Environment for Development

Discussion Paper Series

March 2019 ■ EfD DP 19-05

Understanding Risks and Managing Perceptions in the Nile Basin after the Completion of the Grand Ethiopian Renaissance Dam

Kevin Wheeler, Marc Jeuland, Jim Hall, Edith Zagona and Dale Whittington

The Environment for Development (EfD) initiative is an environmental economics program focused on international research collaboration, policy advice, and academic training. Financial support is provided by the Swedish International Development Cooperation Agency (Sida). Learn more at www.efdinitiative.org or contact info@efdinitiative.org.

Central America
Research Program in Economics and Environment for Development in Central America Tropical Agricultural Research and Higher Education Center (CATIE)

Chile
Research Nucleus on Environmental and Natural Resource Economics (NENRE)
Universidad de Concepción

China
Environmental Economics Program in China (EEPC)
Peking University

Colombia
The Research Group on Environmental, Natural Resource and Applied Economics Studies (REES-CEDE), Universidad de los Andes, Colombia

Ethiopia
Environment and Climate Research Center (ECRC)
Ethiopian Development Research Institute (EDRI)

India
Centre for Research on the Economics of Climate, Food, Energy, and Environment, (CECFEE), at Indian Statistical Institute, New Delhi, India

Kenya
School of Economics
University of Nairobi

South Africa
Environmental Economics Policy Research Unit (EPRU)
University of Cape Town

Sweden
Environmental Economics Unit
University of Gothenburg

Tanzania
Environment for Development Tanzania
University of Dar es Salaam

USA (Washington, DC)
Resources for the Future (RFF)

Vietnam
University of Economics
Ho Chi Minh City, Vietnam

The Environment for Development (EfD) initiative is an environmental economics program focused on international research collaboration, policy advice, and academic training. Financial support is provided by the Swedish International Development Cooperation Agency (Sida). Learn more at www.efdinitiative.org or contact info@efdinitiative.org.

Contents

Understanding Risks and Managing Perceptions in the Nile Basin after the Completion of the Grand Ethiopian Renaissance Dam

Kevin Wheeler, Marc Jeuland, Jim Hall, Edith Zagona and Dale Whittington*

Abstract

The completion of the Grand Ethiopian Renaissance Dam (GERD) will usher in a new era of complexity in both water management and politics in the Nile Basin. The outcomes that will materialize for Ethiopia, Sudan and Egypt will depend on climatic conditions that are inherently unpredictable and on water management actions taken in each country. We use selected historical flow sequences that represent average, high and low flow conditions, and a calibrated Nile simulation model of reservoir operation to construct illustrative scenarios for GERD filling and operation. We focus on how a prolonged drought would create risks to water supply during and after the filling of the GERD. Because a multi-year drought will inevitably occur at some point in the future, we argue, based on our modeling results, that it will need to be carefully managed, and that its possibility should be explicitly addressed in the ongoing negotiations over Nile waters. In the absence of clear and specific agreements, there is increased potential for a breakdown in trust, social amplification of perceived risk via social and traditional media, and adoption of adversarial positions that may lead to continued diplomatic conflicts. We demonstrate how cooperative reservoir management arrangements involving information sharing and pre-agreed water releases at critical times during a prolonged drought can help to mitigate these serious water risks, and therefore contribute to management of risk perceptions.

Key Words: risk, perception, Nile Basin, Grand Ethiopian Renaissance Dam

JEL Codes: Q25, C70

"If a man does not give thought to problems which are all still distant, he will be worried by them when they come." Confucius

Introduction

With the construction of the Grand Ethiopian Renaissance Dam (GERD) well underway, an extraordinary transboundary water situation is at hand: two large, over-year storage dams—the GERD and the Aswan High Dam (AHD)—in two different countries (Ethiopia and Egypt) coexisting on a single river (Nile), without an understanding yet on sharing or collaborative operations. Furthermore, most of the consumptive use of Nile waters occurs in the downstream riparian countries of Egypt and Sudan, in one of the most water scarce basins in the world. Growing populations and the ongoing drive for development will increase water scarcity (NBI 2012). Although Ethiopia's purpose for building the new dam is for power generation rather than consumptive use, when the GERD is completed, the downstream behavior of the basin system will change dramatically, which is likely to surprise many in the basin and require civil society to re-conceptualize how Nile flows should be managed.

The future Nile water regime is inherently unpredictable because of climatic uncertainties; this is unsettling because humans favour the status quo and are averse to situations of ambiguity and severe uncertainty (Ellsberg 1961), particularly when it involves greater real or perceived water insecurity (Slovic & Peters 2006). From a systems perspective, the GERD has the potential to increase economic net benefits in the Nile Basin, but not all stakeholders will necessarily subscribe to this perspective. People tend to value potential losses more highly than gains (Kahneman & Tversky 1979) and perceive risks as more threatening when they do not control them (Slovic, 1987). This will be the situation experienced by the Egyptian people. A prolonged period of relatively benign hydrological conditions (average or above average flows) might breed complacency (Kahneman et al. 1991), undermining efforts to plan for a prolonged drought which will inevitably come.

---

*Kevin Wheeler, University of Oxford, UK. Marc Jeuland, Duke University, Durham, NC, US. Jim Hall, University of Oxford, UK. Edith Zagona, University of Colorado, Boulder, CO, US. Dale Whittington (corresponding author: profdalewhittington@gmail.com), University of North Carolina, Chapel Hill, NC, US.

In raising the issue of the heightened perception of water scarcity and risks experienced by civil society in Egypt and its political consequences and effects on infrastructure operations and other water management behaviors, we do not mean to imply that these responses are irrational or unwarranted. A large body of social science research finds widespread evidence for behavioral responses to risk. We believe that some of these reactions, perhaps especially those related to loss aversion, are amplified in situations involving water. Homo sapiens' fear of loss of access to water is an "ancient instinct" that has evolved and sharpened over tens of thousands of years (Whittington, 2016) because it has been essential to human survival. The potency of this ancient instinct means that fears of losses (and anger directed towards those perceived to be causing the loss) can spread rapidly within an affected group (Kasperson et al., 1988). Looking ahead to the changes that will accompany operation of the GERD, we believe that it is imperative that Egypt, Sudan, and Ethiopia negotiate and implement new and effective agreements for operating the GERD and the AHD, as well as other current and future Nile infrastructures. Throughout the process, political leaders will need to inform their populations about these changes and agreements, particularly in this age of widespread access to social media and information contagion, because the perceptions and well-being of millions of people are at stake (Berger and Milkman, 2012, Vosoughi et al., 2018).

For some time, researchers and water managers have been using sophisticated modeling tools in an attempt to determine how the operating policies of the GERD and the AHD should be coordinated. Several previous studies have sought to identify the tradeoffs between different riparian objectives with regard to Nile management, and the risks and rewards of basin-wide cooperation (see, for example, Arjoon et al. 2014, Block and Strzepek 2010, Digna et al. 2018, Dinar and Nigatu 2013, Geressu and Harou 2015, Jeuland and Whittington 2014, Kahsay et al. 2015, Mulat and Moges 2014, Sangiorgio and Guariso 2018, Strzepek et al. 2008, Wheeler et al. 2016, Wheeler et. al 2018). These modeling efforts provide important insights that will need to be incorporated into binding agreements that create a structure for addressing the often-conflicting interests of the affected countries. With this challenge in mind, the aims of this paper are two-fold: (i) to explain the hydrology and operation of the system to an interdisciplinary audience engaged in the politics and negotiations on the Eastern Nile and (ii) to highlight critical situations in which water risks may become especially severe and socially destabilizing. We demonstrate how an agreement on the filling of the GERD and the subsequent coordination of operations of these two large dams could serve to help manage risks in all three riparian countries.

We organize our discussion into three somewhat stylized eras: 1) the period of filling of the GERD Reservoir (GERDR), which is soon to begin; 2) a "new normal" that may begin in the near future, after filling the GERDR is complete, but during which no severe multi-year drought occurs; and 3) a period after the "new normal" that includes a severe multi-year drought. The periods are stylized because we cannot state with any certainty when they will begin or end. Raising the possibility of an eventual multi-year drought at this time may strike some as alarmist, but is motivated by the regular and unpredictable recurrence of extreme events in the Nile basin (Hurst 1952; Conway 2005), and evidence of increasing hydrologic variability (Siam and Eltahir, 2017). For each of these three stylized eras, we look at the issue of reservoir operation from the perspectives of Egypt, Sudan, and Ethiopia, and discuss the perceptions of risk and concerns that are likely to result in civil society.

Background

The hydrology of the Nile has been the subject of study for many decades (Sutcliffe and Parks 1999); it is characterized by high interannual variability, stark differences in geography and climate, and flows modified by various water infrastructure (Figure 1). Precipitation patterns in the headwaters of the Blue and White Niles differ substantially. Heavy rainfall over Ethiopia from June through September creates highly seasonal flow in the Blue Nile and the Atbara tributaries to the Main Nile. There is a bimodal pattern of rainfall over the equatorial lakes that peaks in March until May, and again from September to December, combined with the buffering effect of the Sudd wetlands, this results in a relatively steady year-round flow from the White Nile. A naturalized hydrologic reconstruction that removes agricultural depletions and management (van der Krogt and Ogink 2013) shows a range of annual flows between 45.6 billion cubic meters (bcm) and 120 bcm at Aswan (Figure 2). On average, approximately 57% of the annual flow of 86.5 bcm comes from the Blue Nile, with the remaining 30% and 13% coming from the White Nile and Atbara Rivers, respectively (Blackmore and Whittington, 2008).

Figure 1: Map of the Nile Basin with Major Infrastructure, including Active Reservoir Storage Volumes

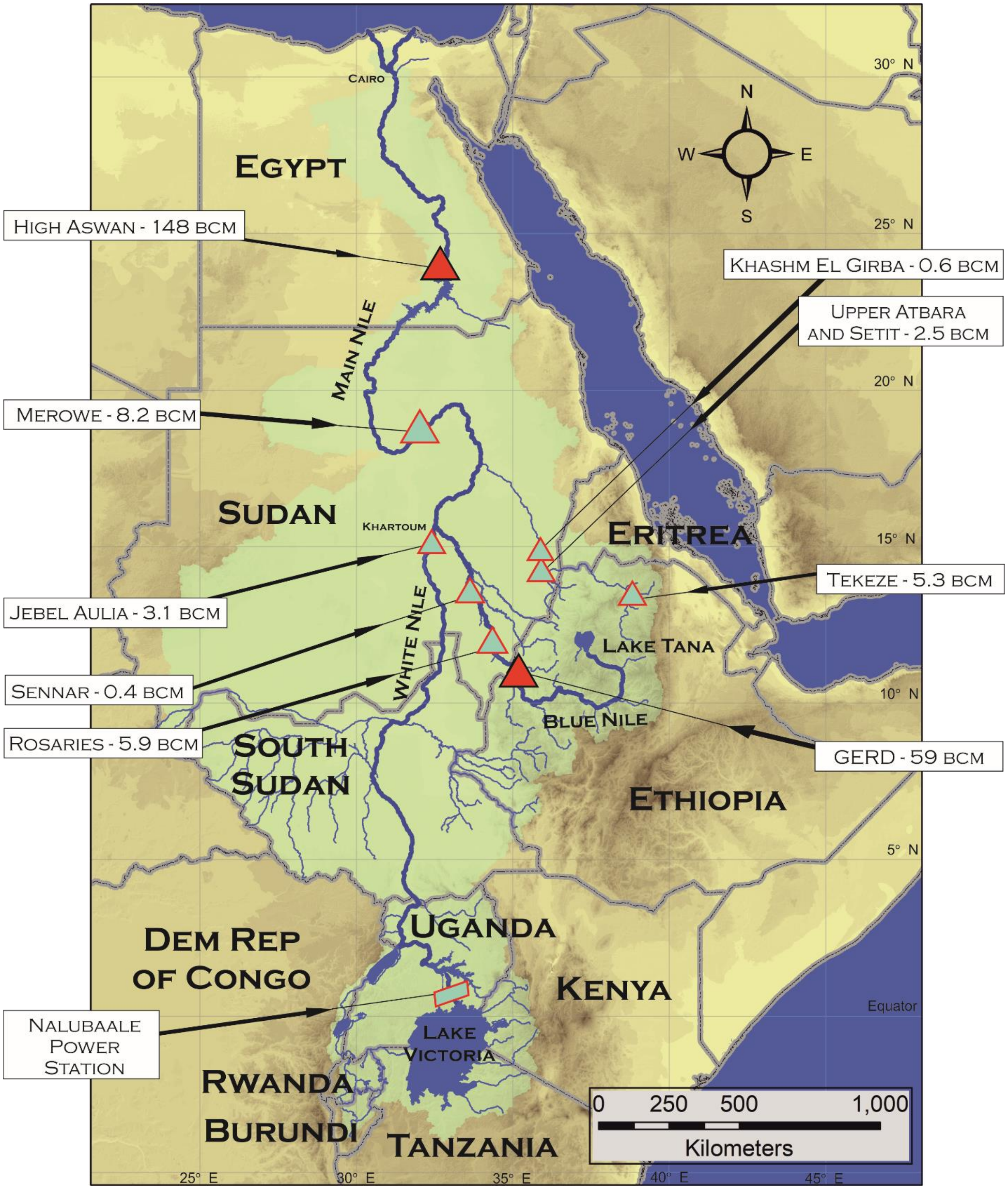
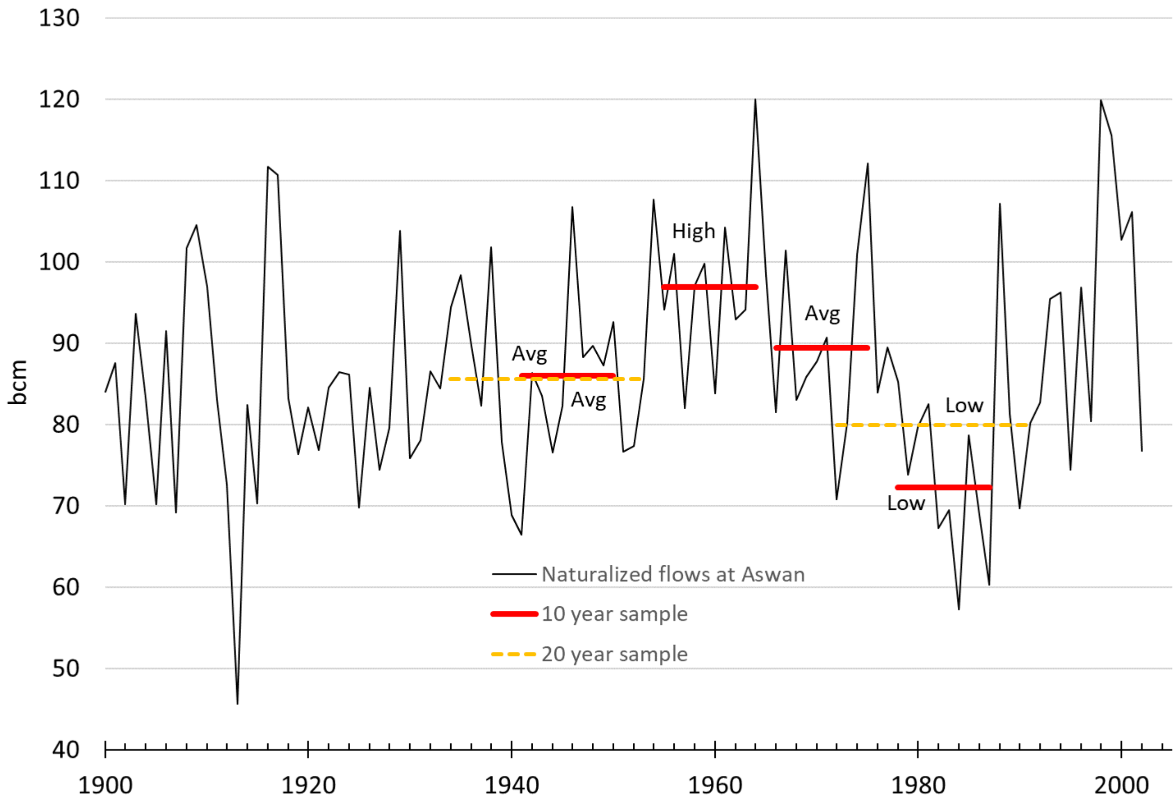


Figure 2: Naturalized Historical Flows at Aswan from 1900 to 2002 Showing Periods from which 10-Year and 20-Year Sequences are used for Simulations (Source: van der Krogt and Ogink, 2013).



The largest infrastructure to date on the Nile is the AHD, with a total storage volume of 161 bcm.[1] Excluding dead storage, the dam can accommodate about 1.5 times the average annual Nile flow.[2] The primary purpose of the AHD is to meet Egypt's agricultural, municipal, and industrial water requirements through regular annual releases of at least 55.5 bcm as specified in the 1959 Nile Waters Agreement between Egypt and Sudan. Not being a signatory to this agreement, Ethiopia has never recognized or felt bound by its terms. In the recent past, due to a relatively wet hydrology and limited upstream water abstractions, Egypt has released more than 55.5 bcm annually from the AHD. Annual releases from the AHD may exceed 55.5 bcm to manage flood risks, and can also be reduced under an existing Drought Management Policy (DMP) if storage falls below 60 bcm (159.4 m)(Moussa 2017).

When completed and fully operational, the GERD, constructed primarily for the purpose of power generation, will be the largest hydroelectric power plant in Africa. The GERDR will

---

[1] bcm = billion m^3

[2] Active storage in the typical operating range is 87.2 bcm; an additional 39.8 bcm is in the flood control zone.

have a total storage volume of 74 bcm, including 59 bcm of active storage, or nearly 1.2 times the average annual flow of the Blue Nile at the dam site. An effective hydropower project typically stores annual variable flow and releases water fairly constantly throughout the year, changing the natural flow regime downstream. It thus produces the most power when the reservoir is full such that hydraulic head through its turbines is maximized. The initial filling period for large dams like the GERD can be particularly disruptive to the flow regime if it is not managed well.

How the GERD should be operated during filling and in the long term is the subject of ongoing negotiations between Egypt, Ethiopia, and Sudan. Additional description of these two important infrastructures (including detailed side profiles of both dams) is included in the supplementary materials to this article, where we also provide information on the other important Eastern Nile infrastructures included in our simulation model.

Analysis Framework and Key Assumptions

Our exploration of the three stylized eras utilizes the Eastern Nile RiverWare Model (ENRM) (Wheeler et al. 2016), a simulation model developed using the rule-based RiverWare platform (Zagona et al., 2001). Known operational rules for each reservoir are translated into logical statements that specify reservoir releases required to meet multiple objectives including satisfying agricultural and municipal needs, meeting power generation demands, achieving seasonal target elevations for sediment transportation, guaranteeing minimum monthly flow requirements, and implementing flood management and shortage avoidance policies.[3]

Our key modeling assumptions are summarized in Table 1. We assume that Ethiopia will release at least the recorded historical minimum (28 bcm) each year during the GERDR filling period based on unofficial verbal commitments from Ethiopia. After the reservoir is filled, we assume a regular hydropower production of 1600 MW based on a 90% maximum reliable hydropower generation rate. We further assume that Egypt will attempt to release 55.5 bcm from the AHD, and that Sudan will withdraw 16.7 bcm (NBI 2012, Wheeler et al. 2018). Ethiopia is assumed to withdraw 0.45 bcm each year at the Finchaa irrigation site (Belissa 2016). Irrigation sites around the Lake Tana are assumed to withdraw between 0.7 bcm to 1.7 bcm each year from the inflows to the lake (van der Krogt and Ogink 2013).[4]

[3] Wheeler et al. (2016, 2018) provide more details about the model configuration.
[4] Diversions are considered requests by each country and do not reflect any endorsement of water rights. Values are estimated uses in the near future, where Egypt limits it uses to 55.5 bcm, and Ethiopia and Sudan do not expand current estimated diversions.

Table 1: Key Modeling Assumptions for the Analysis of Three Stylized Eras

Type of assumption			
Country-specific assumptions	Egypt	Sudan	Ethiopia
Target water demand (bcm/yr)	55.5	16.7	1.1-2.1
Infrastructure operations	AHD release: 55.5 bcm/yr (incl. 4 bcm/yr pumping), adjusted w/DMP, Aug 1 flood control zone	Roseries: Releases for Blue Nile agriculture and min channel flows Sennar: Direct diversion for Gezira/Managil, releases for min channel flows Merowe: Releases for monthly power generation and min channel flows	GERD operates for firm energy generation equivalent to 1600 MW continuous output with 90% reliability.*
GERD filling	n.a.	n.a.	Minimum release: 28 bcm/yr

Hydrological assumptions	Dry	Average	Wet
During filling, years of hydrology	1978-1987	1966-1975	1955-1964
During filling, naturalized average annual flow at Aswan (bcm/yr)	72.3	89.4	96.9
After filling, years of hydrology	Drought onset: 1972-1991 Drought recovery: 1941-1950	New normal: 1934-1953	n.a.
After filling, naturalized average annual flow at Aswan (bcm/yr)	Drought onset: 79.9 Drought recovery: 86.0	New normal: 85.6	n.a.

Notes: DMP is the Drought Management Policy in Egypt (see supplement for details).
* The objective is to generate *firm energy* generation. With the 6450 MW installed capacity of the GERD, it would be possible to generate energy in a very different non-firm pattern.

We select representative historical periods that describe average, high and low flow conditions in the hydrologic record shown in Figure 2. This approach of using time slices from the historical record is restrictive relative to previous papers that have employed large numbers of stochastic flow sequences (Wheeler et al., 2016, 2018), but results are more intuitive and easier to interpret. We recognize that future conditions will not replicate the past and that more severe conditions could quite possibly materialize, especially with a changing climate. However, the representative historical flow sequences allow us to more simply illustrate a wide range of hydrological events and management responses within the Nile system. We also emphasize that the selection and interpretation of these sequences is grounded in modeling that includes the complete set of historical flows, as well as extensive stochastic simulations.

Era 1: Filling the GERD Reservoir

As of September 2018, construction of the GERD was about 65 percent complete, and filling will likely begin in 2019. The first 3.0 bcm that Ethiopia can retain in the GERDR is below the dam’s lowest outlet gates, and an additional 1.5 bcm is required to allow two low-head turbines to operate (see Figure S2 in the supplementary materials). Once stored, this initial 4.5 bcm water will no longer be available for use downstream, and storage in the AHDR will decrease by a similar amount.[5] This loss, equivalent to about 5% of the natural average annual flow in the Nile as measured at the inflow to the AHDR, is best viewed as a one-time "water cost" of building the GERD. To use a financial analogy, one can compare the GERD to a bank account in which water is stored rather than money. This 4.5 bcm is the fixed fee associated with setting up the account. Once paid, it can no longer be withdrawn at a later date for use anywhere in the basin.

After the initial capture of 4.5 bcm, the reservoir level will have reached 565 m asl and all additional flows during the first year can be expected to pass through the dam, with the timing influenced by the testing schedule of the turbines.[6] In the second year, Ethiopia plans to retain an additional 13.75 bcm, which will raise the elevation of the reservoir to 595 m to allow the remainder of the turbines to be tested. Thus, 15% of the natural average annual inflow to the AHDR will be retained in year 2, or 29% of the average flow into the GERDR. The remaining volume of active GERDR storage between 595 m to 640 m will require the retention of about 55.75 bcm. This is approximately 62% of the natural average annual inflow to the AHDR, or 116% of the average flow into the GERDR. It seems logical to assume that Ethiopia will ultimately aim to fill the GERDR to the full supply level (FSL) of 640 m at the peak of the annual flood season. This operating strategy would maximize hydraulic head and energy generated when water passes through the dam's hydropower turbines. The process of retaining water to reach this full supply level is expected to take between 5 to 10 years depending on the rate of retention, and is a central topic of the current negotiations among the countries.

During the filling period, water that would be stored in the AHDR will effectively "shift" upstream to the GERDR. A portion of the water flowing into the GERDR will be released to generate hydropower and meet downstream riparians' water requirements, and the remainder will be held back in the expanding GERDR. As a result, levels in the AHDR will be lower for a period of time than they would be without the GERD, and Egypt will produce less hydropower due to lower hydraulic head on the AHD turbines. When this shift in storage is complete, the average annual volume released from the GERD will be equal to the average annual volume that enters the GERD (48 bcm), less annual evaporation losses of approximately 1.7 bcm. Despite this evaporative loss from the GERDR, the storage levels in the AHDR will begin to recover after the GERDR is filled. The releases from the GERD during and after the filling process will have significantly different seasonal timing than the Blue Nile flows of the past.

[5] See supplementary materials for a more nuanced description of this initial 'cost'.
[6] All elevations are meters above mean sea level.

The downstream consequences of filling the GERD are complicated to understand because they will depend on six key factors: 1) the amount of water stored in the AHDR when filling begins; 2) the magnitude of the flows throughout the basin during filling; 3) how quickly Ethiopia tries to fill the GERDR, i.e., over how many years; 4) how the AHD is operated during the filling period; 5) how power generation from the GERD during the initial years is phased into the regional power grid; and 6) how the GERDR filling influences Sudan's withdrawals. We discuss each of these factors in detail in the supplementary materials. Here we note that recent above average flows into the AHDR and conservation measures taken in Egypt have created a situation where the AHDR is nearly full (approximately 175 m asl), which is fortunate. The active storage zone of the AHDR will thus very likely be close to 87 bcm when filling begins, or 18% more than the volume required to fill the entire GERDR (Figure S2). Because the AHDR is nearly full now (September 2018), it is unlikely that its storage levels will fall to such an extent that Egypt will be forced to curtail its expected releases of 55.5 bcm per year during the filling of the GERDR. However, Egypt may choose to do so to reduce the risk of the reservoir reaching critically low levels, such as the minimum operation level of 147 m.

To continue with our financial analogy, the filling of the GERDR and the ensuing reduction in storage in the AHDR can be viewed as changes in two bank accounts. As the GERDR fills, Nile flows are like revenues, part of which are stored to build up cash balances in Ethiopia's account. These cash reserves can be strategically spent by Ethiopia at any time during the filling process to produce hydropower and simultaneously assist downstream riparians. The Government of Ethiopia has incurred large debts to finance the GERD, so releasing water from the GERDR to generate hydropower for sale will allow Ethiopia to service those debts.

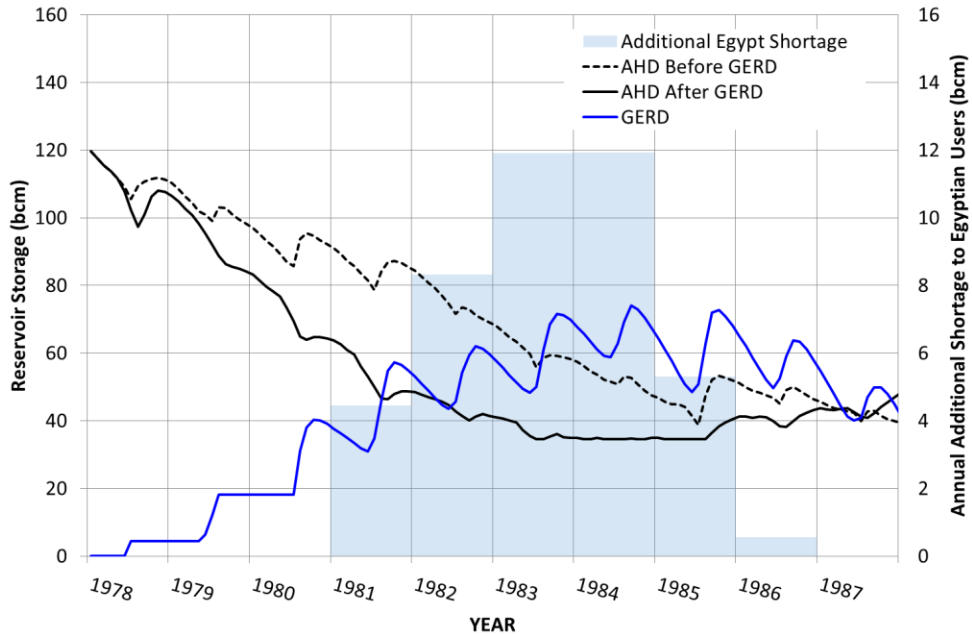
Just as rising balances in a financial account create increased feelings of financial security, the rising water storage in the GERDR will create feelings of increased economic security in Ethiopia. In contrast, the inflows to the AHDR will fall during the filling of the GERDR, similar to a reduction in revenues. The resulting reduction in storage in the AHDR will be like reducing cash balances in a bank account while maintaining current rates of spending. Although it is unlikely that the AHDR will become empty during the filling of the GERDR, feelings of water insecurity will grow, just as feelings of financial insecurity increase if one has declining cash reserves in a bank account.

There are at least three types of policies that could reduce the risk of potential adverse downstream consequences from low flows during the filling period. First, the riparians could agree to a slower filling rate to slow the decline in the volume of water stored in the AHDR. Second, an agreement could be negotiated specifying that filling the GERDR would be curtailed (or slowed) if inflows to the GERD and other Nile tributaries were unusually low, according to some agreed-upon criterion. An adaptive version of these two strategies could be selected, such as an annual release rate that would allow for more water to be retained under high flow conditions and less water to be retained under low flow conditions. A third risk management strategy would be to reduce releases from the AHD based on the state of the system or based on drought forecasts, which would keep the AHDR storage higher. More robust dynamic strategies can further reduce risks and generate benefits for riparians, such as back-up releases from reservoirs during drought conditions (Wheeler et al 2018), or dynamic allocations based on economic benefits (Jeuland et al. 2017).

We illustrate possible results of a filling strategy in which the GERD makes a minimum annual release of 28 bcm and the AHD applies its existing Drought Management Plan (DMP). We simulate the Nile system using the 10-year periods of historically high (1955-1964), average (1966-1975) and low flow conditions (1978-1987) shown in Figure 2. The high and average conditions do not pose significant problems for downstream riparians (see supplementary materials). Therefore, we focus our discussion on the 1978-1987 sequence of low flows. The results are presented in Figure 3, which shows: 1) what the storage of the AHDR would have been if the GERD had not been built; 2) the storage of the AHDR with the GERD in place; 3) the storage of the GERDR; and 4) the magnitude of *additional* annual deficits in Egypt as a result of the GERD, measured as shortfalls from a 55.5 bcm release.

The first thing to note is that a return of the drought conditions of the 1980s would pose significant problems for Egypt even if the GERD had not been built. As shown by the dashed line in Figure 3, storage in the AHDR would fall to 40 bcm during the simulation period. All three tiers of Egypt's drought management plan would be invoked, resulting in a cumulative shortage of 30 bcm over 10 years. Figure 3 demonstrates how filling the GERDR during such a long-term drought would have additional adverse consequences for both Egypt and Ethiopia. In the first five years of the simulation, storage in the AHDR has fallen from 120 bcm to 40 bcm, but the GERD still has only reached storage of 62 bcm. Deficits in Egypt start in the 4th year of the simulation (two years earlier than they would have without the GERD), and peak in the 6th and 7th years, with an additional reduction in releases from the AHD of 12 bcm per year. The cumulative additional deficit as a result of the GERD over the 10 years is about 42 bcm, and these additional deficits occur in 6 of 10 years. At the end of the simulation period, the storage in the AHDR with the GERD in place upstream would actually be slightly greater (47 bcm) than if the GERD had not been built (40 bcm). This is due to the releases from the GERD after filling, which exceed the flows that would have occurred in the system otherwise, owing to Ethiopia's efforts to maintain stable power generation.

Figure 3: GERD Filling Effects under a Historically Dry 10-Year Sequence



A return of a severe multi-year drought today like the one in the 1980s would be worse for Egypt now than what Egypt actually experienced in the 1980s because upstream withdrawals in both Sudan and Ethiopia are higher today than they were in the 1980s. If the filling of the GERDR occurred along with a 1980s type drought, the 10-year cumulative shortages to Egypt would total 72.9 bcm, over half of which would be attributable to the addition of the GERD.

The probability of a reoccurrence of a multi-year drought as severe as 1978-1987 sequence during the GERD filling period is low. However, even if there were only a one in ten chance of such a multi-year drought, this possibility demands careful and cooperative advance planning regarding the best approach to managing downstream deficits. If a multi-year drought were to occur in the Nile basin similar to the 1978-1987 sequence, operations at the GERD could be adapted to release more water to supply Egypt and Sudan (Wheeler et al., 2016). In other words, the downstream water users could be protected with emergency releases from the GERD. The large turbine capacity of the GERD would allow power to be generated from all the water that is released, provided there is sufficient energy demand to use the power when the water is needed downstream. Though not analyzed here, we expect that the basin-wide economic value of such an adaptive filling policy for the GERD would be high, not only because of the protection it would provide for Egypt in a multi-year drought, but also because such a policy would mean that Ethiopia would retain more water in the GERDR in years with normal to high floods. This would allow for hydraulic head to rise faster and evaporative losses downstream to decline, while providing a more reliable supply to downstream water users in critical times.

Despite the likelihood that filling the GERD will occur without serious adverse consequences for Egypt, the results of the simulation in Figure 3 and the simulations of average and high flow sequences in the supplementary materials show why perceptions of upstream and downstream riparians about the risks of filling the GERDR may diverge. As inflows to the AHDR are temporarily reduced during the initial years of filling of the GERDR , falling AHDR storage levels will be visible in photographs taken near the dam, and via satellite imagery. As a result, it should not be surprising if the people of Egypt begin to feel anxiety, fear, and possibly anger at a perceived loss of historical control that they have experienced since the completion of the AHD. Such concerns are likely to spread, and possibly be exaggerated or distorted by biased perspectives aired through traditional and new media platforms (Lazer et. al 2018, Vosoughi et al. 2018).

Combatting such misinformation will require a concerted effort by public officials and others who are able to accurately characterize and communicate risks. The public will need to be reassured that proper plans have been made, and that agreements with Ethiopia and Sudan are being implemented. Egyptians will likely experience some relief when the filling period ends, especially if storage in the AHDR recovers quickly. On the other hand, from the Ethiopian perspective, the GERD has been a massive, complicated engineering project that has required significant financial sacrifices. It is thus natural to expect that the people of Ethiopia will feel proud when filling begins and will be eager to reap its financial benefits as soon as possible, even if flows in the Blue Nile are lower than normal.[7]

Era 2: After the Filling of the GERDR is Complete: A "New Normal"

Once the water in the GERDR has reached an elevation of about 640m at the peak of the flood season, Ethiopia's 'normal' operations will begin to pass the average annual volume that enters the reservoir, less evaporation losses, through the GERD's turbines whenever possible – i.e. during normal, wet conditions and minor droughts. The timing of releases will be determined by the desired power generation of the GERD (whether for baseload or peak power production), and the seasonal management of the Blue Nile flood. In our analysis of a 'new normal', we assume the GERD is operated to produce a baseload of 1600 MW whenever possible. In years with high floods, Ethiopia will pass more water through the GERD and generate more power, and in years with lower than average flows, releases may be reduced to maintain a minimum operating level. In fact, the GERDR will be able to buffer low and high flow years because it has higher active storage (59 bcm) than its annual inflow (48 bcm). Thus, annual outflows from the

[7] Assuming that arrangements are in place to sell the hydropower generated by the GERD to Ethiopia's neighbors (see International Non-partisan Eastern Nile Working Group, 2015).

GERD will tend to be closer to the annual average inflow, and inter-annual variability of downstream flows will decrease. Net evaporation losses from the GERDR will average about 1.7 bcm per year, which will be partially offset by 1.1 bcm of reduced evaporation in the AHDR when the system reaches a new equilibrium. In reality, the net change in evaporation will vary over time and with downstream conditions (see supplementary materials for further discussion of evaporation).

The essential point is that under most hydrologic conditions, the average volume released to downstream riparians will return to normal except for a slight decrease due to evaporation losses. The pattern of releases to Sudan and Egypt will change in that the volumes released will become more regular across months of the year, and to a lesser degree, between years as well.

During this "new normal," the reservoir levels of the GERDR will continue to fluctuate seasonally to provide regular releases for hydropower generation. The reservoir elevation will be highest at the end of the flood season and decline during the winter and spring when releases exceed inflows. By carefully managing power production, Ethiopia should, however, be able to operate the GERD during most years to maintain high water levels for near optimal hydropower generation, and will benefit financially from the sale of more than 15 TWh of electricity generated each year. In this "new normal", evaporation from the GERD will not fluctuate greatly from year to year.

Sudan will be better off in this "new normal" era because GERD operations will smooth Blue Nile flows into Sudan, eliminating flood losses, increasing hydropower generation, decreasing sediment load to the reservoirs and canals, and, most importantly, increasing water for summer irrigation in the Gezira Scheme and other irrigated areas along the Blue Nile (Basheer et al. 2018).[8] However, buffering of Blue Nile floods in the GERDR will adversely affect recession agriculture in Sudan. These Sudanese farmers will need time and money to adjust to the new flow regime.

In the "new normal", the AHDR will fluctuate over a somewhat narrower range than it did prior to construction of the GERD. An overall decline in average inflows into the AHDR can be expected due to evaporative losses from the GERD and from Sudanese reservoirs, since these will likely be operated at higher levels; but evaporative losses from the AHDR will also be reduced as a result (see supplementary materials). Egypt will perhaps no longer feel the same

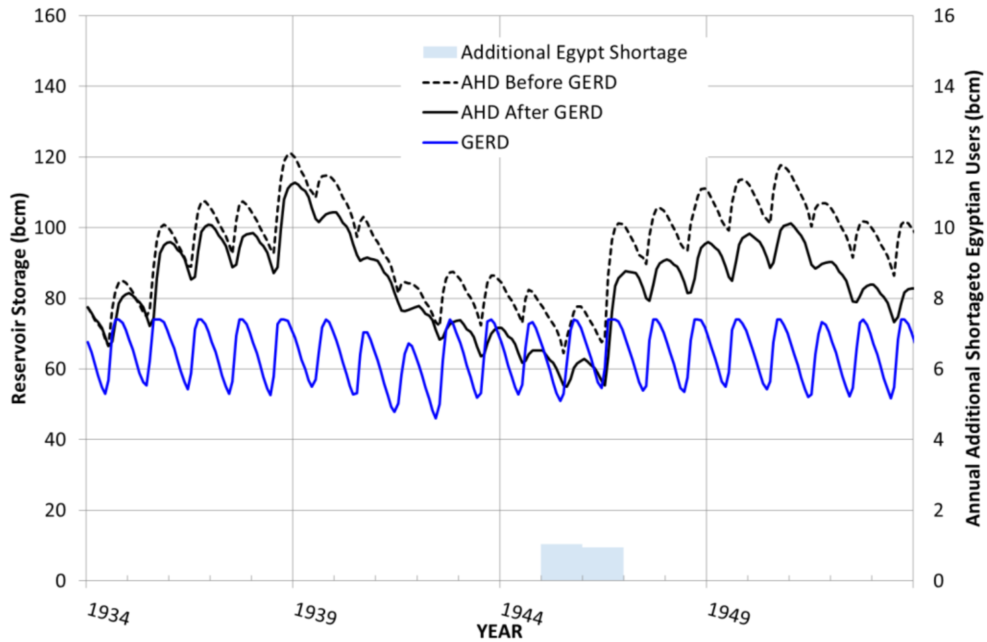
[8] Although the GERD could allow Sudan to increase its irrigation withdrawals to the full allocation under the 1959 Nile Water Agreement of 18.5 bcm as measured at Aswan, the amount of additional water that Sudan can extract is under debate due to ungauged diversions, differences in reporting between Egypt and Sudan, and discussion over how evaporation of various reservoirs should be included. For our analysis, we use an estimate of 16.7 bcm diversion for all eras, exclusive of reservoir evaporation.

security that it experienced in the recent past when the AHDR was often "full." However, the variability of flows into the AHDR between years can be expected to decrease as a result of the GERD, and this will increase predictability. Careful management of the AHD should enable Egypt to provide the same volume and reliability of flows (i.e. 55.5 bcm) almost all the time even without coordinated operation with the GERD – except during a multi-year drought.

Continuing with our financial analogy, during the "new normal," the two bank accounts would perform somewhat differently. In Ethiopia, the management of the GERDR's storage resembles a bank account in which incoming revenues fluctuate wildly, but spending of the cash (analogous to water releases) is fairly stable across months and years. The result will be a rapid oscillation of Ethiopian savings, but kept at or near a maximum balance whenever possible to maximize interest (or hydraulic head for hydropower generation), and minimize future risks. It will be possible to draw the account down in years when revenues are poor, but regular spending will need to continue. Meanwhile, in Egypt, the management of the AHDR's storage will resemble a bank account in which incoming cash flows become somewhat less volatile due to the steady releases from the GERD. Since spending of cash from the Egyptian account (monthly releases to Egyptian water users) will be quite predictable, the fluctuations in the account will be lower compared to the pre-GERD situation.

To illustrate conditions in the "new normal" era, we start the simulation with both reservoirs at normal operating conditions (total storage in the AHDR of 79.6 bcm [165.5 m] and total storage in the GERD of 70.4 bcm [637.9 m]). In other words, we do not assume that the AHDR starts the simulation period full as we did during era 1 for the GERDR filling. We select the 20-year historical sequence from 1934-1953 to simulate outcomes that we consider to be broadly representative of a typical sequence of low and high years, but without extreme multiyear drought conditions such as from 1978-1988 or 1912-1922. Figure 4 (and Table S3 in the supplementary materials) presents the results.

Figure 4: "New Normal" Conditions with the GERD under a Historically Average 20-Year Sequence



As shown, the GERD is able to maintain steady releases over the entire 20-year period of the simulation. Storage in the AHDR gradually rises during the first 6 years of the simulation, and then falls for seven years before recovering. Storage in the AHDR is the same at the end of the 20-year simulation as it was at the beginning (approximately 80 bcm). Egypt only experiences two years in the 20-year sequence with an increased deficit as a result of the GERD, and it is very modest (only 1 bcm per year). Other 20-year "normal" sequences show similar results (e.g. 1927-1946, and 1939-1958, included in the supplementary materials). Additional deficits in Egypt are mostly small and infrequent.

We can speculate how this era of the "new normal" will feel to the people of Ethiopia, Sudan, and Egypt. During a relatively normal sequence of Nile flows without a long multi-year drought, Ethiopia will be able to operate the GERD to maximize hydropower generation, maintaining the reservoir towards an upper elevation range and will not require careful coordination with the AHD. As long as the inflows remain somewhere near or above average, Egypt will not suffer significantly, and the Ethiopian government will probably feel vindicated in its position that the construction of the GERD is a "win-win" for Nile riparians.

The Sudanese people will also feel positively about their support of Ethiopia during the controversies over the construction of the GERD. They will receive the multiple benefits from the GERD (e.g., increased hydropower generation, more consistent water supplies, improved navigation, reduced sedimentation in Sudanese reservoirs) without any evidence that Egypt has experienced significant losses. During this era of the "new normal," the objective benefits that Sudan and Ethiopia will receive from the construction of the GERD will exceed any small losses experienced by Egypt (Whittington et al., 2009; Jeuland and Whittington, 2014).

The era of this "new normal" after the construction of the GERD could lead to a period of complacency, i.e., a feeling that there is little to worry about. The Egyptian people likely will be more concerned than their neighbors upstream when they observe lower storage levels in the AHDR, but even Egyptians may become less anxious over time. During this era, the necessity of coordinating the operations of the AHD and the GERD may lose salience. This would be unfortunate because the hydrology of the Nile is such that the riparians must carefully plan for a severe multi-year drought.

Era 3: After the Filling of the GERDR is Complete: The Consequences of a Severe Multi-Year Drought

Periodically during the era of the "new normal," a sequence of very low flows will occur in the Nile basin. Such low flow periods have occurred throughout the recorded history of Nile flows (Figure 2) and can be expected to happen again (Siam and Eltahir 2017). The probability and severity of specific sequences of low flows are unknowable, especially as climate change unfolds. It is possible that a severe multi-year drought might begin during or immediately after filling the GERD, so it cannot be assumed that Era 2 will precede Era 3.

To illustrate the differing perceptions that may emerge from a multi-year drought and the countries' attempts to manage them, we consider two distinct problems. The first is the problem of entering a multi-year drought from the "new normal" era, and how the water already stored in the AHDR and the GERDR could be used during such a period to reduce deficits. The second is the problem of recovering from a multi-year drought, when both the GERDR and the AHDR would be nearly empty and would need refilling as the drought ends.

The Use of Water Stored in the AHDR and the GERDR as the Drought Begins

At the beginning of a multi-year drought, the Nile riparians will have water stored in both the GERDR and AHDR that can be used for drought relief. Because the AHDR will continue to fluctuate in the era of the "new normal" (albeit less so than prior to the addition of the GERD), the AHDR could be near its minimum operating level, or could be almost full when a drought sets in. In contrast, before the onset of a drought, Ethiopia will likely have maintained a high elevation of the GERDR, and it should therefore be possible to draw down the reservoir during a drought, perhaps as far as 565m to provide additional water to downstream riparians while continuing to generate electricity.

The use of this water in the GERDR to assist downstream riparians during a period of drought could come at a cost to Ethiopia in terms of reduced hydropower generation, and Ethiopia, Sudan, and Egypt will need to negotiate the terms under which such supplemental releases from the GERD would occur. Whether such releases would constitute a significant cost to Ethiopia is hard to determine. Ethiopia will be able to pass water downstream to the minimum operating level of 590m, and potentially to 565m using only two turbines. In this case Ethiopia would generate power in the short term while supplying downstream needs to the greatest extent possible, but this would come at the cost of producing less power over the long term. The difference (net cost) depends on turbine efficiencies and the relative head versus release amounts. Power generation is a multiplicative function of releases, hydraulic head, and turbine efficiencies, and the nonlinear nature of the function makes it hard to determine how Ethiopia would best optimize power. Also, greater power production deferred in time (from keeping storage high) would be worth less than current power due to the time value of money.

There are four main options for structuring an agreement on the timing and magnitude of extra releases of GERDR water for use by downstream riparians. The first, and probably simplest approach, would be for Ethiopia to guarantee a minimum release, ranging from the minimum historical (28 bcm) to the annual average (48 bcm). This would ensure that even in times of drought, downstream riparians could expect a minimum amount of water to be released from the GERD (at least until the active storage was exhausted). During a multi-year drought, this would require Ethiopia to draw down storage in the GERD, which would probably not be its preferred strategy for maximizing hydropower generation.

A second, more sophisticated strategy, would be to trigger supplemental releases from the GERD based on storage levels in the AHDR (Wheeler et al., 2018). Precisely how the supplemental release is determined and the additional volume that it provides would be subject to negotiation between the countries. If there were still significant storage in the AHDR, Ethiopia would probably want Egypt to draw down the AHDR to a relatively low level prior to releasing supplemental water from the GERD as a “last resort” if the drought continues. The main advantages of this option would be that Egypt could be assured of support from Ethiopia, and the elevation of the GERDR would be maintained until the water is really needed downstream, thereby maximizing hydropower generation in Ethiopia. This approach also makes sense from a system-wide perspective, because 1) storage would first be depleted where evaporative losses are highest so that losses would be minimized, and 2) space would be created in the AHDR to capture any intervening inflows. However, Egypt (and also Sudan, if the drought is exceptionally severe) likely would be risk averse and prefer that Ethiopia release water from the GERD early in the drought in order to maintain storage in the ADHR in case the drought persists. Therefore, Egypt would likely prefer that supplemental releases from the GERD be triggered when the AHDR fell to a relatively high storage level.

The challenge of this second option is that storage in the AHDR is a function of AHD releases and thus under the control of Egypt. To agree to provide supplemental water, Ethiopia may ask that Egypt make significant efforts to limit its usage, so as to not draw down the AHDR prematurely. This assurance potentially could be made by incorporating the AHD drought management policy into the agreement, or another similar criterion.

In terms of our financial analogy, the question is, “Who should reduce their cash reserves first?” Because maintaining cash reserves is an important means of managing risk, it is not surprising that each country would want to keep its cash (water) balance intact as long as it can, subject to meeting existing debt servicing and other obligations. By the time a drought hits, Ethiopia might have paid down a substantial portion of its debt for the construction of the dam, so the pressure to generate cash might have declined. Ethiopia might thus be more reluctant to make releases needed by Sudan and Egypt. Of course, Ethiopian releases would still be required to maintain power generation and satisfy energy demands.

A third strategy is for supplemental releases to be triggered by both elevation levels in the AHDR and forecasts of future inflows into the GERDR and the AHDR. Inflow forecasts are inevitably uncertain and the strategy would need to be adapted to shorter timescales. Such a real-time adaptive strategy thus would be challenging to monitor and implement. However, this strategy offers the possibility of more careful management of the timing and magnitude of supplemental releases. It would require a high level of coordination and trust among the riparians, and would likely be more fragile if not designed to consider the potential for disputes over data quality and accuracy.

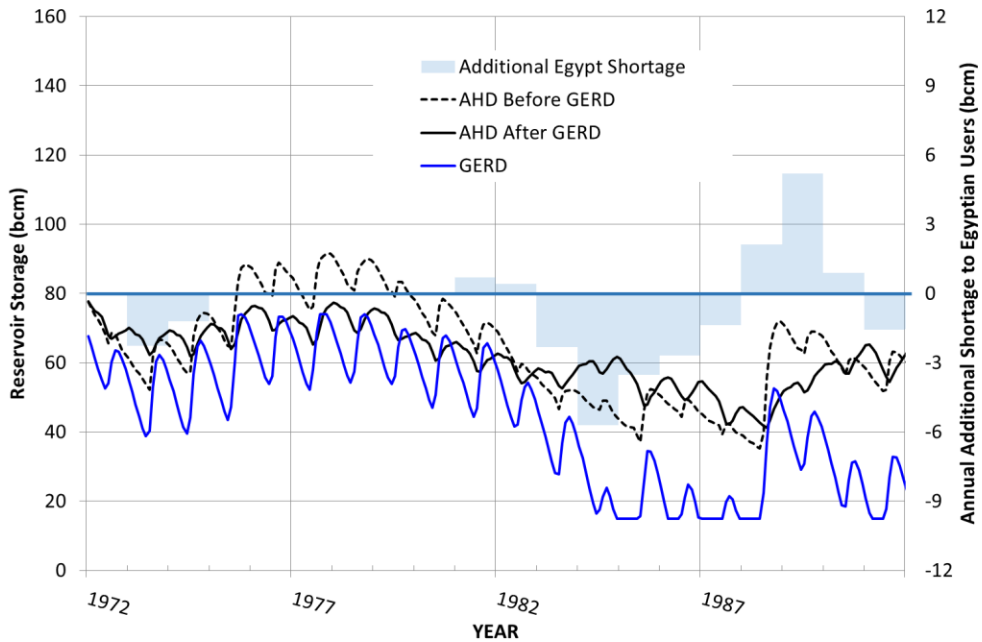
A fourth option would be to allow downstream riparians to trigger releases from the GERD at their discretion, conditional on compensation payments made to Ethiopia. This deal structure would be similar to a “Payments for Environmental Services” contract that pays upstream farmers to preserve forests or adopt conservation practices to improve downstream water quality (Engel et al, 2008). With this fourth option, the negotiations would revolve around the mechanism for setting the price that would be paid for different quantities of water released, and what choices Ethiopia would have to reject the request and forgo the money.

If an agreement could be reached on one or more of these four deal structures, the GERD would be able to provide downstream riparians with an important new option and opportunity to manage droughts. Current analysis suggests that deliveries could be made to Egypt with greater reliability than is now possible (Wheeler et. al 2018). This would require an agreement on coordination of GERD operations and the drought management policy of the AHD, backed by transparent data exchanges and a legal framework to monitor and enforce the agreement.

In our analysis, we do not explicitly examine any of these deal structures. Instead, we continue to assume that Ethiopia operates the GERD to achieve a hydropower target of 1600 MW whenever possible, Sudan operates their reservoirs to meet their own irrigation and energy generation needs, releasing water downstream whenever it cannot be used or captured, and Egypt invokes its current drought management policy as necessary.

Figure 5 (and Table S4) presents results for the 20-year sequence from 1972 to 1991. Storage levels of the AHDR and the GERDR start at levels representative of the “new normal”. The simulation begins with three years of low flows during which the levels of the GERDR and AHDR fall, followed by four average and high years during which storage in both the AHDR and the GERDR recover. Then the multi-year drought of the 1980s begins, and storage in both reservoirs falls. During the worst of the drought, storage in the AHDR is actually *higher* than it would have been if the GERD had not been built, causing a *decrease* in the water deficits to Egypt (indicated in Figure 5 by the “negative bars” during the drought). By drawing down storage in the GERD, Ethiopia is able to increase water availability in Egypt during critical drought periods. Egypt experiences additional deficits in two years when entering the drought, reduced shortages during the next 5 years of the drought, and then three years of increased shortages as the reservoirs begin to refill. The cumulative deficits to Egypt over the 20-year period of the simulation *decrease* by 11.4 bcm as a result of the GERD. During the onset of a drought, Sudan’s interests are also supported by the continued release from the GERD, until the GERD itself reaches its minimum operating level.

Figure 5: Entering Drought Conditions from "New Normal" Operations under a Historically Dry 20-year Sequence



During a drought, decision-makers never know how long the period of low flows will last. Since people are generally averse to losses, managers will be reluctant to utilize water reserves too quickly in an effort to supplement downstream inflows. At some point in a multi-year drought sequence, it is imaginable that storage in both the AHDR and GERDR would be nearly or fully depleted. If and when this point is reached, the Nile riparians will have to agree on how to share the reduced flow of the Nile. For example, should Ethiopia store any water in the GERDR, and if so, how should consumptive water uses in the three countries be reduced? An agreement on how such a situation should be handled needs to be reached before it occurs. The Nile riparians should establish contingency plans before they are needed, not in a time of crisis when feelings of anxiety, fear and anger are high, and when water users are apt to assign blame to those managing the river.

Policy makers should anticipate that behavioral responses to a multi-year drought will be negative, potentially volatile, and difficult to manage as a severe, multi-year drought unfolds. Similar to Era 1, the shrinking storage levels of the AHDR will be visible via satellites and photographs. Given current upstream monitoring and data sharing norms in the basin, it will be difficult to fully understand the reasons why inflows to the AHDR are so low. It may be known that rains in Ethiopia are below normal, but several other aspects will be less clear. First, it may not be known how the GERD is being operated, and what fraction of inflows is being stored versus released. Second, it will be even more difficult to discern precisely how much water is being withdrawn for irrigation and other upstream uses. Low rainfall is beyond any of the riparians' control, but the operating policies of reservoirs and irrigation withdrawals are human decisions, which need to be transparent if they are to be trusted. If one does not understand why something is happening, it is natural to become anxious and suspicious. When a downstream riparian experiences reduced water availability, in the absence of solid data, it is easy to understand how its population could wonder, "Is someone deliberating trying to harm me?" even if this is not the case. A basin-wide, data sharing platform would be helpful to manage such fears, and critical for basin-wide planning.

In such severe drought conditions, a general panic may arise in civil society and spread rapidly through a population via social media. An analogy may be drawn between a "water panic" and a "financial panic", in which hoarding of seemingly scarce resources (e.g. cash, fuel, food supplies) ensues. Both are difficult to predict, can spread rapidly, and be hard to manage without access to data and reassurance by trusted leaders. During a "financial panic", the role of the central bank is to serve as a "lender of last resort." It must provide liquidity to stop a cascade of loan defaults. In a "water panic", the state will have to convince the public that its essential water supplies are secure. Drought management plans need to have widespread support before they are implemented so that everyone knows what is going to happen in an emergency. During the implementation of such measures, water policymakers will need to actively engage with the press and social media to correct misperceptions as they arise and reassure different stakeholders that the drought management plan will be effective and fair. Uses of water with a low economic value may be targeted for reductions, but affected users would need to understand why such actions are necessary and will need to be compensated for their financial losses. The political costs of such curtailments may be significant, but so are the costs of inaction.

Some economists have argued that Egypt can manage significant reductions in releases from the AHDR without large reductions in economic output (Strzepek et al. 2008). This argument holds that targeted reductions in water supply to low-value water-intensive crops would allow Egypt to pull through a multi-year drought with minimal economic consequences. But just as macroeconomic models are not able to account for the human emotions underpinning a "financial panic", these economic models do not account for the possibility of a "water panic." Feelings may run high if people feel that they are unjustly denied access to water or if the burden falls disproportionately on poor, vulnerable farmers. One of the key findings of behavioral economics is that people feel losses much more acutely than gains of comparable size (Kahneman and Tversky 1979). Moreover, people feel water losses more acutely than they do losses in almost any other commodity.

As development in the Nile basin continues, concerns across Egyptian civil society could also increase as a result of a build-up of salinity in the agricultural lands of the Nile Delta (Molle et al. 2018). As noted, Egypt has recently been releasing more than 55.5 bcm annually from the AHD, allowing salts to be flushed from some agricultural lands, and dilution of agricultural return flows to enable re-application to fields. Once the GERD is completed, Sudan will use its full allocation under the 1959 Nile Waters Agreement, and the period of "excess" water reaching Egypt will end. We emphasize that challenges of salinity already exist in the Nile Delta, and no one knows precisely how rapidly salinity levels may accumulate and effect agricultural productivity. There is a potential for blame to be assigned to the GERD rather than to the overall development of the basin. There will likely be a need for improved – and expensive - salinity management. As a result, a 'panic' may emerge due to a general loss of soil productivity due to salt buildup.

The responsibility for averting any type of "water panic" ultimately falls to the states of the riparian countries, perhaps assisted by a multi-national commission of member states. The Nile riparians can help each other prepare for a multi-year drought. Such assistance should be part of the agreement for coordination of the AHD and the GERD during such periods.

The Refilling of the AHDR and the GERDR when the Drought Ends

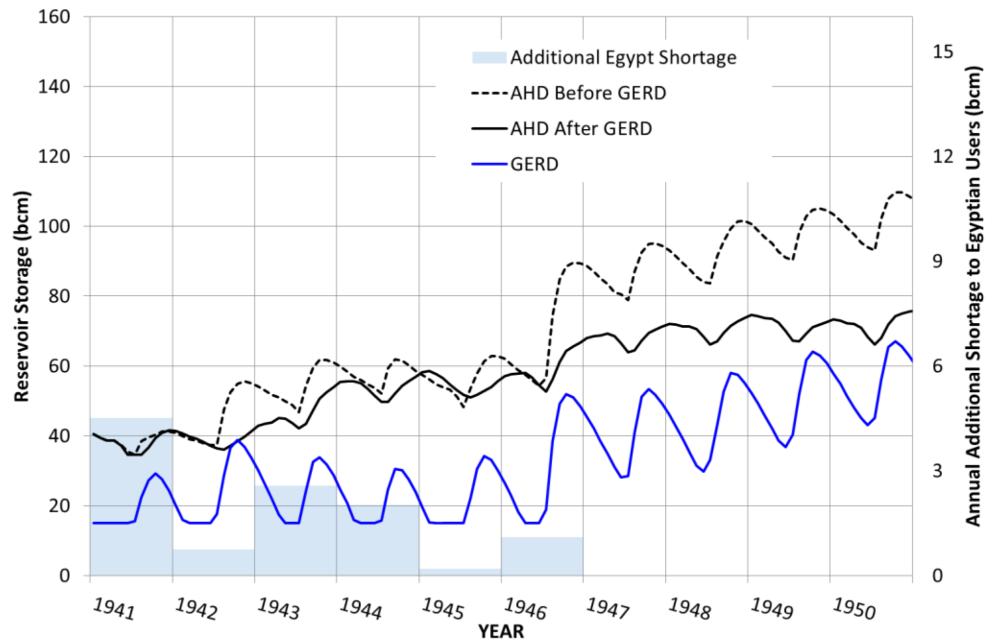
At some point the multi-year drought will end, and a series of average and high floods will arrive. Of course, reservoir managers will not know immediately whether the long drought has actually ended. A high flood could be followed by more years of low floods, or by additional high floods that bring relief and an opportunity to restore basin reserves. At this point, a key question will be: Given that refilling both the AHDR and the GERDR will take years, which reservoir should be refilled first? Or should the "excess" water be shared across both reservoirs? Other reservoirs also exist in the basin, but these do not store anything close to a full year of flow and are therefore much less consequential.

The questions of how fast and in what sequence the AHDR and the GERDR should be refilled will need to be negotiated because both may be emptied during a severe multi-year drought. This case is similar to the initial period of filling the GERDR except that the AHDR will be nearly empty. This difference is crucial because refilling will be much harder to manage. If the GERDR and AHDR were located in one country, reservoir managers would probably fill the GERDR first and the AHDR later subject to meeting most or all downstream water needs because this strategy would more quickly restore hydropower generation and minimize system-wide evaporation losses. In the transboundary context, however, unless downstream riparians have firm guarantees that storage in the GERD will be released to meet water requirements, filling the GERDR first is likely to be perceived by Egypt as unfair.

Figure 6 (and Table S5) illustrates the challenges of coming out of a multi-year drought when both the AHDR and the GERDR have little storage. We start the simulation with storages of 42 bcm in the AHDR and 15 bcm in the GERDR, both close to their minimum operating levels and based on the result of the drought condition described previously. We assume a 10-year sequence of normal historical flows from 1941 to 1950 to simulate a ‘typical’ recovery scenario. We assume the objective of the GERD is to begin generating up to 1600 MW as quickly as possible based on contractual energy needs, though in reality these demands may be scaled back in the wake of the drought. Sudanese reservoirs are assumed to initially capture and divert what they can to meet irrigation needs, releasing the remainder downstream through turbines to meet energy needs or over spillways once their reservoirs are refilled. As shown, increased deficits occur in Egypt in the first six years of the simulation as the GERD captures and releases water needed to maintain its minimum operation level, and Sudan diverting to meet its needs. Storage in the AHDR gradually drifts higher, but even at the end of the 10-year simulation is only at 76 bcm. Similarly, storage in the GERDR increases slowly, reaching 63 bcm by the end of the period. Storage in the AHDR is about 33 bcm less at the end of the simulation than it would have been if the GERD did not exist. This is because of the struggle to refill the AHDR and the GERDR simultaneously. Different hydrological sequences result in different patterns of recovery from a severe multi-year drought. However, all of them show several years of continued deficits in Egypt and slow recoveries in the storage levels of the AHDR and the GERDR.

Although Egypt is affected during this recovery period by the concurrent refilling of both reservoirs, the decision for the GERD to make releases for hydropower generation as soon as the drought ends would be favorable to both downstream countries. A decision by Ethiopia to retain this initial water would lengthen the downstream impacts of the drought.

Figure 6: Recovering from a Severe Multi-Year Drought under a Historically Average 10-Year Sequence



Again, we emphasize that the probability of this situation of completely depleted storage in both the AHDR and the GERDR is very low. Nonetheless, a refilling strategy in this case should be agreed upon well before it needs to be implemented. If such a refilling strategy were to be actually required, people living in all of the Nile riparian countries naturally would be worried about the possible continuation of the multi-year drought they would have been experiencing and would understandably fear losing access to water supplies. The problem of refilling the AHDR and GERDR after a prolonged drought would be technically complicated, likely to cause severe economic hardship, and could potentially cause a "water panic" in civil society even if the Nile riparians manage to successfully navigate the drought itself. Although a sequence of low flows may seem like bad luck that afflicts all riparians, and for which joint sacrifices must be made, this phase of storage recovery could induce a perception of unfairness in civil society, if geographic or other power asymmetries allow one riparian to recover from the multi-year drought more quickly than another.

Conclusions

Sharing the scarce waters of the Nile basin involves balancing competing objectives under conditions of uncertainty. In this paper we have sought to move beyond quantification of the outcomes for the riparian countries of Ethiopia, Sudan and Egypt to also speculate on how those outcomes might be perceived by civil society and how the behavioral responses of civil society might trigger responses by various decision-makers (i.e. diplomats, technical experts, security agencies). This analysis is based upon well-documented phenomena in the psychological literature: loss aversion, ambiguity aversion, cognitive stress in the face of the unknown, status quo bias, complacency, and social amplification of risk. These perceptions and behavioral responses may provide some explanation for the challenges faced in the ongoing negotiations in the Nile basin. Recognizing their origins and implications may assist moves towards a resolution.

In this paper we have sought to provide an accessible description of the Nile river system and the ways in which completion of the GERD will influence the hydrological behavior of the system. Our simulations illustrate outcomes from the construction of the GERD for the three riparians and identify critical situations that need to be resolved in negotiations about GERD and AHD operations. The first critical situation is the imminent initial filling of the GERDR (Era 1). We recognize that the three countries have been actively engaged in negotiations to reach a positive resolution for this pressing issue. The necessary management decisions relate to whether there will be agreed annual releases from the GERD, or whether a more sophisticated strategy should be adopted to manage an extraordinary, yet very plausible, severe drought condition.

Once the GERDR is full, in years of average or above average Nile flows (Era 2) Egypt is unlikely to have to reduce water releases from the AHD to less than its annual target of 55.5 bcm, assuming upstream irrigation withdrawals do not increase more than we have assumed. However, the AHDR will on average be lower than it is at present. Sudan will benefit from less variable Nile flows, including increased summer flows and reduced floods and sedimentation. Ethiopia will benefit from the sale of more than 15 TWh of hydropower.

However, a severe multi-year drought (Era 3) is inevitable at some point in the future. This will be a critical event in terms of managing water risks and perceptions in the Nile basin. In advance of such a drought, a comprehensive basin-wide drought management plan needs to be agreed upon, including a release policy of the GERD. Such agreements should specify how the reduced flow of the Nile would be shared when storage is depleted in both reservoirs to best balance power generation and consumptive use. Possibly the most challenging situation will materialize after a multi-year drought when agreement is required on how quickly and in what sequence the ADHR and the GERDR should be refilled. To maintain confidence that proper planning has taken place, accurate and coordinated messaging to the media and public will be important.

It may in fact be a long time before a cooperative operating strategy for managing a multi-year drought actually needs to be deployed. The Nile riparians may get through the period of the initial filling of the GERDR without mishap and enter a "new normal" during which careful coordination is not required. However, it is important to recognize that this new normal condition is unlikely to last and cannot be the only basis for planning.

Reaching an agreement on a filling strategy is critical and should be achieved promptly. However, it is also urgent to begin planning for how a severe multi-year drought in the Nile basin would be managed when the GERD is completed. No one can predict when a multi-year drought will occur, but we can anticipate both the implications on the system and how it will be perceived by different riparians within the basin. The people living in the downstream riparian countries understandably will be worried, and worry can quickly turn to panic in civil society. It is in the interest of the Nile riparians, as well as the global community, for agreements to be in place to prevent such a "water panic" from developing. Engaging in negotiations over filling rules can build trust and provide a template for discussing the difficult issues related to managing multi-year droughts. Basin-wide drought planning can occur concurrently or begin immediately after an agreement over filling is reached.

Based on our modeling results, developing robust contingency plans should not be an insurmountable task. In most years the GERD and AHD will require only modest coordination, and data transparency may be sufficient to allow proper planning to occur. However, this analysis demonstrates that nobody should be under the illusion that unilateral decision-making is sufficient to manage a severe multi-year drought. At this point in history, the Nile riparians and the global community and need to take seriously the implications of a multi-year drought, including the potential for a "water panic" in civil society, and create a process to establish sound policies and mechanisms to ensure that the associated risks can be managed.

References

Arjoon, D., Mohamed, Y., Goor, Q., and Tilmant, A. (2014). Hydro-economic risk assessment in the eastern Nile River basin. *Water Resources and Economics*, *8*, 16–31.

Basheer, M., Wheeler, K., Ribbe, L., Majdalawi, M., Abdo, G., and Zagona, E. (2018). Quantifying and evaluating the impacts of cooperation in Transboundary River Basins on the water-energy-food nexus: The Blue Nile Basin. *Science of The Total Environment*, *630*, 1309–1323.

Belissa, A. (2016). Establishing optimal reservoir operation of Fincha`a – Amerty Reservoirs. MSc Civil Engineering, Addis Ababa University.

Berger, J., and Milkman, K. L. (2012). What makes online content viral? *Journal of Marketing Research*, *49*,(2), 192–205.

Blackmore, D., and Whittington, D. (2008). Opportunities for cooperative water resources development on the Eastern Nile: Risks and rewards. Final Report of the Scoping Study Team to the Eastern Nile Council of Ministers. October. Washington D.C.: World Bank.

Block, P., and Strzepek, K. (2010). Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate change. *Journal of Water Resources Planning and Management*, *136*(2), 156–166.

Conway, D. (2005). From headwater tributaries to international river: observing and adapting to climate variability and change in the Nile basin. *Global Environmental Change*, *15*(2), 99–114.

Digna, R. F., Mohamed, Y. A., Zaag, P. v. d., Uhlenbrook, S., Krogt, W. v. d., and Corzo, G. (2018), Impact of water resources development on water availability for hydropower production and irrigated agriculture of the Eastern Nile Basin. *Journal of Water Resources Planning and Management*, *144*(5), 05018007.

Dinar, A., and Nigatu, G. S. (2013). Distributional considerations of international water resources under externality: The case of Ethiopia, Sudan and Egypt on the Blue Nile. *Water Resources and Economics*. *2*, 1–16.

Ellsberg, D. (1961). Risk, ambiguity, and the savage axioms. *Quarterly Journal of Economics*, *75*, 643–669.

Engel, S., Pagiola, S., and Wunder, S. (2008). Designing payments for environmental services in theory and practice: an overview of the issues. *Ecological Economics*, *65*(4), 663–674.

Garrick, D.E., J. W. Hall, A. Dobson, R. Damania, R. Q. Grafton, R. Hope, C. Hepburn, R. Bark, F. Boltz, L. De Stefano, E. O'Donnell, N. Matthews, A. Money. (2017). "Valuing water for sustainable development: Measurement and governance must advance together." Science. Policy Forum. November. Vol. 358, Issue 6366: 1003–1005.

Geressu, R. T., and Harou, J. J. (2015). Screening reservoir systems by considering the efficient trade-offs - informing infrastructure investment decisions on the Blue Nile. *Environmental Research Letters*, *10*, 25008.

Hurst, H. E. (1952). The Nile: A general account of the river and the utilization of its waters. Constable: London, UK.

International Non-Partisan Eastern Nile Working Group. (2015). The Grand Ethiopian Renaissance Dam: An opportunity for collaboration and shared benefits in the Eastern Nile Basin. An Amicus Brief to the Riparian Nations of Ethiopia, Sudan and Egypt. Convened at the Massachusetts Institute of Technology on November 13-14, 2014, by the MIT Jameel World Water and Food Security Lab.

Jeuland, M. (2009). "Planning water resources development in an uncertain climate future: A hydro-economic simulation framework applied to the case of the Blue Nile". Dissertation thesis: UNC-Chapel Hill. Available from https://login.proxy.lib.duke.edu/login?url=https://search.proquest.com/docview/304961568?accountid=10598

Jeuland, M., and Whittington, D. (2014). Water resources planning under climate change: Assessing the robustness of real options for the Blue Nile. *Water Resources Research*, *50*. doi:10.1002/2013WR013705.

Jeuland, M., Wu, X., and Whittington, D. (2017). Infrastructure development and the economics of cooperation in the Eastern Nile. *Water International*, *42*(2), 121–141.

Kahneman, D., and Tversky, A. (1979). Prospect theory: An analysis of cecision under risk. *Econometrica*, *47*(2), 263–292.

Kahneman, D., Knetsch, J. L., and Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic perspectives*, *5*(1), 193–206.

Kahsay, T.N., Kuik, O., Brouwer, R., and Vander Zaag, P. (2015). Estimation of the transboundary economic impacts of the Grand Ethiopia Renaissance Dam: A computable general equilibrium analysis. *Water Resources and Economics*, *10*,14–30.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X., and Ratick. S. (1988). The social amplification of risk: A conceptual framework. *Risk Analysis, 8*(2), 177–187.

Lazer, D. M. J., Baum, M. A., Benkler, Y., Berinsky, A. J., Greenhill, K. M., Menczer, F., Metzger, M. J., Nyhan, B., Pennycook, G., Rothschild, D., Schudson, M., Sloman, S. A., Sunstein, C. R., Thorson, E. A., Watts, D. J., and Zittrain, J. L. (2018). The science of fake news. *Science, 359*, 1094–1096. 10.1126/science.aao2998.

Molle, F., Gaafar, I., El-Agha, D. E., and Rap, E. (2018). The Nile delta's water and salt balances and implications for management. *Agricultural Water Management*, *197*, 110–121.

Moussa, A. M. A. (2017). Dynamic operation rules of multi-purpose reservoir for better flood management. *Alexandria Engineering Journal*, https://doi.org/10.1016/j.aej.2017.03.012.

Mulat, A. G., and Moges, S. A. (2014). Assessment of the impact of the Grand Ethiopian Renaissance Dam on the performance of the High Aswan Dam. *Journal of Water Resource and Protection, 06*(06), 583–598.

Nile Basin Initiative (2012). State of the River Nile Basin 2012, Entebbe.

~~Rehman, S., Al-Hadhrami, L. M., & Alam, M. M. (2015). Pumped hydro energy storage system: A technological review. *Renewable and Sustainable Energy Reviews, 44*, 586–598.~~

Sangiorgio, M., and Guariso, G. (2018). NN-based implicit optimization of multi-reservoir systems management. *Water*, *10*(3), 303. https://doi.org/10.3390/w10030303.

Siam, M. S., and Eltahir, E. A. B. (2017). Climate change enhances interannual variability of the Nile river flow. *Nature Climate Change*, *7*, 350.

Slovic, P. (1987). Perception of risk. *Science, 236*(4799), 280–285.

Slovic, P., and Peters, E. (2006). Risk perception and affect. *Current Directions in Psychological Science*, *15*(6), 322–325.

Strzepek, K. M., Yohe, G. W., Tol, R. S. J., and Rosegrant, M. W. (2008). The value of the high Aswan Dam to the Egyptian economy. *Ecological Economics, 66,* 117–126.

Sutcliffe, J., and Parks, Y. (1999). The hydrology of the Nile. Wallingford, IAHS Press.

van der Krogt, W., and Ogink, H. (2013). Development of the Eastern Nile water simulation model. Delft, Deltares.

Vosoughi, S., Roy, D., and Aral, S. (2018). The spread of true and false news online. *Science, 359,*(6380), 1146–1151. doi: 10.1126/science.aap9559.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W., and Dadson, S. J. (2016). Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. *Water International*, doi: 10.1080/02508060.2016.1177698.

Wheeler, K. G., Hall, J. W., Abdo, G. M., Dadson, S. J., Kasprzyk, J. R., Smith, R., and Zagona, E. A. (2018). Exploring cooperative transboundary river management strategies for the Eastern Nile Basin. (under review).

Whittington, D., Hanemann, W. M., Sadoff, C., and Jeuland, M. (2009). The challenge of improving water and sanitation services in less developed countries. *Foundations and Trends in Microeconomics, 4*(6-7), 469–609.

Whittington, D. Ancient instincts: Implications for water policy in the 21st Century. *Water Economics and Policy*, *2*(2). doi: 10.1142/S2382624X16710028.

Whittington, D., Waterbury, J., and Jeuland, M. (2014). The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile.” *Water Policy, 16*, 595–608.

Zagona, E. A., Fulp, T. J., Shane, R., Magee, T., and Goranflo, H. M. (2001), RiverWare: A generalized tool for complex reservoir systems modeling. *Journal of the American Water Resources Association*, *37*(4), 913.

Supplementary Materials

Background

The Nile is the longest river in the world at 6695 km. It drains an area of 3.18 million km^2 located in 11 nations (Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda) (Figure 1). The majority of the flow comes from two major tributaries, the Blue Nile and the White Nile. The Blue Nile is a highly seasonal river that emerges from Lake Tana in the highlands of Ethiopia, and descends through a deep gorge before crossing into Sudan and flowing north to Khartoum, the capital of Sudan. The second major tributary emerges from Lake Victoria as the Victoria Nile at Jinja in Uganda, and flows northwards through Uganda and into the Sudd wetlands of South Sudan. Evaporation there reduces flow significantly, even after it joins with the Bahr el Ghazal and the Sobat rivers to form the White Nile. The Main Nile begins downstream of the confluence of the White and Blue Nile tributaries in Khartoum, and continues northward through the Nubian desert before entering the AHD reservoir (AHDR) in northern Sudan. The seasonal Atbara River joins the Main Nile the in northern Sudan. The AHD controls water releases that flow through the river channel in Egypt towards Cairo and the Mediterranean Sea.

The Aswan High Dam (AHD) was completed in 1970 (Figure S1). It has a minimum operating level of 147 m and corresponding dead storage of 34.7 bcm. The active storage zone goes up to 175 m and corresponds to an additional storage of 87.2 bcm. From 175 to 182 m is the flood zone, which can hold up to 39.8 bcm. Besides use of the flood zone to manage the high seasonality of inflows, operations also include a drought management policy (DMP). Under the DMP, the withdrawals from the AHDR are reduced by 5% if the storage (elevation) of the reservoir falls below 60 bcm (159.4 m), 10% if the reservoir falls below 55 bcm (157.6 m), and 15% if the reservoir falls below 50 bcm (155.7 m).

Figure S1: A Side Profile of the AHD Showing Different Operating Zones and their Volumes and Key Operational Elevations

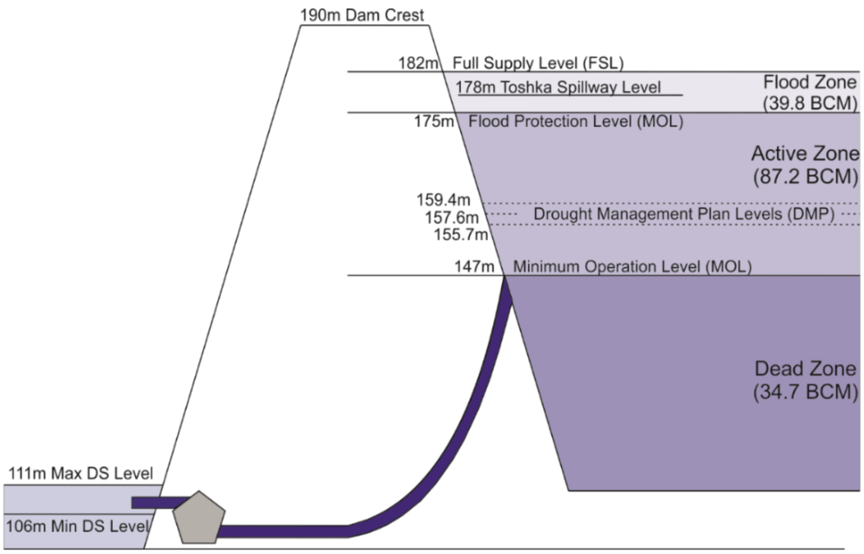
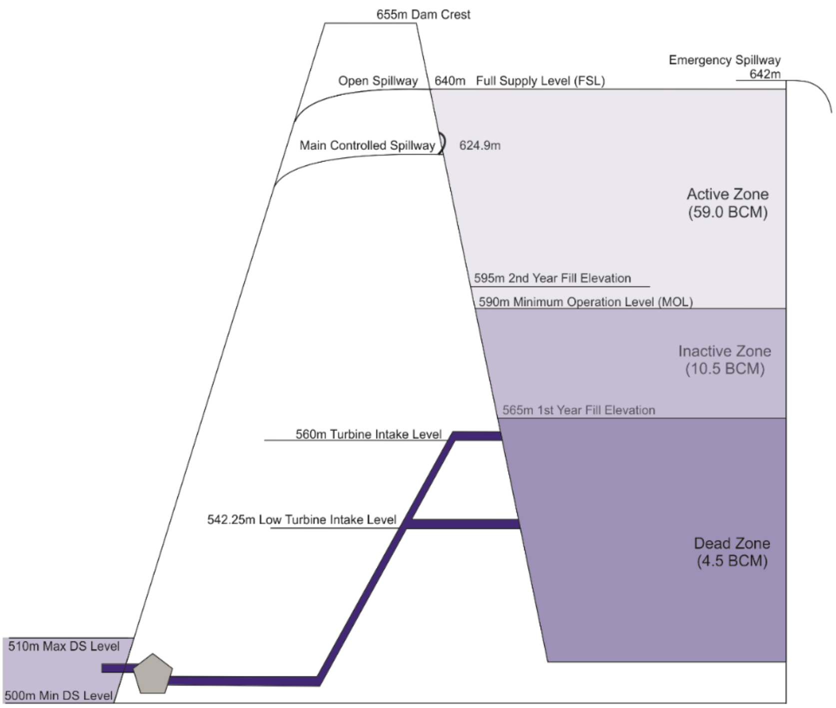


Figure S2: A Side Profile of the GERD Showing Different Operating Zones and their Volumes and Key Operational Elevations



Other infrastructure on the Blue Nile includes the Roseries and Sennar dams in Sudan with combined storage of about 6.5 bcm. The largest reservoir in Sudan is created by the Merowe Dam on the Main Nile, with an active storage volume 8.1 bcm. Details of these dams and other smaller Sudanese and Ethiopian infrastructure are provided in Table S1. Reservoir operations are described in Wheeler et. al (2016).

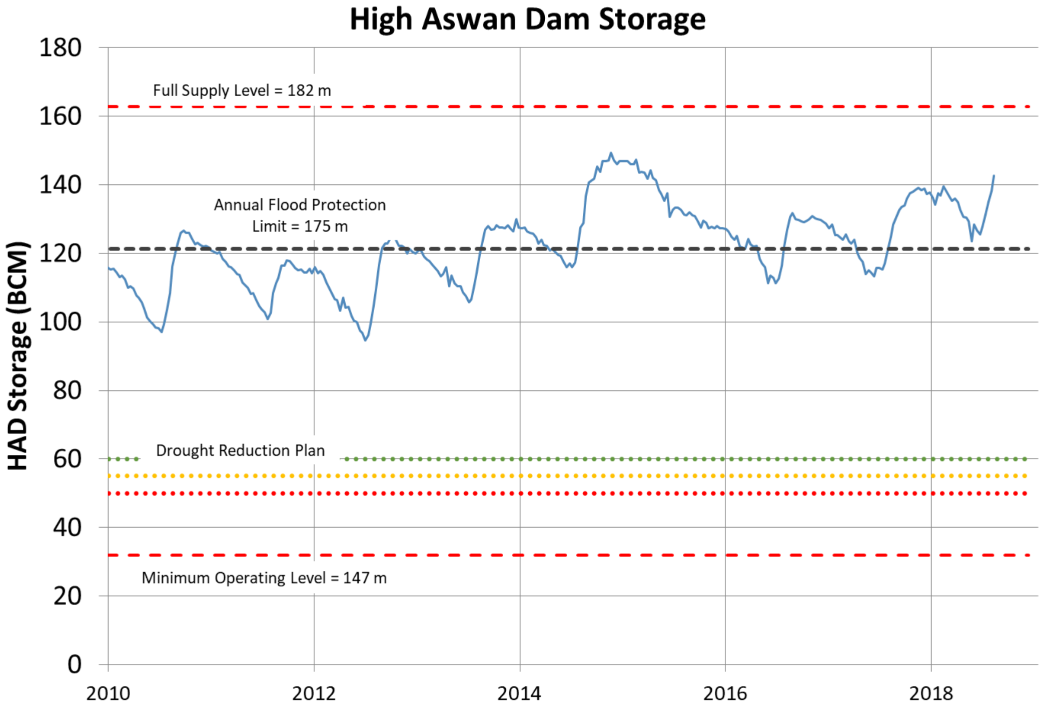
Era 1 - Filling the GERD

Filling the GERD is expected to happen in three stages: (i) retain 4.5 bcm to test 2 low-head turbines at 565m in filling year 1, (ii) retain approximately 13.75 bcm to test the remainder of the turbines (eventually 14) at 595m during filling year 2, and (iii) gradually fill the remaining active storage space to raise the reservoir to 640m at the end of a flood season (or 633m at the beginning of a flood season) over some negotiated duration of time.

We consider the initial 4.5 bcm as a one-time ‘cost’ to fill the reservoir, which is roughly deducted from the inflows to the Aswan High Dam Reservoir (AHDR). More precisely however, a portion of this 4.5 bcm would never have reached the AHDR due to evaporation and seepage between the GERD and the AHDR. In addition, some of this water could in theory be consumed by water users in Sudan, though the consumption lost in Sudan is likely to be minor given existing water uses. Thus, the correspondence between the water held in storage in the GERD and the reduction in storage in the AHDR is somewhat more than one-to-one. In other words, the net storage reduction in the AHDR will be somewhat less than 4.5 bcm.

The downstream consequences of filling the GERD will depend on several natural and human-controlled factors. First, the volume of water in the AHD when the filling begins will be the initial factor to protect Egypt during the filling process. As of August 31, 2018, the storage volume in the AHD was estimated to be 143 bcm with an elevation of 178.8 m above sea level. Conservation measures by Egypt should allow the AHD to start with an elevation around 175 m when the GERD begins to fill. Figure S3 shows the estimated storage of the AHD based on satellite imagery (https://ipad.fas.usda.gov/cropexplorer/global_reservoir/).

Figure S3: AHD Storage Levels by Satellite Imagery



The second important factor that will affect the downstream impact of the GERD will be the magnitude of flows throughout the basin during the filling period. With higher than average flows during filling, the level of the AHDR is still likely to fall, but Egypt probably will not need to reduce releases to avoid the AHDR falling to 147 m, but losses of hydropower will still occur in Egypt. Higher basin flows during the filling period would accelerate the AHDR recovery. High flows in the Blue Nile will be particularly influential since they will shorten the period required for filling of the GERDR.

Conversely, in the event of below-average basin flows during GERDR filling, the pool elevation in the AHD can be expected to decline more abruptly, and the extent of decline and the potential impact on Egypt will depend on the operation of both dams. Under significant drought conditions, Egypt would prefer that Ethiopia not retain water in the GERDR but pass the entire (low) flow to downstream riparians. It is, however, important to emphasize that only about 53% of the annual flows reaching the AHDR passes through the location of the GERD on average. The remainder of the flow comes from the Atbara, the White Nile, and several other smaller tributaries, e.g., Dinder and Rahad, which meet the Nile downstream of the GERD site.

A third factor affecting the downstream impacts of the GERD during the filling process is the operation of the GERD itself and is the primary factor under consideration in negotiations between the three countries. The less water that is released from the GERD during the filling process, the faster the retained water will accumulate in GERDR, but this will also result in more abrupt declines in the AHDR. Egypt would naturally prefer more water to be released from the GERD throughout the filling period, resulting in a longer time required to fill the GERDR and a more gradual decline in the elevation of the AHDR. This would benefit Egypt both in terms of lower losses of power generation (due to higher head) and more water under their immediate control to meet downstream needs. A slower filling also comes at a cost of lower power generation from the GERD, as well as greater evaporation loss from the AHDR relative to that from the GERDR. If the GERDR is filled quickly, the filling period will end sooner, and storage in the ADHR can begin to recover earlier. Furthermore, a longer filling period exposes this process to a longer duration that could be helpful or harmful, since it becomes increasingly likely that a high flood or a major drought might facilitate filling or increase system risks, respectively. We emphasize that there is a tradeoff between filling quickly (getting it over with) versus filling slowly and allowing more time for the GERD to reach 640 m.

A fourth factor affecting the downstream consequences of filling the GERDR is the operating policy of the AHD. Given the inevitability of declines in the elevation of the AHDR during filling, Egypt will have to continuously evaluate whether to continue to release 55.5 bcm annually and risk storage falling to the minimum operating level of 147 m, or to proactively reduce releases from the AHD to lessen this risk. If the reservoir reaches this critical elevation, forced curtailments would result. A proactive approach implies earlier adverse impacts on Egyptian water users, but reduced risk of severe and especially damaging shortages. The current drought management policy of the AHD is one form of a proactive plan to minimize risks. It predates the GERD, however, and therefore should be revisited given the impending changes to seasonal inflow patterns.

A fifth factor that will significantly influence the downstream impacts of the GERD during the filling process will be how rapidly the power generated by the GERD can be integrated into the regional power grid. Ethiopia's ambitious Growth and Transformation Plan (GTP II) indicated an expansion of 4500 km of transmission lines between 2010 to 2015; a rate that is expected to continue in the coming years. Power sharing agreements with neighboring countries is also expected to play a significant role in the ability and willingness of Ethiopia to generate energy from the GERD, possibly reinforced by commitments of prioritization to downstream riparians.

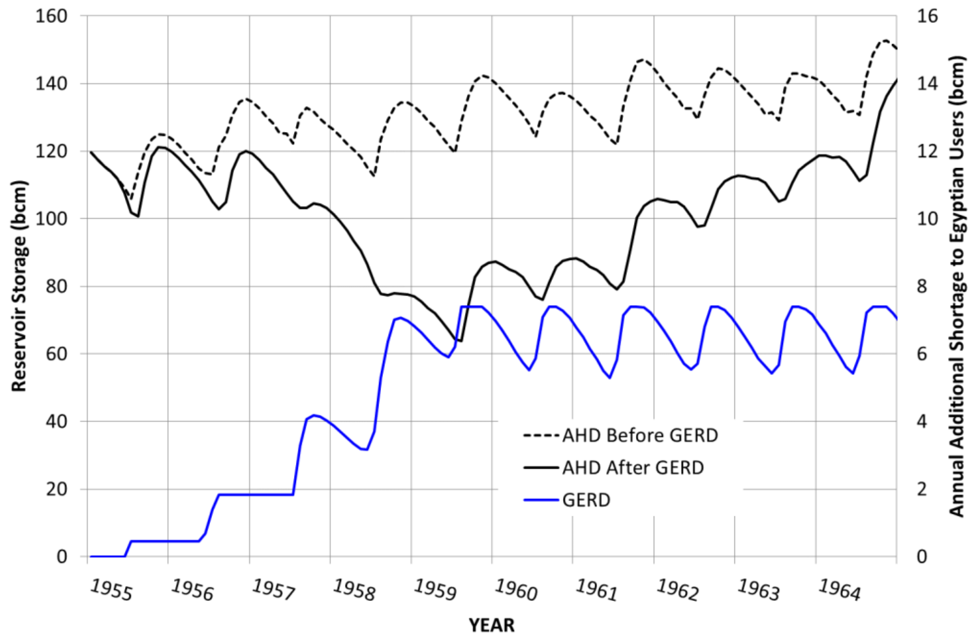
Finally, the downstream consequences will be affected by how Sudan alters its irrigation withdrawals in response to the new flow regime during the filling period. Because the GERD's releases will reduce the monthly fluctuations in the Blue Nile flows, once the reservoir fills, Sudan will have increased water supply during the crucial summer season when crop water requirements are high. This should enable Sudan to increase its irrigation withdrawals up to its maximum allocation of 18.5 bcm (measured at Aswan) under the 1959 Nile Waters Agreement. Due to uncertainties in current withdrawals and lack of agreement about how much additional could be diverted, this study does not include the effects of increased water consumption by Sudan. Whether or not an increase in water consumption by Sudan could occur during the filling process would be a topic of negotiation, particularly between Sudan and Egypt.

The Sudanese government may also have concerns that the GERD will be filled too quickly because, unlike Egypt, it has no over-year water storage to buffer reduced upstream flows. But as long as Ethiopia releases sufficient flows from the GERD to meet current Sudanese irrigation withdrawals and coordination between the GERD and the Sudanese dams takes place, Sudan should not be overly worried. After filling is completed, the GERD will provide Sudan with a wide range of economic benefits, including flood control, increased hydropower from more stable water levels at dams in Sudan, increased summer water supply, reduced sedimentation of its storage facilities – all for free (Jeuland et al. 2017). Sudan is also likely to be a major market for the power that will be produced from the GERD.

Additional Era 1 Simulations

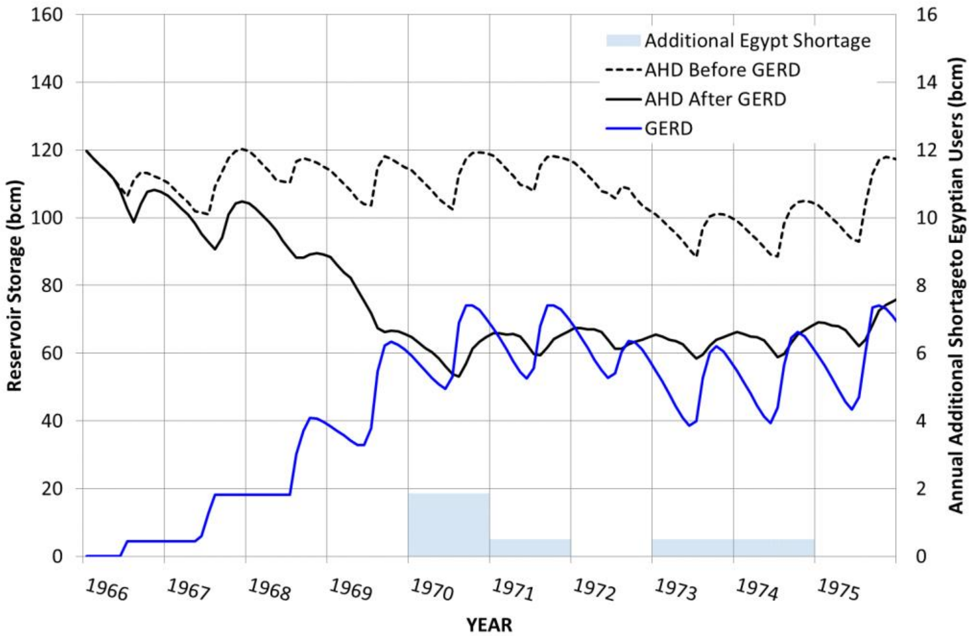
During the 1955-1964 sequence of wet years, filling the GERD poses no problems for Egypt (Figure S4; and Table S2). During the initial 3-year period of the simulation (from 1957 to mid-1959), AHDR storage falls from 120 bcm to 64 bcm as the GERDR fills, but the AHDR recovers over a 4-year period and by the end of the 10-year simulation period is higher than when the simulation started. The GERDR transitions from empty to full in the first four years of the simulation and subsequently maintains a high, stable release pattern throughout the remainder of the 10-year simulation period. Egypt can release 55.5 bcm in every year of the simulation and experiences no shortages. In this simulation of wet years, above average flows have been stored primarily in the GERDR, and then in the AHDR. At the end of the simulation, all riparians in the basin have been able to meet their target water releases *and* increase water held in storage for future use.

Figure S4: GERD Filling Effects Under a Historically Wet 10-Year Sequence



The results for a 10-year sequence of average years are sensitive to the particular pattern of flows selected (i.e., sensitive to the specific historical sequence we choose). Figure S5 (and Table S3) illustrates the results for the 1966-1975 sequence that show a modest cumulative deficit in Egypt of 3.3 bcm (with small shortfalls occurring in 4 of the 10 years of the simulation). Deficits are triggered when the storage volume of the AHDR falls below 60 bcm because Egypt is assumed to invoke the DMP. The AHDR ends the simulation period with 75 bcm in storage, substantially less than its initial storage of 120 bcm.

Figure S5: GERD Filling Effects Under a Historically Average 10-Year Sequence



Some 10-year sequences of average conditions look better for Egyptian water users. For example, the 1932-1941 sequence shows no additional deficits, but the AHDR ends the period with storage of 67 bcm. On the other hand, some 10-year average sequences look worse than the 1966-1975 sequence. For example, the 1900-1909 sequence shows additional cumulative deficits of about 20 bcm over the 10-year period (with additional shortfalls in 6 of the 10 years of the simulation). Interestingly, the AHDR ends that simulation with 93 bcm in storage, down from the initial 120 bcm. In all cases with shortfalls, deficits occur mainly from Egypt's use of the existing DMP; they can thus be considered proactive reductions that reduce the risk of more severe shortages that might come from more serious droughts.

Evaporation Considerations

During GERDR filling, the AHDR will operate at considerably lower levels, such that there will be modest declines in overall system evaporation. After the filling of the GERDR, system evaporation will only remain lower so long as levels in the AHDR remain at considerably lower levels than in the pre-GERD era, which will only occur if the basin enters a period of drought and low flows, and/or if upstream abstractions of water increase. Thus, evaporative savings are greatest when downstream water scarcity is highest. Over the long term and assuming current levels of upstream water use, the addition of the GERD, with the substantial surface area of its reservoir, will increase the net evaporation of the system. After the GERDR filling is complete and the AHDR has recovered, the total additional evaporation from the

GERDR will be 1.7 bcm per year, and the evaporation savings from a lower AHDR will be 1.1 bcm. The GERDR is assumed to have an annual average evaporation rate of 108 cm/year, compared to the AHRD and Merowe reservoirs with 270 cm/year and 275 cm/year, respectively.

Figure S6: Average GERDR and AHDR Evaporation during Filling and 'New Normal' Conditions

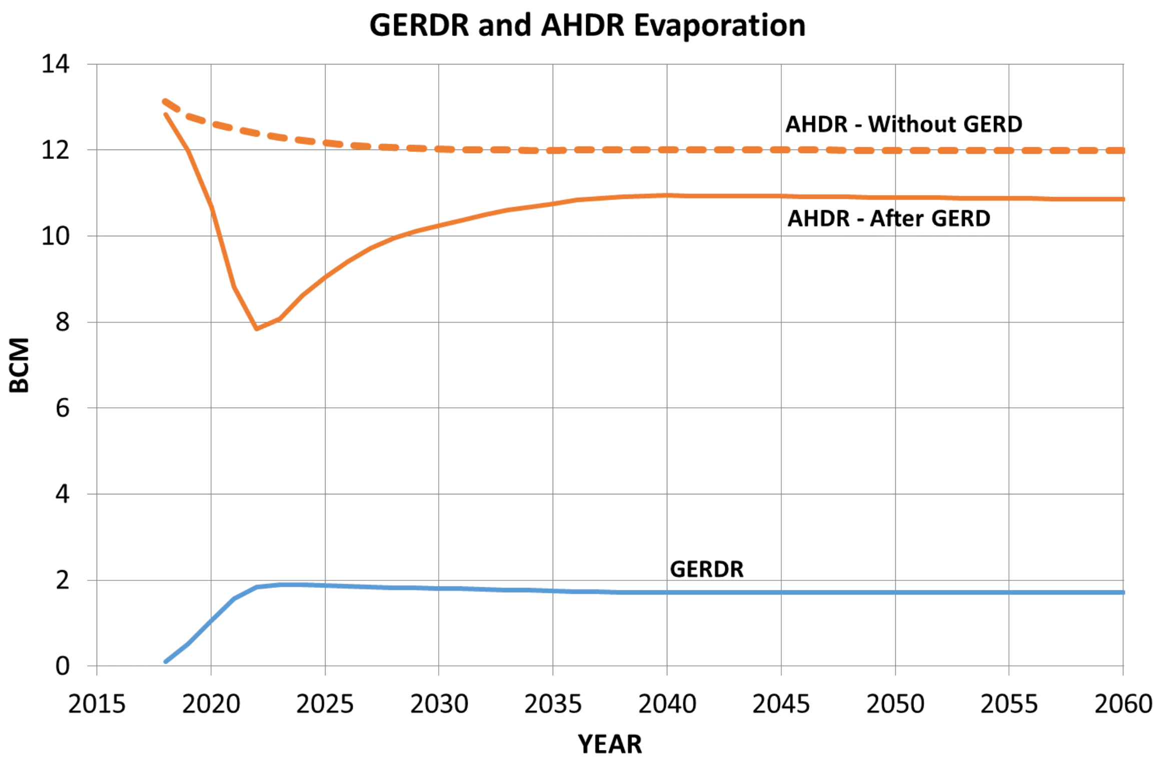


Table S1: Key Elevations and Storage Values of Modeled Reservoirs

	Min Active Pool Elevation (m)	Max Supply Level (m)	Min Diversion Elevation (m)	Max Capacity (MW)	Active Storage Volume (MCM)	Total Storage Volume (MCM)
Tana/Beles	1783.5	1787.5	1783.5	423	12328	41080
Finchaa	2214.0	2219.0	--	134	1050	1120
GERD	590.0	640.0	--	6450	59000	74000
Rosaries	467.0	490.0	--	280	5885	5909
Sennar	417.2	421.7	417.2	15	420	640
Tekeze	1096.0	1140.0	--	300	5289	9293
Upper Atbara/Setit	509.0	521.0	--	320	2508	3688
Khashm El Girba	463.0	474.0	463.5	10.6 + 7.6	597	657
Jebel Aulia	372.0	377.4	372.0	28.8	3065	3290
Merowe	285.0	300.0	--	1250	8182	12396
High Aswan	147.0	182.0	178.0	2100	148040	182700

Table S2. Effects of the GERD Filling Across Low, Average and High Hydrologic Scenarios

	Low Flow Sequence 1978-1987		Average Flow Sequence 1966-1975		High Flow Sequence 1955-1964	
	w/o GERD	with GERD	w/o GERD	with GERD	w/o GERD	with GERD
Ethiopia						
Average annual GERD hydropower generation (TWh)	--	8.85	--	10.37	--	12.70
Average annual GERD evaporation (bcm)	--	1.4	--	1.4	--	1.5
Ending GERD Storage (bcm)	--	44.9	--	71.0	--	72.0
Sudan						
Average annual hydropower generation* (TWh)	7.55	7.73	8.67	9.47	9.21	9.65
Average annual evaporation* (bcm)	2.8	2.9	3.0	3.3	3.0	3.3
*includes Merowe + Roseries + Sennar						
Egypt						
Average annual AHD hydropower generation (TWh)	6.54	5.55	8.05	6.81	8.86	7.75
Average annual AHD evaporation (bcm)	9.0	7.3	12.6	9.4	14.6	11.8
Cumulative deficit (bcm)	30.4	72.9	0.0	3.4	0.0	0.0
No. of years with deficit	5	7	0	4	0	0
Ending AHDR storage (bcm)	39.9	47.0	117.5	75.2	151.3	139.4

Table S3. Effects of the GERD During "New Normal" Operations Under a Selection of Average Hydrologic Conditions

	Average Flow Sequence 1927-1946		Average Flow Sequence 1934-1953		Average Flow Sequence 1939-1958	
	w/o GERD	with GERD	w/o GERD	with GERD	w/o GERD	with GERD
Ethiopia						
Average annual GERD hydropower generation (TWh)	--	15.93	--	15.93	--	15.89
Average annual GERD evaporation (bcm)	--	1.9	--	1.9	--	1.9
Ending GERD Storage (bcm)	--	71.2	--	70.4	--	71.6
Sudan						
Average annual hydropower generation* (TWh)	8.38	10.21	8.50	10.26	8.52	10.27
Average annual evaporation* (bcm)	2.9	3.5	2.9	3.5	2.9	3.5
*includes Merowe + Roseries + Sennar						
Egypt						
Average annual AHD hydropower generation (TWh)	7.42	7.02	7.55	7.17	7.20	6.91
Average annual AHD evaporation (bcm)	10.9	9.9	11.2	10.2	10.4	9.7
Cumulative deficit (bcm)	1.2	3.0	0.0	2.0	17.9	26.5
No. of years with deficit	1	4	0	2	7	7
Ending AHDR storage (bcm)	106.1	88.6	99.9	82.8	134.7	118.8

Table S4. Effects of the GERD During the Onset of Drought

	Low Flow Sequence 1972-1991	
	w/o GERD	with GERD
Ethiopia		
Average annual GERD hydropower generation (TWh)	--	12.92
Average annual GERD evaporation (bcm)	--	1.5
Ending GERD Storage (bcm)	--	26.8
Sudan		
Average annual hydropower generation* (TWh)	8.05	10.07
Average annual evaporation* (bcm)	2.9	3.4
*includes Merowe + Roseries + Sennar		
Egypt		
Average annual AHD hydropower generation (TWh)	6.23	6.18
Average annual AHD evaporation (bcm)	8.2	8.0
Cumulative deficit (bcm)	52.8	41.4
No. of years with deficit	11	11
Ending AHDR storage (bcm)	61.0	61.3

Table S5. Effects of the GERD During the Recovery from a Drought

	Average Flow Sequence 1941-1950	
	w/o GERD	with GERD
Ethiopia		
Average annual GERD hydropower generation (TWh)	--	12.01
Average annual GERD evaporation (bcm)	--	1.2
Ending GERD Storage (bcm)	--	63.0
Sudan		
Average annual hydropower generation* (TWh)	8.60	9.98
Average annual evaporation* (bcm)	2.9	3.3
*includes Merowe + Roseries + Sennar		
Egypt		
Average annual AHD hydropower generation (TWh)	6.38	5.80
Average annual AHD evaporation (bcm)	8.6	7.4
Cumulative deficit (bcm)	31.9	43.0
No. of years with deficit	6	6
Ending AHDR storage (bcm)	108.5	75.6