1995, the International Commission of Large Dams published an investigation of several worldwide surveys, in the process, collecting the largest amount of information available on dam accidents and/or incidents found anywhere. This data compared numbers of existing and failed dams according to their specific category (ICOLD, 1995). The main finding of the study was that most dam failures involve newly built dams. The greatest proportion of dam failures occurs in the first 10 years of operation (70%), and more specifically within the first year after complete filling. According to a survey by Johnson and Illes (1976), out of 114 dam breaks worldwide, 44 dams broke during the first time they released water, 43 dams broke due to overtopping and 27 dam breaks occurred during normal operation. Among 109 large dam breaks reported worldwide until 1979 (except in China), 58 dam breaks occurred during the first 5 years of their service life (Goubet, 1979).

Shahraki et al. (2012) published a Dam Break (DB) study covering a 25-year period where 36 earth dam breaks took place. Twenty dam failures were due to overtopping, 13 were due to eroded embankments and three were due to earthquakes. Moreover, two gravity dam breaks occurred (one a concrete dam and another a masonry dam). That study also indicated that more than 60% of an accumulated 111,000 deaths caused by dam breaks globally (except in China) resulted from just three dam breaks. Those were: (1) the 1963 Vaionet Dam in Italy (overtopping of a side arch concrete dam); (2) the 1979 Machhu II Dam in India (onrush of unanticipated heavy flow); and (3) the 1989 Johnstown Dam in Pennsylvania (overtopping of an earth dam). Interestingly, results from the 1975 Banqiao Dam failure in Henan Province, China were unpublished until 1998 (Yi, 1998). The actual facts of this DB remain controversial, however it is by far the largest, most catastrophic DB known, causing at least 26,000 deaths and displacing 10 million individuals who were left to suffer from famine and disease (He et al., 2008; Zhong et al., 2018). Other estimates of the damage due to this DB are up to 230,000 total deaths and nearly 6 million buildings heavily damaged or destroyed (Graham, 2010). The cause of this DB is alleged to be excessive rainfall rather than poor engineering, construction, and mismanagement, however neither has been proven (Xu et al., 2008; Yap et al., 2015; Yi, 1998).

According to Rico, Benito, and Diez-Herrero (2008); Rico, Benito, Salgueiro, et al. (2008) the key factors of tailing dams' failure are: earthquakes, unusual climatic conditions, differential settlement, seepage, overtopping, dam structure deterioration, rockslides, improper construction, and sabotage. Nevertheless, these can be considered as general key factors of dams' failure, regardless of dam type or function. It should be noted that overtopping that leads to dam breach failure is typically attributed to unusual climatic conditions and wrong operation (mismanagement). It is clear that even though the probability of a dam failure can be considered as low, its occurrence definitely results in catastrophic consequences downstream including major loss of life, property, and natural resources (Kho et al., 2009).

The Grand Ethiopian Renaissance Dam (GERD) is built in an active seismic zone. Over 15,000 tremors have been documented near major rifts in Ethiopia and the Horn of Africa (Abebe et al., 2010; Gouin, 1979; Kinde et al., 2011). During the 20th century, at least 11 of these earthquakes were recorded at a magnitude of 6.2 and higher in the Richter scale, causing significant damage in this seismic hot spot (Kebede & van Eck, 1997). This is a concern that remains consistently unaddressed relative to the GERD, although the immediate area of the dam is cross cut by a widespread system of faults and stress fractures (Abbate et al., 2015; Kazmin et al., 1978).

The construction of the GERD started in April 2011 at an estimated cost of $4.8 billion US dollars (IPoE, 2013). The dam is located on the Blue Nile near Guba, 45 km from the Sudanese border and near the confluence of three troublesome major tectonic plates (Gouin, 1979). The main purpose of the dam has been reported to be power production. It will become one of the largest dams in the world. The massive project consists of a roller compacted concrete dam, two powerhouses, a gated spillway and a rock-fill saddle dam (Tesfa, 2013). The dam itself has a length of 1780 m and a height of 145 m. When filled to its full operational level the reservoir will cover an area of 1850 km^2 with a storage volume of 74 billion cubic meters (BCM; Kahsay et al., 2015). This makes it one of the largest volumes of stored water on the African continent.

The GERD will become one of the largest dams in Africa. Building it has raised potential conflicts among east Nile basin countries (Jeffers et al., 2015). A dam with such capacity requires substantial planning, however, no policy dictating construction, reservoir design, initial filling rate, or operational strategy has been publicly issued or approved (IPoE, 2013). Even if the GERD impounds water only if "streamflow exceeds the long-term historical average," it will have the effect of reducing by 7% the flow at Lake Nasser (High Aswan Dam) over a 5 year period with a larger than expected variance (Zhang et al., 2015). Taye et al. (2016) raised the question: "The

Grand Ethiopian Renaissance Dam: Source of Cooperation or Contention?" especially since the GERD has been criticized for potentially jeopardizing downstream water security and livelihoods through upstream unilateral decision making. Clearly, there is a pressing need for Ethiopia, Egypt, and Sudan to agree on rules for filling the GERD reservoir and on operational rules particularly during periods of drought (Whittington et al., 2014). There is also a need for operating rules during periods of flood. Cooperation and agreement on "no-harm" operational rules during filling, drought, and floods would be a challenge that could benefit all three countries (Wua et al., 2016). An economic study by Kahsay et al. (2015) showed that operational rules for filling the GERD that consider only Ethiopian benefits could easily result in economic losses for Egypt. Their results show that if the GERD impounds water in a dry sequence of years, it could cost Egypt between $137 and $401 million USD in its GDP depending on the amount of water withdrawn in Sudan.

A number of researchers have investigated the impacts of the GERD construction on the downstream countries, from an environmental and water use perspective. However, there have been no studies on possible impacts of GERD releases due to a False Flood Signature which, as shown in this study, has the potential for devastating downstream consequences. In addition, there have been very few studies of the impact of a GERD break on the downstream area. Soliman et al. (2014) utilized Hydrologic Engineering Center River Analysis System (HEC-RAS) to assess the effect of a GERD break on Sudan especially on the Roseires, Sennar, and Merowe Dams and Khartoum city. Regardless of scarce physical parameter data as well as lack of detailed topographic data including land use they stretched their study area to the High Aswan Dam (which is 2760 km downstream of the GERD). The breach parameters selected for their study, along with the constant friction coefficient assumption for lengthy river reaches, the authors believe resulted in an exaggerated impact assessment.

The purpose of this study is to evaluate the impact on Sudan and Egypt of floods that could be created by the potential failure of the GERD. Two flood scenarios were analyzed: (i) a flood due to a DB; and (ii) a flood due to the MisGuided Dam Operation (MGDO) as a result of a false flood signature. The first scenario models a flood wave generated by a structural failure of the dam. While the second scenario simulates a flood hydrograph triggered by a false hydrologic signature that could mislead the GERD operators into unnecessarily releasing some of its storage in addition to all naturally arriving water (natural flow at the Deim Station).

2 | STUDY AREA AND EXISTING RESERVOIRS

The study area covers the water course from the GERD in Ethiopia to the HAD in Egypt, including three existing dams: Roseires, Sennar, and Merowe (in Sudan) as well as the Gezira Irrigation Scheme, all shown in Figure 1. The GERD was designed to have an active storage capacity of 74 BCM at a height of 145 m, thus acting as a multi-annual regulating reservoir. The reported main purpose of the dam (with an installed hydropower capacity of 6000 megawatts) is to generate on average 5 TWH/year of electricity to cover the energy demand of Ethiopia as well as part of East Africa (Arjoon et al., 2014).

The first dam downstream of the GERD is the Roseires Dam, located in Sudan, which is a concrete filled dam built in 1966 and located 550 km upstream of Khartoum and 120 km downstream of the GERD. This dam had an initial storage capacity of 3 BCM and in 2013 the dam was raised to 78 m and this expanded the reservoir capacity to 7.4 BCM (Hassaballah et al., 2012; Shahin, 2003). The second dam is the Sennar Dam across the Blue Nile, located 300 km south of Khartoum. This dam was built in 1929 making it the oldest rock-fill dam in Sudan. It is about 3 km in length and 40 m in height. At its maximum height, it has a capacity of 0.39 BCM which forms a 5 km long lake (Shahin, 2003). It should be noted that this reservoir is also the major source for irrigation water for the massive Gezira Scheme (additional details given below). The third dam is the Merowe Dam which is located about 350 km north of Khartoum on the main Nile. This dam was built in 2009 creating a reservoir with a storage capacity of 12.4 BCM. Its main purpose is power production (Merowe Dam Project Implementation Unit, 2008). It consists of two concrete-faced rock-fill dams on each river bank. The dam has a length of about 9 km and a crest height of 67 m. The reservoir extends for 174 km upstream (McDonald et al., 2009). It is important to point out that the Sudanese reservoirs are designed to accommodate annual, changing priorities of water demand (Hassaballah et al., 2012; Merowe Dam Project Implementation Unit, 2008; Shahin, 2003).

The Gezira Scheme in Sudan is located downstream from the GERD (Figure 1) and is one of the largest irrigation projects in the world. The area of the Geizira Scheme is 8800 km^2, lying in the flat central plains of Sudan between the Blue and White Niles south of Khartoum and north of Sennar (Hussein & El Daw, 1989). The area is intensely farmed and has an estimated population of 3.6 million (Central Bureau of Statistics, 2008). The population density of the Gezira Scheme ranges from 200 to 1000 per km^2.

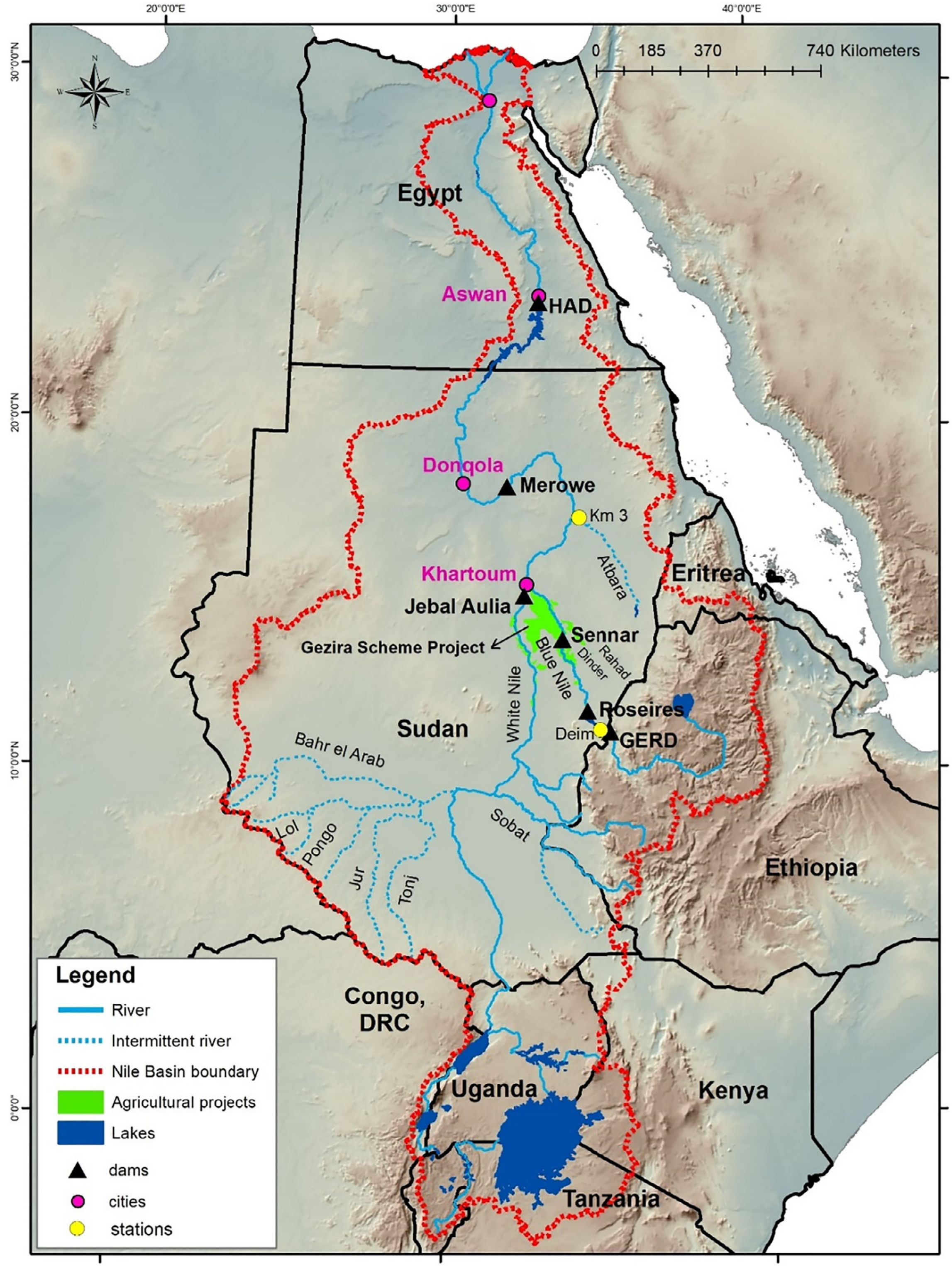

FIGURE 1 Topographic map of the study area

The HAD was built across the Nile River at Aswan, Egypt in 1971. It controls floods, provides water for irrigation and generates hydropower which is critical to many industrial facilities in Upper Egypt. The dam is a 3.83 km long embankment dam with a crest height of 111 m. The HAD's reservoir, named Lake Nasser, is 550 km long with a surface area of 5250 km^2 and a total storage capacity of 162 BCM (Abu-Atta, 1978). The emergency Toshka spillway was built in 1982. The Toshka Canal links Lake Nasser reservoir with the Toshka Depressions

(MWRI, 2003). An economic study by Strzepek et al. (2008) showed that the HAD contributed between 7.1 and 10.3 billion Egyptian pounds annually to the Egyptian economy which was equivalent to 2.7%–4.0% of Egypt's 1997 GDP.

3 | MODELING THE DB SCENARIO

The US National Weather Service has developed a simplified model for predicting downstream flooding due to a significant dam failure. This model, known as the SiMPlified Dam BreaK (SMPDBK) flood forecasting model, produces information needed for delineating areas endangered by near to complete dam-break flood waters. In this study, the SMPDBK was utilized to analyze a hypothetical case of a major DB of the GERD.

The original SMPDBK model was developed in 1983 (Wetmore & Fread, 1983) and it was revised in 1991 (Wetmore & Fread, 1991). SMPDBK can be used to determine the depth of inundation downstream of a dam failure. Combining the SMPDBK results with floodplain delineation allows for the generation of maps showing the extent of flooding resulting from a major dam break. Wetmore and Fread (1991) demonstrated that in many cases the average difference between the peak flow calculated with the DAM BReaK model (DAMBRK; Fread, 1984) and that calculated with the SMPDBK model is 10% or less. A comparative study evaluating a number of dam-breach flood wave models (DAMBRK, FLOW SIM 1, FLOW SIM 2, HEC-1, SMPDBK, TR 66, and the HEC dimensionless graph procedure) concluded that the DAMBRK and SMPDBK were the optimal models for adoption by the Military Hydrology Program of the U.S. (Wurbs, 1986). This conclusion was reached after an extensive comparative evaluation of these DB models with five different case studies representing different configurations some of which are similar to our case study. HEC-RAS, the hydraulic model that the National Weather Service has transitioned to using (Moreda et al., 2009), has been tested for simulating the flood wave for a near to complete DB compared to SMPDBK (Reed & Halgren, 2011). The study found that:

- SMPDBK offers a guaranteed numerical stability while HEC-RAS will likely require cross-section interpolation and time step adjustments to produce a stable run.
- SMPDBK requires fewer cross-sections.
- SMPDBK does not require definition of bank stations.
- SMPDBK does not require defining explicit upstream and downstream boundary conditions.

The SMPDBK model routes the outflow hydrograph by approximating the downstream channel as a prism. This includes the effects of the off-channel (dead) storage where appropriate. It takes into consideration only the peak flows, maximum water surface elevations, and travel times by utilizing dimensionless peak-flow routing graphs that were developed using the DAMBRK model. The applicability of the SMPDBK model is further enhanced by its minimal data requirements.

The SMPDBK model uses the following three steps (Wetmore & Fread, 1983):

1. Calculation of the peak outflow, due to the dam break, using the temporal and geometrical description of the breach and the reservoir volume;
2. Approximation of the channel downstream of the dam as a prismatic channel; and
3. Calculation of the dimensionless peak-flow routing parameters, later used with families of dimensionless routing curves to determine the peak flow at specified cross sections downstream of the dam.

4 | MODELING THE MGDOSCENARIO AS A RESULT OF A FALSE FLOOD SIGNATURE

Manmade floods can be caused by numerous deceiving hydrologic conditions early in the flood season. Typically, the Blue Nile flood is highly irregular and starts in July with a small flood volume, and ends by October. If the July flows are more than one third of the average of annual yield, there is a high probability that the annual yield of the Blue Nile will be high. In some years, the hydrologic flood pattern could be deceiving, where an early false high flood signature (high flows in July) may be detected in the beginning of the season though the annual yields turns to be average. Usually the dam operators are not able to accurately estimate the total yield of the flood season until October. Early false flood signatures may deceive GERD operators to unnecessarily release some of its storage in addition to all naturally arriving water (natural flow at the Deim Station) under the expectation of a flood occurring later in the season which does not actually occur. Two scenarios were derived from historical hydrologic records to demonstrate the potential impacts of a misguided GERD operation.

The Dongola gauge is considered to be the station that records water volumes arriving into the HAD reservoir (AREMoD, 1980). Its records show that the maximum daily inflow to the HAD was 1.31 BCM/day in 1998 (MWRI, 2013b). Figure 2 shows the monthly maximum, minimum, and average inflows to the HAD between

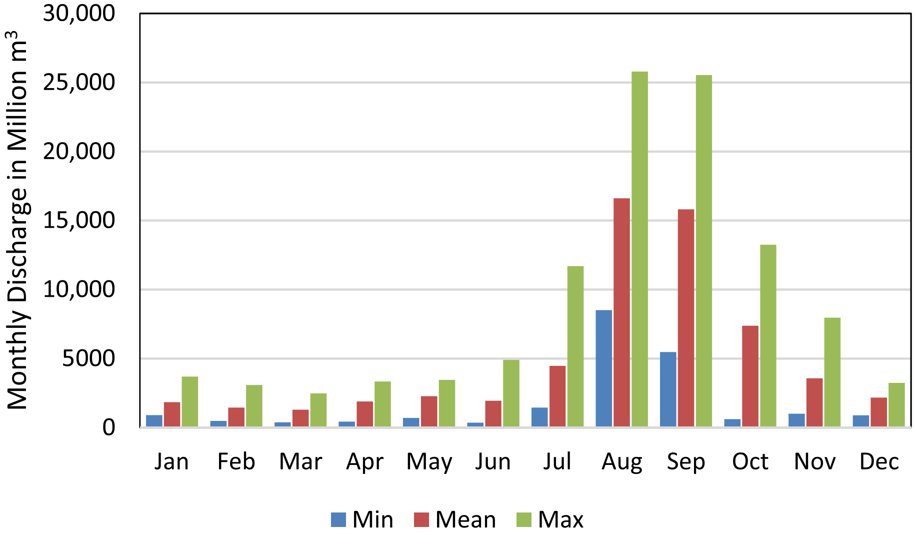

FIGURE 2 Monthly maximum, minimum, and average inflows to the High Aswan Dam (1968–2012)

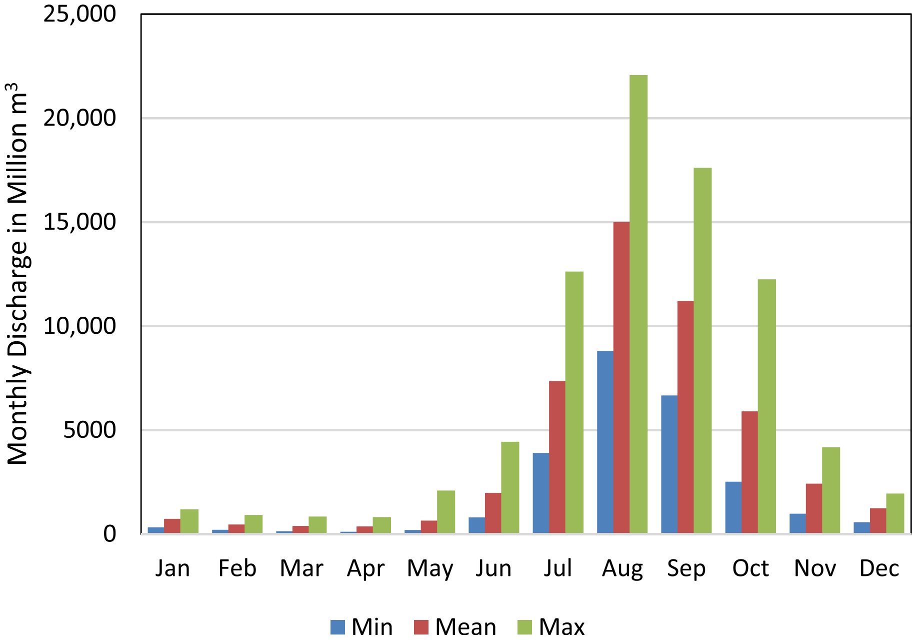

FIGURE 3 Monthly maximum, minimum and average inflows at El Deim gauge (1965–2012)

1968 and 2012. Different water sources contribute to the flow at the Dongola gauge. The largest share of water comes from the Blue Nile, along with lesser contributions from the White Nile and Atbara rivers. Gauge measurements for these three inflow sources are the gauging stations named "El Diem" (downstream of GERD), downstream of "Jebel Aulia Dam," and "Atbara km 3," respectively (Figure 1). Average annual flows for each of these gauges are 47.7, 25.7, and 11.5 BCM, respectively (MWRI, 2013b) and are shown in Figures 3–5. Figure 3 shows the monthly maximum, minimum, and average flows for the period between 1965 and 2012 at the El Diem gauge with sharp flood peaks during the critical period from June to October. Figure 4 shows the normal flows for the White Nile river downstream of the Jebel Aulia Dam between 1944 and 2012. The graph shows no sharp peaks compared with the Blue Nile river at the El Diem gauge. By contrast, as illustrated in Figure 5, the Atbara river (averaged between 1903 and 2012) receives flows only in August and September (maximum flows occur in August). The maximum daily discharge measured at the El Diem gauge was 1.01 BCM/day in 1985 (MWRI, 2013b). Frequency analysis of the El Diem's gauge flows (inflow to the GERD) is shown in Figure 6. It indicates that over a 46 year period, floods have exceeded the 47.7 BCM/year (average Blue Nile river flow) 21 times, reaching a maximum flow of 68.4 BCM in 1998.

As part of this study a flood generation model was developed to estimate the maximum flood that could reach the HAD. The model uses the historical inflow

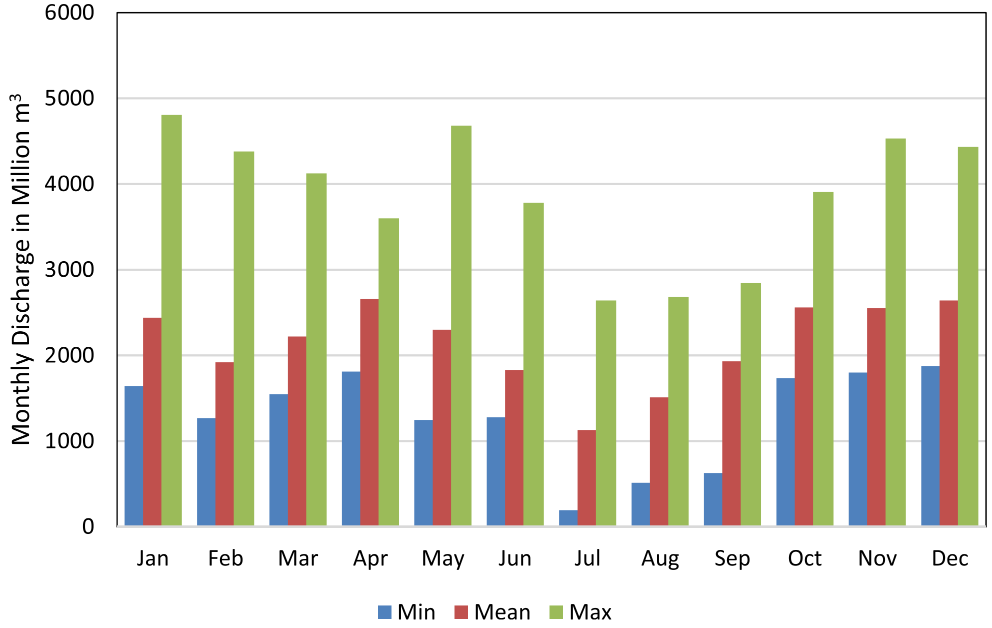

FIGURE 4 Monthly maximum, minimum, and average flows downstream of the Jebel Aulia Dam (1944–2012)

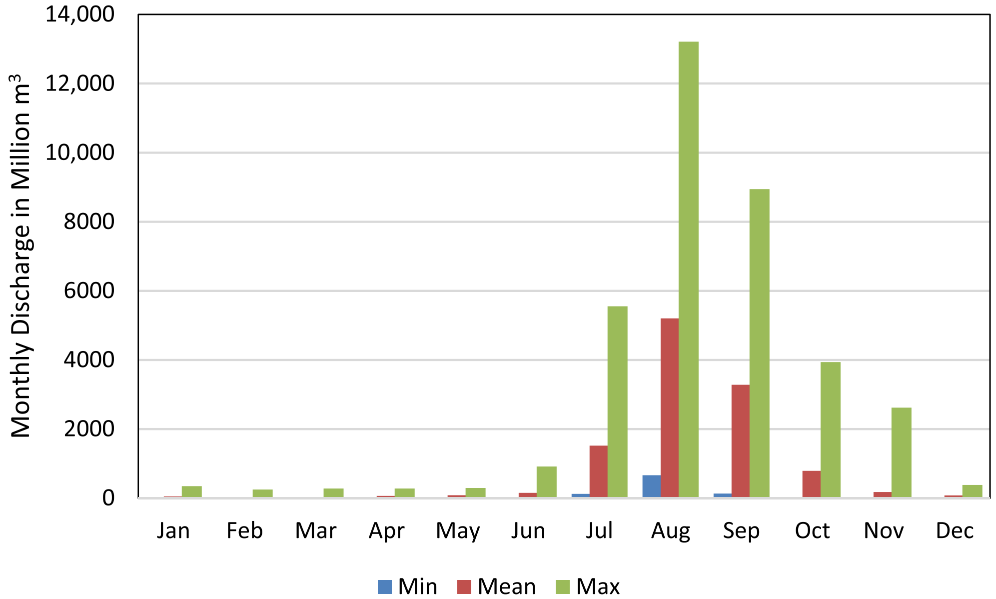

FIGURE 5 Monthly maximum, minimum and average flows at the Atbara river (1903–2012)

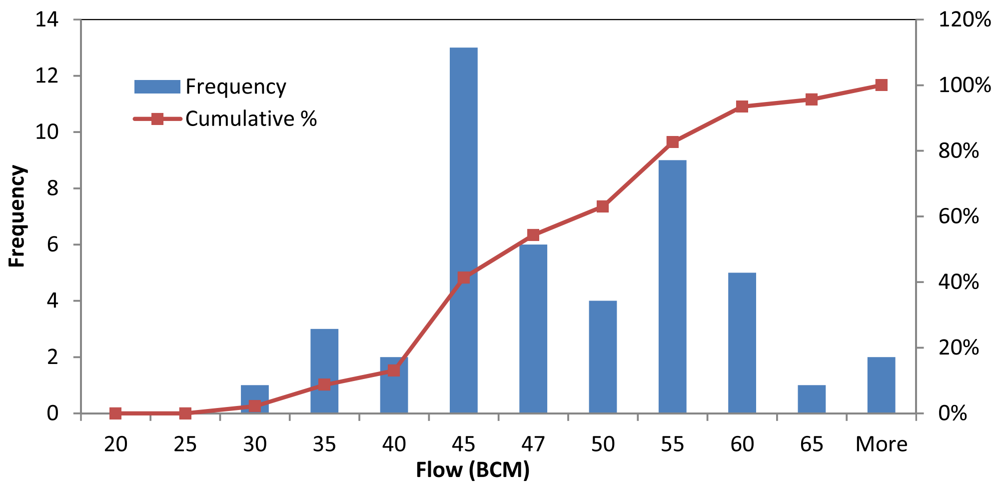

FIGURE 6 Frequency analysis of El Diem's gauging station flows (inflow to the Grand Ethiopian Renaissance Dam)

records to the HAD plus the added flood flows from the GERD. The model formulation is as follows:

$$Max \sum_{t=1}^{t=T} QD_t \tag{1}$$

$$QD_t = QDH_t + QG_{t-l_1} - LGD_{t-l_1} \forall t \tag{2}$$

$$\sum_{t=1}^{t=T} QG_t \le S_{t=1} \tag{3}$$

$$QG_t \le QGMax \ \forall t \tag{4}$$

$$QWH_t + QBH_{t-l_2} + QG_{t-l_2} - LB_{t-l_2} \le CCDK \ \forall t \tag{5}$$

$$QAH_t + QWH_{t-l_3} + QBH_{t-(l_2+l_3)} + QG_{t-(l_2+l_3)} - LB_{t-l_2} - LKA_{t-l_3} \le CCDA \ \forall t \tag{6}$$

Where:

- $CCDA$ = maximum channel capacity (m^3/day) downstream of the "Atbara km 3" gauge;
- $CCDK$ = maximum channel capacity (m^3/day) downstream of Khartoum (the confluence of the Blue and White Nile rivers);
- l_1 = lag time for maximum flow between the GERD and the Dongola gauge (Ismail and El-Moattessm, 2006);
- l_2 = lag time for the maximum flow between the GERD and downstream of Khartoum (Ismail and El-Moattessm, 2006);
- l_3 = lag time for the maximum flow between Khartoum and downstream of the "Atbara km 3" gauge (Ismail and El-Moattessm, 2006);
- LGD_{t-l1} = losses (m^3/day) from the outflow from the GERD in the reach between the GERD and the Dongola gauge at time $t - l_1$;
- LB_{t-l2} = losses (m^3/day) from the total outflow from the GERD and the historical flow recorded at the El Deim gauge in the reach between the GERD and Khartoum at time $t - l_2$;
- LKA_{t-l3} = losses (m^3/day) from the total outflow from the GERD, historical flow recorded at the El Deim gauge, and White Nile river flow measured downstream of the "Jabal Al Awlia" dam, in the reach between Khartoum to downstream of the "Atbara km 3" gauge at time $t - l_3$;
- QAH_t = historical discharge (m^3/day) from the Atbara river measured at the "Atbara km 3" gauge at time t;
- QBH_{t-l2} = historical discharge (m^3/day) from the Blue Nile river measured at the El Deim gauge at time $t - l_2$;

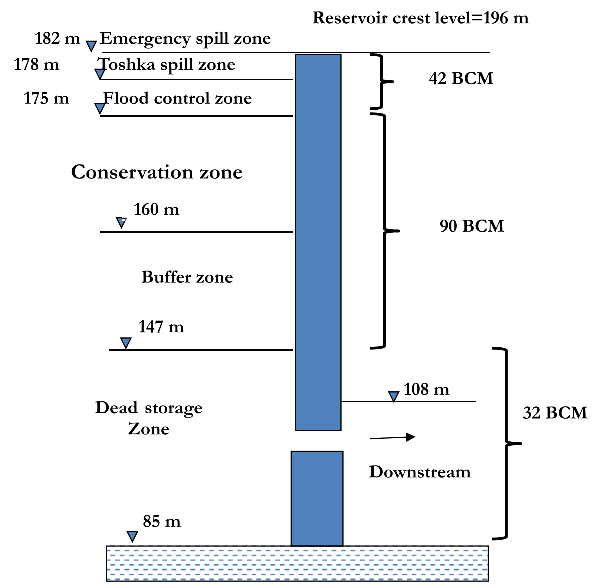

FIGURE 7 High Aswan Dam (HAD) operation zones

- QD_t = discharge (m^3/day) at the Dongola gauge at time t;
- QDH_t = historical discharge (m^3/day) at the Dongola gauge at time t;
- QG_t = GERD releases (m^3/day) at time t;
- $QGMax$ = GERD maximum allowable discharge (m^3/day);
- QWH_{t-l3} = historical discharge (m^3/day) from the White Nile river measured downstream of the "Jabal Al Awlia" dam at time $t - l_3$;
- $S_{t=1}$ = GERD live storage (m^3) at $t = 1$;
- T = simulation period (days).

Although the HAD has been in operation since 1970, its reservoir was not completely filled until 1976. The main operational rule adopted by the Ministry of Irrigation in Egypt is to release the quota assigned to Egypt each average runoff year, and to release more water in years with high floods (Shahin, 1985). At any rate of inflow, on August 1st of each year the reservoir level should not exceed 175 m above mean sea level (AMSL), in order to accommodate a potential flood (Abu-Atta, 1978). The operational policy of the reservoir is based on dividing the lake storage into four zones, as shown in Figure 7 (Abu-Atta, 1978). The "dead storage zone" has a top elevation of 147 m AMSL with a total volume of about 31 BCM. Its main purpose is to store sediments entering the reservoir during the flood period. In this zone, the operational rule is to release no water, regardless of the downstream requirements. The "live storage zone," which amounts to 90 BCM, lies between the elevations of 147 and 175 m AMSL. Within this zone, the dam operators make their releases to meet ever changing downstream requirements. The "flood storage zone," which is equal to 41 BCM, lies between the elevations of 175 and 182 m AMSL. This zone is subdivided into a "flood buffer zone" and a "flood control zone." The level of 178 m AMSL separates the "flood buffer zone" from the "flood control zone," the point at which any accumulated volume has to be released.

The HAD has a free spillway referred to as Toshka which was constructed 250 km upstream of the dam. It is designed to have a crest elevation of 178 m AMSL. In the case of successive high floods, once the water level in Lake Nasser exceeds 178 m AMSL, excess water is diverted through the free spillway to the Toshka depression. If the elevation of the lake continues to rise, the gated emergency spillway is activated to ensure that the elevation of the lake does not exceed 182 m AMSL and the dam is not overtopped. After the 1998–1999 and 2001–2002 floods, the Egyptian Ministry of Water Resources and Irrigation (MWRI) enlarged the Toshka spillway to increase its maximum discharge to 0.2 BCM/day at 181.5 m AMSL (National Water Research Center, 2008).

During 1998 at the peak of the flood season with increasing water levels above 178 m AMSL, MWRI tried to increase the water release through the gated emergency spillway hoping to cause no downstream damage (MWRI, 1999). However, the HAD releases reached 0.27 BCM/day for a few days which resulted in the downstream flooded area increasing rapidly and becoming extensive. As a result, MWRI recommended that even in the case of devastating floods, the water release through the gated spillway should not exceed 0.26 BCM/day. On August 1, 2001 MWRI released 0.27 BCM/day, exceeding its maximum set release of 0.26 BCM/day, due to the fact that the reservoir level was at 175.68 m AMSL and there was a new incoming flood. MWRI published a report describing the level of damage downstream and again emphasized that downstream releases through the gated spillway of the HAD should not exceed 0.26 BCM/day even when faced with significant inflow floods (MWRI, 2002). This recommendation was issued in spite of the fact that MWRI had previously developed a flood map based on allowing 0.35 BCM/day HAD releases during very high inflow events. The flood map was developed to show the extent of a destructive flood in the Nile valley in Egypt. The results showed that assuming a discharge of 0.35 BCM/day for the first 200 km downstream of the HAD the number of inundated structures would include 65 pump stations and numerous houses (Attia & Sadek, 2010). However, the study did not extend further downstream of the first 200 km.

For simulating the MGDO scenarios, an updated version of the HAD model developed and calibrated in 2005 (Mahmoud, 2005) was used. The HAD model updates include using the new version of the HEC-ResSim model (US Army Corps of Engineers, 2007) which uses the modified pulse method for reservoir routing (US Army Corps of Engineers, 1994). This routing method as applied in Hec-ResSim consists of a repetitive solution of the continuity equation, which is appropriate for reservoir routing when using short time steps and the volume of storage is large. The updated HAD simulation model uses daily data instead of monthly data utilized in the 2005 version. The calibration results of the updated model showed a significantly higher degree of accuracy than the 2005 monthly version. The Nash-Sutcliffe efficiency for the updated model was increased from 0.68 in the 2005 to 0.72 in the updated daily version.

5 | DB ANALYSIS

Figure 8 shows the published GERD design capacities and operational reservoir zones. The top level of the "dead zone" is at 590 m AMSL and has a capacity of 14.6 BCM. The "conservation zone" lies between 590 and 640 m AMSL with a corresponding volume of 59.1 BCM. The bottom of the "flood control zone" is set at 640 m AMSL with a depth of 5 m and a capacity of 9.4 BCM (EEPCO, 2012).

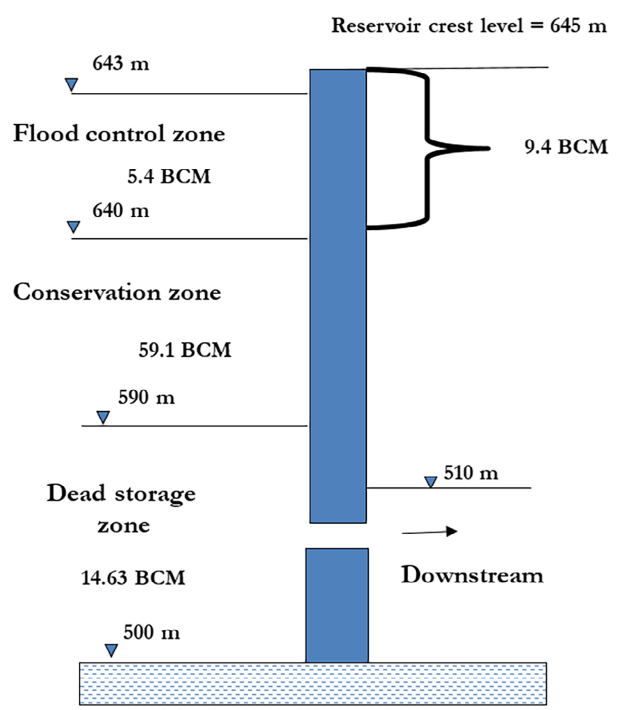

FIGURE 8 Grand Ethiopian Renaissance Dam (GERD) operation zones

The analysis of the DB scenario evaluated as part of this research includes the following two tasks: (1) Prediction of the outflow hydrograph (due to a GERD breach) and routing of the resulting hydrograph through the downstream river channel (from the GERD to Khartoum). The outflow hydrograph was predicted based on a specific selection of dam breach parameters and characteristics; and (2) Determining the water level downstream of the GERD. For determining the water level several cross sections between the GERD and Khartoum were used. The cross sections were generated by digital terrain analysis (Danielson & Gesch, 2011) and the water level was determined in each of the cross-sections.

SMPDBK was used to estimate the flood propagation in terms of the depth and discharge at different cross-sections as well as to estimate the flooded areas. The dam failure was assumed to be limited to either the main body of the dam or the saddle dam. Therefore, the flood volume considered was equal to approximately 75.5 BCM. This volume includes the "live storage" of the GERD (59.1 BCM), the "flood control volume" of 9.4 BCM, and 7 BCM expected from the Roseires Dam, which lies less than 100 km downstream from the GERD, and there is a high probability that it would collapse as the flood wave generated from the GERD break/failure passes.

The DB scenario is based on the following assumptions:

- The main dam breaks when the upstream elevation reaches 645 m AMSL.
- The height of the breach (H) is 55 m, which is the difference between the top elevation of the dam and the dead zone (590 m AMSL).
- The maximum discharge which may be released through the gates and spillways is 11,574 m^3/s (non-breach flow).
- The water depth downstream of the GERD is equal to 10 m (corresponding to the downstream elevation of 510 m AMSL), which represents the normal gauged level.
- The width of the rectangular breach is equal to 275 m. Based on the recommendations from Wetmore and Fread (1991) this width equals 5H.
- Wetmore and Fread (1991) recommend the time to breach is equal to $H/40$. The value of $H/40$ equals 5 min which the authors believe is too short of a breach time and therefore the authors conducted a sensitivity analysis of the breach time as described later.

Broberg and Thorwid (2015) in their study on modes of failure for concrete dams gave some examples of dams (not necessarily RCC dams) that took 30–60 min to fail. The expectation is that the generated flood wave is highly sensitive to breach time. Therefore, multiple breach times (5, 10, 20, 30, and 120 min) were used in running the SMPDBK model in order to be able to conduct a sensitivity analysis of the breach time.

TABLE 1 Simulated discharge and water level values at Khartoum for different breach time scenarios

Time of breach scenario (minutes)	Discharge (m^3/s)	Water level (AMSL)
5	275,585	401.5
10	235,445	401.0
20	105,223	398.8
30	103,295	398.7
120	24,500	396.0

Table 1 shows that the model estimated water level at Khartoum would be 16 m higher than the maximum water level ever recorded (MWRI, 2013a): 380.14 m AMSL (September 2, 1946) in the scenario of the 120 min breach time (the scenario with the least impact). Table 1 also shows that for the same scenario the simulated discharge at Khartoum would be 24,500 m^3/s which is more than twice the maximum flow ever recorded (MWRI, 2013b).

Figure 9 shows the model results for the peak discharge between the GERD and Khartoum for different simulated breach times. There is a significant reduction in the flood peak, for all scenarios analyzed, at kilometer 187 downstream of the GERD. This may be attributed to the Digital Elevation Model (DEM) data between kilometers 156 and 187 downstream of the GERD. Figure 10 shows a drastic change in the channel top width, for the 120 min breach time scenario, from 33 km at kilometer 156 downstream of the GERD to 53.5 km at kilometer 187 downstream of the GERD.

The SMPDBK model computes water levels at 50 x-sections along the Blue Nile river. These levels are superimposed on the DEM to delineate the flooded area by using GIS. Areas are flooded wherever the elevation of the floodwater exceeds that of the land along the stream course (Tate & Maidment, 1999; Yang et al., 2006). Different DEM resolutions were evaluated including: 1 km, 0.5 km, 255 m, 90 m, 30 m (Danielson & Gesch, 2011; Reuter et al., 2007). The STRM DEM with 90-m resolution was selected after being corrected for bias, using many fixed local points with accurate elevations. Based on the model results, of the scenario with the minimum impact (120 min breach time), the flooded area was estimated at 23,700 km^2 with a width that could reach 86 km as illustrated in Figure 11. The Gezira Irrigation

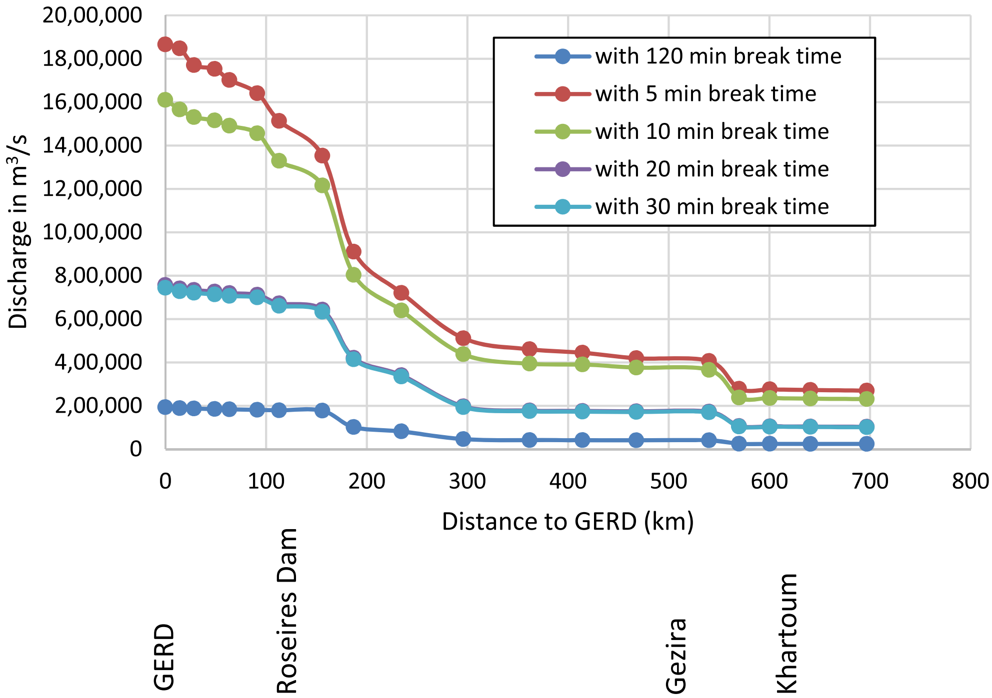

FIGURE 9 Simulated peak discharge profile between the Grand Ethiopian Renaissance Dam and Khartoum for different breach times

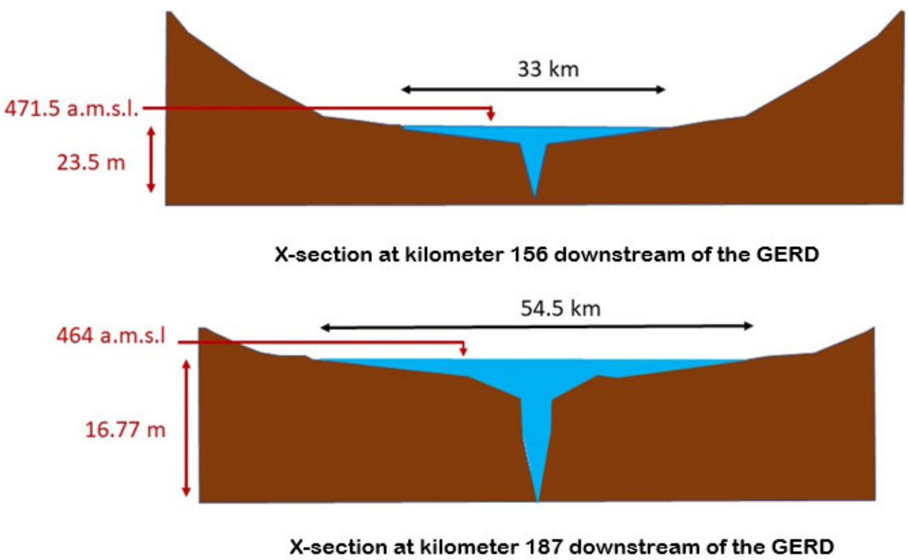

FIGURE 10 Top width comparison at kilometer 156 and kilometer 187 downstream of the Grand Ethiopian Renaissance Dam for the scenario with the least impact (120 min breach time)

Scheme was estimated to be flooded with depths from 1 m to over 25 m, with the higher depths closer to the main channel, and a maximum discharge of up to 40,600 m^3/s. This would result in catastrophic loss of productive farmlands, livestock, small settlements, and people. Impacts downstream of the HAD are out of the scope of the modeling effort of this study. The reach from Khartoum to the Lake Nasser inlet is more than a thousand kilometers with Marawi Lake (12 BCM); therefore, the flood peak that reaches Khartoum will be significantly attenuated before reaching the HAD.

6 | ANALYSIS OF FLOODS GENERATED BY MGDO AS A RESULT OF A FALSE FLOOD SIGNATURE

Two cases, represented by two different hydrologic years, were evaluated under this scenario: (i) The 1993–1994 hydrologic year which has a normal natural flow at the HAD; and (ii) The 1998–1999 hydrologic year which represents the Blue Nile high flood. Daily flow records at the Dongola gauge (on the main Nile), downstream of the

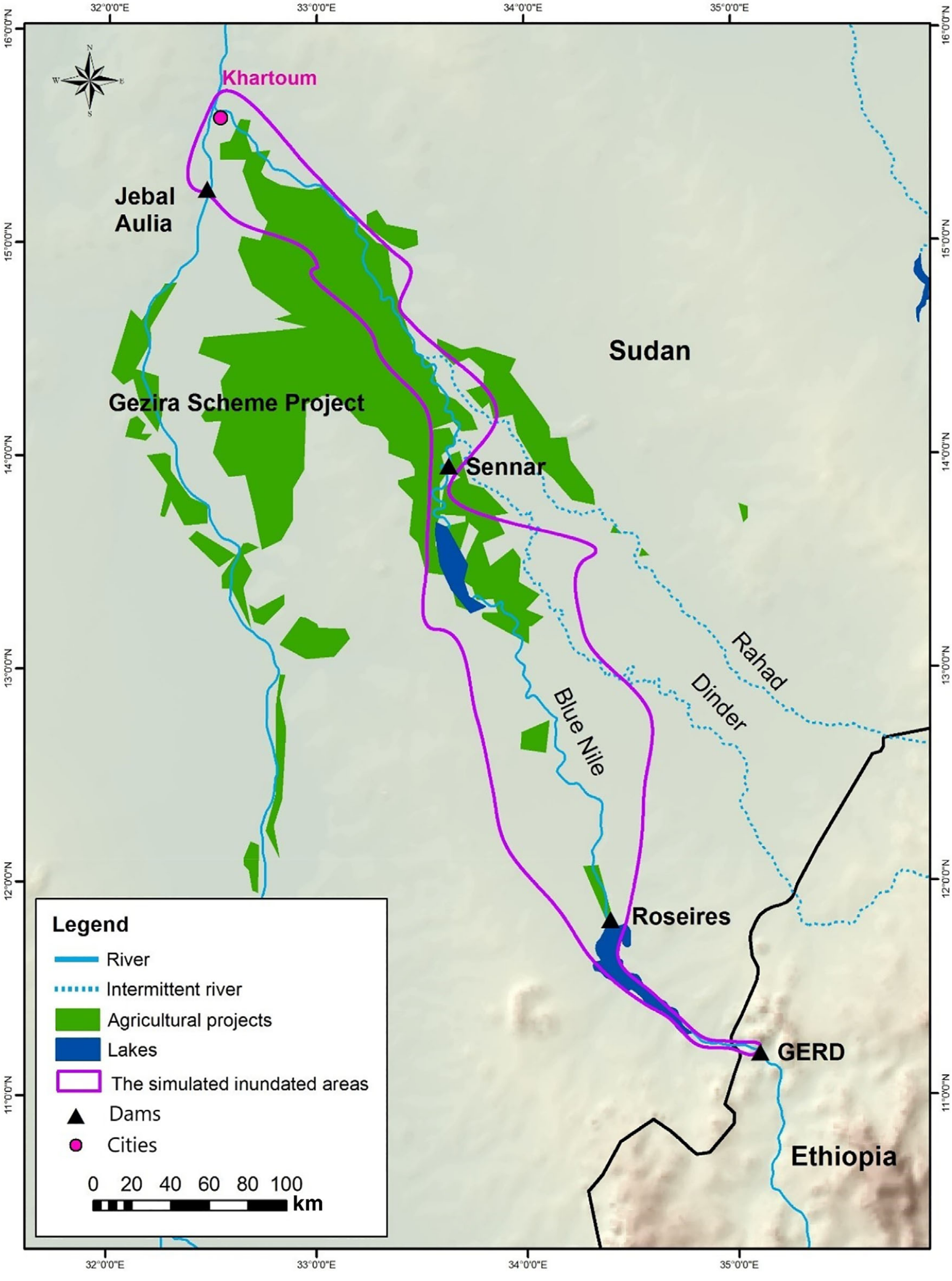

FIGURE 11 Map of the inundated areas for the scenario with the least impact (120 min breach time)

Jabal Al Awlia Dam (on the White Nile), at the Atbara river outlet, and at the El Diem gauge (on the Blue Nile), for these two hydrologic years, were used as input for the flood generation model.

6.1 | Case 1

The 1993–1994 hydrologic year was selected because it corresponds to a normal natural flow of 84 BCM at the

HAD; and the beginning of this flood season has a hydrologic signature of a "high flood season" (54 BCM) at the El Diem gauge. It would be reasonable to assume that this deceiving hydrologic signature could trigger the mishandling of the releases from the GERD. In addition, during this year the standard operational rules of the HAD were followed exactly, and the water elevation of Lake Nasser on August 1st, 1993 was recorded as 175 m AMSL.

Annual flows at several specified locations were as follows: (a) 75.34 BCM was measured at the Dongola gauge; (b) the releases from the Jabal Al Awlia were 23.16 BCM; (c) 7.21 BCM was measured at the Atbara River; and (d) 53.92 BCM was measured at the El Diem gauge. Conveyance losses through the Roseires–Dongola reach were estimated to be 2.5 BCM, almost equal to the flows of the Dinder and Rahad rivers, which were not taken into consideration and therefore offset each other. Historical records indicate that the maximum capacity of the Roseires–Dongola reach is 1 BCM/day with a corresponding travel time of 14 days (MWRI, 2000). Therefore, the flood generation model was formulated such that the GERD evacuated storage due to mismanagement added to the Jabal Al Awlia releases, the El Diem natural flows and the Atbara flows maintain 1 BCM/day at the Dongola gauge. The HAD simulation model was run for a period of one hydrologic year starting on August 1, 1993 using the following standard official operating rules:

- On August 1st at a HAD reservoir level of 175–178 m AMSL the reservoir releases can reach up to 0.24 BCM/day.
- Above a HAD reservoir level of 178 m AMSL releases could reach up to 0.26 BCM/day.
- The Toshka spillway cannot accommodate more than 0.20 BCM/day at a reservoir elevation of 181.5 m AMSL.
- In case, the HAD reservoir level reaches 182 m AMSL, the HAD emergency spillway gates must release 0.35 BCM/day. Such level of release is needed in order to prevent overtopping of the dam; however, it could cause extensive and severe downstream flooding.

Results of the simulation model indicate that the HAD would reach its maximum allowable capacity of 168 BCM in 75 days at a reservoir level of 182 m AMSL. In order to maintain 1 BCM at the Dongola gauge for the 75 day period (including a routing lag time of 14 days), the model estimated that the GERD releases would need to be less than 0.9 BCM/day, which is below the dam outlet capacity. During this period (two and half months) the model estimated that 22.4 BCM would have been evacuated from the GERD storage, which is less than half of its live storage, and all of the arriving natural flows (53.9 BCM) would have been released. In order to prevent the overtopping of the HAD, the simulation model estimated that there would need to be releases from the HAD of 0.35 BCM/day for 111 consecutive days with the assumption that there would continue to be releases of 0.9 BCM/day from the GERD.

6.2 | Case 2

Daily records of the HAD reservoir elevation and dam releases during the 1998–1999 hydrologic year clearly represent a "high flood" event year. Annual flows at several specified locations were as follows: (a) 107.04 BCM was measured at the Dongola gauge; (b) The releases from Jabal Al Awlia were 28.23 BCM; (c) The Atbara River flow was measured as 17.76 BCM; and (d) 68.40 BCM was measured at the El Diem gauge. The same losses in the system, routing lag time, and HAD operational rules as those assumed in the case of the 1993–1994 hydrologic year were used.

The simulation results of the "high flood" case were similar to those of the 1993–1994 case. The results show that the HAD reaches its maximum allowable volume in 75 days. Over this duration, the model estimated that 4 BCM would have been evacuated from the GERD and all of the arriving natural flows (68.4 BCM) would have been released. To prevent the overtopping of the HAD, the simulation model estimated that there would need to be releases from the HAD of 0.35 BCM/day for 166 consecutive days with the assumption that there would continue to be releases of 0.9 BCM/day from the GERD.

7 | CONCLUSIONS

The purpose of this study was to predict the possible impacts to the downstream areas from either a GERD structural failure or operational failure. This was accomplished by developing and running a simulation model for two different scenarios: (i) a DB; and (ii) a MGDO as a result of a false flood signature. The flood peak discharge at Khartoum generated by the model for the DB scenario is significantly greater than the destructive 1946 flood (10,000 m^3/s at Khartoum) which is considered the flood of record. The intensively cultivated Gezira Plain would be inundated with average water depths of more than 10 m, resulting in catastrophic loss of highly productive farmlands, livestock, inhabitants, and infrastructure. Therefore, based on the results of this scenario it is strongly recommended that the GERD safety study be revised and a comprehensive monitoring and safety inspection program be implemented. The SMPDBK model was selected for this study due to its ability to estimate impacts on a large study area with minimum data available; however, a full hydro-dynamic wave model based on extensive physical parameters and topographic data including land use would be beneficial for a more detailed study. A detailed socio-economic impact study is needed to quantify the damage and cost of inundating such large area of the Gezira Plain with depths ranging from 1 m to over 25 m.

The MGDO scenario is based on the premise that a hydrologic year with an early high runoff could deceive GERD operators to evacuate about one third of its storage in addition to its natural inflow. One of the impact of these releases is that the HAD would be at its maximum allowable capacity for two and half months, assuming emergency releases from the HAD were maintained for almost 3 months. At this emergency release levels from the HAD it is expected that significant flooding downstream of it would occur. The high flood case of the MGDO scenario could mislead GERD operators into evacuating small extra releases. However, such small extra releases would require to keep the HAD emergency releases for more than five months while maintaining the HAD at its maximum allowable level for two and a half months. Moreover, if any upstream dam, such as the "Merowe" and "Upper Atbara and Setit Dam", evacuates some of their storage over the same period, this would increase the likelihood of the HAD being overtopped.

The results of this study point out that the operational rules for the HAD may need to be modified to accommodate extra releases from the GERD during flood events. However, providing more flood buffer at the HAD will limit the live capacity that is currently used for fulfilling downstream requirements during drought periods. Moreover, there will be a significant reduction in hydropower generation, resulting in a reduction of the HAD's contribution to Egypt's GDP.

The results of this study also identified the need that a set of coordinated rules for both the HAD and the GERD, as well as all Sudanese dams in between, be identified and agreed upon to avoid any unexpected extra releases from the GERD, especially during the flood season. Such cooperative approach for the operation of these dams will ensure effective use of high inflows and minimize the potential for any unfavorable damages downstream of the HAD.

DATA AVAILABILITY STATEMENT

All data used and/or analyzed during the current study are referenced and available through the corresponding reference. However, help and support can be provided by the authors on reasonable request.

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