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Evaluating the hydropower potential of the Grand Ethiopian Renaissance Dam

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ABSTRACT

One of the largest hydropower projects in Africa is the Grand Ethiopian Renaissance Dam (GERD), which is currently under construction in the Upper Blue Nile (UBN) basin in Ethiopia. The GERD has been billed as a hydropower project that will significantly improve electricity supply in Ethiopia and neighboring countries with a total capacity of 5150 MW. This paper evaluates the hydrological potential of the UBN basin for meeting the declared hydropower production design from the GERD. Our investigation indicated that the hydrology of the UBN can sustain the inflow to the GERD that would produce 13 629 GWh per annum (capacity factor = 0.30). Investigations further revealed that the GERD operation in the current design configuration will likely result in eight (out of 14) idle turbines every year. Our study also demonstrated that current GERD capacity (5150 MW) is more reasonable than previous designs (e.g., 6000 and 6450 MW).

I. INTRODUCTION

Africa faces frequent shortage in electricity, and in some regions, it is a severe crisis (Karekezi and Kimani, 2002 and Wolde-Rufael, 2006). Apart from North Africa, e.g., Egypt and Algeria, where the electrification rate exceeds 95%, only 25.9% of the population in sub-Saharan Africa has access to electricity (Suberu *et al.*, 2013). Thus, hydropower, as a renewable source of energy, can be viewed as an important contributor to the future energy security of Africa. With only 3% of its water used for hydropower generation, Africa is currently an "under dammed" continent (compared to 52% in South Asia) with a high potential of hydropower exploitation (Mataen, 2012). The global boom toward the construction of hydropower dams is now spreading to Africa with more than 160 planned hydropower dams (Zarfl *et al.*, 2015). The Grand Ethiopian Renaissance Dam (GERD), which is currently under construction in Ethiopia, is one such megahydropower project with an installed turbine capacity of about 5150 MW (Basheer *et al.*, 2020 and Eldardiry and Hossain, 2020). This is more than two times that installed in the nearest major hydropower dam—the High Aswan Dam in Egypt commissioned 50 years ago.

The GERD is part of an ambitious energy development strategy by Ethiopia to benefit from hydropower generation potential as a renewable energy source (Block and Strzepek, 2012). However, Ethiopian plans in unlocking this hydropower energy potential face challenges including climate variability, socio-economic impacts, and geo-political situations of the region (Degefu *et al.*, 2015; Nasr and Neef, 2016; Van der Zwaan *et al.*, 2018; and Annys *et al.*, 2019). The most significant challenge to Ethiopian hydropower developments has been the persistent opposition of Egypt to upstream projects, given its historical hydro-hegemonic status in the basin (Blackmore and Whittington, 2008; Cascão, 2009; and Whittington *et al.*, 2014). Such resistance resulted in a lack of international financing options to Ethiopian hydropower projects. The GERD project has regional and continental dimensions as the largest hydropower dam in Africa and is an important component of future electrification of Africa (Kumagai, 2016). With about 83% of Ethiopia's population currently lacking access to electricity, the GERD aims to expand the rural electrification, reduce poverty, and stimulate economic growth in Ethiopia (Barnes *et al.*, 2016). In addition, Ethiopia is expected to be a major electricity exporter in the future by trading 15% of its yearly electricity generation in the Eastern African power pool (EAPP) (Sridharan *et al.*, 2019). Thus, the GERD, as a main component of Ethiopia hydropower development, will benefit EAPP countries including Rwanda, Djibouti, Tanzania, Kenya, Burundi, Uganda, Sudan, and Egypt. Furthermore, the GERD is of interest to countries beyond African and Nile nations. Regional stakeholders such as Saudi Arabia, Kuwait, and the United Arab Emirates can be major importers of agricultural production from Sudan with future regulation of Nile flow by GERD operations (Whittington *et al.*, 2014).

Construction of the GERD poses a challenge for downstream countries, especially Egypt. While Egypt has been historically afforded a position of hegemony in the Nile basin (Whittington, 2004 and Cascão 2009), the building of the transboundary GERD will gradually tip the balance of regional power in Ethiopia's favor (Cascão and Nicol, 2016 and Yihdego *et al.*, 2016). Recently, studies have focused on exploring the impacts of the GERD on downstream countries (King and Block, 2014; Mulat and Moges, 2014; Zhang *et al.*, 2015; Wheeler *et al.*, 2016; and Eldardiry and Hossain, 2020). These studies concluded an expected reduction in downstream streamflow during the filling phase of the GERD. However, studies on the impact of GERD operation and its ability to meet the designed hydropower production goals have not yet been reported in the literature. The operation of the GERD will regulate the flow in the Blue Nile and, therefore, mitigate the increase in the intra-annual variability of Nile flow due to climate change (Siam and Eltahir, 2017).

Recently, criticism has been on the potential over-sizing of the GERD's installed hydropower capacity. Beyene (2013) and Abtew and Dessu (2019) questioned GERD's ability to operate at the design capacity of 5250 MW, which was the initial design capacity before upgrading the turbines to a capacity of 6450 MW (EEPCo, 2019) and then recently changed to 5150 MW. This concern about the GERD's hydropower potential is legitimate when one compares the total storage volume (74 km^3) and installed turbine capacity (5150 MW) of the GERD with its similar counterparts in Africa (see Table I). For instance, the High Aswan Dam (the largest existing hydropower dam in Africa) features a total storage volume of 162 km^3 with an installed turbine capacity of only 2100 MW. In this study, we investigate the possible overdesign of the GERD's hydropower capacity from the hydrologic perspective of the Upper Blue Nile (UBN), where the GERD is located. *Our study builds upon a hydrological modeling of the UBN integrated with the reservoir optimization scheme to evaluate the hydropower potential of the GERD*. The remainder of this paper is organized as follows. First, we describe the study area and the specifications of the GERD in Sec. II. Data sources and methods are introduced in Sec. III. Results for the GERD operation and its hydropower production under various scenarios are discussed in Sec. IV, and finally, concluding remarks and future implications of this work are summarized in Sec. V.

II. UPPER BLUE NILE AND GRAND ETHIOPIAN RENAISSANCE DAM

The Grand Ethiopian Renaissance Dam (GERD) is located at the outlet of the Upper Blue Nile basin (UBN) in Ethiopia (Fig. 1). The UBN extends from Lake Tana in the Ethiopian highlands to the Sudanese border at Eldiem with a drainage area of 176 000 km^2 [more than half of the Blue Nile basin's (BNB) area]. The climate of UBN climatology varies from humid to semiarid. The annual precipitation increases from northeast to southwest and ranges from 1200 to 1600 mm (Conway, 2000). The mean annual temperature and potential evapotranspiration in UBN are estimated to be about 18.5 °C and 1100 mm, respectively (Kim *et al.*, 2007). The UBN provides more than 90% of the total flow in the Blue Nile basin at the Sudanese capital Khartoum, where the confluence of the Blue Nile and the White Nile is located. The steep topography in the Blue Nile gorge provides two particular features for perfect dam locations: (1) high heads for hydropower generation and (2) low surface-to-volume ratios (Whittington *et al.*, 2014). In 1964, the U.S. Bureau of Reclamation (USBR) conducted a comprehensive study to explore viable sites for potential development projects in the Blue Nile basin. The study proposed multiple locations of hydropower dams along the UBN. The current GERD location is the same site proposed by USBR for a smaller dam called the Border Dam near the Ethiopian–Sudanese border.

The construction of the GERD started in 2011 and is currently more than 70% completed [see, for example, Fig. 1(b) for a satellite image retrieved from Google Earth on November 2019]. The construction site of the main dam is at a ground level of 506 m AMSL (above mean sea level) and is designed to store water to a level of 640 m AMSL with the support of a saddle dam (to the west of the GERD). The GERD will have three spillways: (1) a main gated spillway located to the left of the main dam at a base elevation of 624.9 m AMSL and 84 m wide at the outflow gates; (2) an ungated spillway, or auxiliary spillway, located at the center of the main dam with a base level at 640 m [the full supply level (FSL) of the reservoir]; and (3) an emergency spillway located to the right of the curved saddle dam, with a base level at 642 m (Fig. 2).

With its current design of turbines (5150 MW), the GERD will become the largest hydropower dam in Africa in terms of generation capacity. Such a design capacity is expected to greatly improve electricity supply in Ethiopia and neighboring African countries that have rapidly growing populations [see Fig. 3(a) for comparison of eastern Nile countries population]. In addition, the GERD is expected to significantly improve the hydropower production in Ethiopia, which currently represents more than 95% of the country's total electricity generation capacity [compared to about 8% in Egypt; Fig. 3(b)].

III. DATA AND METHODS

A. Modeling UBN hydrology

In our study, we used a macroscale hydrological model developed by Eldardiry and Hossain (2019) over the Blue Nile basin (BNB) using

TABLE I. Comparison of the GERD with examples of major hydropower dams in Africa.

Dam	River	Country	Storage volume (km^3)	Average annual flow (km^3/yr)	Maximum head (m)	Installed capacity (MW)
GERD	Blue Nile	Ethiopia	74	49	133	5150
High Aswan Dam	Nile	Egypt	162	84	74	2100
Akosombo	Volta	Ghana	148	31	68.8	1038
Kariba	Zambezi	Zambia and Zimbabwe	180	60	92	1626
Merowe	Nile	Sudan	12.5	84	51	1250

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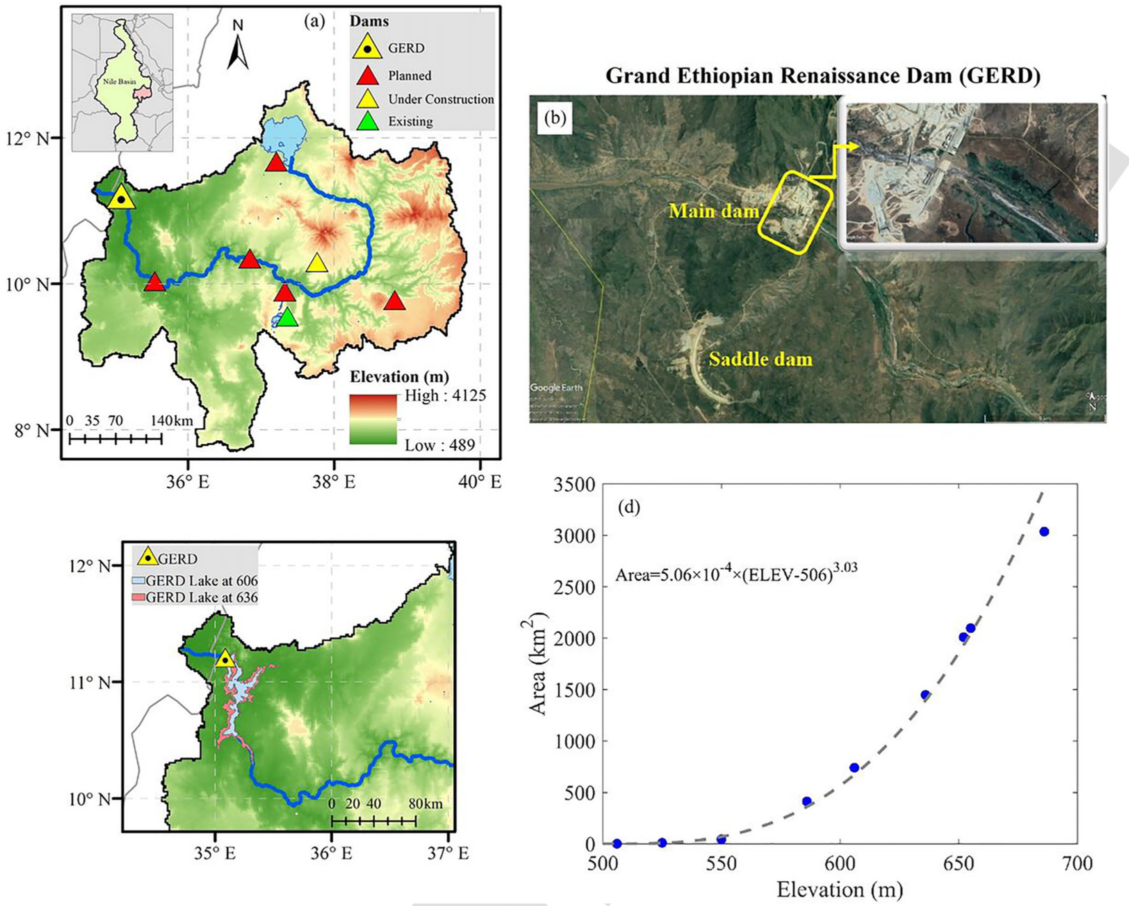

FIG. 1. Map of the Upper Blue Nile with the location of the existing, planned, and under construction dams (Lehner *et al.*, 2011 and Zarfl *et al.*, 2015). The location of the GERD is highlighted near the Ethiopian–Sudanese border. (b) Satellite image of the current construction stage for the GERD and the accompanied saddle dam (retrieved from Google Earth on 20 November 2019). (c) Delineation of the inundation extent of the GERD at elevations of 606 (light blue only) and 636 m (pink and light blue) above mean sea level (AMSL). (d) Area-elevation curve (AEC) derived for the reservoir lake of the Grand Ethiopian Renaissance Dam using satellite observations of land elevation from shuttle radar topography mission (SRTM).

the variable infiltration capacity (VIC). The VIC model was implemented at a spatial resolution of 0.1° (~10 km) for the BNB and driven by high spatial and temporal resolution of satellite observations, e.g., SRTM, CHIRPS, and MODIS. The satellite-based forcing was processed over the BNB at a daily scale and re-gridded to the 0.1° spatial scale to drive the VIC model land surface simulations. The runoff (from the VIC outputs) over each grid cell was then routed separately using the routing model scheme of Lohmann *et al.* (1998). The simulation runs were performed for 37 years spanning the period from 1981 to 2017. The reader is referred to Eldardiry and Hossain (2019) for more details on the VIC modeling framework over the BNB. The satellite-driven VIC model for the BNB is used in our study to characterize the hydrology of the UBN and the streamflow climatology upstream of the GERD location.

B. Area-elevation curve

An area-elevation curve (AEC) is required to calculate the lake area and, therefore, the water volume stored in the reservoir. We established the AEC for the GERD using a 30 m resolution digital elevation model (DEM) provided by the shuttle radar and topography mission (SRTM). The SRTM image was classified into 1 m elevation bands over the reservoir and surrounding area. The surface area of each band provides an estimate of the reservoir surface when water reaches that elevation. Deriving the area-elevation curve using satellite-based estimates has been widely employed in previous studies [see, for example, Wang *et al.* (2013) over the three-gorge reservoir]. Since the GERD is still an under construction dam, the reservoir had not been formed when SRTM overpassed in 2000. Thus, scenarios of different heights for the dam and the resulting reservoir levels are modeled in order to estimate the corresponding lake area. The exact locations of the GERD and its saddle dam were retrieved from recent satellite images and modeled as barriers on the SRTM DEM with various elevation scenarios [Fig. 1(b)]. Figure 1(c) shows two examples of the GERD lake formed at 606 and 636 m. The derived area elevation curve [Fig. 1(d)] is very close to what has been published by the Ethiopian Electric Power Corporation (EEPCo, 2019).

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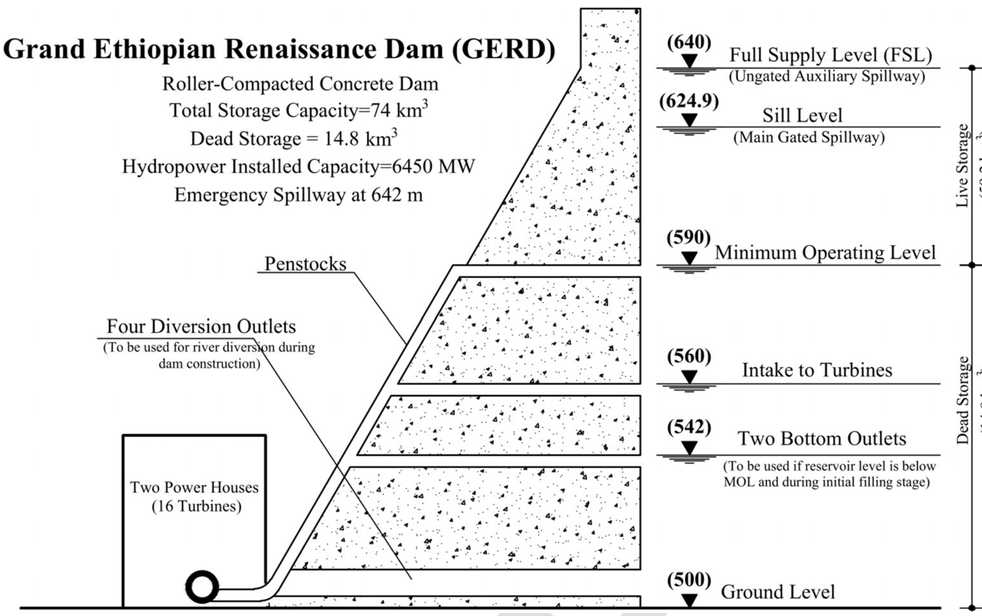

FIG. 2. Cross-section of the Grand Ethiopian Renaissance Dam with assumed hydraulic capacities. All elevations are above mean sea level [source: MIT (2014); Wheeler *et al.* (2016); and Abtew and Dessu (2019)].

In addition, Eldardiry and Hossain (2020) showed the reasonable skill of satellite-based AEC of the GERD when compared with those published in previous studies (Abtew and Dessu, 2019 and Basheer *et al.*, 2020 for the GERD).

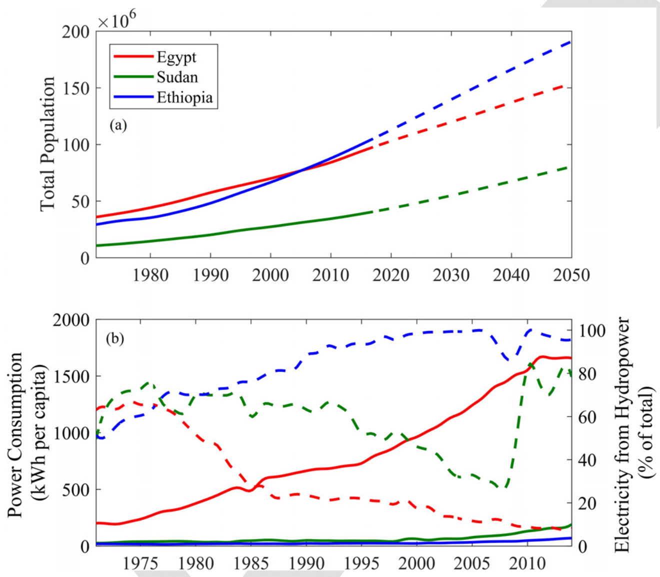

FIG. 3. (a) Annual population change in the eastern NRB countries (dashed lines indicates the projected population). (b) Solid and dashed lines indicate the power consumption per capita (left y-axis) and the percentage of hydropower generation from the total electricity production (right y-axis), respectively (data source: World Bank Database).

C. Reservoir operation

The GERD has been reviewed by an International Panel of Experts (IPoE, 2013) from Egypt, Sudan, and Ethiopia. One key recommendation acknowledged by this panel was the unavailability of complete design documents and test data to critically review the project design (Abtew and Dessu, 2019). Such data sharing is a common hurdle in transboundary basins and complicates technical feasibility or review studies for hydro projects through international cooperation. Thus, it is important to simulate how the GERD is likely to operate by deriving its reservoir rule curve. For deriving the rule curve, we adopted an optimization scheme that is based on the deterministic dynamic programing (DDP) approach. The approach is developed by Karamouz and Houck (1982) to determine a safe range of releases that would avert flooding downstream of the dam (very high releases) or drought conditions (low releases). The problem under consideration is then how to operate the GERD reservoir for T time periods (months or years) in order to minimize the total losses or damage that would incur in case the releases are beyond the safe range. A discrete, finite horizon dynamic program was established to solve the optimization problem. The optimal release was, therefore, decided based on a piecewise exponential form of the penalty function [P(R_t)] as follows:

$$P(R_t) = \begin{cases} A\left[\exp\left(\dfrac{R_t}{R_{max}}\right) - \exp(1)\right] & R_t \geq R_{max} \\ 0 & R_{min} \leq R_t \leq R_{max}, \\ B\left[\exp\left(-\dfrac{R_t}{R_{min}}\right) - \exp(-1)\right] & R_t \leq R_{min}, \end{cases} \quad (1)$$

where R_t is the dam release at a time step (t), R_{max} is the maximum dam release or the upper limit of the safe zone (assumed to be equal to 120% of the mean annual flow), R_{min} is the minimum dam release or

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the lower limit of the safe zone (assumed to be equal to 80% of the mean annual flow), and (A and B) are two constants that are defined based on how much damage will occur downstream the dam when the release is outside the safe zone. Due to the lack of information on the damage predictions downstream of the GERD, we adopted the same values used by Karamouz and Houck (1982) and Eldardiry and Hossain (2020) ($A = 3.88 \times 105$ and $B = 1.58 \times 106$) such that the penalty function would result in losses equal to 10^6 units when the release is zero or twice the mean annual flow. Note that changing the constants (A and B) will only result in different magnitude of the penalty cost without changing the optimal operation of the reservoir. This assumption is reasonable since it implies that the operation is penalized similarly when there is no release (drought condition) or there is a flooding condition (defined as cases when release is twice the mean inflow). The reservoir operation was then derived such that the total losses over a time horizon (T) are minimized. It is worth noting that the GERD is assumed to be operated primarily for hydropower production, given its location at the Ethiopian–Sudanese border. The DDP optimization scheme is employed using a set of discrete water levels (or storage volumes) to optimize the GERD release such that the hydropower generation is maximized. The stages of the DDP approach are time periods (monthly in our case), and the states are reservoir water levels (with 0.01 m increments). The reservoir storage fluctuates between the minimum operating level (MOL) and the full supply level (FSL). In the case of the GERD, Mulat and Moges (2014) used an MOL of 622 m, while other studies also stated that the minimum operating level can go down to 590 m (e.g., IPOE, 2013). We here showed the results of GERD operation only for MOL = 622 m, which would result in the increase in the potential head and, thus, maximize the hydropower production (or the GERD hydropower potential). The AEC for the GERD [Fig. 1(d)] was used to derive the reservoir storage corresponding to the water level state. A water balance equation was then applied to compute the GERD reservoir release (R_t) as follows (assuming negligible groundwater interactions):

$$R_t = Q_{in} - \frac{dS}{dt} + P - E, \quad (2)$$

where Q_{in} is the GERD inflow in km^3/month, R_t is the reservoir discharge downstream of the GERD in km^3/month, P is the precipitation over the GERD lake, E is the open water evaporation modeled by the VIC model in km^3/month, and dS/dt represents the change in the storage volume with time in km^3/month. The monthly inflow to the reservoir (Q_{in}) was obtained from routing of the VIC modeled runoff at Eldiem station (location of GERD; Eldardiry and Hossain, 2019). The optimal GERD release ($R_t|opt$) is then derived as the storage level corresponding to the minimum loss [$P(R_t)$].

The hydropower generation from the GERD was calculated based on the optimized release (and the corresponding storage level) derived from the DDP program using the following equation:

$$HP = R_{turbine} * \eta\gamma h. \quad (3)$$

Here, HP is the hydropower production (watt), η is the power plant efficiency, γ (N/m^3) is the specific weight of water, and h (m) is the effective head of water (m). $R_{turbine}$ (in m^3/s) is the turbine flow of the GERD. The turbine flow is set equal to the optimal GERD release ($R_t|opt$). If the power produced exceeds the GERD turbine capacity, then the turbine flow is calculated using the maximum HP (based on the installed capacity) and the excess flow is diverged through the dam spillway.

The assessment of GERD hydropower potential was based on running the reservoir operation model using the streamflow resulted from the modeling of hydrologic conditions in the UBN for 37 years (1981–2017). The variability in the streamflow plays a paramount role in studying the hydropower generation as it significantly impacts the operation of the dam at inter-annual (from year to year) and intra-annual (monthly or seasonal) scales. Considering such variability using a long record of historical streamflow helps identify the hydrologic controls on hydropower generation under diverse climatic conditions including dry and wet years.

IV. RESULTS

A. Characterization of UBN hydrology

The UBN is characterized by a wet rainy season (locally called kiremt season) from June through September, while the dry season starts from November through April (October and May are transition months between wet and dry seasons) (Conway, 2000). Figure 4 shows the average precipitation and evaporation in the rainy season of the UBN (June through September). These are key variables to understand the inputs of the GERD reservoir, e.g., inflow and lake evaporation. The average monthly precipitation in the rainy season is 236 mm (standard deviation = 11.4 mm) compared to only 24.5 mm (standard deviation = 7.8 mm) in the dry season months. Similar variations are also noticed for evaporation with higher rates in rainy season months (the maximum and minimum monthly evaporation is in August = 130 mm and March = 31 mm, respectively). As depicted in Figs. 4(a) and 4(b), lower elevation areas downstream of Lake Tana have higher precipitation and evaporation rates. Figure 4(c) shows the resultant monthly precipitation and evaporation over the GERD lake [delineated in Fig. 1(c)]. The months from April through September experience higher precipitation than evaporation with the maximum difference in June (92.6 mm). Conversely, the dry season months have higher evaporation rates with the maximum difference between precipitation and evaporation in November (−81.5 mm).

Figure 5 shows the comparison of the VIC modeling of streamflow with the observed discharge at Eldiem station for a 12-year period (1993–2005). The model generally showed close agreement between the simulated and observed monthly streamflow with an NSE and a correlation coefficient of 0.79 and 0.90, respectively. A NSE value AQ3 greater than 0.50 is considered satisfactory for simulating streamflow at a monthly time step (Moriasi *et al.*, 2007). On average, the annual simulated streamflow is in good agreement with the observed discharge with a slight overestimation of 1.25 km^3 (mostly in the wet season months) [Fig. 5(b)]. Figure 5(c) shows a climatological time series of annual simulated streamflow, or GERD inflow, during the 37-year simulation period (1981–2017). The streamflow in the UBN varies from one year to another because of the effect of timing and sequence of El Niño and La Niña in the UBN (Zaroug *et al.*, 2014). The annual streamflow reaching the GERD has an average of 48 km^3 and ranges from 65 km^3 in 1993 (wet year) and 30.6 km^3 in 2007 (dry year).

B. Deriving the GERD operating rule

We derived the GERD operating rule using the DDP optimization approach explained in Sec. III C with the objective of hydropower maximization. The results in this section are only shown for the

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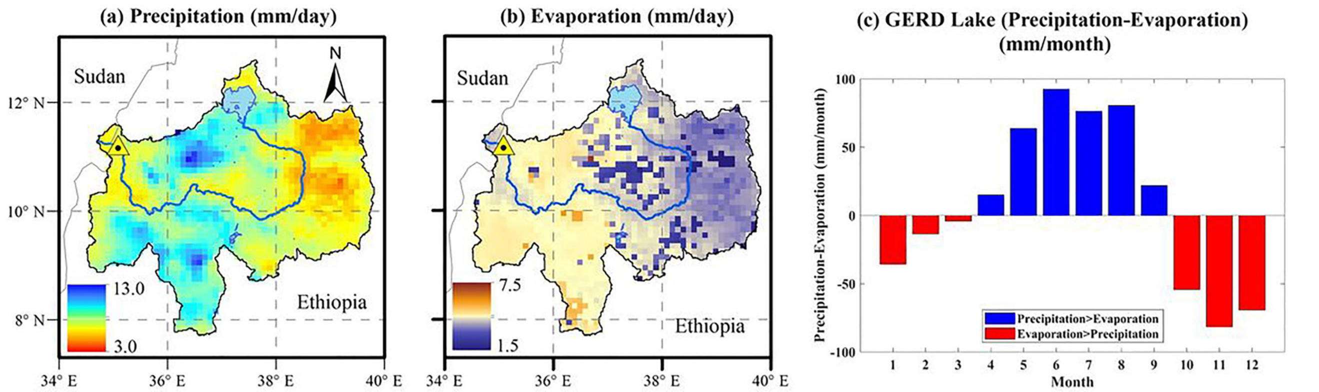

FIG. 4. Hydrologic characterization of the Upper Blue Nile (UBN). Average (a) precipitation and (b) evaporation during the rainy season (June through September) of the UBN. (c) Difference between monthly precipitation and evaporation over GERD lake [delineated in Fig. 1(c)].

baseline scenario of GERD operation, i.e., the installed capacity is 5150 MW and MOL = 622 m. Figure 6(a) shows the range of monthly storage water levels during the operation of the GERD. The dam is expected to operate at higher storage levels later in the rainy season (September and October), while lowering its storage early in the summer to prepare for the coming flood. For instance, the GERD has average storage levels of 636.96 m (ranges between 631 and 640 m) and 622.1 m (ranges between 622 and 623.1 m) in September and June, respectively. The GERD releases an average monthly discharge of 4 km^3/month with higher releases in September (peak discharge = 5.56 km^3/month). The inter-annual variability in the GERD releases varies significantly in September when the inflow reaches its peak [Fig. 6(b)]. The reason for that is the failure of the dam to store enough of the inflow in September (due to limiting its storage to a presumed level of 640 m), which, therefore, resulted in a wider range of releases.

C. GERD hydropower potential

Figure 7 shows the range of monthly hydropower production from the GERD under a baseline scenario that assumes the current design criteria of GERD operation, i.e., capacity = 5150 MW. On

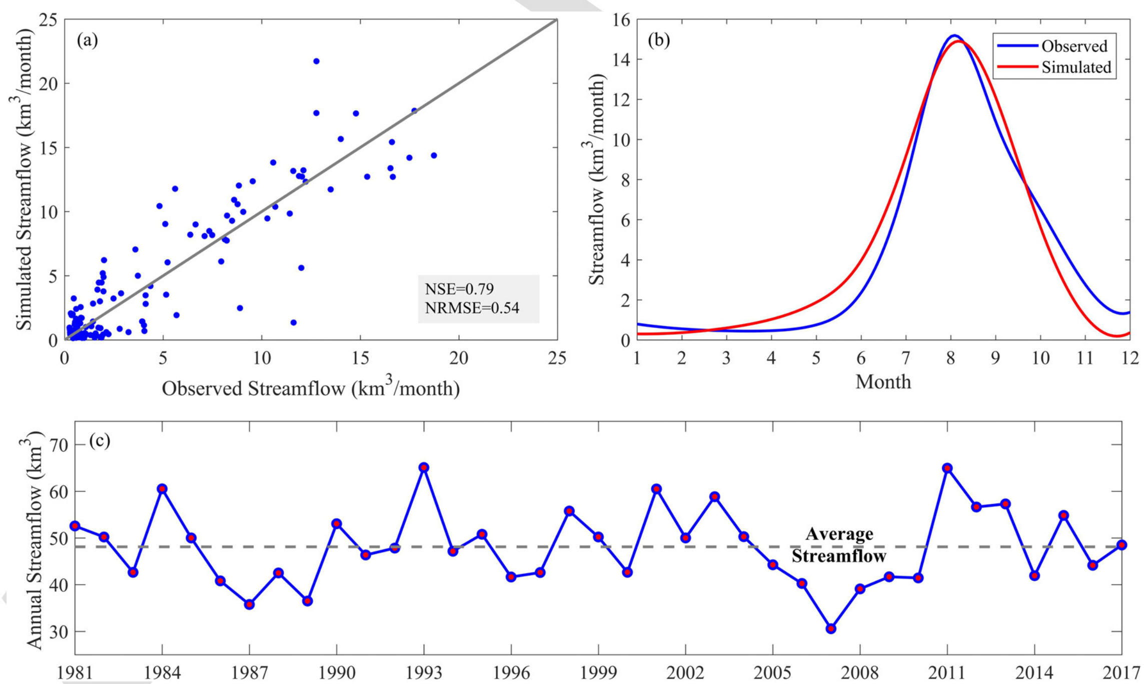

FIG. 5. (a) Scatter plot of observed and simulated streamflow at Eldiem station [location of the GERD and outlet of the Upper Blue Nile (UBN)]. (b) Monthly streamflow (observed vs simulated) averaged over the 12-year period (1993–2005). (c) Annual simulated streamflow (GERD inflow) for the 37-year simulation period (1981–2017) at Eldiem station.

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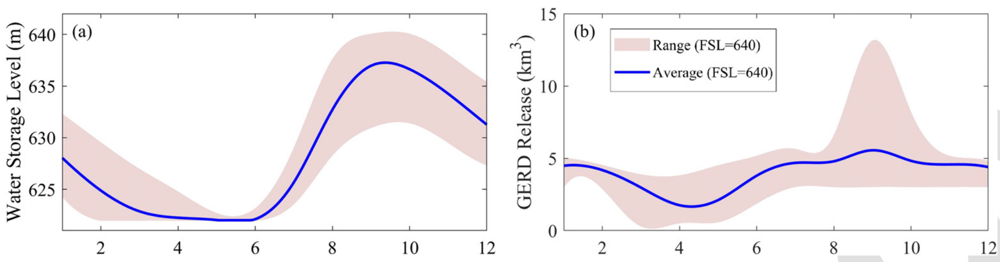

FIG. 6. GERD operation based on 37-year historical climatology of streamflow (1981–2017) and an installed capacity of 5150 MW (baseline scenario). (a) GERD storage level and (b) GERD release (summation of turbine and spillway release). The blue line indicates the average operation, while the shaded area represents the range of operation (minimum and maximum) due to streamflow variability.

average, the GERD can yield an annual hydropower production of 13 629 GWh with a peak production in September (1630 GWh). The monthly production changes significantly when considering streamflow variability with an average monthly production of 1136 GWh (standard deviation of 286 GWh). On average, the baseline scenario can exploit between 456 MW (9% of installed capacity) and 2264 MW (44% of installed capacity) in April and September, respectively. Exploiting the total installed capacity was observed only in 1993 and 2011 (two very wet years), when the annual streamflow was 65.1 and 64.9 km^3/year, respectively [Fig. 5(c)]. Hence, any plans to change the installed turbine capacity should consider the hydrology of the UBN if it can sustain enough streamflow to exploit the installed capacity. As expected, variations in the design levels of the GERD, e.g., MOL or FSL, will affect the hydropower production due to changes in the effective head [h in Eq. (3)]. For example, when assuming an MOL of 590 m (as suggested by IPOE, 2013), the GERD operation can produce an average annual hydropower of 10 045 GWh (Fig. S1 in the supplementary material).

Figure 7(c) depicts the number of idle turbines during monthly GERD operation. The number of idle turbines is calculated as the number of turbines, which are completely not used in each month. The median number of idle turbines ranges between 8 turbines (in the months following the flooding season; September through December) and 12 turbines (in April and May). The median exploited capacity (corresponding to 50% probability) is 1660 MW [Fig. 7(d)]. When considering climate variability with wet and dry years, the number of idle turbines can range between 4 (wet years) turbines and 10 (dry years) turbines in September and October. This analysis shows the importance of considering the number of turbines as a factor to evaluate the GERD hydropower efficiency.

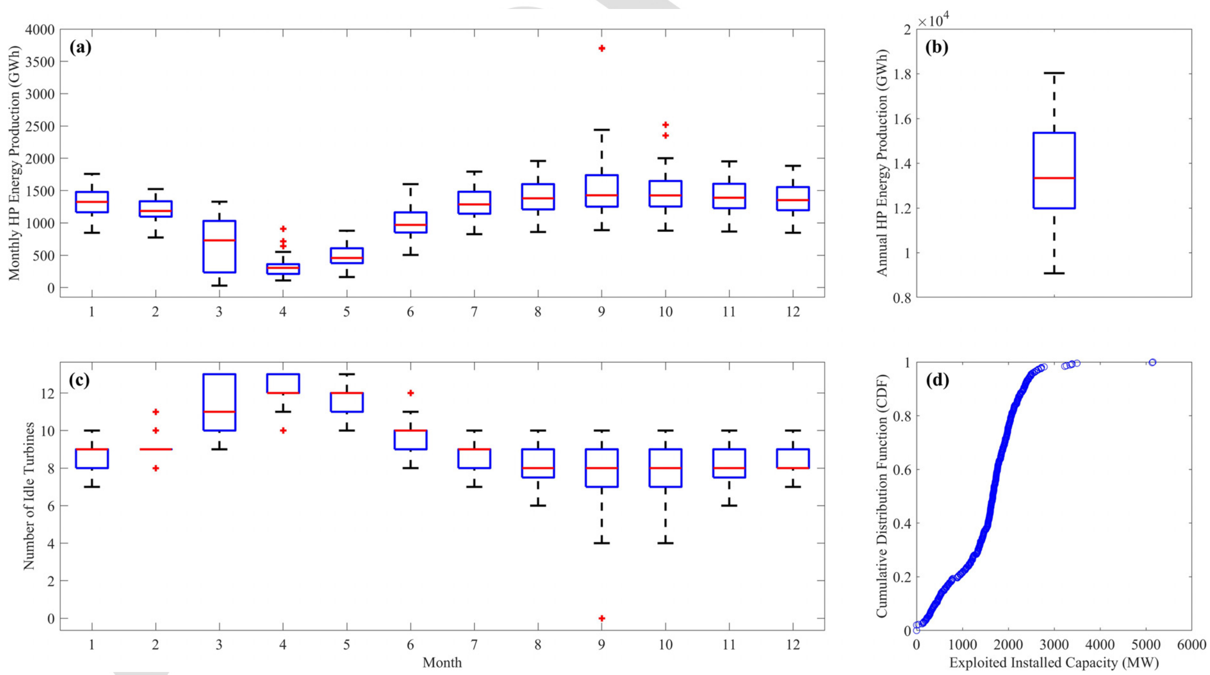

FIG. 7. Box plot of the (a) monthly and (b) annual hydropower production of the GERD and (c) number of idle turbines during the monthly GERD operation at the baseline scenario with an installed capacity of 5150 MW. (d) The empirical cumulative probability of the monthly exploited installed capacity based on 37 years of GERD operation.

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Figure 8 shows the capacity factor (CF) of the GERD under different scenarios of installed capacity (ranging from 16 turbines of 6450 MW to 8 turbines of 2900 MW). The capacity factor indicates the percentage of hydropower generation in a period of time relative to the theoretical maximum possible generation if all the turbines worked at full capacity without interruption. The capacity factor for the specific hydropower plant varies due to different factors including basin hydrology, plant age, mode of operation, and relative contribution of hydropower to the overall energy portfolio of an electric grid. For example, the three Gorges Dam in China has the largest hydropower capacity in the world (22 500 MW) and operates at a capacity factor of 46.7% (Qin *et al.*, 2020). In US, the median hydropower capacity factor has been 38.1% in recent years (Uria-Martinez *et al.*, 2018) with values as low as 25% and as high as 75%. The baseline scenario (with an installed capacity of 5150 MW) resulted in an average capacity factor of 0.30. On the contrary, when assuming a lower turbine capacity of 2900 MW, the electricity produced can attain 53% of the full capacity of the plant (Fig. 8).

V. DISCUSSION AND CONCLUSIONS

Our study evaluated hydropower production potential of the GERD that is supported by the hydrology of the Upper Blue Nile (UBN). Historical characterization of the GERD inflow using a 37-year simulation of the UBN hydrology indicated a median flow of 48 km^3/year, which can produce an annual production of about 13 629 GWh (capacity factor = 0.30). On average, the current installed capacity (5150 MW) would result in about eight idle turbines (out of 14 installed turbines) throughout the year. Our analysis showed that the total installed capacity can be fully exploited in September in the case of extreme wet years, e.g., high streamflow in 1993 and 2011 (although practically not feasible due to some turbines being in maintenance status). Therefore, it is obvious from our assessment that the current design with 5150 MW is more reasonable to offset the hydrologic constraints of the UBN and benefit from the hydropower potential of the GERD as compared to previous designs (e.g., 6000 and 6450 MW). While operating a hydropower dam to satisfy the peak or base power load is a more realistic scenario, the analysis presented in our study for the maximum production might be favored in the GERD case since the dam is billed to export much of the produced electricity to the neighboring countries.

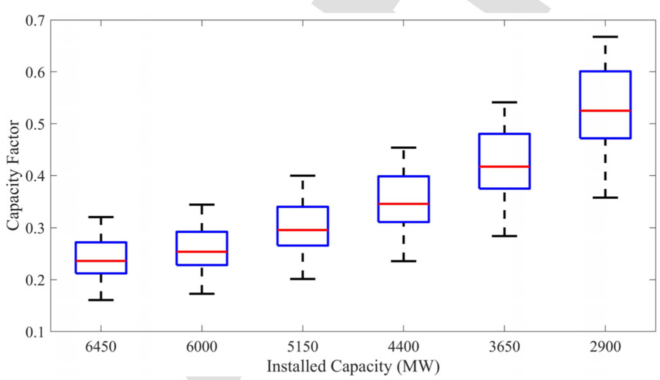

FIG. 8. The range of the capacity factor (CF) as a function of the GERD installed capacity.

While the current study assessed the GERD hydropower potential under the current hydrological conditions of the UBN, future hydropower production may even be reduced by climate change impacts, e.g., expected modification in hydrology and reservoir sedimentation (Teklemariam *et al.*, 2017 and Borji, 2013). As climate change is a key driver of future basin hydrology, any change in the streamflow regime may jeopardize the hydropower potential of the dam. In addition to alterations in streamflow, the sedimentation rate in reservoirs, which is currently estimated to cause an annual loss of about 0.8%–1% of reservoir capacity, may also increase (Gaudard and Romerio, 2014). As installed hydropower capacity continues to grow globally, considering such risks associated with basin hydrology and climate change is important to analyze the life cycle of planned hydropower projects and find out the optimum power plant design that is economically efficient and can live up to the declared promise of energy security.

SUPPLEMENTARY MATERIAL

See the supplementary material for GERD operation at the minimum operating level of 590 m AMSL.

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DATA AVAILABILITY

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

REFERENCES

Abtew, W. and Dessu, S. B., *The Grand Ethiopian Renaissance Dam on the Blue Nile* (Springer International Publishing, 2019).

Annys, S., Adgo, E., Ghebreyohannes, T., Van Passel, S., Dessein, J., and Nyssen, J., "Impacts of the hydropower-controlled Tana-Beles interbasin water transfer on downstream rural livelihoods (northwest Ethiopia)," J. Hydrol. **569**, 436–448 (2019).

Barnes, D. F., Golumbeanu, R., and Diaw, I., "Beyond electricity access: Output-based aid and rural electrification in Ethiopia," Technical Report No. ■, 2016. AQ4

Basheer, M., Wheeler, K. G., Elagib, N. A., Eticha, M., Zagona, E. A., Abdo, G. M., and Harou, J. J., "Filling Africa's largest hydropower dam should consider engineering realities," One Earth **3**(3), 277–281 (2020).

Beyene, A., "Why is the hydroelectric dam on the Blue Nile, the Grand Ethiopian Renaissance Dam (GERD), sized for 6000 MW?," ■ ■, ■ (2013); retrieved 25 November 2019. AQ5

Blackmore, D. and Whittington, D., "Opportunities for cooperative water resources development on the eastern Nile: Risks and rewards," Report No. ■ (Report to the Eastern Nile Council of Ministers, Nile Basin Initiative, Entebbe, 2008).

Block, P. and Strzepek, K., "Power ahead: Meeting Ethiopia's energy needs under a changing climate," Rev. Dev. Econ. **16**(3), 476–488 (2012).

Borji, T. T., "Sedimentation and sustainability of hydropower reservoirs: Cases of Grand Ethiopian Renaissance Dam on the Blue Nile River in Ethiopia," Master's thesis (Institutt for vann-og miljøteknikk, 2013).

Cascão, A. E., "Changing power relations in the Nile River Basin: Unilateralism AQ6 vs. cooperation?," Water Altern. **2**(2), ■ (2009).

Cascão, A. E. and Nicol, A., "GERD: New norms of cooperation in the Nile Basin?," Water Int. **41**(4), 550–573 (2016).

Conway, D., "The climate and hydrology of the Upper Blue Nile River," Geog. J. **166**(1), 49–62 (2000).

Degefu, D. M., He, W., and Zhao, J. H., "Hydropower for sustainable water and energy development in Ethiopia," Sustainable Water Resour. Manage. **1**(4), 305–314 (2015).

See http://www.eepco.gov.et/abouttheproject.php?pid=1andpcatid=2 for "Grand Ethiopian Renaissance Dam" (EEPCo, Ethiopian Electric Power Corporation, 2019), last accessed 5 November 2019.

Eldardiry, H. and Hossain, F., "Understanding reservoir operating rules in the transboundary Nile River Basin using macroscale hydrologic modeling with satellite measurements," J. Hydrometeorol. **20**, 2253 (2019).

Eldardiry, H. and Hossain, F., "The value of long-term streamflow forecasts in adaptive reservoir operation: The case of high aswan dam in the transboundary AQ7 nile river basin," J. Hydrometeorol. ■, ■ (2020).

Eldardiry, H. and Hossain, F., "A blueprint for adapting high Aswan dam operation in Egypt to challenges of filling and operation of the Grand Ethiopian AQ8 Renaissance Dam," J. Hydrol. ■, 125708 (2020).

Gaudard, L. and Romerio, F., "Reprint of "The future of hydropower in Europe: Interconnecting climate, markets and policies," Environ. Sci. Policy **43**, 5–14 (2014).

IPOE, "International panel of experts for Grand Ethiopian Renaissance Dam," Final Report No. ■ (IPoE, Addis Ababa, Ethiopia, 2013).

Karamouz, M. and Houck, M. H., "Annual and monthly reservoir operating rules generated by deterministic optimization," Water Resour. Res. **18**(5), 1337–1344, https://doi.org/10.1029/WR018i005p01337 (1982).

Karekezi, S. and Kimani, J., "Status of power sector reform in Africa: Impact on the poor," Energy Policy **30**(11–12), 923–945 (2002).

Kim, U., Kaluarachchi, J. J., and Smakhtin, V. U., "Generation of monthly precipitation under climate change for the upper blue nile river basin, Ethiopia 1," AQ9 J. Am. Water Resour. Assoc. **44**(5), 1231–1247 (2008).

King, A. and Block, P., "An assessment of reservoir filling policies for the Grand Ethiopian Renaissance Dam," J. Water Clim. Change **5**(2), 233–243 (2014).

Kumagai, J., "The Grand Ethiopian Renaissance Dam gets set to open," IEEE Spectr. **30**, ■ (2016).

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P. *et al.*, "High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management," Front. Ecol. Environ. **9**(9), 494–502 (2011).

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D. P., "Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model," Hydrol. Sci. J. **43**(1), 131–141 (1998).

Mataen, D., *Africa–the Ultimate Frontier Market: A Guide to the Business and Investment Opportunities in Emerging Africa* (Harriman House Limited, 2012).

MIT, *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 from the International, Non-Partisan Eastern Nile Working Group* (Massachusetts Institute of Technology, Boston, AQ10 2014).

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L., "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations," Trans. ASABE **50**(3), 885–900 (2007).

Mulat, A. G. and Moges, S. A., "Assessment of the impact of the Grand Ethiopian Renaissance Dam on the performance of the high aswan dam," J. Water Resour. Prot. **6**(06), 583 (2014).

Nasr, H. and Neef, A., "Ethiopia's challenge to Egyptian hegemony in the Nile River basin: The case of the Grand Ethiopian Renaissance Dam," Geopolitics **21**(4), 969–989 (2016).

Qin, P., Xu, H., Liu, M., Du, L., Xiao, C., Liu, L., and Tarroja, B., "Climate change impacts on Three Gorges Reservoir impoundment and hydropower generation," J. Hydrol. **580**, 123922 (2020).

Robinson, J. A. and Torvik, R., "White elephants," J. Public Econ. **89**(2–3), 197–210 (2005).

Siam, M. S. and Eltahir, E. A., "Climate change enhances interannual variability of the Nile river flow," Nat. Clim. Change **7**(5), 350–354 (2017).

Sridharan, V. and Coauthors, "Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation," Nat. Commun. **10**(1), 302 (2019).

Suberu, M. Y., Mustafa, M. W., Bashir, N., Muhamad, N. A., and Mokhtar, A. S., "Power sector renewable energy integration for expanding access to electricity in sub-Saharan Africa," Renewable Sustainable Energy Rev. **25**, 630–642 (2013).

Teklemariam, D., Lanckriet, S., Azadi, H., Asfaha, T. G., Haile, M., Witlox, F., and Nyssen, J., "Effects of land deals on peak discharge and sediment transport in the catchments around the Grand Ethiopian Renaissance Dam," Land Degrad. Dev. **28**(6), 1852–1861 (2017).

Uria-Martinez, R., Johnson, M., and O'Connor, P., "2017 hydropower market report highlights," Report No. ■ (Oak Ridge National Lab. (ORNL), Oak Ridge, TN, 2018).

Van der Zwaan, B., Boccalon, A., and Dalla Longa, F., "Prospects for hydropower in Ethiopia: An energy-water nexus analysis," Energy Strategy Rev. **19**, 19–30 (2018).

Wang, X., Chen, Y., Song, L., Chen, X., Xie, H., and Liu, L., "Analysis of lengths, water areas and volumes of the three gorges reservoir at different water levels using Landsat images and SRTM DEM data," Quat. Int. **304**, 115–125 (2013).

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M. *et al.*, "Cooperative filling approaches for the Grand Ethiopian Renaissance Dam," Water Int. **41**(4), 611–634 (2016).

Whittington, D., "Visions of Nile basin development," Water Policy **6**(1), 1–24 (2004).

Whittington, D., Waterbury, J., and Jeuland, M., "The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile," Water Policy **16**(4), 595–608 (2014).

Wolde-Rufael, Y., "Electricity consumption and economic growth: A time series experience for 17 African countries," Energy Policy **34**(10), 1106–1114 (2006).

Yihdego, Z., Rieu-Clarke, A., and Cascão, A. E., "How has the Grand Ethiopian Renaissance Dam changed the legal, political, economic and scientific dynamics in the Nile Basin?," Water Int. **41**, 503–511 (2016).

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., and Tockner, K., "A global boom in hydropower dam construction," Aquat. Sci. **77**(1), 161–170 (2015).

Zaroug, M. A., Eltahir, E. A., and Giorgi, F., "Droughts and floods over the upper catchment of the Blue Nile and their connections to the timing of El Niño and La Niña events," Hydrol. Earth Syst. Sci. **18**(3), 1239–1249 (2014).

Zhang, Y., Block, P., Hammond, M., and King, A., "Ethiopia's Grand Renaissance Dam: Implications for downstream riparian countries," J. Water Resour. Plann. Manage. **141**(9), 05015002 (2015).