The Nile Water-Food-Energy Nexus under Uncertainty: Impacts of the Grand Ethiopian Renaissance Dam

Hamdy Elsayed[1], Slobodan Djordjević[2], Dragan A. Savić[3], Ioannis Tsoukalas[4], and Christos Makropoulos[5]

[1]PhD Student, Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, Univ. of Exeter, Exeter EX4 4QF, UK; Teaching assistant, Faculty of Engineering, Menoufia Univ., Shebin Elkom, Menoufia, 32511, Egypt, (Corresponding author)

[2]Professor of Hydraulic Engineering, Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, Univ. of Exeter, Exeter EX4 4QF, UK

[3]Chief Executive Officer, KWR, Water Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands; Professor of Hydroinformatics, Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, Univ. of Exeter, Exeter EX4 4QF, UK

[4]Postdoctoral Researcher, Dep. of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical Univ. of Athens, Heroon Polytechneiou 5, 15780 Zographou, Greece

[5]Associate Professor, Dep. of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical Univ. of Athens, Heroon Polytechneiou 5, 15780 Zographou, Greece; Principal scientist, KWR, Water Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands

ABSTRACT

Achieving Water, Food and Energy (WFE) nexus balance through policy interventions is challenging in a transboundary river basin because of the dynamic nature and inter-sectoral complexity that may cross borders. The Nile basin is shared by a number of riparian countries and is currently experiencing rapid population and economic growth. This has sparked new developments to meet the growing water, food and energy demands, alleviate poverty and improve the livelihood in the basin. Such developments could result in basin-wide cooperation or trigger conflicts among the riparian countries. A System Dynamics model was developed for the entire Nile basin and integrated with the Food and Energy sectors in Egypt to investigate the future of the WFE nexus with and without the Grand Ethiopian Renaissance Dam (GERD) during filling and subsequent operation using basin-wide stochastically generated flows. Different filling rates, from 10-100% of the average monthly flow are considered during the filling process. Results suggest that the GERD filling and operation would affect the WFE nexus in Egypt, with the impact likely to be significant if the filling process occurred during a dry period. Food production from irrigated agriculture would be reduced by 9 to 19% during filling and by about 4% during GERD operation compared to the case without it. The irrigation water supply and hydropower generation in Sudan

will be reduced during the filling phase of the GERD, but this is expected to be improved during the dam operation phase as a result of the regulation afforded by the GERD. The Ethiopian hydropower generation is expected to be boosted by the GERD during the filling and operation of the dam, adding an average of 15,000 GWh/year once GERD comes online. Lastly, the results reveal the urgency of cooperation and coordination among the riparian countries to minimize the regional risks and maximize the regional rewards associated with the GERD.

Keywords: GERD, Nile Basin, Stochastic Analysis, System Dynamics Modelling, Water-Food- Energy Nexus

INTRODUCTION

Water, food and energy are essential resources on which societies rely to achieve their social, economic and environmental goals. The three domains are inextricably linked, and the Water, Food, Energy (WFE) nexus concept recognizes the interdependencies among its components. The nexus considers the different dimensions of water, food and energy components equally (FAO 2014) and provides a transparent framework for investigating trade-offs and synergies among them, without compromising sustainability. The interlinkages between water, food and energy are well documented (Bazilian et al. 2011; Hoff 2011; Lawford et al. 2013; FAO 2014). From a food production perspective, water and energy are inputs, while from an energy perspective water and biomass, e.g., biofuels, are resource requirements. Considerable energy is required for irrigation especially for groundwater pumping, as well as in the production of agricultural fertilizers. Thermal power stations and fossil fuel extraction require water and can cause serious environmental pollution. Achieving the WFE nexus balance and improving long-term sustainability through policy interventions is challenging in a transboundary river basin, because of the nexus dynamics and inter-sectoral complexity that may cross borders (UNECE 2018). With population and economic growth in riparian countries, each country aims at maximizing its own water, food and energy resources in the basin to meet the growing demands (Jalilov et al. 2016). Such developments (e.g., dams) and policies could either promote cooperation among riparian countries or result in conflict. Therefore, the nexus approach has the potential to identify trade-offs between competing riparian stakeholders for the water, food and energy resources and promote an understanding of shared benefits and cross-sectoral developments in the basin (Lawford et al. 2013; UNECE 2018). Moreover, the nexus approach is relevant for managing interlinked resources and related socio-economic dynamics in transboundary river basins (Jalilov et al. 2016; Basheer et al. 2018; UNECE 2018).

The water, food and energy interlinkages need to be addressed at the river basin scale (Lawford et al. 2013; Jalilov et al. 2016; UNECE 2018). Recently the numbers of studies that address the tight connections among the water, food and energy in transboundary river basins are increasing (e.g., Keskinen et al. 2015; Jalilov et al. 2016; Pittock et al. 2016; Yang et al. 2016; Basheer et al. 2018; Yang et al. 2018; Allam and Eltahir 2019; Amjath-Babu et al. 2019, to name but a few). These studies provided different frameworks to explore the WFE nexus interdependencies in transboundary river basins considering dam and irrigation developments in the riparian countries. For example, Jalilov et al. (2016) developed a hydro-economic optimization model to investigate the WFE nexus in the Amu Darya basin under the planned Rogun dam in Tajikistan. An agent-based modelling approach was utilized to analyse the impacts of water agent's management decisions on the food-water-energy-environment nexus at the basin level (e.g., Yang et al. 2018; Khan et al., 2017). However, most of the above-mentioned studies utilize the loose coupling of models (e.g., Yang et al. 2018; Khan et al., 2017) that fail to address the dynamic feedbacks and interactions between the individual sectors within the nexus (Amjath-Babu et al. 2019) and particularly between the nexus and socio-economic components (Liu et al. 2017). Furthermore, the long-term uncertainty associated with river flows has been seldom addressed. Despite the progress in nexus studies, there is no unified framework to address the domain interdependencies and the nexus predominantly stays in the conceptual domain (Albrecht et al. 2018). Systematic tools that adequately quantify the nexus interdependencies and address the trade-offs among the nexus domains in river basins are required (Bazilian et al. 2011; Lawford et al. 2013; Liu et al. 2017).

The Nile is a transboundary river in East Africa shared by 11 riparian countries and is currently experiencing rapid population and economic growth. Food consumption, access to water, access to electricity and income per capita in most of the Nile countries are among the lowest in the world except for Egypt (NBI 2016b). Increased pressure from growing population, economies and urbanization have induced the riparian countries to develop ambitious master plans to tap the resources potential in the basin to meet their growing water, food and energy demands and sustain their economies (Whittington et al. 2005; Awulachew 2012). Prefeasibility and feasibility studies for a number of planned projects (e.g., irrigation expansions and hydropower projects) have been completed with few projects currently being under construction in the riparian countries (Cervigni et al. 2015). The largest of those developments is the Grand Ethiopian Renaissance Dam (GERD), which has the potential to improve long-term sustainability through collaboration between all riparian countries, but also has caused tensions and could lead to hydro-political conflicts. However, conflicts among the riparian countries are likely to emerge without cooperation, coordination and with unilateral developments (Digna et al. 2018). That makes the nexus approach relevant for addressing the WFE nexus interdependencies in the Nile river basin. Due to its importance for riparian countries, a number of studies have been conducted to investigate water management challenges and plan potential interventions (e.g., multipurpose dams and irrigation expansion) in the Nile basin. The long-term developments in the basin were investigated in several studies (e.g., Whittington et al. 2005; Georgakakos 2006; Block and Strzepek 2010; Goor et al. 2010; Digna et al. 2018). The announcement of the GERD construction in

2011 has led to several new studies (e.g., Arjoon et al. 2014; Mulat and Moges 2014; Abdelhaleem and Helal 2015; Wheeler et al. 2016; Zhang et al. 2016, to mention but a few). While to some extent these previous studies addressed water management in the basin and also the implications on the irrigation supply and hydropower generation at different temporal and spatial scales, there is no comprehensive study of the entire basin. Furthermore, some of these models are limited to exploring the Nile historical flow records and applying a deterministic approach that cannot adequately address the long-term uncertainty in future river flows.

In the WFE nexus context, the impacts of the GERD filling and operation on the WFE nexus have been recently explored (Passell et al. 2016; Tan et al. 2017; Basheer et al. 2018; Allam and Eltahir 2019) with other studies concern the WFE nexus in the Nile countries (e.g., Al-Riffai et al. 2017; El Gafy et al. 2017). These studies provided various approaches to better understand the WFE nexus interdependencies and their complex nature in the Nile basin. However, most of these studies (e.g., Tan et al. 2017; Passell et al. 2016; El Gafy et al. 2017) did not consider significant infrastructures in Egypt and Sudan and some other investigations were limited to the Blue Nile basin (e.g., Basheer et al. 2018 Allam and Eltahir 2019). What appears to be lacking is a tool that can support an improved understanding of the nature of the nexus in the entire Nile basin and equip decision-makers with negotiation and policy tools for achieving cooperation among riparian countries.

The current study presents a novel approach that considers the interactions between the WFE nexus and the socio-economic sectors in the river basin together with the inherent uncertainty of the river flow regime through the application of basin-wide stochastically generated river flows. The framework was employed for the Nile river basin as a case study to investigate possible future of the WFE nexus in the basin with and without the GERD. The impact of the GERD development is investigated during the filling and operation stages of the dam by employing stochastic flow analysis and assuming that the current WFE nexus management policies in the basin stay unchanged. The application of the framework involves: (1) consideration of the entire Nile river basin water resources system, (2) the complete WFE nexus analysis for Egypt and (3) a partial consideration of the nexus for other countries (food production was not considered but irrigation water demand is accounted for as a proxy for food production from irrigated agriculture). The limitations of the WFE nexus study for the regions outside Egypt are due to restricted availability of data. The paper is organised in five major sections: (1) Study area description, (2) Materials and methods, (3) Model sectors, (4) Results and discussion, and (5) Conclusions.

STUDY AREA DESCRIPTION

The Nile is a transboundary river shared between eleven riparian countries, Burundi, DR Congo, Egypt, Eretria, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. Population and economic projections in the Nile basin indicate continued growth (NBI 2016b). This, in turn has sparked new developments across the riparian countries (e.g., the recently commissioned Merowe dam in Sudan, the TK5 dam, the Koga dam and the Fincha-Amerti-Neshe dam in Ethiopia and the Bujagali hydropower station in Uganda) aimed at meeting the growing demand for water, food and energy, while also contributing to poverty alleviation and improving the livelihood in the basin (Whittington et al. 2005). With a length of about 6,700 km, the Nile is the longest river in the world and its drainage area covers about 3 million km^2. It is considered one of the most complex rivers because of its transboundary nature, its size, a variety of climates, topographies and the high system losses (Sutcliffe and Parks 1999). Although large in terms of length and its importance to riparian countries, the mean annual Nile runoff is relatively small compared to major rivers in the world (84 km^3). The Nile originates from two main tributaries, the White Nile and the Blue Nile (Fig. 1.). The White Nile starts at the Equatorial Lakes that contribute annually about 8 km^3. The evaporation and transpiration water losses are high in the Sudd region and are estimated to be approximately half of the Sudd inflows. The average annual inflow of the White Nile at Malakal is 28.5 km^3, which is characterised by steady (a relatively less variable) flows throughout the year. The Blue Nile originates from the Ethiopian highlands and contributes to about 60% of the total annual flow of the Main Nile. Inside Sudan, the Blue Nile receives water from two major tributaries, the Dinder and the Rahad. The long-term mean annual discharge at the Sudanese-Ethiopian borders is estimated at 48.66 km^3 (Sutcliffe and Parks 1999). Unlike the White Nile, it is characterised by large seasonal and annual flow variations. The rainfall occurs during a single period (July-October) and depends on the seasonal fluctuation of the InterTropical Convergence Zone. At Khartoum, the confluence of the White Nile and the Blue Nile forms the Main Nile, and the Main Nile receives the last tributary, the Atbara River and drains areas of northern Ethiopia and Eritrea. The Atbara River is a seasonal river characterised by high seasonality and runs dry for about 5 months (January-May) each year, unlike the Blue Nile that flows all the year. While the remaining months represent the wet season with peak flow occurring in August. The Main Nile continues its journey through arid to hyper-arid regions until it reaches Lake Nasser or (Lake Nubia) at Wadi Halfa in Egypt. The water released from Lake Nasser through the High Aswan Dam (HAD) is used to meet different water demands in Egypt and the river reaches the Mediterranean Sea near Cairo.

Most of the existing water resource infrastructure has been located in Egypt and Sudan with little developments in the upstream countries. The Old Aswan Dam (1902) and Jebel Aulia Dam (1937) on the White Nile were constructed to provide water for irrigation in Egypt, while the Sennar Dam (1925) on the Blue Nile was built to irrigate the Gezira scheme in Sudan. The Owen Falls Dam (1953) - currently the Nalubaale power station - was constructed for hydropower generation in Uganda without affecting the natural flows of Lake Victoria (Howell and Allan 1994). The 1959 agreement for full utilization of the Nile waters between Egypt and Sudan led to the construction of the Roseires Dam (1966) on the Blue Nile, the Khashm El Girba Dam (1964) on Atbara River in Sudan and the High Aswan Dam (1970) in Egypt. The agreement was based on the long term annual runoff of the Nile 84.0 km^3 which was allocated as follows: 55.5 km^3 to Egypt, 18.5 km^3 to Sudan and 10 km^3 were assumed to be lost by evaporation from Lake Nasser (Howell and Allan 1994). Other Nile countries were not involved in the agreement and never ratified it. Some new developments have recently emerged in the basin, e.g., the Koga Dam (2012) in the Lake Tana basin that was developed for irrigation. Moreover, there are recent hydropower projects commissioned, e.g., TK5 (2009), the Tana Beles diversion (2010), the Fincha-Amerti-Neshe scheme (2012) in Ethiopia, the Merowe Dam (2009) on the Main Nile in Sudan and the Bujagali hydropower plant (2012) in Uganda. The basin has large hydropower potential (over 20 GW) with about 13 GW in the Blue Nile basin (NBI 2016b). Arable land suitable for irrigation is estimated to be 10-11 million ha (Hilhorst et al. 2011). Various development plans are set by the riparian countries to tap the resources potential within the Nile basin to meet the growing water, food and energy demands from the population and sustain their expanding economies (for details see supplementary data section S1). Such plans have the potential to lead to basin-wide cooperation or conflict among the riparian counties.

MATERIALS AND METHODS

The modelling framework of the WFE nexus and key socio-economic drivers are shown in Fig. 2. The nexus components are linked with the socio-economic drivers, future developments in the basin, policy options along with a stochastic generator to complete the framework. The framework allows for investigating the WFE nexus interactions, policy options, future developments across the basin and the socio-economic impacts on the WFE nexus in the basin. In this study, a water balance for the entire Nile basin is integrated with the food and energy demand and consumption in Egypt. A System Dynamics Modelling (SDM) approach was chosen for this study because of its ability to: (a) address the broader interdependency and feedbacks among the nexus components and the socio-economic dynamics, (b) provide a quantitative and qualitative platform to better understand the WFE nexus interrelationships and the socio-economic dynamics without any additional software packages. This makes SDM a suitable approach for addressing the WFE nexus interdependencies along with socio-economic dynamics and exploring the synergies among WFE nexus components in a large transboundary river basin such as the Nile.

System Dynamics Modelling

SDM is based on dynamic systems and control theory. It is a general modelling technique that can be applied to any dynamic system at various temporal and spatial scales (Sterman 2000). The method has been applied to investigate a wide range of systems, e.g., business and strategy, environmental, health, and water resources

(Sušnik et al. 2013), distributed water infrastructure planning (Rozos et al. 2016) as well as the interaction between technical and social subsystems in the context of, for example, water demand management (Baki et al. 2018). SDM depends on qualitative and quantitative analysis to understand the interactions among different system elements. First, the interrelationships between the system elements, and the system feedback structure are captured qualitatively through the causal loop diagrams (CLDs), (Sterman 2000). CLDs consists of variables connected by arrows and headed by positive/negative signs to represent the causal relationship between the system variables. The combination of positive and negative relationships might form feedback loops. There are two types of feedback loops: (a) reinforcing feedback loop (R) and (b) balancing feedback loop (B). Based on CLDs, the stock and flow diagrams (SFDs) are developed to quantify the system elements. SFDs comprise: (a) Stocks, which represent anything that accumulates (e.g., reservoir), (b) Flows, which are activities that fill or deplete the stocks (e.g., inflow and outflow), (c) Connectors, which link model elements and transfer information among the elements of the system, and (d) Convertors, which include arithmetic operations that can be performed on flows and logical functions that operate the system (e.g., operating rules of a reservoir). The Simile software environment is employed here (Simulistics 2019). The software is based on a set of differential equations also used in other SDM simulation software tools, e.g., Ventana Systems 2019. The CLDs for the WFE nexus interactions in the Nile basin are illustrated in Fig. 3. It is worth mentioning that the complete WFE nexus framework developed here was applied to Egypt. The approach can be applied to the rest of the riparian countries in the same manner and considering the specific features of the WFE nexus in each country, but that was beyond the scope of this paper. SDM tools allow for breaking down a complex system into interconnected subsystems, and this feature was utilized in Simile here. The next paragraphs provide the CLDs quantification and describe the underlying structure of each sub-model and their interactions.

MODEL SECTORS

The Nile water resources sub-model

A water balance model for the entire Nile basin was developed to simulate the key hydrological features and different activities that affect the surface water availability (e.g., water withdrawals) and management of water infrastructures (e.g., dams and diversions). For this purpose, two generic structures were considered in building the water resources sub-model: (a) river reach and (b) reservoir (see supplementary S2 for model development). The entire model was developed in Simile environment by linking the river reach/reservoir to the relevant elements sequentially until the whole basin's hydrology, water management and abstraction activities were represented. The model is divided into three main sub-models: (a) the White Nile sub-model, (b) the Blue Nile sub-model, and (c) the Main Nile in Egypt. The main infrastructures considered are summarized in Table 1, and a schematic layout of the Nile water resources sub-model is shown in Fig. S4, supplementary data. Downstream of the HAD, the model was integrated with the other water resources in Egypt including (agricultural drainage water reuse, shallow groundwater, deep groundwater, rainfall, desalination and treated wastewater). The underlying equations of the model (e.g., reservoir storage and releases) and Egypt water demands are provided in supplementary data, S2 and S3 respectively.

Egypt food sub-model

The agricultural sector in Egypt is a source of economic growth in the country, contributing to about 11.2% of the country's GDP in 2018 (The World Bank 2019). Irrigated agriculture is dominant in Egypt with water supplied mainly from the Nile together with little contribution from groundwater. The irrigated land is estimated at 9.1 million feddans (1feddan=0.42ha) Central Agency for Public Mobilization and Statistics (CAPMAS Various years-b). While rain-fed agriculture is limited to the narrow strip along the Mediterranean coast with the area accounting for about 0.1 million feddans. There are three cropping seasons in Egypt: (a) winter (November-May), (b) summer (April-October) and (c) Nili season (July-October). Dominant crops in each season are: (a) wheat, sugar beet and clover for the winter season, (b) maize, sorghum, rice, cotton and sugar cane for the summer season, and (c) maize for the Nili season. Vegetables (e.g., tomatoes, potatoes, etc.) are also cultivated in the three seasons, together with fruits (e.g., citrus, mango, banana, etc.). The food sub-model represents food demand and consumption per food groups. Food production considered here is the output from irrigated agriculture for the considered food crops (wheat, sugar beet, long clover, maize, sugar cane, rice, sorghum, vegetables and fruits). Domestic food production can be estimated by multiplying the cropland area by the crop yield. The crop area is calculated based on the agricultural land and the adopted cropping pattern. A simple form of the crop yield decrease due to the relative reduction in crop evapotranspiration is considered using an approach similar to that of FAO (K_y) (Steduto et al. 2012; Abdelkader et al. 2018). The ratio of the actual crop water consumption to the crop irrigation water demand is considered as a proxy for the ET_a/ET_c ratio. This assumes the reduction in the crop evapotranspiration is equal to the reduction in the irrigation supply (i.e., ignoring water stored in the soil from previous irrigation application). This approach is considered to be relevant for the case of Egypt where irrigation is predominantly practiced and effective rainfall is found to be insignificant at the national level. However, this method could overestimate the reduction in food production. The sensitivity of this assumption was tested and showed negligible impacts (<1%) on food production (not shown here). The yield response factors for the considered crops were available (Steduto et al. 2012). The food production (FP) (ton) can be estimated as follows:

$$FP = \sum_{i=1}^{n} A_i Y_{ai} \quad (7)$$

Where, A_i denotes the area of the crop i (feddan), and Y_{ai} the actual yield of crop i (ton/feddan). The latter quantity is obtained by $Y_{ai} = Y_{mi}\big(1 - K_{yi}(1 - (ET_{ai}/ET_{ci}))\big)$, where Y_{mi} stands for the maximum possible yield of crop i under full water supply, K_{yi} for the yield response factor of crop i, and ET_{ai}/ET_{ci} denotes the ratio of actual evapotranspiration of crop i to the maximum evapotranspiration of crop i.

The food demand is mainly driven by the population and the living standards are represented here as per capita gross domestic product (GDP). A common measure of human nutrition needs is "kg food per capita or kilocalories (Kcal) per capita", and the Kcal per capita is considered here at a national level. The food balance sheets from FAO provide the patterns of different food supply and consumption within a country for a certain period. They contain information about domestic food production, food imports, food exports, humans' food, animal feed, seeds and losses. A relationship between the income per capita and Kcal per capita per day is considered based on GDP per capita and daily Kcal consumption in the country. A similar relationship that represents the share of the food commodity in the food mix is developed. The food commodities considered here are; wheat, maize, sorghum, sugarcane, vegetables, fruits. They constitute about 75% of the total daily food intake in Egypt. The food demand per capita corresponding to a certain GDP per capita is hereby referred to be the "desired total Kcal per capita per day". Both food demands and productions are calculated on annual basis, and the changes in stocks are not considered here (i.e., the model did not assume equilibrium, thus there is no need for a stock (Gerber 2015). In other words, food commodities are assumed to be consumed within the same year. The food imports were estimated based on the difference between food demand and domestic food production.

Egypt population sub-model

The population sub-model is composed of 15 age groups; each age group represents five years, except the youngest and oldest age groups, i.e., (0-1), (1-4) and (65 and above). The model structure is similar to the population model developed by (Meadows et al. 1974). The population is increased by the new births through the first age group (0-1), while the other age groups increase through the ageing of the younger age groups, i.e., maturation. The delay in maturation from each age-specific group to the next age group is assumed as a first-order delay by assuming that it will be equal to the average number of years each person stays in that group, e.g., 5 years. The number of births (N_b) can be calculated from the following relationship:

$$N_b = \frac{Pop_{(15-44)} FW_r}{P_{time}} \quad (8)$$

Where, $Pop_{(15-44)}$ denotes the population in age group (15-44), F the fertility rate (number of children per woman), W_r women ratio to the age group (15-44) population (assumed to be 0.50) and P_{time} the reproductive woman lifetime (assumed 30 years).

On the other hand, the population is decreased by deaths and the ageing from the younger age group to the next older age group. The number of deaths (N_d) for a specific age group can be calculated as follows:

$$N_d = Mor_{rate} Pop_{group} \tag{9}$$

Where Mor_{rate} is the mortality rate of each age-specific group and is a function of the life expectancy and Pop_{group} is the population in the age group.

The total population (Pop_T) is the sum of all population from each age group, i.e., $Pop_T = Pop_{(0-14)} + Pop_{(15-44)} + Pop_{(45-64)} + Pop_{(65+)}$

Egypt energy sub-model

The energy sub-model accounts for the energy use for the different activities in the water and food systems. Food production requires energy for machinery used in agriculture, fertilizer production, and irrigation practices. The energy demand in domestic water includes energy for pumping water, water treatment, desalination, and wastewater treatment (Fig. 3). The energy demand in food production considers pumping water for irrigation from groundwater and surface water, irrigation water application (e.g., drip irrigation), and machinery used in land preparation and other agricultural activities. The approach used here considers the energy intensity of each activity to estimate the energy use in the water and food sectors. Actual estimates of energy intensities of the aforementioned activities in Egypt were not available while widely reported estimates were obtained from (Napoli and Garcia-Tellez 2016). Energy for machinery was considered for tractors only since they dominate the machinery use. The energy demands are estimated in GWh per year. The energy demand in water activity ($EDWA$) (GWh) can be estimated by multiplying the water quantity required for an activity by the energy intensity of the activity as follows:

$$EDWA = \frac{EI_{activity} Q_{water}}{10^6} \tag{10}$$

Where, $EI_{activity}$ denotes the energy intensity of water activity (kwh/m^3), and Q_{water} the water quantity in (m^3).

Egypt economic sub-model

The economic model simulates the Gross Domestic Product GDP (constant 2010 \$) at an aggregated level. The first-order accumulation of GDP is considered through a reinforced loop (the growth rate in GDP), and the annual growth rate is an exogenous variable, (Fig. 3). The per capita GDP (GDP_{pc}) can be estimated by dividing the total GDP by the total population (i.e., $GDP_{pc} = GDP/Pop_T$). Particularly,

$$GDP_{t+1} = GDP_t(1 + r_{GDP}) \quad (11)$$

Where, GDP_t and GDP_{t+1} are the GDP at time t and $t+1$ respectively, and r_{GDP} stands for the annual GDP growth rate.

Data requirements

The available basin-wide hydrologic inputs, irrigation demands and diversions across the basin, domestic water demands, and reservoir data (e.g., operating rules, storage zones, etc.) were available from the Nile Basin Decision Support System (NB-DSS) database for the period (1950-2014) at a monthly basis (NBI 2016a). It is worth mentioning that inflow data for the tributaries are a by-product of the MIKE rainfall-runoff model (NBI 2016a) Current water demands in the Nile countries upstream of Egypt are assumed to stay unchanged in future simulations and estimated at 18.1 km^3/yr with 15.1 km^3/yr for Sudan as obtained from the NB-DSS database (NBI 2016a). While Egypt is estimated to withdraw 61.3 km^3/yr in this study, which is a value higher than the often reported 55.5 km^3/yr according to the 1959 treaty. However, our results suggest that Egypt is currently withdrawing close to its annual Nile quota (Hilhorst et al. 2011) and this is in agreement with previous estimates (e.g., Hilhorst et al. 2011; Siderius et al. 2016; Multsch et al. 2017). Future demands in Egypt are projected to dynamically increase under agricultural land expansion and population growth. Water resources (e.g., groundwater, agricultural drainage reuse, rainfall, desalination, and treated wastewater) in Egypt were obtained from various sources (Abu-Zeid 1992; ICID 2004; MWRI 2005; Allam and Allam 2007; El-Din 2013; CAPMAS Various years-b). Domestic water consumption rates were available from the Egyptian code of practice for drinking water supply (MHUUC 2010). Data on agricultural land, crops yield, and cropping patterns were available from (FAO 2019; CAPMAS Various years-b). Food Balance Sheets were available from FAOSTAT database (FAO 2019). Demographic data (e.g., fertility rates and mortality rates) were obtained from the Population Division, Department of Economic and Social Affairs, (United Nations 2017). Economic data (e.g., GDP and GDP growth rates) were obtained from the World Bank Open Data, (The World Bank 2019). Data on machinery numbers, average working hours per machine, fuel consumption rate were available from (Soliman and Migahed 1994; CAPMAS Various years-a).

Model testing

The sub-models are interconnected and communicate with each other via links. The model defines a set of differential equations that have to be solved by numerical integration methods available in Simile. The historical

WFE model for Egypt runs at a monthly time step from 1980 to 2014, while the historical water resources model runs at a monthly time step from 1950 to 2014 due to the longer data record available. The water resources sub-model was calibrated during 1950-1969 and followed by validation over the period 1970-1989 at the key hydrological gage locations across the basin. Basin-wide inputs, e.g., dam operation rules, actual commission dam dates, tributaries inflows, water diversions and evaporation and rainfall rates over dams and natural lakes are used to drive the simulations. Calibration and validation results showed a satisfactory performance according to the recommended criteria by Moriasi et al. (2007), see supplementary data section (S4). The performance of the other sub-models, in Egypt, was evaluated by: (1) comparing the simulated and observed data, and (2) using the following statistical measures; Percent bias (PBIAS), Root Mean Square Percent Error (RMSPE), Theil Inequality Coefficient (TIC), and Theil Inequality Statistics (see supplementary S4.2 for the equations). These statistical measures quantify the overall behaviour discrepancy of the model (Barlas 1989; Sterman 2000). The comparison of the model simulation results and observed data for population, domestic water consumption, agricultural land, food production and food imports shows that the simulated data fits the observed data and their historical trends (see supplementary data S4.2). The statistical tests results are shown in Table 2. The PBIAS for the model variables are small (< 10%), the RMSE values are small (3-13%) except for food imports, and TIC has low values that ranged from 0.01 to 0.08. Based on the comparison of the simulated and observed data and the statistical indicators, the model was able to reproduce the observed data with satisfactory accuracy (Stephan 1992; Sterman 2000) and capture the trends in the observed data. The sensitivity analysis of the model is provided in the supplementary data section (S5).

Stochastic simulation

To assess the hydrological regime of the area, the input flows of the water resources sub-model for the period (1950-2014) were assumed representative of future Nile flows and no climate change impacts were specifically considered in the present study. To cope with the inherent uncertainty of the streamflow regime, exploit the significant natural variability embedded in these long historical time series and to a large extent 'uncertainty-proof' the analysis, we utilized the notion of stochastic simulation. The key concept is to generate a large number of synthetic streamflow time series (encapsulating the uncertainty of streamflow) and use them to drive the whole system and assess the response(s) of interest. The use of synthetic time series has been widely adopted in several studies in water resources, such hydro-systems studies (e.g., Koutsoyiannis and Economou 2003; Celeste and Billib 2009; Tsoukalas and Makropoulos 2015b, a; Tsoukalas et al. 2016), and risk analysis of floods or drought (Wheater et al. 2005; Haberlandt et al. 2011). Arguably, an important aspect of such approaches is to employ a stochastic model able to reproduce the main characteristics of hydrological processes, such as, non-Gaussianity, intermittency (at fine time scales), dependence (temporal or spatial) and periodicity (Koutsoyiannis 2005; Tsoukalas et al. 2019).

Among the numerous approaches that are described in the literature (for a brief discussion see Tsoukalas et al. 2018a; Tsoukalas et al. 2018b), in this work we employed a novel stochastic simulation method (Tsoukalas et al. 2017, 2018a) that is based on the notion of Nataf's joint distribution model. The employed stochastic model can simulate multivariate cyclo-stationary processes with seasonally varying marginal distributions and correlation structure, such as monthly streamflow. It is also noticed that this approach is not exclusively designed for streamflow simulation (see, Kossieris et al. 2019 for simulation of fine time-scale water demand series) and it avoids the generation of unrealistic dependence patterns among consecutive time steps, a recently revealed problem (Tsoukalas et al. 2018c) associated with the seminal model of Thomas and Fiering (1962).

In this vein, one hundred synthetic flow series of the river inflows of 65-year length were generated using the abovementioned synthetic streamflow generator, as implemented in the *anySim* R-package (Tsoukalas and Kossieris 2019). Future simulations run at monthly time step under the basin-wide synthetic flows from 2015 to 2080 to investigate the WFE nexus in the Nile basin during the filling and subsequent operation of the GERD. Various filling strategies and policies were investigated in the literature as discussed by Wheeler et al. (2016). Several filling rates (10%, 15%, 25%, 50%, and 100% - i.e., as a percentage of the monthly inflows upstream of the GERD) are adopted here for filling of the reservoir. This filling strategy allows for sharing the risks and rewards associated with the variability of the flows (Zhang et al. 2016). Dynamic filling scenarios (i.e., by assigning high fill rates to wet months/years and low fill rates to dry months/season) can be also investigated, however, this was beyond the scope of the current paper. Also, the 100% fill rate is a purely theoretical scenario that is considered for comparative purposes and to illustrate the impact of an extreme fill condition. According to the recent announcement by the Ethiopian Minister of water and energy (Maasho 2019), "750 MW is the planned initial hydropower production with two turbines" by the end of 2020 and the GERD is expected to be fully operational by the end of 2022. Therefore, the model assumes the GERD will start filling in January 2020 with two turbines (375 MW) operating and will be fully operational by the end of 2022. Once the reservoir reaches the design level of 590 m, the electricity can be generated while the filling process continues until the reservoir water level reach the full supply level (F.S.L) (640 m). For each filling scenario, once the reservoir reaches the F.S.L, the filling phase ends and the GERD operation phase proceeds till the end of the simulation. During the operation phase, the GERD is operated for hydropower generation only with the target hydropower level of 1730 MW (NBI 2016a). This policy agrees with previous hydropower targets as discussed by Digna et al. (2018). The model allows the reservoir to reach the full hydropower capacity (6,000 MW) if the reservoir conditions allow (e.g., the reservoir is full along with high inflows). The reservoir is not allowed to fall below the level of 590 m. The current status of the system in terms of water management, water demands and withdrawals across the basin are kept the same. For the WFE nexus calculations in Egypt, the demands were allowed to increase due to the projected population growth and agricultural land expansion.

RESULTS AND DISCUSSION

Time to fill GERD

The time required to fill the GERD reservoir (i.e., reach the F.S.L) under different filling rates and including hydrologic variability, which is assessed using synthetic flows series, are shown in Fig. 4. The average time to fill the reservoir and the variability in the average filling period is reduced with the increase in the filling rate of the reservoir. The average time to fill the reservoir in this study was found to range from 20 to 231 months, depending on the fill rate. This agrees with the range of the average GERD filling time reported in the literature, as shown in Table 3. After the reservoir reached the F.S.L, the GERD is assumed to operate for hydropower generation only until the end of the simulation. Only one set of simulation results for the GERD operation is presented since the differences among the filling scenario results for all the operational phases are found to be negligible (less than 0.25%).

Hydropower generation

The annual hydropower generation across the basin for the case without the GERD is shown in Fig. S10 for the main regions. The annual hydropower generation during the filling and operation of the GERD in Egypt, Ethiopia and Sudan is shown in Fig. 5 as box plot graphs. In Egypt, the hydropower generation will be generally reduced during the GERD filling and operation compared to the case without the GERD (Fig. 5.a and Table 4). The average hydropower reduction in the case of a 100% fill rate is less than the average hydropower reduction in other fill rates, i.e., 10-50%. This is due to the relatively short filling period for the 100% fill rate compared to other fill rate policies, the over year storage of HAD, and the expected water demands in Egypt during the 100% fill policy being less than the expected water demands during the other fill rates (as the assumed demands in Egypt are projected to increase over time due to population growth and land development). During the operation of the GERD, the median (and average figures given in brackets) HAD hydropower generation decreases by about 11% (7%) compared to the case without the GERD as HAD will operate at lower levels (Guariso and Whittington 1987) due to the combined effect of river flow regulation and reduction caused by evaporation from the GERD reservoir (see S8) and increased water demands in Egypt. Analysis of the lower quartile and probability of non-exceedance (see supplementary data, S9) of HAD hydropower performance reveals the non-exceedance probability of generating hydropower below 7,000 GWh/year would increase, depending on the fill rate, during the filling compared to the case without the GERD. Furthermore, the minimum hydropower generation would further reduce by about 15% for fill rates above 15% compared to the case without the GERD. This reflects the risks associated with HAD hydropower generation and the GERD filling during dry periods. It is worth mentioning here that dry periods refer to dry years classified as such based on model outputs that fall below the average value and the wet periods (years) are classified for output values above the average value. On the other hand, the minimum HAD hydropower generation during the GERD operation would increase by about 30% compared to the case without GERD, which reflects the role of the GERD in providing improved low flows especially during dry periods.

In Ethiopia, the annual hydropower generation will be boosted by the GERD, (Fig. 5.b and Table 4) during the GERD filling and operation. During the filling phase, the annual hydropower generation is reduced with the increase in the filling rate due to the reduction in the amount of water released through the GERD turbines (i.e., the water is stored), Table 4. However, the median (average) of hydropower generation would be increased by up to 287% (258%), depending on the fill rate. Also, the hydropower generation would be greatly impacted and reach a minimum level if the GERD filling coincides with low flow periods, (Fig. 5.b). Once the filling process finishes, the GERD will be able to generate average hydropower of about 15,000 GWh/year (see supplementary data, S9) which is similar to the values reported by (Elsayed et al. 2013; Digna et al. 2018; Hamed 2018) and boost the hydropower generation in Ethiopia by about 360%, Table 4. Furthermore, there is a 20% chance Ethiopia would achieve hydropower generation above 22,000 GWh/year.

The Sudanese hydropower would be directly impacted by the GERD filling and operation in different ways. During the GERD filling the hydropower generation would be reduced by about 2-30% compared to the case without the GERD depending on the fill rate, (Fig. 5.c and Table 4). Also, the reduction in hydropower generation is increased as the fill rate increases. On the other hand, during the GERD operation the hydropower generation would increase and the median (average) hydropower generation would rise by about 6% (8%), a value that is below the reported range 14-17% in the literature (e.g., Digna et al. 2018). The improvement in Sudanese hydropower generation is due to the river flow regulation caused by the GERD operation (i.e., increase of low flows during the dry season and reduction of the high flows during the flooding season). The lower quartile of the hydropower generation would be further reduced by 4-32% during the GERD filling. However, during the GERD operation, the minimum hydropower generation would increase by about 30% compared to the case without the GERD.

River flow regime

The average monthly flows of the Main Nile at Dongola station (upstream of the Lake Nasser) and the Blue Nile at El Diem station (at the Ethiopian-Sudanese border) are shown in Fig. 6. The impact of the GERD filling rates is reflected in the offset of the river flows during the filling phase (Fig. 6.). The Blue Nile and the Main Nile flows will be more regulated when the GERD comes online (i.e., the low flows during the dry season will be increased while the high flow during the flood season would be reduced) (Arjoon et al. 2014; Digna et al. 2018). Furthermore, the peak of the Blue Nile flows will be delayed by one month due to the water attenuation in the reservoir, (Fig. 6.a). The median (average) annual Blue Nile flows at El Diem would be reduced by about 6% (3%) during the GERD operation. The median and average annual Main Nile flows at Dongola would be reduced by 6-40% during the GERD filling and the median (average) annual flows would be reduced by 4% (2%) during the GERD operation as a result of the evaporation from the GERD reservoir (see S8). The probability of non-exceedance of the annual water quota for Egypt (65.5 km^3/year) according to 1959 agreement between Egypt and Sudan will be increased from 0.40 (without GERD) to 0.50 (during the GERD operation), i.e., a 25% increase (see supplementary data S10). The annual Main Nile flows at Dongola will be further impacted by the GERD operation, for example, the annual flows below 59 km^3 will slightly increase compared to the case without the GERD due to improved low flows. The flows above this value will be reduced due to increased evaporation from the GERD reservoir, (see S8 and S10).

Irrigation supply reliability

The average monthly supply to demand ratio (i.e., irrigation supply reliability) will be impacted by the filling and operation of the GERD, Table 5. The ratio will be reduced by about 1% during the filling phase and a further reduction of about 3% is expected during the GERD operation due to the combined effect of increased water demands in Egypt and reduced annual river flows caused mainly by retaining the water in the GERD reservoir. The average annual water shortage volume (the sum of the monthly water shortage values) will increase by 3-14% for low fill rates (i.e., 10-15%) and decrease by about 4-28% for high fill rates (25-100%) compared to the case without the GERD. This happens because of the different periods (i.e., the GERD fill time) over which data was averaged and due to the increased water demands in Egypt over the fill time (the longer the fill time, the higher the demand is due to increased population and land development, see Fig. S12). During the GERD operation, the average volume of water shortages would increase by 21%, while the maximum shortage volume would decrease by about 19% due to improved low flows during dry periods. This reveals the importance of the GERD during the low flow periods and future droughts (Arjoon et al. 2014). A potential coordinated policy among the system reservoirs could help alleviate the risks during low flows and dry periods.

In Sudan, the irrigation supply reliability will be impacted by the higher fill rates (i.e., 50-100%) and the 100% fill rate could significantly reduce the irrigation supply reliability (to 49%). However, the irrigation supply reliability would be improved during the GERD operation as a result of improved water supply caused by the river flow regulation by the GERD as discussed in MIT (2014). The annual water shortage volume will increase with the increase in the fill rate and will be greatly impacted by the 100% fill rate compared to the other fill rates, (Fig. 7.b) as a result of no downstream releases from the GERD. The average annual water shortage would be in the range of 40 to 6100 Million m^3 depending on the fill rate compared to just 30 Million m^3 in the case without the GERD. It could be concluded that the Sudanese irrigation supply could be impacted in the short- to medium-term (i.e., during the GERD filling, especially with higher fill rates), while it will be improved in the long term (i.e., during the GERD operation). Further details about the irrigation supply to demand ratio can be found in S6.

Egypt results

The application of the WFE nexus framework to Egypt and the model simulation results are presented here considering the GERD filling and operation, which is then compared to the case without the GERD. The model population results agree with the population projection from the United Nations estimates (United Nations 2017), as shown in Fig. 8.a. The population is expected to grow to about 180 Million by 2080. With the growth in population and continuation of current per capita consumption rates, the domestic water demand is expected to double between 2020 and 2080, (Fig. 8.b). Domestic water demand is expected to reach the level of about 18 km^3/year by 2080. Likewise, energy demand in the domestic water sector is expected to grow and could be doubled under current water and energy consumption rates, (Fig. 8.d). The agricultural land is expected to grow till the year 2036 as a result of the continuation of the planned land development. However, the area of agricultural land will start to decline as a result of the lack of available land suitable for irrigation and the continuation of land loss. Food production and imports are impacted by a number of factors, including population growth, agricultural land expansion, and available water resources. Food production in the case without the GERD is expected to grow but at a slow rate and then to decline following the agricultural land pattern. Furthermore, food production will be impacted by the decline in the water available for irrigation due to increased domestic water demand (i.e., domestic water sector is given higher priority over the irrigation sector). Food production could be reduced by about 60% during dry periods due to significant reductions in the available water for irrigation, while it would be increased by 16% during wet periods due to improved irrigation water supplies. On the other hand, food imports are expected to grow in the case without the GERD as a result of population growth and variations in domestic food production. The energy in the agricultural sector is expected to follow the agricultural land pattern as a result of land developments and with the assumption of no changes to the current management of the system (e.g., pumping rates, and using efficient irrigation methods).

The model simulation results during the GERD filling and operation phases reveal the impact of the GERD on the WFE nexus in Egypt. The impact of the GERD on the Nile inflows, the volume of water shortages and hydropower generation in Egypt during the GERD filling and operation are discussed above, the extension of these impacts will be further discussed here. Food production will be reduced during the GERD filling and operation phases compared to the case without the GERD due to reduction in Nile inflows caused by the GERD (filling and operation) as shown in (Fig. 8.e). The outcome will be affected by the filling rates of the GERD, with higher filling rates resulting in a greater reduction in gross food production within the range of about 9-19% for the median and 8-24% for the average, Table 6. Higher fill rates cause higher reductions to the food production but for a shorter time compared to lower fill rates, and overtake food production for the lower fill rate cases (i.e., higher fill rates finishes the filling phase faster than slow fill rates), (Fig. 8.e). However, the reduction in the aggregate food production over the period from the fill start to reaching the equilibrium state increases from 5-7% as the fill rate increases, compared to the case without the GERD. After the filling phase finishes and the system reaches an equilibrium state, the food production levels for different fill rates overlap as the filling rate is no longer practised. During the GERD operation the median (average) food production will be reduced by about 4% (3%) compared to the case without the GERD.

Moreover, the changes to food production during the GERD filling and operation compared to the case without the GERD are shown in Table 6. Food production will likely be less affected if the GERD filling occurs during the average and above-average flow years. However, the filling process could cause significant losses to food production in Egypt if it occurred during dry periods, as discussed in MIT (2014). For example, changes to food production values below the median are 2-3 times higher than the changes to the median values during the GERD filling, Table 6. Another interesting result is that the minimum food production values during GERD operation will be higher than in the case without the GERD, which reveals the role of the GERD during the dry periods for downstream users, as discussed above. The food gap in Egypt will continue to grow as a result of population growth, increased competition between domestic and municipal water and the agricultural sector, variability in the Nile flows, and the agricultural land degradation. During the GERD impoundment, the food imports are expected to increase by about 14-37% for the median and 9-41% for the average compared to the case without the GERD. Moreover, the total food imports over the period from start the GERD filling to the equilibrium state is increased with the increase in filling rate, with a range of about 8-12% compared to the case without the GERD over the same period. However, food imports are expected to grow faster mainly due to population growth, (Fig.

8.f) and the median (average) would increase by about 3% (2%) during the GERD operation compared to the case without the GERD. The energy demand for the agricultural sector will continue to grow and follow the agricultural land trend. They will not be significantly affected during the filling and the operation of the GERD. The energy demand for agriculture is less sensitive to the reduction in surface water compared to other parameters (e.g., groundwater pumping and machinery use), (Fig. S9).

The above-discussed results show the basin-wide impacts of the GERD during filling and operation from a WFE nexus perspective. Results show that the GERD filling during above-average years is likely to have a little impact on the downstream countries and it could accelerate the reservoir filling. On the other hand, the reservoir filling during dry years is likely to cause significant impacts on the downstream countries. This suggests implementing dynamic filling strategies that allow for maximizing benefits and reducing risks to the riparian countries. Once the GERD becomes operational, the dam will be able to generate enormous hydropower and could offer a cheap energy source for the riparian countries. However, downstream countries could be impacted by the GERD operation in different ways. Sudan would have improved water supplies for irrigation and hydropower generation as a result of river flow regulation caused by the GERD. While Egypt's hydropower generation and irrigation water supply will on average be reduced, the GERD will offer improved water supply during low flow years. The latter suggests a coordinated policy among the system reservoirs is highly beneficial and can reduce the risks for downstream water supply. This also shows the importance of cooperation among the riparian countries over their planned developments and the role of the nexus approach as an analytical tool for identifying synergies and trade-offs among nexus domains. The purpose of the current study is to investigate the long-term impacts of the GERD development on the riparian countries rather than improving operation based on actual predictions. However, the developed model can be coupled with real-time streamflow forecasting tools that have been successfully developed for the region (e.g., Blum et al. 2019). This can inform decisions leading to dynamic filling strategies that allow for applying higher fill rates during wet periods and vice versa.

The analysis provided here should be carefully interpreted as the study is bounded by several assumptions and conceptual limitations. The current water management and water diversions were kept the same during the simulation and the study considered no climate change. Future research will include planned developments in other riparians and consider the climate changes effects for example by introducing a percentage of change, e.g., ±10% to the average river flows. The groundwater storage capacity in Egypt was not considered here since the study assumes the current water resources management policy to stay unchanged with no additional water resources development. The current groundwater abstractions are below their sustainable abstraction levels (MWRI 2011) , thus they are assumed not to affect groundwater sustainability. However, future research is needed into the groundwater capacity and to explore the impacts of the potential groundwater overexploitation on the WFE nexus. Also, impacts of food prices on supply and demand were not considered i.e., food imports were estimated to be the difference between the demand and domestic food production by assuming the economy will have the capacity to secure food imports. Given the fact that the food subsidy system in Egypt covers approximately 77% of the population (Talaat 2018), it is difficult to capture the impact of food prices on supply and demand patterns from historical data (Abdelkader et al. 2018). However, it is worth considering the effects of food prices in future work. The dynamics of the energy use regarding the pumping water levels were not considered in this research, however it will be included in future work. Rainfed agriculture and its potential for increasing food production in the basin (Siderius et al. 2016) were not considered in this current research. Despite these limitations, the study provides a framework to investigate and understand the water, food and energy interdependencies in a transboundary river basin. Through the application of the WFE nexus framework to Egypt with and without the GERD, the analysis showed the potential impacts and synergies during the GERD filling and operation compared to the case without the GERD. Also, the framework has the potential to include other riparian countries in the same manner and consider other planned developments in all Nile countries. The inclusion of the socio-economic dynamics (e.g., population and GDP) gave a better understanding of the overall WFE nexus. Furthermore, the study provided an analysis of the possible impacts on the riparian countries during the GERD filling and operation under different hydrological conditions. The potential of the GERD to provide means of cooperation among the riparians, for example providing flows during dry periods, was also highlighted.

CONCLUSIONS

The current study provides a framework for investigating the interdependencies among the WFE nexus and the socio-economic dynamics in a transboundary river basin. The developed framework was applied to the River Nile basin considering the GERD reservoir development in Ethiopia during filling and subsequent operation. A full WFE nexus approach was developed for Egypt, while a partial consideration of WFE nexus was also provided for the other riparian countries. Results suggest that during the GERD filling, the downstream impacts are likely to be significant if the filling stage takes place during below average and dry flow periods. During the GERD operation the riparian countries would be impacted in different ways:

- In Egypt, the water, food and energy could be impacted by the GERD during both filling and operation phases. During the filling stage, the average annual river flows could be reduced by 6-40%, food production could be reduced by 9-19%, and hydropower generation by about 3-9% depending on the fill rate. During the GERD operation, the average annual river flows are expected to be reduced by 2%, food production reduced by 4%, and hydropower generation by about 7% compared to the case without the GERD.

- The average annual hydropower generation in Ethiopia would be augmented during the filling phase by about 258%, depending on the fill rate. Hydropower generation in Ethiopia will increase by 360% during the GERD operation, and the hydropower plant will add an average of 15,000 GWh/year.
- Sudan could be adversely impacted during the GERD filling, especially if high fill rates are adopted during dry periods. Sudanese hydropower generation could be reduced by 2-29% during the GERD filling and the irrigation supply reliability could be reduced by as much as 50%. During the GERD operation the situation would improve, e.g., the hydropower generation would increase by 6% while the irrigation supply reliability would increase compared to the case without the GERD due river flow regulation (i.e., low flow increase and reduction in high flows) and improved water supply afforded by the GERD.

It is also argued that the GERD could present an opportunity for cooperation among the riparian countries, especially during dry periods by releasing water to meet downstream demands. At the more general level, the presented framework is a step towards investigating and understanding the WFE nexus interdependencies while considering planned projects in river basins – including but not restricted to the challenging case of transboundary basins. Moreover, the framework can be extended in future studies, to include for example additional stochastic analysis of river flows, as well to investigate the impact of climate change on the nexus.

DATA AVAILABILITY STATEMENT

All data, models, code that support the findings of this study are available from the corresponding author upon request.

ACKNOWLEDGEMENTS

The first author would like to express his gratitude to the Ministry of Higher Education (MoHE), Egypt and College of Engineering, Mathematics and Physical Sciences (CEMPS), University of Exeter, UK for the financial support of his research (PhD Scholarship) and to the University of Exeter for providing the tools and facilities to execute his work. DHI Group provided free licenses of MIKE HYDRO BASIN and MIKE HYDRO RIVER. Dr Abdulkarim H. Seid, Head of the Water Resources Management Department and his team from ENRTO, Nile Basin Initiative kindly offered their NB DSS model. The Simile team from Simulistics and Jasper Taylor in particular provided technical support during model building. The authors are also grateful to the three anonymous reviewers whose valuable suggestions improved the quality and clarity of the paper.

REFERENCES

Abdelhaleem, F. S., and Helal, E. Y. (2015). "Impacts of Grand Ethiopian Renaissance Dam on Different Water Usages in Upper Egypt." British J. Applied Sci. Tech. 8(5), 461-483.

Abdelkader, A., Elshorbagy, A., Tuninetti, M., Laio, F., Ridolfi, L., Fahmy, H., and Hoekstra, A. Y. (2018). "National water, food, and trade modeling framework: The case of Egypt." Sci. Tot. Environ. 639, 485-496.

Abu-Zeid, M. (1992). "Water resources assessment for Egypt." Canadian J. Development Studies/Revue canadienne d'études du développement 13(4), 173-194.

Albrecht, T. R., Crootof, A., and Scott, C. A. (2018). "The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment." Environmental Research Letters 13(4), 043002.

Allam, M., and Eltahir, E. (2019). "Water-Energy-Food Nexus Sustainability in the Upper Blue Nile (UBN) Basin." Frontiers Environ. Sci. 7, 5.

Allam, M. N., and Allam, G. I. (2007). "Water Resources In Egypt: Future Challenges and Opportunities." Water Int. 32(2), 205-218.

Amjath-Babu, T. S., Sharma, B., Brouwer, R., Rasul, G., Wahid, S. M., Neupane, N., Bhattarai, U., and Sieber, S. (2019). "Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin." Applied Energy 239, 494-503.

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

Awulachew, S. B. (2012). The Nile River Basin: water, agriculture, governance and livelihoods, Routledge.

Baki, S., Rozos, E., and Makropoulos, C. (2018). "Designing water demand management schemes using a socio-technical modelling approach." Sci. Tot. Environ. 622, 1590-1602.

Barlas, Y. (1989). "Multiple tests for validation of system dynamics type of simulation models." European J. operational research 42(1), 59-87.

Basheer, M., Wheeler, K. G., Ribbe, L., Majdalawi, M., Abdo, G., and Zagona, E. A. (2018). "Quantifying and evaluating the impacts of cooperation in transboundary river basins on the Water-Energy-Food nexus: The Blue Nile Basin." Sci. Tot. Environ. 630, 1309-1323.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, S.J., and Yumkellaa, K. K. (2011). "Considering the energy, water and food nexus: Towards an integrated modelling approach." Energy Policy 39(12), 7896-7906.

Block, P., and Strzepek, K. (2010). "Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate change." J. Water Resour. Plann. Manage. 136(2), 156-166.

Blum, A. G., Zaitchik, B, Alexander, S., Wu, S., Zhang, Y., Shukla, S., Alemneh, T., and Block, P. (2019). "A Grand Prediction: Communicating and Evaluating 2018 Summertime Upper Blue Nile Rainfall and Streamflow Forecasts in Preparation for Ethiopia's New Dam." Frontiers in Water 1(3).

CAPMAS (Various years-a). "Agricultural Machinery and Equipment." Central Agency for Public Mobilization and Statistics, Cairo, Egypt.

CAPMAS (Various years-b). "Statistical Yearbook." Central Agency for Public Mobilization and Statistics, Cairo, Egypt.

Celeste, A. B., and Billib, M. (2009). "Evaluation of stochastic reservoir operation optimization models." Advan. Water Resour. 32(9), 1429-1443.

Cervigni, R., Liden, R., Neumann, J. E., and Strzepek, K. M (2015). Enhancing the Climate Resilience of Africa's Infrastructure: the Power and Water Sectors, The World Bank.

Digna, R. F., Mohamed, Y. A., van der Zaag, P., Uhlenbrook, S., van der Krogt, W., and Corzo, G. (2018). "Impact of water resources development on water availability for hydropower production and irrigated agriculture of the eastern nile basin." J. Water Resour. Plann. Manage. 144(5), 05018007.

El-Din, M. M. N. (2013). Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources & Irrigation in Egypt, UNESCO-Cairo Office.

Elsayed, S. M., Hamed, K., Asfaw, G., Seleshi, Y., Ahmed, A. E., Deyab, D. H., Yon, B., Roe, J. D. M., Failer, E., and Basson, T. (2013). "International Panel of Experts (IPoE) on Grand Ethiopian Renaissance Dam Project (GERDP)." IPoE, Addis Ababa, Ethiopia.

FAO (2014). "The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture." Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (2019). " FAOSTAT database." Food and Agriculture Organization of the United Nations, available from http://www.fao.org/faostat/en/#data.

Georgakakos, A. P. (2006). "Decision Support Systems for water resources management: Nile Basin applications and further needs." In: CPWF: Proc. of the Working conf., Nazareth, Ethiopia.

Gerber, A. (2015). "Agricultural Theory in System Dynamics." 33rd Int. Conf. System Dynamics Society, System Dynamics Society.

Goor, Q., Halleux, C., Mohamed, Y. A., and Tilmant, A. (2010). "Optimal operation of a multipurpose multireservoir system in the Eastern Nile River Basin." Hydr. Earth System Sci. 14(10), 1895-1908.

Guariso, G., and Whittington, D. (1987). "Implications of ethiopian water development for Egypt and Sudan." Int. J. Water Resou. Develop. 3(2), 105-114.

Haberlandt, U., Hundecha, Y., Pahlow, M., and Schumann, A. H. (2011). Rainfall generators for application in flood studies. In: Schumann A. (eds) Flood Risk Assessment and Management, Springer: 117-147.

Hamed, K. H. (2018). Stochastic Investigation of the GERD-AHD Interaction Through First Impoundment and Beyond. In: Negm A, Abdel-Fattah S (eds) Grand Ethiopian Renaissance Dam Versus Aswan High Dam., Springer, Cham: 95-117.

Hilhorst, B., Balikuddembe, W. O., Thuo, S., and Schütte, P. (2011). Food for Thought in the Nile Basin for 2030. The Food and Agriculture Organization of the United Nations, Rome, Italy.

Hoff, H. (2011). Understanding the Nexus: Background paper for the Bonn2011 Nexus Conference, SEI.

Howell, P., and Allan, J. (eds) (1994). The Nile: Sharing a Scarce Resource: A Historical and Technical Review of Water Management and of Economical and Legal Issues, Cambridge University Press.

ICID, International Commission on Irrigation and Drainage (2004). "Background Report On Application of Country Policy Support Program (CPSP) for Egypt (2004).", Cairo, Egypt.

Jalilov, S. M., Keskinen, M., Varis, O., Amer, S., and Ward, F. A. (2016). "Managing the water–energy–food nexus: Gains and losses from new water development in Amu Darya River Basin." J. Hydr. 539, 648-661.

Keskinen, M., Someth, P., Salmivaara, A., and Kummu, M. (2015). "Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake, Mekong River Basin." Water 7(10), 5416-5436.

Kossieris, P., Tsoukalas, I., Makropoulos, C., and Savic, D. (2019). "Simulating marginal and dependence behaviour of water demand processes at any fine time scale." Water 11(5), 885.

Koutsoyiannis, D. (2005). "Stochastic simulation of hydrosystems." Water Encyclopedia 3, 421-430.

Koutsoyiannis, D., and Economou, A. (2003). "Evaluation of the parameterization‐ simulation‐ optimization approach for the control of reservoir systems." Water Resour. Res. 39(6).

Lawford, R., Bogardi, J., Marx, S., Jain, S., Wostl, C. P., Knüppe, K., Ringler, C., Lansigan, F., and Meza, F. (2013). "Basin perspectives on the water–energy–food security nexus." Current Opinion in Environmental Sustainability 5(6), 607-616.

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., Qi, J., Strasser, L. de, Yillia, P. T., and Zheng, C. (2017). "Challenges in operationalizing the water–energy–food nexus." Hydrol. Sci. J. 62(11), 1714-1720.

Maasho, A. (2019). Ethiopia expects Nile dam to be ready to start operation in late 2020, REUTERS, Jan. 3.

Meadows, D. L., Behrens, W. W., Meadows, D. H., Naill, R. F., Randers, J., and Zahn, E. (1974). Dynamics of growth in a finite world, Wright-Allen Press Cambridge, MA.

MHUUC, Ministry of Housing, Utilities and Urban Communities (2010). "Egyptian Code for Design and Implementation of Pipelines for Drinking Water and Sewage Networks. Ministry of Housing, Utilities and Urban Communities, Egypt.", Cairo, Egypt.

MIT (2014). The Grand Ethiopian Renaissance Dam: An Opportunity for Collaboration and Shared Benefits in the Eastern Nile Basin, Abdul Latif Jameel World Water and Food Security Lab, Massachusetts Institute of Technology, USA: 1-17.

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

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

Multsch, S., Elshamy, M. E., Batarseh, S., Seid, A. H., Frede, H. G., and Breuer, L. (2017). "Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin." J. Hydr. : Regional Studies 12, 315-330.

MWRI (2005). "Integrated Water Resources Management Plan." Ministry of Water Resources and Irrigation, Egypt.

MWRI (2011). "Water Resources Development and Management Strategy up-to 2050 Horizon." Ministry of Water Resources and Irrigation, Egypt.

Napoli, C., and Garcia-Tellez, B. (2016). "A framework for understanding energy for water." Int. J. Water Resour. Develop. 32(3), 339-361.

NBI, Nile Basin Initiative (2016a). "Nile Basin Decision Support System.", Entebbe, Uganda.

NBI, Nile Basin Initiative (2016b). "Nile Basin Water Resources Atlas.", Entebbe, Uganda.

Passell, H. D., Aamir, M. S., Bernard, M. L., Beyeler, W. E., Fellner, K. M., Hayden, N., Jeffers, R. F., Keller, E. J. K., Malczynski, L. A., Mitchell, M. D., Silver, E., Tidwell, V. C., Villa, D., Vugrin, E. D., Engelke, P., Burrow, M., and Keith, B. (2016). "Integrated Human Futures Modeling in Egypt." Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).

Pittock, J., Dumaresq, D., and Bassi, A. M. (2016). "Modeling the hydropower–food nexus in large river basins: A mekong case study." Water 8(10), 425.

Rozos, E., Butler, D., and Makropoulos, C. (2016). "An integrated system dynamics – cellular automata model for distributed water-infrastructure planning." Water Supply 16(6), 1519-1527.

Siderius, C., Van Walsum, P. E. V., Roest, C. W. J., Smit, A. A. M. F. R., Hellegers, P. J. G. J., Kabat, P., and van Ierland, E. C. (2016). "The role of rainfed agriculture in securing food production in the Nile Basin." Environ. Sci. Policy 61, 14-23.

Simulistics, Ltd (2019). "Simile." available from http://www.simulistics.com/.

Soliman, I., and Migahed, M. (1994). Economic Efficiency for agricultural Tractor operation. Proc. 5th Conf. Agricultural Development Research, The Faculty of Agriculture, Ain Shams Uni., Cairo, Egypt.

Steduto, P., Hsiao, T. C., Fereres, E., and Raes, D. (2012). "Crop yield response to water." FAO, Rome, Italy.

Stephan, T. D. (1992). "The use of statistical measures to validate system dynamics models." Master thesis, Naval Postgraduate School, Monterey, CA.

Sterman, J. D. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World, Irwin McGraw-Hill

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D., and Kapelan, Z. (2013). "Integrated modelling of a coupled water-agricultural system using system dynamics." J. Water Climate Change 4(3), 209-231.

Sutcliffe, J. V., and Parks, Y. P. (1999). The hydrology of the Nile, International Association of Hydrological Sciences Wallingford, Oxfordshire, UK.

Talaat, W (2018). "The targeting effectiveness of Egypt's Food Subsidy Programme: Reaching the poor?" Inter. Social Security Review 71(2), 103-123.

Tan, C. C., Erfani, T., and Erfani, R. (2017). "Water for Energy and Food: A System Modelling Approach for Blue Nile River Basin." Environments 4(1), 15.

The World Bank 2019. "The World Bank Open Data." available from https://data.worldbank.org/.

Thomas, H. A., and Fiering, M. B. (1962). "Mathematical synthesis of streamflow sequences for the analysis of river basin by simulation." Design of water resources-systems, 459-493.

Tsoukalas, I., Efstratiadis, A., and Makropoulos, C. (2017). Stochastic simulation of periodic processes with arbitrary marginal distributions. Proc. 15th Int. Conf. Environ. Sci. Tech., Rhodes, Greece.

Tsoukalas, I., Efstratiadis, A., and Makropoulos, C. (2018a). "Stochastic periodic autoregressive to anything (SPARTA): Modeling and simulation of cyclostationary processes with arbitrary marginal distributions." Water Resour. Res. 54(1), 161-185.

Tsoukalas, I., Efstratiadis, A., and Makropoulos, C. (2019). "Building a puzzle to solve a riddle: A multi-scale disaggregation approach for multivariate stochastic processes with any marginal distribution and correlation structure." J. Hydr. 575, 354-380.

Tsoukalas, I., and Kossieris, P. (2019). "anySim: Stochastic simulation of processes with any marginal distribution and correlation structure.R package.". (Available at: http://www.itia.ntua.gr/en/softinfo/33/.)

Tsoukalas, I., Kossieris, P., Efstratiadis, A., and Makropoulos, C. (2016). "Surrogate-enhanced evolutionary annealing simplex algorithm for effective and efficient optimization of water resources problems on a budget." Environ. modelling & software 77, 122-142.

Tsoukalas, I., and Makropoulos, C. (2015a). "Multiobjective optimisation on a budget: Exploring surrogate modelling for robust multi-reservoir rules generation under hydrological uncertainty." Environ. Modelling & Software 69, 396-413.

Tsoukalas, I., and Makropoulos, C. (2015b). "A surrogate based optimization approach for the development of uncertainty-aware reservoir operational rules: the case of nestos hydrosystem." Water Resour. Manage. 29(13), 4719-4734.

Tsoukalas, I., Makropoulos, C., and Koutsoyiannis, D. (2018b). "Simulation of Stochastic Processes Exhibiting Any- Range Dependence and Arbitrary Marginal Distributions." Water Resour. Res. 54(11), 9484-9513.

Tsoukalas, I., Papalexiou, S., Efstratiadis, A., and Makropoulos, C. (2018c). "A cautionary note on the reproduction of dependencies through linear stochastic models with non-gaussian white noise." Water 10(6), 771.

UNECE, The United Nations Economic Commission for Europe (2018). A nexus approach to transboundary cooperation.

United Nations (2017). "World Population Prospects 2017." available from https://population.un.org/wpp/.

Ventana Systems, inc. (2019). "Vensim." available from http://vensim.com/.

Wheater, H. S., Chandler, R. E., Onof, C. J., Isham, V. S., Bellone, E., Yang, C., Lekkas, D., Lourmas, G., and Segond, M-L. (2005). "Spatial-temporal rainfall modelling for flood risk estimation." Stochastic Environmental Research and Risk Assessment 19(6), 403-416.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W., and Dadson, S. J. (2016). "Cooperative filling approaches for the Grand Ethiopian Renaissance Dam." Water Inter., 1-24.

Whittington, D., Wu, X., and Sadoff, C. (2005). "Water resources management in the Nile basin: the economic value of cooperation." Water Policy 7(3), 227-252.

Yang, J., Yang, Y. C. E., Khan, H. F., Xie, H., Ringler, C., Ogilvie, A., Seidou, O., Djibo, A. G., van Weert, F., and Tharme, R. (2018). "Quantifying the Sustainability of Water Availability for the Water-Food-Energy-Ecosystem Nexus in the Niger River Basin." Earth's Future 6(9), 1292-1310.

Yang, Y. C. E., Wi, S., Ray, P. A., Brown, C. M., and Khalil, A. F. (2016). "The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories." Global Environ. Change 37, 16-30.

Zhang, Y., Erkyihum, S. T., and Block, P. (2016). "Filling the GERD: evaluating hydroclimatic variability and impoundment strategies for Blue Nile riparian countries." Water Inter. 41(4), 593-610.

Table 1. Main infrastructures across the basin, location, purpose and installed hydropower capacity

Reservoir	Location	Purpose	Installed capacity (MW)
Gogo falls RoR	Migori tributary, Lake Victoria basin	Hydropower generation	2
Sondu Mirriu RoR	Sondu and Mirriu, Lake Victoria basin	Hydropower generation	60
Sang'oro RoR		Hydropower generation	21
Kiira power plant	Lake Victoria outlet	Hydropower generation	200
Nalubaale power plant	Lake Victoria outlet	Hydropower generation	180
Bujagali RoR	Victoria Nile	Hydropower generation and regulate Lake Victoria outflows	250
Alwero Dam	Alwero, Sobat catchment	Irrigation	-
Gabal Aulia Dam	White Nile	Hydropower generation and Irrigation	28.8
Tana Beles	Beles	Hydropower generation	460
Koga Dam	Koga	Irrigation	-
Tis Abbay Dam	Blue Nile	Hydropower generation	73
Fincha Dam	Fincha	Hydropower generation and Irrigation	130
Amerti Neshe Dam	Amerti Neshi	Hydropower generation and Irrigation	97
El Roseires Dam	Blue Nile	Hydropower generation and Irrigation	280
Sennar Dam	Blue Nile	Hydropower generation and Irrigation	15
TK5 Dam	Tekeze River	Hydropower generation	300
Khasm ElGirba Dam	Atbara River	Hydropower generation and Irrigation	17.8
Merowe Dam	Main Nile	Hydropower generation and Irrigation	1250
High Aswan Dam	Main Nile	Hydropower generation and Irrigation	2100

Table 2. Statistics of model parameters tests

Variable	PBIAS	RMSE (%)	TIC	Theil Inequality Statistics		
				U^M	U^S	U^C
Population	-3.70	4.0	0.02	0.97	0.03	0.00
Domestic water consumption	-4.70	13	0.07	0.13	0.33	0.54
Agricultural land	-0.53	3.0	0.01	0.03	0.00	0.97
Food production	-4.60	6.0	0.03	0.68	0.01	0.31
Food imports	11.40	22.0	0.08	0.39	0.02	0.59

Note: RMSPE: 10% is an acceptable level of error, (Sterman 2000);
$0 \leq TIC \leq 1.0$ (0 perfect prediction, 1.0 worst prediction), (Stephan 1992);
TIC<0.40 very good/excellent model and TIC>0.70 poor model, (Stephan 1992);
$U^M+U^S+U^C=1.0$

Table 3. Average GERD filling time (months)

Fill policy	This study	Other studies	Source
10%	231	(140-285)	(King and Block 2014; Zhang et al. 2016; Keith et al. 2017)
15%	143	94	(Keith et al., 2017)
25%	82	(60-140)	(Zhang et al., 2016; Keith et al., 2017)
50%	40	34	(Keith et al., 2017)
100%	20	(21-36)	(Wheeler et al. 2016; Keith et al. 2017)

Table 4. Percent of change (%) in median (average) annual hydropower generation for GERD filling scenarios and operation with reference to the case of no GERD

Country	GERD filling[1]					GERD operation[2]
	10%	15%	25%	50%	100%	
Egypt	-7(-5)	-9(-7)	-8(-8)	-5(-9)	0(-3)	-11(-7)
Ethiopia	287(258)	266(241)	227(216)	160(161)	1(1)	360(371)
Sudan	-2(-2)	-4(-4)	-7(-7)	-14(-15)	-29(-30)	6(8)

Note: [1]calcuated over its own time to fill and [2]calcuated over the rest of the simulation (subsequent operation of each fill scenario had similar results) compared to the case of no GERD (full simulation length)

Table 5. Average monthly supply to demand ratio percentage (irrigation supply reliability %) for GERD filling and operation and the case of no GERD

Country	No GERD[1]	GERD filling[2]					GERD operation[3]
		10%	15%	25%	50%	100%	
Egypt	90	89	89	90	90	92	87
Sudan	99	99	99	99	95	49	100

Note: [1]averaged over full simulation length, [2]averaged over own time to fill and [3]averaged over the rest of the simulation (subsequent operation of each fill scenario had similar results)

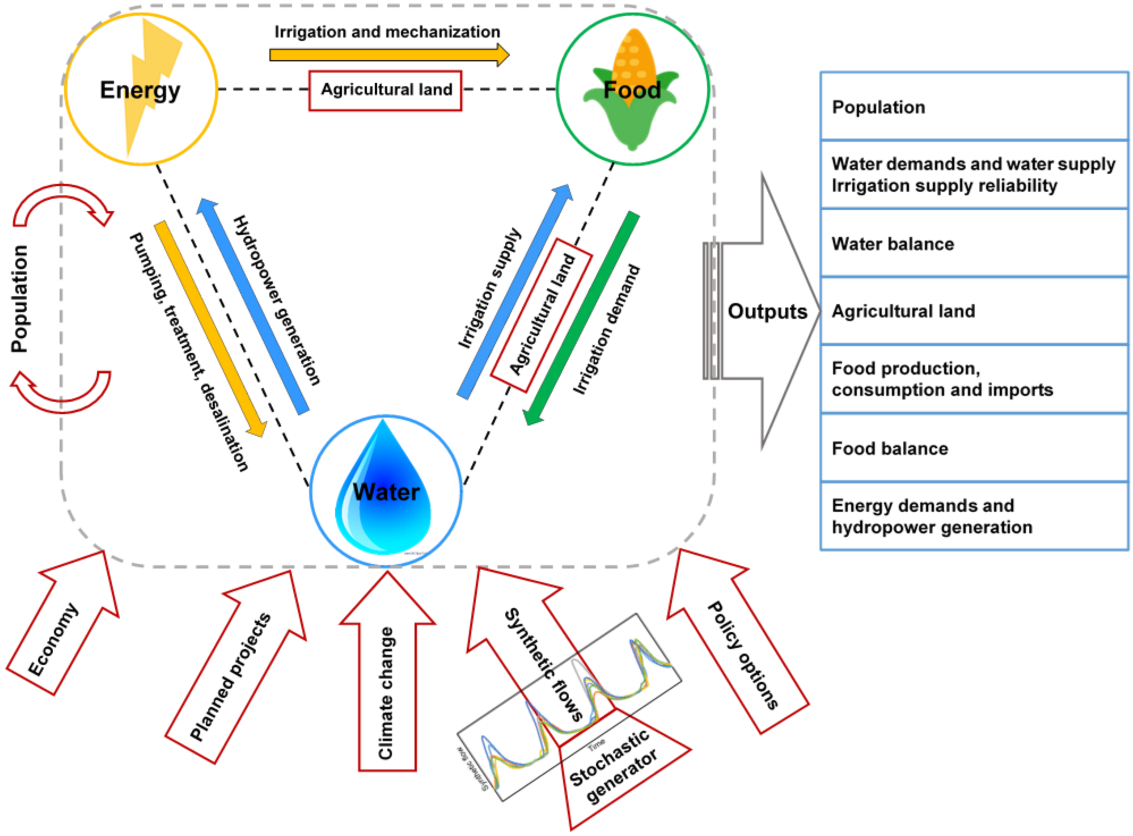
Table 6. Changes to food production (%) during GERD filling and operation compared to the case without GERD

Quartile	GERD filling[1]					GERD operation[2]
	10%	15%	25%	50%	100%	
Min	-24	-37	-62	-69	-66	+13
1st Quartile	-18	-24	-29	-42	-22	-6
Median	-9	-12	-14	-19	-9	-4
3rd Quartile	-6	-8	-9	-5	-2	-4
Maximum	0	0	0	0	0	0
Average	-8	-11	-17	-24	-15	-3

Note: [1]calcuated over their time to fill and [2]calcuated over the rest of the simulation (subsequent operation of each fill scenario had similar results) compared to the case of no GERD

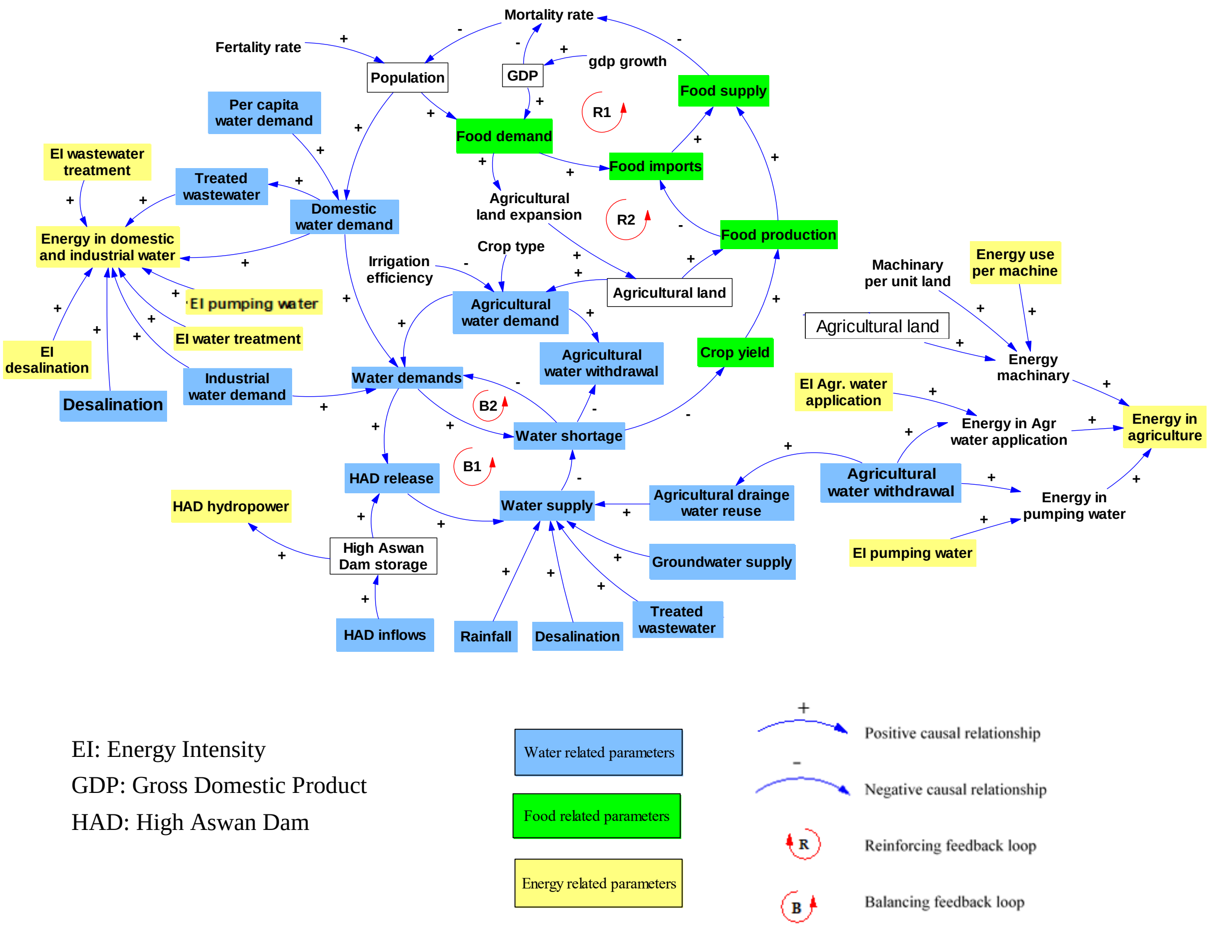
Figure

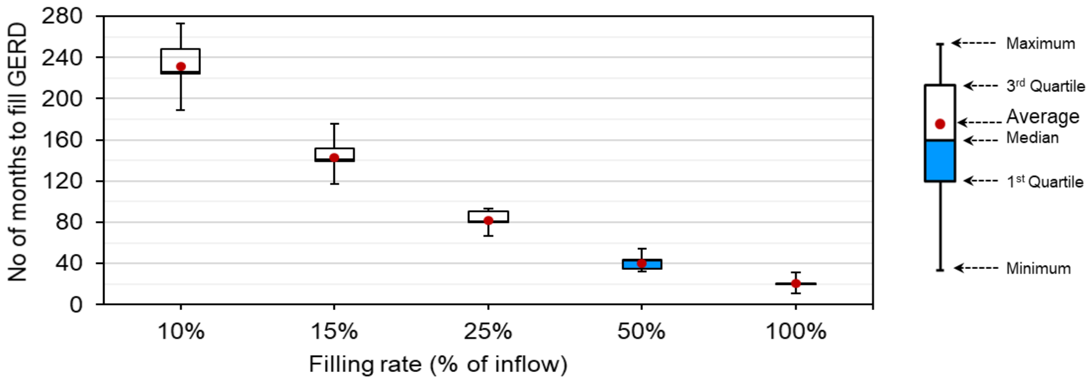
Click here to access/download;Figure;Fig. 1.pdf

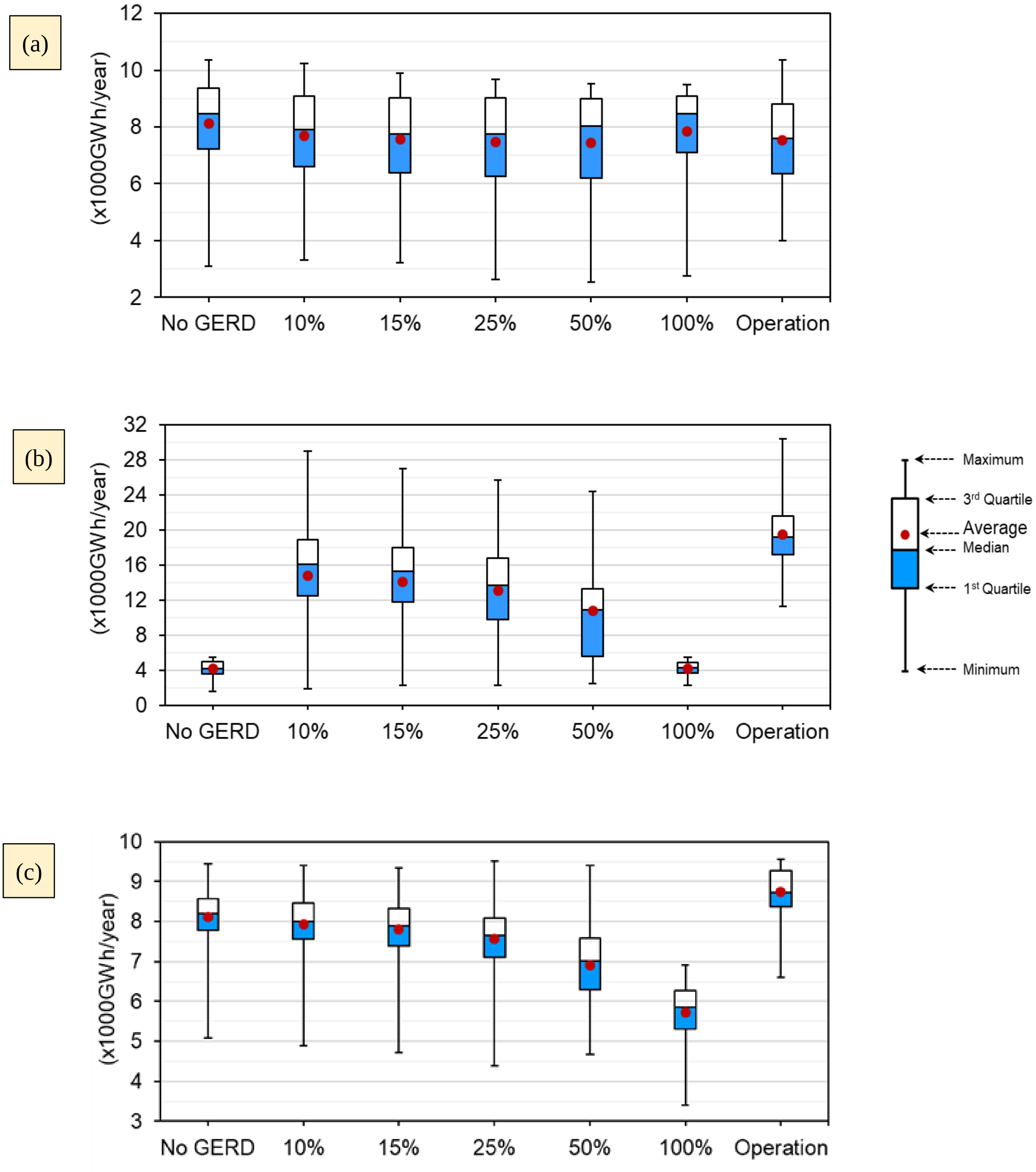

Energy
Irrigation and mechanization
Agricultural land
Food
Population
Pumping, treatment, desalination
Hydropower generation
Irrigation supply
Agricultural land
Irrigation demand
Water
Outputs
Population
Water demands and water supply
Irrigation supply reliability
Water balance
Agricultural land
Food production, consumption and imports
Food balance
Energy demands and hydropower generation
Economy
Planned projects
Climate change
Synthetic flows
Stochastic generator
Policy options

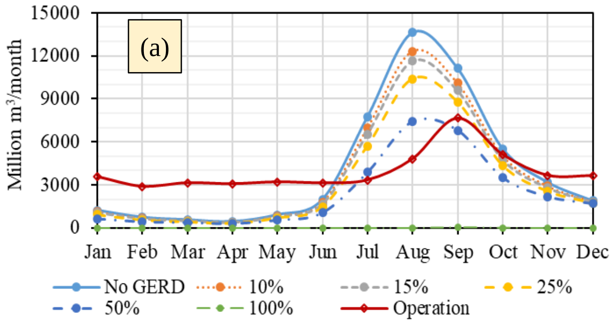
Figure

Click here to access/download;Figure;Fig. 3.pdf

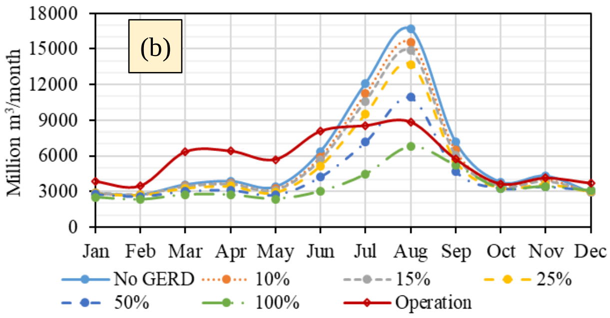



No of months to fill GERD
280
240
200
160
120
80
40
0
10%
15%
25%
50%
100%
Filling rate (% of inflow)
Maximum
3rd Quartile
Average
Median
1st Quartile
Minimum

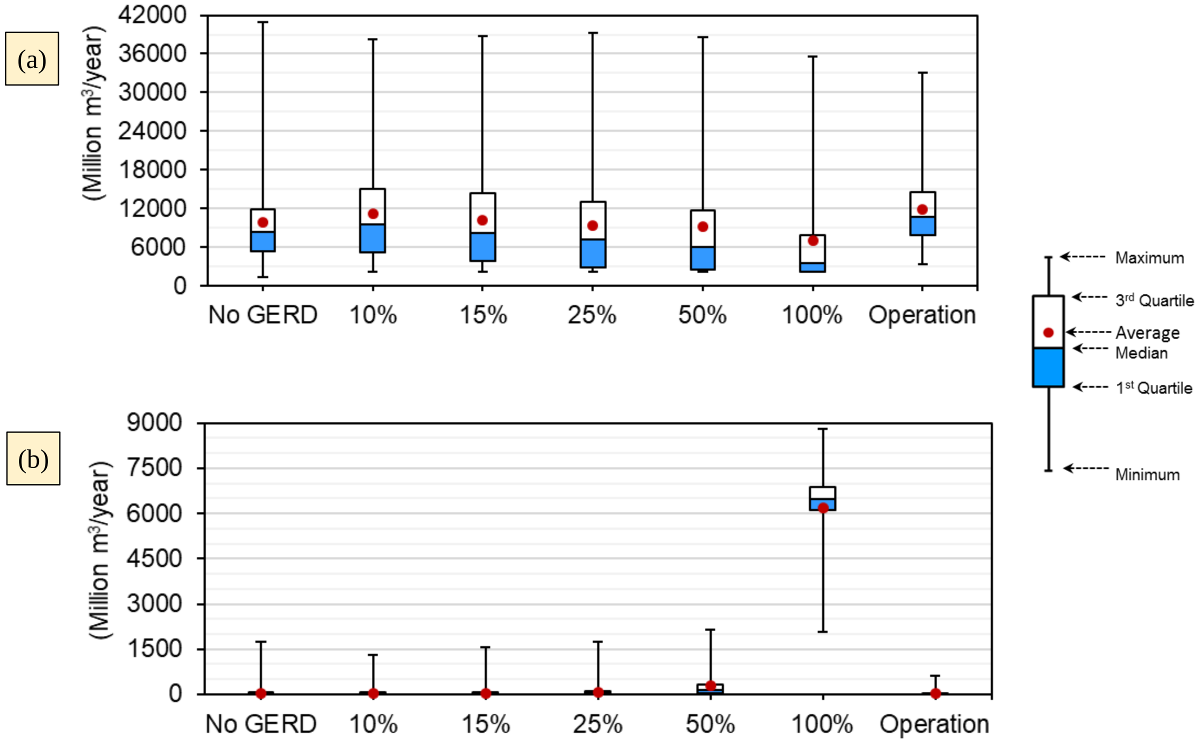

(a)
(x1000GWh/year)
12
10
8
6
4
2
No GERD
10%
15%
25%
50%
100%
Operation
(b)
(x1000GWh/year)
32
28
24
20
16
12
8
4
0
No GERD
10%
15%
25%
50%
100%
Operation
Maximum
3rd Quartile
Average
Median
1st Quartile
Minimum
(c)
(x1000GWh/year)
10
9
8
7
6
5
4
3
No GERD
10%
15%
25%
50%
100%
Operation

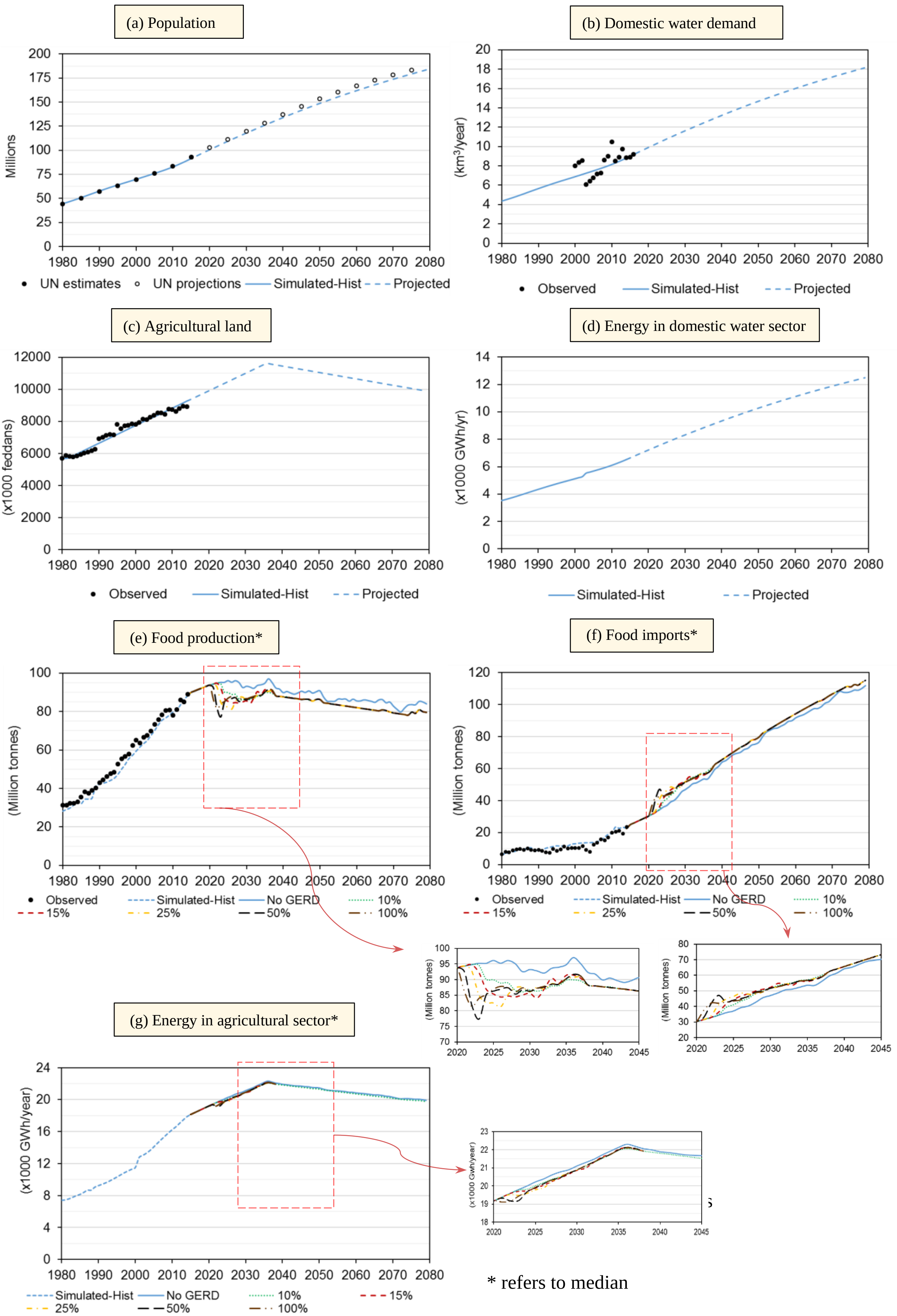


(a)
Million m³/month
15000
12000
9000
6000
3000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
No GERD
10%
15%
25%
50%
100%
Operation



(b)
Million m³/month
18000
15000
12000
9000
6000
3000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
No GERD
10%
15%
25%
50%
100%
Operation


(a)
(Million m³/year)
42000
36000
30000
24000
18000
12000
6000
0
No GERD
10%
15%
25%
50%
100%
Operation
(b)
(Million m³/year)
9000
7500
6000
4500
3000
1500
0
Maximum
3rd Quartile
Average
Median
1st Quartile
Minimum



* refers to median

Fig. 1. The Nile River basin

Fig. 2. Modelling framework for WFE nexus and socio-economic interactions in river basin

Fig. 3. CLDs of the WFE nexus and socio-economic interactions in Egypt.

Fig. 4. Box plots of the GERD filling time under filling rates 10-100%

Fig. 5. Annual hydropower generation during GERD filling for each fill scenario, subsequent operation and the case of no GERD in (a) Egypt, (b) Ethiopia, and (c) Sudan.

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is over the subsequent period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

Fig. 6. Average monthly flows during the filling and the operation of GERD at: (a) El Diem, and (b) Dongola station compared to the case without GERD

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is over the subsequent period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

Fig. 7. Box plots of the annual water shortage volume during GRED filling and operation compared to the case without GERD for (a) Egypt (b) Sudan

Note: Shown results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is based on the post-filling period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

Fig. 8. WFE nexus results for Egypt, during the GERD filling and operation compared to the case without GERD

Click here to access/download
Supplemental Materials File
Supplementary Data.docx