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Comment on 'Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam filling scenarios'

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E-mail: dale_whittington@unc.edu**Keywords:** Grand Ethiopian Renaissance Dam, Nile, Egypt, Sudan, Ethiopia, Aswan High Dam Reservoir

Abstract

In their recent paper in ERL, 'Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam (GERD) filling scenarios,' Heggy *et al* (2021 *Environ. Res. Lett.* **16** 074022) paint an alarming picture of the water deficits and economic impacts for Egypt that will occur as a consequence of the filling of the GERD. Their median estimate is that filling the GERD will result in a water deficit in Egypt of ~ 31 billion $\text{m}^3 \text{yr}^{-1}$. They estimate that under a rapid filling of the GERD over 3 yr, the Egyptian economy would lose US\$51 billion and 4.74 million jobs, such that in 2024, Gross Domestic Product (GDP) per capita would be 6% lower than under a counterfactual without the GERD. These and other numbers in Heggy *et al* (2021 *Environ. Res. Lett.* **16** 074022) article are inconsistent with the best scientific and economic knowledge of the Nile Basin and are not a dependable source of information for policy-makers or the general public. In this response to Heggy *et al* (2021 *Environ. Res. Lett.* **16** 074022) we draw on high quality peer-reviewed literature and appropriate modeling methods to identify and analyze many flaws in their article, which include (a) not accounting for the current storage level in the High Aswan Dam reservoir (b) inappropriately using a mass-balance approach that does not account for the Nile's hydrology or how water is managed in Egypt, Sudan and Ethiopia; (c) extreme and unfounded assumptions of reservoir seepage losses from the GERD; and (d) calculations of the economic implications for Egypt during the period of reservoir filling which are based on unfounded assumptions. In contrast to Heggy *et al* (2021 *Environ. Res. Lett.* **16** 074022), robust scientific analysis has demonstrated that, whilst there is a risk of water shortages in Egypt if a severe drought were to occur at the same time as the GERD reservoir is filling, there is minimal risk of additional water shortages in Egypt during the filling period if flows in the Blue Nile are normal or above average. Moreover, the residual risks could be mitigated by effective and collaborative water management, should a drought occur.

1. Introduction

The climate, hydrology and water management in the Nile Basin have been extensively studied, including the implications of hydropower development in Ethiopia. The planning and construction of the Grand Ethiopian Renaissance Dam (GERD) near the border between Ethiopia and Sudan has triggered a proliferation of applied studies that have analyzed the implications of this major new infrastructure (van der Krogt and Ogink 2013, King and Block 2014, Geressu and Harou 2015, Kahsay *et al* 2015, 2017, Zhang *et al* 2015, Nigatu and Dinar 2016, Wheeler *et al* 2016, 2018, 2020, Boehlert *et al* 2017, Jeuland *et al* 2017, Liersch *et al* 2017, Eldardiry and Hossain 2021). The recent study by Heggy *et al* (2021), ‘Egypt’s water budget deficit and suggested mitigation policies for the GERD filling scenarios,’ seeks to add to that literature. However, it contains multiple errors and implausible assumptions. In this rebuttal we explain why the published article misrepresents the implications of the GERD for Egypt, in ways which are not only scientifically untenable but are also misleading for crucial decisions about the management of the Nile waters.

Though there is long list of problems with the article, we organize the discussion here to focus on the two most important deficiencies of the analysis: (a) miscalculation of the water deficit that could result from filling the GERD reservoir, and (b) misrepresentation of the economic implications of any water deficits that would result. We have framed the discussion of each of these issues around two questions, each of which have several subcomponents. First, are the water deficits that Egypt might face due to filling the GERD reservoir calculated and portrayed accurately? As part of this question, we discuss the critical role of the High Aswan Dam (HAD) in mediating water shortages, the assumptions of Heggy *et al* (2021) about seepage from the GERD, and the portrayal of Egypt’s ‘intrinsic’ water deficit. Second, are the economic losses to Egypt that would occur from a given size of water deficit portrayed accurately? To address this question, we unpack the approach the authors used to estimate economic losses. Drawing on a rich body of existing literature specific to the Nile, we discuss why the approach they used is inappropriate, and explain how an appropriate economic methodology would have generated radically different results.

We note that the focus of Heggy *et al* (2021) is on potential impacts on Egypt resulting from filling the GERD reservoir rather than assessing the regional benefits that the GERD might provide if cooperative agreements for operating the dam are reached, or the economic implications to Ethiopia of delaying hydropower generation. Therefore, in this rebuttal we focus on assessing the methods used by Heggy *et al* (2021)

in their analysis, whilst here noting the absence of consideration of these aspects of the GERD in their analysis.

2. Question 1: Are the water deficits that Egypt might face as a result of filling the GERD calculated and portrayed accurately by Heggy *et al* (2021)?

No. The water deficits predicted for Egypt by Heggy *et al* (2021) are grossly overestimated. To show this, we begin by examining the authors’ methods and assumptions, and explain how results from previous studies were used and misinterpreted by Heggy *et al* (2021). It is important to note that the published article does not clearly explain how the deficit predictions were calculated; we therefore requested access to the authors’ analysis, a request to which they responded positively. On reviewing the spreadsheet analysis provided, it became clear that a model of the Nile River and reservoir systems was not used to make predictions of potential GERD-induced deficits. Rather, Heggy *et al* (2021) selectively used results from previous studies, including several conducted by authors of this response. Moreover, a key part of the analysis of Heggy *et al* (2021) was its referencing of a large-scale water balance model that was used to estimate Egypt’s ‘intrinsic’ water deficit, which conflates issues of water accounting in a misleading way. There are many shortcomings in their approach—below we focus attention on the three most important issues: (a) the lack of accounting for the role of the HAD and other aspects of water management; (b) the lack of an evidence basis for predictions of seepage losses; and (c) the conceptual problems with Heggy *et al*’s (2021) approach linking Egypt’s long-term intrinsic water deficit to the short-term impacts of filling of the GERD reservoir.

2.1. Question 1a: How did Heggy *et al* (2021) obtain their predictions of the additional water deficits attributable to the GERD, and do those methods appropriately capture the most critical elements of the Nile system?

Heggy *et al* (2021) reviewed recent modeling studies, which they used to create a list of changes in downstream flows implied by different filling rates for the GERD reservoir. Because the referenced studies report these changes in different ways, converting them to consistent changes in water supply to Egypt requires a series of assumptions that are not always clear in the authors’ spreadsheet. Nonetheless, a key assumption in all of the authors’ calculations is that the quantity of water retained by the GERD reservoir during filling translates exactly into a deficit in supplies to water users downstream of the HAD in Egypt. This ignores the storage that exists in

the HAD reservoir¹ and all of the other natural and human modifications to the Nile flowing between the GERD and the HAD. It is puzzling that these crucial aspects of the system are neglected, as there are well-calibrated models that have been widely used to predict water flows and availability on the Eastern Nile, which we demonstrate below using updated probabilistic model-based calculations, initialized with the latest observations of reservoir levels.

2.1.1. Omission of the role of the HAD reservoir in mediating water supplies in Egypt

Omission of the HAD from the authors' assessment of the impacts of GERD filling overlooks an obvious fact that has defined water resource management in Egypt since the 1970s: the HAD was constructed to manage variability in the Nile's flows into Egypt. The HAD, completed in 1970, has led to the formation of the HAD reservoir (also known as Lake Nasser in Egypt and Lake Nubia in Sudan), which has a maximum storage capacity of 162 billion cubic meters (BCM) and an active storage capacity of 127 BCM. Including the flood storage volume with maximum elevation of 182 meters above sea level (masl), the HAD reservoir capacity is 174% of the average annual inflow of roughly 73 BCM yr⁻¹ that has occurred over the last 50 yr. Lake Nasser, known as the 'national freshwater bank of Egypt' (Abd Ellah 2020) 'converted an uncertain and highly variable intra-annual Nile flow into a predictable source of steady downstream supply resulting in economic gain due to increased transport productivity and a shift to more valuable summer crops' (Strzepek *et al* 2008). The possible impacts on water availability in Egypt resulting from the filling of the GERD therefore depend on the extent to which the HAD reservoir continues to provide reliable water supplies during the filling period. This, in turn, depends crucially on the initial storage level of the HAD reservoir when the GERD reservoir begins to fill (Wheeler *et al* 2016, 2020). Today, even as the second year of filling has been completed and the GERD reservoir has retained approximately 8.5 BCM, the HAD reservoir is nearly at its maximum storage capacity². The deficits estimated by Heggy *et al* (2021), however, assume that this current unusually large amount of storage would not be used to maintain Egypt's water supply during filling of the GERD reservoir. Once filling is complete, the entire flow of the Blue Nile in Ethiopia (minus the evaporation losses from the GERD reservoir) will be released through the GERD's hydropower turbines or over the

spillways, continuing the supply of water that can be retained in the HAD reservoir.

Heggy *et al* (2021) estimate that the reduced water supply to Egypt due to the GERD reservoir filling would range between 2.72 and 22.67 BCM yr⁻¹, depending on the filling time, with a median 9.64 BCM yr⁻¹. The estimate of the median incorrectly assumes that various scenarios that Heggy *et al* (2021) selected from the literature are all equally likely, even though they come from studies that analyze different filling policies. The analysis of Heggy *et al* (2021) gives equal weight to a number of these studies, some of which only use a single rainfall/flow scenario, and several of which do not rely on peer-reviewed models or results.

Nonetheless, if we consider the median estimate, the equation from figure 1 in Heggy *et al* (2021) implies a corresponding filling duration of 8.8 yr. The total median shortfall in supply to Egypt from filling the GERD reservoir then superficially appears to be 8.8 yr × 9.64 BCM yr⁻¹ = ~84.8 BCM, which is slightly greater than the capacity of the new reservoir, owing to assumptions about increased evaporation and seepage loss from the GERD. However, as the HAD reservoir is now nearly full with 110 BCM of active storage, the HAD reservoir could fully compensate for the water required to completely fill the remaining space in the GERD reservoir, even without considering other mitigating aspects that we describe below. In fact, the anticipated operating arrangements mean that the cumulative impacts of filling the GERD should stop when the reservoir reaches 625 masl and has retained an additional 41 BCM above the current storage volume, which is 37% of the current active storage current in the HAD reservoir. All water retained above that level—24.7 BCM between 625 and 640 masl—will be released downstream each year to prepare for the next flood season.

Moreover, Egypt already has a well-established drought management policy which incrementally reduces releases from the HAD to downstream water users by 5%, 10% and 15% as the storage volume in Lake Nasser falls below 60 BCM (159.4 masl), 55 BCM (157.5 masl) and 50 BCM (155.7 masl), respectively. These drought management policies are designed to conserve water in the HAD during times of low flow in the Nile and thus help to mitigate the overall impacts of such events (Wheeler *et al* 2018). The effect of policy was not considered in the analysis of Heggy *et al* (2021).

2.1.2. Inadequate methods for analysis of impacts of filling the GERD reservoir on Egyptian water supply

The preceding discussion highlighted the necessity of including HAD storage and operations in any analysis of impacts in Egypt of modification to the Nile's flow. Furthermore, there is another fundamental problem with Heggy *et al* (2021) estimation of Egyptian deficits, which is the assumption that decreased flow

¹ To be fair, the authors do include HAD management as one of their 'mitigation strategies', but their inclusion of mitigating measures is rudimentary at best, and relegating these to a side analysis is deeply misleading (a point to which we return in much more detail in our discussion of the economic implications of the GERD).

² As of 6 August 2021 when this comment was submitted for publication, the HAD reservoir was at 179.1 masl or ~145 BCM of total storage, exceeding the Toshka spillway elevation of 178 masl.

downstream of the GERD translates into an equal reduction in flow in Egypt. This assumption neglects the fact that there are many other water users and hydrological modifications between the GERD and the HAD. The losses include evaporation from those reservoirs as well as the HAD reservoir, net seepage to groundwater, and water spilling into the Toshka depression. There are several storage reservoirs in Sudan that are used for irrigation or hydro-power, as well as water abstractions from the river for municipal water supplies and irrigated agriculture located near the river. Strategies for management of this infrastructure will respond to the presence of the GERD. Yet understanding such strategies requires a detailed, calibrated hydrological model that can accurately simulate operational policies, not a simple, aggregate calculation such as that conducted by Heggy *et al* (2021).

The approach used by Heggy *et al* (2021) did not consider the implications of variability in the Nile's flows from year to year, which are a fundamental challenge for water managers. The exact impacts of filling the GERD reservoir on water availability downstream in Egypt cannot be known in advance because they will depend on rainfall and river flow conditions that will occur during the filling period. Rainfall is highly variable in the Nile Basin, so it is necessary to use a hydrological modeling approach that accounts for this variability; this has been shown by numerous existing studies to be fundamental for properly evaluating the risks of water shortfalls in Egypt (van der Krogt and Ogink 2013, King and Block 2014, Zhang *et al* 2015, Wheeler *et al* 2016, 2020). As demonstrated in Wheeler *et al* (2020), water shortages in Egypt during GERD filling are highly unlikely under hydrological conditions that would be considered to be 'normal' or 'wet' relative to the historical observed records³. Only if drought conditions were to occur during the filling period would there be a risk of shortages relative to Egypt's annual planned release. A major study conducted by the consulting firm Deltares, for the Egyptian Ministry of Water Resources and Irrigation (MWRI), agreed with this finding and stated that no shortages in water releases from the HAD would occur under average hydrological conditions (Deltares 2019). However, all studies recognize that shortages are possible if severely dry conditions occur during multiple years when the GERD reservoir is filling. Any shortages in water supply from the HAD to Egypt would likely remain modest, as we demonstrate below.

The standard practice in water resources planning and management is to analyze the risks of water

shortage using a range of hydrological conditions, usually generated from a stochastic process model trained on observations of flow. Although some of the published studies that Heggy *et al* (2021) used to derive their conclusions included this variability, they simply took the mean results from these studies, thereby neglecting the implications of hydrological variability of the Nile. To contrast the resulting differences when using a rigorous stochastic approach, we have updated the model and methods of Wheeler *et al* (2018, 2020) to reflect the reservoir storage conditions that were observed in January 2021 and Ethiopia's current filling plan for the GERD⁴. We reran this model to analyze how the storage levels in the HAD would respond to all of the hydrological conditions that have been observed in the period 1900–2002. We used these results to conduct a probabilistic evaluation of the impacts of filling the GERD reservoir under many possible future hydrological conditions (figure 1).

The median HAD reservoir elevation prediction across all the hydrological sequences in the observation record is shown by the red line in figure 1; this level decreases to 163.4 masl before beginning to recover. Of critical importance, this projected median elevation remains above the threshold that would trigger the HAD drought management policy (159.4 masl); thus, there would be zero water shortages for Egypt in the median hydrologic condition. If there is no change in the drought management plan, there is a 29% probability that the HAD storage will fall below 60 BCM (159.4 masl), which would trigger a 5% reduction in releases, to 52.7 BCM yr⁻¹ instead of Egypt's stated objective of 55.5 BCM yr⁻¹. There is a 19% probability that the HAD storage will fall below 55 BCM (157.6 masl), when only 50.0 BCM yr⁻¹ would be released in the affected years, and a 10% probability that storage will fall below 50 BCM (155.7 masl), when releases from the HAD would be limited to 47.2 BCM yr⁻¹. Finally, there is only a 4% probability that the HAD will fall to the very critical pool elevation of 147 masl, when water shortages in Egypt would be potentially severe. We emphasize here that under historically wet, normal, and even mildly dry hydrological conditions, there would be no need for Egypt to reduce annual releases below 55.5 BCM yr⁻¹. The probability of the HAD reservoir falling below various pool elevations is shown in figure 2.

³ The possibility of Nile flows that are outside of the historical record, perhaps due to climate change, cannot be excluded. However, there is very little consensus in the scientific literature on the hydrological implications of climate change in this region and especially how it might affect the filling period.

⁴ Ethiopia expects to retain approximately 10.5 BCM each year until the filling process is complete, while allowing a minimum of either 31 BCM or the inflow to pass downstream. Our assumptions of drought management reflect Ethiopia's position as of mid-2021; however, refinements of it are still under negotiation. Changes to these assumptions would only reduce the impacts presented in this analysis, therefore these results can be considered a 'worst case' for the HAD.

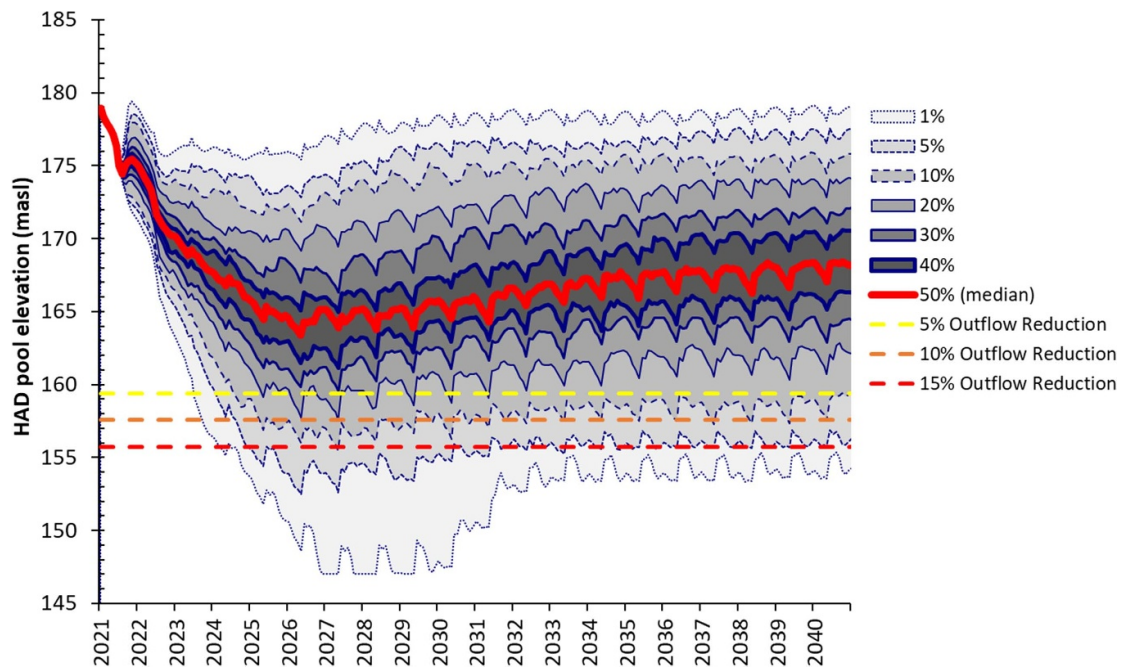


Figure 1. Probabilistic predictions of HAD reservoir elevations during the GERD reservoir filling using 103 historical river flow sequences and the recently observed reservoir elevations. Red line indicates the median value across all river flow sequences at each time step. Shaded zones encompass exceedance and non-exceedance values. Horizontal lines indicate the elevation thresholds that trigger the HAD drought management policy.

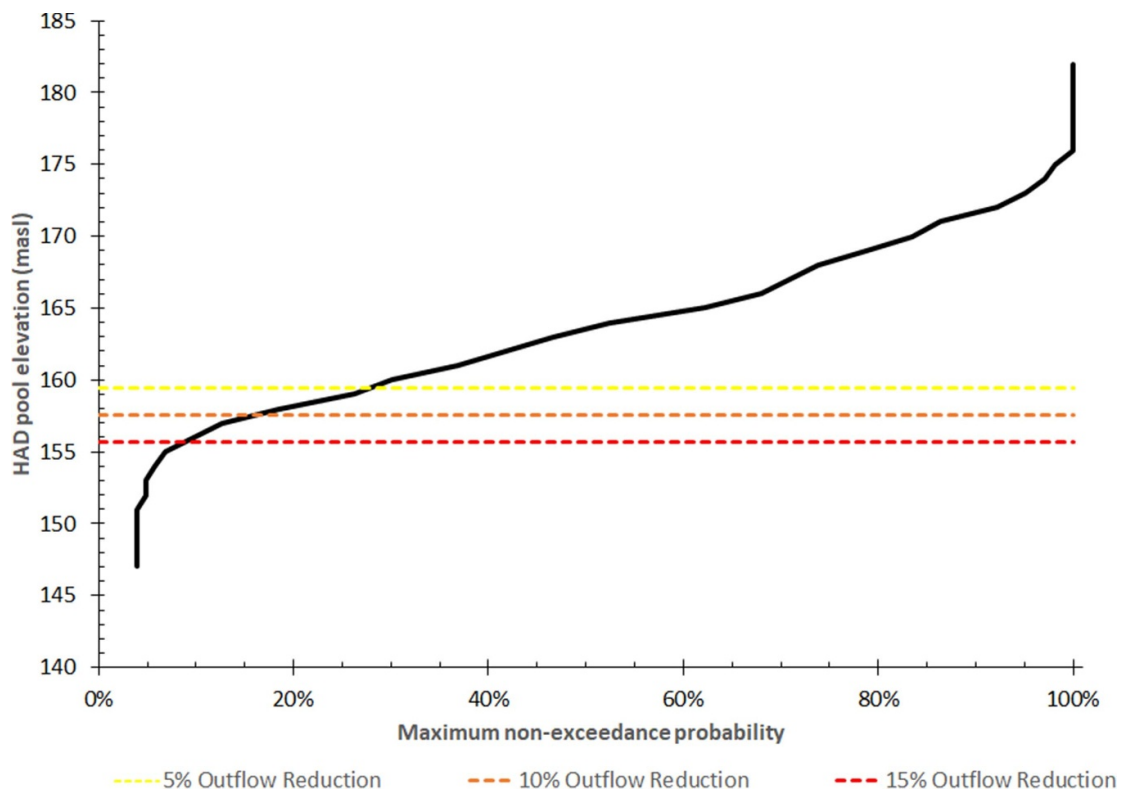
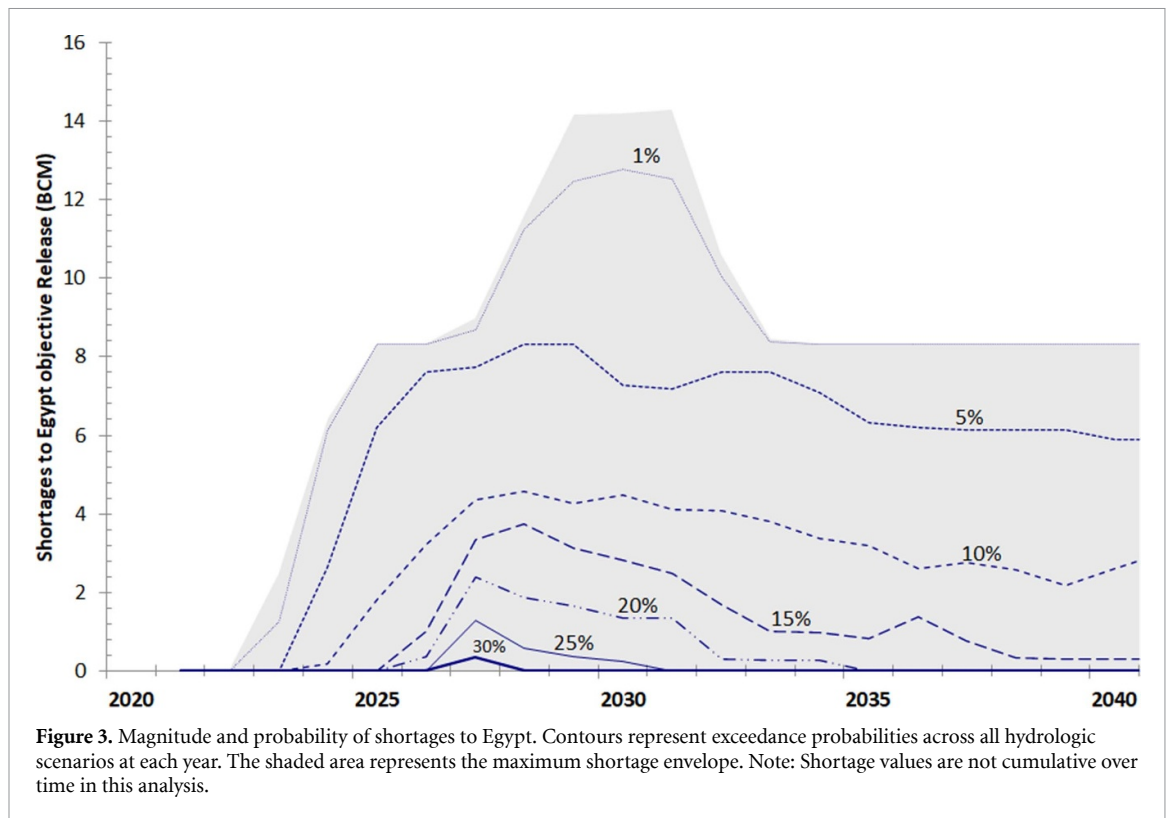


Figure 2. Maximum probability of the HAD reservoir falling below elevations throughout the GERD reservoir filling. Horizontal lines indicate the elevation thresholds that trigger the current HAD drought management policy.

Using a well-calibrated model of the Nile system under multiple hydrologic conditions, we then estimated the probability of water releases from the HAD being less than 55.5 BCM yr^{-1} (figure 3),

demonstrating that modest shortages are possible, and mainly result from the proactive HAD drought management policy. Significant shortages comparable to those predicted in Heggy *et al* (2021) as



median shortages (i.e. 9.64 BCM yr^{-1}) are possible, but have less than a 4% probability of occurring according to our analysis.

Furthermore, it has been demonstrated how the GERD filling strategy could itself be modified to protect users in Egypt, by making ‘safeguard’ releases triggered by critical HAD reservoir elevations. As described in Wheeler *et al* (2016), such a policy could be contingent on an Egyptian commitment to invoke drought management measures and having sufficient storage in the GERD. As can be seen in figures 1–3, such measures are unlikely to be needed, but would provide assurance to Egypt that the filling will not have a negative impact.

2.2. Question 1b: Did Heggy *et al* (2021) appropriately assess the contributions of seepage from the GERD to water deficits?

No. A particularly surprising aspect of Heggy *et al* (2021) analysis was the inclusion of the possibility of large losses due to seepage from the GERD reservoir. This was surprising because we are unaware of any rigorous evidence or public data sources for estimating such potential losses, which are difficult to characterize without detailed *in-situ* measurements. In their analysis, Heggy *et al* (2021) specify a median additional loss of 2.5 BCM yr^{-1} and a range of $0.043 \text{ BCM yr}^{-1}$ – 10.4 BCM yr^{-1} . They state that ‘The hydrogeological setting could cause major leakage of water from the reservoir, which could reach up to 25%.’ Apparently, this assumption was derived

from Liersch *et al* (2017), who conducted a sensitivity analysis using daily seepage rates of 0.001%, 0.01% and 0.1% of the stored volume in the GERD reservoir. We contacted Liersch *et al* (2017) to inquire about the basis for this analysis, and he replied: ‘The high seepage rate [0.1%] scenario was included because Nouredin (2013) assumes that, due to rock formations, seepage losses may amount to 25% of the actual storage volume’. The reference to Nouredin (2013) was published in a commentary article in a popular newspaper in Egypt, without scientific justification.

Liersch *et al* (2017) did not attempt to calculate distributions of seepage values and treated the three seepage rates as purely hypothetical values. Heggy *et al* (2021), however, assumed these hypothetical rates to be equally probable (see figure 2 in the paper). Using a median or a mean from a sensitivity analysis that has no physical or statistical basis is misleading, particularly when the scenarios analyzed apply values that are orders of magnitude apart. In addition, when selecting scenarios from Liersch *et al* (2017) to calculate the GERD reservoir filling rates and associated impacts on deficits (i.e. to derive figure 1 in the paper), Heggy *et al* (2021) only chose scenarios that assumed the maximum seepage (see table 1 in Heggy *et al* 2021). By using scenarios from Liersch *et al* (2017) that already incorporated seepage losses when determining the filling times, and then calculating seepage losses separately, these losses were effectively considered twice for these scenarios.

Unfortunately, an estimation of seepage losses from the GERD reservoir based on field tests at the site is not available to the scientific community. It certainly would have been prudent to undertake the geological studies needed to understand the potential for such losses at the time of design of the GERD, but we cannot say whether this was done, as details have not been made public by the Government of Ethiopia^{5,6}. In the original site assessment of the GERD location, however, the US Bureau of Reclamation stated ‘The reservoir basin is underlain by precambrian rock mantled with clayey soil deposits, and leakage should not be a serious problem’ (USBR 1964). Geological maps indicate that the basin is dominated by precambrian syntectonic granitoids and post-tectonic granitoids (Britto 1973). Seepage during first filling can absorb a significant volume of water to initially saturate the reservoir banks. Once the banks are saturated, water will slowly seep back into the reservoir as the water level drops, or again into the banks as the level rises. These volumes are typically small in relation to evaporation losses and as standard practice are not accounted for in reservoir simulations.

A further issue to note is that seepage flows beneath a reservoir are normally in the downstream direction, underneath the dam foundations and along the flanks. These flows are typically measured at the outlets of the drainage galleries, and then contribute to the downstream river flow. Should groundwater flow laterally from the reservoir and exit as spring flows into an adjacent valley, they would still remain in the Nile valley and likely find their way to the river downstream. Heggy *et al* (2021) assumed, again without any evidence, that seepage from the reservoir would be permanently removed from the Nile system, which contradicts their own source of seepage information who states: ‘... an unknown, but possibly large fraction may contribute to groundwater discharges downstream and would thus not necessarily be considered as a loss from the hydrological system, but as a loss for [hydropower production]’ (Liersch *et al* 2017).

Whether significant seepage has taken place during the first two years of the filling is difficult to know for certain. However, since all the downstream reservoirs are full, any seepage has not had an

appreciable negative effect on water supplies in Sudan and Egypt.

2.3. Question 1c: Is Heggy *et al*’s (2021) characterization of an ‘intrinsic’ deficit accurate?

No. A final brief note on the characterization of impacts on Nile water supplies in Egypt concerns the ‘intrinsic deficit’ in water resources existing today in Egypt. It is well known that Egypt does not have enough water to provide for all of its domestic food consumption with irrigated agriculture, so food imports are essential (Allan 1992, 2001, 2004, 2011, Asseng *et al* 2018, Nikiel and Eltahir 2021). Heggy *et al* (2021) draw on a large-scale mass balance model, developed by Mazzoni *et al* (2018), to describe the long-term water imbalance in the broader region of which Egypt is a part. Such models may be useful for understanding the long-term implications of drivers of change in the water balance, such as climate change, population growth and changing patterns of food consumption. However, such mass balance models are not designed to understand short-term interactions between hydrology and infrastructure. In fact, Mazzoni *et al* (2018) state that ‘the objective of our model is limited to the estimate of the overall magnitude of the groundwater volume depletion and its timescale for each major transboundary aquifer as a consequence of the simultaneous aggregate withdrawal of one or more riparian countries on a regional scale.’ Ignoring this stated purpose, Heggy *et al* (2021) apply the same model to quantify deficiencies in surface water availability. They then add this figure to their estimates of the downstream impacts of the GERD filling (which, as we have argued above we believe to also be wrong) to arrive at a projected deficit of ‘an average +35.5% of its current internal annual water demand’. However, this ‘deficit’ bears no relationship to the probability of water shortages occurring during the filling of the GERD reservoir, which as we and others have calculated, is unlikely.

3. Question 2: Are the economic losses in Egypt that could occur due to water shortages portrayed accurately by Heggy *et al* (2021)?

No. In this section, we explain why the economic losses will be much lower than those estimated by Heggy *et al* (2021). To support this argument, we begin with a description of the over-simplified analytical approach used by Heggy *et al* (2021). We then identify several conceptual errors and methodological inaccuracies of this approach and direct the reader to the various modern economic analyses that have been used to study the Nile and the economic implications of the GERD. We note that the authors do not cite or compare their results to the growing peer-reviewed

⁵ The Sudan MWRI and Electricity did itself commission a study on the effects of the GERD on groundwater recharge in Sudan, which predicted minimal effects resulting from the altered flow regime (Water Research Center 2016).

⁶ Seepage estimates for the Sudanese Roseries Reservoir immediately downstream of the GERD have been estimated to be around 0.1 BCM yr⁻¹ prior to this dam being heightened by 10 meters in 2013, and after this heightening took place, groundwater levels downstream of the dam increased, indicating an impact on the shallow aquifer rather than significant a deep percolation loss.

literature on this topic. Finally, we provide a more realistic summary of the economic implications of the filling of the GERD on Egypt based on the probabilistic risk of water shortages.

3.1. Question 2a: How did Heggy *et al* (2021) estimate the economic losses of water deficits to Egypt?

Heggy *et al* (2021) use what they call a ‘simplified economic model’. Their paper does not explain precisely what this simplified economic calculation is. However, they did provide us with the spreadsheet version of their model and underlying data. We were mostly able to replicate their calculations and reproduce the results provided in their paper. Their calculations essentially comprise a series of linear functions that relate water deficits to loss of productive agricultural land and agricultural land area to agricultural Gross Domestic Product (GDP).

The main problem with the assumption of a linear relationship between water deficits and agricultural GDP is that it does not represent how the Egyptian economy makes adjustments to reduce the economic consequences of deficits in inputs to production, in this case water. The value of water supply is best represented by its marginal product in its various uses, not by the average value of GDP from a sector that uses water as one of many inputs (Young and Loomis 2014). Producers and consumers re-optimize their behavior at a micro-level to adapt to changes in the relative cost and availability of inputs, including water⁷.

Heggy *et al* (2021) also argue that their estimate of economic losses is too low because (a) they have only valued losses in agriculture, omitting impacts on higher value industrial and municipal water use, and (b) costs would increase non-linearly with increasingly severe water shortages. The first part of this argument is also incorrect for two reasons. First, industrial and municipal water use is primarily non-consumptive with more than 80% of withdrawals returned to downstream water bodies. Second, we know from observations of drought management in many countries worldwide that at times of water shortage, municipal and industrial water users would be prioritized. The economic impacts tend to be

borne by the lowest value agricultural users, which minimizes the economic impacts of water scarcity^{8,9}.

3.2. Question 2b: Did Heggy *et al* (2021) appropriately apply the ‘simple economic calculation’ to estimate the economic losses to Egypt of filling the GERD reservoir?

No. Upon detailed review of the text and supplemental material of Heggy *et al* (2021) we noted several specific problems in their application of their simple economic calculation. The three most important issues from our perspective are discussed below.

3.2.1. The unrealistic deficit

As we have demonstrated above, Heggy *et al* (2021) estimate of median deficits relative to expected releases from the HAD reservoir is wrong. As the economic loss is a function of the deficit, so too will the economic loss estimates be wrong. A proper estimate of the economic risk would use probabilistic predictions of the reductions in water releases from the HAD reservoir (see figures 1–3 above) and integrate these with the consequential economic impacts, perhaps also weighting for risk aversion. The appropriate calculation of expected economic loss is as follows:

$$E[l] = \int_{-\infty}^{\infty} l(s) \cdot p(s) ds, \quad (1)$$

where $E[l]$ is expected loss, $l(s)$ is loss as a function of water shortage s and $p(s)$ is the associated probability density function for water shortage. To obtain an estimate of $E[l]$, one would have to determine, using an appropriate hydro-economic model (see Question 2c below), the magnitude of losses associated with the

⁸ Distributional concerns may lead policymakers to impose some costs of water shortfalls on urban and industrial users in order to spare farmers, but decision-makers would surely seek to avoid large restrictions on these high value uses. In any case, no economic model would predict proportional sharing of water deficits across low and high value users.

⁹ Another problematic assumption in Heggy *et al*’s estimate of the economic losses from water deficits is their medium GDP growth assumption of 4.47%. This is an economy-wide assumption, but the authors assume that agricultural GDP will also grow at this rate. This brings up two issues. First, how will this happen in light of Egypt’s fixed allocation of 55.5 BCM in the 1959 Nile Waters Agreement between Egypt and Sudan? If the answer is increased water efficiency, increased inputs, and technological progress, as well as changes that favor higher value crops, why would these trends stop under conditions of increased water shortage? If anything, one would expect them to accelerate. Second, agricultural GDP is currently 11% of total Egyptian GDP, down from 30% in 1970. Egypt is one of the fastest growing economies in Africa, but Egypt’s high growth rate in recent years was driven by international tourism, growth in trade & logistics, and the ICT market, not by agriculture. This suggests that the growth of agricultural GDP will continue to lag average GDP growth (as it does currently, at only one third the rate of overall GDP growth). A proportional growth assumption thus overestimates the loss from agricultural water deficits.

⁷ A simple thought experiment demonstrates the problem with assuming that a reduction in water supply causes a proportional reduction in agricultural GDP. Since water is an essential input in all economic activities, this logic would imply that a 50% deficit in water should reduce overall GDP by 50%, because the average value of the affected sectors would be reduced by 50%. The appropriate value to use is not this average sector value, but rather a measure of the specific contribution of water to the value generated in the affected activities. For large (non-marginal) reductions in water availability, this marginal value (or the demand for water) may vary and likely increases, but the essential point is that farmers would not simply stand by and watch their water-intensive crops be destroyed. They would adjust inputs, cropping choices, time and labor allocation, and deploy available capital to buffer the impact.

range of potential different shortfalls, that is, map the shortage probabilities shown in figure 3 above to their corresponding economic losses, and then sum the product of losses and probabilities together. Though a fully updated analysis of that type is beyond the scope of this rebuttal, in 2c (below) we review published results in the hydro-economic literature where such calculations have been conducted.

3.2.2. Impacts on agricultural GDP and employment

The simplified 'lower bound' economic model of Heggy *et al* (2021) further assumes that all agricultural GDP and employment is related to land under irrigation and that each of these would be hit in direct proportion to the size of the water deficit. Yet agricultural GDP in Egypt comprises crop production, livestock production and fisheries. The Food and Agriculture Organization reports that 'the livestock sector, which currently accounts for about 40% of agricultural value added, could become the largest contributor to the value of agricultural production,' while fisheries are only a minor economic activity. Thus, agricultural GDP losses for any level of deficits may be overstated by as much as 40% (though one should also include the lost value of the irrigated fodder crops that are used in livestock production, which would somewhat reduce the extent of the overestimate)¹⁰.

3.2.3. Results reported in the text are inaccurate and do not match Heggy's supporting materials

In the text Heggy *et al* (2021) state '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 yr filling scenario, ~\$28 billion for the 5 yr filling scenario, ~\$17 billion for the 10 yr filling scenario, and ~\$10 billion for the 21 yr filling scenario.' This statement is inconsistent with the author's own calculations for at least two reasons:

- Losses are a function of the assumed growth rate which is not stated. Nonetheless, the reported ~\$51 billion for the 3 yr filling scenario does not match the results in the supporting materials, or that in the model provided by the authors, for the medium growth rate assumption, which is \$60.4 billion, nor even for the low or high

growth rate scenarios (\$55.3 and \$66.9 billion, respectively).

- The results also do not reflect the authors' own figure 4 or an accurate summation of impacts. Ironically, due to inaccuracies in the way the authors calculate water deficits, the authors' figure 4 and the spreadsheet provided to us show *smaller* GDP impacts for a shorter filling time once one considers the entire time horizon over which the water supply reduction is supposedly experienced. In the quote above, they truncate their analysis to only sum up losses incurred in the first 3 years, even when assessing the 5, 10 and 21 yr filling scenarios.

3.3. Question 2c: Did Heggy *et al* (2021) have to rely on such a simple economic calculation to estimate the economic losses to Egypt of filling the GERD?

No. In fact, many studies have applied hydro-economic models to the Nile Basin, with several focusing upon the impacts of dams on the Blue Nile in Ethiopia (Guariso and Whittington 1987, Whittington *et al* 2005, Wu and Whittington 2006, Jeuland 2009, Block and Strzepek 2010, Goor *et al* 2010, Dinar and Nigatu 2013, Arjoon *et al* 2014, Geressu and Harou 2015, Satti *et al* 2015, Nigatu and Dinar 2016, Wu *et al* 2016, Jeuland *et al* 2017). Furthermore, economy-wide computable general equilibrium (CGE) models enable analysis of the price adjustments and resource reallocations that will occur during times of water scarcity. Robinson and Gelhar (1995), Lofgren *et al* (1996), Yates and Strzepek (1996), Osman *et al* (2016), Kahsay *et al* (2015) have all developed CGE models of Egypt that explicitly include water as an input to production activities. Again, none of these are referenced in Heggy *et al* (2021) or used for comparison to their results. In these economic models, reductions in water releases from the HAD cause shifts in cropping patterns and substitution of labor and capital to mitigate the consequences of the reduction of water in the agricultural sector. They also demonstrate substitution of fossil and renewable electricity to compensate for the losses of hydropower production from the HAD. These CGE models all demonstrate that the relationship between water releases from the HAD and Egyptian GDP is highly nonlinear, not linear as Heggy *et al* assumed.

3.4. Question 2d: If Heggy *et al* (2021) had used an appropriate economic model of the relationship between water and economic activity, would their conclusions have been different?

Yes. Heggy *et al* (2021) suggest that the economic impact of a three-year GERD filling scenario to Egypt would be a 6% decrease in GDP per capita per year. Even absent the issue of inaccurate and overstated deficits, Robinson *et al* (2008) demonstrated that

¹⁰ A similar discussion could also be had concerning predicted impacts on agricultural and overall employment. Agricultural production relies on a combination of land, labor, energy, and water as factors of production. These factors are partial substitutes; for small deficits, additional labor may help reduce the impact of water deficits (e.g. performing night irrigation and managing deliveries to reduce water losses), somewhat lessening impacts. Even if some agricultural activity ceases entirely, the increase in labor availability will reduce wages and lead to increased employment in other sectors. Though there will be impacts, this will help reduce employment losses.

using an assumption of a linear fixed factor Input-Output Model of the Egyptian economy that nonetheless accounts for basic sectoral linkages correctly would overestimate the cost of water supply reductions by a factor of six, relative to a nonlinear CGE, which alone would reduce Heggy *et al*'s estimate of economic losses to 1% of GDP. Moreover, as noted above, Heggy *et al*'s (2021) approach is not conceptually correct in substituting the average value of agriculture for the marginal productivity of water¹¹. Correcting for these two economic errors would reduce the estimated losses to less than 0.1% of GDP.

Kahsay *et al* (2015), Kahsay *et al* (2017) and Boehlert *et al* (2017) all performed analyses of the impacts of 3 yr filling scenarios for the GERD on Egyptian GDP per capita. Those papers report a range of decreases from 0.01% to 0.1% in GDP per capita, depending on upstream hydrological conditions and uncertainty related to Sudanese management responses. The most risk averse decision-makers might look to the high end of this range. We believe that results would likely be similar using the information plotted in figure 3. Heggy *et al* (2021) have overestimated the economic losses to Egypt by nearly two orders of magnitude.

4. Conclusions

The construction of the GERD has focused political and public attention upon the allocation and management of the Nile's water resources. A political agreement between the riparian states will depend upon sound scientific analysis of the Nile's hydrology, engineering expertise in operating the water infrastructure, and economic insight into the value of water for the people that depend upon the Nile. There is an extensive corpus of scientific analysis that has sought to shed light on these crucial issues. Because of inevitable uncertainties in hydrological science and economic knowledge, along with the ever-changing human interventions in the management of the Nile, this literature is not completely in agreement and takes multiple perspectives on a complex system. Nonetheless, there is considerable agreement on the basic facts of the Nile system and the plausible ranges of future scenarios.

The paper by Heggy *et al* (2021), to which we have responded in this article, does not represent the

high standards of science that we expect at a reputable journal like ERL. We have identified a series of errors and assumptions that should have been subject to greater scrutiny and led to rejection during the peer review process. Furthermore, the lack of serious analysis on the benefits versus the costs that will be incurred during filling of the GERD reservoir is apparent. The implications of this publication extend far beyond its lamentable legacy in the scientific literature. The work has already been very extensively circulated in mainstream and social media, with inflammatory consequences. In social media and interviews to the press since the publication of the article, Heggy has described the consequences of the GERD as 'catastrophic' for Egypt (Al-Jazeera 2021). The authors of Heggy *et al* (2021) have recently defended their analysis by arguing: 'If there was any mistake in the results, it is not from our model. Our model has been published in a reputed peer-reviewed journal. We base our model assumptions on published studies on GERD. If there is any mistake in the results, it comes from other papers.' (Al-Jazeera 2021). We reject this assertion because, as we have explained at length in this article, there are two major flaws in the analysis of Heggy *et al* (2021).

First, their analysis assumes implausible water deficits to Egypt during the filling period of the GERD. Their estimates of large water deficits will not occur because: a) the HAD storage, which is currently at a high level, will be used to maintain supplies to water users in Egypt; and b) their estimates of seepage losses from the GERD incorporate values that are unrealistically high, not based on any scientific analysis, and incorrectly assume that seepage into the groundwater will not return to the Nile system. After two years of filling the GERD reservoir, the HAD reservoir is still near its maximum level due to favorable hydrological conditions in the system and planning efforts in Egypt. These facts demonstrate that it is incorrect to assume that water retained by the GERD will immediately create deficits in Egypt and harm the Egyptian economy. Furthermore, in the unlikely event that deficits do occur, they are likely to be small and manageable.

Second, Heggy *et al* (2021) present estimates of the economic losses due to water deficits without relying on any of the economic models that exist for Egypt. Instead, they use simple spreadsheet calculations that we have shown, referencing this literature, will grossly overstate economic losses. Even in the unlikely event that modest shortages in water supply occur, the economic losses to Egypt would be much less than Heggy *et al* (2021) estimate because of adjustments within the economy which are known, from many analogous situations worldwide, to occur during times of water scarcity. Any deficits would mostly be borne by low-value agricultural water uses, but even these uses would not be affected as predicted by the authors.

¹¹ The consequence of this error in economic valuation is more difficult to assess, but one simple way to understand why it dramatically overstates economic losses is to ask what Egyptian farmers would be willing to pay for water, which is the marginal value of water in Egyptian irrigation. Prior work suggests that the marginal value of water in irrigation in Egypt is on the order of US\$0.05–US\$0.10 per m³ (Jeuland and Whittington 2014). This implies that the 'median' deficit of 12 Bcm yr⁻¹ predicted by the authors during the filling period would cost the agriculture sector US\$0.6–1.2 billion yr⁻¹, or only 3%–6% of the annual loss that Heggy *et al* predict.

Conflating Egypt's long-standing water scarcity challenges with exaggerated short-term impacts from filling the GERD reservoir is misleading and complicates the ability of the riparian nations to reach an agreement on coordinated management of the dam infrastructure on the Nile. This agreement is of critical importance, not only to manage the small risk of additional impacts during the filling of the GERD reservoir, but also to prepare for a prolonged drought which will inevitably occur sometime in the future (Wheeler et al 2020).

Policy makers and the general public rely upon high standards of scientific analysis from researchers who write about important public policy issues. Refereed journals have an important role to play in ensuring that policy makers and civil society have access to high-quality research to inform their opinions, policies and actions. The scientific community, policy makers and civil society have not been well served by the paper by Heggy et al (2021).

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