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Ethiopian Dam Optimum Hydraulic Operating Conditions to Reduce Unfavorable Impacts on Downstream Countries

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Abstract

As noted by several researchers, the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River is expected to have unfavorable consequences for downstream countries like Egypt and Sudan. To limit GERD's negative effects on downstream countries, its operation should be secure, and its upstream water level should be ideal. However, none of the studies carried out the ideal operating scenarios from the perspective of controlling the number of gate openings. Accordingly, this study evaluates the optimal operating scenarios of the GERD and its impact on downstream countries by adopting a mathematical model to analyze the number of gates that can be opened and the depth of opening during different filling years. The paper also presents an environmental impact assessment of some GERD significant factors during construction, filling, and operation, with the goal of developing a mitigation strategy. The results showed that opening 5 gates at 4.56 m over a 10-year filling period would be the safest, most accepted, and most advantageous for Ethiopia and downstream countries. Moreover, creating a water-saving management plan in Egypt to overcome GERD's negative impacts would cost 877 billion Egyptian pounds.

Keywords: GERD; Filling Scenarios; Gates; Hydraulic Jump; Dam; Egypt.

1. Introduction

Egypt is classified as a "dry arid region", with summer temperatures typically topping 38ºC and low annual rainfall [1]. Due to these constraints, the Nile River is regarded as Egypt's principal water source, providing 97% of the country's demands [2]. The Grand Ethiopian Renaissance Dam (GERD) is the first significant dam built on the Blue Nile River, as shown in Figure 1, with a reservoir capacity of 74 billion cubic meters once full. Egypt relies on the Nile River from two sources: the Blue River, which supplies 80-85% of the entire streamflow to Aswan, and the Great Lakes region of Africa, which provides almost 15% of the Nile River streamflow to Aswan [3-5].

The GERD is divided into 3 structures: (1) the main gravity dam; (2) the main spillway of the gate; and (3) the rockfill dam. It is around 500 kilometers northwest of Addis Ababa and consists of two dams; the RCC main dam and the saddle dam. The spillway is a separate structure from the main dam and saddle dam [6]. The GERD reservoir is a massive body of water. It covers an area of 522 to 1736 km^2, with a maximum supply level of 640 m.a.s.l. and a minimum operating level of 590 m.a.s.l. [7]. The reservoir has a volume of around 73 BCM. The operating range is 50 m, and the dead storage is 14.8 BCM [1].

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Figure 1. Grand Ethiopian Renaissance Dam locations [5]

The Ethiopian Renaissance Dam (GERD) construction would have a direct impact on the water sharing of downstream nations such as Egypt and Sudan. With a population of more than 100 million people, Egypt faces a tremendous risk since GERD will impact the river's water level, affecting numerous areas, including agriculture and industries that rely on the Nile for water. Furthermore, the electricity supply, which accounts for 5.68 percent of Egypt's total electricity, is gradually declining. These are major threats to Egypt that could lead to political conflict between the two countries.

The process of filling the GERD dam is divided into two phases: long-term and short-term. The operation of the dam is represented by the long-term period. Filling the reservoir of the dam will not have an immediate impact on the downstream countries, but the consequences will take time to become apparent. The GERD dam filling period is represented by the short term. Even if it is extended for a number of years, the effect is only temporary.

As a result, this study contributes to minimizing and determining the best approach to obtain the most beneficial (if any) benefits from GERD. This research will address various scenarios for the operation of the dam's gates and the impact on the Aswan High Dam and Egypt in general. Furthermore, this research develops a mathematical model to identify the feasible operational actions (number of opened gates and gate openings) for controlling the Grand Ethiopian Renaissance Dam (GERD) with sluice gates that account for all combinations of stream flows and tailwater levels.

2. Literature Review

A study was conducted by Mohammad [8] to study the expected GERD impacts on the Aswan High Dam (AHD). Three different scenarios were studied. The filling period of GERD in the first scenario was three years, and the filling period of GERD in the second and third scenarios was five years. For the third case, after the GERD operation, the monthly discharge was reduced by value 0.5 BCM. The results showed that the lake Nasser will be severely affected by its initial water level at the beginning of the filling operation. If the inflow does not decrease after the filling time is over, the water level of Lake Nasser will return to its original level. In addition, the paper shows that the AHD turbine will reach its minimum at the end of the filling period. It will be decreased by about 15% compared to the base year, and if the inflow does not decrease, it will be increased again. However, according to this paper, the advantage of GERD over AHD is only to reduce the evaporation loss of Lake Nasser.

Another study by Mulat and Moges [9] showed the impact of GERD on the Aswan High Dam (AHD) reservoir and the energy produced by the dam. The study was done using a Mike Basin River basin simulation model to evaluate the expected impact of GERD on AHD during the filling and operation phases. The results showed that during the period from January 2011 to January 2014, AHD operating conditions will not be affected by the impoundment of the GERD reservoir. However, between January 2014 and June 2015, due to the storage of water in GERD, the water level in AHD will be slightly affected. As GERD impounds water from July 2015 to December 2019, the AHD level will drop significantly.

Studies have shown that when the GERD filling period is 6 years, AHD flow conditions will be reduced by 13 BCM without affecting agriculture. On the other hand, it will affect the average annual power generation by 13%, and the annual AHD power generation will lose 0.5% to 24% during the filling period. Lastly, the AHD evaporation losses will be reduced compared to the current situation. The evaporation loss during the filling process is approximately 3.5 BCM of water. This means that the cumulative loss from the two reservoirs will be less than the current situation's loss. 12907 MCM will be the average annual loss of the two reservoirs, which is 16% less than the loss of the AHD operation alone. The controversy around GERD rapidly grew from its construction aspect and engineering design to the effect of filling on Egypt and Sudan from the beginning of the construction of GERD. The number of years of initial reservoir filling is one of the disputes in Egypt because the filling time depends on the decrease in flow.

The U.S. Military Academy's report on the West Point Military Academy implemented 33 GCM models in predicting climate change in the Nile River Basin. In addition to theoretical variation and climate change, this study also uses historical flow data from 1994 to 2012 to estimate the impact of GERD flooding years on the Blue Nile. During the period 2014-2100, simulated traffic has been generated for more than 30 years. The approximate result of the GERD filling study is that in the 20-year filling year, the flow of the Blue Nile will be reduced by 4.22%, and the filling rate will be 5% of the total supply of the dam. In another case, the annual flow rate of the 10-year filling will be reduced by 8.77%, and the filling rate will be 10% of the total supply of the dam. In another case, the annual flow rate of 7 fillings will be reduced by 13.55 percent, and the filling rate will be 15% of the total supply of the dam. In another case, the five-year water filling volume will be reduced by 16.18%, and the filling rate will be 20% of the total dam supply. In addition, the four-year water filling volume will be reduced by 20.72%, and the filling rate will be 25% of the full dam volume. In general, a shorter filling time will cause a system shock, while a longer filling time will cause long-term stress [10].

Abtew and Dessu [11] carried out another analysis to demonstrate the potential reduction in flow due to filling and the consequences for downstream storage. The simulation of the reservoir operation is used with annual flow data to estimate the fill time for a fraction of the reservoir flow. The results show that the reservoir can store water for 8 to 9 years and can reduce the annual flow by 20% every year. The AHD of 132 BCM, the historical average level of the Nile, took 6 years (1971-1976) to completely flow into Aswan as the largest river flow, with an annual flow of 84 BCM.

A study by El Baradei et al. [12] simulates the effect of alternative GERD reservoir filling scenarios on the High Aswan dam's water footprint. The Aswan dam's hydropower impact is also evaluated. All evaluations used mathematical modelling. 3 years, 5 years, and 6 years of GERD filling are studied. Length of GERD filling affects High Aswan dam's hydropower water footprint. GERD filling period inversely affects Aswan High dam's electricity water footprint.

A study was conducted by Heggy et al. [13] to analyse the implications of GERD on short-term Egyptian Nile streamflow availability by simulating different filling scenarios and techniques. Then, Egypt's total water budget shortfall from GERD filling, seepage, and population increase were calculated. The study examined the feasibility of suggested mitigating actions to overcome the gap and discuss the socioeconomic implications of each GERD filling scenario.

Abou Samra & Ali [14] were applied to monitor the first and second GERD reservoir filling periods using *VV* polarized SAR data. Using ALOS global DEM and Sentinel-1 data, the study approximated GERD water storage after the first and second fillings. This study will help decision-makers improve GERD filling management measures for downstream riparian countries.

Kansara et al. [15] conducted a project that aims to offer up-to-date and accurate monitoring of GERD filling utilizing satellite imagery from Sentinel-1 and Sentinel-2, water storage from GRACE, precipitation from GPM, and topography from STMM (SRTM). This analysis will inform future GERD management decisions for Egypt, Sudan, and Ethiopia. Wheelar et al. [16] showed how HAD reservoir could decrease to levels not seen in decades during filling, despite Egypt's water scarcity danger is low. Ethiopia and Sudan will benefit from the new normal, but Egypt won't. Multi-year droughts require careful coordination to limit harm.

The aforementioned research studies investigated the impact of GERD on AHD operation, both in terms of water level and energy generation during and after filling. They also mentioned the dam's size and the type of gate employed. However, none of the publications determined the number of opened gates and gate openings to determine the ideal operating scenario with the least amount of damage or impact on AHD and downstream countries, assuming that the gates are sluice gates.

3. Methodology

An Excel spreadsheet was used to develop a mathematical model to assess the optimum operating scenarios of the GERD and its influence on downstream countries in this study. The calculations are based on different scenarios, such as the amount of water discharged over different filling years, the number of gates, and their openings. The research methodology processes are shown in Figure 2.

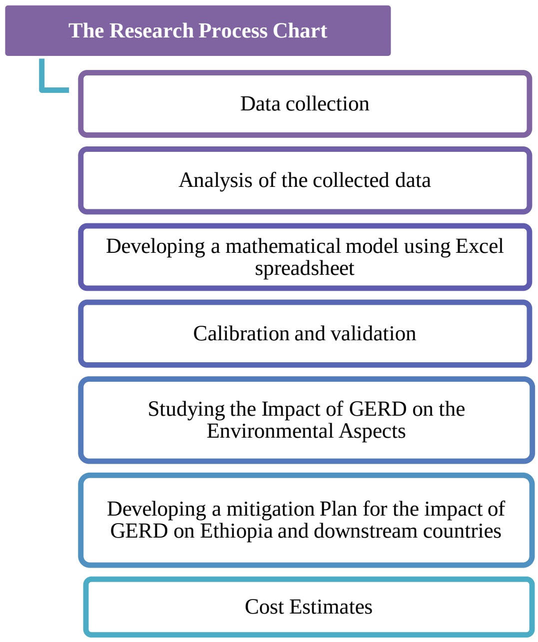

Figure 2. The research processes charts

The parameters used in this research are gate openings and gate depth because they affect the upstream water level, which should remain constant. Moreover, the dam's primary function is to generate hydropower. Therefore, there must be a consistent head for hydropower generation. This study examines the number of functioning gates required to maintain the water level in the upstream while minimizing the impact on the downstream countries. Also, one of the parameters studied in this research is the submergence factor where it should be within a certain ranges so that the water released from the dam should be well balanced to not cause devastation on the downstream users.

3.1. Q_{out} Calculations

Over a given time period, the mass flow balance of a dam or water storage can be expressed as:

$$Q_{out} - Q_{in} = \frac{dv}{dt} = Q_{rain} - Q_{fill} - Q_{evap} - Q_{seepage} \tag{1}$$

And;

$$Q_{out} = Q_{in} + Q_{rain} - Q_{fill} - Q_{evap} - Q_{seepage} \tag{2}$$

where, Q_{out} is the outflow volume flow rate from the dam gates; Q_{in} is the inflow volume flow rate to the dam gates; Q_{rain} is the average rain flow rate; Q_{fill} is the reservoir filling rate; Q_{evap} is the average evaporation rate; and $Q_{seepage}$ is the seepage rate.

3.2. Hydraulic Jump Calculations

When high-velocity water discharges into a zone of lower velocity, such as a spillway, an abrupt rise on the surface occurs, as does high turbulence at the bottom in the form of rollers. This phenomenon is referred to as a hydraulic jump [17]. The rapidly flowing water is quickly slowed and raised, turning kinetic energy into potential energy, with some energy lost irreversibly due to turbulence. The Froude number Fr, defined as the ratio of flow velocity to gravity wave speed, is crucial to the properties of a standard hydraulic jump [18]. Figures 3 and 4 show the hydraulic jump phenomenon occurring in free surface flows in both free and submerged modes.

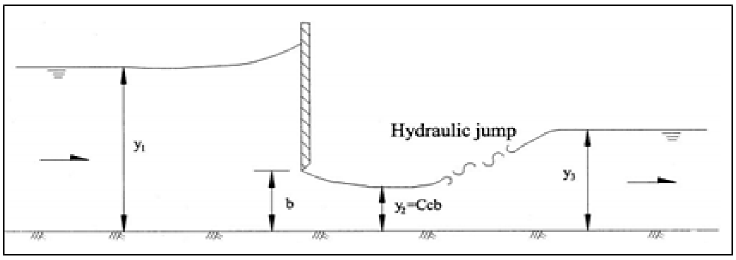

Figure 3. Free Hydraulic Jump

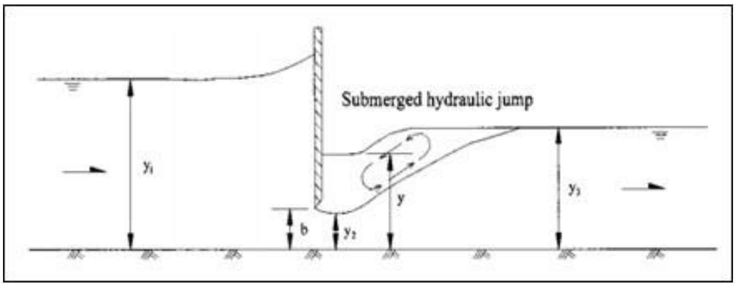

Figure 4. Submerged Hydraulic Jump

A hydraulic jump can be classified into several types based on topographical features, bed surface roughness, and a variety of other natural interface relationships. The water outflow from the dam along with its high kinetic energy are likely to cause damage to the dam downstream side such as erosion of the riverbed. Even with the construction of stilling basins, still the type of hydraulic jump in the channel must be precisely defined to avoid scouring effects on the downstream side of the dam structure and neighbouring structures. This hydraulic jump type can most likely be described using Froude's number which is a dimensionless quantity used to represent the effect of gravity on fluid motion as shown in Table 1.

Table 1. Types of Hydraulic Jump [19]

Froud Number	hydraulic jump types	Description
1	No jump	Flow so critical
1 to 1.7	Undular jump	The water surface shows undulations
1.7 to 2.5	Weak jump	A series of small rollers form on the surface of the jump, but downstream water surface remains smooth. Velocity is uniform and energy loss is low.
2.5 to 4.5	Oscillating jump	Causes unlimited damage to the earth banks of the rivers. Not recommended
4.5 to 9	Steady jump	The jump is well balanced, and the performance is at its best.
> 9.0	Strong jump	The jump action is rough.

In order to determine the Froude number, the following calculations should be followed:

$$Q_g = \frac{Q_{out}}{no.\ of\ opened\ gates} \tag{3}$$

where, Q_g is the discharge passing through one gate, Q_{out} is the total discharge going through all gates.

$$V_j = \frac{Q_g}{W_g * C_c * b} \tag{4}$$

where, V_j is the velocity at the beginning of the jump, W_g is the gate width, C_c is the contraction coefficient, and b is the gate opening as shown in Figure 5.

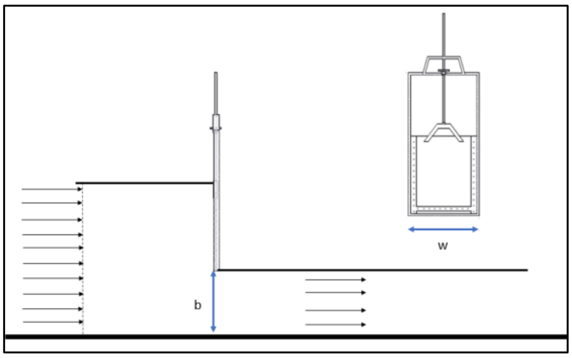

Figure 5. Sluice gate opening and width

$$Y_2 = C_c * b \quad (5)$$

where, Y_2 is the flow depth at vena contracta.

To determine the type of the hydraulic jump, Froude number should be calculated using the following equation:

$$F = \frac{V_j}{\sqrt{g * y_j}} \quad (6)$$

where, F is the Froude number, g is the gravitational acceleration; and y_j is the depth at the beginning of the jump.

In order to determine the jump kind, the following conditions will be used:

$$\textit{Free flow:} \quad y_1 \geq 0.81 y_3 (\frac{y_3}{b})^{0.72} \quad (7)$$

$$\textit{Submerged flow:} \quad y_3 < y_1 < 0.81 y_3 (\frac{y_3}{b})^{0.72} \quad (8)$$

3.3. Submergence Factor, Energy Loss, and Efficiency Calculations

The characteristics of the jump are determined by the submergence ratio, S. In order to calculate submergence factor, the conjugate depth should be calculated:

$$y_{2*} = \frac{y_{1*}}{2} * (\sqrt{1 + 8F^2} - 1) \quad (9)$$

where, y_2* is Conjugate depth, y_1* is the jet thickness, and F is the Froude number.

Submergence factor (S):

$$S = \frac{y_3 - y_{2*}}{y_{2*}} \quad (10)$$

where, Y_3 is the downstream water level.

$$Energy\ Loss = \frac{(y_3 - y_{1*})^3}{4 * y_{1*} * y_3} \quad (11)$$

$$Efficiency = \frac{(8F_1^2 + 1)^{\frac{3}{2}} - 4F_1^2 + 1}{8F_1^2 (2 + F_1^2)} \quad (12)$$

4. GERD Operating Scenarios Identification

4.1. Data Collection

Egypt and Sudan get their water from the Blue Nile and its tributaries, as well as the White Nile. 85% of the Nile waters flowing to Egypt originate in Ethiopia which accounts for 63 BCM/year [20]. The annual rainfall in Ethiopia is 1125 mm [21] and the GERD surface area is 1874 km^2 [22]. The GERD's upstream water level is 90 m, and its downstream water level is 17 m [16]. In the design and operating scenarios, it was considered that the operation ranged from 1 gate to 6 rectangular sluice gates. The width of each gate is 5.5 m, and the bed width is 2800 m [1]. The gate openings ranged from 0.01 to 15 m with a 0.05m opening intervals. In this study, five filling periods were considered: three, five, seven, ten, and fifteen years.

4.2. Calibration and Validation

Equation 2 was used to define the volume flow rate (Q_{out}) while neglecting $Q_{seepage}$ since it's too small to get the water reduction percent. The calculation procedure is shown below in the following example:

$$Q_{in} = 74 \times 0.85 = 63\ BCM \tag{13}$$

$$Q_{rain} = 1125\ mm\ anually\ \times 1874\ km^2 = 2.11\ BCM \tag{14}$$

$$Q_{evaporation} = 1.125\ m \times 1874\ km^2 = 2.11\ BCM \tag{15}$$

Calculations for Q_{fill} for 20 years:

$$Q_{fill} = \frac{74}{20} = 3.7\ \frac{BCM}{year} \tag{16}$$

$$Q_{out} = 63 + 2 - 2 - 3.7 = 59.3\ BCM \tag{17}$$

Then,

$$\frac{59.3}{63} = 0.941 = 94.1\ \% \tag{18}$$

The reduction in Q downstream = 100 – 94.1= 5.9%.

The previously mentioned scenario represents a sample for the way the equation was used to get the Q_{fill}. All the other scenarios were calibrated with the results of keith et al. [10]. study. The percentages of error are shown in Table 2 where the average of errors is 2.6% which is very small. This could be explained due to the small variation between the used discharges in calculations. Therefore, it is reliable to calculate, model, and predict the required data for the research.

Table 2. Calibration Results

No. of years	Qout (BCM)	Reduction%	Reduction to Blue Nile % [10]	Error %
3	38.33	39.2%	-	-
5	48.2	23.5%	16.8%	7.32
7	52.43	16.8%	13.15%	3.65
10	55.6	11.8	8.77%	3.03
15	58.1	7.8%	-	-
20	59.3	5.9%	4.22%	1.68

5. Results

Tables 3 and 4 summarize the results for each operating scenario that can be used to maintain safe operations in Ethiopia and downstream countries. The number of gates that are opened at 0.21 to 15 m in different filling periods of 3, 5, 7, 10, and 15 years, respectively was 6 or less gates. The table is showing the most favourable scenarios, accepted, and rejected ones. Based on the results in Table 3, the type of steady hydraulic jump that was obtained with a non-negative submergence factor for the number of opened gates 3 to 6 was the best type of hydraulic jumps because the jump is well balanced and performs optimally.

Table 3. Best Case Scenarios for 3, 5, 7, 10, and 15 filling scenarios

Q	No. of Gates	b	F	Y2*	Jump Kind	Type of Jump	Energy loss	Efficiency	Submergence Factor	Comment
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 3 years filling scenario, Q=1215.44 m³/s)										
202.5733	6	3.16	4.504303	11.16676	Free	Steady Jump	26.72568	0.554727	0.522376	Best
243.088	5	3.56	4.520271	12.62836	Free	Steady Jump	22.60981	0.553157	0.346177	Best
382.1025	4	4.81	4.524163	17.08	Free	Steady Jump	14.32666	0.552775	0.00	Best
405.1467	3	5.01	4.51265	17.74	Free	Steady Jump	13.40688	0.553905	0.00	Best
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 5 years filling scenario, Q=1528.41 m³/s)										
254.735	6	3.66	4.544048	13.05671	Free	Steady Jump	21.72681	0.550832	0.302013	Best
305.682	5	4.11	4.582295	14.79502	Free	Steady Jump	18.30853	0.547128	0.149035	Best
382.1025	4	4.81	4.524163	17.07831	Free	Steady Jump	14.32666	0.552775	0	Best

Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 7 years filling scenario, Q=1662.54 m^3/s)										
277.09	6	3.86	4.563687	13.83432	Free	Steady Jump	20.10415	0.548925	0.228828	Best
332.508	5	4.36	4.561927	15.61983	Free	Steady Jump	16.72986	0.549095	0.08836	Best
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 10 years filling scenario, Q=1763.06 m^3/s)										
293.8433	6	4.01	4.570621	14.39544	Free	Steady Jump	18.99846	0.548254	0.180929	Best
352.612	5	4.56	4.522991	16.18614	Free	Steady Jump	15.59908	0.55289	0.050281	Best
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 15 years filling scenario, Q=1842.35 m^3/s)										
307.0567	6	4.16	4.520167	14.75637	Free	Steady Jump	17.9767	0.553167	0.152045	Best
368.47	5	4.71	4.502427	16.63665	Free	Steady Jump	14.81823	0.554912	0.021841	Best

Table 4. Worst Case Scenarios for 3, 5, 7, 10, and 15 filling scenarios

Q	No. of gates	b	F	Y2*	Jump Kind	Type of Jump	Energy loss	Efficiency	Submergence Factor	Comment
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 3 years filling scenario, Q=1215.44 m^3/s)										
202.5733	6	3.31	4.201615	10.84948	Free	Oscillating	25.06115	0.586025	0.566896	Avoid
243.088	5	3.76	4.16445	12.20633	Free	Oscillating	20.89286	0.590076	0.39272	Avoid
303.86	4	4.61	3.834406	13.67973	Free	Oscillating	4.586989	0.62819	-0.19589	Avoid
405.1467	3	6.06	3.392183	15.71936	Free	Oscillating	9.653318	0.685736	0.081469	Avoid
607.72	2	3.41	12.05446	33.87136	Free	Strong	24.03574	0.228362	-0.4981	Avoid
1215.44	1	4.96	13.74317	56.37201	Free	Strong	13.62931	0.201236	-0.69843	Avoid
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 5 years filling scenario, Q=1528.41m3/s)										
254.735	6	4.76	3.063756	11.02861	Free	Oscillating	14.56967	0.733546	0.541445	Avoid
305.682	5	5.86	2.691531	11.74027	Free	Oscillating	10.25412	0.792695	0.448008	Avoid
382.1025	4	6.76	2.715412	13.67921	Free	Oscillating	7.863188	0.788762	0.242762	Avoid
509.47	3	7.16	3.321429	18.14522	Free	Oscillating	7.018564	0.695668	-0.06311	Avoid
764.205	2	5.36	7.691988	33.41295	Free	Steady	11.9757	0.348675	-0.49122	Avoid
1528.41	1	3.26	32.43317	88.74402	Free	Strong	25.59836	0.086584	-0.80844	Avoid
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 7 years filling scenario, Q=1662.54 m^3/s)										
277.09	6	5.21	2.910316	11.39761	Free	Oscillating	12.5634	0.757337	0.491541	Avoid
332.508	5	5.51	3.211076	13.45076	Free	Oscillating	11.42297	0.711564	0.263869	Avoid
415.635	4	4.81	4.921193	18.69423	Free	Steady	14.32666	0.516143	-0.09063	Avoid
554.18	3	4.91	6.362159	25.07439	Free	Steady	13.85665	0.413904	-0.32202	Avoid
831.27	2	4.01	12.93009	42.80933	Free	Strong	18.99846	0.213453	-0.60289	Avoid
1662.54	1	3.41	32.9774	94.40197	Free	Strong	24.03574	0.085167	-0.81992	Avoid
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 10 years filling scenario, Q=1763.06 m^3/s)										
293.8433	6	4.31	4.101813	13.76359	Free	Oscillating	17.03006	0.59701	0.235143	Avoid
352.612	5	5.66	3.270758	14.10187	Free	Oscillating	10.90243	0.702906	0.205514	Avoid
440.765	4	3.86	7.259423	22.6471	Free	Steady	20.10415	0.367614	-0.24935	Avoid
587.6867	3	4.56	7.538319	27.83199	Free	Steady	15.59908	0.355185	-0.38919	Avoid
881.53	2	4.11	13.21449	44.86836	Free	Strong	18.30853	0.209017	-0.62111	Avoid
1763.06	1	2.91	44.36123	108.668	Free	Strong	29.89497	0.063447	-0.84356	Avoid
Discharge, Number of opened gates, gate opening, and jump characteristics (Case of 15 years filling scenario, Q=1842.35 m^3/s)										
307.0567	6	5.51	2.965289	12.30908	Free	Oscillating	11.42297	0.748712	0.381094	Avoid
368.47	5	5.06	4.043452	15.90901	Free	Oscillating	13.18921	0.603595	0.068577	Avoid
460.5875	4	4.96	5.207935	20.48108	Free	Steady	13.62931	0.492292	-0.16997	Avoid
614.1167	3	5.46	6.012261	26.26471	Free	Steady	11.60351	0.435076	-0.35274	Avoid
921.175	2	5.06	10.10863	41.91047	Free	Strong	13.18921	0.270148	-0.59437	Avoid
1842.35	1	2.76	50.18622	116.7079	Free	Strong	32.0809	0.05612	-0.85434	Avoid

In the case of one and two gate opening scenarios, all filling years scenarios are rejected as the submergence factor is negative in all gate opening scenarios. A total of 1806 gate opening scenarios were studied in this investigation for each filling year, where 69 scenarios were considered the best scenario in the case of 3 filling years, which means that around 4% of the scenarios can be implemented. While for the 5 filling years' scenarios a 2.5% were only accepted as 45 scenarios were considered the best scenario in this case. For a 7 filling years' scenario, the calculations show that 35 scenarios with 1.9% of all the given scenarios are the best scenario. Table 3 represents the best possibilities for filling scenarios of 3, 5, 7, 10, and 15 years. The results showed that opening five gates (4.56-meter opened gates) with 10 years of filling minimizes the Froude number, making it the safest and most well-known operating situation. So, after calculating and offering 1806 for each filling years' scenario, which means around 9000 scenarios, the only accepted scenarios were 199, representing 2.2% of the whole scenarios considered the best scenario. Tables 3 and 4 show only part of the result s but more calculations and scenarios are done without being included in the table.

Table 4, on the other hand, shows all the avoided gate openings and as demonstrated, all the negative submergence factors are rejected. Also, in the case of oscillating jumps, the gate openings are rejected since they inflict endless damage to the earth banks of rivers, which is not recommended.

6. Results

The previous calculations showed that the number of filling years, the Froude number, the number of gates, the gate openings, and the submergence factor significantly affect the operational scenarios of the GERD and, hence affecting the downstream countries. The relation between the number of years and the percentage reduction in the volume flow rate of the downstream countries is plotted in Figure 5 where it showed that the increase in the GERD filling years caused a significant improvement in reducing the volume flow rate for the downstream countries. Moreover, Figure 6 shows that as the filling years increases, the volume flow rate increases.

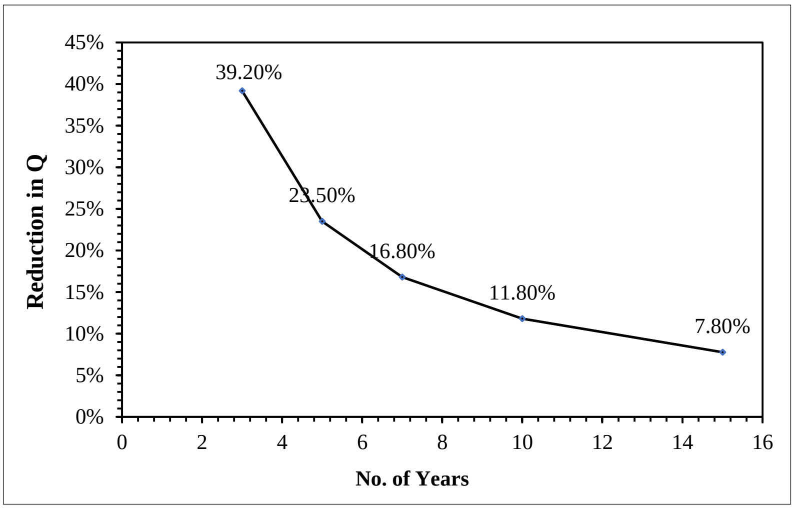

Figure 6. Reduction in Q with respect to No. of filling years

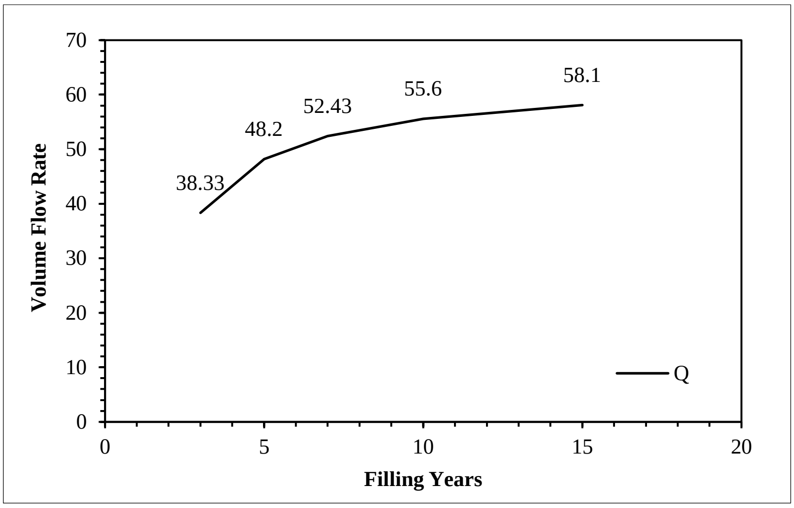

Figure 7. Volume flow rate with respect to the filling years

Moreover, the python script was to plot the data obtained from the mathematical model developed on excel. Figure 8 shows the relation between several parameters such as gate opening, number of filling years, and number of open gates and the decision on the validity of the operation scenario. The decision is made based on Froude number, hydraulic jump type, and submergence factor as described in section 3. A one open gate is not an acceptable scenario regardless of the number of filling years or gate opening. Furthermore, best operating scenarios can be noticed at 5 and 6 open gates with 2 to 4 meters gate opening for all filling years. Thus, we can conclude from Figure 6 the number of filling years most appropriate to reduce filling effects on downstream countries.

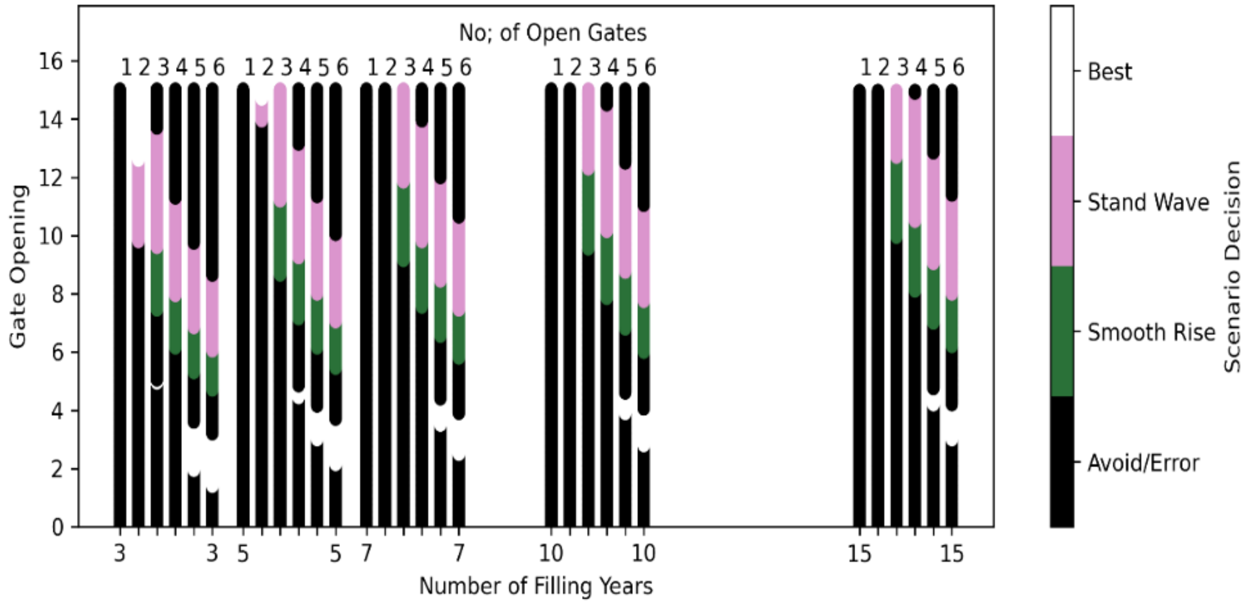

Figure 8. Effect of Filling years, Gate Opening, and No; of Open Gates on the feasibility of the operation scenario

7. Water Resources Management Plan

The Water Resources Management Plan detects potential water shortages in the future and lays out the possible solutions needed to keep the balance between available water and future demand. The process begins with considering several environmental factors or aspects that may be impacted during the various stages of GERD (Construction, Filling, and Operation) and how to limit their impact. Furthermore, the process displays as many potential solutions as possible to find viable options for each water resource zone where deficits are expected. These viable options are reviewed using an industry-standard methodology which is a method using requirements agreed upon by groups of companies and individuals working in specific industries to provide preferred options for resolving any supply shortages in terms of financial, environmental, and social costs.

7.1. 1.1. Impact of GERD on the Environmental Aspects

The Grand Ethiopian Renaissance Dam's environmental impact includes direct and indirect effects on the river's biological, physical, and chemical characteristics and the surrounding ecosystem. Changes in water temperature, dissolved oxygen, chemical composition, salinity, and physical qualities of the impoundment occur too quickly for the species to adjust. Furthermore, the presence of non-native and invasive species may threaten the survival of natural animals and plants. A second element that could endanger the situation is the dam's separation of animal spawning and rearing habitats. The distribution of wild animals and plants is also influenced in the river watershed. Forests and river banks will be flooded, forcing animals and plants to migrate uphill. Rapid habitat changes may put animals and plants at risk of extinction, putting the biodiversity of the catchment in peril.

The following Matrix (Table 5) illustrates the impacts of the GERD on some of the environmental aspects during several phases: Construction, Filling, and Operating.

Table 5. Environmental aspects affected by the GERD

Environmental aspects	Project activities									Comment
	Construction			Filling			Operating			
Degree of Impact	No effect	Small effect	Severe effect	No effect	Small effect	Severe effect	No effect	Small effect	Severe effect	
Water quality		X			X				X	Affecting downstream countries.
Noise			X	X			X			Affecting Ethiopia in the construction phase.
Air quality			X	X			X			Affecting Ethiopia in the construction phase.
Land contamination and degradation			X	X			X			Affecting Ethiopia, the most during the construction phase.
Water Reduction affecting downstream countries	X					X			X	At the filling phase: Affecting Downstream countries depending on the period of filling. At the operating phase, the effect will be severe if Ethiopia does not abide by the international laws of the riparian countries.
Increase in water salinity	X				X				X	At the filling phase: Evaporation is the major factor affecting salinity. The rate of filling may overcome the evaporation rate.
Flora (for example, Carbonation-Tropical Shrub)			X			X	X			Affecting Ethiopia.
Fauna (Animal Life)		X				X			X	Fish get killed while migrating through the dam.
Surface Water Hydrology		X				X			X	-
Agriculture	X				X				X	At operating and filling phase: Affecting Downstream Countries.
Energy			X	X			X			In construction phase it is the energy related to operating the construction machines, i.e., loaders, bulldozers. In the filling phase it depends on if the turbines are going to be operated or not. In the operating phase the turbines produce power.

7.2. Mitigation Plan for the Impact of GERD on Ethiopia and Downstream Countries

Steps should be taken towards reducing the impact of the GERD on Ethiopia and downstream countries. This could happen by limiting the impact of the construction process on the environmental aspects by reducing fuel usage and expediting the project. Expediting is utilized to mitigate risks and ensure that the contract deadlines complete the project. Expediting the construction process helps reduce noise pollution and emissions. Moreover, there should be proper disposal of the waste. By reusing and recycling existing materials, materials harming the environment could be cut down. Green technology makes buildings more energy-efficient and sustainable, resulting in a lower carbon footprint and less environmental effect. This helps reducing air and water pollution.

The impact of filling and operating of the dam and reservoir on the environment should be mitigated to have a sound mitigation plan for the GERD on Ethiopia and downstream countries. This could be achieved by increasing the filling period. During the filling period of the GERD, the downstream countries' river water level would be severely affected, and the effect could be noticed depending on the chosen scenario for filling the dam. So, it is evident that the longer the filling process would take, the lower the effect on the Nile water level on the downstream countries will be, and the time taken to bring back the water level to its average level would be shorter. It could take almost no time for the water level to return to the average level since the effect on the water level could be unnoticeable.

Moreover, as the dam's construction is in a tropical region, it has living animals among the constructed area. So, it will lead to animal migration to other safe places. It could also threaten animal life for animals that could not migrate during the filling of the reservoir or animals that struggle while finding other tropical areas to live. Accordingly, reforestation of tropical shrubs and fauna could be a solution for mitigating the GERD impact on the living creature to avoid endangering the plant life in this region and preventing global warming caused by the carbon dioxide emissions resulting from the decomposed plants under the reservoir. The most typical plantation on the proposed reservoir location is a tropical shrub. The initial filling of the reservoir floods the existing plant material, causing the plants to die and decompose. The decomposing plant matter settles to the reservoir's non-oxygenated bottom, decomposing and producing dissolved methane. The carbonation amounts for each reservoir volume scenario ranged from one to eight million tons of carbon dioxide emissions [23].

8. Cost Estimates

Water resource challenges are one of the most severe economic and social issues of the century globally. Egypt is one of the countries that faces significant issues, including groundwater, rainfall, and desalination water limitations, due to its fixed share of Nile water. Consequently, this study establishes the cost for the existing and new water resources in Egypt that require a monetary investment. Egypt has a 30-billion-cubic-meter water shortage; it requires at least 110 billion cubic meters of water yearly to meet its needs. However, it now possesses just 80 billion cubic meters, of which 55,5 billion cubic meters are supplied by the Nile [24].

The following sections discuss alternative water resources (mitigation measures) that Egypt could use to reduce the negative effects of GERD on water availability in the country. A cost plan is also designed to provide an estimate of the economic impact of the GERD on Egypt as a result of these mitigation measures. Starting by the smart taps, they play a vital role in saving water or decreasing water consumption. It is preferred that the government makes people pay for smart taps as there are around 25 million households in Egypt. The minimum cost of smart taps could be up to 800 EGP based on surveying their prices in various websites. Accordingly, it would be a considerable amount of money to be covered by the country when they could use such an amount in another field is essential as well.

Greywater for irrigation is considered an effective water resource. Single Residential home should expect to pay between 62538.81 EGP to 124984.27 EGP for a grey water system and an additional EGP 20535.13 for installation [25]. This does not include licenses or the price of retrofitting a home in order to install a system. Therefore, an average cost of 60000 EGP is a good estimate for cost of the grey water system, licenses, and installation per residential home.

Water Desalination is considered in this study. It is already one of the initiatives taken by Egypt. It was recently announced that the government intends to invest around 135 billion EGP until 2030 to double the amount of desalinated water used in the country's drinking water [26].The desalination projects are part of the government's efforts to better use the country's water resources, particularly in light of future Nile water shortages due to the construction of the Grand Ethiopian Renaissance Dam. In Egypt, the cost of desalination ranges from EGP 10 to EGP 15 per cubic meter of water, which is extremely costly, with electricity accounting for 44% of the whole cost [24].

Moreover, rainwater harvesting can be collected and used to irrigate gardens and lawns, as well as purified and used to operate washing machines and other home appliances to augment the municipal supply. Approximately 51 billion cubic meters of rain fall in Egypt each year, according to the UN’s Food and Agriculture Organization (FAO) data, nearly equaling Egypt's portion of the Nile's yearly water flow. There are three different price ranges for collecting rainwater. The first one is the lowest one, which cost 2400 EGP using a 55-gallon rain barrel with a spigot [27]. The second is using a 5000-gallon polyethylene storage tank ‘dry’ system installed costs 40,000 EGP [27]. The last and highest cost is the steel tank, sprinkler, and water treatment system, and it costs 240,000 EGP [27]. In this study, the cheapest way of collecting rainwater was chosen.

Table 6 shows each resource and its cost estimate, as well as the total amount needed for all the water resources to be implemented. Finally, the total cost of the mitigation plan is estimated at approximately 877 billion Egyptian Pounds.

Table 6. Cost Estimate for all the water resources needed to be implemented

Water Resources	Amount (millions)	Cost/unit	Total Cost (Billions)
Smart Taps	25 household	800	EGP 20.00
Greywater system	12 household	60000	EGP 720.00
Harvesting Rainwater (55-Gallon)	1 rain barrel	2400	EGP 2.40
Water desalination plants	--	--	EGP 135.00
			EGP 877.40

9. Conclusion

The Grand Ethiopian Renaissance Dam (GERD) was planned to be constructed on the Blue Nile River by the Ethiopian government in 2011. Large dams like this one would have devastating effects on Egypt and Sudan, which are located downstream. In this work, the authors examined potential dam operation scenarios from the perspective of the countries affected by them. The study also covered topics including water management in Egypt and ways to lessen the impact of GERD on the environment, as well as how to manage water resources in Egypt.

In conclusion, this research aimed to examine the opening of the sluice gates under different filling years and discharges while maintaining a constant upstream water level. The decision-making process involved the calculation of four parameters: the Froude number, the efficiency, the energy loss, and most significantly, the submergence factor. One of the main limitations of this study is getting data about the GERD. Tables 3 and 4 show that the most effective hydraulic jump is a steady jump, which has a non-negative submergence factor throughout all filling scenarios. However, negative submergence factor and oscillatory jumps were avoided to protect the riverbanks and riverbed from erosion and damage. The results showed that the safest and most widely accepted operating scenario is to open 5 gates (4.56-meter opened gates) with 10 filling years, as this minimizes the number of Froude numbers.

Additionally, this research characterized and evaluated the environmental implications of the GERD throughout its construction, filling, and operational phases and how to mitigate these impacts through water conservation management to make up for anticipated water level declines. Results showed that 877 billion EGP would be needed to fully implement the management strategy, which includes tapping into other water supplies. Future studies can further explore how the discharge will affect the performance of electricity generation at the Aswan High Dam (AHD).

10. Declarations

10.1. Author Contributions

Conceptualization, S.A.E.B.; methodology, S.A.E.B., N.H., Z.A., M.E., M.A., and H.N.; software, A.A.; validation, S.A.E.B., N.H., Z.A., M.E., M.A., and H.N.; formal analysis, S.A.E.B.; A.A., investigation, S.A.E.B.; A.A.; data curation, S.A.E.B., and A.A.; writing—original draft preparation, N.H.; writing—review and editing, S.A.E.B. A.A.; visualization, A.A., N.H., Z.A., M.E.; supervision, S.A.E.B.; project administration, S.A.E.B.; All authors have read and agreed to the published version of the manuscript.

10.2. Data Availability Statement

The data presented in this study are available in the article.

10.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

10.4. Conflicts of Interest

The authors declare no conflict of interest.

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