



Examining the Accuracy of Using a Single Short-Term Historical Flow Period to Assess the Nile's Downstream Water Deficit from GERD Filling: A Technical Note

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Abstract

Increasing water and energy demands, hydroclimatic fluctuations, damming, and usage rights disputes present major challenges in managing transboundary rivers worldwide. Of particular interest is the Eastern Nile River Basin (ENRB), which is subject to broad debate over which modeling approach should be applied to resolve the disparities in transboundary water management among the river's riparian nations, under increased upstream damming. Several studies have simulated the downstream High Aswan Dam (HAD) storage change during the Grand Ethiopian Renaissance Dam (GERD) filling under different hydrological conditions. However, their findings diverge regarding the impacts of GERD filling on HAD storage, especially when considering a specific, naturalized, historical 10-year period to represent the average flow condition used, as a benchmark for assessing potential downstream impacts. Our extended analysis of the Nile flow historical records demonstrates that considering a single historical 10-year period to simulate the downstream water budget, as performed in Wheeler et al. (Nat Commun 11:5222, 2020, <https://doi.org/10.1038/s41467-020-19089-x>), widely communicated to policymakers as a robust proof that GERD filling will not generate a deficit at HAD under average flow conditions, is inconclusive as it strongly depend on the selection of the historical inflow period, due to the river high interannual flow variability. Our simulation results of 20 average/near average historical flow periods in Wheeler et al. (Nat Commun 11:5222, 2020, <https://doi.org/10.1038/s41467-020-19089-x>)'s datasheet indicates that 60% of them generates a downstream water deficit ranging from 0.5 to 14.5 BCM under the same modeling conditions and filling policy. Therefore, considering the simulation results of multiple flow sequences is crucial for accurately reflecting the impact of the Nile's high interannual flow variability on downstream water deficit assessments, thereby settling the disparities in transboundary water management forecasts for the impacts of GERD filling and operation.

Keywords Nile's megadams · Hydroclimatic fluctuations · Water deficit · Collaborative water management · Transboundary rivers

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1 Introduction

General Circulation Models (GCMs) concur that the Nile Basin is witnessing a persistent increase in temperature and the frequency of extreme hydrological events, such as droughts and floods, due to climate change (Conway 2017; Mana et al. 2023). Simultaneously, the projections of precipitation trends and patterns show a high variation between the different models (Hasan et al. 2018; Mekonnen and Disse 2018; Abdelmohsen et al. 2020; Tariku et al. 2021), with a decreasing tendency of precipitation and low flow reported for all GCMs except for the CNRM in the Upper Blue Nile Basin (Mekonnen et al. 2018). The projected changes in temperature and precipitation are directly linked to changes

in river flow with high runoff sensitivity of the Nile River in arid zones (e.g., Egypt and Sudan), where only a 10% decrease in precipitation leads to a decrease in runoff of 30%, while a 10% precipitation increase resulted in a runoff increase of 22% (Hasan et al. 2018). Moreover, observed streamflow and rainfall variations, as well as climate model simulations, suggest that climate change enhances the year-to-year variability of the Nile flow (Conway 2017; Siam and Eltahir 2017; Malede et al. 2022; Reda et al. 2022), which could challenge future water resource management scenarios in the Eastern Nile Basin. The Nile River experiences significant flow fluctuations due to El Niño Southern Oscillations (ENSO) in the Pacific area. Around 25% of natural fluctuations in the river's yearly flow are attributed to these oscillations (Camberlin 2009; Siam et al. 2014). The Indian monsoon also significantly influences summer precipitation in the Nile basin. The sea surface temperatures SSTs in the Pacific and Indian oceans can explain up to 84% of the inter-annual variability in the Nile's flow Siam and Eltahir (2017).

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile (Fig. 1) has focused political and public attentions on the allocation and management of the Nile water resources in the absence of a joint operational collaborative framework for the two largest reservoirs, GERD and High Aswan Dam (HAD), which both account for ~272% [234 Billion Cubic Meter (BCM)] of the average annual river flow (~86 BCM). Such a collaborative framework should depend upon an accurate scientific analysis of the Nile Basin hydrology and realistic forecasts of the risks associated with different water management scenarios. These scenarios should also consider the complexity and the high interannual variability of the Nile flow. Of particular interest is how the filling of the GERD will impact the water storage downstream in the HAD reservoir, which is the strategic water reserve for hyper-arid and populous Egypt (Abotalib et al. 2021, 2023). Historically, the depletion of the HAD during drought periods, such as the period from 1978 to 1987, led to nationwide restrictive measures in water usage, impacting food sufficiency and socioeconomic instability (AbuZeid 2021; Ngcamu and Chari 2020; Heggy et al. 2021, 2022a, b).

Since 2011, several studies have simulated the change in HAD storage during the filling of the GERD under short-term hydrological conditions of the Nile River (e.g., Donia and Negm 2018; Medhat 2019; Deltares 2019; Wheeler et al. 2020; Eldardiry and Hossain 2021). However, these studies diverge on the downstream impact of GERD filling on the HAD under average conditions, which have been used as a benchmark. For instance, Wheeler et al. (2020) simulated the downstream water budget in the HAD reservoir during the filling of the GERD under the Nile's wet, average, and dry hydrological conditions using a single 10-year historical sequence to represent each of the above states. The study

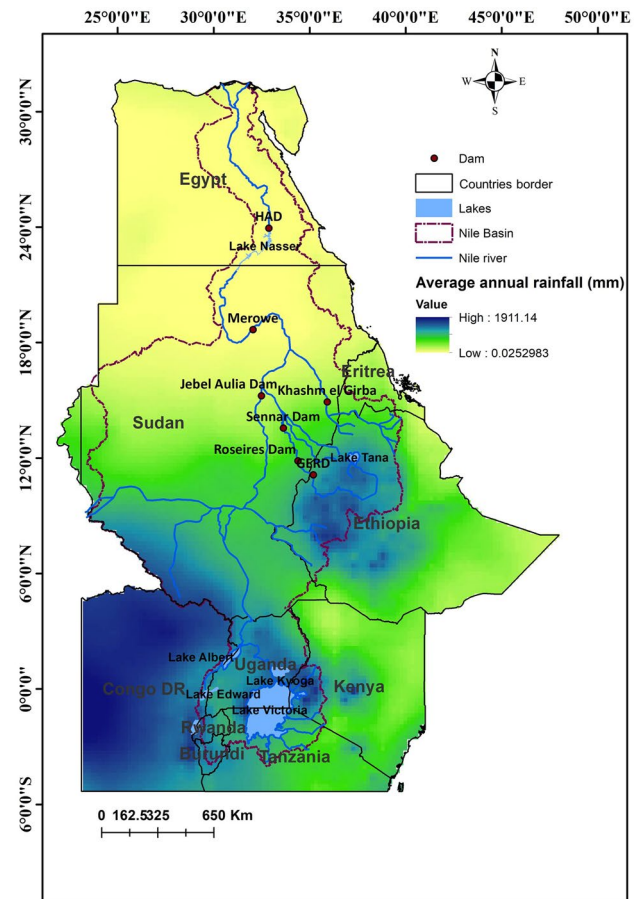


Fig. 1 Map of the Nile showing the locations of both HAD and GERD megadams and the average annual precipitation distribution over the basin. The Nile River represents a unique and complex hydrological system as it flows across four climate regions: tropical, humid tropical, semi-arid, and arid, with different precipitation patterns causing its high interannual flow variability (Precipitation data from CRU TS version 4.05)

adopts a single-filling proposal, introduced as a formal suggestion by the National Independent Scientific Research Group (NISRG) in 2019. They concluded that filling the GERD will take 5 years under average flow conditions, used as a benchmark to assess the downstream impact and that Egypt's Drought Management Policy (DMP)¹ will not be invoked given that HAD will not reach its critical storage level below 60 BCM. Hence, no water budget deficit will be applied downstream from it. However, other studies (e.g., Donia and Negm 2018; Deltares 2019; Eldardiry and Hossain 2021) which simulate the impact of GERD filling on HAD level using single short term periods (5–7 years)

¹ DMP reduces the delivery to downstream water users by 5% when the storage volume in HAD falls below 60 BCM, 10% (5.5 BCM) when below 55 BCM, and 15% when below 50 BCM.

representing different hydrological conditions. These studies concluded that filling the GERD in 5 years will result in a shortage of water volume downstream at the HAD reservoir and can additionally be associated with a reduction in hydropower generation. For example, Donia and Negm (2018), simulated the impact of GERD filling on the HAD level under a single 5-year average flow period. They concluded that the water level in HAD reservoir will decrease to the minimum level of 147 m amsl and its storage will decrease to 33 BCM (i.e., dead storage) in case of reaching the full storage capacity of GERD (i.e., 74 BCM). Furthermore, the hydropower generation will be stopped in the 5th year filling of GERD.

The above divergence in the modeling of the downstream impacts, which is associated with the hydraulic modeling approach, selection of the boundary conditions, and the hydrophysical assumptions, is natural and represents a constructive effort to represent the complexity of the Nile River system, enabling a realistic understanding of the impacts of upstream damming (Heggy et al. 2022b). For instance, the divergence could be related to the different hydrological model settings, inputs of HAD initial levels, seepage and evaporation rates, filling policy, and simulating a single short average historical sequence and overlooking the stochastic nature of the Nile and its high interannual flow variability (Conway 2017; Turhan 2021).

However, this technical note examines the divergence in modeling outcomes within a given hydraulic model when using different average historical flow periods under the same boundary conditions, as in Wheeler et al. (2020). As such, the divergence in the simulation results under the same boundary conditions, when using other average historical flow periods that comply with the simulation assumptions, merits a thorough investigation to examine its causes. The latter is particularly crucial when the hydrological simulation of a single short-term (i.e., 10 years) historical flow sequence is aimed to enlighten policymakers on the downstream risks from filling GERD as presented in Wheeler et al. (2020). The study has been widely communicated to the public, media, policymakers, and scientific community as proof of the low impact of the GERD filling on downstream nations under the suggested NISRG policy.

To examine the accuracy of using a single short-term average historical flow period to deduce the absence of downstream deficit as presented in Wheeler et al. (2020), we requested access to the Eastern Nile River Model (ENRM) used in their simulation, a request to which the authors responded positively. It is important to note that, we selected the ENRM and the datasets provided by Wheeler et al. (2020) as they incorporate all historical records used in previous studies. Thereby, examining and extending the simulation flow periods using ENRM and associated datasets in Wheeler et al. (2020) can reveal how accurate is the

approach of considering a single 10-year historical flow period and provide insights into one of the main sources of the divergence between previous downstream water deficit assessment efforts.

In this technical note, we show the discrepancy in assessing the downstream water deficit at HAD when considering a single 10-year average historical period to represent the average hydrological conditions of the Nile flow. We demonstrate the limitation of this approach under the interannual variability of the Nile flow (Conway 2017; Siam and Eltahir 2017). The above is addressed by extending the assessment of the downstream shortage at the HAD from the outcomes of the single near-average 10-year period presented in Wheeler et al. (2020)—i.e., the period from 1943 to 1952—to all 19 other periods, as shown in Table 1, representing the average/near-average flow conditions in the last 118 years incorporated in ENRM.

2 Methodology

2.1 Examination of the Simulation Entry Parameters

In their study, Wheeler et al. (2020) examined the Nile's historical inflow between 1900 and 2018. They used a statistical analysis of Non-Exceedance Probability (NEP) to select characteristic 10-year periods for wet, average, and dry hydrological conditions (see Suppl. Table 3 and Figure 5 of Wheeler et al. 2020). In the datasheet provided by Wheeler et al. (2020) and their suppl. Table 3, they identified the value of 86.1 BCM/year as representative of the average flow conditions which corresponding to the 1909–1918 historical sequence (NEP = 0.5). In addition, nineteen other near-average periods with almost the same average flow volume (85–86.9 BCM) were identified. However, they only simulated the 1943–1952 period (avg. 86.08 BCM/year; NEP = 0.48). Based on their single short-term historical sequence results, they concluded that no deficit would be observed downstream of HAD under average conditions as shown in Fig. 4 of Wheeler et al. 2020 and summarized in the flowchart in Fig. 2 herein.

We extended the simulation analysis to include the twenty average historical sequences identified in Wheeler et al. (2020)'s datasheet. Using the same Eastern Nile River Model (ENRM), their provided spreadsheets, and filling policy files, we reproduce their results for the single period accounted for in their analysis (i.e., 1943–1952, Fig. 3a). We then considered all the other 19 average/near-average flow periods (Table 1) to simulate GERD's filling and the change in HAD storage using the same NISRG filling policy as shown in the flowchart in Fig. 2.

Table 1 Assessment of the cumulative downstream deficit at the HAD for filling the GERD under the twenty average/near-average hydraulic Nile flow periods in Wheeler et al. (2020) datasheet. It

is noteworthy that the same average inflow volume of 86 BCM can yield different cumulative deficits (i.e., 0.5 and 14.5 BCM) due to the interannual flow variability

Simulation period, 10 years	Average inflow years (BCM)	Non-exceedance Probability	DMP ^a Invoking	Cumulative deficits (BCM)	No. of years with deficit
1932–1941	85.066	0.42	No	0	0
1973–1982	85.499	0.43	No	0	0
1900–1909	85.560	0.44	Yes	4.59	4
1972–1981	85.861	0.45	Yes	0.5	1
1941–1950	85.968	0.46	Yes	5.72	2
1926–1935	85.987	0.47	No	0	0
1943–1952 (Wheeler et al.)	86.087	0.48	No	0	0
1909–1918 (Main average)	86.101	0.5	Yes	14.5	3
1931–1940	86.233	0.51	No	0	0
1944–1953	86.299	0.52	No	0	0
1902–1911	86.409	0.53	Yes	7.73	3
1988–1997	86.423	0.54	Yes	1.954	2
1914–1923	86.438	0.55	No	0	0
1927–1936	86.504	0.56	Yes	0.5	2
1903–1912	86.656	0.57	Yes	1.473	2
1971–1980	86.676	0.58	Yes	0.5	1
1916–1925	86.765	0.59	Yes	0.84	1
1915–1924	86.812	0.60	No	0	0
1901–1910	86.857	0.61	No	12.04	4
1930–1939	86.926	0.62	Yes	0.633	1

^aEgypt's Drought Management Policy (DMP) reduces deliveries to downstream water users by 5% when the storage volume in Lake Nasser falls below 60 BCM, 10% (5.5 BCM) when below 55 BCM and 15% when below 50 BCM

The bold italicized periods are the near-average of 1943–1952, presented in Wheeler et al. (2020), and the main average of 1909–1918 (from the same study's datasheet) that, without explanation, is not visualized in the study's results

2.2 Historical Flow Dataset

The naturalized historical inflows to the HAD reservoir from 1900 to 2018 are incorporated in the ENRM model. By removing the effects of upstream agricultural activities in terms of water consumption, this naturalized dataset reconstructs the flow conditions before significant human involvement. For naturalizing the historical flow data, the consulting company Deltares used a hydrologic reconstruction derived from gauge sites using the gauged flows at Dongola and adjusted for expected Sudanese usage throughout this period (Wheeler et al. 2020). We examined the validity of the above naturalized historical flow (1900–2018) by comparing the spreadsheet provided by Wheeler et al. (2020) with the naturalized data that we obtained from the Ministry of Water Resources and Irrigation (MWRI) of Egypt (Personal communication), both datasets are identical.

The extended analysis in the present study simulates a total of twenty 10-year historical sequences representing the average and near-average flow periods (85–86.9 BCM/year), as shown in Table 1.

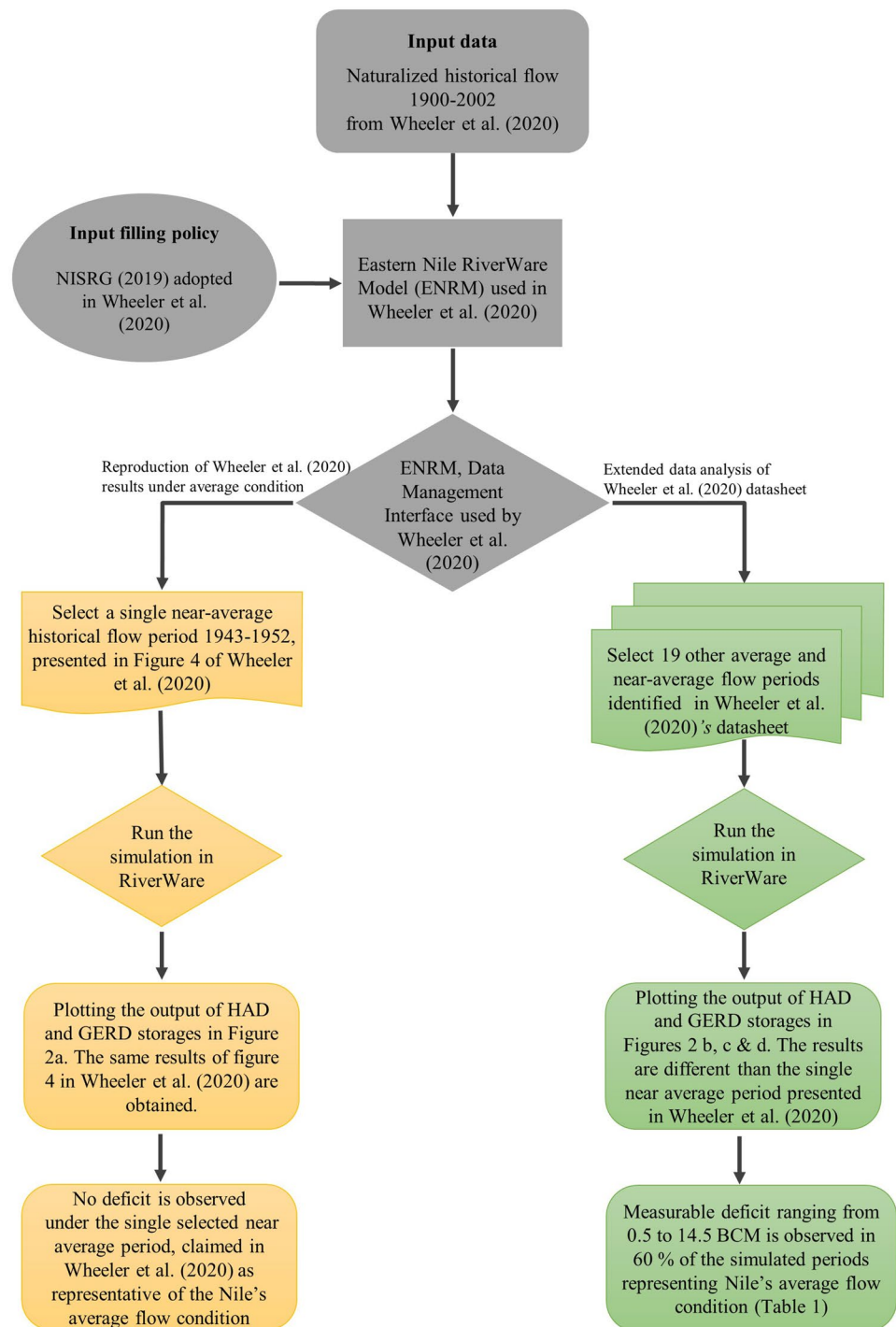
2.3 Simulation Model and Policy

To test the consistency in assessing the downstream deficit at HAD associated with GERD filling using a single 10-year period, our investigation utilizes the same Eastern Nile River Model (ENRM), filling policy, and dataset used in Wheeler et al. (2020), where all the simulation parameters are detailed.

The ENRM, which was developed initially using the rule-based RiverWare platform contains all the hydraulic characteristics of the Eastern Nile Basin, including those of all the reservoirs on the Blue Nile such as HAD, Merowe, Rosaries, Sennar, Gebel Aulia, Khashm Elgirba, Tekeze, Atbara and Setit, Finchaa, and Tana Lake in addition to demand structures and gauges. Detailed characteristics of the model parameters and schematics can be found in Wheeler and Setzer (2012).

According to the NISRG filling policy, as stated in Wheeler et al. (2020) and used in our simulation, the GERD Reservoir will be filled to the minimal levels necessary for turbine functioning during the first 2 years of filling, which equals 595 m above mean sea level (m amsl), according to

Fig. 2 Flowchart of the extended analysis of the average historical flow periods identified in Wheeler et al. (2020)'s datasheet showing the difference in assessing the downstream water deficit at HAD between the selected 1943–1952 period and 19 other ones identified in their datasheet but not visualized in their original study results. The flowchart shows the importance of considering multiple historical flow periods to provide a realistic assessment of the downstream impact of filling GERD under Nile's high interannual variability that has been underestimated in Wheeler et al. (2020)



this policy. In year 1, GERD will impound 4.9 BCM, in the second year, GERD will impound 13.5 BCM to reach the level of 595 m (~ 18.4 BCM) amsl and enable the testing of additional turbines. The policy anticipates that GERD authorities would release at least 35 BCM annually and would continue to fill the GERD reservoir up to the Full

Supply Level (FSL) of 640 m amsl during the peak of the flood season to optimize hydraulic head and energy production, even if the filling process may formally end when the reservoir elevation reaches 625 m amsl during the dry season (Wheeler et al. 2020).

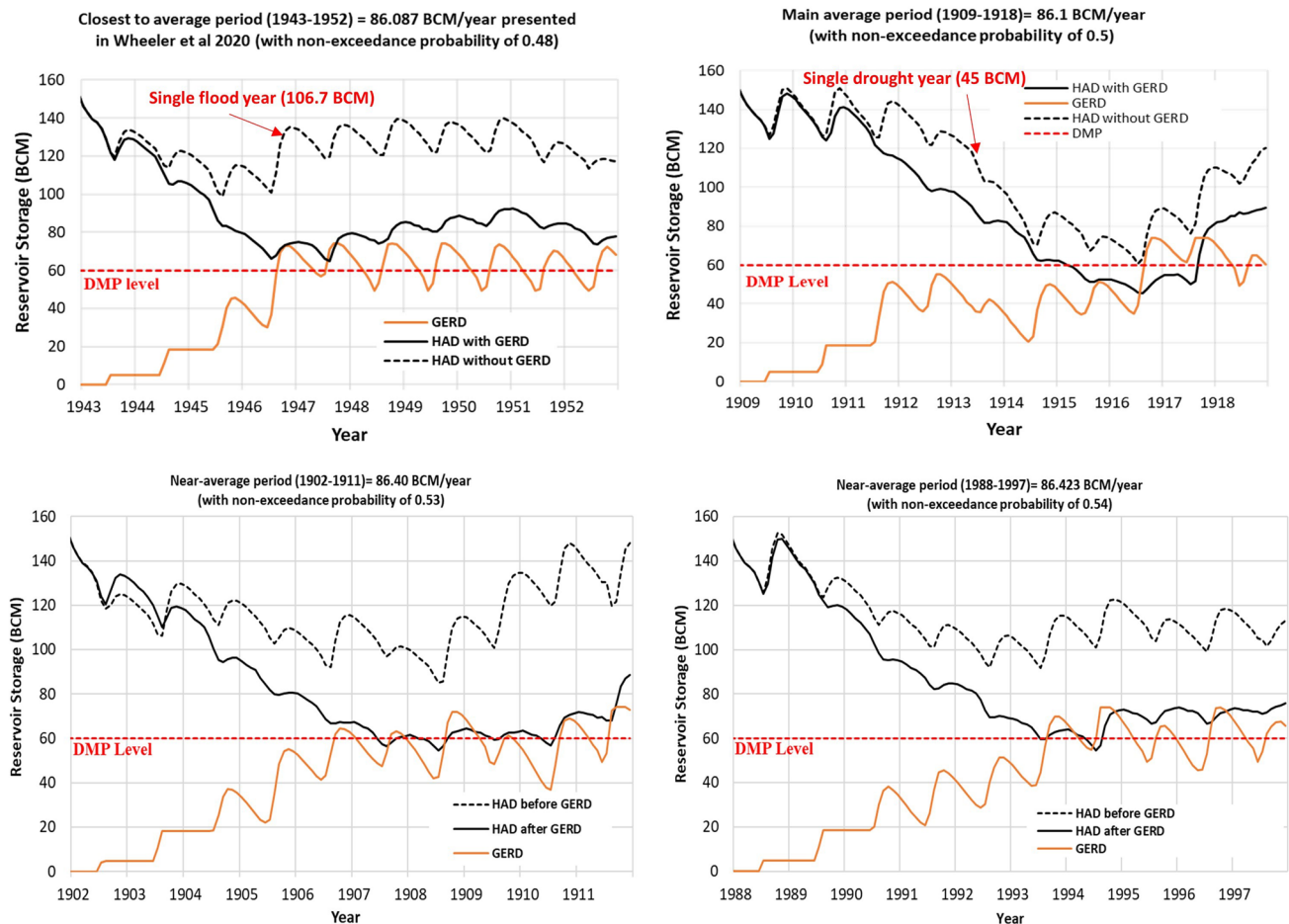


Fig. 3 Simulated HAD storage during the GERD's initial filling under four representative periods of average Nile flow conditions from Wheeler et al. (2020) datasheet. **a** near-average period 1943–

1952 used in Wheeler et al. (2020), **b** main average period 1909–1918, **c** near-average period 1902–1911, and **d** near-average period 1988–1997

For the HAD conditions, the initial storage for all simulations is fixed at ~151.5 BCM (equivalent to ~180.3 m amsl, i.e., almost full). During the GERD filling, the HAD will release 55.5 BCM/year until reaching the Drought Management Policy level of 159.4 m amsl (60 BCM). Once reached, the released downstream water is reduced by 5%. When the storage reaches 55 BCM, the downstream release is reduced by 10% and then by 15% when it reaches 50 BCM.

The limitations of the ENRM model, as implemented in Wheeler et al. (2020), include the overlooking of the seepage losses from HAD and GERD reservoirs. However, several studies estimated the annual seepage losses from HAD to range between 1.15 and 6 BCM/year (Kim and Sultan 2002; Elsawaf et al. 2014; Abdelmohsen et al. 2020). In the present study, we used the same assumptions provided by Wheeler et al. (2020) and did not consider seepage to solely examine the consistency of their results under different average flow periods from the study datasheet.

3 Results

Our extended simulation result for the 1909–1918 historical sequence, which has a non-exceedance probability of 0.5, fully represents the main average flow conditions (Fig. 3b). Using the same assumptions and filling policy applied in Wheeler et al. (2020), the simulation shows that the GERD filling will take 8 years to reach its total filling capacity of 74 BCM and that HAD will be below its critical DMP level (60 BCM) for 3 years during that process, triggering the DMP and leading to a measurable cumulative water deficit of 14.5 BCM downstream of the HAD (Fig. 3b; Table 1). Furthermore, our simulation results of the other 19 average periods, also referred to as near-average (see Figs. 3c–d; Table 1) show that only 8 of the 20 considered will not trigger the DMP. The other 12 periods, i.e., 60% of the average identified periods, will show a measurable deficit invoking the DMP and leading to cumulative deficits ranging from 0.5 BCM in 1 year to

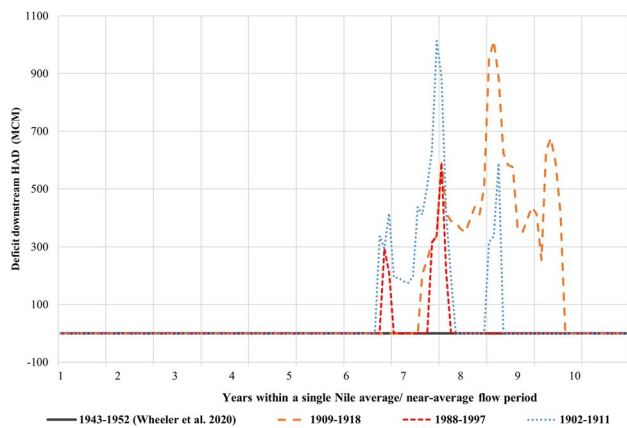


Fig. 4 Comparison of the distribution of water deficit at the High Aswan Dam (HAD) over the simulated 10-year average/near-average flow periods (Fig. 2a–d) using the same filling policy and parameters examined in Wheeler et al. (2020)

14.5 BCM in 3 years (Table 1, Fig. 3), contradicting the conclusion of the outcome of using a single 10-year flow period to represent the average flow hydrological conditions, which suggests that no downstream deficit will occur (e.g., 1943–1952, Wheeler et al. 2020). The above deficits should not be invalidated by comparing them to the total volume of flowing water during the 10-year period (~550 BCM). This is because this comparison ignores the temporal distribution of these deficits, which can trigger specific years of measurable water stress that such averaging can overlook. For instance, observing a total deficit of 14.5 BCM averaged over 10 years (i.e., 1.45 BCM/year) is substantially different from observing it over a shorter period of 1–3 years (i.e., 14.5–4.83 BCM/year) in terms of water management schemes, as shown in Fig. 4.

It is important to note that triggering the DMP involves a series of conservation measures and water usage restrictions on the national scale for the agricultural and industrial sectors in Egypt that correlate not only to the volumes of the deficits but also to the time-lapse over which they occur. The socioeconomic impacts are thus measured by whether the DMP is triggered or not and not only for the volume of the associated deficit. Furthermore, as Egypt already has an intrinsic water budget deficit of ~40 BCM/year since 2010s (Nikiel and Eltahir 2021), increasing this figure has consequences that should not be underestimated, especially in a research analysis primarily aimed at supporting policymakers as stated by Wheeler et al. (2020). For instance, to fill any additional and temporal water deficit, Egypt heavily relies on reusing wastewater, for which the treatment of 1 BCM costs, on average, ~180 million US dollars (Tawfik et al. 2021), which is a sizeable cost of the overall budget of a developing nation (Reuters 2021) that is undergoing the world's second most considerable external debts (CNN 2022). On

the other hand, reusing the wastewater introduced an accelerated phase of heavy metal pollution in the Nile Delta system, compromising water quality and crop production and aggravating Egypt's vulnerable food security (Abotalib et al. 2023; Fouad et al. 2022).

The discrepancy between the downstream water deficit outcomes of the different Nile average/near-average flow periods, as summarized in Fig. 3 and Table 1, calls into question the reliability of using a single 10-year average historical flow sequence to inform policymakers on the risks of downstream water deficit under Nile average flow conditions.

4 Discussion

Hydroclimatic fluctuations in the Nile basin and their impacts on the river flow volumes are one of the primary concerns for water resources managers and policymakers (Gleick and Adams 2000; Fouad et al. 2023), as it has a marked effect on the repeatability of the river hydrological cycles (Kundzewicz and Robson 2004). Among several atmospheric parameters, the variability in precipitation is the most critical factor in determining the spatiotemporal influence of the climate system on the Nile's hydrological conditions, and its consequences on the uncertainties in water management scenarios are underestimated when using the single 10-year period approach, as shown above.

The discrepancy between the calculated downstream deficit of the single 10-year period in Wheeler et al. (2020) and multiple other ones in their datasheet is due to the inter-annual flow variability resulting from the changes in precipitation patterns in the Eastern part of the Nile basin. This variability is accentuated by the observed climatic changes in the Nile River system (Conway 2017). Neglecting the above by considering a particular near-average historical flow period to represent all average/near-average flow periods underestimates the high interannual variability of the Nile flow and leads to non-repeatable findings over most of the other average/near-average historical flow periods, as shown in Fig. 3 and Table 1. Moreover, detailed verification of the annual flow rate in the selected average period 1943–1952 in Wheeler et al. (2020) shows that the year 1946 inflow, assumed to be the fourth year of the GERD's initial filling, witnessed a significant flood of 106.7 BCM (Fig. 3a). The above explains a controversial result in Figs. 3 and 4 in Wheeler et al. (2020), where the GERD reservoir would be filled faster- in 4 years- under average flow conditions and slower- in 5 years- under the wet one with a higher inflow rate to the reservoir (Heggy et al. 2022a, b). Furthermore, including a flood year in the considered near-average period in their Fig. 4 contradicts Wheeler et al. (2020) own assumptions for selecting representative periods that must avoid

anomalous events such as single-year floods or droughts during the initial filling years as they stated “*This selection used both parametric and non-parametric criteria, including a statistical analysis of periods of flows along with hand selection to avoid anomalous events, such as single-year floods or droughts. Instead, high, average and low samples of 10-year average flows used for the Era 1 analysis were chosen to include persistent extreme periods (high and low), and average conditions.*” (Supplementary of Wheeler et al. 2020, lines 242–246). Similarly, the period of 1909–1918 which is the main average period with $NEP=0.5$, contains a drought year (Fig. 3b), and hence it is equally non-compliant with Wheeler et al. (2020) assumption as the period 1943–1952 but yields a cumulative downstream deficit of 14.5 BCM. Therefore, it is unmistakable that in Wheeler et al. (2020), the outcomes for assessing the downstream deficit strongly depend on the selection of the historical inflow period due to the interannual flow variability in the considered periods rather than the 10-year average water flow volume. For example, a detailed analysis of the last 118 years identifies the period of 1902–1911 as one of the most compliant with the method selection criteria of Wheeler et al. (2020) for average flow conditions, as it does not include a single-year flooding or drought. However, using this compliant period would result in a downstream water shortage triggering the DMP, leading to a cumulative downstream deficit of 7.7 BCM in 3 years for Egypt during the GERD filling, as shown in Fig. 3c and Table 1.

A noteworthy additional observation that demonstrates the limitation of using the single period is that the average flow period of 1909–1918 (Fig. 3b) has a higher average flow volume than 1943–1952 (used in Wheeler et al. 2020, Fig. 3a), but yet yields a higher downstream deficit (Table 1). The above calls for the importance of considering the interannual flow variability of the Nile River by simulating several flow periods to reduce these ambiguities in assessing the downstream water deficits. More rigorous assessment, considering long-term flow periods (e.g., 40 years) (e.g., Sharaky et al. 2019; AbuZeid 2021) or the average of several short-term periods, will substantially reduce the uncertainties associated with the upcoming climate change impacts on the interannual flow variability. The above will significantly contribute to building confidence between the different hydrological analyses performed by the river riparian nations, supporting policymakers with realistic modeling that accounts for the complexity of the river system to converge toward an executable collaborative framework for a sustainable transboundary management of the river’s water resources. Moreover, the comprehensive understanding of the impacts of climate change-induced interannual flow variability helps the Eastern Nile Basin states to adapt to scenarios of both too little and too much water through expanding in groundwater exploration and

rainwater harvesting strategies to cope with the former scenario (Attwa et al. 2021; Khalil et al. 2021) and to develop some flood management strategies to overcome any adverse impacts of the latter one (Abdelmohsen et al. 2022).

Although, this technical note utilizes the same approach used in Wheeler et al. (2020), it evaluates the methodological limitation in using a single short-term hydrological flow sequence to inform policymakers on the long-term hydrological response of river systems, especially under climate change-induced high interannual flow variability. The interannual flow variability is expected to increase under climate change conditions in several rivers worldwide (e.g., São Francisco River in Brazil, Congo River, Colorado River) (e.g., Moquet, et al. 2016; Syvitski et al. 2014; Schöne, et al. 2003) thus it is necessary to reveal any methodological shortcomings in river flow simulations as performed in this technical note. For example, in Tigris-Euphrates basin, the year 2019 witnessed an unprecedented extreme flooding event in 100 years that exceeds the long-term average precipitation with about 200 BCM (Abdelmohsen et al. 2022). The aforementioned event was preceded by an unprecedented 100-year extreme drought event that lasted 11 years between 2007 and 2018, with an average precipitation of 130 BCM below the long-term average (Abdelmohsen et al. 2022). Such climate change-induced river interannual flow variability should be monitored, and its impact should be properly quantified by integrating realistic datasets in hydrological models, as presented in this technical note.

5 Conclusion and Recommendation

Our analysis examined the validity of considering a single 10-year historical flow period to be representative of the average Nile hydrological conditions in assessing the downstream water deficit during the filling of GERD. Extending the simulation to include the main average period and 19 other identified average periods of inflow under the NISRG 2019 policy is crucial to verify the stability of the method that is used as a benchmark to inform policymakers on the downstream impacts from filling dams. The reproduction of these other average/near-average flow periods yielded different results than the single near-average period of 1943–1952 used in Wheeler et al. (2020), indicating a 60% chance of observing a downstream water shortage under the same filling policy. The latter will lead to a measurable downstream water deficit of 0.5 BCM in 1 year to 14.5 BCM in 3 years, as shown in Table 1, compared to the no deficit suggested by the 1943–1952 period reported in Wheeler et al. 2020. The above demonstrates that a single period cannot be conclusive in assessing the downstream deficit under a given filling policy as widely used in the Eastern Nile Basin. Today, as of September 2023, GERD is expected to be filled

with ~42 BCM which accounts for ~56% of its total capacity of 74 BCM (Ethiopia News 2023). Therefore, updating the filling policy to represent current and future reservoir volume impoundments and considering long-term periods or multiple flow periods is highly recommended for better constraining the uncertainties around the impacts of GERD filling and operation on the downstream water budget. The ongoing negotiations on the water management framework in the Eastern Nile basin can greatly benefit from the revised analysis provided in this technical note, reducing the ambiguities in assessing the downstream water budget deficit at HAD reservoir and thus helping to converge toward an operational collaborative framework for megadams.

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Author Contributions EH, MR, and AZA conceived the study, conducted the analysis, and examined and verified the results. All authors wrote and edited the manuscript.

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Data Availability All data sources are available in Wheeler et al. (2020) in the data tables, figures, and supporting information. A copy of the manuscript's data, graphs, and model outputs will be available on request.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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