communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01821-w

Grand Ethiopian Renaissance Dam can generate sustainable hydropower while minimizing downstream water deficit during prolonged droughts

Check for updates

Essam Heggy[1,2] ✉, Abotalib Z. Abotalib[1,3], Jongeun You[4], Emmanuel Hanert[5,6] & Mohamed Ramah[5,7]

Optimizing hydropower generation from the Nile upstream mega-dams during prolonged droughts while minimizing the downstream water deficit is the cornerstone in resolving the ongoing major water conflict in the Eastern Nile River Basin. A decade of negotiation and mediation has been unsuccessful, mainly due to the hydraulic uncertainties associated with operating the Grand Ethiopian Renaissance Dam during prolonged droughts. Based on the negotiation outcomes, we provide comprehensive assessments of the efficiency of multiple drought-mitigation policies for the impact of dam operation. Our results suggest it can generate almost optimal hydropower without a noticeable downstream deficit during wet, average, and temporary drought flow conditions. For prolonged drought, we identify an ideal operation policy allowing the Grand Ethiopian Renaissance Dam to generate a sustainable energy of 87% of its optimal hydropower without generating additional downstream water deficit. Furthermore, we provide four intermediate policies demonstrating enhanced upstream hydropower generation while minimizing dam-induced downstream water deficits. Our findings attempt to bridge the negotiation disparities in the Nile hydropower mega-dams operations during prolonged drought and foster an actionable and collaborative framework.

The Nile is the longest continental river on Earth; it traverses eleven countries and runs through diverse climatic, topographic, environmental, and socio-economical landscapes[1] (Fig. 1). Flowing across five climatic zones (equatorial, humid, semi-arid, arid and Mediterranean), the Nile River represents a unique hydrological and environmental system that is an essential freshwater resource, especially for downstream riparian countries located in the hyper-arid Eastern Sahara (e.g., Egypt and parts of Sudan)[2,3]. The annual flow rate of the Nile River has witnessed enormous variations over the late Holocene, as recorded in the river landscape and the sediments left behind within the Nile gorge and surrounding tributaries[4]. In modern history, the Nile's flow controlled every aspect of life for downstream countries, including periods of famine associated with extreme droughts and times of prosperity when the river's flow was average or above average[5], as well as human health for thousands of years[6].

More recently, the average annual natural flow of the Nile has been consistently decreasing since 1900, even before the era of establishing mega-dams along its main course, due to changing precipitation patterns over the Nile River Basin[7,8]. For instance, the average yearly flow at Aswan decreased from 109 bcm (billion cubic meter, $10^9 m^3$) between 1871 and 1897, to ~86 bcm between 1900 and 2002[8] (Fig. 2). The construction and operation of mega-dams on the Nile, since the 1960s, has been subject to disputes that attract global attention to water allocation and management in the Nile River Basin[9]. Today, the Grand Ethiopian Renaissance Dam (GERD) on the mainstream of the Blue Nile, which has a maximum storage capacity of 74 bcm, and the Aswan High Dam (AHD), which has the largest reservoir

---

[1]University of Southern California, Viterbi School of Engineering, Los Angeles, CA, USA. [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. [3]Department of Geology, National Authority for Remote Sensing and Space Sciences, Cairo 1564, Egypt. [4]Department of Political Science and Public Administration, Northern Michigan University, Marquette, MI, USA. [5]Earth and Life Institute, UCLouvain, Louvain-la-Neuve, Belgium. [6]Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Louvain-la-Neuve, Belgium. [7]Geophysical sciences department, National Research Centre, Giza, Egypt.
✉e-mail: heggy@usc.edu

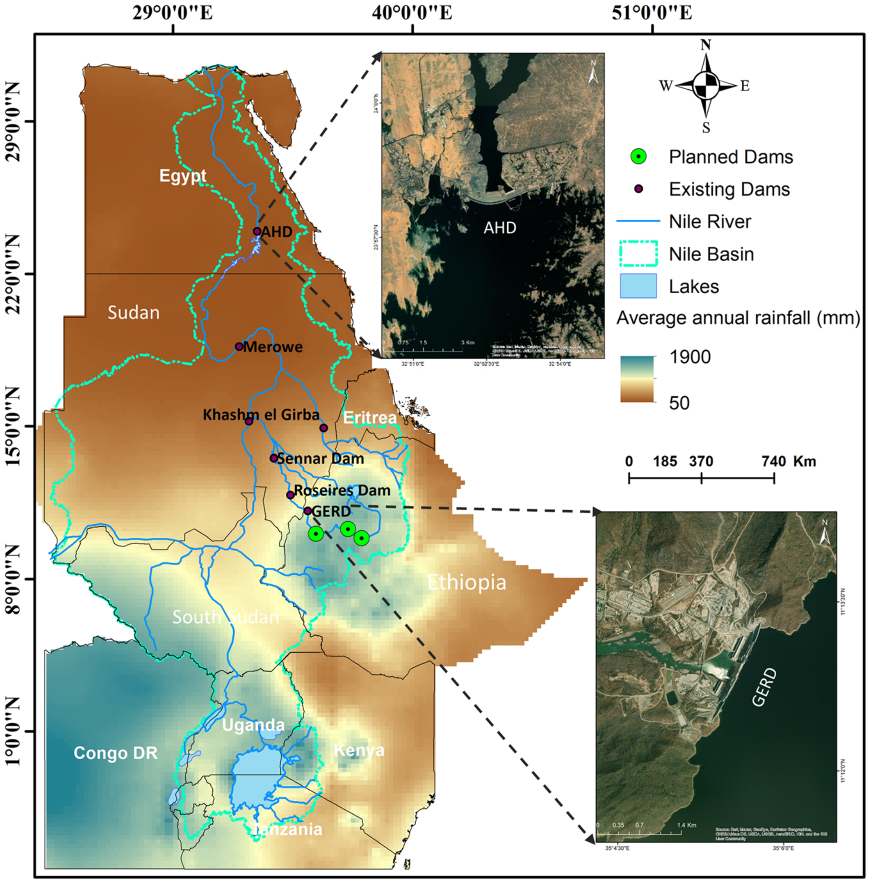

Fig. 1 | Hydro-climatic map of the Nile River Basin. The Map shows the locations of the mega-dams with average annual precipitation distribution over the basin. The precipitation data are based on the CRU TS Version 4.05, during the period of 1900–2010.

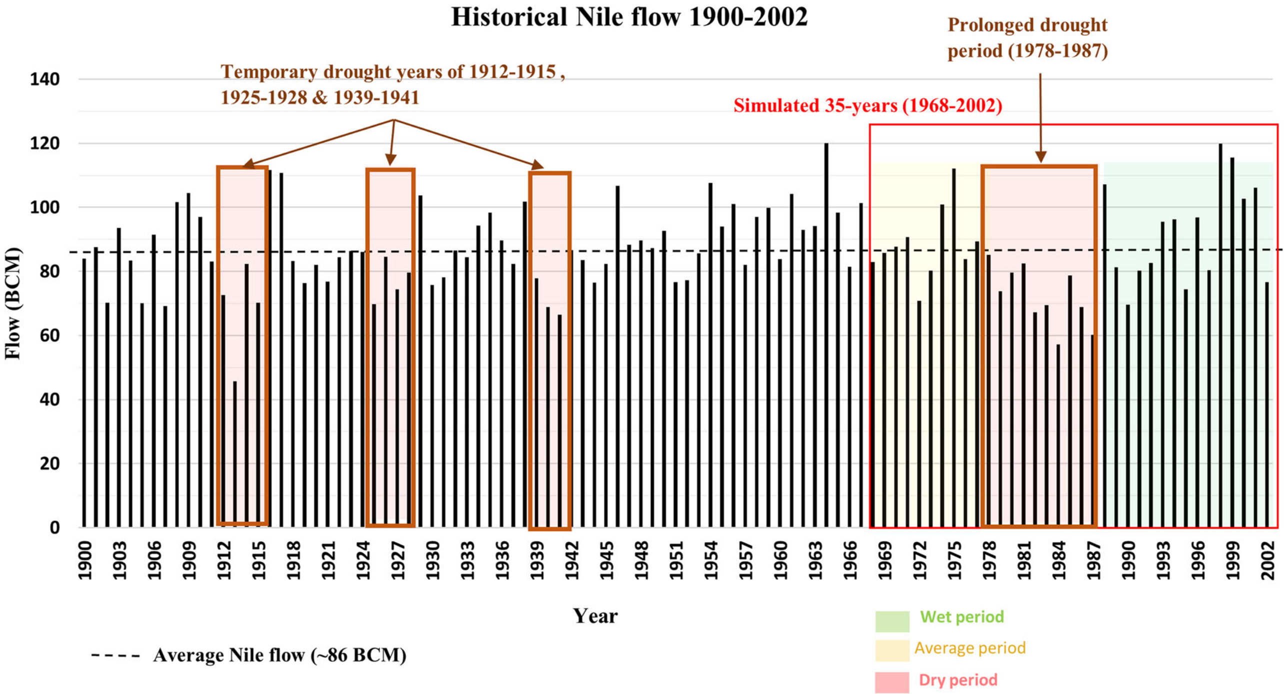

Fig. 2 | Historical annual naturalized flows at Aswan. These flow volumes include the upstream obstructions for the period 1900–2002[15,49,50].

capacity in Africa of ~162 bcm, entirely control the river's flow, overriding its natural drivers. Combined, the storage of the two mega-dams accounts for ~280% of the average annual river flow at Aswan[10]. GERD has the largest hydropower generation in Africa, and it is expected to generate up to ~16,000 GWh of electricity annually, compared to the ~10,000 GWh generated from AHD. The above underscores the different usage of both dams, which address different challenges across the river. For instance, Ethiopia has minimal electricity services, with only 45% of the population having electricity access, which places the country at one of the lowest per capita consumption rates of electricity in Africa. GERD intends to address this pressing power shortage upstream, doubling the electricity production in Ethiopia and serving as a regional energy hub for other African countries. Meanwhile, AHD primarily serves as a strategic water reserve downstream against prolonged droughts[11,12]. More details on the needs of both upstream power and downstream water can be found in Supplementary Note 1.

The four filling phases of the GERD reservoir started in July 2020 and benefited from mostly favorable wet flow conditions (three wet years in 2020, 2021, and 2022, and one average year in 2023) and the high initial storage of AHD of ~138 bcm[13]. However, lacking a functional framework with the AHD during the filling and operating stages has resulted in divisive perceptions of GERD's impacts on water resources and electricity generation[14] in downstream countries during prolonged droughts. The rising disparities between the riparian countries are further intensified by the lack of confident predictions of the Nile's future flow, which could lead to severe socioeconomic problems during prolonged drought conditions similar to the period of 1978–1987[15]. Climate model projections struggle to determine whether the mean annual precipitation will increase or decrease in response to climate change[16]. Multiple global and regional climate models, however, indicate that there would be fewer light and moderate precipitation events globally (0.1–2.0 mm/hr), whereas the intensity and frequency of heavy (0.1–10 mm/hr) and major (>10 mm/hr) precipitation events will likely to increase[17–19]. Similarly, daily river flow data derived from high-resolution general circulation models were used to derive decadal global river flow projections up to the year 2100, which indicate a considerable rise in the frequency and intensity of droughts[18]. Consequently, changes in rainfall intensity and distribution can lead to more pronounced seasonal variability in river flow[1]). During the rainy periods, the Nile experience higher flows, however, during the dry periods, the river flow is reduced[35]. Regionally, several studies forecast that the major river basins in Africa, such as the Niger, Congo, and the Nile River Basin[20], are likely to witness an increasing frequency of extreme droughts and floods under climate change[21,22]. All of the above provide legitimate causes for upstream damming to regulate the flow and generate sustainable hydropower. However, it also raises concerns about the downstream impacts[23]. More details on the downstream water stress and upstream electricity needs are summarized in Supplementary Note 1, respectively.

Since the Ethiopian authorities started building the GERD in 2011, the Blue Nile River Basin countries, Egypt, Sudan, and Ethiopia, have negotiated for over a decade on filling and operation[24]. In 2019, two proposals emerged: The Egyptian proposal and the Ethiopian proposal of the National Independent Scientific Research Group (NISRG)-2019 committee. Both agreed on the first stage of filling GERD, which would reach a minimum operation level of 595 m above mean sea level (amsl, note that reservoirs levels mentioned in our analysis are in meters referred to the amsl), equivalent to ~18.4 bcm of storage over two years (Supplementary Table 1). However, they diverged on the amount of water to release in the second filling stage and operation during prolonged drought periods (Supplementary Table 1). In 2020, negotiations mediated by the United States government and the World Bank in Washington DC aimed to reconcile the disparities between the Nile River Basin countries. The mediators suggested a proposal introducing the first GERD filling phase to reach a minimum operation level of 595 m (18.4 bcm) in two years. In the second filling phase, GERD should release a minimum of 37 bcm/yr and impound the rest of the annual flow (on average ~49 bcm/yr) until reaching its maximum capacity of 74 bcm[25].

Regarding the long-term operation, they suggested that the GERD would operate between its whole supply level (640 m) and its optimal operating level (625 m) during normal hydrological conditions, i.e., under the river average and wet flow status (Supplementary Table 1). However, during prolonged droughts, the GERD Operation Rule Level (ORL), which can also be referred to as Minimum Operation Level (MOL), should be minimized to release the water amount above 603 m instead of 625 m to reduce the water budget deficit at AHD[25]. The Washington DC draft proposal defined the prolonged drought as: if the average release from GERD over the preceding 4 hydrological years is <39 bcm, the GERD will release a total of 100% of the storage above 603 m over the following 4 mitigation release year[25,26].

Only the Egyptian side endorsed the above proposal, seeing that it would minimize the water deficit at AHD. However, the Ethiopian side withdrew from the negotiation, appealing that these suggested measures would severely limit GERD's capacity to generate electricity and called for defining the prolonged drought as a period of four consecutive years with an average annual flow below 35 bcm and not 39 bcm[25] (For more details on the significance of these suggested values, refer to Supplementary Note 2). While no agreement has been reached, the three countries established the normal operation rule (i.e., wet and average, non-drought conditions) for the GERD, which would operate between its full supply level (640 m) and its optimum operating level (625 m)[25–27]. The remaining two points of persistent disparities are the prolonged drought definition and the associated mitigation measures that would be implemented during GERD operation to minimize the downstream water budget deficit at AHD that rests largely disagreed upon. The above is perceived as the primary technical cause impeding reaching an excusable framework between the river countries.

To address the above disparity and unlock the negotiation to reach a win-win operational framework, it is crucial to answer two questions: (1) what is the best definition of prolonged drought in the context of climate uncertainty, and (2) how can GERD and AHD operate jointly during this extreme hydroclimate condition. In particular, what is the suitable operation rule level GERD should maintain under a prolonged drought to sustain hydropower generation from GERD while reducing the downstream water budget deficit? Answering these two questions requires introducing a reasonable definition for prolonged drought conditions and assessing the benefits and impacts of the previously suggested drought-mitigation operation policies (Supplementary Table 1) under this extream condition. In addition, suggesting more operation policies to fill the gap between these suggested proposals is crucial to advancing the negotiation process to reach a collaborative framework. Hence, the disparities accentuated by the ongoing conflicts and socioeconomic instabilities in Egypt, Ethiopia, and Sudan are resolvable. The above crucial answers are not fully addressed in the previous studies[15,28–33].

Thus, to answer these questions and support the ongoing negotiations, our study introduces the critical level of AHD at 165 m (~78 bcm) as the threshold for defining the prolonged drought and the start of mitigation measures activation once the reservoir draws below this level. The rational justifying this threshold is detailed in section "Materials and methods". Our approach solves the disparities in the number and volume of flow under the future hydroclimatic uncertainties over the Nile River Basin. Moreover, the study applies the above-suggested prolonged drought definition to investigate the impacts and benefits of previously suggested operation policies that can address the uncertainties in the negotiation process associated with both mega-dams operations during prolonged drought. Furthermore, to support the negotiation, we used the max-min negotiation approach by suggesting four intermediate-negotiations policies to fill the gaps and achieve a win-win policy that reduces potential adverse downstream impacts between the proposals that fully addresses the Egyptian concern (P1), and the one that maximizes upstream hydropower generation, meeting the Ethiopian demand (P7), during prolonged droughts (Supplementary Table 2). The study simulation utilizes the naturalized flow data at Aswan from 1900 to 2002, which are part of the Eastern Nile RiverWare Model (ENRM). We use the historical Nile flow period of 1968 to 2002 to simulate the interaction between GERD and AHD water levels under various climatic conditions, such as average, dry (i.e., period of drought), and wet conditions (for more details, see below the Material and Methods section). Our study mainly focuses on the drought period, which is the main point of disparity in the negotiations. We consider the simulation initial water levels of GERD (620 m, the fourth filling level) and AHD (180.4 m, December 2023)[34] and assume that the summer of 2024 will be the last filling phase of GERD in order to reach its optimal level at 625 m. Finally, we quantify the direct economic consequences of seven simulated mitigation policies,

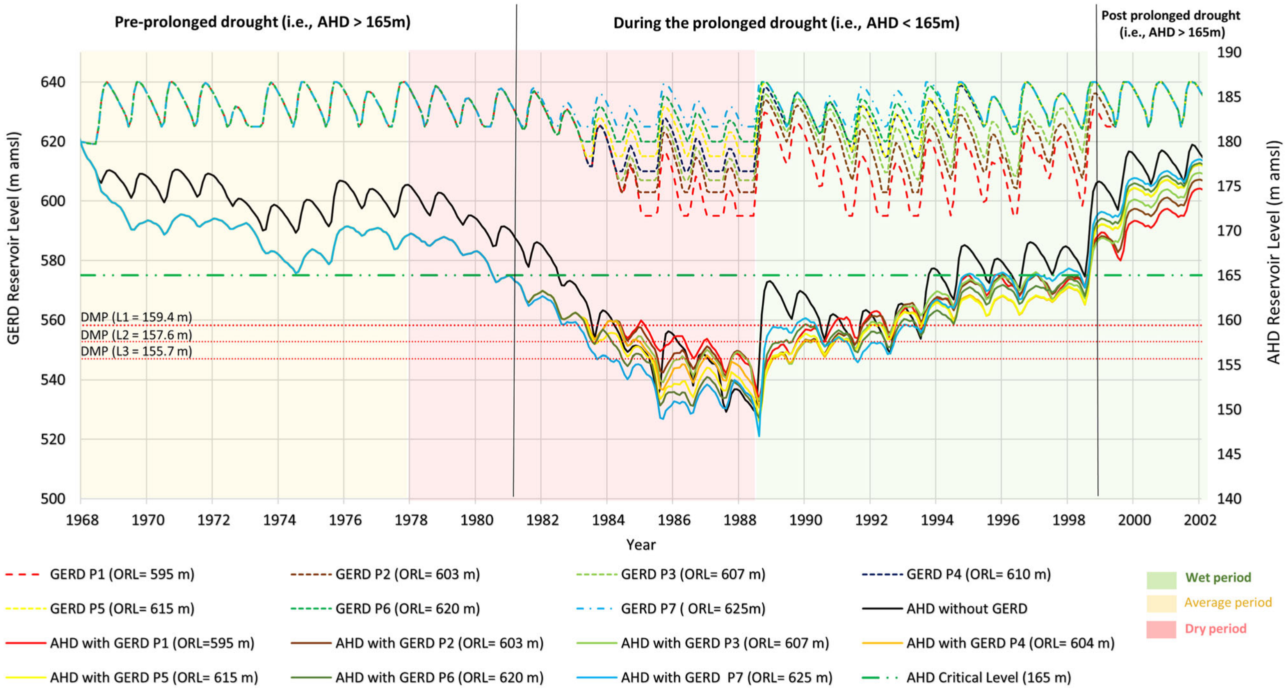

Fig. 3 | The interaction between AHD and GERD water levels under the seven polices and during the period of 1968–1977. The monthly time-step simulation (started from December 1967) results of GERD and AHD levels interaction under the seven GERD suggested operation policies during the selected historical flow period of 1968–2002. This period includes the above-average flow period of 1968–1977 followed by the prolonged flow period of 1978–1987 and near wet period of 1988–2002. The simulation considers the initial level of AHD and GERD as of December 2023; we start the simulation with an AHD level of 180.4 m, equal to ~152 bcm and GERD fourth filling year level of 620 m to equal ~42.5 bcm.

which can provide the decision-makers and mediators with a quantifiable assessment of different options to resolve the main points of disparity to reach an executable framework ensuring sustainable water and hydropower resources for all parties. Our simulated operation policies show that during normal operation under average and wet flow conditions (i.e., non-drought), GERD can generate optimal hydropower without noticeable downstream triggered deficit. We identify an optimized policy for prolonged droughts where GERD can generate sustainable energy of more than 87% of its optimal hydropower without triggering a dam-induced downstream water deficit. Our suggested intermediate solutions to the outcomes of negotiations show an enhanced hydropower generation for GERD while minimizing the dam-induced downstream water budget deficit to bridge the gap between the two ends, reconciling the persistent disparity.

Results

The GERD reservoir is filled when its level reaches the normal/optimal operation level at 625 m (49.5 bcm) and then changes to normal operation mode between 625 m and the full supply level of 640 m (74 bcm)[27]. The main downstream concerns (i.e. Egypt) are the potential water shortage and power reduction at AHD throughout GERD filling and operation during prolonged drought periods[25,27]. Egypt's drought management policy is triggered if the AHD storage falls below 60 bcm (~159.4 m)[32]. The Drought Management Policy (DMP) measures involve three levels: (1) a reduction of 5% of the Aswan High dam downstream release if its storage falls below 60 bcm, (2) a reduction of 10% if the storage falls below 55 bcm, and (3) a reduction of 15% if the storage falls below 50 bcm[32]. The most crucial factor governing the downstream impacts from filling and operating GERD depends on the flow conditions in the Eastern Nile River Basin (i.e., average, dry, and wet)[35]. GERD authorities filled the reservoir for the fourth year (Supplementary Table 3) with an adjustable rate during the favorable wet years[4]. In the summer of 2024, the fifth filling year is expected to be the last filling phase, as GERD will reach its normal/optimal operation level at 625 m (49.5 bcm). In fall 2024, GERD will transform into operation mode between 625 m and its full supply level of 640 m.

The question for that operation phase is: what operation rule level should GERD maintain during prolonged drought conditions to minimize the dam-induced water deficit at AHD? To answer this question, we simulated GERD and AHD's water levels and energy production for seven suggested GERD operation policies (P1–P7) under prolonged drought conditions[25,27]. In particular, our simulated operation policies quantify the evolution of water storage and hydropower generation at both AHD and GERD during prolonged droughts, as shown in Figs. 3–6.

The study simulation results consider the extended period of 1968–2002, which is classified into three periods: (1) Pre-prolonged drought (i.e., AHD > 165 m), (2) during prolonged drought (i.e., AHD < 165 m), and (3) Post prolonged drought (i.e., AHD > 165 m) as detailed below. The advantage of this approach is that instead of considering complex climatic conditions to assess the flow state, we use the downstream AHD critical level of 165 m (~78 bcm) to reflect the level of downstream water stress during prolonged droughts. All the simulation starts with the levels of GERD and AHD almost similar to their levels in December 2023 of 620 m and 180.4 m, respectively.

Pre-prolonged drought (AHD > 165 m)

When the AHD is above the critical drought level of 165 m as in 1968–1980, as shown in Fig. 3, the GERD hydropower generation and the AHD water deficit are not affected by any of the considered policies (Figs. 3–6). However, the hydropower generation at AHD will decrease from the operational value of 8293 GWh/yr (without GERD during this period) to 7720 GWh/yr (with GERD) (Fig. 5). Under pre-prolonged drought, GERD operation in all simulated policies will affect the hydropower generation at AHD with an average loss of 572 GWh/yr, which costs ~13.2 million USD/yr with a cumulative loss of 171 million USD per the entire simulated period of 13 years (1968–1980), considering the average price of 1 business GWh between Ethiopia and Egypt to be 23,000 USD[36] (Table 1).

During Prolonged drought (AHD < 165 m)

When the AHD is below the critical level of 165 m (1981–1998, Fig. 3). In all simulated policies, the GERD and AHD hydropower generations, and AHD water deficit will be affected as follows:

P1 policy (based on NISRG suggestion and implemetning the herein prolonged drought definition): The results of the simulation policy P1, where the operation rule level of GERD will decrease from 625 m to 595 m, show that the average annual hydropower generation from GERD will decrease from 14,027 GWh/yr (operation rule level = 625 m), to 12,275 GWh/yr (operation rule level = 595 m) in Fig. 4 with loss of 1752 GWh/yr that would cost ~40.3 million USD/yr (Fig. 4, Table 1). The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 4050 GWh/yr (with GERD) with a loss of 2373 GWh/yr (Fig. 5), which costs ~54.6 million USD/yr (Table 1). On the other hand, the natural cumulative water deficit at AHD decreased from 38.8 bcm (without GERD) to 37.9 bcm (with GERD operation rule level = 595 m) with a gain of 0.9 bcm, which has an equivalent economic value of ~0.8 billion USD to Egypt (Table 1).

P2 policy (based on Washington DC draft proposal and implemetning the herein prolonged drought definition): The results of the simulation policy P2, where the operation rule level of GERD will decrease from 625 m to 603 m, show that the average annual hydropower generation from GERD will decrease from 14,027 GWh/yr (operation rule level = 625 m) to 12772 GWh/yr (operation rule level = 603 m) with a loss of 1255 GWh/yr (Fig. 4) that should cost at ~28.9 million USD/yr. The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3704 GWh/yr (with GERD) with a loss of 2728 GWh/yr (Fig. 5), which costs ~62.7 million USD/yr (Table 1). Additionally, the cumulative water deficit at AHD is increased from 38.8 bcm (the natural deficit without GERD) to 45.5 bcm triggered by GERD operation rule level = 603 m, which increased Egypt's water budget deficit by 6.7 bcm (Table 1) distributed along ten years (1984–1993) (Fig. 6). This has an equivalent negative economic impact of 6.03 billion USD.

P3 policy (Suggested by this study): The results of the simulation policy P3, where the operation rule level of GERD will be decreased from 625 m to 607 m, show that the average annual hydropower generation from GERD will decrease from 14,027 GWh/yr (operation rule level = 625 m) to 13.017 GWh/yr (operation rule level = 607 m) with loss of 1010 GWh/yr (Fig. 4) corresponding to ~23.2 million USD/yr. The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3627 GWh/yr (with GERD) with a loss of 2796 GWh/yr corresponding to ~64.3 million USD (Fig. 5, Table 1). In addition, the cumulative water deficit at AHD increased from 38.8 bcm (the natural deficit without GERD) to 51.2 bcm triggered by GERD operation rule level = 607 m, increasing Egypt's water budget to a loss of 12.4 bcm (Table 1) distributed along ten years (Fig. 6). This has an equivalent economic impact of 11.16 billion USD.

P4 policy (Suggested by this study): The results of the simulation policy P4, where the operation rule level of GERD will decrease from 625 m to 610 m, show that the average annual hydropower generation from GERD will decrease from 14,027 GWh/yr (operation rule level = 625 m) to 13,464 GWh/yr (operation rule level = 610 m) with loss of 563 GWh/yr (Fig. 4) corresponding to ~12.9 million USD/yr. The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3437 GWh/yr (with GERD) with a loss of 2986 GWh/yr (Fig. 5), corresponding to ~68.7 million USD/yr (Table 1). Additionally, the cumulative water deficit at AHD increased from 38.8 bcm (the natural deficit without GERD) to 55.8 bcm triggered by GERD operation rule level = 610 m, which increased Egypt's water budget to loss, 17 bcm distributed over 11 years (Fig. 6). This has an equivalent economic impact of 15.3 billion USD (Table 1).

P5 policy (Suggested by this study): The results of the simulation policy P5, where the operation rule level of GERD will decrease from 625 m to 615 m, show that the average annual hydropower generation from GERD will be reduced from 14,027 GWh/yr (operation rule level = 625 m) to 13,620 GWh/yr (operation rule level = 615 m) with loss of 407 GWh/yr (Fig. 4) corresponding to ~9.4 million USD/yr. The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3265 GWh/yr (with GERD) with a loss of 3158 GWh/yr (Fig. 5, Table 1), corresponding to ~72.6 million USD/yr (Table 1). On the other hand, the cumulative water deficit at Aswan High dam increased from 38.8 bcm (the natural deficit without GERD) to 55.06 bcm triggered by GERD operation rule level = 615 m, which increased Egypt's water budget to a loss of 16.26 bcm distributed over 11 years (Fig. 6). This has an equivalent economic impact of 14.6 billion USD.

P6 policy (Suggested by this study): The results of the simulation policy P6, where the operation rule level of GERD will decrease from 625 m to 620 m, show that the average annual hydropower generation from GERD will be reduced from 14,027 GWh/yr (operation rule level = 625 m) to 13,830 (operation rule level = 620 m) with loss of 197 GWh/yr (Fig. 4) corresponding to ~4.5 million USD/yr. The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3165 GWh/yr (with GERD) with a loss of 3258 GWh/yr (Fig. 5), which costs ~74.9 million USD/yr (Table 1). On the other hand, the cumulative water deficit at AHD increased from 38.8 bcm/10 years (the natural deficit without GERD) to 58.5 bcm/12 years triggered by GERD operation rule level = 620 m, which increased Egypt's water budget deficit by 19.7 bcm distributed over 12 years (Fig. 6) which has an equivalent economic impact of 17.7 billion USD.

P7 policy (No drought mitigation measures during prolonged drought): The results of the simulation policy P7, where the operation rule level of GERD is kept at level 625 m even with the AHD level going below 165 m, show that the maximum possible hydropower (also referred herein after as optimal hydropower) is generated during this period of 14027 GWh/yr (Fig. 4). The hydropower generation at AHD will decrease from the operational value of 6423 GWh/yr (without GERD) to 3382 GWh/yr (with GERD) with a loss of 3041 GWh/yr (Fig. 5), corresponding to ~69.9 million USD/yr (Table 1). On the other hand, the cumulative water deficit at AHD increased from 38.8 bcm (the natural deficit without GERD) to 63.5 bcm triggered by GERD operation rule level = 625 m, which increased Egypt's water budget by an additional 24.7 bcm distributed over 12 years (Fig. 6) which has an equivalent economic impact of 22.23 billion USD.

Post Prolonged drought (AHD > 165 m)

The simulation results of the seven proposed GERD operations during the period of 1999–2002 when the AHD returns above the critical drought level of 165 m. The GERD hydropower generation and the AHD water storage will not be affected in all simulated policies. However, the hydropower generation at AHD will decrease from the operational value of 8930 GWh/yr (without GERD) to 8283 GWh/yr (with GERD) on average. As shown above, the GERD operation in all simulated policies will change hydropower generation in AHD with a loss of 647 GWh/yr, corresponding to ~14.9 million USD/ yr (Table 1).

The simulation results of the rest of Nile's historical flow record of 1902–1967 (Supplementary Figs. 2–5, Table 4) show that the impact of GERD operation is minor and can be mitigated. GERD can operate most of the time under the Normal Operation Rule (NOR) between 625 m and 640 m, generating the maximum possible (i.e., optimal) hydropower of 15721 GWh/yr (Supplementary Table 4). In comparison, the AHD hydropower generation will decrease from the operational value of 8012 GWh/yr (without GERD) to 7395 (with GERD) GWh/yr with an average loss of 617 GWh/yr, corresponding to ~14.19 million USD/yr and cumulative of 922 million USD over the simulated 65 years, not considering future inflation (Supplementary Table 4). On the other hand, the cumulative water deficit at AHD increased from 0 bcm (without GERD) to 5.3 bcm triggered by GERD under simulated P1–P6, and 6.3 bcm under P7, which increased Egypt's water budget to a loss of 6 bcm, on average, distributed over five years (1917, 1928, 1929, 1945 and 1946) (Supplementary Fig. 5) which has an equivalent economic impact of 5.4 billion USD.

Table 1 | The impacts and benefits of GERD operation under the seven suggested GERD operation policies during the selected historical flow period of 1968–2002

	Pre-AHD prolonged drought level >165 m (1968–1980) (13 years)		AHD prolonged drought level <165 m (1981–1998[a]) (18 years)								AHD prolonged drought level > 165 m (1999–2002) (4 years)	
Simulation period	**Without GERD**	**P1–P7**	**Without GERD**	**P1 (595 m)**	**P2 (603 m)**	**P3 (607 m)**	**P4 (610 m)**	**P5 (615 m)**	**P6 (620 m)**	**P7 (625 m)**	**Without GERD**	**P1–P7**
Drought management policy[b]	×	×		√	√	√	√	√	√	√	×	×
Cumulative water deficit (bcm) at AHD (natural + GERD-related)	0	0	38.8	37.9	45.5	51.2	55.8	55.06	58.5	63.5	0	0
Number of years with deficits at AHD	0	0	10	11	10	10	11	11	12	12		
The cumulative water deficit triggered by only GERD operation (bcm)	–	–	–	Gain +0.9	Loss −6.7	Loss −12.4	Loss −17	Loss −16.26	Loss −19.7	Loss −24.7	–	–
Estimate of the cumulative cost of the GERD-related water deficit (billion USD)	0	0	–	Gain +0.8	Loss −6.03	Loss −11.16	Loss −15.3	Loss −14.6	Loss −17.7	Loss −22.23	0	0
Average annual AHD hydropower generation (GWh/yr)	8293	7720	6423	4050	3704	3627	3437	3265	3165	3382	8930	8283 (on Ave.)
The average annual AHD hydropower generation loss triggered by GERD operation compared to without GERD (GWh/yr)	–	572	–	2373	2728	2796	2986	3158	3258	3041	–	647
The economic cost of average annual AHD energy loss under GERD operation compared to without GERD (million USD/year)	–	13.2	–	54.6	62.7	64.3	68.7	72.6	74.9	69.9	–	14.9
Average annual GERD hydropower generation (GWh/yr)	–	13,898	–	12,275	12,772	13,017	13,464	13,620	13,830	14,027	–	17,153 (on Ave.)
The average annual GERD hydropower generation difference between P7 and other simulated policies P1–P7 (GWh per year)[b]	–	-	–	1752	1255	1010	563	407	197	0	–	–
The economic value of average annual GERD hydropower generation difference between P7 and other simulated policies P1–P6 (million USD per year)	–	–	–	40.3	28.9	23.2	12.9	9.4	4.5	0	0	0

[a] The year 1998 had a high flood volume that started at the flood session in June month.

[b] The drought management policy measures involve (1) a reduction of 5% of the AHD downstream release if the falls below 60 bcm, (2) a reduction of 10% if the storage falls below 55 bcm, and (3) a reduction of 15% if the storage falls below 50 bcm.

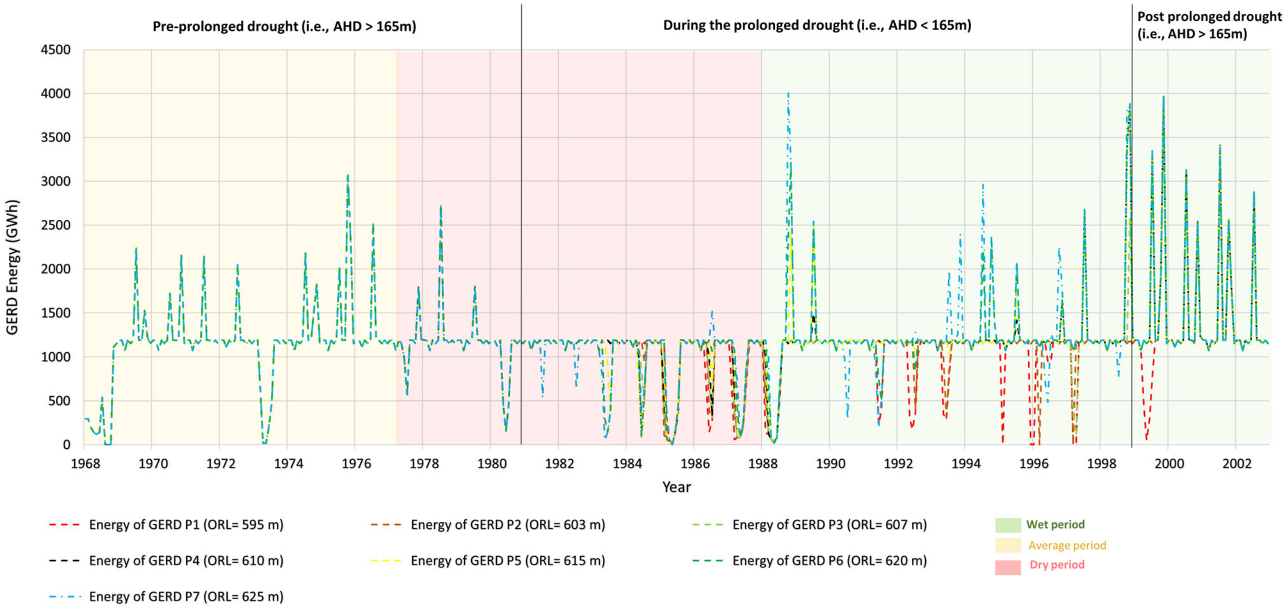

Fig. 4 | The monthly time-step simulation results for the GERD hydropower generation. The simulation is under the seven suggested GERD operation policies using the selected historical flow period of 1968–2002 that includes the average flow period of 1968–1977 followed by the prolonged drought flow period of 1978–1987 and near wet period of 1988–2002.

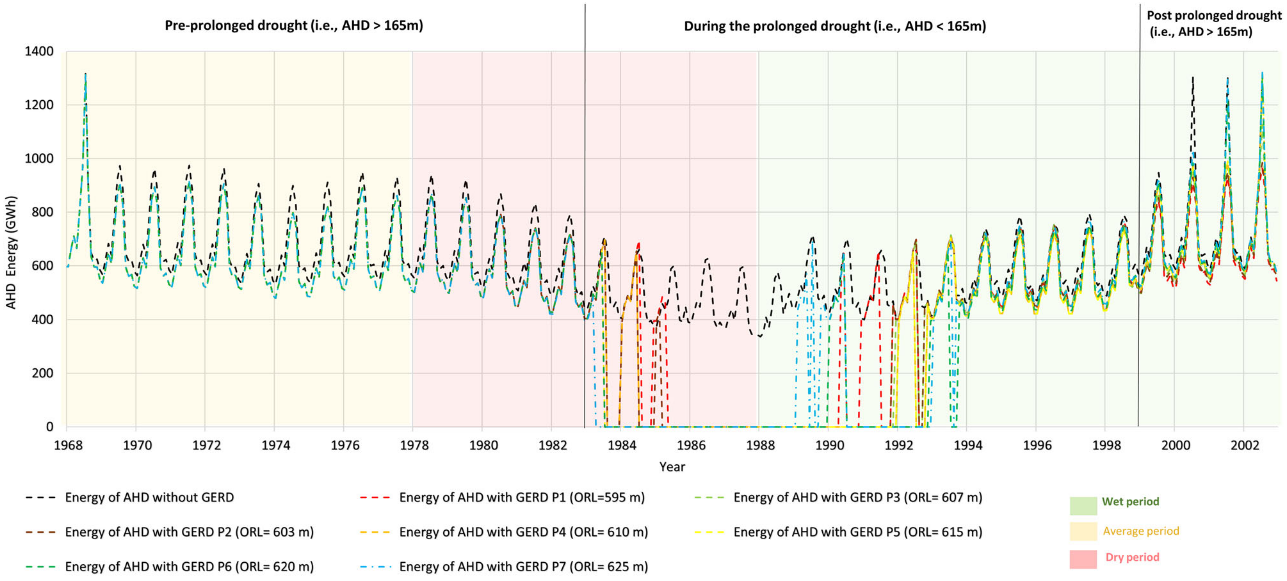

Fig. 5 | The monthly time-step simulation results for the AHD hydropower generation. The simulation is under the seven suggested GERD operation policies using the selected historical flow period of 1968–2002 that includes the average flow period of 1968–1977 followed by the prolonged drought flow period of 1978–1987 and near wet period of 1988–2002.

Discussion and recommendations

Our study simulates the efficiency of seven proposed operation policies to mitigate the upstream and downstream impacts for GERD and AHD under suggested defination of the prolonged drought state, where the AHD drawdown is below its critical level of 165 m (~78 bcm). These proposed operation policies are based on outcomes of the negotiation rounds (NISRG, 2019 and Washington, DC), in addition to four suggested policies by our study herein. Our results fill a key gap left by previously proposed policies in considering the prolonged drought (similar to 1978–1987). In particular, we focus on the water budget and hydropower generation deficit at AHD and energy generation from GERD using the historical flow period of 1968–2002, which includes the most representative prolonged drought period (1978–1987). This allows us to account for the pre-and post-drought impacts of AHD below and above 165 m and to test the efficiency of the suggested policies in the normal flow conditions (Figs. 3–6).

Our results pertain to three main findings that constrain uncertainties regarding the risk of downstream water shortage and hydropower generation reduction and, therefore, provide ways to bridge the disparities among drought-mitigation measures and policies[25,27].

First, our findings show that expressing the prolonged drought in terms of the critical level of AHD (~165 m) can solve the disagreement on the number of dry years and associated flow volume under any future climatic fluctuation. In addition, the operation rule level of GERD controls the downstream impacts on water deficit at AHD and hydropower

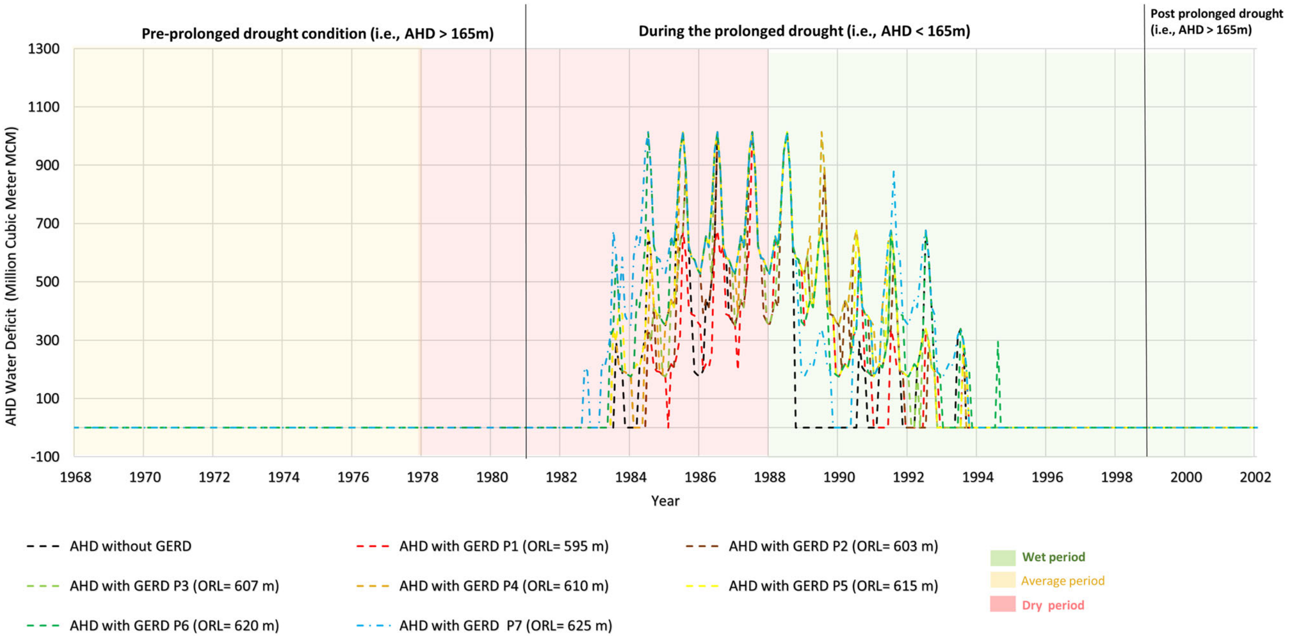

Fig. 6 | The monthly time-step distribution of the water deficit at AHD during the simulated period 1968–2002.

generation from both AHD and GERD under prolonged drought conditions. In the typical case, during the wet and average periods when the AHD level is above the critical level of 165 m and GERD at the optimum operation level of 625 m, GERD can generate the maximum possible hydropower energy (i.e., optimal hydropower), and no water deficit at AHD will be triggered by GERD operation. However, during the prolonged drought period, when the AHD level is below the critical level of 165 m, while maintaining GERD at the optimum operation level of 625 m to maximize hydropower generation, the hydropower generation at AHD will be decreased. As, the Nile flows will be reduced, and will not be able to maintain the AHD level. The AHD level will be kept at a low levels all over the year that can reach below it minimum operation level of 159 m, which can decrease the average annual hydropower generation at the AHD from 6423 GWh/yr (without GERD) to 3382GWh/yr (with GERD operation rule level = 625 m) with a loss reaching 47% as shown in Table 1.

Second, our findings quantify the difference between the seven operation policies, based on NISRG, Washington DC, and the newly suggested four policies. The GERD hydropower gains under simulated GERD operation policies are minimal compared to the downstream water deficit and hydropower generation losses at AHD. For instance, all seven GERD policies can generate more than 87% of the optimal hydropower generation (Table 1, Fig. 7a). Consequently, the equivalent economic cost difference of the GERD-generated energy between the simulated policies ranges from 0–40.3 million USD/yr and 0–725 million USD for the entire period where AHD drought level below 165 m of 1981–1998 (Table 1). On the other hand, the simulated GERD operation policies are more detrimental downstream at the AHD water level, resulting in a considerable water budget deficit and energy reduction resulting from the GERD's operations compared to the case without GERD. The hydropower generation from AHD decreased in all the simulated GERD policies as follows: in P1, AHD energy generation decreased by 36%, P2 decreased by 42%, P3 decreased by 43%, P4 decreased by 46%, P5 decreased by 49%, P6 decreased by 50%, and P7 decreased by 47% (Table 1, Fig. 7a). The equivalent economic cost difference of AHD hydropower generation between the simulated policies ranges from 54.6–69.9 million USD/yr and ~0.983–1258 million USD from 1981 to 1998 where AHD is below its critical level of 165 m.

In addition, the cumulative water budget deficits triggered by GERD operation are increased, compared to the natural water deficit without GERD (38.8 bcm), in all simulated proposed policies, except for the P1 policy which reduces the natural water deficit at AHD by 0.9 bcm (37.9). The rest of the simulated GERD operation policies P2–P7 increase the cumulative deficit: P2 by 6.7 bcm, P3 by 12.4 bcm, P4 by 17 bcm, P5 by 16.26 bcm, P6 by 19.7 bcm and P7 by 24.7 bcm (Fig. 6b). The equivalent economic cost difference of AHD water deficit triggered by GERD operation between the simulated policies P2–P7 ranges from 6.03–22.23 billion USD/yr (Fig. 7b, Table 1).

According to the above, the economic hydropower loss of GERD under all suggested collaborative and drought-mitigation policies ranges from 0.081–0.725 billion USD during the entire period (18 years) of AHD drought level below 165 m (Table 1). While the cumulative economic loss in Egypt associated with the above water deficits and hydropower generation at AHD ranges from 0.178 to 23.5 billion USD integrated over 18 years (Fig. 7c). Regardless of whether operating GERD under any suggested policy P1–P7, GERD energy production will increase by 197–1752 GWh/yr (Table 1), with an equivalent economic gain of 0.081–0.725 billion USD integrated over 18 years of AHD drought level below 165 m. One can note that the annual average GERD hydropower generation differences between all simulated policies are minor compared to the significant differences in downstream water shortages and AHD energy losses among the simulated policies P2–P7, which account for 7.4–23.5 billion USD, respectively. The only policy that show a minimal economic impacts of GERD operation on the AHD water budget deficit, and hydropower generation is P1, which will loss the Egyptian economy 0.178 billion USD.

It is important to note that under the seven simulated policies, GERD will not lose hydropower energy during all drought periods; it should only minimize hydropower generation levels during prolonged drought periods. However, during temporary drought periods (Supplementary Fig. 2) similar to 1912–1915, GERD almost generated the optimal hydropower generation, as shown in Figs. 2–5, and Table 4 of the supplementary information.

The above potential water shortages are the main concern for crop irrigation in Egypt because, in addition to their economic impacts, they can increase socioeconomic instability to alarming levels due to unemployment in the agricultural sector and a rise in food prices[37]. The GERD impact study by Deltares[37] suggests that a shortage of 1 bcm of the Egypt water budget would reduce agricultural land by 123,480 ha, which in turn would decrease the agricultural production values by 0.430 billion USD, increasing imports by 0.15 billion USD, causing a loss of income for 290,000 farmers. As the

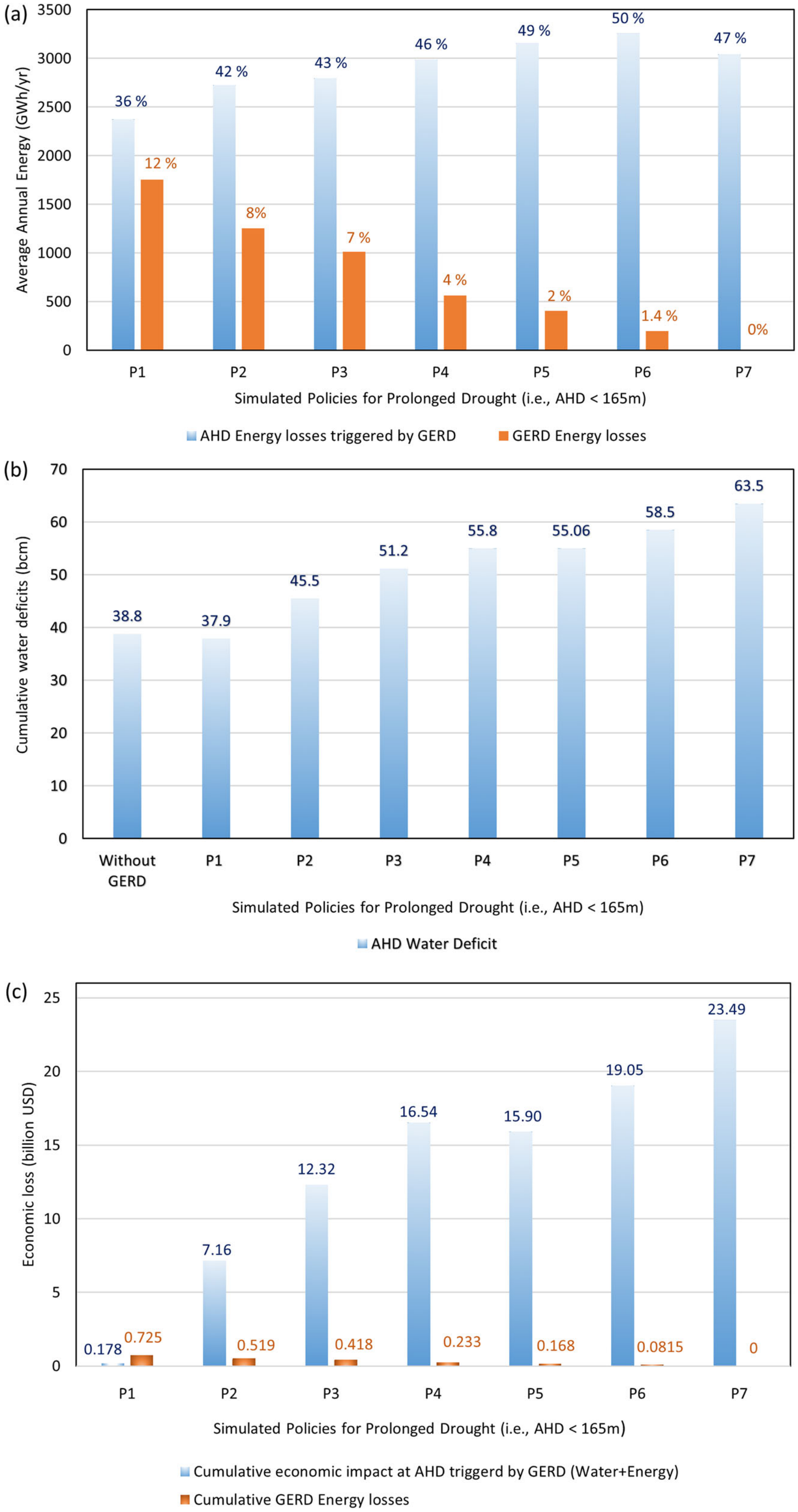

Fig. 7 | The comparison between the AHD and GERD losses under the simulated seven polices. **a** The comparison between the average annual losses of the hydropower generation at AHD compared to the state without GERD and hydropower generation at GERD compared to the optimal energy generation of GERD optimum operation level = 625 m (P7), under the seven suggested policies during the prolonged drought period of AHD level below 165 m (1981–1998). **b** The cumulative water deficit at AHD with GERD compared to the state of natural drought without GERD, under the seven suggested policies during the prolonged drought period of AHD level below 165 m (1981–1998, 18 years). **c** The compression between the cumulative economic impact of water deficit and hydropower generation at AHD triggered only by GERD operation, and economic value of hydropower loss from GERD compared to the optimal hydrpower generation of GERD optimal operation level = 625 m under the seven suggested policies during the prolonged drought period of AHD level below 165 m (1981–1998, 18 years).

Eastern Nile River Basin continues to witness rapid population growth with more demand on the water and energy sectors, climate fluctuation and persisting socioeconomic instabilities[38] may accentuate the differences in the impacts of the seven considered drought-mitigation policies on both water management and hydropower generation.

Several studies explored the GERD's economic impacts and mitigations under multiple collaborative scenarios[33] using the Computable General Equilibrium (CGE) model. However, the budget required to achieve the suggested mitigation measures in these studies is not evaluated in the analysis using CGE models[39]. Herein, we have considered several possible GERD operation policies under the prolonged drought period leading to AHD level draws below 165 m to portray the value of collaboration and the adverse impacts of persistent disparities in the GERD's filling and operation plans.

Moreover, our investigation shows that the risk of downstream water deficit is not limited to the GERD's initial filling period and can extend into its long-term operations, especially during prolonged drought periods. As such, the risks of downstream water deficit during operation should be considered under increasing uncertainties about the future frequency of drought periods. Hence, the sequence of flow periods following the initial GERD filling plays an instrumental role in assessing downstream risks. For instance, in Fig. 3, although the GERD's initial filling period started with almost wet years where GERD is filled by 42.5 bcm[40] and AHD is practically full at a level of 180.4 m, the inter-annual flow variability of the Nile can change the flow from wet to average conditions, and then to dry years, which would trigger a measurable downstream water deficit in Egypt in the short-term[35], especially during the prolonged drought under long-term operation (Fig. 3).

Furthermore, during wet and average periods, operating the GERD at Normal Operation Rule (non-drought condition) between 625 m and 640 m is recommended to maximize the hydropower generation from GERD; however, fixing the operation rule of GERD between 625 m and 640 m during prolonged drought periods will worsen the situation of the AHD reservoir level to reach near its dead storage at 147 m, leading to increases of the water deficit at AHD from the natural water deficit of 38.8 bcm (without GERD) to 63.5 bcm (with GERD operation rule level = 625 m, P7). Also, it will diminish hydropower energy production at the AHD by 3041 GWh/yr, which costs ~70 million USD/yr (Table 1). In contrast, operating GERD to minimize the operation rule level of GERD to 595 m (P1) only when the AHD drought level is below 165 m will reduce the natural water deficit at AHD by 0.9 bcm. Moreover, minimizing GERD operation rule level as suggested in the simulated policies P2–P6 (603–620 m) can reduce the significant impacts triggered by GERD compared to fixing GERD operation level above 625 m (P7). Additionally, the GERD's refilling impacts are drastic during and straight after the first impoundment until the system regains its original balance, as seen in Fig. 3. During this recovery period, the AHD is most vulnerable to prolonged droughts. Our analysis indicates that the impacts on AHD will be severe if a drought period similar to the one in the 1980s recurs during or soon after the GERD's initial filling, as shown in Fig. 3.

Third, from a hydropower perspective, our findings show that the GERD can only generate the designed power capacity for three months each year during the summer flood season (July, August, and September) (Fig. 4). Eldardiry and Hossain (2021)[41] suggest that only 8 of the 13 turbines will operate during these few months of the flood period and will most likely be idle for the rest of the year. The latter supports Asfaw's[42] hypotheses that the GERD is oversized and that constructing two smaller dams could have produced more electricity than the GERD, while the construction cost of the two dams would have been at least 40–45% of the GERD's cost. Our simulations results in Figs. 3–4 are aligned with these studies[41,42] and suggest that the adverse impacts of operating upstream megadams as the GERD under considered policies are significant at the AHD, reducing the reservoir's storage and hydropower energy while yielding a comparatively small benefit in hydropower generation. This difference is naturally accentuated during prolonged drought periods.

Eventually, AHD will unavoidably come to or near its dead storage during its operation in response to a prolonged drought like the 1980s drought period. Underestimating these hydrological facts, i.e., the repeated droughts and the high interannual flow variability that have been witnessed throughout the Nile's history[35,43,44] (Fig. 2), adversely impacts the ability to settle disparities between the Nile's riparian countries' water management plans for these mega-dams. As these aspects remain widely unaddressed and thus represent the source of disputes in the Nile River Basin, the present study carefully suggests solutions for addressing them. To simultaneously refill both reservoirs would be more perplexing than the current circumstances of the GERD's initial filling, as today, the AHD reservoir is fortunately at almost its total capacity of ~150 bcm[34]. The repetition of such a favorable setup in the future remains subject to several climatic and anthropogenic factors that are far from being predictable and quantifiable. As such, reaching a collaborative GERD filling and operation framework is crucial for mitigating the adverse impacts of water and hydropower shortages beyond its initial filling.

The operation rules of the GERD have a direct impact on the length of the recovery period for the Aswan High Dam's water levels. For instance, during prolonged droughts, if the GERD prioritizes water retention to ensure its own operational needs (e.g., hydropower generation, P7), this could significantly delay the recovery of AHD levels, as less water would be available downstream. On the other hand, if the GERD operates with a more coordinated release strategy aligned with the needs of downstream countries (P1), it can help stabilize and potentially accelerate the recovery of the AHD's water levels. For example, releasing water from GERD during the dry season or during periods of low inflow can support the AHD in maintaining or recovering its levels more quickly.

Our study concludes with three recommendations to facilitate joint and cooperative transboundary management of the Nile flow under the current need for upstream damming. The first pertains to understanding that upstream mega-dams on the Nile have a measurable impact on downstream countries during the operation stage or depending on the Nile's hydrological conditions (i.e., prolonged drought). These impacts can be significantly reduced if a mutually functional operation framework can be established between the upstream and downstream countries. Such a framework relies on assessing the riparian countries ‘ water and hydropower needs and their mutual understanding of the effects of the river's interannual flow variability on their water and electricity management schemes in light of upcoming climatic changes, as attempted in this study.

Second, our simulation suggests there may be more cost-effective solutions than constructing mega-dams upstream of the Nile River for hydropower generation. This result is aligned with previous preliminary studies[41]. In the case of GERD, the system is designed to operate at a near-high peak flow frequency. However, significant flows occur only during the few months of the rainy season[41,42]. As such, the dam cannot produce the designed power capacity for more than three months of the year. Therefore, lowering the operation rule level of GERD below 625 m, as suggested in our study, only when the prolonged drought period of AHD level would enable GERD to generate sustainable amount of its optimal hydropower while minimizing the downstream dam-induced water budget deficit to manageable levels (Fig. 7c). As such, the P1 policy is an ideal trade-off where GERD can generate sustainable energy of more than 87% of its optimal hydropower during prolonged droughts without triggering a dam-induced downstream water deficit. In addition, the suggested intermediate policies (P2–P6) show slightly enhanced hydropower generation for GERD compared to P1 while triggering a dam-induced downstream water budget deficit ranging from 6.7 to 19.7 bcm during the prolonged drought period. Compared to the 24.7 bcm dam-induced downstream water budget deficit in P7, the latter shows an enhancement in the trade-off between hydropower generation from GERD and water volume at AHD.

Third, the average annual GERD hydropower generation difference between the seven simulated and suggested policies is minor. In contrast, the difference between the downstream water deficit and hydropower generation at the AHD is substantial. Hence, as an alternative approach to providing incentives for cooperative transboundary management where Egypt can consider supporting Ethiopia in mitigating any economic losses associated with any decrease in GERD hydropower generation when applying the drought mitigation policies, as the costs of these upstream losses that occur in a few specific years of drought are insignificant compared to the costs from the water deficit downstream under the non-collaborative situation (Fig. 7). For instance, some mutual power trade agreements at prices that favor both countries (i.e., lower than global market prices) to foster cooperation. It is important to note that Egypt has achieved self-sufficiency in electricity since June 2015. In 2022, the country possessed an electricity surplus of more than 25 percent[45]. In early August of 2023, Egypt launched a plan to reduce local power consumption by cutting the amount of natural gas used in generating electricity to direct the savings for export to increase levels of foreign currency[45]. However, neither the current state of energy sector in Egypt requires import power nor does the current large economic debt allow for the increasing imports of any kind[38]. Ultimately, acknowledging that both upstream and downstream riparian countries may witness adverse economic impacts under the cooperative operation is crucial for reaching a functional framework that avoids larger ones during the forecasted natural variabilities of the river's flow.

Materials and methods

The present study utilizes the Eastern Nile RiverWare Model (ENRM), which has almost up-to-date reservoir entries and policies. The ENRM, developed initially using the rule-based RiverWare platform[46], is a versatile modeling tool for river and reservoir operations, enabling scheduling, forecasting, planning, policy evaluation, and decision-making. It can model hydrologic processes, hydropower production, energy uses, water rights, ownership, and quality. The software offers two solvers for multi-objective analysis: rule-based simulation and linear preemptive goal programming. Furthermore, RiverWare includes utilities and analysis tools, such as a system control table, a data management interface, a multiple-run manager, and a scenario manager, enhancing usability and facilitating real-time operational decision-making. Moreover, RiverWare offers various hydropower modeling tools, which accurately represent hydropower goals in various planning and operational models[47].

ENRM contains all the hydraulic characteristics of the Eastern Nile River Basin, including those of all the reservoirs on the Nile, such as AHD, Merowe, Rosaires, Sennar, Gebel Aulia, Khashm Elgirba, Tekeze, Atbara and Setit, Finchaa, and Tana Lake in addition to demand structures and gauges. The ENRM characteristics, parameters, and schematics were initially constructed by Wheeler and Setzer[48]. In the ENRM, specific operation procedures are given to each reservoir to represent the water management plans in terms of prioritized rules to describe the volume of releases, diversions, and losses from each reservoir. Moreover, the inflow data in the Nile River are expressed in terms of naturalized flow at Aswan for the period between 1900 and 2002 (Fig. 2), which are mainly compiled from different sources, including Deltares and Dongola gauge station[49,50] and Wheeler et al.[15].

ENRM updates

The updated version of ENRM used in this study includes five main modifications as follows:

a. The AHD Minimum Power Generation level: the public release of ENRM considered the minimum power elevation level of AHD to be equal to the AHD dead storage level = 147 m, while AHD authority and previous publications[51–53] confirmed that the minimum power generation elevation is 159 m, below which the turbines are bypassed to deliver water downstream. Accordingly, in the updated version of ENRM used here, we change AHD's minimum power generation elevation to 159 m instead of 147 m.
b. In the operation stage, we added the rules of seven simulated policies into the policy file for each simulated policy, as discussed in detail below.
c. We updated the simulation policy to start with the most up-to-date pool elevation of GERD (~620 m) reached after the fourth filling year, December 2023. In addition, it is proposed that the fifth filling phase this year, 2024, will be the final filling phase, as the GERD reservoir will reach its optimal operation level at 625 m (49.5 bcm) and it will transform into the normal operation state between 625 m and its full supply level of 640 m (74 bcm).
d. Considering the level of AHD as of December 2023, we start the simulation with an AHD level of 180.4 m, equal to ~152 bcm.
e. For the hydropower generation setup, all simulated policies adopt the target generated power from GERD to be 1600 MW[33].

Simulation parameters

Selecting historical flow periods. Our simulations are based on naturalized flow data at Aswan from 1900 to 2002, which are already part of the ENRM[15]. This naturalized dataset reconstructs the original and unaltered river's hydraulic flow conditions by restoring the flow alteration from irrigation, damming, and any water management activity[15,49,50] (Fig. 2). Based on the analysis of this dataset (Supplementary Fig. 1), we select a 35 years' historical flow period of 1968–2002 that starts with ten average flow years of 1968–1977 (88.4 bcm/yr) (Fig. 2) followed by the most representative drought period of the Nile River Basin 1978–1987 (72 bcm/yr) then followed by 15 years of near-wet flow during the period of 1988–2002 (92.2 bcm/yr) (Fig. 2). Our rationale for selecting this period is to account for the interannual variability of the Nile flow, which gives a holistic insight into the effectivity of the proposed policies under the different flow conditions and under both AHD level situations below and above 165 m.

In addition, we simulated the rest of the historical flow record period of 1902–1967, which mainly incorporated wet and average periods and a few short dry periods. The aim of simulating this period is to examine the suitability of our suggested policies during all possible temporary and prolonged periods of wet, average, and dry conditions of the available historical flow record for the Nile River (1902–2002).

Simulation of GERD operation policies. In 2019, NISRG agreed upon the first filling stage, in which the GERD will reach the minimum turbine operation level of 18.4 bcm in two years[25]. However, they differed on the second stage of GERD filling to get from 18.4 to 74 bcm. The Ethiopian proposal suggested releasing 31 bcm/yr, while the Egyptian proposal suggested releasing 40 bcm/yr[25,27] during the second filling stage. As for the operation stages under a prolonged drought period, both sides disagreed on the definition of "prolonged drought" as a function of flow volume, as detailed in the introduction. Moreover, both sides diverged on the operation rule level that GERD should be upon during the prolonged drought period, as the Egyptian side proposed the GERD operation rule level should be maintained at or above 595 m. At the same time, the Ethiopian side has not proposed drought mitigation measures, (Supplementary Table 1)[27]. In November, 2019 till February 2020, the Nile countries resumed the negotiation in Washington DC, where the World Bank and the USA were acting as mediators. Based on previously suggested proposals, the mediators proposed a compromise policy named the "Washington DC proposal draft." In the suggested proposal, the GERD should be filled to reach the minimum turbine level of 18.4 bcm in the first two years (Supplementary Table 1). After that, GERD authorities shall release 37 bcm/yr until the reservoir is filled to 74 bcm, and the GERD operation level must decline to 603 m[25–27] to maintain the downstream flow reduction during prolonged drought period (Supplementary Table 1). Only the Egyptian side signed the Washington DC proposal draft.

In September 2023, the fourth filling year, the GERD reservoir level reached 620 m, equivalent to ~42.5 bcm[40] (56% of total capacity). The Fifth filling is planned for the summer of 2024, and it is predicted to be the last filling over 5 years, where the reservoir is expected to reach its optimum operation level of 625 m (49.5 bcm) and then transform to operation mode. Thus, studying the initial filling scenarios of GERD is out of date at this stage. Hence, future negotiations will focus only on the operation policies, especially under a prolonged drought period, and mitigation measures for expected downstream water deficit, which are the main disparities that hinder reaching an executable framework between the Nile River Basin countries. In summary, a decade of negotiation failed to reach an agreement framework due to the disagreement on (1) the prolonged drought definition as a function of flow volume under future climatic uncertainties. As in the Washington DC draft proposal, the prolonged drought is defined as the average release from GERD over the preceding four hydrological years to be below 39 bcm[25], which was only agreed upon by Egypt, while Ethiopia called to redefine the prolonged drought as a period of four consecutive years with an average annual flow below 35 bcm[27], and (2) the drought mitigation measures to reduce the downstream water deficit at AHD, (i.e., the operation rule level GERD must reach to maintain the AHD hydropower generation and water level). The Egyptian side agreed upon the mitigation measure suggested by the Washington DC draft proposal, which stated that the GERD operation level must decline to 603 m to maintain the AHD level during the prolonged drought period. In contrast, the Ethiopian side withdrew from the negotiation due to concerns that the decline of the GERD operation level below 625 m would decrease its capability to generate the targeted hydropower amount.

Resolving the persistent disparities between the Eastern Nile River Basin countries and reaching a mutual win-win framework depends on providing a reasonable definition for prolonged drought and agreeing on the operation rule level of GERD. To address the above two points, our study suggests two measures:

First, we introduced the critical level of AHD a 165 m as the threshold expressing the prolonged drought condition. The drought mitigation measures should be activated whenever AHD draws below this level. However, above this level, the GERD should operate normally. The rationale for using the level of 165 m (78 bcm) as a threshold to designate prolonged drought is that both Egypt and Ethiopia agreed upon the same Minimum Operation Level (MOL) at 159 m and Critical Level (CL) at 165 m for the AHD as clearly mentioned in Helal and Bekhit[27] and its associated supplementary materials[27]. Thus, the reservoir volume between the MOL and the CL is designated as a strategic water reserve to be used to mitigate the drought conditions that may cause the AHD to drop to its MOL (159 m). Herein, we base on the above negotiation outcomes by introducing the agreed upon critical level of AHD of 165 m as a marked level designating the prolonged drought condition. Also, using the CL of 165 m is crucial as a proactive action to allow sufficient time to increase the releases from GERD to prevent AHD from reaching the MOL of 159 m and avoid triggering the AHD drought management policy. Hence, expressing the prolonged drought in terms of the critical level of AHD can solve the disagreement on the number of dry years and associated flow volume under any future climatic fluctuation. Moreover, considering the AHD critical level of 165 m as an expression of prolonged drought integrates water budget contribution from the flow of both the White and the Blue Nile, which is more realistic compared to considering only the flow from the Blue Nile. Furthermore, this allows us to consider the full hydraulic condition resulting from the entire river basin with its different climatic zones rather than depending only on the single one of the Blue Nile. Finally, this approach can also better reflect any potential reverse sapping from the groundwater system surrounding the AHD to its reservoir once it reaches below the water table[54,55].

Second, regarding the disparity on the operation rule level that GERD should invoke to mitigate the downstream water deficit at AHD resulting from the prolonged drought period, our study provides a comprehensive assessment of the impact and benefits of the previously suggested mitigation measures in (based on NISRG and Washington DC draft proposal). In addition, we applied the min-max negotiation approach to suggest four intermediate policies to fill the gaps between the previously suggested prolonged drought mitigation policies and reach a win-win policy. These suggested intermediate policies (P3–P6) aim to reduce potential adverse downstream impacts between the proposal that fully addresses the Egyptian concern (P1) and the one that maximizes upstream hydropower generation, meeting the Ethiopian demand (P7) during prolonged droughts. The above quantifies the disparities in these negotiations, facilitating converging toward an agreeable solution. The political advantages of these simulated policies lie in the use of a single metric that can independently be monitored to trigger collaborative efforts between upstream and downstream countries to provide relief to each other from the potential impacts of prolonged droughts. This would substitute the convoluted list of commitments requested from downstream countries for the upstream one that are often hard to commit under the river's high inter-annual flow variability.

Based on the above, our study focused on assessing the water budget and hydropower generation deficits at AHD and energy generation from GERD under a prolonged drought period, taking the example of the one from 1978 to 1987 (Fig. 2). We extended the simulation period for 35 years around this prolonged drought period, covering from 1968 to 2002. Covering this extended period allows us to assess the long-term impacts of prolonged droughts on the downstream water budget and hydropower generation deficits at both AHD and GERD, considering seven operation policies, depending on the level of AHD, as shown in Supplementary Table 2. The simulation starts with the water level of AHD (180.4 m) and GERD (620 m), considering that July 2024 will be the last GERD filling phase to reach its optimum operation level of 625 m (49.5) bcm, and it will turn to operation mode after the flood season of 2024.

It is important to note that our monthly time-step simulation of the GERD operation policies is based on the critical level of the AHD being set at 165 m and the monthly data exchange (at the start of every month) between GERD and AHD authorities (Supplementary Table 2). As such, the normal operation rule is when the level AHD is >165 m; the Drought-mitigation rule is when the level AHD is <165 m.

Minimum (Min)-Maximum (Max) approach. The Min-Max approach, often used in game theory and decision-making processes, can be effectively applied to address water conflicts by balancing the needs and interests of different stakeholders while minimizing potential losses and maximizing potential gains. This approach aimed to bring stakeholders together for discussions facilitated by neutral parties. Use the Min-Max approach to present scenarios where everyone's minimum needs are met, and collective benefits are maximized. Thus, we simulate the downstream and upstream impacts of the previously proposed policies (based on NISRG and Washington DC suggestions) in addition to four suggested intermediate policies by our studies to address the uncertainties in operation during prolonged droughts when AHD gets below the critical level of 165 m (Supplementary Table 2). All of the simulated GERD operation policies proposed that in a normal operation period, when the AHD level is >165 m, GERD will operate between the optimal operation level of 625 m and 640 m to generate the optimal hydropower generation as the three parties agreed upon. However, if the AHD level is below the critical level of 165 m during prolonged drought conditions, the simulated policies differ in the GERD operation rule level as follows:

P1 (based on NISRG suggestion): When the AHD level falls below the critical level of 165 m, the operation rule level of GERD should be reduced to 595 m instead of 625 m to maintain the AHD level and decrease the downstream water deficit. After the AHD level is restored to above the critical level of 165 m, the operation rule level of GERD should be back between 625 m and 640 m to generate the optimal energy, and so on (Supplementary Table 2).

P2 (based on Washington DC): When the AHD is below the critical level of 165 m, the operation rule level of GERD should be reduced to 603 m instead of 625 m to maintain the AHD level. After the AHD level is maintained above the critical level of 165 m, the operation rule level should be back between 625 m and 640 m to generate the optimal energy, and so on (supplementary Table 2).

P3 (Suggested by this study): When the AHD level is below the critical level of 165 m, the operation rule level of GERD should be reduced to 607 m instead of 625 m to maintain the AHD level. After the AHD level is maintained above the critical level of 165 m, the GERD operation rule level should be back between 625 m and 640 m, and so on.

P4 (Suggested by this study): When the AHD is below the critical level of 165 m, the operation rule level of GERD should be reduced to 610 m instead of 625 m to maintain the AHD level. After the AHD level is maintained above the critical level of 165 m, the GERD operation rule level should be back between 625 m and 640 m, and so on.

P5 (Suggested by this study): When the AHD is below the critical level of 165 m, the operation rule level of GERD should be reduced to 615 m instead of 625 m to maintain the AHD level. After the AHD level is maintained above the critical level of 165 m, the GERD operation rule level should be back between 625 m and 640 m, etcetera.

P6 (Suggested by this study): When the AHD is below the critical level of 165 m, the operation rule level of GERD should be reduced to 620 m instead of 625 m to maintain the AHD level. After the AHD level is maintained above the critical level of 165 m, GERD operation rule level should be back to 625 m, and so on.

P7 (No drought mitigation measures): The operation rule level of GERD will be kept between 625 m and 640 m; whatever the state of AHD is above or below, it is a critical level of 165 m to generate the optimal hydropower (Supplementary Table 2).

Economic impacts

The equivalent economic losses or gains are calculated using the estimated cost of the water deficit and the standard electricity prices in upstream and downstream countries[28,36,56]. In this regard, using more data can strengthen the quantification of economic impacts. For example, we can specify electricity revenue streams by applying different selling prices per customer. We can also use social discount rates to tally up costs and benefits. However, it requires more data that is not accessible at this point. Accordingly, in this study, we provide a simple linear economic calculation based on the direct financial impact as follows:

Costing hydropower: We used electricity prices for businesses in Egypt and Ethiopia to calculate the economic gain or loss of hydropower[36]. The electricity prices per kWh for businesses in both countries are nearly the same at 0.022 USD for Ethiopia and 0.024 USD for Egypt. It is important to note that these values are market-driven, and the ones used herein are the ones announced at the time of the submission. The prices are per kWh and include all items in the electricity bill, such as the distribution and energy cost, various environmental and fuel cost charges, and taxes[36]. In our study, we used the average value of 0.023 USD per kWh, equivalent to 23,000 USD per 1 GWh, for the economic calculations of energy cost.

Costing water deficits: The economic impacts of the Nile downstream water deficit at AHD in Egypt are reported in several studies[25,28,56]. Accordingly, the total economic impact of 1 bcm shortage is tentatively estimated to be 0.9 billion USD on average (for more details, see Supplementary Note 1), which we consider in this study.

Simulation sensitivity

It is important to note that the findings reported in our hydraulic simulation could have some quantifiable margins that do not alter the trends observed in our results. These include the uncertainties associated with using the historical versus stochastic flow models, the Nile riparian's current and projected socioeconomic states, and environmental concerns on water quality that are partially covered in a separate study[57]. The Nile River has a long record of more than 100 years of hydraulic flow measurements. Thus, we can select long-term historical flow sequences to simulate the river system behavior in response to the altered hydrological conditions imposed by upstream damming. However, using historical flow sequences to simulate the behavior of a river system may not be fully comprehensive as it undermines floods, droughts, and several combinations of flow irregularities[15]. Notably, the current disparities among the Eastern Nile River Basin countries in the negotiations primarily focus on the risks associated with prolonged droughts such as the one in the 1980s. Therefore, policymakers have agreed to use the observed historical flow series as the standard benchmark in several complex transboundary river basin negotiations[15,58]. Wheeler et al.[15] synthesized the advantages of using historical flows, which have three benefits. First, the transparency of simulations using historical flows, as they relate to flow measurements and real lived experiences, makes these simulations easily understood. Second, the modeling inputs are not subject to manipulation or bias by modelers[15]. Third, such an approach is especially advantageous in river basins like the Nile River, with significantly inconsistent climate change forecasts on precipitation and river inflow[15]. It is important to note that we only used the historical data from 1902 to 2002 and could not extend the analysis from 2002 to 2024 as the full flow data for the upstream tributaries of the Nile are not available at the present time for the authors to input into the ENRM. In addition, considering the period from 2002 to 2024 in our simulations will not change our findings as this period doesn't contain a prolonged drought sequence.

Moreover, the equivalent economic losses are calculated using the estimated cost of the water deficit cost and the standard electricity prices in upstream and downstream countries[36,56]. In this regard, using more data can strengthen the quantification of economic impacts. For example, we can specify electricity revenue streams by applying different selling prices per customer. We can also apply social discount rates to tally up costs and benefits. It is important to note that we used the average value of 0.023 USD per kWh, which is equivalent to 23,000 USD per 1 GWh, for the economic calculations of energy cost[36]; the latter value was the averaged one announced at the time of the submission of this study and hence the one considered in our analysis.

To address future climatic uncertainties, our study introduces the critical level of AHD of 165 m as the threshold of prolonged drought. When reached at any point in the future, the drought mitigation measures should be activated. As well as above this AHD level, the normal GERD operation will return. This approach is based on the prolonged drought period suggested by the two parties, which will cause the AHD drawdown below its critical level of 165 m. Hence, expressing the prolonged drought with the critical level of AHD can resolve the disagreement on the number of dry years and associated flow volume under any future climatic fluctuation.

The disadvantages of using the AHD level of 165 m (~78 bcm) as a drought threshold are that it may not give sufficient advance to implement water conservation efforts before the situation becomes critical[11]. For instance, it may limit the ability to implement adaptive measures, such as reducing water consumption or adjusting agricultural practices.

In our simulation, the annual release from AHD don't exceed than 55 bcm that can be monitored using several high resolution altimetry such as (Swot, G-realm, Theia… etc.)[59,60].

Furthermore, the hydro-political context surrounding both the GERD and the AHD is complex and multifaceted, involving a range of historical, geopolitical, economic, and environmental factors and negotiation disparities that are discussed in details in the recently published paper by Helal and Bekheit[27]. Our study provides a path forward to resolve the scientific disparities between the Nile River Basin countries and reach a win-win collaborative framework.

Finally, we simulated the impacts of GERD operation on AHD under several suggested policies. However, the GERD operation may have benefits or adverse effects on the Sudanese dams, which need to be simulated and studied separately and are not part of this study. Sudan has a larger water share per capita than Egypt; hence, its vulnerability to potential water shortage by GERD is substantially lower. Additionally, GERD will provide a needed regulation of the Blue Nile flow for Sudan, allowing more sustainable agricultural development in the southeastern part, which is advantageous. However, the expansion of agriculture developments in Sudan and, hence, the increasing need for crop irrigation could exacerbate the deficit in Egypt, which needs to be quantified in a separate study.

Data availability

All data required to generate the outcomes and figures of this study is made available at the following link in the Center for Open Science repository: https://OSF.IO/2Z8MQ.

Code availability

This study used an updated version of the public release of the ENRM which is available in https://OSF.IO/2Z8MQ. The original public release version of ENRM has been open requested by Dr. Kevin Wheeler from Oxford university.

Received: 15 April 2024; Accepted: 19 October 2024;
Published online: 09 December 2024

References

1. Said, R. *The River Nile: geology, hydrology and utilization* (Elsevier, 2013).
2. Dumont, Henri J. ed. The Nile: origin, environments, limnology and human use. Vol. 89. (Springer Dordrecht, 2009).
3. Awulachew, S. B., Smahktin, V., Molden, D. & Peden, D. (eds.) *The Nile River basin: Water, agriculture, governance and livelihoods* (Routledge, 2012).
4. Abotalib, A. Z. & Mohamed, R. S. Surface evidence supporting a probable new concept for the river systems evolution in Egypt: a remote sensing overview. *Environ. Earth Sci.* **69**, 1621–1635 (2013).
5. Hurst, H. E. Long-term storage capacity of reservoirs. *Trans. Am. Soc. Civ. Eng.* **116**, 770–799 (1951).
6. Abdel-Ghaffar, F., Sobhy, H. M., Metwaly, K. S., AbdEl-Monem, S. & Mehlhorn, H. Nile River, impact on human health in Egypt from pharaohs until now. In *Parasite and Disease Spread by Major Rivers on Earth: Past and Future Perspectives* (eds. Mehlhorn, H. & Klimpel, S.), 237–277 (Springer Chem, 2019).
7. Riehl, H. & Meitin, J. Discharge of the Nile River: a barometer of short-period climate variation. *Science* **206**, 1178–1179 (1979).
8. Tayia, A., Ramos Barrado, A. & Alonso Guinea, F. The evolution of the Nile regulatory regime: a history of cooperation and conflict. *Water Hist.* **13**, 293–317 (2021).
9. You, J. Policy conflict around the Grand Ethiopian Renaissance Dam. *World Water Policy* **9**, 960–972 (2023).
10. Mahmoud, M. R., Fahmy, H. & Garcia, L. A. Potential impacts of failure of the Grand Ethiopian Renaissance Dam on downstream countries. *J. Flood Risk Manag.* **15**, e12793 (2022).
11. Fouad, S. S. et al. Landscape-based regeneration of the Nile Delta's waterways in support of water conservation and environmental protection. *Ecol. Indic.* **145**, 109660 (2022).
12. Heggy, E., Sharkawy, Z. & Abotalib, A. Z. Reply to Comment in 'Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam filling scenarios. *Environ. Res. Lett.* **17**, 088002 (2022).
13. Ahmed, M., Abdelrehim, R., Elshalkany, M. & Abdrabou, M. Impacts of the Grand Ethiopian Renaissance Dam on the Nile River's Downstream Reservoirs. *J. Hydrol.* **633**, 130952 (2024).
14. Salman, S. M. The Grand Ethiopian Renaissance Dam: the road to the declaration of principles and the Khartoum document. *Water Int.* **41**, 512–527 (2016).
15. Wheeler, K. G., Jeuland, M., Hall, J. W., Zagona, E. & Whittington, D. Understanding and managing new risks on the Nile with the Grand Ethiopian Renaissance Dam. *Nat. Commun.* **11**, 5222 (2020).
16. Gabr, M. E. Impact of climatic changes on future irrigation water requirement in the Middle East and North Africa's region: a case study of upper Egypt. *Appl. Water Sci.* **13**, 158 (2023).
17. Papalexiou, S. M. & Montanari, A. Global and regional increase of precipitation extremes under global warming. *Water Resour. Res.* **55**, 4901–4914 (2019).
18. Giorgi, F., Raffaele, F. & Coppola, E. The response of precipitation characteristics to global warming from climate projections. *Earth Syst. Dyn.* **10**, 73–89 (2019).
19. Dai, A., Rasmussen, R. M., Liu, C., Ikeda, K. & Prein, A. F. A new mechanism for warm-season precipitation response to global warming based on convection-permitting simulations. *Clim. Dyn.* **55**, 343–368 (2020).
20. Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. & Kimoto, M. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sci. J.* **53**, 754–772 (2008).
21. Milly, P. C. D., Wetherald, R. T., Dunne, K. A. & Delworth, T. L. Increasing risk of great floods in a changing climate. *Nature* **415**, 514–517 (2002).
22. Tariku, T. B. et al. Global warming impact to River Basin of Blue Nile and the optimum operation of its multi-reservoir system for hydropower production and irrigation. *Sci. Total Environ.* **767**, 144863 (2021).
23. Fouad, S. S. et al. Egypt's waterways conservation campaigns under growing intrinsic demand and Nile upstream damming. *J. Hydrol. Regional Stud.* **50**, 101537 (2023).
24. Rashad, M. & Shaaban, M. Minimizing Risks Due to the Filling of the Grand Ethiopian Renaissance Dam on Egypt's Nile Flows. In *2022 IEEE International Conference on Power Systems Technology (POWERCON)*. (pp. 1–6). (IEEE, 2022).
25. Edrees, M. Letters dated (1 May and 19 June, 2020) from the Permanent Representative of Egypt to the United Nations addressed to the President of the Security Council. Digital Library of United Nations (2020).
26. Berhanu, B., Gebretsadik, Y. & Awulachew, S. B. Stage-Based Filling of Grand Ethiopia Renaissance Dam (GERD): Flexible, Adaptive, and Cooperative Approach. Nile and Grand Ethiopian Renaissance Dam: Past, Present and Future. 235–244 (2021).
27. Helal, M. & Bekhit, H. M. So near, yet so far: an Egyptian perspective on the US-facilitated negotiations on the Grand Ethiopian Renaissance Dam. *Water Int.* **48**, 580–614 (2023).
28. Heggy, E., Sharkawy, Z. & Abotalib, A. Z. Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam filling scenarios. *Environ. Res. Lett.* **16**, 074022 (2021).
29. Zhang, Y., Block, P., Hammond, M. & King, A. Ethiopia's Grand Renaissance Dam: implications for downstream riparian countries. *J. Water Resour. Plan. Manag.* **141**, 05015002 (2015).
30. Keith, B., Ford, D. N. & Horton, R. Considerations in managing the fill rate of the Grand Ethiopian Renaissance Dam Reservoir using a system dynamics approach. *J. Def. Model. Simul.* **17**, 33–43 (2017).
31. King, A. & Block, P. An assessment of reservoir filling policies for the Grand Ethiopian Renaissance Dam. *J. Water Clim. Change* **5**, 233–243 (2014).
32. Wheeler, K. G. et al. Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. *Water Int.* **41**, 611–634 (2016).
33. Basheer, M. Cooperative operation of the Grand Ethiopian Renaissance Dam reduces Nile riverine floods. *River Res. Appl.* **37**, 805–814 (2021).
34. Theia, water levels of rivers and lakes (Hydroweb). Available at: https://www.theia-land.fr/en/product/water-levels-of-rivers-and-lakes-hydroweb/ (2023).
35. Heggy, E., Ramah, M. & Abotalib, A. Z. Examining the Accuracy of Using a Single Short-Term Historical Flow Period to Assess the Nile's Downstream Water Deficit from GERD Filling: A Technical Note. *Earth Syst. Environ.* **7**, 723–732 (2023).
36. Global Petrol Prices. Retail energy price data. https://www.globalpetrolprices.com (2023).
37. Heggy, E., Sharkawy, Z. & Abotalib, A. Z. Reply to Comment on 'Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam filling scenarios' by Kevin Wheeler et al. *Environ. Res. Lett.* **17**, 128001 (2022b).
38. The World Bank. International Debt Statics. https://datatopics.worldbank.org/debt/ids/country/egy (2023).
39. Osman, R., Ferrari, E. & McDonald, S. Water scarcity and irrigation efficiency in Egypt. *Water Econ. Policy* **2**, 1650009 (2016).
40. Account. Ethiopian officials New Year event at Gerd Site. Borkena Ethiopian News. https://borkena.com/2023/09/12/ethiopian-officials-new-year-event-at-gerd-site/ (2023).
41. Eldardiry, H. & Hossain, F. Evaluating the hydropower potential of the Grand Ethiopian Renaissance Dam. *J. Renew. Sustain. Energy* **13**, 024501 (2021).
42. Asfaw. Ethiopia's Biggest Dam Oversized, Experts Say. Interview in International Rivers, https://archive.internationalrivers.org/resources/ethiopia%E2%80%99s-biggest-dam-oversized-experts-say-8082 (2013).

43. Conway, D. Future Nile river flows. *Nat. Clim. Change* **7**, 319–320 (2017).
44. Sutcliffe, J., Hurst, S., Awadallah, A. G., Brown, E. & Hamed, K. Harold Edwin Hurst: the Nile and Egypt, past and future. *Hydrological Sci. J.* **61**, 1557–1570 (2016).
45. Nader, N. Egypt electricity production up by 30,000 MW in 6 years: Ministry spokesperson. https://english.ahram.org.eg/NewsContent/3/16/473983/Business/Energy/Egypt-electricity-production-up-by-,-MW-in--years-.aspx (2022).
46. Zagona, E. A., Fulp, T. J., Shane, R., Magee, T. & Goranflo, H. M. RiverWare: A generalized tool for complex reservoir system modeling. *J. Am. Water Resour. Assoc.* **37**, 913–929 (2001).
47. Brown, C. M. et al. The future of water resources systems analysis: Toward a scientific framework for sustainable water management. *Water Resour. Res.* **51**, 6110–6124 (2015).
48. Wheeler, K. G. & Setzer, S. *"Eastern Nile RiverWare planning model"*, Report to Nile River Basin Initiative (Addis Ababa, 2012).
49. Sudan MoIWR. *Gage Flows at Dongola Station (Sudan Ministry of Irrigation and Water Resources, 2019)*. Valentin Blain Felizitas (2015) The Grand Ethiopian Renaissance Dam. (AV Akademikerverlag, 2019).
50. Van der Krogt, W. & Ogink, H. *Development of the Eastern Nile Water Simulation Model*. Report No. 1206020-000-VEB-0010 (Deltares, Delft, 2013).
51. Wheeler, K. G. et al. Exploring cooperative transboundary river management strategies for the Eastern Nile Basin. *Water Resour. Res.* **54**, 9224–9254 (2018).
52. Sharaky, A. M., Hamed, K. H. & Mohamed, A. B. Model-based optimization for operating the Ethiopian Renaissance Dam on the Blue Nile River. In *Grand Ethiopian renaissance dam versus Aswan high dam: A view from Egypt*, 119–148 (Springer, Cham, 2019).
53. Kamel, A. M., Amin, D. M. & Eldin, M. M. N. Assessment the harm from the Grand Ethiopian Renaissance Dam on the water inflow to Egypt. *Int. Res. J. Eng. Technol.* **6**, 218–225 (2019).
54. Abdelmohsen, K. et al. Response of deep aquifers to climate variability. *Sci. Total Environ.* **677**, 530–44 (2019).
55. Ramah, M., Heggy, E., Nasr, A., Toni, M., Gomaa, M. M., Hanert, E. & Kotb, A. Nubian aquifer linkage to the High Aswan Dam Reservoir: Initial assessments of processes and challenges. *J. Hydrol*. **644**, 131999 (2024).
56. Aty, M. A. Managing Risks on Egypt Water Resources Security: Climate Change and Grand Ethiopian Renaissance Dam (GERD) as Challenging Aspects. In: *Water Security Under Climate Change. Water Resources Development and Management* (eds Biswas, A. K., Tortajada, C.) (Springer, 2022).
57. Abotalib, A. Z. et al. Irreversible and Large-Scale Heavy Metal Pollution Arising from Increased Damming and Untreated Water Reuse in the Nile Delta. *Earths. Future* **11**, e2022EF002987 (2023).
58. Sandoval-Solis, S., Teasley, R. L., McKinney, D. C., Thomas, G. A. & Patiño-Gomez, C. Collaborative modeling to evaluate water management scenarios in the Rio Grande Basin. *J. Am. Water Resour. Assoc.* **49**, 639–653 (2013).
59. Abdelmohsen, K., et al. Watching the grand Ethiopian renaissance dam from a distance: Implications for sustainable water management of the Nile water. *PNAS Nexus*, **3**, pgae219 (2024).
60. Elhaddad, H. et al. Optimization of floodwater redistribution from Lake Nasser could recharge Egypt's aquifers and mitigate its excessive floods. *Commun. Earth Environ.* **5**, 385 (2024).

Acknowledgements

The authors are grateful to Dr. Elizabeth M. Palmer for the helpful discussions and proofing of this manuscript. This research is funded under support from the Zumberge Research and Innovation Fund of the University of Southern California, allocated to the Arid Climates and Water Research Center—AWARE. The US Department of State also funds part of this research under the Fulbright award to Heggy and Palmer. Heggy's research was carried out at USC under contract from the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) (SAA-00630). The funders had no role in the study design, data collection, analysis, publication decision, or manuscript preparation.

Author contributions

E.He., M.R., and A.Z.A. conceived the study and conducted the analysis. J.Y. and E.H. verified the modeling and examined the results. All authors wrote and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01821-w.

Correspondence and requests for materials should be addressed to Essam Heggy.

Peer review information *Communications Earth and Environment* thanks Jianshi Zhao, Mohamed Elshamy and the other, anonymous, reviewer for their contribution to the peer review of this work. Primary Handling Editors: Rahim Barzegar and Martina Grecequet. A peer review file is available.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2024