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Cooperative filling approaches for the Grand Ethiopian Renaissance Dam

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ABSTRACT
Strategies for filling the Grand Ethiopian Renaissance Dam and implications for downstream water resources are analyzed using a river basin planning model with a wide range of historical hydrological conditions and increasing coordination between the co-riparian countries. The analysis finds that risks to water diversions in Sudan can be largely managed through adaptations of Sudanese reservoir operations. The risks to Egyptian users and energy generation can be minimized through combinations of sufficient agreed annual releases from the Grand Ethiopian Renaissance Dam, a drought management policy for the High Aswan Dam, and a basin-wide cooperative agreement that protects the elevation of Lake Nasser.

Introduction

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile offers a unique and timely opportunity for cooperation among the Eastern Nile countries of Ethiopia, Sudan and Egypt. While the potential benefits of the GERD for Ethiopia and surrounding countries in improved electrification are apparent (EDF & Scott Wilson, 2007), questions of how the GERD will affect water supply and power generation in downstream countries has been the focus of ongoing debates among numerous stakeholders and institutions both internal and external to the basin. We acknowledge the historically rich and geopolitically complex situation that currently exists in the region. Consequentially, this study explicitly does not attempt to address issues of this larger context but focuses exclusively on the physical characteristics of the system, including the operation of current and planned infrastructure, along with the potential for coordination and collaboration among the parties involved.

A review of existing design documents by an international panel of experts indicated the need for further analysis of the period during which the 74 billion cubic metre (BCM) storage reservoir behind the GERD will initially be filled (IPoE, 2013). A recent

declaration of principles signed by the leaders of the three countries exemplifies the willingness of the parties to cooperate on these matters (DoP, 2015). However, the technical details of how this cooperation would manifest with respect to reservoir filling have yet to be established. While this period could result in the first effects on downstream countries, it also provides the first opportunity to translate the principles of cooperation into tangible actions.

Numerous computer models have been developed that simulate the long-term development of the Eastern Nile Basin (Arjoon, Mohamed, Goor, & Tilmant, 2014; Blackmore & Whittington, 2008; Block & Strzepek, 2010; Guariso & Whittington, 1987; McCartney & Girma, 2012; Yao & Georgakakos, 2003), and recently efforts have been conducted to analyze possible GERD filling strategies (Bates, Tuncok, Barbour, & Klimpt, 2013; King & Block, 2014; Mulat & Moges, 2014; Zhang, Block, Hammond, & King, 2015). While all the modelling tools listed above have strengths and have provided valuable insight on the basin, studies concerning GERD filling strategies have either limited the analysis to a handful of hydrologic scenarios, resulting in deterministic results (Bates et al., 2013; Mulat & Moges, 2014), lack detail of the current complex operations of existing reservoirs (King & Block, 2014; Zhang et al., 2015), or provide limited flexibility to test creative and incremental degrees of coordination among stakeholders.

This article compares the findings of 224 potential and practical filling strategies, developed from combinations of (1) various operations of the GERD during filling; (2) modifications to the current operations (reoperation) of the Sudanese and Egyptian reservoirs; (3) explicit coordination of releases from the GERD to avoid critical downstream impacts; and (4) starting conditions of the High Aswan Dam (HAD). Each management alternative was analyzed using 103 sequences of hydrologic inflow data to compare the filling strategies and scenarios with a risk-based framework. This article demonstrates that the degree to which cooperation takes place on a technical level is a continuum ranging from unilateral operations to truly dynamically cooperative solutions that reflect an awareness of the benefits and risks to others (Sadoff & Grey, 2005). As a result, a wide variety of solutions can be identified that can inform a negotiation process; yet the complexities of implementing cooperative strategies must not be underestimated.

Finally, this article argues that, although an agreement ultimately should not be based solely on technical studies, a successful negotiation can be supported through a well-designed hydro-policy modelling framework. We define such a framework as one that provides sufficient accuracy, transparency and flexibility for stakeholders to develop and test innovative solutions and explore the trade-offs and benefits of compromise. Such a framework should provide a sufficient representation of the physical characteristics of a system alongside an accurate representation of the existing and potential operational policies. In this spirit, a particular 'optimal' filling solution is intentionally not identified, but a potential pathway of mutual benefit through joint management is identified for further exploration by stakeholders in the basin.

Study area

The Nile Basin encompasses 3.18 million km^2 of Eastern Africa, including the 11 nation-states of Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda. The river system is formed

by two distinct major tributaries, commonly called the Blue Nile and the White Nile, which merge in Sudan to form the Main Nile. The Blue Nile flows from Lake Tana in Ethiopia and carves a deep clockwise-turning canyon through the Ethiopian plateau before it passes into Sudan, contributing substantially to its agriculture-based economy (Craig, 1991) before joining the White Nile in the capital city of Khartoum. The flows that eventually become the White Nile begin in the complex of lakes, wetlands and rivers in the Equatorial Lakes region of Burundi, Democratic Republic of Congo, Kenya, Rwanda, Tanzania and Uganda, and emerge from Lake Victoria as the Victoria Nile in Uganda. After passing through the Sudd Wetlands of South Sudan as the Bahr el Jebel and joining the Bahr el Ghazal and the outflow of the Baro-Akobo-Sobat tributary sub-basin, the river enters Sudan as the White Nile. Downstream of the confluence of the two major branches of the Nile in Khartoum, the intermittent Atbara River, originating in Ethiopia and Sudan as the Tekeze River (called the Setit River in Sudan), joins to form the last major contribution before winding through the Nubian Desert and into Egypt (Figure 1).
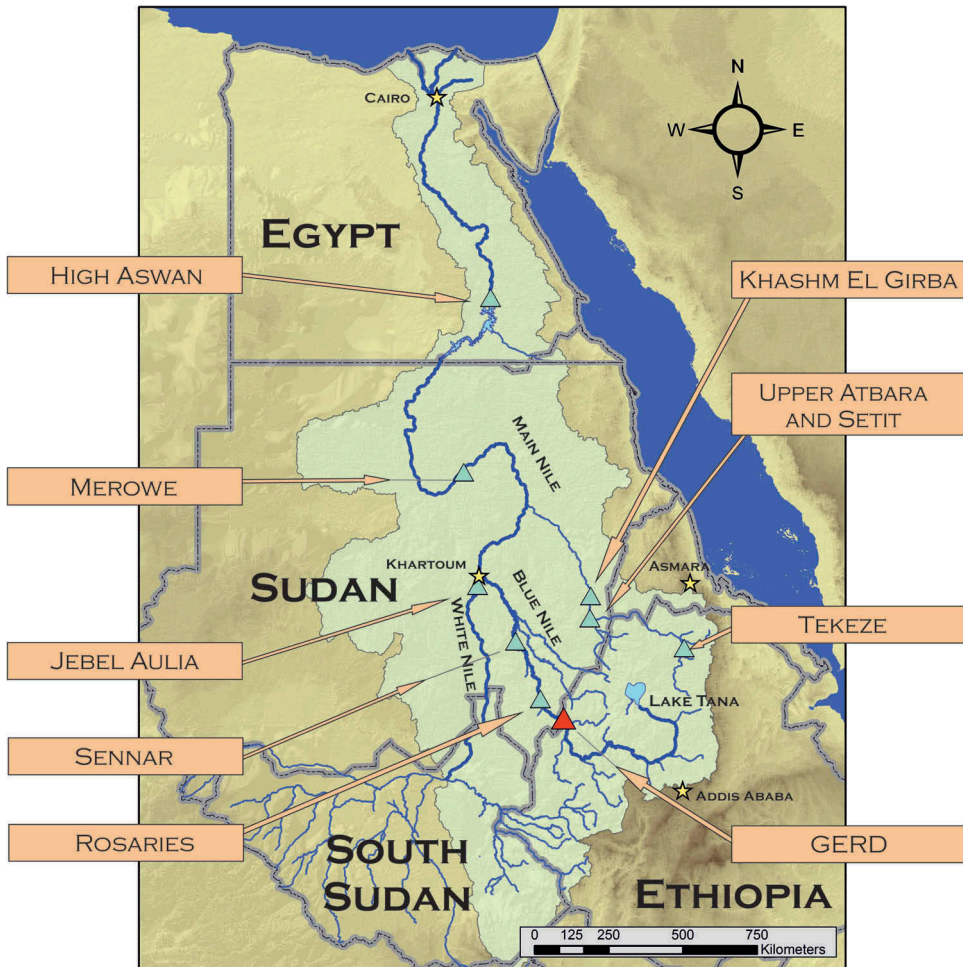
Figure 1. Map of Eastern Nile region, with reservoir locations.

The monsoonal rainfall over the highlands of Ethiopia generates the majority of the flow into the system via the Blue Nile, the Tekeze-Setit-Atbara, and the Baro-Akobo-Sobat sub-basins (Sutcliffe & Parks, 1999), while only approximately half of the contributions from the Lake Victoria region emerge from wetlands of South Sudan. As a result, the Blue Nile contributes approximately 57% of the total runoff into the Main Nile as measured inflow to Egypt, while the White Nile and the Atbara River contribute 30% and 13%, respectively (Blackmore & Whittington, 2008; NBI, 2012). Although the majority of precipitation falls in Ethiopia and the Equatorial Lakes region, Egypt and Sudan consume the vast majority of water. This geographic disparity between where the rivers begin and where the water is consumed provides both the potential for conflict and the rationale for cooperation.

Infrastructure

The construction of the GERD is the latest chapter in a substantial history of infrastructure development in the Eastern Nile Basin. Although coordinated planning and operation of infrastructure across international borders has occurred briefly in the past, the longevity of this coordination has been limited with respect to actual operations. The Low Aswan Dam (1902), Sennar Dam (1925) and Jebel Aulia Dam (1937) were constructed under British colonial influence with a vision of coordinated management that would extend the availability of seasonal floodwaters in Egypt and open up the agricultural potential in Sudan with the Gezira irrigation scheme (Tvedt, 2004). After Egypt and Sudan achieved independence, the Khashim El Girba Dam (1964), Rosaries Dam (1966) and High Aswan Dam (HAD, 1970) were constructed under the auspices of a 1959 treaty between the two countries (Nile Treaty, 1959). This agreement established a joint technical committee to oversee data collection and periodic technical assessments. However, joint operation of the reservoirs was not established, and the storage volume of the HAD made any previous coordination between the original Aswan Dam and the Sudanese dams irrelevant. The relatively recent development projects of Ethiopia's Tekeze Dam (2009) and Sudan's Merowe Dam (2009) have been effectively independent of international coordination during construction and operation, with hydropower as essentially their only purpose. At the current time, joint management of infrastructure across international boundaries in the Eastern Nile basin is non-existent (see Salman, 2016, and Yihdego, in press, in this issue, for more detail).

With 169 BCM of storage capacity, Egypt's HAD is the only structure in the basin that creates a storage volume comparable to that of the GERD. Even though the benefits of the HAD have been shown to be substantially positive for the economy of Egypt (Strzepek, Yohe, Tol, & Rosegrant, 2008), the development of additional storage upstream has been met with concern due to uncertainty regarding the implications for both Sudan and Egypt.

GERD project

The US Bureau of Reclamation (1964) conducted a study on behalf of the government of Ethiopia that identified four potential dam sites on the Blue Nile, including one which has now become the location of the GERD. As described in greater detail in the introduction to this special issue, Ethiopia began the GERD construction project in 2011; it has a planned full supply elevation of 640 m and will create 74 BCM of reservoir
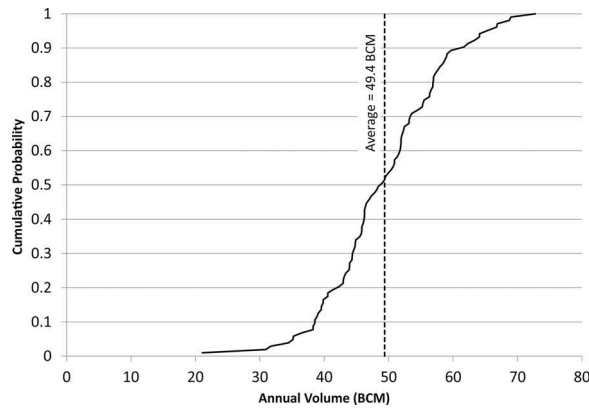
Figure 2. Annual flow volume at the Grand Ethiopian Renaissance Dam.

storage – approximately 1.5 times the average annual flow at the dam location (Figure 2).

The addition of 6000 MW of installed generation capacity to the approximately 6833 MW that currently exists within the basin (NBI, 2012) suggests that the GERD is likely to be a significant step change for the region as a whole with respect to access to electricity (NBI, 2012; Whittington, Waterbury, & Jeuland, 2014). Furthermore, the additional storage on a river system that produces an average 94.5 BCM of annual runoff into Egypt (Blackmore & Whittington, 2008) could potentially allow greater reliability of flows for Sudan and Egypt. In addition to the Ethiopian hydropower benefits, supporters of the dam claim that increased control over the natural flow regime will result in reduction of the flooding risk to Sudan, reduction of sediment in the river (which currently challenges the management of reservoirs and agricultural schemes), hydropower efficiency benefits for Sudanese reservoirs, improved depth for navigation and reduced pumping costs for water users (Ethiopian NPoE, 2013).

Critics of the dam claim that there are risks of reduced downstream water availability and reduced Egyptian hydropower, the likely loss of recession agriculture in Sudan, losses to the brick production industry that uses the sediment deposits, reduced land fertility due to the reduction of nutrient-rich sediment, and unknown environmental impacts (Beyene, 2013; Egyptian Chronicles, 2013). Although these critics claim the reservoir's planned storage and turbine capacity are oversized, the Ethiopian government believes the benefits will be worth the USD 4.8 billion construction cost.

Independent assessments note both potential costs and benefits, and have called for more studies to be conducted (Bates et al., 2013; MIT, 2014). While Ethiopia seeks to take greater advantage of the benefits the river may provide, it is still unclear how these benefits and costs may be incurred, especially during the reservoir filling period.

Previous studies

Various analyses have been conducted regarding the development of the Nile, often focusing on the development potential of the Blue Nile and its likely implications. Guariso and Whittington (1987) demonstrated that there is little conflict between the objectives of Ethiopian hydropower and Egyptian and Sudanese agriculture, using a

classical multi-objective optimization framework. Block and Strzepek (2010) demonstrated the economic benefits for Ethiopia of large-scale Blue Nile development under historical hydrologic conditions, but also showed the possibility of a reduced degree of benefit using stochastic hydrology influenced by climate changes. Similarly, McCartney and Girma (2012) provided an analysis of multi-use infrastructure development within Ethiopia and the resulting benefits to Ethiopian agriculture and hydropower while considering the risks of climate change and reduced flows. Jeuland (2010) provided a hydro-economic framework for integrating climate change impacts into infrastructure planning and found a high sensitivity of economic benefits to runoff conditions; this work was furthered with a real-options approach for analyzing the selection, sizing, sequencing and operation of reservoirs within Ethiopia (Jeuland & Whittington, 2014). Arjoon et al. (2014) used a stochastic dual dynamic programming approach within a hydro-economic framework to optimize operations for the benefits of hydropower and agriculture production under various build-out scenarios. Although some of these studies discuss the operation and filling of possible reservoirs, they use either simplified or idealized reservoir operations. While quite useful as planning tools to demonstrate how the system could be developed and managed, they are often less applicable for establishing reservoir operation guidelines that are subject to political and practical constraints.

Another class of models developed for the analysis of the Nile Basin is decision support tools, which are generally commissioned by institutions and designed to be used by multiple stakeholders. Models such as the Nile Decision Support Tool (Yao & Georgakakos, 2003) integrate with a database to form a decision support system (DSS) to bring together vast amounts of spatially and temporally discrete and distributed hydrologic data. More recently, the Nile Basin Initiative (NBI), which is commissioned to conduct studies on behalf of member countries, developed the Nile Basin DSS to provide a user-accessible platform that can incorporate a variety of models designed for various purposes (NBI, 2014). Water resource planning models using the generalized software platforms of MIKE HYDRO (formerly MIKE BASIN – Jonker et al., 2012) and WEAP (Yates, Sieber, Purkey, & Huber-Lee, 2005) have been developed and integrated into the Nile Basin DSS, while another cadre of models developed by the Eastern Nile Technical Regional Office (ENTRO) of NBI, including SWAT (Hassan, 2012), Ribasim (van der Krogt & Ogink, 2013) and RiverWare (Wheeler & Setzer, 2012), can potentially be integrated into the Nile Basin DSS. All modelling platforms have their strengths and thus cater to particular applications (Brown et al., 2015), such as the hydrologic focus of SWAT, the river basin planning focus of WEAP or the reservoir planning and management focus of RiverWare.

Three recent studies have considered the filling of the GERD. Bates et al. (2013) analyzed specific fixed monthly release patterns ranging from 20.8 to 40.0 BCM/y under three deterministic scenarios (average, moderate drought and severe drought) and using three starting elevations of the HAD. A combination of tools was used in this study, including MIKE BASIN and the RAPSO model (EDF & Scott Wilson, 2007), and separate runs were required to capture the transition of policies from filling to normal operations. Similarly, Mulat and Moges (2014) used MIKE HYDRO to simulate a single historical period of 1973–1978 that represents 'average' conditions to analyze a pre-defined single six-year filling strategy. This study considered a single hydrologic inflow node on each of the Blue and White Nile tributaries, and included the GERD and HAD, but contained no information on Sudanese reservoirs or any intervening flows. King

and Block (2014) and Zhang et al. (2015) described a model to simulate five potential filling policies, including retention of 5%, 10% and 25% of inflows, and retention of flows over the historical annual mean average and 90% of this amount. This study used stochastically generated inflows from a precipitation-driven hydrologic model and included the potential effects of climate change, yet the model was simplified, with four inflow nodes and considering only the GERD and no other reservoirs.

While the studies published to date provide insight by analyzing a number of possible filling strategies, there remains an urgent need for a robust analytical policy-oriented modelling framework that can adequately represent all the major infrastructure in the system with its existing operational criteria, simulate the many potential GERD filling arrangements that can be envisaged by the negotiators, and be physically accessible and logically verifiable by parties in the basin. Cash et al. (2003) describe the essential role and criteria of knowledge systems to enhance the credibility, legitimacy and saliency of the information they provide. Olsson and Andersson (2007) emphasize that the acceptance and influence of water resource management models depends on the access and ability of stakeholders to understand and be able to critique the methods and assumptions embedded in the tools. In essence, the 'hydro-policy' modelling framework needed for this analysis should represent a system with sufficient *accuracy*, be sufficiently *flexible* in its architecture, and be *transparent* enough to be understood and trusted by stakeholders. Furthermore, any study should demonstrate a completeness of sampling hydrology and management strategies.

Method

Modelling framework

For the purposes of developing and testing various potential filling strategies for the GERD, the RiverWare platform was selected based on its flexible rule-based design (Zagona, Fulp, Shane, Magee, & Goranflo, 2001) and ability to meet the above criteria. This capability has been demonstrated by its recent successful use in transboundary negotiations over international management of the Colorado River (United States of America and United Mexican States, 2012).

RiverWare uses an object-oriented workspace to represent physical items in the basin. Engineering algorithms are selected from extensive libraries that compute facets of water management for each object based on the known physical characteristics of the system. Data resulting from user inputs and these algorithms are propagated throughout the model network through links, typically resulting in an under-determined system wherever management decisions must be made. The prioritized rule-based simulation then provides the model objects with additional scripted user input which characterizes the myriad of multi-objective operational policies that govern the management of water, including international and intra-national agreements between users, water rights arrangements, legal constraints and essentially any form of dam management guidelines.

Nile basin model structure

The RiverWare model of the Eastern Nile developed for this study was structured to contain all the major features in the basin that significantly affect water management and distribution, including: Lake Tana, with the Tana-Beles Hydropower Project, and Tekeze Reservoir in Ethiopia; the Rosaries, Sennar, Jebel Aulia, Khashim El Girba and Merowe reservoirs in Sudan; and Lake Nasser/Lake Nubia, formed by the HAD, in Egypt. The recently raised Rosaries Dam, the newly developed Upper Atbara and Setit Dam complex, and the GERD are included in simulations of future conditions. Monthly naturalized hydrologic input locations include 162 inflow nodes in South Sudan, Ethiopia, Sudan and Egypt. Demand locations reflect the major Sudanese diversion structures of the Gezira-Managil, New Halfa and Rahad schemes, as well as the minor diversions from the Jebel Aulia Reservoir and small aggregated demands between gauged locations. Consumptive or non-consumptive water uses within Egypt are not modelled beyond expected monthly releases from the HAD and necessary spills into the Toshka diversion works.

Data requirements

The basin-wide hydrologic inflow data were developed by van der Krogt and Ogink (2013) and provided by the ENTRO office of NBI. This study compiled historical hydrologic data from a variety of sources with differing periods of record and filled in missing data using site-specific regression and partitioning techniques to reconstruct a complete naturalized data-set – meaning non-depleted and unregulated by anthropogenic effects – of 103 years (1900–2002). Stochastic hydrologic conditions were developed using the index-sequential method (Ouarda, Labadie, & Fontane, 1997), which applies a historical sequence of naturalized hydrologic flows to the future modelled period (2016–2059), with a start date that corresponds to each of the years in the reconstructed historical record. The length of the simulation period was selected to allow the model to reach equilibrium after the effects of filling under all hydrologic conditions. We acknowledge that the selected hydrologic method does not reflect future transient climate change conditions (Milly et al., 2008) or the 'Hurst effect' of persistent behaviour of flows (Hurst, Black, & Simaika, 1965); however, the approach is considered sufficiently robust for this analysis given the short-term nature of the filling process.

Estimates of current irrigation water use were obtained during the Nile Basin DSS development (Carron, Parkin, O'Donnell, & O'Connell, 2011). Historical diversions from the Nile Encyclopaedia (Nile Control Staff, 1933-Present) were used for calibration when available, and the Nile Basin DSS data were used otherwise, recognizing that they probably overestimate historical uses. Diversions for the Gezira/Managil scheme were updated with recent monthly averages from September 2012 to August 2014 (Sudan MoWE, 2015). Future target annual diversion volumes were assumed to remain constant throughout the modelled period to isolate the effects solely attributable to the GERD from any further changes to water use that could be partially attributable to the GERD or future development in the basin. For the purposes of this study, Ethiopia's diversions from the Nile are assumed to remain insignificant, while Sudan's diversions

are assumed to remain at the current estimated volume of 16.0 BCM/y using the data sources described above, and Egypt's annual diversions are assumed to be 55.5 BCM, the allocation specified in the 1959 treaty with Sudan (Nile Treaty, 1959). Although these assumptions were incorporated into this study to reflect our best understanding of the current reality (see the online supplemental data at http://dx.doi.org/10.1080/02508060.2016.1177698), variations could be readily explored should new water use estimates become available.

Current reservoir operations were obtained from numerous information sources throughout the basin, including the Nile Basin Initiative (ENTRO, 2013), water resource agencies (Egypt MWRI, 2005; Sudan MoIHP, 1968), engineering reports (Lahmeyer International, 2005; PB Power, 2003; Salini Costructtori, 2006; SMEC International, 2012) and analysis of various existing models (Jonker et al., 2012; Mulat & Moges, 2014; van der Krogt & Ogink, 2013; Yao & Georgakakos, 2003). In the absence of further information, operations of single-purpose hydropower reservoirs were simulated to generate a target power production. Reservoirs with more available information were simulated as being managed for a combination of hydropower production, control of sediment accumulation by seasonal reduction of pool elevations, irrigation diversions from the reservoir and downstream flow requirements (Table 1). Because the requirements that govern actual dam operations change throughout the year, prioritized operation rules were written to simulate these changing objectives. The model was made available and refined through seven training workshops conducted between 2012 and 2016 at NBI-ENTRO, Addis Ababa University, University of Khartoum, Cairo University, Sudan's Dams Implementation Unit of the Ministry of Water Resources, Irrigation and Electricity, and Egypt's Water Resources Research Institute of the Ministry of Water Resources and Irrigation. After operational policies were simulated in the rules with the best available information, modifications were made to explore alternative management policies. All rules in the model were transparently written to allow the technically trained stakeholders to readily understand the operational logic. Participation in these training sessions does not imply endorsement of the model or the results.

Model calibration and validation

Basin-wide model calibration and validation were performed by simulating historical conditions, including hydrologic flows, channel diversions and dam operations. Actual reservoir pool elevations and historical dam operation policies were used whenever available to drive the simulation, including historical dam construction dates and filling periods. Calibration parameters include travel times using time-lag routing and storage routing, flow and time-dependent channel gains and losses, channel evaporation and evaporation from the swamps. Calibration adjustments were performed over the period of 1951–1970, followed by validation using 1971–1990. Table 2 shows the Nash-Sutcliffe efficiency, percent bias and ratio of RMSE to standard deviation of the observations (RSR) at each gage location. All metrics were considered *very good* or *good* according to published criteria (Moriasi et al., 2007). The appendix (in the online supplemental data) provides additional calibration results.

Table 1. Prioritized operation parameters of existing reservoirs.

	Rosaries[a]			Sennar[a]			Jebel Aulia[a]		Khashm El Girba[a]			Merowe			HAD[a]
Priority	1	2	3	1	2	3	1	2	1	2	3	1	2	3	1
	Min Outflow (MCM)	Down-stream Demands (MCM)	Target Elev. (m)	Min Outflow (MCM)	Direct Div. (MCM)	Target Elev. (m)	Direct Div. (MCM)	Target Elev. (m)	Min Outflow (MCM)	Direct Div. (MCM)	Target Elev. (m)	Min Outflow (MCM)	Target Elev. (m)	Target Power (MW)	Target Release (MCM)
Jan	1240	b	–	372	856	421.7	56	377.4	62	113	474	1875	–	470	3510
Feb	1240	b	–	372	794	421.7	60	377.4	62	96	474	1875	–	536	3920
Mar	1240	b	–	372	416	421.7	75	376.9	62	74	474	1875	–	565	4380
Apr	1240	b	–	372	69	421.7	81	375.4	62	44	474	1875	–	639	4120
May	1240	b	–	372	138	417.0	88	373.9	62	52	474	1875	–	699	5080
Jun	1240		470	372	659	417.0	92	372.5	62	106	464	1875	290	861	6320
Jul	1240		469	372	937	417.0	185	376.5	62	122	464	1875	290	860	6760
Aug	1240		469	372	474	417.0	193	376.5	62	138	464	1875	290	740	5900
Sep	1240		487	372	938	418.7	352	377.4	62	134	474	1875	298	861	4150
Oct	1240		490	372	1040	421.7	418	377.4	62	148	474	1875	300	860	3890
Nov	1240	b	–	372	926	421.7	351	377.4	62	121	474	1875	300	625	3840
Dec	1240	b	–	372	922	421.7	99	377.4	62	121	474	1875	300	511	3630

Monthly power generation is assumed to be a by-product of other operations

[b]Release = [Rosaries storage / (Rosaries + Sennar storage)] * (Gezira + DS Sennar demands) + Rosaries to Sennar demands - Rosaries to Sennar inflows

[c]Not shown: Tekeze Dam operated for 112 MW constant hydropower, Upper Atbara and Setit Dam complex operated for 43 MW constant hydropower

Table 2. Calibration and validation results.

Location	Calibration period (1951–1970)			Validation period (1971–1990)		
	NSE	PBIAS	RSR	NSE	PBIAS	RSR
Blue Nile at Kessie	0.99	−0.73	0.10	0.99	−2.87	0.07
Blue Nile at El Diem	1.00	−0.84	0.05	1.00	−2.9	0.06
Blue Nile at Khartoum Soba	0.98	−5.31	0.16	0.91	−11.62	0.30
Baro at Gambella	0.83	−4.5	0.42	0.93	−1.78	0.26
Sobat at Hillel Doleib	0.85	−1.69	0.39	0.81	−7.03	0.44
Atbara Kilo3	0.89	−1.9	0.33	0.79	−10.58	0.46
White Nile at Malakal	0.89	1.76	0.34	0.85	0.79	0.39
White Nile at Melut	0.89	2.17	0.33	–	–	–
White Nile at Mogren	0.67	1.06	0.57	0.72	1.18	0.53
Nile at Tamaniat	0.97	−2.53	0.17	0.93	−6.59	0.26
Nile at Dongola	–	–	–	0.94	−5.76	0.24

Note. NSE = Nash-Sutcliffe efficiency; PBIAS = percent bias; RSR = RMSE–observations standard deviation ratio; – = insufficient data at the gage location.

Reservoir filling scenarios

General approach

Previous studies have recognized that effects on downstream users depend on the hydrology during the filling period, the starting conditions of current reservoirs and the filling policy implemented (Bates et al., 2013; IPoE, 2013; King & Block, 2014; Zhang et al., 2015). The goals of this study were to identify and evaluate potential filling and management options, and to test the major dimensions of water distribution to, and energy production from, the three countries during the filling period. Many filling strategies were envisaged and tested throughout this study, and the current article reflects only a subset of these. Two general paradigms of GERD management during filling emerged: reach an agreement for the GERD to release a minimum flow or volume over time; and adopt a specified or capped filling rate over time. Only the minimum-flow paradigm allows the GERD to fill faster during wet years and slower during dry years while meeting a minimum water requirement for Sudan and Egypt (MIT, 2014), so this paradigm is the focus of the results reported herein.

Common assumptions

Certain characteristics of the GERD filling were assumed for all scenarios, based on the stated criteria of the chief dam construction engineer (S. Bekele, personal communication, 12 June 2015) and known physical characteristics of the GERD (IPoE, 2013; MIT, 2014). The reservoir is assumed to fill during the initial year (2016) to 560 m (3.58 BCM) to test the first two installed turbines and remain at that elevation until the start of the second-year flood period (2017). Additional turbines are assumed to come online every two to three months. Downstream releases may be passed through the increasing number of installed turbines, through bottom outlets, or over the incrementally raised open spillway (Figure 3). Starting in 2017, monthly release patterns from the GERD during the filling period are assumed to evenly distribute an agreed annual release volume throughout the year to the extent possible (Ethiopian NPoE, 2013), readjusting continuously if shortfalls are encountered. Once the minimum operation level of 590 m (14.7 BCM) is reached, maintaining this level is assumed to take priority over downstream releases. The filling is considered complete when the reservoir level reaches
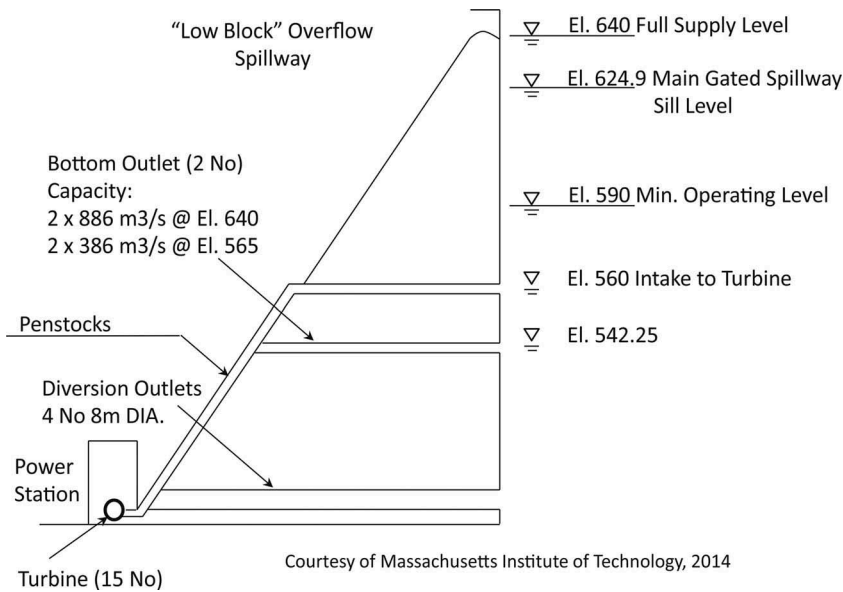
Figure 3. Cross-section of the Grand Ethiopian Renaissance Dam with assumed hydraulic capacities. Source: MIT (2014).

640 m (74.0 BCM) (Mulat & Moges, 2014), at which time a policy of regular energy generation of 1308 GWh per month begins.[1] All of these assumptions are based on best available knowledge and are subject to refinement.

The HAD is assumed to be operated primarily to meet downstream demands that total 55.5 BCM per year. The minimum elevation for power generation and downstream releases is 147 m (31.9 BCM), and the elevation range from 175 to 182 m (121 to 167 BCM) is reserved for emergency storage or flood protection operations. Pool elevations above 178 m are assumed to begin spilling into the Toshka canal (van der Krogt & Ogink, 2013). A drought management policy reduces deliveries to downstream water users by 5% as the storage volume in Lake Nasser falls below 60 BCM (159.4 m), 10% below 55 BCM (157.6 m), and 15% below 50 BCM (155.7 m) (Egypt MWRI, 2005; K. Hamed, personal communication, 2012).

Scenarios analyzed

The model was used to study the effects of modifying five factors within the system. Some are simple numerical changes that represent the sensitivity of a particular parameter, while others represent conceptual changes to operation policies that respond to the existence of the GERD. The five factors analyzed in this article are:

Total agreed annual release volume from the GERD during the filling period. Six agreed annual release values, 25, 30, 35, 40, 45 and 50 BCM/y, were analyzed – a range from below the 1984 drought flow (30.9 BCM) to above the average annual flow (49.4 BCM). A rapid-fill scenario (0 BCM) was also analyzed for comparative purposes. The GERD

will attempt to release this volume every year until the filling is complete, using the assumptions provided above.

Starting conditions for the HAD. A range of four starting pool elevations (165, 170, 175 and 180 m) was used to demonstrate the possible effects in Egypt resulting from initial conditions.

Sudan reservoir operations. Two potential scenarios were simulated: all reservoirs use current operation rules; and reservoirs are operated at the maximum elevation feasible, with releases only to meet hydropower demands (Merowe), downstream demands (Rosaries and Sennar) and flood control operations, thus forgoing seasonal flushing for sediment.

HAD drought management policy. Two potential HAD operation scenarios were simulated: no drought management policy; and the drought management policy that reduces downstream deliveries based on low storage thresholds, as described above.

GERD-HAD safeguard policy. A policy was envisaged that uses the storage in the GERD to ensure that the minimum power pool elevation of the HAD (147 m) is protected. This alternative evaluates whether the pool elevation of the HAD is expected to fall below 150 m (providing a 3 m buffer), and if so, an additional release is made from the GERD to try to maintain this elevation. This additional release is made after any decision to implement the HAD drought management policy is made, and thus reduced HAD releases are maintained. This policy terminates when the GERD reaches 640 m. Two potential scenarios were simulated: no GERD support of the HAD; and the GERD explicitly supporting the HAD with the above criteria. Additional thresholds and release volumes can be explored.

The five dimensions described above were used to generate 224 combinations of policies and initial conditions, each being subject to 103 hydrologic traces, thus requiring around 23,000 simulations.

Results

Time to fill the reservoir

A key metric across the potential scenarios is how much time would be required to fill the GERD. Figure 4 demonstrates the increase in average time to fill and the variance in that time given hydrologic variability with an increasing agreed annual release. Including the first year of fill to 560 m to test the turbines, the earliest possible time to fill the reservoir to the full supply level of 640 m would be during the flood of the third year (2018). In situations where the agreed annual release exceeds the average annual flow rate of 49.4 BCM, the reservoir on average cannot fill completely.

Effects on downstream consumptive uses

A major concern of downstream countries is whether the GERD will negatively affect the reliability of their water supply. Table 3 demonstrates the risk of shortages for Sudan users with and without the GERD, and before and after any reoperation of the Sudanese reservoirs in response to the GERD. The current management practices of the Blue Nile reservoirs in Sudan are designed to operate the reservoirs at a minimum
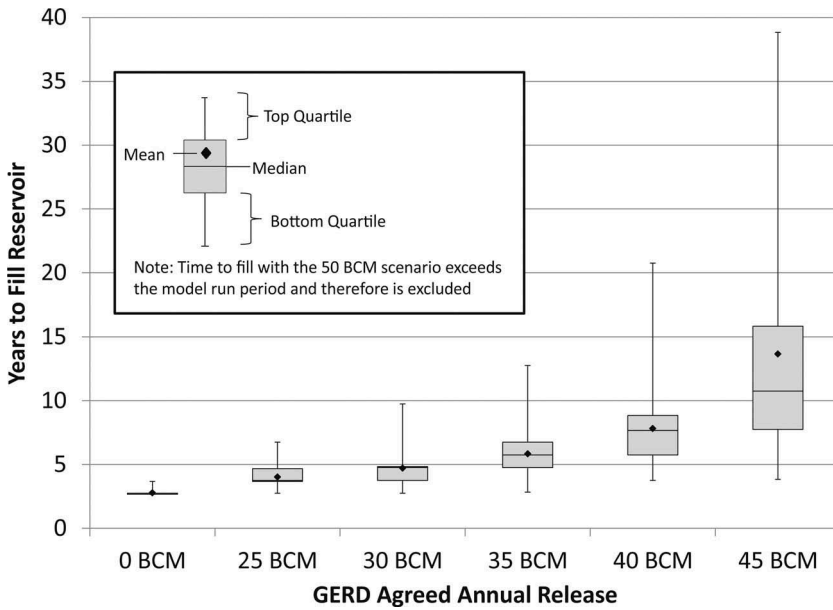
Figure 4. Years required to fill the Grand Ethiopian Renaissance Dam under various agreed annual releases.

Table 3. Shortages for Sudan water users (2016–2025).

|		Maximum probability of shortage		Average annual shortage (BCM)	
		Before dam reoperations	After dam reoperations	Before dam reoperations	After dam reoperations
GERD agreed annual release	50 BCM	100%	0%	0.3	0.0
	45 BCM	100%	0%	0.6	0.0
	40 BCM	100%	0%	0.6	0.0
	35 BCM	100%	0%	0.5	0.0
	30 BCM	100%	0%	0.5	0.0
	25 BCM	100%	0%	0.5	0.0
	0 BCM	100%	100%	1.4	0.9
	No GERD	4%		0.008	

Note. GERD = Grand Ethiopian Renaissance Dam.

elevation to pass sediment until late September, and then capture the end of the flood flow to retain sufficient storage to meet the needs of the Gezira-Managil diversion. The results show that this current operation plan is not compatible with the assumed constant operation of the GERD during filling. However, by starting the Sudanese reservoirs at the maximum capacity when the filling of the GERD begins and reoperating them to make releases only to meet downstream demands and allow necessary spills during flooding, the risk of shortages to Sudanese irrigated agriculture and municipal uses is essentially eliminated. This reoperation may be feasible due to sediment capture of the GERD, but warrants further investigation.

Figure 5 demonstrates the average volume of shortages for Egyptian water users relative to the 55.5 BCM delivery assumption if no HAD drought management policy is used, no GERD-HAD safeguard policy is in place, and Sudanese reservoirs have been
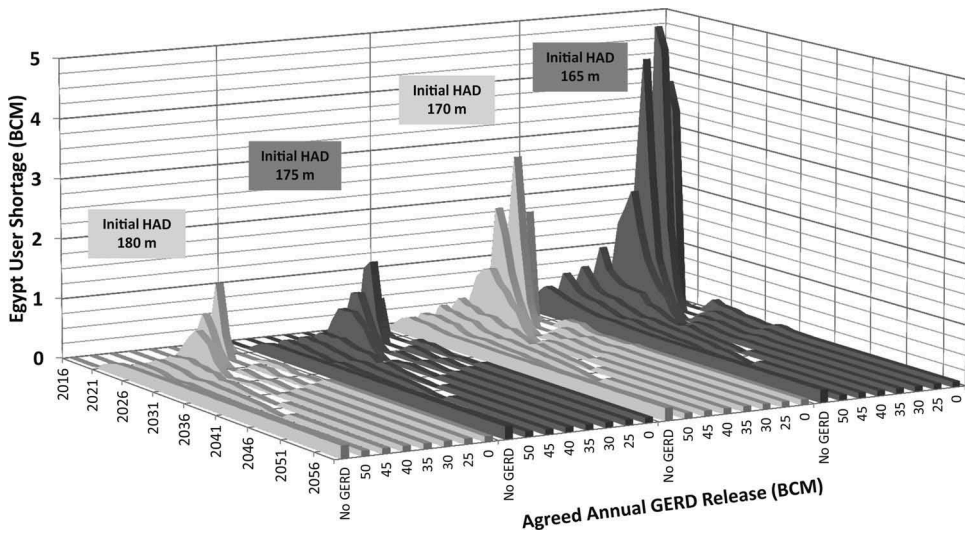
Figure 5. Average annual shortages for Egyptian water users without the HAD drought management policy or GERD-HAD safeguard policy.
Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam.

reoperated as described above. Although such a lack of adaptation to the construction of the GERD is unlikely, it shows the effects of the initial elevations of the HAD and agreed releases from the GERD. While simplifying the probabilistic distribution of shortages, it demonstrates that agreed annual releases of 35 BCM and greater reduce the average shortage volume, while releases of 30 BCM or less may be insufficient to keep up with the 55.5 BCM annual Egyptian demand. It can also be noted in Figure 5 that as the effects of filling subside, the long-term risk of shortages for Egypt decreases relative to the baseline condition due to the benefit of flow regulation that the GERD provides. However, this warrants further analysis of future water resource developments and potential operations after filling is complete.

By taking 175 m as the approximate starting pool elevation of the HAD at the start of 2016 (I. Selah, personal communication, 2016), more specificity in the results can be explored. Figure 6 demonstrates the probability of exceedance of shortages for Egypt during the initial 10 years after filling commences and across the various agreed annual releases for all four combinations of inclusion and exclusion of the HAD drought management policy and the GERD-HAD safeguard policy. While these cumulative plots demonstrate the potential range of shortages across policies and their relative probabilistic distributions over the time period, they do not reflect specific annual risks. Figure 6(a) shows that significant shortages are possible under dry conditions with neither the HAD drought management policy nor the GERD-HAD safeguard policy in place. Figure 6(b) demonstrates the effect of implementing the HAD drought management policy, which reduces the risk of severe shortages while increasing the likelihood of proactive reductions for water users; but it also demonstrates that the risk of shortages beyond these planned reductions is not eliminated for agreed annual releases of 30 BCM and less. Figure 6(c) shows that the GERD-HAD safeguard policy by itself does mitigate the vast majority of the risk without the need for proactive reduced
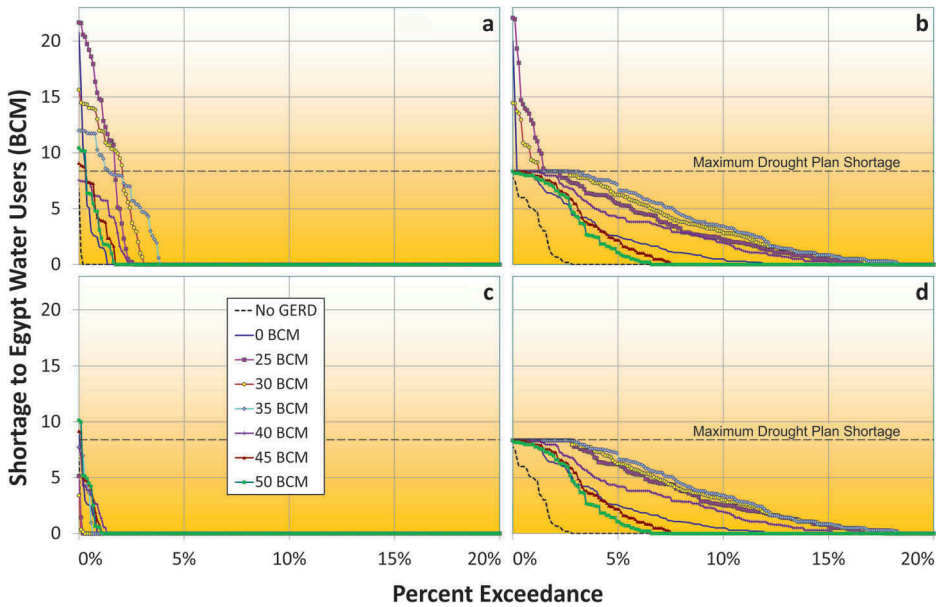
Figure 6. Cumulative probability of exceedance of annual shortages to Egypt across 2016–2025 with 175 m initial HAD pool elevation: (a) no HAD drought policy, no GERD-HAD safeguard policy; (b) HAD drought policy, no GERD-HAD safeguard policy; (c) GERD-HAD safeguard policy, no HAD drought policy; (d) HAD drought policy and GERD-HAD safeguard policy.
Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam.

deliveries; however, the possibility of high-magnitude shortages remains under extreme conditions due to the minimum operation level of 590 m for the GERD and the assumed immediate termination of the policy after filling. In Figure 6(d), the combination of both the HAD drought management policy and the GERD-HAD safeguard policy is shown to completely eliminate the risk of unplanned shortages for Egyptian water users. Each of these plots demonstrates the paradox that higher agreed annual releases provide guaranteed delivery downstream during filling, but also prolong the filling process and therefore extend the risk for downstream users.

Table 4 highlights the differences between the policies in more critical terms by calculating the maximum probability of the HAD reaching 147 m across all points in time throughout the 43-year model run period. Below this elevation, power cannot be produced and requested downstream releases cannot be made; therefore, the model reduces downstream releases to maintain this elevation. Table 4(a) shows this probability if neither the HAD drought management policy nor the GERD-HAD safeguard policy is used. Table 4(b) shows the degree to which the assumed HAD drought management policy alone cannot protect the minimum pool elevation, and Table 4(c) shows the extent to which the GERD-HAD safeguard policy alone leaves a risk due to limitations of the minimum operating level of the GERD and immediate termination of the policy. When applying either of these policies independently, it can be seen that much of the risk of reaching this critical elevation is reduced, but some remains. Finally, Table 4(d) shows that the combination of the HAD drought management policy and the GERD-HAD safeguard policy provides almost complete protection for the HAD.

Table 4. Maximum probability of High Aswan Dam reaching minimum power-production elevation (147 m) under four management scenarios across the run period (2016–2059).

		A. No HAD drought mgmt. policy, no GERD-HAD safeguard policy				B. HAD drought mgmt. policy, no GERD-HAD safeguard policy			
		Initial HAD elevation				Initial HAD elevation			
		180 m	175 m	170 m	165 m	180 m	175 m	170 m	165 m
No GERD		0%	0%	0%	0%	0%	0%	0%	0%
GERD	50 BCM	3%	4%	6%	10%	0%	0%	0%	2%
agreed	45 BCM	3%	4%	6%	11%	0%	0%	0%	3%
annual	40 BCM	5%	6%	7%	13%	0%	0%	0%	5%
release	35 BCM	7%	9%	15%	31%	1%	1%	3%	6%
	30 BCM	7%	9%	21%	45%	4%	5%	6%	11%
	25 BCM	8%	9%	27%	47%	6%	7%	9%	18%
	0 BCM	2%	7%	17%	37%	1%	3%	10%	20%
		C. GERD-HAD safeguard policy, no HAD drought mgmt. policy				D. HAD drought mgmt. policy and GERD-HAD safeguard policy			
		Initial HAD elevation				Initial HAD elevation			
		180 m	175 m	170 m	165 m	180 m	175 m	170 m	165 m
GERD	50 BCM	2%	4%	5%	8%	0%	0%	0%	1%
agreed	45 BCM	2%	3%	4%	8%	0%	0%	0%	1%
annual	40 BCM	2%	3%	3%	7%	0%	0%	0%	2%
release	35 BCM	2%	2%	3%	7%	0%	0%	0%	1%
	30 BCM	2%	2%	3%	5%	0%	0%	0%	2%
	25 BCM	2%	3%	4%	7%	0%	0%	1%	1%
	0 BCM	2%	3%	5%	21%	0%	0%	2%	2%

Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam.

Effects on hydropower generation

Table 5 reports the average annual change in Ethiopian, Sudanese and Egyptian hydropower generation with the addition of the GERD averaged across two time frames: the initial 10 years starting from the commencement of filling (short-term); and the following 20 years (medium-term). The results for Sudan assume that no reoperation of Sudanese reservoir management takes place, and the results for Egypt assume that Sudan reoperations have taken place, but no HAD drought management policy or GERD-HAD safeguard policy has been implemented. Although this not a likely scenario, this arrangement illustrates the result of inaction of each country to adapt to the GERD. Table 6 presents similar results, but assuming that adaptation has taken place by reoperation of the Sudanese reservoirs, and implementation of both the HAD drought management policy and the GERD-HAD safeguard policy. The differences between Table 5 and Table 6 demonstrate the largely positive effects of these operational changes, averaged over the short- and medium-term periods.

These tables provide direct comparisons of energy gains and losses between the countries and allow contrasts with the risk of shortages for Sudan (Table 3) and for Egypt (Figure 6(a,d)). For example, an agreed annual release of 35 BCM would add an average of 11,441 GWh of energy each year for Ethiopia in the short term, and assuming the initial elevation of the HAD of 175 m and no adaptation policies (Table 5), would reduce production by an average of 1493 GWh each year for Egypt and incur a 3% cumulative risk of shortages of at least 5 BCM over the short-term period (Figure 6(a)).

Table 5. Change of average annual energy generation (GWh/y) due to the GERD, without downstream adaptations.

		Ethiopia		Sudan (no reops)		Egypt (no drought management, no GERD-HAD safeguard)							
						Short-term effect				Medium-term effect			
						Initial HAD pool elevation				Initial HAD pool elevation			
		Short-term effect	Medium-term effect	Short-term effect	Medium-term effect	180 m	175 m	170 m	165 m	180 m	175 m	170 m	165 m
GERD agreed annual release	50 BCM	10,339	13,481	561	1029	−872	−953	−1049	−1094	−386	−417	−482	−536
	45 BCM	10,660	14,011	376	1076	−1090	−1180	−1289	−1330	−363	−400	−471	−531
	40 BCM	11,106	14,037	272	1136	−1314	−1408	−1508	−1540	−290	−324	−389	−434
	35 BCM	11,441	13,815	253	1147	−1405	−1493	−1582	−1599	−200	−228	−282	−310
	30 BCM	11,675	13,547	282	1144	−1393	−1480	−1559	−1553	−169	−197	−245	−262
	25 BCM	11,784	13,460	296	1140	−1374	−1455	−1528	−1509	−164	−191	−237	−255
	0 BCM	11,890	13,306	230	1134	−1135	−1224	−1305	−1299	−140	−164	−210	−235

Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam. Short-term = average of 2016–2025 (10 years); medium-term = average of 2026–2045 (11–30 years)

Table 6. Change of average annual energy generation (GWh/y) due to the GERD, with downstream adaptations.

		Ethiopia		Sudan (with reops)		Egypt (with drought management and GERD-HAD safeguard)							
						Short-term effect				Medium-term effect			
						Initial HAD pool elevation				Initial HAD pool elevation			
		Short-term effect	Medium-term effect	Short-term effect	Medium-term effect	180 m	175 m	170 m	165 m	180 m	175 m	170 m	165 m
GERD agreed annual release	50 BCM	10,339	13,481	1498	2262	−869	−943	−1024	−1030	−342	−369	−425	−456
	45 BCM	10,660	14,011	1360	2234	−1086	−1167	−1259	−1259	−309	−341	−399	−425
	40 BCM	11,106	14,037	1216	2244	−1309	−1393	−1469	−1443	−211	−233	−267	−275
	35 BCM	11,441	13,824	1158	2246	−1384	−1459	−1507	−1460	−139	−158	−188	−194
	30 BCM	11,662	13,556	1081	2227	−1370	−1440	−1482	−1430	−121	−138	−160	−169
	25 BCM	11,780	13,477	996	2223	−1356	−1426	−1456	−1403	−118	−131	−155	−162
	0 BCM	11,891	13,306	952	2206	−1124	−1198	−1233	−1181	−98	−116	−137	−141

Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam. Short-term = average of 2016–2025 (10 years); medium-term = average of 2026–2045 (11–30 years).

Several general results emerge from examining these two tables. The average annual energy generation in Ethiopia (dominated by the GERD) increases with decreased agreed annual release in the short term, which is largely based on completing the filling early and transitioning to normal operations. Sudanese energy generation is improved by reoperating their reservoirs. In contrast, the combination of the HAD drought management policy and GERD-HAD safeguard policy results in competing factors for increases and decreases in energy generation for Egypt. These include reduced HAD turbine flows, additional water made available from the GERD, increased pool elevation, and lower likelihood of reaching the minimum power generation elevation.

Various nonlinear behaviours can be observed in Table 5 and Table 6 that are largely based on the timing in which filling is achieved relative to the time periods used for averaging. The maximum energy generation in Ethiopia occurs at the point of transition to normal operations when the GERD is at 640 m; therefore, this peak occurs in the short term under low agreed annual releases and in the medium term for higher releases. Similar behaviour in Sudanese and Egyptian power generation can be seen as well. One notable result is the nonlinearity from the 50 BCM agreed annual release scenario, which is due to this release exceeding the average annual flow of 49.4 BCM, resulting in the GERD not

Table 7. Change in reliability of a 1308 GWh/month firm energy generation of the GERD due to implementation of the GERD-HAD safeguard policy.

		Short term: 2016–2025					Medium term: 2026–2045				
		No safeguard	Initial HAD elevation				No safeguard	Initial HAD elevation			
			180 m	175 m	170 m	165 m		180 m	175 m	170 m	165 m
GERD	50 BCM	10.1%	0.0%	0.0%	0.0%	0.0%	34.1%	0.0%	0.0%	0.0%	0.0%
agreed	45 BCM	12.9%	0.0%	0.0%	0.0%	0.1%	65.6%	0.0%	0.0%	0.0%	0.0%
annual	40 BCM	28.4%	0.0%	0.0%	0.0%	0.2%	79.5%	0.0%	0.0%	0.0%	0.0%
release	35 BCM	42.6%	0.0%	0.0%	−0.1%	0.1%	80.0%	−0.1%	−0.1%	−0.1%	−0.1%
	30 BCM	52.6%	0.0%	0.0%	−0.5%	−0.7%	78.2%	0.1%	0.1%	0.2%	0.2%
	25 BCM	59.0%	−0.2%	−0.4%	−0.6%	−1.2%	77.6%	0.1%	0.1%	0.2%	0.3%
	0 BCM	69.6%	0.0%	−0.1%	−0.3%	−0.8%	76.5%	0.0%	0.0%	0.0%	0.0%

Note. GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam.

being able to reach full capacity on average and consequentially less medium-term energy generation for Ethiopia but slightly greater generation for Egypt and Sudan.

While the change in energy generation in Ethiopia between Table 5 and Table 6 is quite small, indicating that minimal concessions are required, Table 7 provides another perspective to demonstrate the forgone energy benefit to Ethiopia to provide assurance to Egypt through the GERD-HAD safeguard policy. The exceedance probability of generating the target energy of 1308 GWh/month is shown as a function of the agreed annual delivery and starting elevation of the HAD. This table again demonstrates that the ability to meet this power generation target is essentially unchanged when protecting the HAD power pool elevation, given that any additional release from the GERD can be passed through the turbines to generate electricity. Assumptions were made regarding the ability of the GERD to generate energy throughout the filling period while making the necessary releases and the uniform energy demand pattern after the filling is complete. However, the demand for energy will depend on factors such as the local market demand, capacity of transmission lines and timely completion and/or expansion of the regional interconnection projects (Block & Strzepek, 2010; MIT, 2014). This highlights the opportunity to match the agreed annual release to these energy demands and the need for flexible energy demands if additional releases are required.

Discussion

The results indicate that the GERD will indeed provide a substantial amount of hydropower once the turbines are installed and the reservoir begins to fill. The study demonstrates that under the assumed hydrologic conditions and non-increasing demands during the filling period, the risks to existing downstream consumptive uses and hydropower generation can be managed with the combination of an agreed annual release from the GERD, proactive reoperation of the Sudanese reservoirs, implementation of a drought management policy for the HAD, and a safeguard release from the GERD if the HAD pool elevation falls below a critical level. Assured protection of Egypt's needs across all hydrologic conditions is only feasible with cooperative management of the upstream infrastructure in Ethiopia and Sudan.

Maintaining reliable water supplies to the large irrigated agricultural areas of Sudan will require modifications to the operations of the Rosaries and Sennar dams to

accommodate the intra-annual timing of releases from the GERD. With effective communication and coordination between Ethiopia and Sudan, the supplies to these large diversions can be assured throughout the filling period. This would require the Rosaries and Sennar reservoirs to reach their full capacity during the first year of GERD filling and make releases only to meet direct diversion requirements to the Gezira/ Managil canals, satisfy the minimum downstream flow requirements and pass any floodwater, while retaining the maximum possible volume of storage. However, without agreed annual GERD releases and proper reoperation of Sudanese reservoirs, losses to energy generation in Sudan of up to 28% may occur in the initial years. Once filling is complete, increases in energy generation of up to 21% can result, thanks to greater available flows during the non-flood period and reduction of spills during the flooding season. Implications of sediment management during this transitional period were not analyzed in this study, and we did not attempt to evaluate the impacts on flood-recession agriculture in Sudan, either along the river or around the reservoirs, due to revised dam operations. Developing detailed reoperation plans for the Sudanese reservoirs was beyond the scope of this current study, but is a topic for further analysis.

Risks to Egyptian water supplies and energy production depend on the initial storage in Lake Nasser when filling begins, the hydrologic conditions that occur during the filling period, the agreed annual release from the GERD and the operational policies of the HAD and all upstream reservoirs. This study quantifies this risk and demonstrates that it can be significantly reduced with proper planning. Egypt will lose both hydropower generation from the HAD and the ability to fully satisfy downstream demands simultaneously if the HAD pool elevation falls below the intake elevation of 147 m. In this study, management of this risk was analyzed across different agreed annual releases and by examining two policies: Egypt proactively reducing releases through the HAD drought management policy; and Ethiopia making additional releases when the elevation of the HAD is expected to fall below a pre-specified trigger elevation and Sudan allowing this water to pass downstream to Egypt. By relying only on an agreed annual release, the risk of reaching this minimum elevation ranges from 2% to 47% depending significantly on the release value and the initial storage of the HAD (Table 4a). The HAD drought management policy can reduce the risk of large shortages by making planned reductions; however, some risk of reaching this elevation remains, particularly if an agreed annual release of less than 35 BCM is used.

In contrast, the GERD-HAD safeguard policy endeavours to maintain the HAD at an elevation of 150 m regardless of an agreed annual release. In this case, the extra volume released is dynamically estimated to assure that the 150 m pool elevation is maintained based on the expected incoming hydrology and downstream Egyptian demands. However, due to losses, lags, extreme hydrologic conditions and infrastructure limitations, maintaining this level is not always certain. The results indicate that the GERD-HAD safeguard policy alone largely protects the HAD and avoids the need for Egypt to proactively reduce releases downstream of the HAD. However, the minimum power elevation of the GERD can be a limiting factor when providing this supplemental water, and Egypt's risk persists after the GERD reaches maximum elevation. This policy may need to be extended for a period of time after the GERD is filled, to assure that the risk to Egypt is alleviated.

To eliminate essentially all risks of the HAD reaching the minimum power elevation, a combination of the HAD drought management policy and the GERD-HAD safeguard policy was shown to be effective (Table 4d). While this policy suggests potential proactive

reductions to Egypt's deliveries from the HAD, it avoids the risk of unplanned shortages for Egyptian water users. Support from the GERD can be made to maintain the pool elevation of 150 m after assuming planned downstream releases subject to the HAD drought management policy. Any such collaboration between the GERD and the HAD requires an increased level of cooperation that assures that particular releases are made from each reservoir.

The large generation capacity of the GERD would allow Ethiopia to provide the HAD safeguard releases with only small reductions in hydropower production. The forgone benefit depends on Ethiopia's ability to utilize the energy generated when the water is needed downstream. If there is demand and transmission capacity that can absorb the energy generated when these excess flows are required, then protecting the HAD with flows from the GERD could be economically beneficial (Tawfik, 2016). In addition to the use of the HAD drought management policy, the three key additional components of this strategy – an agreed annual release, a trigger elevation for protecting the critical HAD power pool elevation, and the calculation of a safeguard release volume – are subjects for negotiation and further analysis.

Conclusions

Although much dialogue and analysis have taken place regarding the GERD and its potential downstream benefits and impacts, there remains a need for specific arrangements to manage the process of filling the GERD. This study has presented some possible arrangements of reservoir coordination to achieve this goal and demonstrated an analysis framework that quantifies the benefits and risks. Reservoir coordination is a continuum, ranging from unilateral management to dynamic operations that reflect current needs. Unilateral actions by Ethiopia may result in both positive and negative externalities, such as improved energy generation for Sudan or reduced energy generation for Egypt. An agreed annual release from the GERD demonstrates a greater degree of coordination that results in increased benefits and reduced downstream risks. Further along this continuum is a dynamic awareness of the water security situation between co-riparians. This study demonstrates this concept by analyzing safeguard releases from the GERD to support the HAD under critical circumstances, which minimizes severe risks.

Risks to water supply and hydropower generation have always existed on the Nile, and changes to the system may alter this risk profile, either positively or negatively and either temporarily or permanently. This study, along with others that consider the filling of the GERD, can provide important technical information for the negotiation process. A single correct solution is unlikely from any study, but the analysis allows negotiators to understand how significant the changes of risks might be, whether they are acceptable, how they might be managed and whether alternative approaches must be pursued. Ultimately, we believe that this study demonstrates that a middle ground does indeed exist.

Note

1. In the absence of future estimated energy demand patterns, 1308 GWh per month represents the projected 15,692 GWh/y energy generation, distributed evenly over the year (IPoE, 2013). While the reservoir will have a 6000 MW installed capacity and hence

the ability to provide peak power generation and avoid all spills, the assumption used will require power generation to exceed 2000 MW in less than 2% of all cases.

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