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Water-food-energy nexus for transboundary cooperation in Eastern Africa

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ABSTRACT

Establishing cooperation in transboundary rivers is challenging especially with the weak or non-existent river basin institutions. A nexus-based approach is developed to explore cooperation opportunities in transboundary river basins while considering system operation and coordination under uncertain hydrologic river regimes. The proposed approach is applied to the Nile river basin with a special focus on the Grand Ethiopian Renaissance Dam (GERD), assuming two possible governance positions: with or without cooperation. A cooperation mechanism is developed to allocate additional releases from the GERD when necessary, while a unilateral position assumes that the GERD is operated to maximize hydropower generation regardless of downstream users' needs. The GERD operation modes were analysed considering operation of downstream reservoirs and varying demands in Egypt. Results show that average basin-wide hydropower generation is likely to increase by about 547 GWh/year (1%) if cooperation is adopted when compared to the unilateral position. In Sudan, hydropower generation and water supply are expected to enhance in the unilateral position and would improve further with cooperation. Furthermore, elevated low flows by the GERD are likely to improve the WFE nexus outcomes in Egypt under full cooperation governance scenario with a small reduction in GERD hydropower generation (2,000 GWh/year (19%)).

Key words: system dynamics, the grand ethiopian renaissance dam (GERD), the nile river basin, transboundary cooperation, water-food-energy nexus

HIGHLIGHTS

- Water-Food-Energy Nexus framework is applied to explore cooperation opportunities in shared rivers.
- Cooperation is likely to increase total average hydropower generation compared to the unilateral mode.
- Downstream drought-related risks could be reduced with negligible impacts on upstream objectives if countries agree to share the risk.
- A high level of coordination among countries is required to achieve the cooperation benefits.

INTRODUCTION

Rivers play important roles in human societies. River basins have been and will continue to: (i) be at the core of regional economic activities and growth, (ii) shape human societies, and (iii) influence the geopolitical environment. Globally, 310 transboundary river basins are shared by 150 countries, covering 47.1% of the land surface of the Earth and representing home for 52% of the global population (McCracken & Wolf 2019). Population growth, economic development and urbanization in riparian states are key drivers of increased demands for water, food and energy resources. Together with growing resource demands, the situation is particularly challenging when the river crosses or forms political borders due to the lack of equivalent national institutions with ultimate authority, management policies for water, food and energy are less coherent across countries (Sadoff & Grey 2002; Lawford *et al.* 2013; Yu *et al.* 2019). In a shared river basin, competitions over the river resources are likely to cause disputes among the riparian countries. These disputes combined with other historical, cultural, legal and environmental factors can make transboundary rivers a source of cooperation or conflict (Sadoff & Grey 2002).

The Water-Food-Energy (WFE) nexus has emerged as an integrated approach to analyse and highlight cross-sectoral interactions, reduce trade-offs, and build synergies among different sectors and regions without compromising sustainability (Hoff 2011). However, in shared river basins the implementation of the nexus approach is particularly challenging because of intersectoral complexity and impacts that occur on various spatial and temporal scales, while often crossing borders. Riparian states in an international river basin have varying interests and often conflicting priorities over the river resources. Furthermore, riparian countries may wish to develop infrastructure projects to utilize water resources within their territories to meet the growing demands of the population and promote economic development. Such developments and management activities at different locations in the basin may lead to conflicts among co-riparians, especially with weak research and governance policies (Sadoff & Grey 2002; Lawford *et al.* 2013). Therefore, cooperation among co-riparians and approaches to facilitate collaborative decision making in a shared river basin are urgently needed.

According to Sadoff & Grey (2002), cooperation in transboundary river basins could provide benefits to the river system itself, improve resource management, advance regional economic development and integration, and promote regional stability. Conversely, the non-cooperation situation is likely to cause river degradation, increase hydrological losses and generate additional costs (Sadoff & Grey 2002). Although encouraging cases of cooperative governance and management of shared rivers exist, e.g., the cases of Mekong river, Senegal river and Orange river, such situations for transboundary rivers are rare (Yu *et al.* 2019). The nexus approach offers a solid basis for a better understanding of the benefits and implications of inter-sectoral management while promoting regional cooperation and reducing tensions among stakeholders, sectors and regions (Cervigni *et al.* 2015; UNECE 2018; Ravar *et al.* 2020; Saidmamatov *et al.* 2020).

Joint operation of multi-reservoir systems provides an opportunity for achieving cooperation among stakeholders in transboundary river basins and increasing basin-wide benefits (Madani & Hooshyar 2014). Tools for analysing and quantifying cooperation in transboundary river basins are thus required (Yu *et al.* 2019). Multi-reservoir systems operation and coordination have been extensively addressed in the literature. Examples of application include: the Mekong River basin (Yu *et al.* 2019; Do *et al.* 2020), the Yangtze River basin (Xu *et al.* 2018), the Zambezi River basin (Giuliani & Castelletti 2013), and the Nile River basin (Digna *et al.* 2018; Wheeler *et al.* 2018; Verhagen *et al.* 2021). Optimization-based methods to maximize total system benefits (Koutsoyiannis & Economou 2003; Labadie 2004; Goor *et al.* 2010; Reed *et al.* 2013; Bai *et al.* 2015; Tsoukalas & Makropoulos 2015b; Tsoukalas *et al.* 2016; Loucks & van Beek 2017) and cooperative game theory approaches (Madani & Hooshyar 2014; Yu *et al.* 2019; Do *et al.* 2020) are some of the most often encountered. However, optimization methods are not always acceptable or practical in real-world problems, e.g., in transboundary river basins where riparian countries are only interested in their own gains (Madani *et al.* 2014). Cooperative game theory approaches are promising, however, they require reliable and mutually agreed upon information, which is particularly challenging to obtain in shared river basins (Yu *et al.* 2019). While the literature has addressed different aspects of governance and cooperative water management and allocation including to some extent food production and hydropower generation, the WFE nexus interdependencies are largely overlooked. Therefore, there is a lack of studies utilizing the nexus approach to explore cooperation opportunities in shared river basins. Applying a nexus approach in transboundary river basins could help to gain a holistic understanding of the complex linkages among WFE nexus elements, explore trade-offs and identify synergies among sectors and regions. This research is motivated by the need to implement comprehensive nexus frameworks and tools to better understand and analyse the impact of reservoir operation and their interactions with the WFE nexus system in river basins (Gao *et al.* 2021). In that context, this paper explores cooperation pathways in transboundary river basins using a nexus-based approach while considering reservoir system operation and coordination under variable hydrological conditions. This is explored here by taking the Nile river basin as a case study with a special focus on the long-term operation of the Grand Ethiopian Renaissance Dam (GERD) using System Dynamics modelling approach. Furthermore, this research contributes to the actively ongoing research exploring the wider impacts of the GERD on the Nile region. The rest of the paper is organised as follows: (1) Methods, (2) Results and Discussion and (3) Conclusions.

METHODS

Study area description

With a length of 6,700 km, the Nile is the longest river in the world. The Nile rises from the east African highlands and stretches over eleven countries on its journey northward to the Mediterranean Sea. The Nile River is considered one of the most complex river systems in the world because of its unique characteristics, e.g., size, transboundary nature, wide variety of climatic zones and topography, low runoff and high system losses in addition to its geopolitical importance (Howell & Allan 1994; Sutcliffe & Parks 1999; Awulachew 2012). The Nile has two main tributaries: The White Nile that originates from the Equatorial Lakes region and the Blue Nile that rises from the Ethiopian highlands, Figure 1. The confluence of the two tributaries at Khartoum, Sudan, forms the main Nile, Figure 1. The Atbara River – which originates also from the Ethiopian highlands – is the last major tributary to join the main Nile before flowing north to Egypt, the last downstream country in the basin.

The Nile basin covers an area of about 3.2 million km^2, however, the river runoff is unevenly distributed. The runoff is mostly generated from two main regions with high rainfall: the Equatorial lakes region and Ethiopian highlands. The White Nile flows are relatively constant throughout the year as a result of the hydrologic buffer of the Sudd wetlands. At Malakal, just downstream of the Sobat confluence, the average annual White Nile flow is estimated at 31.0 km^3/year and the flow peak in October is about 3.45 km^3/month (Sutcliffe & Parks 1999; NBI 2016b). On the other hand, the Blue Nile flows are characterised by large seasonality and inter-annual variability, following the rainfall regime in the Ethiopian part. The average annual Blue Nile flows measured at El Diem station that is located near the Ethiopian–Sudanese border, are estimated (between 1915 to 2014) at about 50 km^3 and contribute to about 60% of the total Nile runoff (NBI 2016b). The majority of the Blue Nile flows (about 70%) are generated during the wet season (Jun.–Sept.) with the peak flow in August estimated at 15.2 km^3/month (Sutcliffe & Parks 1999; NBI 2016b). The Atbara River is the most seasonal tributary in the basin that runs dry for about five months (Jan.–May) with an average annual flow of 11.4 km^3/year (Sutcliffe & Parks 1999; NBI 2016b). The average naturalized annual Nile flows (between 1900 to 2018) at Aswan are estimated at 86.5 km^3/year (Wheeler *et al.* 2020).

The Nile basin countries have devised ambitious master plans to utilise the potential resources in the basin (e.g., irrigation expansion and hydropower projects) to meet the growing water, food and energy demands of their populations and sustain their economies. The largest of these developments is the GERD that is located on the Blue Nile in Ethiopia at about 20 km from the Ethiopian-Sudanese border. With a capacity of 5,150 MW, once completed, the GERD's hydropower plant will be the largest in Africa. Since it started in 2011, the GERD construction has resulted in numerous diplomatic initiatives and caused tensions between Egypt, Ethiopia and Sudan. Yet, there is still no agreement among the key riparian states on the filling of the reservoir, which has already started, and future operation. The Ethiopian Prime Minister has announced that the first filling phase was completed on 21 July 2020 with 4.9 km^3 of water stored in the GERD reservoir (Meseret 2020). On 19 July 2021, Ethiopia announced the completion of the second phase of filling the reservoir (Endeshaw 2021) with estimates of reaching the level of 573 (a.m.s.l) and retaining no more than 4.5 km^3 at this stage (Alamin & Marks 2021).

Modelling scenarios

Here we attempt to explore different operation scenarios and identify means for cooperation over the GERD during the long-term operation using a nexus-based approach. System Dynamics (SD) (Sterman 2000) is an established system-based method that has been utilized in the nexus literature (e.g., Elsayed *et al.* 2020; Sušnik *et al.* 2021). With its capacity to capture the interlinkages and feedback among nexus domains, SD offers qualitative and quantitative analyses to better understand the nexus aspects. We employ an integrated simulation model that was developed for the entire Nile basin using SD (Elsayed *et al.* 2018; Elsayed *et al.* 2020). The model was developed in the Simile environment (Simile version 6.10p2, Simulistics 2021). The integrated simulation model covers the entire Nile basin and includes basin-wide inflows, main reservoirs and hydropower plants, basin-wide water withdrawals, and food production from irrigated agriculture. The model runs at a monthly time step and takes into account the uncertainty of the river flow regime through the application of stochastic simulation. For further details about the nexus modelling framework, model development and input data, see Elsayed *et al.* (2020) and Elsayed *et al.* (2018). The developed model is adjusted to accommodate the changes to the system and management strategies explored in this work as given below.

Similarly to previous results found in the literature (e.g., Digna *et al.* 2018; Elsayed *et al.* 2020), the Blue Nile flows during low-flow and dry periods are expected to improve due to flow regulation caused by the GERD when it comes online.

Figure 1 | The Nile River Basin, NBI (2012).

Therefore, cooperation among the riparian countries over the GERD can result in additional releases from the dam to meet downstream water demands during droughts or when needed. This concept has been previously considered and explored in the literature (e.g., Basheer *et al.* 2018; Digna *et al.* 2018; Wheeler *et al.* 2018), together with other approaches investigating adaptation strategies for operating High Aswan Dam (HAD) during the filling and subsequent long-term operation of the GERD (Eldardiry & Hossain 2021a). However, most of these studies assumed that Egypt's annual water demands from HAD are fixed at 55.5 km^3/year (based on the 1959 water agreement with Sudan) and rarely considered changes in water demand. While to some extent these studies explored cooperation opportunities with the GERD, a few of them were limited to the Blue Nile basin such as Basheer *et al.* (2018) and Allam & Eltahir (2019), and others did not consider significant infrastructure in Sudan (Eldardiry & Hossain 2021a).

In this work, two extreme positions are investigated: (a) the full cooperation mode among the riparian countries and (b) unilaterally motivated policies. The two positions are considered here together with different demand conditions in Egypt and with various options for the operation of the GERD and the Sudanese reservoirs, Figure 2. Basin-wide impacts will be investigated for the unilateral and cooperation governance modes in comparison with the base case of no GERD. Development plans (e.g., agricultural projects) outside Egypt were not considered in this analysis due to uncertainty associated with their implementation and limited data availability for such plans in the public domain. However, the approach can accommodate them once they are accessible. Therefore, the assumptions of water uses and related water management do not imply any endorsement for water rights in the Nile basin.

The unilateral governance mode considers the hypothetical situation by which the riparian countries do not share information about the operation of their infrastructure or downstream releases. Accordingly, the current operation rules of the existing reservoirs in the basin are assumed to remain unchanged in the unilateral situation and the GERD is operated to maximise the hydropower generation regardless of potential downstream shortages (similar to assumptions considered in Arjoon *et al.* (2014)). In the cooperation mode, the assumption is that the riparian countries agree to cooperate, i.e., coordinate their reservoir operations and share information about reservoir states, e.g., releases, storage levels, etc. Therefore, downstream users can request additional releases from the GERD in the case of experiencing a water shortage. It should be noted that the unilateral position assumes that each country works to maximize their resources regardless of the needs of other riparian countries, a trend that is on the increase in the Nile basin (Cascão 2009; Verhagen *et al.* 2021). In contrast,

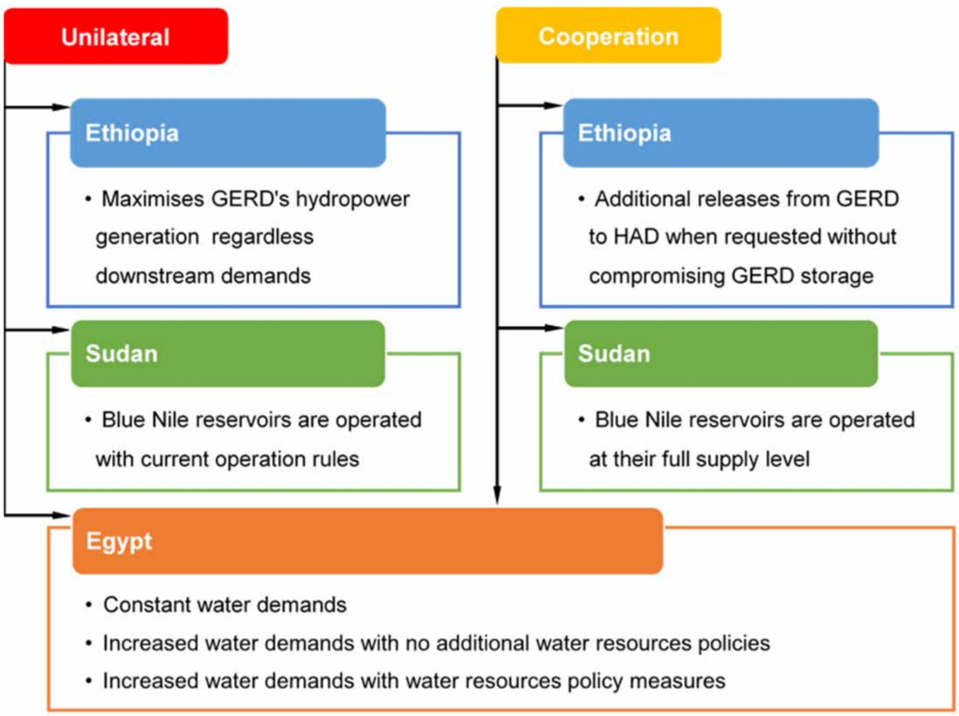

Figure 2 | Unilateral and cooperation positions explored in Egypt, Ethiopia and Sudan following GERD opeation.

the cooperation positions assume that the riparian countries agree to manage the river resources and their infrastructure to reduce risks and trade-offs. Although they represent two extreme situations with various possible shades of grey in between, those two extreme positions are employed to gain a better understanding of how to improve governance and move toward integrated resource planning and management in river basins.

In Egypt, a number of varying demand conditions were considered to explore opportunities and challenges for cooperation in the Nile basin. The assumed water demand scenarios are as follows: (a) constant water demand levels as in 2015, (b) increased demands due to population growth and expansion in agricultural land, but without developing additional water resources, and (c) the same as in case (b) with the additional assumption that Egypt succeeds in implementing water policy measures listed in Table 1. The listed measures cover a wide range of management options for the supply and demand sides (MALR 2009; MWRI 2011). Water supply-side policies aim at increasing water supply from different sources such as expansion in groundwater abstraction, utilizing rainfall, expansion in water reuse and desalination. Agricultural drainage water reuse is currently estimated at 11.3 km^3/year in the period 2013–2016 (CAPMAS Various years-a) and is projected to reach its potential permissible value of 12.0 km^3/year by 2050 (MWRI 2011; CAPMAS 2014). Treated wastewater reuse is estimated at 1.28 km^3/year, which is equivalent to 13% of municipal water consumption between 2013 and 2016 (CAPMAS Various years-b). Future projection of treated wastewater rate (i.e., a fraction of municipal water consumption) is assumed to reach 55% by 2050, close to the value assumed by Abdelkader *et al.* (2018). In contrast, to predicted increases, the water demand management measures include increasing the water use efficiency in (i) the agricultural sector by improving the irrigation system efficiency and changing the cropping pattern, and (ii) the domestic sector through reducing the per capita water consumption and improving the pipe network efficiency. It should be noted that the adopted demand scenarios are calculated at the national level in Egypt. In contrast, the water supplies in Egypt include Nile water releases from HAD together with other available water resources such as water reuse and groundwater (see Table S.1 in Supplementary Data section for the assumptions of each demand scenario).

The three demand conditions were tested for the unilateral and cooperation conditions together with the case of no GERD. A drought policy for the HAD was also applied in all the simulations (Donia 2013; Hamed 2018). The policy applies a sliding fraction reduction to the downstream demands based on the storage level at the HAD, Table 2. The HAD drought policy aims

Table 1 | Adopted water policy measures in Egypt

Policy measure		Description	Source
Deep groundwater		4.0 km^3 by 2050	WRDMS 2050[a]
Shallow groundwater		8.0 km^3 by 2050	WRDMS 2050[a]
Rainfall		1.5 km^3 by 2050	WRDMS 2050[a]
Agricultural drainage water reuse		Increase to potential ($\ngtr$12 km^3) by 2050	WRDMS 2050[a]
Treated wastewater reuse		Current rate of increase will continue (13% in 2015 to 55% to 2050)	Assumption
Desalination		2.0 km^3 by 2050 3.5 km^3 by the end of simulation	WRDMS 2050[a] Assumption
Irrigation efficiency	Old lands New lands	Increase from 0.61 to 0.75 Apply efficient irrigation methods (Drip irrigation with 90% efficiency and Sprinkler irrigation with 70% efficiency)	WRDMS 2050[a], SADS 2030[c]
Control cropping pattern	Limiting rice crop area Limiting sugarcane area	(Crop area $\ngtr$546,000 ha) (Crop area $\ngtr$147,000 ha)	WRDMS 2050[a], SADS 2030[c]
Domestic water sector	Reduce urban water consumption	Reduce from 270 l/c/d to 220 l/c/d by 2050	Assumption based on Egyptian Code of practice[b]
	Reduce rural water consumption	Reduce from 130 l/c/d to 100 l/c/d by 2050	
	Improving pipe network efficiency	Increase from 0.70 to 0.80 by 2050	Assumption

Sources [a]MWRI (2011); [b]MHUUC (2010); [c]MALR (2009).

Table 2 | Demand reduction factor for High Aswan Dam (HAD)

HAD storage (km^3)	HAD level (m)	Demand reduction factor (%)
55<S≤60	158.02<L≤159.44	5
50<S≤55	157.92<L≤158.02	10
S≤50	L≤157.92	15

Note: S: storage and L: water level in the reservoir.

at reducing the chance of the reservoir being fully depleted. This is achieved by distributing water shortages over longer periods and thus eliminating severe water deficits (Hamed 2018).

Water allocation procedure for a cooperation mode of operation

The cooperation mode assumes that the HAD operator will be able to request additional releases from GERD in case there is a water shortage in Egypt. Water shortages are expected to occur if the supply to demand (S/D) ratio falls below a certain level and this is called the 'agreed threshold'. Two agreed ratios are investigated here: 85% and 100% and can be considered as a proxy to the level of cooperation. The former value is compatible with the maximum reduction factor to water demands from the HAD during droughts, Table 2, and similar to the adequate supply reliability range (80–85%) that allows for applying deficit irrigation practices without causing detrimental impacts on crop yields (Steduto *et al.* 2012). On the other hand, the 100% ratio assumes the complete willingness of riparian countries to jointly work on mitigating their individual risks as far as possible.

In this vein, the model (Elsayed *et al.* 2020) calculates monthly water demands from the HAD and forecasts whether a water shortage will occur. If the S/D ratio falls below an agreed level, the model estimates the additional water required to reach it on a monthly basis, named here the Desired Additional Flow (DAF), Figure 3. After that, the HAD requests DAF from the GERD and the additional flows are then released based on the storage condition in the GERD reservoir. Furthermore, maintaining the GERD reservoir at the Minimum Operating Level (MOL=590 a.m.l) takes priority over downstream releases. It should be noted that a reduction factor to monthly downstream releases (20%) from the GERD is applied if the water level in the reservoir falls below 638 m (a.m.s.l), following the GERD operation rules according to NBI (2016a). This rule takes precedence over the DAF requests. The procedures of estimating and allocating HAD demands from the GERD are summarised in Figure 3.

In Sudan, it is assumed that under unilateral governance conditions the Blue Nile reservoirs (El-Roseires and Sennar) are operated using their current rules as discussed above. In contrast, the cooperation governance mode assumes that Sudan can operate its reservoirs at near their maximum level without concerns over dam overtopping that might result from unanticipated releases from the GERD (Wheeler *et al.* 2016; Basheer *et al.* 2018). Therefore, the Blue Nile reservoirs in Sudan – in the cooperation mode – will be operated at their maximum feasible level, with releases aimed at meeting downstream demands, hydropower generation and flood control, while forgoing seasonal flushing for sediment since the GERD will reduce the sediment fluxes entering the downstream reservoirs (Wheeler *et al.* 2020).

In Ethiopia, the GERD will be operated for hydropower generation only in both governance models. Under the unilateral mode of operation, the GERD will aim to maximise hydropower generation targeting a fixed power level of 1,730 MW with an average hydropower generation of 15.15 TWh/year, similar to the assumption made by Elsayed *et al.* (2020) and agrees with the literature, e.g., Digna *et al.* (2018). On the other hand, the cooperation mode assumes that the GERD will satisfy a power level of 1,730 MW (first priority), in addition to releasing supplementary flows to HAD when requested, as explained above (Figure 3). The model also considers reaching a full capacity of hydropower generation from the GERD (i.e., 6,000 MW, a number greater than current installed capacity but to make our results comparable to those found in the literature) if the reservoir storage condition allows (Elsayed *et al.* 2020). The significance of the latest modification of the GERD installed capacity (i.e., now at 5,150 MW) on our results is found to be insignificant given the focus of this study and the installed capacity will not likely be fully utilized throughout the year (Eldardiry & Hossain 2021b) (see Supplementary Data b.1). In the event of the GERD receiving a request from HAD, the model first checks the GERD storage level. The model determines – by trial-and-error – the additional releases to HAD without violating the MOL condition of GERD, see Figure 3 and Supplementary Data (b.2).

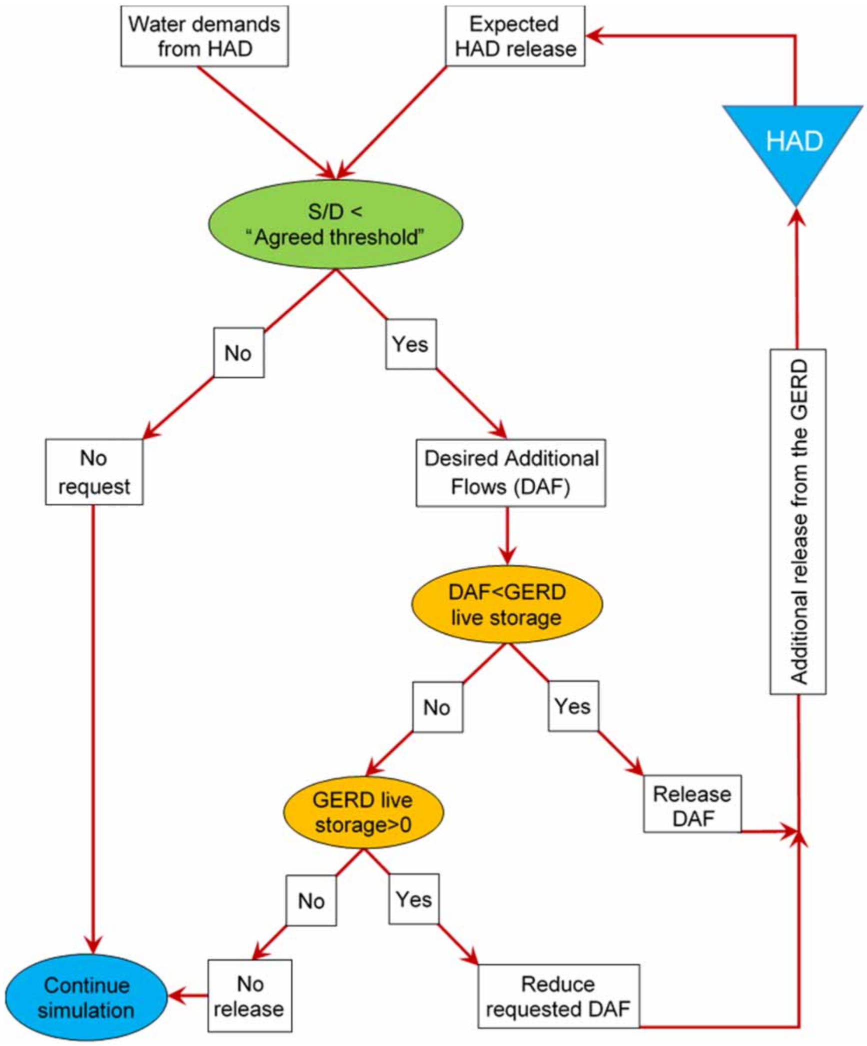

Figure 3 | Allocation procedure of additional flows from GERD to HAD.

The assumption here is that the first impoundment of the GERD reservoir is complete, and it is in the normal operations phase. At the beginning of each simulation, all reservoirs are assumed to be full and the water level in HAD is at 170 m (a.m.s.l) for flood control purposes. This value was selected based on preliminary simulations as the average reservoir water. In total, 12 simulation scenarios were considered: 3 (demand conditions in Egypt)×4 (system states: no GERD, unilateral and two cooperation levels over GERD (i.e., agreed S/D)). To account for the uncertainty associated with the river flows regime, the stochastic simulation and synthetic data generation were employed. This is an approach that has been used in a wide range of water resources studies (Koutsoyiannis & Economou 2003; Celeste & Billib 2009; Giuliani *et al.* 2014; Tsoukalas & Makropoulos 2015a, 2015b; Feng *et al.* 2017; Elsayed *et al.* 2020).

In this work, 100 basin-wide, synthetic monthly streamflow datasets (each 65-years long) were generated using the anySim R-Package (Tsoukalas *et al.* 2019; Tsoukalas *et al.* 2020). The model enables the simulation of random variables, processes and random fields with any marginal distribution and correlation structure (assuming that the former have finite variance and the latter is positive definite). In particular, we employed the multivariate cyclostationary model of Tsoukalas *et al.* (2017, 2018), since the available dataset comprises monthly streamflows from 72 locations, thus dictating the need for such a model (i.e., capable of accounting for the seasonality of the processes). The available basin-wide Nile flows were obtained from the Nile Basin Decision Support Systems (NBI 2016a) for the period 1950–2014. Each of the 100 synthetic data sets consists of 72 time series with a total of 780 time steps (12 [months]×65 [years]) (Elsayed *et al.* 2020). All simulations start 'arbitrarily' at the year 2030 and the stochastically generated river flows are employed to drive the integrated model with a monthly time-step.

RESULTS AND DISCUSSION

Regional impacts for both unilateral and cooperation modes of operation are analysed considering the above-described system arrangement. The focus for the cooperation mode is on the lower quartile interval (between 25th percentile (75th percentile) and the minimum (maximum) value) of the water, food, and energy-related variables including minimum values, and x_{95} (value of the variable x that equalled or exceeded 95% of the time) or the 5th percentile in the boxplot graphs. The median and average values will be also reported for significant changes in the outcomes. The two cooperation modes will be reported as Coop_{85} and Coop_{100} with agreement levels of 85 and 100, respectively.

River flow regime

The average monthly river flow under GERD's operation modes with different demand patterns in Egypt is shown in Figure 4. Also, the case of no GERD is presented for comparison purposes. We analyse the river flows at two different locations that will be affected by the considered operation modes of the upstream reservoir(s) and demand patterns in Egypt: (I) at El-Diem gauge station on the Blue Nile, and (II) at Dongola gauge station on the Main Nile.

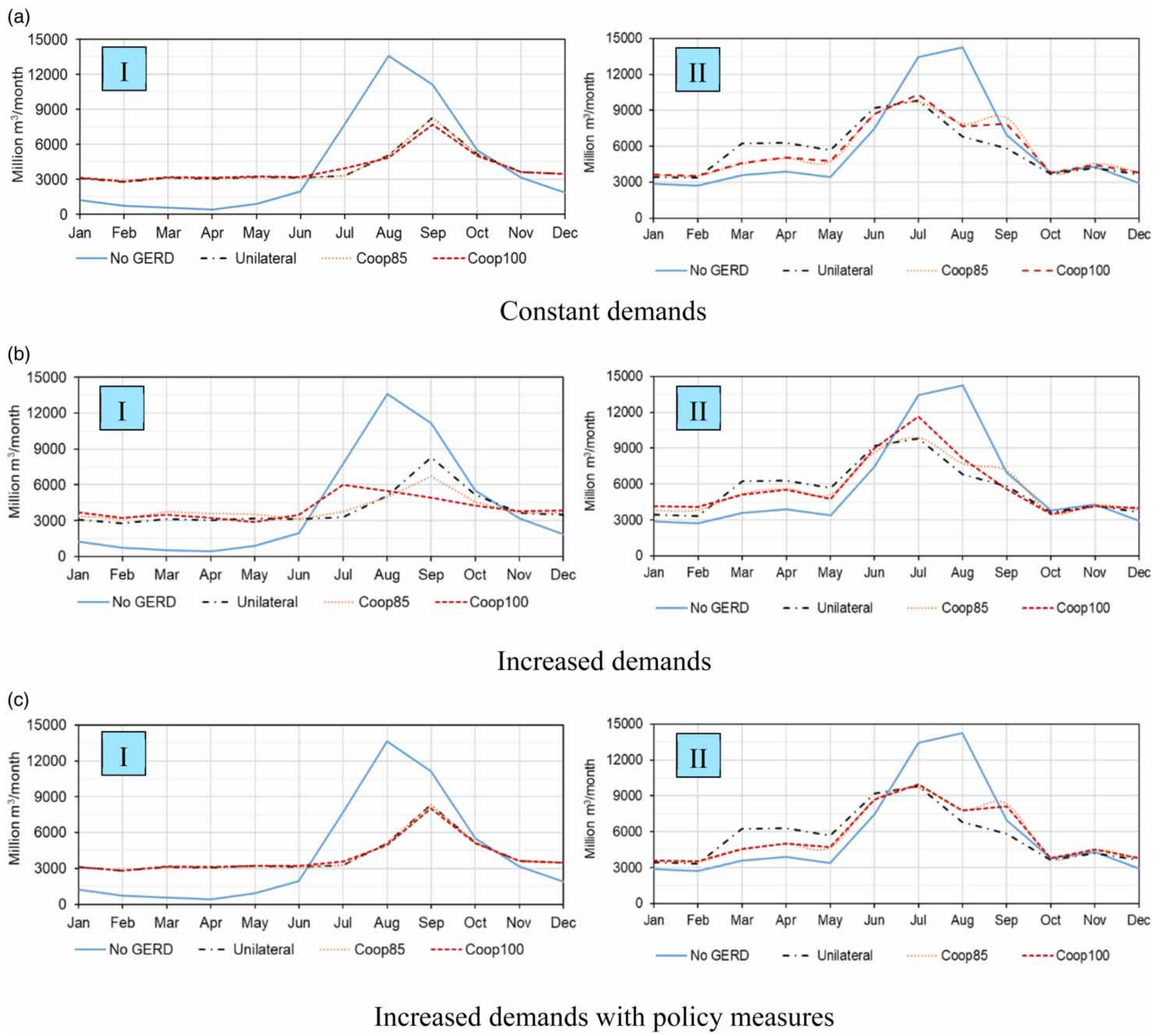

Figure 4 | Average monthly flows of: (I) Blue Nile at Diem gauge and (II) Main Nile at Dongola gauge under demand conditions in Egypt with and without GERD. Results are based on average values of all years of stochastic model simulations.

Once the GERD becomes operational, the Blue Nile and Main Nile flows will be more regulated. The changes in the river flow regime are influenced by the operation mode and demand patterns in Egypt, Figure 4. We also compare the average monthly flows (averaged throughout all years of simulation) for the cooperation and non-cooperation (unilateral) cases. In the constant demand scenario, the average monthly Blue Nile flows in the $Coop_{85}$ case are found to be similar to the unilateral case. In the $Coop_{100}$ case, the Blue Nile flows are slightly changed during the high demand season in Egypt (i.e., Jul.-Oct.) by up to 0.665 million m^3/month when compared to the unilateral state, Figure 4(a.I). The latter shift in the Blue Nile flows reflects the impact of the high demand season in Egypt on GERD releases in the cooperation mode. In contrast, the main Nile flows in the cooperation mode are altered from the unilateral state. The monthly flows are reduced before the flood season by up to 1,730 million m^3/month, but then they increase during the flood season by about 2,500 million m^3/month, Figure 4(a. II). This shift resulted from operating the Blue Nile reservoirs in Sudan at their full supply level.

The second demand scenario shows the significant impact of additional releases from the GERD on the Blue Nile flows particularly in the $Coop_{100}$ case, Figure 4(b.I). The Blue Nile flows in the case of $Coop_{85}$ have a similar pattern to the flows in the unilateral mode but with considerable changes during the high demand season in Egypt, with a reduction by over 1,500 million m^3 in July. Unlike the $Coop_{100}$ case, the Blue Nile flows become more regulated during the year and July peaks following continuous GERD releases to the HAD that increase the probability of reaching the MOL of the GERD. Furthermore, river flows are substantially reduced during the flood season with a maximum reduction in September by about 3,388 million m^3/month, as the GERD reservoir fills up. This shows the impact of increased requests from the GERD on the Blue Nile flows and the flood season in particular. The change in the Blue Nile flows is reflected in the main Nile flows. The main Nile flows in the two cooperation states showed a similar pattern to the unilateral mode. However, the river flows in the $Coop_{100}$ case are higher than the other two cases (unilateral mode and $Coop_{85}$) by up to 1,824 million m^3/month during the high demand season in Egypt (Jun.-Sep.); but become close to the unilateral mode flows by the end of the high demand season in Egypt, unlike in the $Coop_{85}$ case.

The third scenario shows that the average monthly Blue Nile flows in the cooperation mode have a similar pattern to those in the unilateral state. The average monthly flows of the main Nile in the two cooperation states are found to be similar. The water demand levels from the HAD in both the first and third scenarios are found to be alike and result in limited additional water demands from the GERD. Therefore, the river flows under the first and third scenarios are found to be similar, unlike in the second demand scenario where a considerable increase in downstream demands would lead to a significant change in the river flow regime. The comparison between the river flows in the three demand scenarios under cooperation positions illustrates the impact of downstream demands on the river flow regime. Moreover, it shows the significance of coordination among riparian countries and timely releases from the GERD to downstream users, particularly during low flow and drought periods.

The average annual river runoff (R) under the unilateral mode of operation is reduced by 1,432 million m^3/year (2%) due to additional evaporation caused by the GERD reservoir (see Supplementary Data (c, d)). Furthermore, the minimum annual river flow is increased by 9,398 million m^3/year (29%) and the R_{95} increased by 597 million m^3/year (1%) due to improved low flow augmentation resulting from GERD regulation. The minimum annual Nile flow for the unilateral case is found to be higher than those of cooperative cases following the additional releases from the GERD to HAD and the reduction in GERD water levels, especially in the $Coop_{100}$ case, (see Figure S.3, Supplementary Data (c)). In contrast, the average annual Nile flows in the cooperation modes for the first and third demand scenarios were similar to those of the unilateral case. Furthermore, the minimum flow is increased by 7,913 million m^3/year (24%) in $Coop_{85}$ and by up to 2,674 million m^3/year (8%) in $Coop_{100}$ compared to the case of no GERD. The average annual river flows in the second demand scenario are reduced by 874 million m^3/year (1%) in the $Coop_{85}$ case, while the $Coop_{100}$ case showed no changes compared to the case of no GERD. The minimum flows are increased by 3,722 million m^3/year (11%) in $Coop_{85}$, by about 4,220 million m^3/year (13%) in $Coop_{100}$ compared to the case of no GERD.

Water shortage

The water shortage in Egypt is only discussed here, while Sudan water supplies are found to be improved following the GERD operation (Elsayed *et al.* 2020) and showed no difference under the various GERD operation modes (see Supplementary Data (e)). Also, it was determined based on simulations that most of the water shortages in Sudan occur in the Atbara basin due to inadequate water supplies and siltation problems (Awulachew 2012). The impact of the GERD operation modes on water shortage (W) in Egypt for the three demand conditions is shown in Figure 5. The maximum water shortage will be reduced

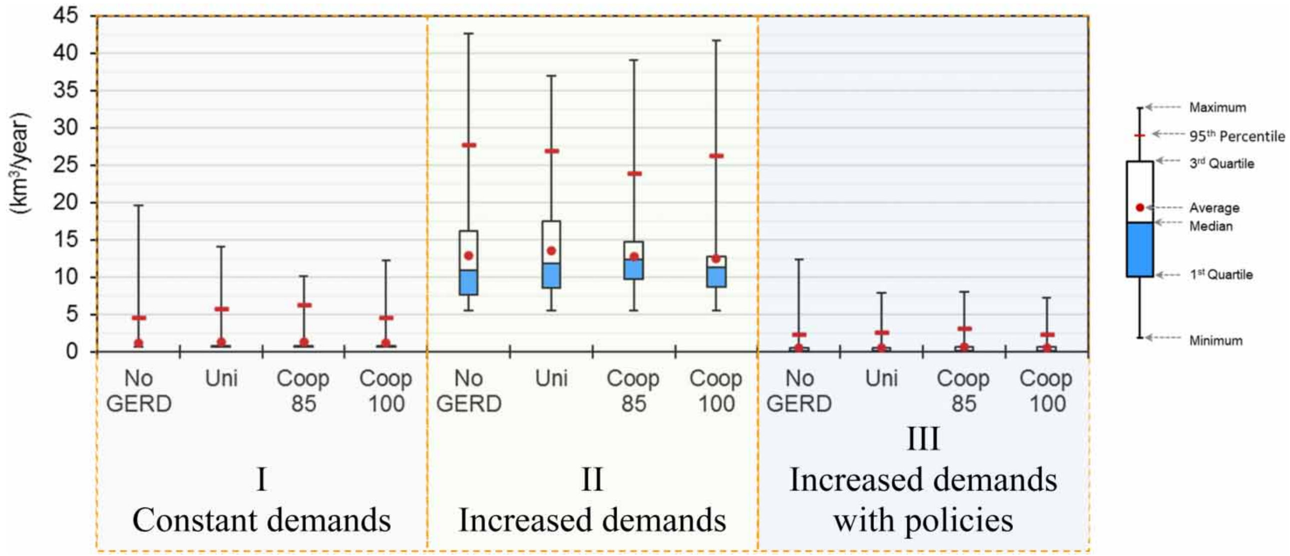

Figure 5 | Annual water shortage in Egypt for the case of no GERD, and unilateral and cooperation positions per each demand scenario.

with the GERD both under unilateral or cooperation conditions, due to improved low flow augmentation offered by the GERD.

The first demand scenario in Egypt indicates that the average water shortage is increased by 0.174 km^3/year (16%) in the unilateral case, 0.253 km^3/year (23%) in the $Coop_{85}$, and 0.091 km^3/year (8%) in the $Coop_{100}$ when compared to the case of no GERD. Moreover, W_{95} increased by 1.156 km^3/year (25%) in the unilateral state, and 1.629 km^3/year (35%) in the $Coop_{85}$ case, but the case $Coop_{100}$ showed no significant changes (0.023 km^3/year) compared to the case of no GERD. The case of $Coop_{85}$ significantly reduces the maximum water shortage (9.397 km^3/year in $Coop_{85}$ compared to 5.480 km^3/year in the unilateral case and 7.311 km^3/year in $Coop_{100}$ case), however, the duration of water shortages increased compared to the other cases, Figure 6(a). The increase in average water shortage and W_{95} for the case of $Coop_{85}$ can be explained by the HAD requests from the GERD being limited to dry periods (i.e., S/D<85%) that may last over multiple years. Additional releases from the GERD during droughts are likely to deplete its reservoir, consequently, prolonging the drought period. Unlike the $Coop_{100}$ case, in which additional flows are released from the GERD once there is a water shortage in Egypt. Such releases from the GERD during below-average flow years (i.e., before multi-year drought starts) are likely to alleviate greatly the impact of significant droughts compared to the other cases, Figure 6(a). In some cases, additional releases from the GERD are not enough to raise the HAD storage level to reduce the demand reduction factor, Table 2. However, the additional releases are stored instead and can be later used especially in severe drought periods. The latter case indicates that the HAD can store additional releases from the GERD and in turn reduce the overall water shortage in Egypt. Moreover, the risks of such a water shortage particularly during drought periods can be substantially reduced with proper coordination among the riparian countries.

The second demand case demonstrates the impact of increased demands and cooperation levels on water shortage in Egypt. The average water shortage increased by 0.674 km^3/year (5%) in the unilateral mode, while it decreased by 0.126 km^3/year (1%) in the $Coop_{85}$ case, and 0.441 km^3/year (3%) in the $Coop_{100}$ case compared to the case of no GERD. The maximum water shortages and W_{95} (reported here in brackets) under both governance conditions are decreased by: 5.669 km^3/year (0.835 km^3/year) in unilateral position, 3.580 km^3/year (3.932 km^3/year) in $Coop_{85}$ case, and 0.925 km^3/year (1.503 km^3/year) in $Coop_{100}$ case. The maximum water shortages in the cooperation mode are higher than the unilateral state, but with a probability of less than 1%, Figure 6(b). The average water shortage is reduced, and the non-exceedance probability of the above-average water shortage is increased, in the cooperation state, compared to the unilateral and the case of no GERD, Figure 6(b).

The third scenario reveals the significance of implementing water policy measures and cooperation over the GERD in reducing the water shortage in the face of increased demands. Average water shortage increased by 0.019 km^3/year (4%) in the unilateral state, 0.068 km^3/year (13%) in the $Coop_{85}$ case and 0.004 km^3/year (1%) in the $Coop_{100}$ case compared to the case

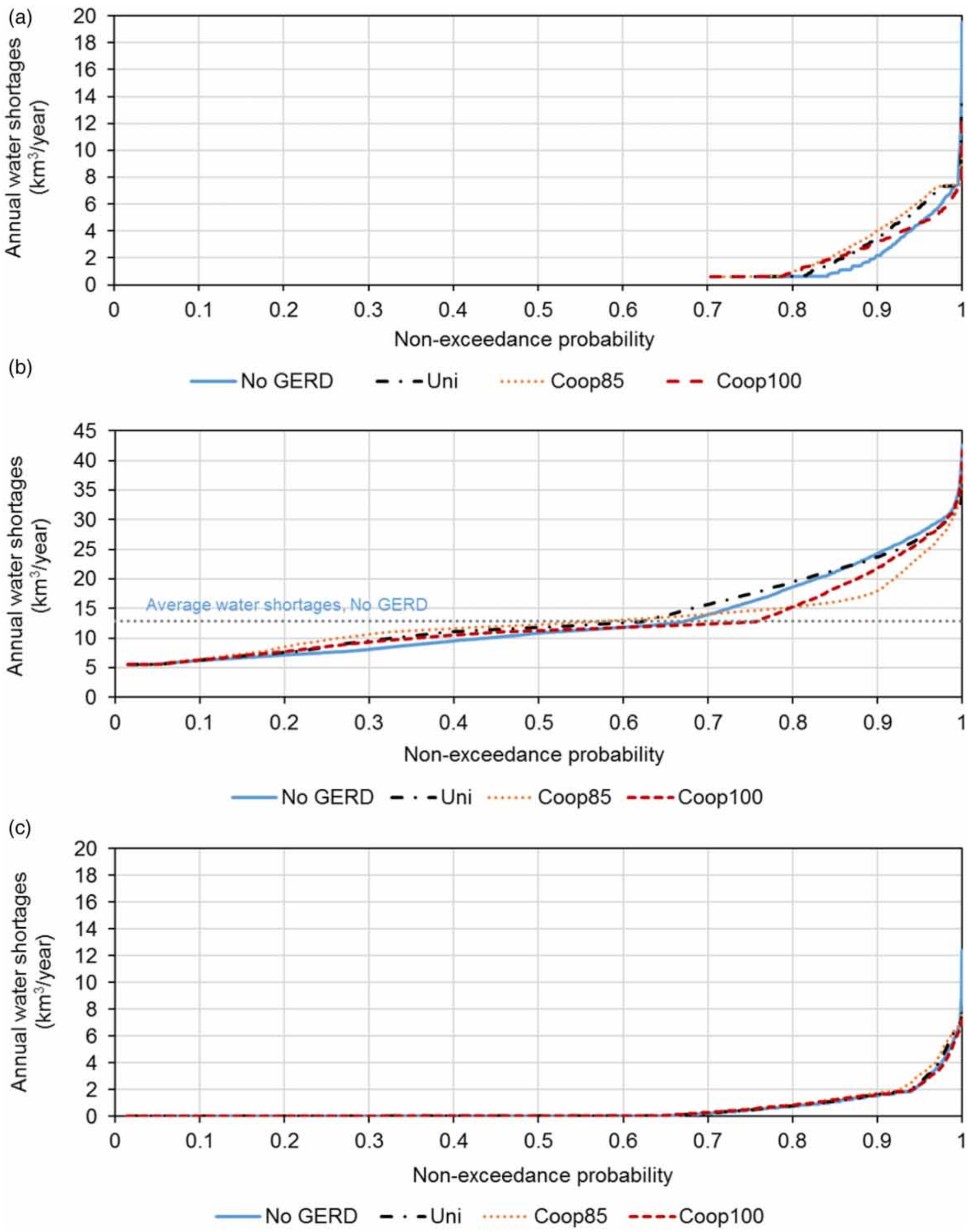

Figure 6 | Non-exceedance probability of annual water shortage under three demand conditions in Egypt with and without GERD. (a) Constant demands. (b) Increased demands. (c) Increased demands with policy measures.

of no GERD, Figure 5. The W_{95} increased by 0.175 km^3/year (7%) in the unilateral state and 0.711 km^3/year (30%) in the $Coop_{85}$ case, while the $Coop_{100}$ case showed no change compared to the case of no GERD. Maximum water shortages reduced by more than 4.5 km^3/year (36%) with and without cooperation in comparison with the case of no GERD. The non-exceedance probability of the above-average water shortage in the $Coop_{100}$ case is found to be similar or higher than the other cases, Figure 6(c). Unlike the $Coop_{85}$ case, the frequency of annual water shortages (>2 km^3/year) increased compared to other cases, Figure 6(c).

The above-shown results suggest that future water demands are expected to exceed water supplies in Egypt and the Nile water in particular. This is in agreement with similar findings by Nikiel & Eltahir (2021). Nevertheless, water policy measures (i.e., 3rd scenario) are likely to alleviate the severity of water shortages due to increased water demands in Egypt (i.e., 2nd scenario). On the other hand, the average annual water shortage in Egypt are expected to increase by up to 0.253 km^3 (1st demand scenario), 0.674 km^3 (2nd demand scenario), and 0.068 km^3 (3rd demand scenario) when the GERD comes online. However, these quantities represent a maximum of 1.1% of the average annual water released downstream of the HAD. Our results, particularly for the first and third scenarios, align well with previous research which concluded that Egypt water uses will not be significantly affected by the GERD operation for an average hydrologic year (see Wheeler *et al.* (2020)). The average water shortages in the third demand scenario are found to be lower than those in the two other scenarios.

The cooperation positions in all demand scenarios indicate that water shortages, particularly during dry periods, can be minimized by releasing additional water from the GERD to Egypt when required. Also, our results suggest that additional water releases before and during droughts (i.e., $Coop_{100}$) are likely to reduce water shortage levels more than in the case of releasing additional releases during droughts only ($Coop_{85}$), suggesting that additional releases from the GERD propagate through the HAD and hence reduce the extreme (maximum) water shortage in Egypt. The results of $Coop_{85}$ scenario exemplifies the joint responsibility and risk redistribution among riparian countries to mitigate the negative impacts of droughts. Conversely, in the current practice of transboundary water resources management the $Coop_{100}$ case may be unrealistic, but indicates what could be possible if implemented. It is worth noting that these results are neither an endorsement of water rights nor support for an individual country over others in the Nile basin. Instead, they provide a guide for policy makers and stakeholders on how to improve resource governance in the basin and promote integrated resource planning and management. Furthermore, our results imply and stress the need for and benefit from a high level of coordination among the riparian countries to reduce the risks associated with droughts in the entire basin.

Food production

The impact of the different system configurations on food production (FP) in Egypt is shown as box plot graphs, Figure 7. The positive impact of the GERD due to improved low flows during dry periods, with and without cooperation, is shown (i.e., 1st quartile of food production) for the three demand patterns in Egypt. This critical finding indicates that the improved low flows by the GERD during the dry season propagate through the HAD during dry periods. For the case of an unchanged demands pattern in Egypt, the minimum food production will increase on average (averaged through all years of simulations) by 0.95 million tonnes (2%) for the unilateral state, 1.89 million tonnes (3%) for $Coop_{85}$ and 3.37 million tonnes (5%) for $Coop_{100}$ compared to the case of no GERD. By looking at the $FP_{95\%}$ values, FP_{95} will reduce by 3.0 million tonnes (4%) in unilateral state and by 3.67 million tonnes (5%) in $Coop_{85}$ compared to the case of no GERD. In contrast, the case of $Coop_{100}$ showed no changes to the FP_{95}. Interestingly, GERD operation modes did not have a significant effect on average food production in Egypt (less than 1%).

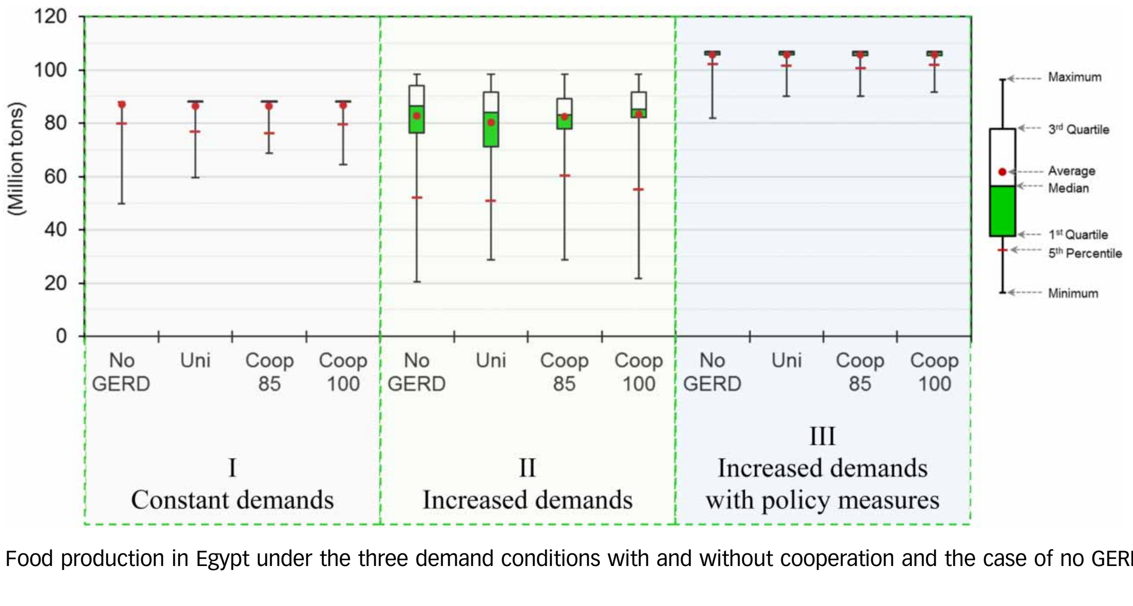

Figure 7 | Food production in Egypt under the three demand conditions with and without cooperation and the case of no GERD.

The second demand pattern demonstrates the potential combined impacts of GERD operation and increased future water demands without policy measures in Egypt on food production. The minimum food production is increased on average by 2.98 million tonnes (11%) in the unilateral state, 7.05 (19%) in $Coop_{85}$ case, and 5.46 million tonnes (14%) in $Coop_{100}$ case. However, FP_{95} in the unilateral state is decreased by 1.37 million tonnes (3%), while it increased by 8.22 million tonnes (16%) in the cooperation case $Coop_{85}$, and 2.76 million tonnes (5%) in the cooperation case $Coop_{100}$. Average food production will be reduced by approximately 2.58 million tonnes (3%) in the unilateral case and by 0.46 million tonnes (<1%) in the cooperation case $Coop_{85}$, while it increased by 0.55 million tonnes (<1%) in the cooperation case $Coop_{100}$. The variability of food production around the median in the cooperation modes is reduced as opposed to the unilateral state and the case of no GERD (Figure 7) as a result of reduced agricultural water shortages following increased water supplies from the GERD. It can be argued that food production under the cooperation modes is improved compared to the unilateral state. This indicates the role of cooperation in improving the downstream situation in general, while the associated upstream impacts will be discussed in detail below. On the other hand, the cooperation case $Coop_{100}$ illustrates the extended impacts of additional releases from the GERD on the overall system. The case of $Coop_{100}$ resulted unexpectedly in minimum values of food production that are lower than in the unilateral case, Figure 7. Regular high releases from the GERD to the HAD particularly during multi-year drought are likely to deplete the GERD reservoir, and in turn, prolong the drought period compared to the unilateral state and even the case of no GERD. These findings demonstrate the limitations on cooperation, as a result of water availability, in shared river basins.

The third demand scenario illustrates the impact of the GERD operation modes and water policy measures on food production. The minimum food production (averaged throughout the simulation), is found to increase by about 0.61 million tonnes (<1%) in the unilateral case and by 1.19 million tonnes (1%) in the cooperation case of $Coop_{100}$ when compared to the case of no GERD. In contrast, the cooperation case $Coop_{85}$ showed no changes in the minimum food production. The FP_{95} is reduced by 0.65 million tonnes (<1%) in the unilateral state, and 1.65 million tonnes (2%) in the cooperation case $Coop_{85}$ when compared to the case of no GERD, unlike in the cooperation case $Coop_{100}$ that showed no changes. Interestingly, the operation modes of the GERD showed negligible effects on the average food production in comparison with the case of no GERD.

The comparison between food production under the second and third demand scenarios shows the water-food nexus interdependency. Increasing the pressure on the water resources could significantly impact food production (the second scenario), while implementing water policy measures is likely to considerably improve food production (the third scenario). Average food production in the third scenario is higher than those under the second scenario by more than 22 million tonnes (>22%), Figure 7. Although the second demand scenario might not seem to be preferred, it emphasises the significance of improving water use efficiency and the role of cooperation among the riparian countries in shared river systems to improve the system outcomes. Furthermore, the second demand scenario is a critical scenario that indicates the impact of business as usual strategies on food production on an individual country and the entire basin if the countries agree to cooperate. It is also noteworthy that average food production under the three demand scenarios did not change significantly under different GERD operation modes when compared to the case of no GERD. This means that for an average hydrologic year, there is no conflict between GERD operation modes and food production in Egypt assuming that the current demand pattern from the HAD stays unchanged. Our findings are in agreement with previous studies such as Arjoon *et al.* (2014) and MIT (2014). On the other hand, the minimum food production is increased in the three demand scenarios when compared to the case of no GERD as a result of enhanced dry season flows offered by the GERD. The comparison between the results of $Coop_{85}$ and $Coop_{100}$ shows the extent of cooperation level on food production.

Hydropower generation

The impact of hypothetical cooperation and unilateral scenarios on the total hydropower generation (HP) in Egypt, Ethiopia and Sudan under different demand patterns in Egypt is shown in Figure 8. For the first and third demand conditions, average regional hydropower generation will be higher in the cooperation position than in the unilateral position by up to 1.5%. In other words, cooperation positions are likely to add up to an average of 547 GWh/year that is equivalent to hydroelectricity generation from a power plant with a capacity of 62 MW. In contrast, a further increase in water demands in Egypt, particularly without adequate water policy measures (i.e., second scenario), is likely to reduce the average hydropower generation in the basin by up to 1,152 GWh/year (3%) even if cooperation is considered. Excessive water releases from the GERD to meet increased downstream water demands are likely to reduce the GERD's hydropower generation in particular and the regional

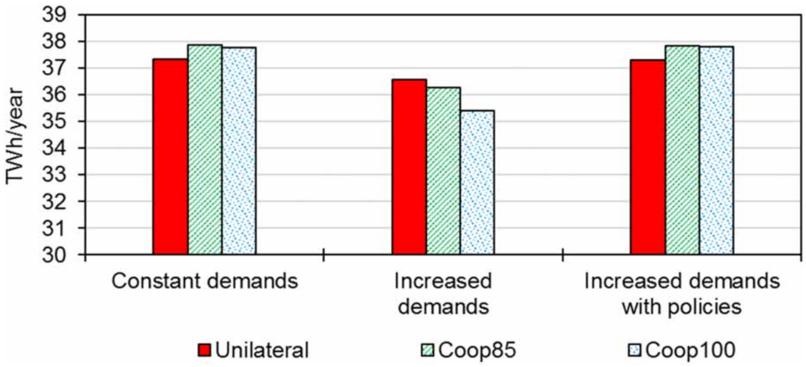

Figure 8 | Total average hydropower generation in Egypt, Ethiopia, and Sudan under the three operation modes of GERD and three demand conditions in Egypt.

hydropower generation as well. The latter reflects the limits of the cooperation mode in the case of continued downstream demands, unlike the third demand scenario in which water policy measures are adopted to meet growing water demands in Egypt. Meanwhile, maintaining current operation rules and downstream releases from the HAD (i.e., third scenario where policy measures are applied to meet growing water demands) is crucial to improving regional hydropower generation particularly if cooperation is adopted.

The impact of GERD operation modes on hydropower generation in individual countries per each demand scenario is also presented. The hydropower generation in Egypt and Sudan will be reported with reference to the case of no GERD, while in Ethiopia it will be reported for the operation modes of GERD as compared to the unilateral state (i.e., preferred condition). For the unchanged demand pattern, the minimum hydropower generation in Egypt would increase under both the unilateral by 585 GWh/year (15%) and cooperation conditions by more than 900 GWh/year (23%), Figure 9(a). However, HP_{95} is reduced by 310 GWh/year (5%) in the unilateral state and 440 GWh/year (6%) in the cooperation case $Coop_{85}$, while it did not change in the cooperation case for $Coop_{100}$ when compared to the case of no GERD. Also, the average HAD hydropower generation in the unilateral and the two cooperation states is reduced by more than 150 GWh/year (approximately 2%). The reduction in average hydropower generation in Egypt can be attributed to the reduction in the HAD levels (see Supplementary Data (f)), which is associated with the reduction in average annual Nile flows following increased evaporation from the GERD reservoir (see Supplementary Data (d)). The hydropower generation in Ethiopia is found to be affected only in the cooperation state $Coop_{100}$, Figure 9(b). The minimum hydropower generation, in $Coop_{100}$, is reduced by 2,000 GWh/year (19%), however, the hydropower generation below 14.5 TWh/year has less than 2% of a chance of falling below the level of the unilateral state. Conversely, HP_{95} increases by 295 GWh/year (2%), following additional releases from the GERD turbines. Also, the average hydropower generation could be reduced by 126 GWh/year (less than 1%) in this position.

In Sudan, the hydropower generation will be improved in both cooperation and unilateral states, when compared to the case of no GERD, following river flow regulation offered by the GERD, Figure 9(c). For instance, the minimum hydropower generation is increased by 1,289 GWh/year (24%) in the unilateral state, 1,970 GWh/year (36%) in $Coop_{85}$ case and 930 GWh/year (17%) in the $Coop_{100}$ case. Furthermore, HP_{95} is increased by 523 GWh/year (7%) in the unilateral state and by more than 1,300 GWh/year (18%) in the two cooperation states, Figure 9(c). Average hydropower generation is increased by 520 GWh/year (6%) in the unilateral state and 1,100 GWh/year (12%) in the cooperation state. Interestingly, each of the GERD regulation and operating the Blue Nile dams at their full supply level equally increase the average hydropower generation in Sudan by about 570 GWh/year (6%). The minimum hydropower generation in Ethiopia and Sudan for $Coop_{100}$ case is lower than $Coop_{85}$ case, due to operating the reservoirs – particularly the GERD and the Sudanese dams – at lower levels in the $Coop_{100}$ during dry periods. However, the latter case has only a minimal chance to occur as shown above and in the literature (Wheeler *et al.* 2018; Wheeler *et al.* 2020).

In the second demand pattern, the minimum hydropower generation in Egypt is increased by approximately 875 GWh/year (28%) in the unilateral state, 273 GWh/year (9%) in $Coop_{85}$ and 337 GWh/year (11% in $Coop_{100}$). Counterintuitively, the unilateral state gives higher values for the minimum values of hydropower generation compared to the cooperation states, due to the increased probability of reaching the minimum operating level of the HAD and the GERD under the cooperation state. HP_{95} is reduced by 84 GWh/year (2%) in the unilateral case, while it increases by 373 GWh/year (7%) in $Coop_{85}$ and 69

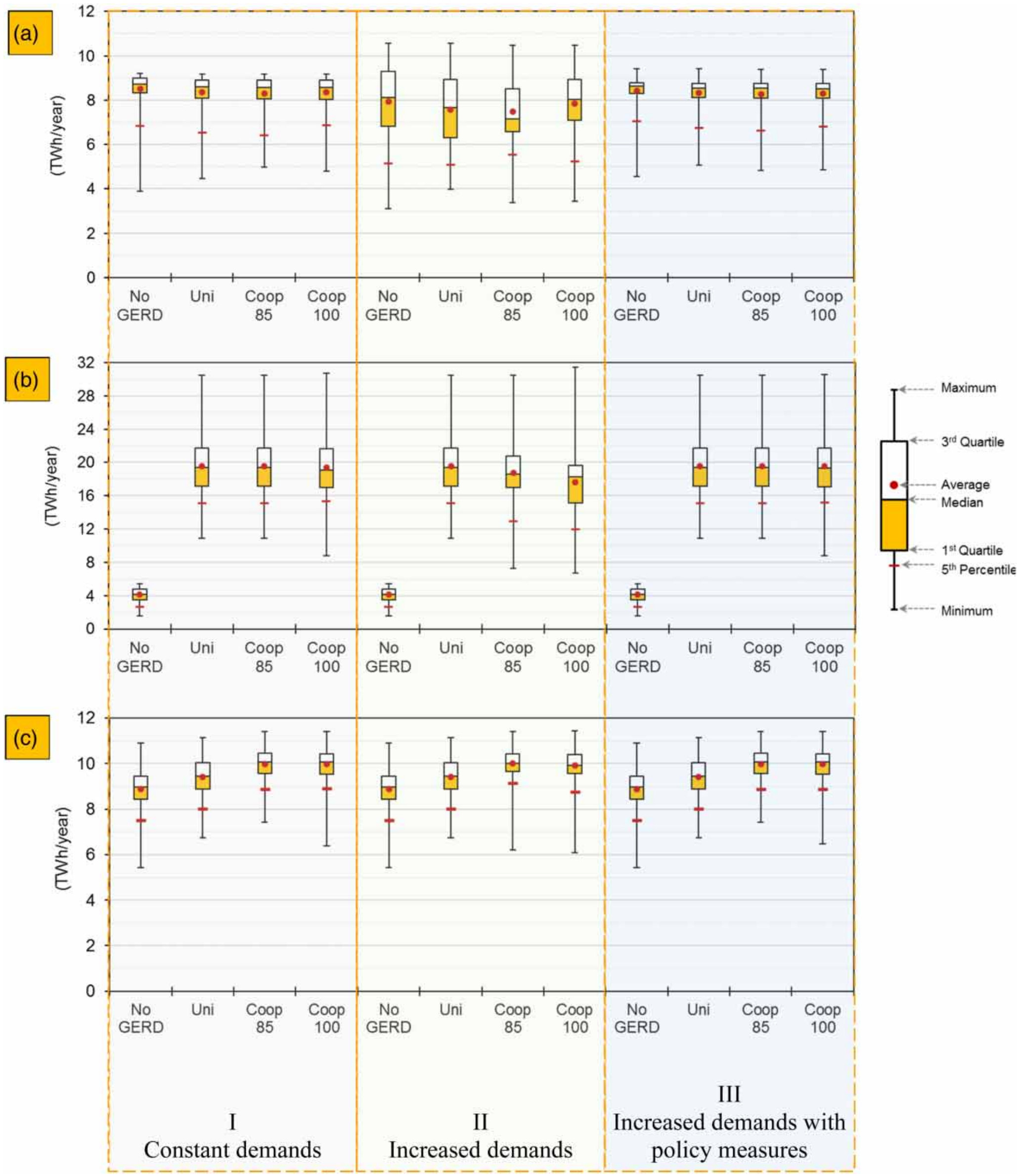

Figure 9 | Hydropower generation in (a) Egypt, (b) Ethiopia and (c) Sudan with and without cooperation under the three demand patterns in Egypt.

GWh/year (1% in $Coop_{100}$). Moreover, average hydropower generation is reduced by up to 440 GWh/year (6%) in both unilateral and cooperation positions while $Coop_{100}$ is the least affected case (reduced by 1%), Figure 10.

Regular additional releases from the GERD to the HAD – in the second demand scenario – are likely to significantly reduce hydropower generation in Ethiopia and the GERD hydropower in particular, as shown in Figure 9(b). The minimum hydropower generation in Ethiopia under the two cooperation positions is reduced by up to 4,168 GWh/year (38%). Moreover, HP_{95} could be reduced by more than 2,142 GWh/year (14%), due to the increase in the frequency of operating the GERD at lower levels. Average hydropower generation is also reduced by 1,932 GWh/year (10%) in $Coop_{100}$ and 776 GWh/year (4%) in $Coop_{85}$, Figure 10. Conversely, the hydropower generation in Sudan is only marginally affected under this demand scenario. Average hydropower generation will be increased by up to 1,120 GWh/year (13%) and HP_{95} increased by up to 1,646 GWh/year (22%) under the two cooperation positions. Also, the minimum hydropower generation in the two cooperation positions is increased by up to 774 GWh/year (14%), which is less than those of the first demand scenario

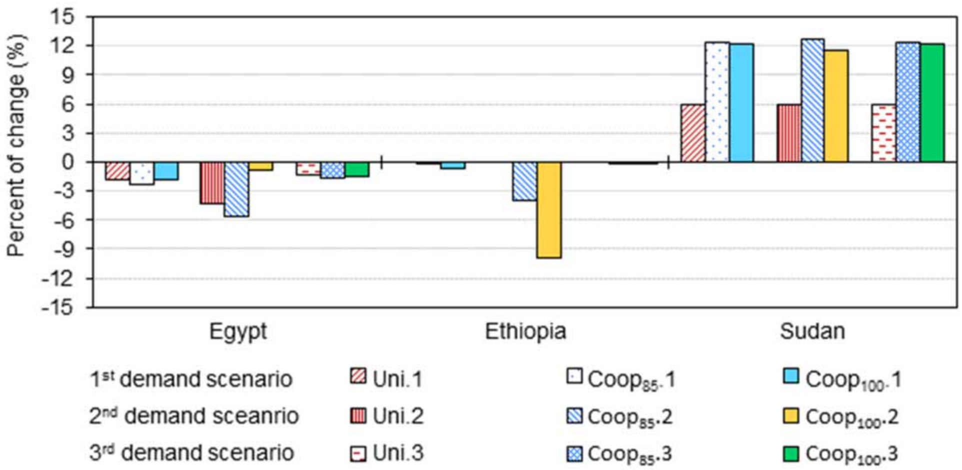

Figure 10 | Percentage of change in average hydropower generation per each demand pattern under different GERD operation modes in Egypt, Ethiopia, and Sudan. *Note*: Egypt and Sudan results are with reference to the case of no GERD; Ethiopia results are with reference to the unilateral position.

(by up to 16%). The second scenario shows the limitation to cooperation among the riparian countries as increased demands from downstream users could lead to undesirable results across the basin.

The third scenario indicates that the average hydropower generation in Egypt is slightly decreased by 110 GWh/year (1%) in the unilateral state and up to 142 GWh/year (2%) in the cooperation states compared to the case of no GERD. HP_{95} is reduced by 286 GWh/year (4%) in the unilateral state, by up 400 GWh/year (6%) in $Coop_{85}$, and 231 GWh/year (3%) in $Coop_{100}$. However, the minimum hydropower generation is increased by 507 GWh/year (11%) in the unilateral mode and up to 304 GWh/year (6%) in both cooperation conditions. In Ethiopia, cooperation mode has a negligible impact on average hydropower generation, Figure 10. However, the minimum hydropower generation could be reduced by 2,067 GWh/year (19%), but with a 1% chance to fall below the level experienced in the unilateral state. The impacts of GERD operation modes on the hydropower generation in Sudan are found to be similar to those of the first scenario.

The comparison among the assumed scenarios under cooperation positions provides interesting insights. The second scenario, although an extreme situation, presents the potential impacts of increased future downstream demands on basin-wide hydropower generation, while the third scenario shows the need for a high level of coordination and commitment between both upstream and downstream countries to maximize system outcomes (i.e., downstream countries, Egypt in this case, adopt adequate water policy measures, while upstream countries, Ethiopia in this position, releases additional water from the GERD when needed). Basin-wide and in-country hydropower generation are less likely to be significantly impacted by the cooperation positions in the first and third scenarios, unlike in the second scenario. Average hydropower generation in Egypt under the third scenario is found to be close to those under the first scenario and higher than the second scenario by up to 826 GWh/year (see Figure 9(a)), following similar water levels in the HAD reservoir observed under the first and third scenarios (see Supplementary Data (f)). Similarly, in Ethiopia, average hydropower generation is found not to be significantly impacted under the first and third scenarios (reduced by less than 1%). On the other hand, Sudan is found to be positively impacted by the GERD operation modes either in cooperation or unilateral positions under the three demand conditions. The level of redistribution of risks among the riparian countries during drought periods is illustrated here by the analysis of the two cooperation modes, $Coop_{85}$ and $Coop_{100}$. The $Coop_{85}$ case indicates that the riparian countries can mitigate the impacts of a drought with negligible impacts on their hydropower generation. In contrast, the $Coop_{100}$ case shows the extent of full cooperation on hydropower generation at the national and basin level. While maximum water shortages are reduced and minimum food production is increased in this case, the minimum guaranteed hydropower generation in Ethiopia and Sudan could be reduced. Thus, our approach should be considered in a multilateral framework for regional cooperation that goes beyond shared water aspects where overall gains (e.g., food, energy and water) are anticipated to be higher (see discussion in Keskinen *et al.* 2021). Broader themes for regional cooperation might include trade, economic and peace agreements, and political relations among the basin countries (Keskinen *et al.* 2021). In return, an incentive-based compensation mechanism could be incorporated to support the affected countries when managing drought-based risks.

The unilateral position considered in our analysis shows the impacts of upstream decisions on downstream users. In contrast, the second demand scenario exemplifies externalities generated from increased downstream demands even if the riparian countries agree to cooperate (see discussions in Sadoff & Grey (2002)). Our results indicate that increased downstream water demands are likely to impact basin-wide hydropower generation including upstream users under cooperation positions. Average basin-wide hydropower generation in the second scenario is less than those of the first and third scenarios by 4% (in $Coop_{85}$) and 6% (in $Coop_{100}$), (see Figure 8). Moreover, during below-average and dry years the hydropower generation in the second scenario is lower than for the two other scenarios by up to 6,375 GWh/year (27%) (see Supplementary Data (g)). However, maintaining current water demand levels from the HAD are likely to reduce these impacts (i.e., third scenario).

CONCLUSIONS

We proposed a WFE nexus-based simulation framework to analyse cooperation opportunities as well as understand associated risks with a multi-reservoir system in shared river basins. We developed a mechanism to achieve cooperation on the ground through a joint operation of system reservoirs where agreed additional water volumes could be released from an upstream reservoir to downstream users when needed, assuming that countries collaborate to mitigate potential drought-related risks. Moreover, the developed mechanism allows for testing cooperation level and shared responsibility among riparian countries by employing a variable water supply to demand ratio (e.g., 90%) for a downstream user. We applied the developed framework to the Nile River basin considering the GERD reservoir development in Ethiopia as a case study. Varying demand levels in Egypt were considered: (a) current water demand levels (2015), (b) increased water demands but without developing additional water resources and (c) similar to (b) but with water policy measures in force. We examined two positions of the system reservoir operation: (a) cooperation among riparian countries and (b) unilaterally motivated policies. A System Dynamics model for the entire Nile basin that incorporates the aforementioned governance conditions was employed here. The examined unilateral positions under the three demand scenarios investigate the impacts of upstream decisions on downstream users. In contrast, the cooperation position under the second demand scenario illustrates the impact of downstream abstraction levels on the upstream users and the entire system.

Our results suggest that the low flow augmentation offered by the GERD are likely to improve the WFE nexus position in Egypt during dry periods in both unilateral and cooperative governance modes compared to the case of no GERD. In Sudan, the river flow regulation caused by the GERD operation will improve hydropower generation and water supply levels in the unilateral position and the outcomes have the chance to further increase with cooperation. The cooperation among the riparian countries over the GERD has the potential to reduce risks to downstream countries, especially during drought periods with small to negligible impacts on the GERD hydropower generation. The scenarios of current and increased water demands with policy measures (i.e., first and third scenarios) during the long-term operation of the GERD suggest that:

- Cooperation positions are likely to add an average of 547 GWh/year at the basin level.
- Average annual Nile flows and hydropower generation in Egypt are likely to decrease by 2%, with negligible impacts on average food production.
- Food production, hydropower generation and water supply are likely to improve during dry periods, particularly under full cooperation case ($Coop_{100}$).
- In Ethiopia, average hydropower generation is not likely to be significantly impacted by the cooperation positions (showed less than 1% reduction).
- In Sudan, average hydropower generation will increase by 6% in unilateral and by 12% in cooperation positions.
- The cooperation position $Coop_{85}$, where countries share the risk to mitigate drought-related impacts, indicates that downstream risks could be reduced with negligible impacts on upstream objectives.
- During dry periods, the full cooperation position showed that the WFE nexus outcomes in Egypt are likely to improve, while the minimum hydropower generation in Ethiopia and Sudan are likely to fall below those of the unilateral position (by about 2,000 GWh/year) but with a low likelihood (a 1% chance). This suggests a compensation-based mechanism could be considered along with our approach for the affected countries through an anticipated regional comprehensive socio-economic framework for cooperation and integration.

The second demand scenario (i.e., increased water demand) in Egypt is an explorative scenario demonstrating the limits of cooperation in a shared river basin as a result of increased water demands against limited water availability. Despite being an extreme scenario, it resembles the impact of the continuation in business as usual strategies on individual countries and the entire basin when countries seek cooperation. Average basin-wide hydropower generation is likely to decrease by 4–6% under cooperation position(s), while below-average values of hydropower generation could reduce by up to 27% when compared to the cooperation positions of the two other scenarios. While Egyptian average water shortages could be reduced and average food production and hydropower generation increased under cooperation positions, the outcomes are likely to be adversely impacted during dry periods.

The comparison between the second and the third scenarios indicates that maximizing cooperation benefits depends on: (i) the commitment and the success of implementing policies in Egypt to balance the growing demands and (ii) the willingness of Ethiopia, coupled with incentives, to cooperate and release additional flows to Egypt when needed. Furthermore, a high level of coordination, commitment and trust among the riparian countries is urgently required to achieve the cooperation benefits. These results reveal the challenges in shared river basins, particularly with increased pressure from population growth and that proper water management from downstream users and high coordination among the riparian countries are crucial to gain cooperation benefits. For example, future water demands in Egypt are likely to exceed potential water supply, including Nile water in particular, while water policy measures are expected to narrow the gap between supply and demand. The results also call for further investigation of coordinated operation policy for the reservoir system. Future work can be extended to explore cooperation while considering future planned upstream infrastructure projects and water abstractions as well as under climate change.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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