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Egypt's water budget deficit and suggested mitigation policies for
the Grand Ethiopian Renaissance Dam filling scenariosEssam Heggy^{1,2,*} , Zane Sharkawy³ and Abotalib Z Abotalib¹ ¹ University of Southern California, Viterbi School of Engineering, Los Angeles, CA 90089, United States of America² Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, United States of America³ Cornell University, Charles H. Dyson School of Applied Economics and Management, Ithaca, NY 14853, United States of America

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Abstract

The Nile River is a unique environmental system and essential water resource for its basin riparian nations. Population growth, changes in precipitation patterns, damming and usage rights disputes present extreme challenges in utilizing and managing the basin's primary water resource. These stress factors are of particular concern for highly populated Egypt, the furthest downstream recipient of the Nile's water flow. Previously, colonial agreements had granted Egypt and Sudan the majority of water use rights on the Nile without neighboring Ethiopia receiving any specific allocation. Today, Ethiopia plans to increase its energy production through its Nile-powered Grand Ethiopian Renaissance Dam (GERD). While the 74-billion cubic meter (BCM) dam presents promising development opportunities for Ethiopia, the Nile's altered flow will increase the existing water deficit for Egypt—the quantification and mitigation of which are still largely unconstrained and under intense debate. To address this deficiency, we estimate that the median total annual water budget deficit for Egypt during the filling period, considering seepage into the fractured rocks below and around the GERD reservoir, as well as the intrinsic water deficit and assuming no possible mitigation efforts by Egyptian authorities, will be $\sim 31 \text{ BCM yr}^{-1}$, which would surpass one third of Egypt's current total water budget. Additionally, we provide a feasibility index for the different proposed solutions to mitigate the above deficit and assess their economic impact on the GDP per capita. Our results suggest that the unmet annual deficit during the filling period can be partially addressed by adjusting the Aswan High Dam (AHD) operation, expanding groundwater extraction and by adopting new policies for cultivation of crops. If no prompt mitigation is performed, the short-term three-year filling scenario would generate a deficit that is equivalent to losses to the present cultivated area by up to 72% resulting in a total loss of the agricultural GDP by \$51 billion during the above-mentioned filling period. Such figures are equivalent to a decrease in the total national GDP per capita by $\sim 8\%$, augmenting existing unemployment rates by 11%, potentially leading to severe socioeconomic instability.

1. Introduction

The Nile, the longest and one of the oldest rivers on Earth, is a unique environment and ecosystem that crosses four climatic zones (Dumont 2009). It is also an important source of water for 11 countries in Africa: Burundi, the Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The

main tributaries of the Nile are the White Nile, originating in the Great Lakes region in Central Africa, and the Blue Nile, Sobat, and Atbara rivers, streaming from the Ethiopian Highlands (Melesse *et al* 2014). Conversely, the exploitation of the Nile is mostly concentrated in the downstream riparian countries, namely through Egypt and Sudan, which are dependent on the Nile water for 98.26% and 96.13% of their annual water demand, respectively (FAO 2015).

During the past decades, upstream riparian countries, which could count on a higher endowment of fresh-water resources, were not actively involved in disputes over the Nile's water sharing rights, but the climatic and anthropogenic pressures have and will potentially intensify their current and future water needs. This can trigger one of the largest water stress cases in modern era.

The Nile has always been the primary source to sustain the irrigation practices in the basin for over 5000 years (Hughes 1992). The development of large-scale hydroelectric infrastructures began in the early twentieth century. This included the Aswan Low Dam in 1902, followed by the Aswan High Dam (AHD) in 1961. Because of these dams, the lower part of the basin has experienced increasing environmental repercussions, particularly regarding the reduction of sediment flow downstream. This has reduced soil fertility of agricultural lands and the overall water provision (Smith 1986) while accelerating the Nile delta coastal erosion and seawater intrusion (Negm 2017, Rateb and Abotalib 2020).

The exploitation of the Nile is critical for ensuring water usage for more than 260 million people living in the riparian countries and will be even more so as populations surge in Egypt, Ethiopia, and Sudan. These nations alone are expected to reach a total population of about 340 million by 2050 (Swain 2011). This population growth, coupled with the economic development and the projected changes in precipitation patterns and groundwater depletion induced by global warming, are expected to increase the regional water demand and to pose additional stress and challenges on its utilization (Mazzoni *et al* 2018). Moreover, the transboundary nature of the Nile basin and the uncertainties surrounding the evolution of its flow dynamics, with highly variable precipitation patterns in the recharge catchment basins, is causing an increasing debate on water rights over the river water shares. This is most notably the case with the British colonial era, which sought to maximize Nile flow into their colonized Egypt and Sudan. Britain did so by creating an agreement with the king of Ethiopia that prevented any work on the Blue Nile that obstructed water flow into the Nile's other tributaries (Abteu and Dessu 2019). The agreement between two now defunct monarchies is argued to be nullified.

Disputes over water rights over the Nile River started in 1959 when the two downstream riparian countries, Egypt and Sudan, signed the bilateral agreement 'for the full utilization of the Nile water'. No water budget was specifically allocated to any of the upstream riparian countries. Throughout the years, disputes were mediated by international organizations, such as the World Bank, whose funding for any development project on the Nile is subject to the approval of all co-riparian states. However, Egypt has often used this requirement in its favor, limiting the construction of any large infrastructures on the

river, which could impact its share of water from the Nile. Nonetheless, major efforts towards cooperation were achieved in 1999 with the foundation of the Nile Basin Initiative (Swain 2011). All the riparian states joined the initiative, except for Eritrea, which remains an observer. Since then, a growing number of infrastructure projects have been implemented or planned along the Nile.

In 2011, the Ethiopian government announced a plan to construct a hydroelectric dam on the Blue Nile River named the Grand Ethiopian Renaissance Dam (GERD). Ethiopia's current stated goals are to increase its hydropower generation potential in order to produce excess energy to be exported to the neighboring countries, to further their fishing activities and to expand the local economy road network. The unilateral decision of the Ethiopian government reflects the lack of real cooperation among the riparian states and opens up the claim for the revision of the water rights over the Nile. This is especially the case with such an uncertain future marked by increasing water stress. With the projected population growth in both Sudan and Egypt, the regional water stress is expected to rise (Mazzoni *et al* 2018). Both countries also fear a reduction in their water shares during the initial filling period of the GERD.

The Ethiopian government claims that no major effects will be observed regarding the water availability for the two downstream riparian countries (Abteu and Dessu 2019). Conversely, there is a broad consensus that there will be measurable effects caused by the different filling policies of the reservoir on the water share for Sudan and Egypt (Hamada 2017). To this day, no univocal environmental and/or economic impact assessments highlighting the influence of the impounding and future operation of the dam have been made. During the filling phases, the downstream discharge of the Blue Nile will be reduced, decreasing the amount of water that flows into the Nile. This will have clear, measurable effects on the water security for Egypt and Sudan in terms of both budget and quality.

Between May 2011 and May 2013 and based on an invitation from the Ethiopian government to the downstream countries (i.e. Egypt and Sudan), an international panel of experts (IPOE) conducted a thorough review of the design documents and the geotechnical characteristics of the GERD (IPOE 2013). However, the final report of the IPOE indicated that the submitted documents by the Ethiopian government lack the economic justification for the proposed power capacity of 6000 MW (International Panel of Experts (IPOE) 2013). Following a few years of strong hydropolitical divergence, Egypt, Sudan, and Ethiopia converged on the establishment of the first agreement on the management of the Dam in March 2015 (Tawfiq 2016). This mediation contained a 'Declaration of Principles' to be followed as a guideline for what concerns the overall management of water use. There is still a great deal

of uncertainty regarding the effective impacts of the GERD on Egypt's water supply, let alone on the ecosystem of the Nile River, especially given the lack of published information regarding the technical specifics of the project. The international water science community has been exploring several scenarios on the possible additional water deficit created by the dam along with mitigation proposals (e.g. Bastweesy 2015, Bekhit 2016, Donia and Negm 2018). Nonetheless, none of the models that have studied this issue have considered the forecasted growth of the intrinsic water deficit that Egypt will experience on its own (without accounting for external contributing factors such as the GERD), which has to be included when considering future mitigation or adaptation solutions as addressed herein.

The GERD is located approximately 500 km northwest of the capital, Addis Ababa, along the Blue Nile, ~20 km from the southern border of Sudan. When the dam starts operating, it will be the largest hydropower project in Africa (Chen and Swain 2014) with a lateral extension of 1800 m, a max wall height of 155 m, and an overall total capacity of 74 billion m³ (BCM). The project also includes two hydroelectric power stations installed at the right and left banks of the downstream river comprising of 13 Francis turbines that will grant a total installed power capacity of 6 GW, and estimated yearly potential production of 15 GWh (Salini Impregilo 2018). Among the benefits for the downstream countries, the GERD is expected to retain most of the sedimentary silt material that flows with the Blue Nile. This would allow the hydropower dams in Sudan to produce up to ~36% more energy per year and greatly reduce the annual costs of dredging the reservoirs and canals (Kahsay *et al* 2015). Furthermore, the GERD will create a more regular flow regime over the whole year for the Blue Nile in Sudan, which will also be reflected in the main part of the Nile River. A more continuous flow should guarantee a more stable annual electricity production and irrigation water supply for Sudan. As for Egypt, the Nile flow continuity, regularity and sedimentation control are currently achieved by the gauge control on the AHD.

This large infrastructure project has been under construction since 2011 and is reportedly in final completion phase. The first phase of the GERD filling project started during the rainy summer season of 2020 (Kansara *et al* 2021), yet it is still uncertain when the subsequent filling phases will begin, and what regional environmental impacts the Nile's altered flow will generate in both the short and long term on the downstream communities and ecosystems. As pointed out by a recent report from the MIT Abdul Latif Jameel World Water and Food Security Lab (Al Jameel 2014), four major technical concerns require a resolution: (1) Planning needed for coordinating the operation of the AHD and the GERD during the period of filling and eventual prolonged drought,

(2) Technical agreement on the design of the GERD (seepage and spillage prevention), which relates also with the uncertainty related to the volume of water granted to Egypt and Sudan during the filling period, (3) Need for an agreement on the sale of hydropower from the GERD, and (4) Assessment of the potential downstream impacts on Egypt and Sudan, particularly for the agricultural sector.

The construction of the GERD triggered inconclusive debates on the hydrological, engineering, economics and geopolitical perspectives of the project. It is challenging to identify where the current and future policies for cooperation should aim since both the available information on the project and the potential technical-scientific support are often scattered, contradictory whenever publicly available. Even at these final stages of the project, little data or information is publicly available on the GERD to allow proper simulation of the overall environmental and economic impacts that the establishment of the dam will have on the three riparian countries. Due to the nationally and internationally sensitive nature of the topic, the Ethiopian government has announced only the major outlines of the project with insufficient technical details. Nonetheless, more information is becoming available as the project progresses, and thus future predictions are becoming more precise. For these reasons, while performing a thorough literature review on the GERD, we have mostly focused our analysis on the latest available peer-reviewed publications and reports.

While there is substantial uncertainty regarding the effective influence of the dam on the resulting outflow (Abtew and Dessu 2019), there is a broad consensus that the major impacts in terms of water deficit for the downstream riparian countries will be mostly observed during the filling years (Negm and Abdel-Fattah 2019). In general, the duration of the filling period is inversely proportional to the decrease of the water flow, although one has also to consider the different effects of seepage and evaporation. Since no official announcements on the filling policies have been given yet, all the considered studies have tested different, but comparable, filling scenarios by establishing fixed or variable impounding rates for the dam. Furthermore, other differentiating characteristics include the modeling of climatic variability, the estimation of some unknown technical aspects of the dam infrastructure, and the types of results that they provide.

We have also observed that there are no currently published studies that consider the water budget deficit from a more global perspective by combining the downstream effects of the GERD to the existing significant water scarcity that countries like Egypt are already experiencing and that will worsen in the near future (Mazzoni *et al* 2018). Egypt is already experiencing severe water stress, which it is currently being mitigated through the repeated reuse of the

agricultural drainage water. This, in turn, affects the overall water quality by increasing its salinity and the concentration of pollutants (Hegazy *et al* 2020). Furthermore, very few studies have accounted for the overall analysis of the additional water supply that the GERD will require to cope with the losses due to the natural seepage from the reservoir (Liersch *et al* 2017). The Nubian Block, on top of which the GERD reservoir and dam are constructed, is composed of highly fractured igneous and metamorphic rocks (Mohamed and Elmahdy 2017). This hydro-geological setting could cause major leakage of water from the reservoir, which could reach up to ~25% (Liersch *et al* 2017). Even though the entire reservoir will be built to store up to 74 BCM, the actual volume that will be needed to fill-up the basin may be even higher as shown in the studies summarized in table 2 if we account for the losses due to seepage and evaporation. Wheeler *et al* (2020) simulated the response of the AHD during scenarios of different filling periods as well as the period after the reservoir fill including a multi-year drought scenario and arguably concluded that the risk of water shortage in Egypt, in response to the construction of GERD, is relatively low. Nevertheless, adoption of new agricultural policies that depend on low water-consuming crops will be feasible to avoid adverse impacts of the multi-year drought.

In the present study, we evaluate the effects of the GERD on the short-term Egyptian availability of the Nile streamflow by considering different filling scenarios and strategies simulated in the most recent published literature. Then, we assess Egypt's total water budget deficit arising from the GERD filling scenarios, seepage and the intrinsic one resulting from population growth. We evaluate the feasibility of the suggested mitigation policies to address the resulting deficit and discuss the socioeconomic impacts considering each of the proposed filling scenarios for the GERD.

2. Methods

2.1. Filling scenarios of the GERD

The scenarios incorporated in our analysis of the water budget deficit in Egypt include the impact of the GERD filling scenarios and the associated storage capacities, and are summarized as follows (table 1):

- (a) Donia and Negm (2018) assumed three storage capacity scenarios: 74, 35, and 18.5 BCM and three filling period scenarios: 5, 10, and 20 years. The results indicated that with the five-year filling period of the GERD at a storage capacity of 74 BCM, the AHD reservoir will empty and will reach its minimum water level of 147 m by the fifth year.
- (b) Keith *et al* (2017) examined seven filling rate strategies: retaining 100%, 50%, 25%, 20%, 15%, 10%, and 5% of the Blue Nile inflow. Their

analysis showed that annual reservoir fill rates of 8%–15% can be beneficial for hydroelectric power generation for Ethiopia with a minimal effect on stream flow into Egypt assuming no significant impact of climate change until 2039. They also concluded that larger fill rates beyond the policy of 15% will have adverse impacts on the stream inflow. For example, with a 100% fill rate policy (equivalent to 2.5 years to reach full supply level (FSL)) will result in a 55% reduction of stream flow.

- (c) King and Block (2014) examined five policies; three policies with impounding 5%, 10% or 25% of total monthly inflow, while the other two policies are conditional on exceeding the historical average streamflow (HASF) or 90% of the HASF. The results showed that the 5% filling policy will not significantly affect downstream flow but also will not help reaching the FSL of the reservoir. On the other hand, the 25% policy, can reduce the average downstream flows by more than 10 BCM per year.
- (d) Liersch *et al* (2017) assumed three scenarios based on monthly minimal discharges to be released downstream: 75%, 50% and 25%. Each of these scenarios was simulated with three seepage rate assumptions (low, medium, and high), resulting in 18 filling scenarios considering climate change under wet and dry conditions. The results showed that with the release of Q_{50} and Q_{75} of average monthly discharge, the flows might be reduced by 10%–19% and 16%–44%, respectively, while releasing monthly Q_{25} discharges will reduce only 5%–13% of the average monthly discharge to downstream countries and the FSL will be reached in eight years. The simulated evaporative losses during the filling process correspond to 6.5%–8.7% of average annual inflows while the seepage losses ranged between negligible to 24%–32% of inflows. The maximal seepage loss scenario is particularly highlighted in the present study.
- (e) Omran and Negm (2018) indicated that in a scenario of filling the GERD in seven years, Egypt will face a significant shortage in water quantity associated with a reduction of 20% to 30% of electricity production from the AHD.
- (f) Wheeler *et al* (2016) analyzed five different annual release scenarios: 25, 30, 35, 40, and 45 BCM yr⁻¹. The results indicated that reducing the risks to stream inflow into Egypt and energy generation can be achieved through combinations of agreed annual releases from the GERD as well as adopting a drought management policy for the AHD.
- (g) Zhang *et al* (2015) considered five filling policies: impounding of 5, 10, and 25% of the Blue Nile inflow and retaining quantities greater than HASF or 90% of HASF with possible

Table 1. Filling scenarios considered in our water budget deficit analysis for Egypt.

Reference	Num. of Scenarios ⁴	Description
Donia and Negm (2018)	6 (4)	3 storage capacities scenario: 74, 35, and 18.5 BCM. ⁵ 3 filling period scenarios: 5, 10, and 20 years.
Keith <i>et al</i> (2017)	7 (6)	7 filling rate strategies: retaining 100%, 50%, 25%, 20%, 15%, 10%, and 5% of the Blue Nile inflow ⁶
King and Block (2014)	5 (4)	3 policies as fractions of total monthly inflow: impounding of 5, 10 or 25% 6. 2 policies with retention rates contingent on exceeding the HASF ⁷ retain any quantity greater than HASF or of 90% HASF.
Liersch <i>et al</i> (2017)	18 (4)	3 scenarios based on monthly minimal discharges to be released downstream: monthly exceedance probabilities of 75%, 50% and 25% ⁸ . 3 scenarios based on seepage rate assumptions: low, medium, and high ⁹ 2 hydro-climatic scenarios: wet or dry. In our analysis we only used 4 scenarios including Q75 and Q50 under wet and dry conditions and assuming maximal seepage (32%) in all scenarios.
Omran and Negm (2018)	1	seven years, Egypt will face a significant shortage in water quantity associated with a reduction of 20% to 30% of electricity production from the AHD.
Wheeler <i>et al</i> (2016)	5	5 annual release values: 25, 30, 35, 40, and 45 BCM yr ⁻¹ .
Zhang <i>et al</i> (2015)	5 (4)	5 filling policies: impounding of 5, 10, and 25% of the Blue Nile inflow and retaining quantities greater than HASF or of 90% HASF ⁵ . 8 possible precipitation changes −20, −10, −5, 0, +5, +10, +15, and +20% by year 2060 ¹⁰
Zhang <i>et al</i> (2016)	6	2 scenarios with fractional impounding: 10 and 25% of inflow. 1 threshold filling strategy that allows any streamflow volume in excess of the HASF to be impounded in the reservoir. 3 absolute filling strategies: 4, 6, and 8 years.

⁴ In parenthesis the number of scenarios considered in our study.

⁵ Scenarios with 35 and 18.5 BCM capacity are not considered in this study.

⁶ 5% fill rate is not considered in this study given their unlikelihood of adoption (>50 years filling duration).

⁷ HASF: historical average stream flow.

⁸ 25% scenario not considered in our study since filling would not be reached before 20 years.

⁹ Seepage effects considered on a separate analysis.

¹⁰ Results averaged among different climatic scenarios.

precipitation changes of −20, −10, −5, 0, +5, +10, +15, and +20% by the year 2060. The results showed that impounding 10% or 25% of monthly streamflow will result in a 6% or 14% average reduction in streamflow into Egypt during the first 5 years, respectively.

- (h) Zhang *et al* (2016) proposed two scenarios with fractional impounding: 10 and 25% of inflow, one threshold filling strategy that allows any streamflow volume in excess of the HASF to be impounded in the reservoir and three absolute filling strategies: 4, 6, and 8 years. The results indicated that the 25%, 6 years and 8 years scenarios can provide the best scenarios for both upstream and downstream countries.

In order to assess the total water budget deficit, the best mitigation policies and the socio-economic impacts of each of the filling scenarios for the GERD, we use three methods that are summarized herein.

2.2. Water budget deficit assessment

To constrain the ambiguity around the forecasts in Egypt's total water budget deficit during the suggested filling periods of the GERD, we use the estimates of the water budget deficit from the water budget model in Mazzoni *et al* (2018) and considering future

population projections under the Shared Socioeconomic Pathways, Regional rivalry (SSP3) scenario. The SSP3 scenario is favorably selected because it incorporates the highest challenges towards mitigation and adaptation, with strong regional rivalry (Mazzoni *et al* 2018). Moreover, we implement the different filling scenarios in terms of time scales and retained volumes that we derive from a thorough literature review and collect the most recent analysis. Table 1 summarizes these different filling scenarios or strategies adopted by each study. We then derive the additional average annual water deficit for Egypt generated by the GERD filling and by the losses due to seepage and evaporation from Liersch *et al* (2017) and Wheeler *et al* (2020). A special emphasis is given to the water loss from the GERD due to seepage due to two reasons. First, the seepage losses have been largely underestimated in previous studies that dealt with evaluating the impact of the GERD and second, the seepage-related losses can reach annually up to 15 BCM compared to a much lesser annual evaporation-related losses of only 3.8 BCM (Liersch *et al* 2017).

In our analysis, we only select studies published on the topic in the last 5 years since some of the main technical specifications of the GERD have been publicly released only lately (such as the dam total capacity). Among all considered studies, different filling policies have been explored by either considering an

a priori fixed number of years for the duration of the filling period, by using fractional retention rates of the total monthly stream flow entering in the reservoir that guarantees a permanent impoundment of water every month to fill-up the dam, or again by employing threshold-based policies, with retention rates conditional to a certain fixed value, which instead do not assure retention for storage in the years where the stream flow is lower than the selected baseline. To be able to compare the outcomes of the different studies we average their results across the climatic scenarios that they have considered in their analysis to match our use of the SSP3 one.

2.3. Feasibility index for the different mitigations

In table 2, we summarize what are all the most plausible proposed strategies that Egypt could undertake to mitigate the short-term and temporary effects of the GERD filling in terms of water deficit in particular: AHD Operation reduction (i.e. AHD rules to be readjusted to cope with the water reduction), groundwater extraction expansion, crop type selection, modernizing the irrigation system, changing fields canals to pipes, increasing wastewater reuse, rain harvesting, expanding desalination and reducing evaporation in lake Nasser. We then develop a corresponding feasibility index calculated through a first-order duration-cost-benefit analysis of the proposed mitigation strategies to obtain a parametric indicator that allows us to evaluate the practicability of each possible solution. The index is expressed as an inversely proportional function of the time required for implementing the strategy (i.e. hereafter is referred to as implementation swiftness) and its annual costs, and directly proportional to the benefits in terms of water volume in BCM yr⁻¹:

$$\text{Feasibility Index} = f(\text{Duration}^{-1}, \text{Costs}^{-1}, \times \text{Benefits}),$$

$$\begin{aligned} \text{Feasibility Index} = & \beta_D \left(\frac{1}{\text{Duration}} \right)_{\text{norm}} \\ & + \beta_C \left(\frac{1}{\text{Costs}} \right)_{\text{norm}} \\ & + \beta_B \text{Benefits}_{\text{norm}}. \end{aligned}$$

The three coefficients β_D , β_C , and β_B are set equal to 1/3 to give the same weight to each variable. For the duration variable, we select five scenarios with their respective incremental abstract values: short term = 1, short-mid term = 2, mid term = 3, mid-long term = 4, and long term = 5. For the costs, we account for both the yearly expenditure due to the capital expense (CAPEX) costs depreciated over the lifetime span of the solution itself and the annual operating expense (OPEX) costs. We first derive a lower and upper bound for all the variables for each mitigation strategy, we then normalize each variable

to a [0,1] interval, and we finally compute the overall feasibility index as a weighted sum of the three components. Given that there are different ranges and values for the costs and the implementation time of each measure, a range of values is given for the feasibility index of each mitigation strategy.

2.4. Modelling the economic impact

We use a simplified economic model to assess the impacts of the total water budget deficit under the different GERD's filling scenarios on the evolution of Egypt's agricultural GDP. This model presents a first-order analysis providing a lower limit estimate of the equivalent economic impact of the total water budget deficit on the agricultural sector due to loss in crop productivity arising from land degradation from lack of irrigation) and not accounting for the consequences on the industrial sector that are difficult to assess due to the lack of published records. The model (suppl. figure S1 available online at stacks.iop.org/ERL/16/074022/mmedia) uses average GDP growth rates projections from historical data for three cases: low (1.76%), medium (4.47%), or high (7.16%) growth rates from projections of Egypt's GDP (World Bank 2016). These projections represent the non-GERD GDP estimates. We then calculate the decrease in GDP for the 3, 5, 7, 10, and 21 years GERD filling scenarios. We finally calculate the GDP per capita using historical data and the population projections from the 2019 Revision of World Population Prospects (UN World Population Prospects 2019) for both the GERD and non-GERD cases. Yearly water budget loss and equivalent land loss are approximated using relationships from Mazzoni *et al* (2018) and Hamada (2017) respectively, where the loss of each 5 BCM would result in total degradation of ~0.42 million hectares (~1.2 million feddan). Egypt's total agricultural land area (~9.1 million feddan equivalent to ~3.822 million hectares) is valued as Egypt's agricultural GDP to calculate the decrease in GDP due to total degradation often expressed in the local unit feddan (one Feddan is equal to 4200 m²). We also assess the increase in the unemployment due to land degradation in the agricultural sector (which employ a fourth of the work force in Egypt) using the average number of farmers per feddan from the Egyptian Ministry of Water Resources and Irrigation (MWRI 2014).

3. Results

Our investigation results pertain to three findings: the first is on constraining the total water budget deficit projections during the different GERD filling scenarios, the second is on the feasibility of mitigation strategies to address this deficit and the third is on the economic impact corresponding to the the total water budget deficit as detailed below.

Table 2. Proposed mitigation strategies.

Reference	Description	Duration	Costs	Benefits
Abdelhaleem and Helal (2015)	Pump stations with floating intake design	No mitigation vs. water deficit		
	Additional intakes for existent pumps	No mitigation vs. water deficit		
	AHD rules to be readjusted to cope with the water reduction	Short term	Loss from 11.5% to 44.3% of produced energy in AHD per year \rightarrow 1026–3952 GWh $\text{yr}^{-1} \rightarrow$ 71.8–277 M\$ yr^{-1} ¹¹ .	2.8–22.2 BCM yr^{-1} .
	More reliable water management policies	Unknown		
	Water management of based on principle of equitable use	Unknown		
Donia and Negm (2018)	Win-win strategy by Egypt and Ethiopia Agreement on GERD capacity	Unknown		
	Water harvesting project in the Nile basin	Long term (10–30 yrs.)	4.05 \$ m^{-3} (Singapore) or 5.45 \$ m^{-3} (Berlin) ¹²	Current use 1 BCM, max 1.8 BCM yr^{-1} ¹³ .
	Reuse of wastewater	Strategy 2030 ¹⁴	8.57 B\$ CAPEX + 340 M\$ OPEX ¹⁴	5 BCM/yr produced wastewater: 3.7/yr BCM treated \rightarrow 1.3 BCM/yr potential source ¹⁵ . 2030 Annual wastewater to reach 11.7 BCM yr^{-1} (11.6 BCM/yr treated) ¹⁴

(Continued.)

Table 2. (Continued.)

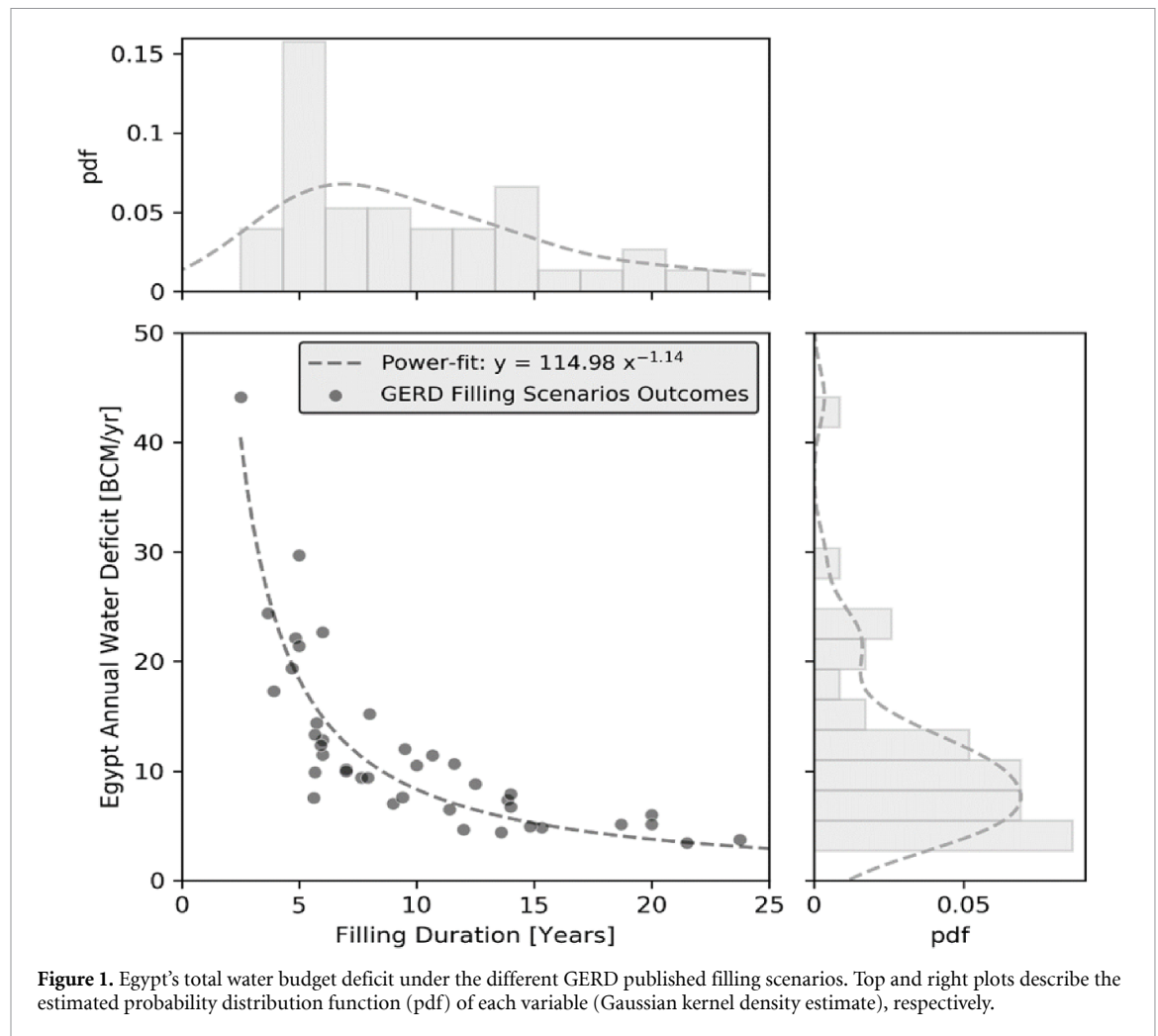
Reference	Description	Duration	Costs	Benefits
El-Nashar and Elyamany (2018)	Water desalination expansion	Long term (2–5 yrs.)	10–20 \$ m ⁻³ CAPEX + 0.65–0.77 \$ m ⁻³ yrOPEX ¹⁶	Planned for 268 MCM yr ⁻¹ ¹⁷ Potential of <3.5 BCM yr ⁻¹ by 2020 ¹⁸
	New irrigation methods (e.g. drip irrigation)	Long Term	8.5–17 B\$ ¹⁹	Modern systems efficiency of 80% →could save 8.8 BCM yr ⁻¹ 14.8 BCM yr ⁻¹ ¹²¹
	Changing crop patterns to use less water	Short Term	1.623 B\$ for rice + 636 M\$ for sugarcane ²⁰	
	Use modern irrigation systems Eliminating/Diminishing cultivation of rice and other water consuming plants (e.g. sugarcane) Converting small field surface canals to pipes	See similar entry above See similar entry above Long Term (>5 yrs.)		
Ibrahim and Emara (2010)			Similar to above: 8.5–17 B\$ ¹⁹	Save 42% of water losses →could save 7.4 BCM yr ⁻¹ ¹²¹ .
	Reuse drainage water and treated wastewater Water condensers next to evaporation areas Expand the use of groundwater	See similar entry above Short Term See similar entry above	Low costs	Very low production
	Desalination capacity expansion Using fixed furrow irrigation system	See similar entry above		
				efficiency >35% →could save 9.36 BCM yr ⁻¹ .

(Continued.)

Table 2. (Continued.)

Reference	Description	Duration	Costs	Benefits
Keith <i>et al</i> (2017)	Construction of desalination plants Technological innovation (irrigation systems, farming practices, desalination)	See similar entry above See other entries for more details on each specific solutions		
Liersch <i>et al</i> (2017)	Modifying the operations of the Rosaries and Sennar dams (Sudan)	Short term (1 year)	Unknown	
Omran and Negm (2018)	Maximizing the use of groundwater	Short Term	0.1–6 M\$ yr ⁻¹ . ²²	Potential 3.65–4.65 BCM yr ⁻¹ (1.65 BCM from fossil aquifers and 2–3 BCM from the Nile Aquifer) ²³
	Maximizing the use of rainwater in Egypt Reduce evaporation at Lake Nasser: changing water levels at AHD, cultivating special crops on the lake surface, closure of a secondary channel (khor), circular foam sheet.	See above See other entries for more details on each specific solutions		

¹¹ Assuming an average electric price of 0.07 \$ KWh⁻¹.¹² From Zhang *et al* (2017).¹³ From Abdel-Shafy *et al* (2010).¹⁴ From AbuZeid and Elrawady (2014).¹⁵ From Elbana *et al* (2017).¹⁶ Based on "The Cost of Desalination", Advisian. Available online: www.advisian.com/en-gb/global-perspectives/the-cost-of-desalination Article accessed on [2018/11/27].¹⁷ From Mazzoni *et al* (2018).¹⁸ Retrieved from Verdier (2011).¹⁹ Calculated based on 17 Mha of cultivated land and assuming a cost for modernizing the irrigation systems between 500 and 1000 \$ ha⁻¹.²⁰ Calculated at price of 257.7 \$/Tn for Rice and 40.37 \$/Tn for Sugarcane → production of 6.3 MT of rice and 1.57 MT of Sugarcane in 2016.²¹ Self-calculation.²² Calculated using 3.65 and 4.65 BCM as target, with an average yield per well of 5000 to 60 000 m³ d⁻¹ → 167–2548 wells → well cost from 17 000\$ to 70 000\$ CAPEX and no relevant costs for OPEX → 2.9–178 M\$, which is distributed on an average lifespan of 30 years.²³ From El-Nashar and Elyamany (2018).



3.1. Assessing the water budget deficit

Figure 1 shows the resulting distribution of the outputs of each considered scenario in terms of years needed to fill the GERD and the expected annual total water budget deficit of Egyptian renewable freshwater supply by this process. Clearly, each selected filling rate will have different implications on the time to fill the reservoir and thus a proportional effect on the downstream flow reductions. As a result, we found that the estimated required time to fill up the GERD is distributed between a minimum of 2.5 and a maximum of 29.6 years, with a mean value of 10.86 (median: 9.19, Q1: 5.79, and Q3: 13.97 years). For more details on the effect on annual flows into Egypt, figure 2 summarizes in a box-plot format the statistical distribution of the resulting annual water deficit caused by the GERD filling, the seepage inferred from Liersch *et al* (2017), and the forecasted intrinsic Egyptian water budget gap derived from Mazzoni *et al* (2018). The main component of the overall water deficit for Egypt originates from the intrinsic water gap between the internal demand and the presently available renewable water supply. This difference, corresponding to $18.35 \text{ BCM yr}^{-1}$ in median value, is currently compensated by the

reuse of drainage water within the Nile Delta and by unlawful withdrawal of deep groundwater (CAPMAS 2018). Both contribute to deteriorate the overall water quality (Mohie and Moussa 2016). It is worth mentioning that the above-mentioned amount of water deficit in Egypt does not include the annual groundwater recharge from Lake Nasser and northern Sudan to the Nubian Aquifer (Abdelmohsen *et al* 2019, Sultan *et al* 2013, Abdelmohsen *et al* 2020). It was estimated using a two-dimensional groundwater flow model that, at lake level of 178 meters above sea level (masl), the Nubian aquifer receives an annual recharge of 6 BCM yr^{-1} compared to 0.7 BCM yr^{-1} , when the lake level drops to 170 masl. Collectively, the annual groundwater recharge from Lake Nasser and the northern Sudan basin can reach up to 8.5 BCM yr^{-1} during periods of intensified precipitation on equatorial Africa (e.g. the period between 2012 and 2015; Abdelmohsen *et al* 2019). The amount of annual groundwater recharge from precipitation over the northern Sudan platform, which can be roughly estimated from the GRACE terrestrial water storage as 2.5 BCM yr^{-1} (Abdelmohsen *et al* 2019), will not be affected by the construction of the GERD, yet the different scenarios for

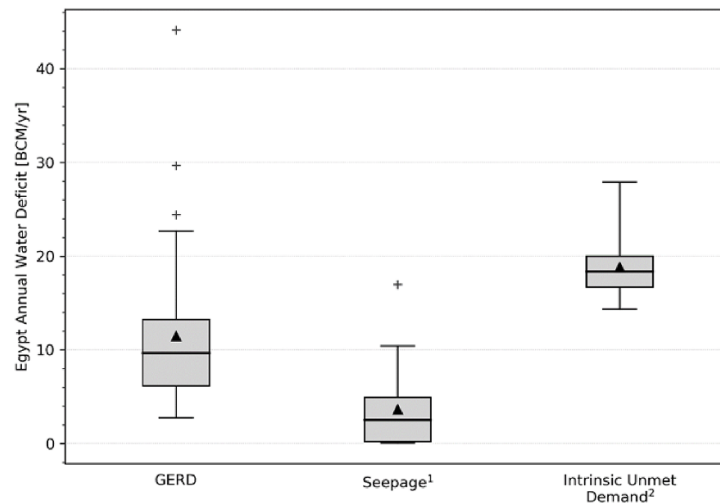


Figure 2. The three components defining the annual total water budget deficit for Egypt during the GERD filling period by source considered in our study. Note that for each box-plot, the line inside the box represents the median, the triangle delineates the mean (also referred to as average), the box edges represent the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually in crosses. References: ¹Liersch *et al* (2017); ²Mazzoni *et al* (2018). The left box (GERD) refers to the annual water deficit induced by water impounding in the GERD reservoir during the filling period (numbers are statistically derived from available scenarios in table 1). The middle box (Seepage) refers to the annual water deficit resulting from seepage losses in the GERD reservoir after ¹Liersch *et al* (2017). The right box refers to the current intrinsic water deficit in Egypt after ²Mazzoni *et al* (2018). The sum of the median value of the three is referred to as the annual total water budget deficit.

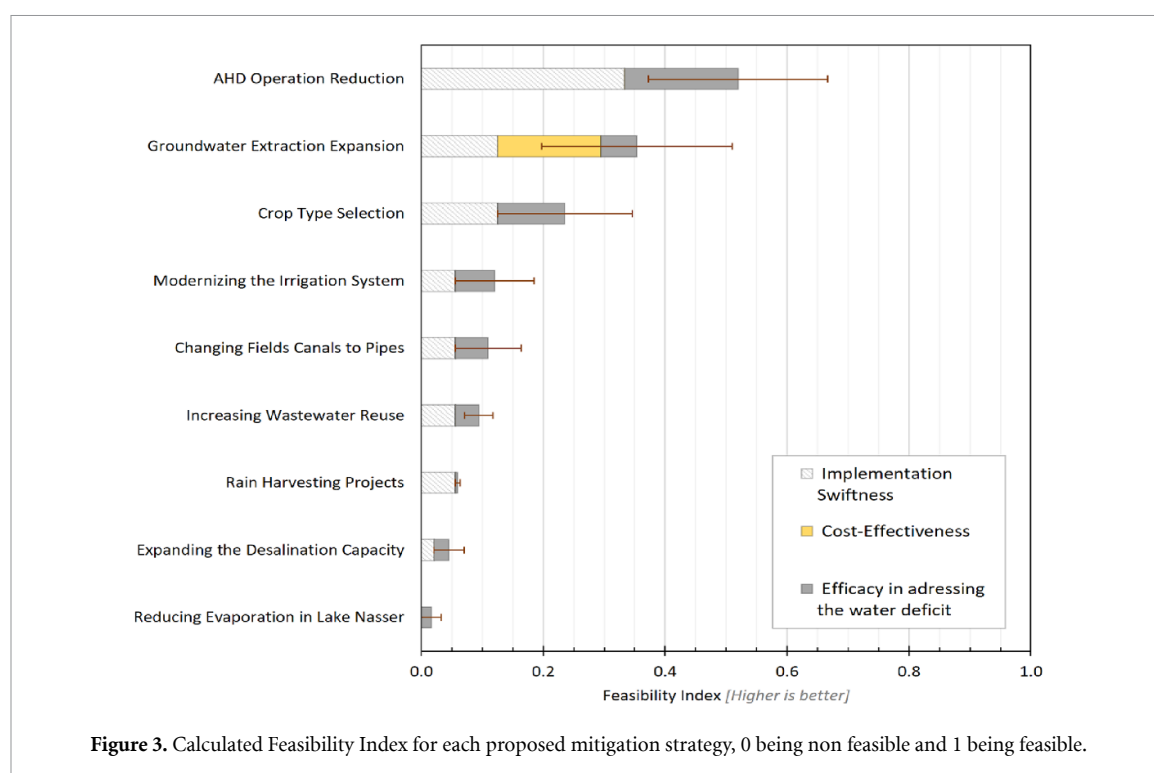
the GERD will consequently affect Lake Nasser levels and hence the annual recharge to the deep Nubian Aquifer will be significantly impeded. The response of the Nubian Aquifer to the different scenarios of the GERD filling should be investigated to estimate a reliable total water budget deficit in Egypt.

The other two components (i.e. water impounding during the filling period and seepage from the GERD), which are instead directly related to the construction of the GERD, collectively create an additional median water gap of $\sim 12.15 \text{ BCM yr}^{-1}$ considering all the expected lengths for the filling periods of the dam. The decrease in streamflow for Egypt due to the seepage losses in the GERD, not considering the outliers, could range from a minimum of 43 MCM yr^{-1} to a maximum of 10.4 BCM yr^{-1} (median: 2.5, Q1: 0.185, and Q3: 4.9 BCM yr^{-1}) assuming the total inflow to range between 43.2 and 53.3 BCM and seepage rates of 1% and 32% (Liersch *et al* 2017). However, for Egypt, the actual main reduction in the annual water supply is due to the filling itself of the upstream dam. The estimated loss, excluding outliers, ranges between 2.72 and $22.67 \text{ BCM yr}^{-1}$ (median: 9.64, Q1: 6.13, and Q3: $13.22 \text{ BCM yr}^{-1}$). In percentage, the effects of the GERD would create an additional increase of the present water deficit for Egypt between +34.4% and +98.7%, of which in average $\sim 83\%$ is due to the filling and the remaining $\sim 17\%$ to the seepage assuming a maximal seepage rate. If we account for all the components, Egypt may experience in the years of filling of the GERD a total annual water deficit from 24.7 to 36.5 BCM yr^{-1} (distributed in percentage as: 32% due to

GERD filling, 8% for seepage under GERD, and 60% of intrinsic water budget deficit), which corresponds to an average +35.5% of its current internal annual water demand. It is worth mentioning that these estimates represent the worst-case scenario, where no actions are taken from the Egyptian authorities to mitigate these expected rates of water deficits due to technical shortage or political instability. Additionally, enhanced flood events over the White Nile can positively impact the Egyptian water budget by introducing more than 25 BCM to Lake Nasser over a period of three years (e.g. the flooding event between 1999 and 2001; Bastawesy *et al* 2008).

3.2. Feasibility index

Figure 3 shows the resulting feasibility of each proposed solution and the relative contribution of each mitigation strategy that we considered for computing the index that ranges from 0 (non feasible) to 1 (feasible). Inspection of the feasibility index estimations (figure 3) indicates that among all the proposed solutions to address the water budget deficit, the most practical option (feasibility index $>50\%$) for Egypt in the short term would be to temporarily reduce or even completely suspend the operations at the AHD to partially offset the lower streamflow during the filling of the GERD. The loss in the Aswan basin reservoir can be recovered and distributed in the following years after the GERD starts operating when the main Nile streamflow will return to its regular rate. This would, of course, drastically reduce the electricity production from the Aswan hydropower plant (here accounted as cost for the proposed strategy)

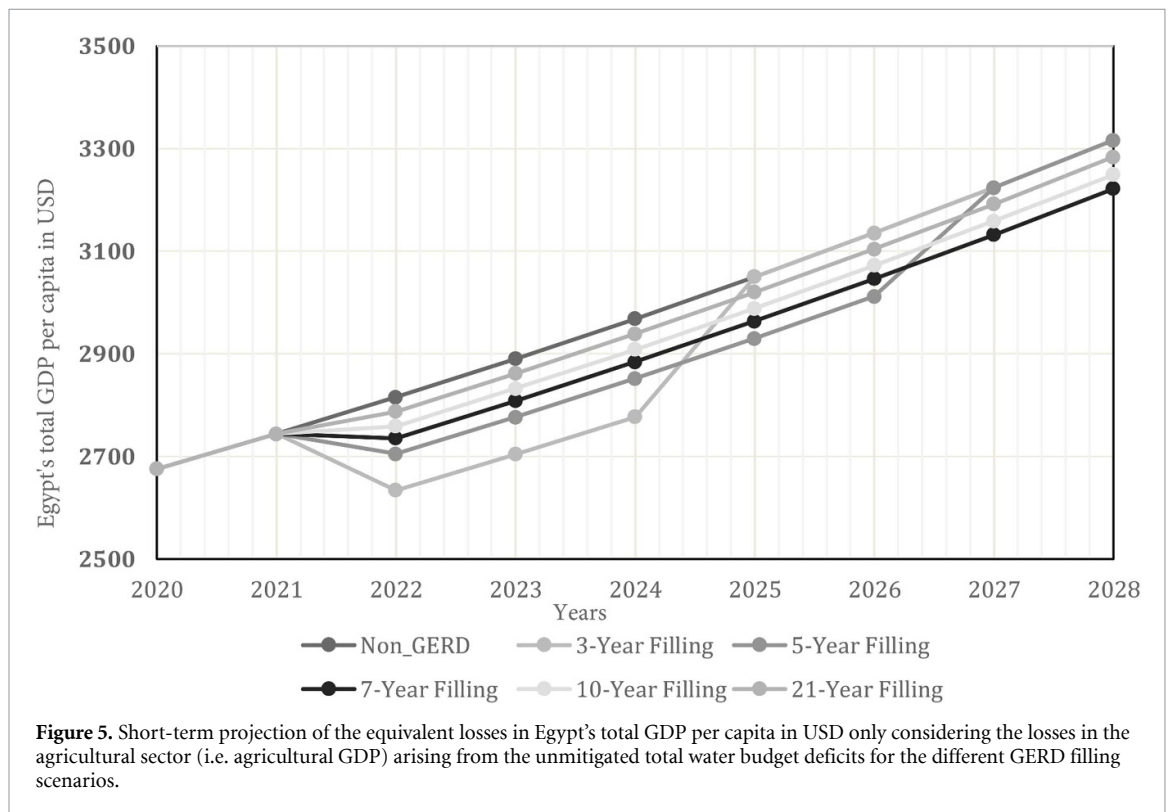
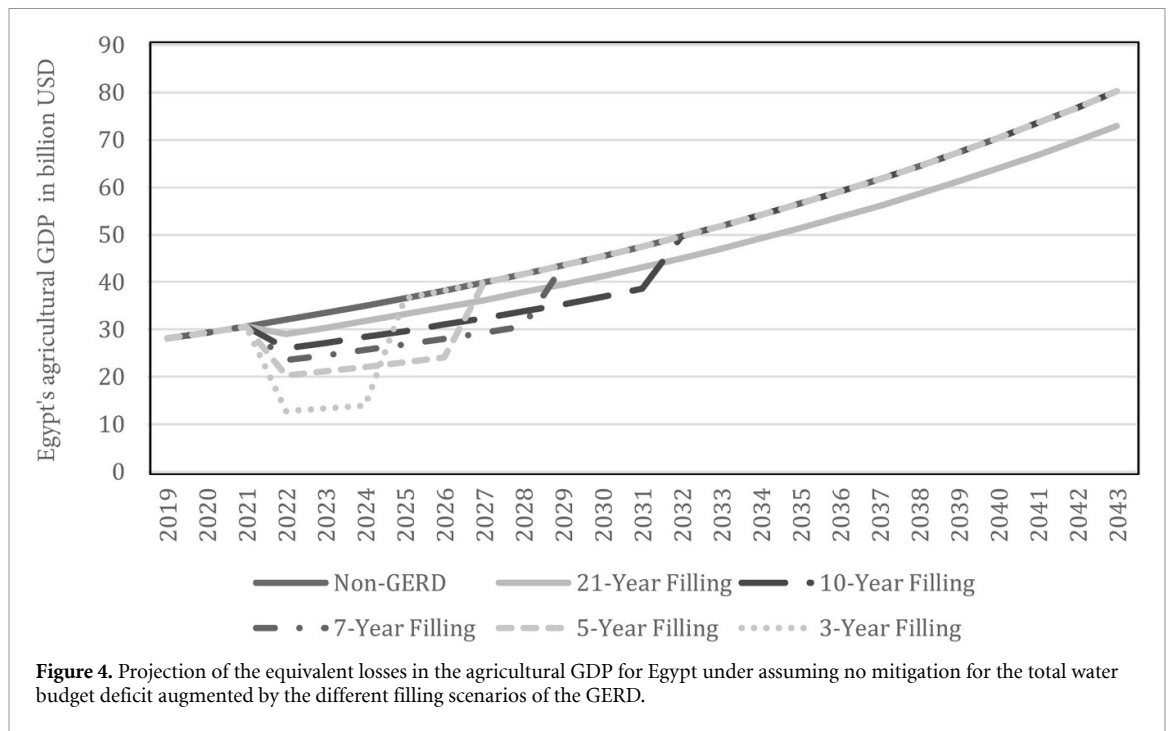


and to account for all the subsequent effects of this option. Other effective solutions include maximizing groundwater withdrawal (feasibility index >35%), although here we do not account for the environmental effects on degradation of fossil aquifers systems. However, this measure is highly cost effective compared to other measures (figure 3; table 2), yet the total production of current wells cannot bridge the GERD-induced water deficit gap with a total potential of 4.65 BCM yr⁻¹ (Omran and Negm 2018). This solution could be improved through the expansion of groundwater extraction from shallow aquifers east and west of the Nile Delta (Abotalib *et al* 2016, El-Saadawy *et al* 2020, Hegazy *et al* 2020, Khalil *et al* 2021). Furthermore, the largely unexplored fractured limestone aquifers east and west of the Nile Valley represent valuable corridors for expanding groundwater extraction due to: (1) the fractured and karstified nature of the aquifer that results in high groundwater yield of up to 1600 m³ d⁻¹ (Yousif *et al* 2018), (2) the abundant recharge from the deep Nubian aquifer through artesian upwelling along faults and thus naturally bringing deep water (up to 1500 m) to shallow levels (<600 m) at no cost (Hussein *et al* 2017, Abotalib and Heggy 2018; Abotalib *et al* 2019), and (3) the low water salinity for domestic and agricultural purposes (<3000 mg l⁻¹; Ibrahim and Lyons 2017, Yousif *et al* 2018). The feasibility index estimation also shows that changing the agriculture system toward the cultivation of crops that require less water could also be a feasible solution (feasibility index >20%). The current crop water use rate in Egypt is 1.4 m³ m⁻² yr⁻¹ (Mohie El Din and Moussa 2016) and thus 53.7 BCM of water every year is

needed to irrigate the 9.1 million feddans. Replacement of the sugarcane with sugar beet and limitation of the rice cultivation to the official number of feddans (almost 1 million feddan, which is 850 000 feddan below the actual rice lands in Egypt 1.9 million feddan), the crop water use rate will be as low as 1 m³ m⁻² yr⁻¹ (Din *et al* 2016), which only requires 38.3 BCM to irrigate the 9.1 million feddans. Other options have a feasibility index lower than 10%, which means that they either require too much time for their implementation or the cost is too high, again resulting in a low efficacy in mitigating the water deficit. For example, modernizing the irrigation system is a costly and time-consuming process, where upgrading the irrigation systems of only 3140 ha in Upper Egypt costs up to 11.6 million US dollars (Takoueu 2020). The current irrigation system is a surface irrigation system (i.e. flood irrigation) that depends almost entirely on the AHD to regulate water through more than 29 000 km of canals and sub-canals leading to the loss of more than 3 BCM of Nile water annually through evaporation in addition to the water shortage at canal tail end. These negative impacts of the surface irrigation encourage the Egyptian government to apply modern methods of irrigations such as sprinkler systems, drip irrigation and bubble irrigation (Abdelhafez *et al* 2020) as well as to line the irrigation canals (Khalil *et al* 2021).

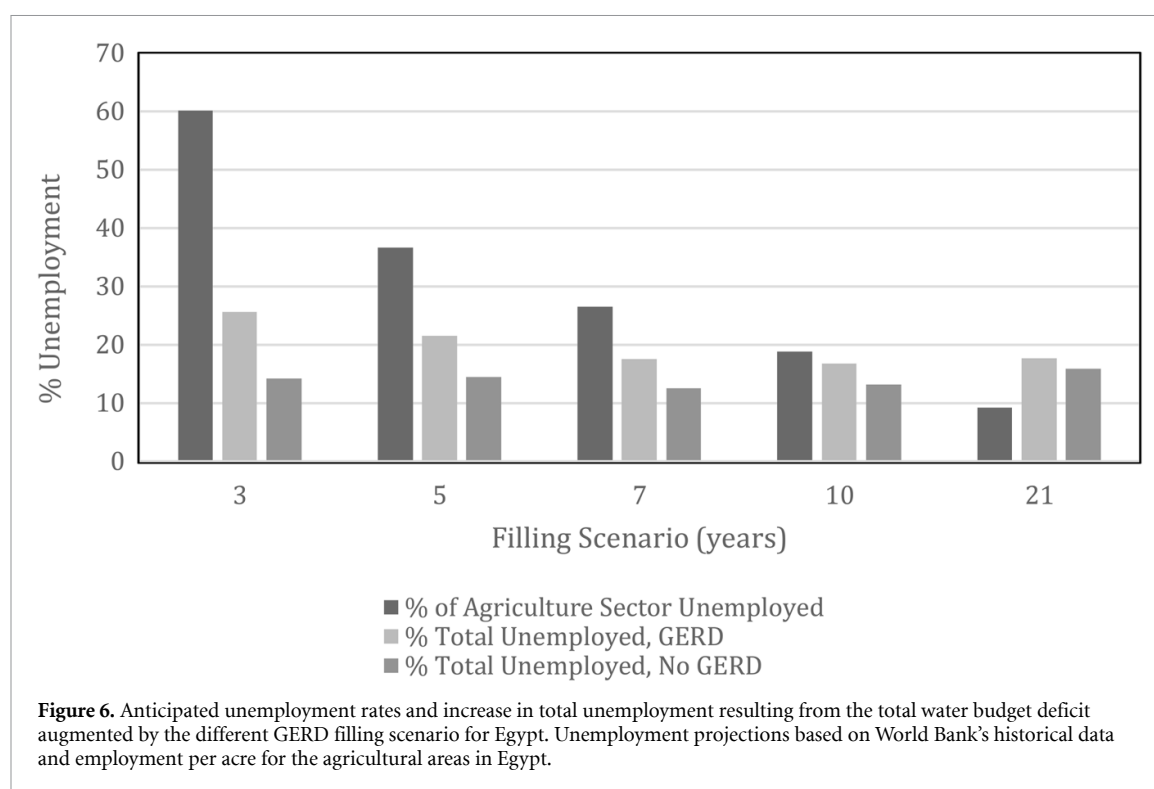
3.3. GDP and unemployment projections

Growth rate GDP projections for agriculture and for total GDP per capita can be found in figures 4 and 5, respectively, considering the sum of the water losses in figure 2. In the years 2022, 2023 and 2024, our first



order model suggests an equivalent agricultural GDP losses arising from the unmitigated total water budget deficit, for the total filling period, of ~\$51 billion for the 3 years filling scenario, ~\$28 billion for the 5 years filling scenario, ~\$17 billion for the 10 years filling scenario, and ~\$10 billion for the 21 year filling scenario. These economical losses reflect the degradation in crop production due to the unmitigated deficit in necessary irrigation water to maintain agricultural

activities. The above reduces the existing cultivation area as explained in sections 2.4 and 3.2 and hence the associated agricultural GDP. The losses in the agricultural sector (i.e. Agricultural GDP) will decrease the total projected GDP per capita for Egypt for the years 2022, 2023 and 2024 from \$ 2815, \$ 2890 and \$ 2968, for the case without the GERD, down to \$ 2633, \$ 2703 and \$ 2777 when accounting only for the agricultural losses arising from the unmitigated



total water budget deficit under the GERD short-term filling scenarios.

Unemployment projections for Egypt's agricultural sector are shown in figure 6 and the supplemental tables. Of Egypt's 28.8 million employed, about 5.5 million work in the agricultural sector (Central Agency for Public Mobilization and Statistics, (CAPMAS) 2018). Approximately each ~ 1.4 feddan (0.6 ha) of agricultural land employ one person; hence the unmitigated total water budget deficit under the GERD proposed three-year short term filling scenario may degrade 2.8 million hectares of land, which would result in 4.75 million jobs losses in downstream in Egypt. This would result in an alarming loss of over three quarters of Egypt's agricultural land and resulting in more than 60% of agricultural workers unemployed. The total unemployment rate would rise from the current 11% to a future 25%.

Our economic impacts model's accuracy is limited by a few key factors. Firstly, it does not account for time the Nile will need to restore full flow after GERD filling ends, and as a result, does not account for the economic effects in the years following the GERD's filling. The immediate upshoot in GDP during the year after the filling period ends is highly unlikely as many of the environmental and socioeconomic impacts could be irreversible. The 10 to 21 years filling scenarios, with the lowest net present value impact on Egypt's GDP, thus appears to be the best scenarios with long-term manageable economic impacts to a country that is already highly stressed by socio-economic instabilities and rapid increase in

population. Secondly, the model hypothesizes that for every unit loss in the Nile River inflow, its distributaries will experience an equal unit loss of water. The downstream impacts such as land loss and available water for industrial and municipal use are more likely to be manifested as a non-linear decrease at a much higher rate for every unit decrease in the Nile itself. Furthermore, the model assumes that the distribution rates of water across agriculture, industry, and municipal use will remain unchanged. Lastly, these figures do not include the economical impacts on the growing food manufacturing and processing sector which contributed to $\sim 6\%$ of Egypt's GDP in 2019 (USDA, 2020). Other service industries connected to industry and agriculture are likely to experience significant consequences because of decreased production capabilities. As such, the results on the equivalent decrease in the GDP per capita and the rise of unemployment should be considered as lower limits, the economic damage considering all the above factors will be higher.

4. Implications and mitigation strategies

The purpose of this study is to evaluate the effects of the GERD on the short-term Egyptian total water budget deficit by considering different filling scenarios simulated based on the most recent published peer-reviewed records and considering seepage and the growth in Egypt's intrinsic water budget deficits. Our findings concur with several studies (e.g. Zhang *et al* 2016, Kansara *et al* 2021) that short-term filling scenarios (3–5 years) will cause measurable shortages

in the water supply for Egypt during the dam filling phase. This additional water budget gap is estimated to correspond to an overall increase of the present water deficit in Egypt by more than one third (+34%) to almost double (98.7%). Of this water budget gap, on average ~83% would be due to the amount of water needed to fill up the dam, while in an extreme case, up to ~17% could be lost to natural seepage within the GERD reservoir.

These water shortages if unmitigated will have dire consequences for Egypt's economy, employment rates, migration outflow and food sufficiency. The above-modeled GDP loss does not account for unemployment in connected industries, such as transportation or tourism, nor for damage done by resulting food scarcity, as these effects lie beyond the immediate economic impact of unemployment. Municipal water loss, which is also not immediately translatable into monetary loss, would present significant long-term detrimental effects to the affected populace. In the case of a large wave of unemployment, the socioeconomic stability of much of Egypt's workforce would also be at stake, and the adverse effects of reduced economic activity and increased unemployment have the dangerous potential to become cyclical (Brand 2015). In turn, economic damage in Egypt could force less spending on education, decrease small business activity and health quality, and increase crime rates (Irons 2009).

Water scarcity is specifically dire due to its effects on the behaviors of populations and governments. The conflict for Zambezi Island, Mekong River disputes, the Euphrates-Tigris disputes, and water riots across the world in the past few decades are all indicators that the current dispute between Egypt and Ethiopia has the potential to erupt into external conflict, while civil unrest may also arise within Egypt (Guarino 2017). Water loss due to climate change is already expected to have negative effects on North Africa and the Middle East, the region most vulnerable to GDP loss from further water scarcity, driving increased migration and rekindling older conflicts (World Bank 2016). It is essential to consider these devastating consequences in order for Egypt to reallocate its resources toward the mitigation solutions described in figure 3 and for Ethiopia to consider slowing the GERD's filling.

On the other hand, the construction of the GERD will have some positive impacts on the downstream countries. In Egypt, the simulated reduction of sediment accumulation in the Aswan High Dam Lake (AHD) by 90%–97% in the year 2060, compared to the amount of sediment accumulation in the year 2020 without GERD operation/construction, will arguably increase the lifetime of the AHD (Negm *et al* 2018). In Sudan, the GERD construction and consequent reduction in sediment accumulation in Lake Nubia (i.e. the Sudanese portion of the AHD), will provide an opportunity for scooping out accumulated

muds and silts through dredging and constructing onshore sediment ponds that can be used for agricultural purposes and the development of small communities (Abulnaga 2018).

We also considered numerous management actions and mitigation strategies that could secure Egypt's water demands by minimizing the effects of the GERD project. By using a feasibility index defined ad hoc, we find that the best option for Egypt would be to re-evaluate the current operation of the AHD hydropower plant to mitigate the upcoming water shortages, together with the increase of groundwater withdrawal as a backstop option to temporarily sustain the water demand. Water conservation strategies should also be incorporated especially in the agriculture sectors by switching the national production towards crop types that require less water.

If Ethiopia's government decides on one of the shorter filling periods, possible compensation methods are available to offset Egypt's agricultural losses, which we have identified as the primary economic downside of the 3-year filling scenario of the GERD. Since Ethiopia is currently leasing its agricultural land to multiple international investors, it could provide a long-term lease, at a preferential rate, of some of its surplus farming land for Egypt's use as a method of direct compensation for the loss in crop production. Egypt in exchange can develop the needed infrastructure in these farming lands to become highly productive crop areas with irrigation infrastructure that preserves the Nile ecosystem. In the long term, this solution would also be advantageous to Ethiopia when the leased lands are restored back to Ethiopian management.

Alternatively, Ethiopia could make use of some of the surplus electricity generated by the GERD to financially compensate Egypt for its GDP loss arising from the GERD unmitigated water budget deficit (and not the total water budget deficit that include the intrinsic component), even though this solution is unlikely as it requires mutual recognition of the size of the financial damages arising from the GERD, which are unachievable in the current political and economic context. The GERD is expected to generate ~16 000 Gigawatt hours per year of electricity and 1 billion Euros in surplus sales (Pichon 2020). Egypt currently produces on average 184,000 Gigawatt hours per year of electricity (Kwakwa 2017). Despite their similar populations, Egypt consumes 15 times as much electricity as Ethiopia consumes. Offering subsidized electricity or an electricity allowance to Egypt would also be a viable solution that would allow Egypt to slow the use of its own AHD and increase their yearly water access on their own end.

While our study presents preliminary results, it unambiguously suggests an alarming upcoming total water budget deficit for Egypt during a three-year short term filling scenario. Longer-filling scenarios

above 7 years will allow a more manageable deficit below 10 BCM yr⁻¹ that can be mitigated using existing resources and minimize the associated socio-economic impacts. The more technical information that can be obtained on the GERD future operational plans, the more accuracy that can be achieved in modeling and forecasting the water budget deficit as well as the associated socio-economic impacts. However, since all findings converge on a temporal yet severe decrease in Egypt's water supplies, it is plausible that a win-win strategy can be found to mitigate the impacts on food security and socio-economic stability. The above requires an accurate forecast of Egypt's total water budget deficit, its impact on the agricultural sector and the total GDP, as attempted herein, in addition to addressing the nature of the short- and long-term environmental and ecological impacts of constructing mega reservoirs on the Nile River system, which remain poorly constrained let alone understood at this stage.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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