Future pathways of water, energy, and food in the Eastern Nile Basin

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Key Points

- A framework for the assessment of future WEF plans in the Eastern Nile Basin (ENB) countries is introduced.
- The analysis reveals significant WEF planning tradeoffs among the basin countries, specific plans with reduced tradeoffs are highlighted.
- Climate change results in high uncertainty to planning outcomes, dealing with this requires high cooperation between the ENB countries.

Abstract

The Eastern Nile Basin (ENB) countries of Egypt, Sudan, South Sudan, and Ethiopia are subject to pronounced water, energy, and food (WEF) insecurity problems. There is a need to manage the WEF nexus to meet rapidly increasing demands, but this is extremely challenging due to resource scarcity and climate change. If countries that rely on shared transboundary water resources have contradictory WEF plans, that could diminish the expected outcomes, both nationally and regionally. Egypt as the downstream Nile country is concerned about ongoing and future developments upstream, which could exacerbate Egypt's water scarcity and affect its ability to meet its WEF objectives. In this context, we introduce a multi-model WEF framework that simulates the ENB's water resources, food production, and hydropower generation systems. The models were calibrated and validated for the period 1983-2016, then utilized to project a wide range of future development plans, up to 2050, using four performance measures to evaluate the WEF nexus. A thematic pathway for regional development that showed high potential for mutual benefits was identified. Results indicate that the ENB countries could be nearly food self-sufficient before 2050 and generate an additional 42000 GWh/yr of hydropower, with minimal impacts on Egypt's water scarcity problems. The WEF planning outcomes for the region are sensitive to climate change, but, if social drivers can be managed (e.g., by lowered population growth rates) despite the difficulties involved, climate change impacts on WEF security could be less severe.

1 Introduction

Pressures on global water, energy, and food (WEF) systems are rapidly expanding. WEF demands are highly increasing, driven by population and socioeconomic growth. However, increasing the WEF supply is challenged by resource scarcity (Beck and Walker, 2013). Climate change exacerbates the problem, as it may increase demand and reduce supply in several regions (Hanjra and Qureshi, 2010). This gains more importance, knowing that WEF resources and sectors are interrelated in what is known as the WEF nexus (Cai et al., 2018; Wu et al., 2021). The region of the Eastern Nile Basin (ENB) is one where the ability to meet its growing WEF demands is increasingly challenging, with possible climate change leading to increasing concerns among the region's countries about future WEF conditions.

The ENB in north-eastern Africa encompasses parts of Egypt, Sudan, South Sudan, and Ethiopia, with a total area of 1.8 million km^2 (Figure 1). The characteristics of the region's WEF systems differ among the four countries. The Nile River is the main river system that connects the four countries and sustains the livelihood of more than 50% of their populations. The Nile has two main sources, the equatorial lakes, which contribute 15% to its mean annual flow, and the Ethiopian highlands, which contribute the remaining 85%. Ethiopia is the ENB's water richest country, as it has the highest annual precipitation and 12 major river basins, three of which contribute to the Nile (i.e., Blue Nile, Atbara, and Sobat; Figure 1). South Sudan and Sudan receive considerable precipitation but have no major perennial rivers except for the Nile and its tributaries. Although there is a relative higher availability of water in Sudan, South Sudan, and Ethiopia, there is a significant accessibility problem, especially for municipal uses, due to poverty and the absence of necessary infrastructure. Egypt is the water-poorest country in the ENB with negligible rainfall; the country is 97% dependent on the Nile River flow for its water uses. Over the past 60 years, the Egyptian population, as well as that of the rest of the basin, has grown by four-fold while the country's renewable water resources from the Nile have not changed, hence the country suffers severe water scarcity (Mekonnen and Hoekstra, 2016).

The rainfall in Ethiopia, Sudan, and South Sudan allows them to produce most of their food from rainfed agriculture, while Egyptian food production almost solely depends on irrigated agriculture. In the last 40 years, Egypt has boosted its food production by adopting new technologies (i.e., fertilizers, soil enhancements, pesticides, and using highly productive strains of seeds, etc..) that have significantly increased crop yields (FAO, 2021). However, Ethiopia, Sudan, and South Sudan mainly produce their food from rainfed agriculture, with much lower crop yields, as this type of agriculture lacks access to technology and is mainly performed on small-scale farms owned by poor farmers (Namara et al., 2008). Currently, Egypt's crop yield is twice that of the three other ENB countries (FAO, 2021). With all the improvements that Egypt has made, food production is still hindered by water scarcity, and insufficient and declining fertile land area. Food production is insufficient to meet the growing demand, which creates a pronounced food gap (i.e., shortage of local production to meet national food demand; Abdelkader et al., 2018). The rest of ENB is not doing better, however, their food gaps can be attributed to the lack of use of technologies to enhance crop yields, in addition to natural climate variability (Rockström et al., 2010) affecting their rainfed agriculture. Egypt fills its food gap by importing food from the global market, while the low purchasing power of the three other countries does not always allow this to happen. Portions of the population are left with unfulfilled food demands, resulting in malnutrition, and sometimes famines (Mera, 2018).

There is large potential for energy production in the basin countries, with a significant reserve of natural gas in Egypt, considerable oil reserves in South Sudan, and several opportunities for renewable energy in each of the basin's countries. However, among the various sources of energy, hydropower generation, especially in Ethiopia, is the major source that is directly tied in a nexus with the water and food sectors in the ENB region. Currently, Egypt is the only country that has energy production that exceeds its demand, with the surplus exported; 100% of its population has had access to electricity since 2016. Notably, Egyptian electricity is mainly generated from fossil fuel. Hydropower constitutes only 8% of the national electricity production with very limited potential for expansion (MOEE, 2021). The three other basin countries lack the capital and investments necessary for the production and distribution of energy, which leads to a significant energy deficit. South Sudan is the largest sufferer, with only 7% of its population having access to electricity, followed by 48% and 54% for Ethiopia and Sudan, respectively (World Bank, 2019).

There is clearly an immense need to improve the WEF conditions for the less fortunate portion of the 260 million people living in the region, but also for the projected 170 million increase in population by 2050 (United Nations, 2022). However, development plans to address WEF shortages can be problematic because of their dependence on scarce resources (e.g., water), which can lead to undesired trade-offs between sectors, either in the same country or across the basin. A contemporary example is the large hydropower dam (i.e., Grand Renaissance Ethiopian Dam; GERD) under construction on the major upstream tributary of the Nile (i.e., the Blue Nile; Figure 1). The GERD has triggered political tensions between Egypt and Sudan on one side and Ethiopia on the other side. In the future, the situation may worsen, given uncoordinated plans to build further dams and withdraw more water from the shared water resources in the basin, leading to more potential conflicts. Accordingly, the overarching objective of this study is to aid future WEF planning by identifying development pathways that could lead to common benefits and reduce the potential for conflicts among the ENB countries.

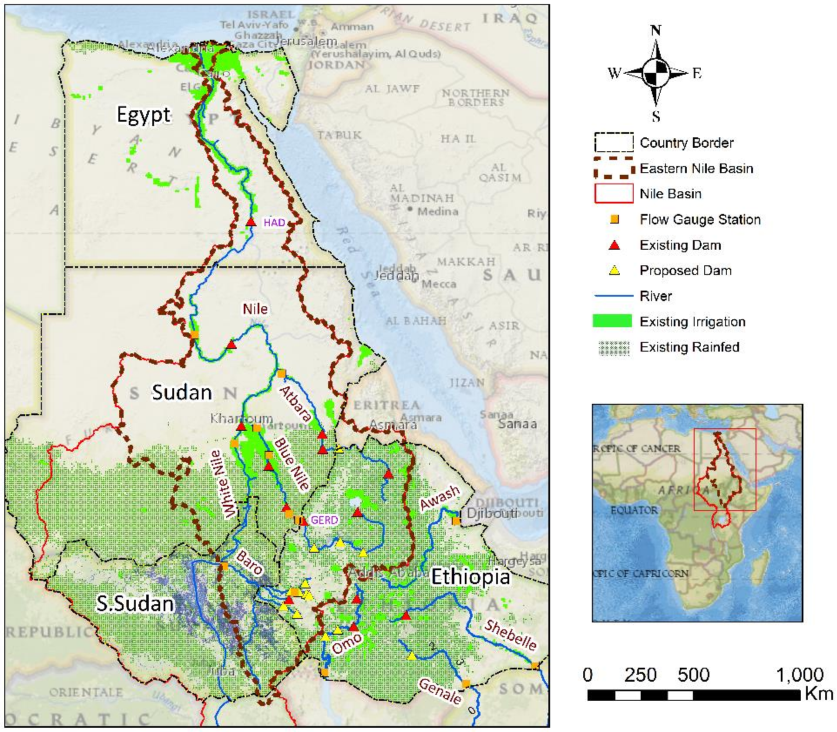

Figure 1: The study area of the Eastern Nile Basin (ENB) countries

2 Relevance of WEF Nexus Concept to the Eastern Nile Basin

WEF nexus is particularly important in regions such as the ENB, with shared resources between countries, where attempts by individual countries to maximize their benefits may result in conflicts that are complex to resolve (Bernauer, 2002; D'Odorico et al., 2018). The advantage of the WEF nexus paradigm is that it does not require all solutions to align solely with the planning objectives of a single sector/country. Instead, it encourages broader planning concepts, such as equitable trade-offs between the WEF sectors and synergistic thinking, promoting shared benefits and cooperation rather than conflict (Cai et al., 2018; Al-Saidi and Hefny, 2018). The WEF nexus was conceptualized to address global issues, but more effort is required to scale its understanding to generate implementable regional and national planning methods (Wu et al., 2021; Benson et al., 2015). To this end, it is important to provide policymakers with future WEF pathways, highlighting synergies and trade-offs.

In projecting future WEF pathways, it is essential to consider the uncertainty of unknown future WEF drivers. In particular, climate variables are significant drivers of all three WEF sectors. Climate change has been extensively studied for the ENB, where there is consensus among climate models over future temperature increases, which are consistent also with observations (Mohamed and El-Mahdy, 2021). Projected precipitation changes were perceived to have major differences in projected magnitude and direction of change among climate models (Elshamy et al., 2009). However, more recent studies show that the majority of climate models project increasing precipitation (Alaminie et al., 2021; Liersch et al., 2018). Climate uncertainty can be incorporated in WEF planning in the form of climate change scenarios generated from global or regional climate models (Wu et al., 2022). But also, it could be incorporated by generating synthetic climate time series that feature potential climate conditions (Culley et al., 2019).

Several studies have aimed at understanding the complexities and possible future changes in the ENB WEF systems. However, most focused on the water-energy system, especially the impacts of filling and operating the GERD on water and hydropower in the Nile basin (Digna et al., 2018; Wheeler et al., 2016; Basheer et al., 2018). Only a few studies have considered the water-food systems. In particular, Siderius et al. (2016) indicated that Sudan, South Sudan, and Ethiopia can meet all their food demands by 2025 through the intensification and expansion of rainfed agriculture. This conclusion was also valid for 2050, except for Ethiopia, which might be constrained by the availability of suitable land (Ayyad and Khalifa, 2021). Multsch et al. (2017) showed that improving irrigation efficiency of the ENB might not completely enable the ENB countries to meet their water demands, nonetheless, it would significantly reduce stresses on the Nile system.

Among studies that have considered an integrated analysis of the WEF systems, Allam and Eltahir (2019) identified trade-offs between water supply for food production, hydropower generation in the upper Blue Nile basin in Ethiopia, and the various demands of downstream countries. Elsayed et al. (2020) projected Egypt's WEF conditions until 2080, indicating that the long-term operation of the GERD could reduce Egypt's food production and hydropower generation by 4% and 7%, respectively.

In the above-mentioned studies, various tools and methods were used, however, all depend on one of two approaches, namely: the optimization-based approach or the scenario-based approach, while a few studies combined both (Allam and Eltahir, 2019). The former approach is advantageous in identifying the trade-offs that face decision-makers in WEF systems planning and helps in minimizing them. However, there is a common misperception that the solutions found are "optimal" or "best" solutions. Moreover, those tools do not generally consider how the system will transform from its current state to the future state required to reach the suggested "optimal" solutions. On the other hand, tools that use the scenario approach are free of such misperceptions as they do not usually search for the "best" outcomes of the WEF systems, rather, they are used to evaluate the system performance under a wide range of plausible changes to the system drivers. In both approaches, decision-makers need to be well-informed about the underlying assumptions and limitations, so they can avoid misleading decisions. Significant social, environmental, and political dimensions that govern the planning decisions of WEF systems are difficult to represent mathematically and are often overlooked.

In the above, various limitations related to the projected future changes of WEF conditions can be identified. Notably, most studies were "single-project-centered", where the impacts of a single WEF development project (e.g., GERD) were the focus. Long-term future conditions (e.g., to 2050) were identified based on this single project, ignoring the fact that the long-term needs and plans of WEF sectors in the region might necessitate further development to meet the growing demands. The scale of the study area was another issue, as most studies considered small-scale (e.g., sub-basin) WEF changes (Basheer and Elagib, 2019; and Allam and Eltahir, 2019). Thus, impacts beyond the boundaries of the sub-basin under consideration were neglected, resulting in limited spatial analysis, ignoring impacts on other basin countries. We argue that in a transboundary river basin, such as the ENB, it is necessary to analyze long-term WEF developments at the regional scale, which could be significant in revealing the possibilities to reduce conflicts and reach common benefits in the region as a whole.

Most studies have underestimated the significance of rainfall in the ENB region, overlooking its important role in rainfed agriculture and food production. Siderius et al. (2016) indicated the potential to solve the persistent food gaps in the ENB region through enhanced rainfed rather than irrigated agriculture. Hence, it is important to include rainfed agriculture systems and their possible future changes when projecting future WEF conditions. Finally, in almost all studies, there was a lack of proper consideration of future uncertainty; important WEF variables like water, food, and energy demands were assumed fixed or assumed to change under a very limited range of variations

(Basheer et al., 2018; Elsayed et al., 2020). More importantly, none of the reviewed studies considered the impacts of climate change on the three WEF sectors at the national and basin scales. Given the observed trend of increasing temperature, the possibilities of precipitation changes, and the fact that climate variables are major drivers of the WEF systems, it is important to consider climate change and quantify its impacts on future WEF conditions in the ENB.

To address the above-mentioned limitations, this study aims to investigate a wide spectrum of long-term projected conditions for the WEF nexus for the ENB at national and regional scales. The WEF nexus assessment framework (WEFNAF), introduced in this study, integrates the significant rainfed agricultural sector into the food security of the region and considers a wide range of development plans up to the year 2050. Multiple combinations of developments are considered, including building up to 16 dams and improving rainfed and irrigated agriculture, while addressing the future uncertainty of the major WEF drivers (i.e., climate change and socio-economic drivers).

3 Methodology

The water-energy-food nexus assessment framework (WEFNAF) contains two simulation models: (1) a SWAT-based hydrological model and (2) a WEF nexus model. The hydrological model requires four major inputs of climate, topography, landcover, and soil data and uses them to generate river streamflow, which is used to drive the second model. The WEF nexus model was built using a system dynamics simulation environment to simulate national demand and supply of water and food and to estimate national hydropower production in each ENB country. For this purpose, the model incorporates a component to simulate the ENB's surface water resources system, in which the daily streamflow generated from the hydrological model is used as a boundary condition for simulating the river and reservoir network. Operational rules are the major input used to simulate reservoir operation and hydropower production at each reservoir location. Water demands were calculated within the model based on climatic and socioeconomic drivers at respective river reaches, and water is supplied by prioritizing municipal, then industrial, and lastly irrigation uses. Moreover, the WEF nexus model incorporates a component that simulates the crop production for both irrigated and rainfed agriculture. The ENB was divided into small agriculture calculation units (ACUs), and in each unit, a daily soil water balance was performed based on antecedent soil moisture, irrigation supply for irrigated areas, precipitation, and potential evapotranspiration. Accordingly, crop yields were adjusted for water stress conditions and multiplied by crop cultivated land areas to estimate the production of each crop. Additionally, food demand was estimated within the model based on relevant socioeconomic drivers. The model requires economic inputs of prices and production costs for crops and hydropower, such that the economic evaluation of agriculture and hydropower production can be determined.

WEFNAF incorporates four performance measures used to assess the WEF conditions of each country, namely renewable water use, reliable hydropower generation, food gap, and the combined gross margin of agriculture and hydropower (i.e., the difference between the revenue and the variable production costs). The framework was set to run under historical and future conditions, in which the future runs can feature changes in (a) variables controlled by decision-makers (combined changes of those variables constitute future development plans); and (b) WEF drivers, which are those exogenous variables that have a significant impact on WEF conditions, but over which decision-makers have limited or no control (these includes climate and socioeconomic variables). Figure 2 shows the WEFNAF framework components as outlined above, while a more detailed explanation is provided in the supplemental file, section S1.1.

Implementation of the WEFNAF framework includes four steps. The first is model validation for a historical period from 1983 to2016, in which the hydrological model was calibrated and validated using observed daily and monthly flow data at 13 gauge stations. Likewise, the WEF nexus model outputs were validated against observed data, which included reservoir water levels, water supply, hydropower generation, and food production. In the second step, the validated WEFNAF models were used to simulate a future reference scenario for the period 2017 to 2050, assuming no development plans were implemented, with future WEF drivers maintaining their historical patterns and values. In the third step, a wide range of possible development plans were investigated for the period 2017 to 2050 and assessed using the four WEF nexus performance measures. Accordingly, a group of development plans that resulted in relatively reduced trade-offs were identified and named *thematic development pathway*. In the fourth step, a single development plan from this thematic pathway was selected and analyzed under a wide range of possible changes in climate and socioeconomic driver for the period 2017 to 2050.

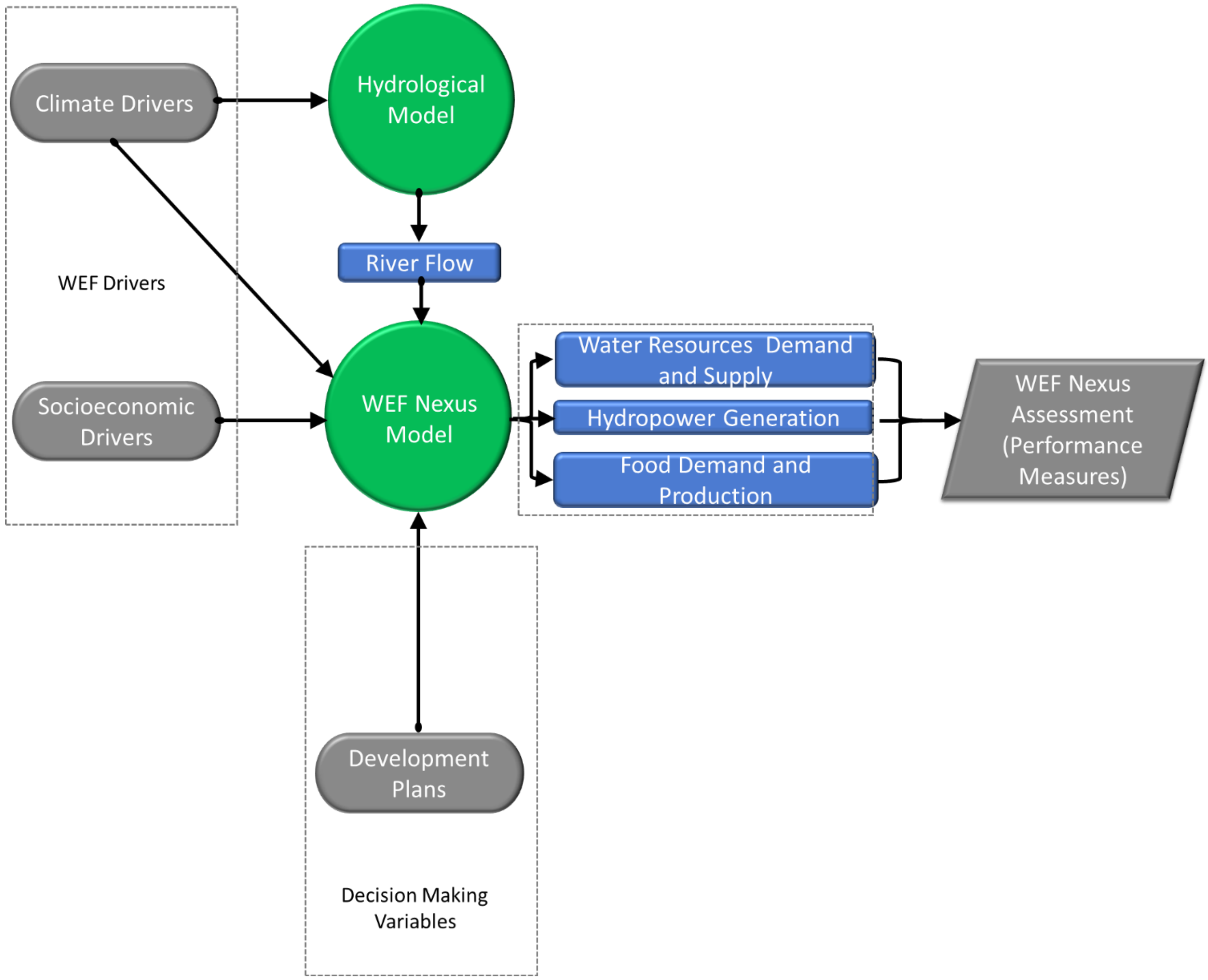

Figure 2: a schematic drawing of the major components of the WEFNAF framework

3.1 Data Sources

The hydrological model used in this study (SWAT; Arnold, 1994) was forced using daily precipitation and temperature. The precipitation data used are the climate hazards group infrared precipitation with station data (CHIRPS; Funk et al., 2015), while the temperature data were taken from the observational reanalysis hybrid temperature dataset (ORH; Sheffield et al., 2006). Notably, these two datasets showed high accuracy in representing daily precipitation and temperature timeseries within the study area (Gebrechorkos et al., 2018). The daily data for both variables are available for a common period between 1981 and 2016 in gridded format with a spatial resolution of 0.05° for CHIRPS and 0.25° for ORH. The hydrological model is semi-distributed and required ground elevation, soil, and landcover data, retrieved from NASA Shuttle

Radar Topography Mission (SRTM; Rabus et al., 2003), International Soil Reference and Information Centre (ISRIC, 2012), and the European Space Agency (ESA, 2010), respectively. Observed streamflow time series data were compiled from NBI (2018).

In addition, the WEF nexus model required spatial data for soil available water capacity, retrieved from Dunne and Willmott (1996). The annual total irrigated and rainfed areas were compiled from NBI (2017) and FAO (2015a; 2016; 2021) reports. The partitioning of each crop area among the agriculture sub-sectors (i.e., irrigation and rainfed) was retrieved from ENTRO (2017). The spatial distribution of crop areas was estimated based on satellite data compiled from Portmann et al. (2010). Crop yields, food demand, production losses, food prices, and production cost data were compiled from FAO (2021). Operation of the GERD, which is under construction, was set based on an operation rule that fulfills the targeted annual hydropower generation (Wheeler et al., 2016). The operational data for other existing reservoirs were based on historical observed operation, while future reservoirs were set to operate based on rules that maximize hydropower generation for hydropower dams and minimize water shortages of future irrigation projects for irrigation dams, compiled from ENTRO (2020).

3.2 WEF Nexus Performance Measures

The modeled WEF nexus in each of the ENB countries was assessed using four performance measures that address the WEF issues of concern to decision-makers. These measures allow tracking and comparison of the nexus state under different development plans and possible driver changes and are intended to support the WEF nexus planning decisions.

The first measure is renewable water use (RWU; m^3/cap/yr), which is important to evaluate water scarcity in the study area, especially for Egypt. RWU is a modified version of the water stress index (Falkenmark 1989; Damkjaer and Taylor, 2017), calculated for a given country as the summation of water withdrawals from rivers and the proportion of the national green water potential (i.e., the portion of precipitation that is stored in soil and is abstractable by vegetation) used by crops, divided by the population of this country, as in Eq. 1. This formulation allows decision-makers to investigate the impact of variables such as population growth and water use efficiency on water use. When applied to a downstream country, it allows investigation of the compound impact of upstream climate change and water use on downstream water availability and stress.

$$\mathrm{RWU}_c\ (\mathrm{t}) = \frac{W_c\ (t) + (ETR_c\ (t) * AR_c(t) * 10)}{POP_c\ (t)} \qquad (1)$$

where, $W_c\ (t)$ is the annual withdrawals from renewable river flow (m^3/yr), and $(ETR_c\ (t) * AR_c(t))$ is the annual green water available in a country c and year t, estimated as the product of annual actual evapotranspiration averaged over crops cultivated in the rainfed system of this country ($ETR_c\ (t)$; mm/yr), and the maximum potential land suitable for rainfed agriculture in year t ($AR_c(t)$ ha). The value of 10 is a unit conversion factor. $POP_c\ (t)$ is the population of a country c in a year t.

The second measure is the food gap (FG; %; Abdelkader et al., 2018), which is important for each of the countries in the study area, as almost all suffer from persistent food gaps. In this study, FG was calculated for each country as the percentage of the per capita food demand that is not met by the national food supply, as indicated in Eq. 2.

$$FG_c\ (\mathrm{t}) = \frac{\sum_{i=1}^{n} DEM_{ci}(t) - SUP_{ci}(t)}{POP_c\ (t) * NED_c\ (\mathrm{t})} \qquad (2)$$

where, $DEM_{ci}(t)$ is the national demand for food product i consumed in a country c and year t expressed in energy units (Kcal/yr), $SUP_{ci}(t)$ is the national supply of the same food product (Kcal/yr), n is the total number of food products that have a supply deficit. The national supply of each product i was calculated within the model as its national production after subtracting production losses. NED_c (t) is the per capita nutritional energy demand (NED; kcal/cap/yr).

The third measure is the reliable annual hydropower generation (RHP; GWh/yr), estimated as the annual hydropower that could be generated in a country with a given level of reliability, in this study assumed as 80% (as explained in section S1.2). RHP is calculated as the generated annual hydropower that corresponds to a predetermined cumulative probability of exceedance (i.e., is exceeded for 80% of simulation period), as in Eq. 3. This measure is important especially for Ethiopia, which plans to depend on hydropower as the main source of future energy generation.

$$RHP_c(\mathrm{t}) = \left(\sum_{j=1}^{m} HP_{cj}\ (t)\right)\{r\} \qquad , \mathrm{r = P \times (T+1)} \qquad (3)$$

where, $HP_{cj}\ (t)$ is the annual hydropower generated (GWh/yr) in a country c in a year t from a dam j, summed for the total number of dams in this country (i.e., m), $\{r\}$ is a notation for the rank of the RHP among the annual hydropower generated for all years of simulation, arranged from the highest to lowest, and was calculated as the multiplication of the probability of exceedance (i.e., P; 80%) and the number of years in the simulation period (T) plus one (according to Weibull plotting position; Gumbel, 1958).

The last measure is the combined gross margin of agriculture and hydropower (GM; USD/yr), which expresses the long-term net economic revenues from water usage in agriculture and hydropower for each country. As Eq. 4 shows, it was calculated as the summation of agriculture gross margin (AGM) and hydropower gross margin (HGM). The gross margin of any economic activity is calculated as the difference between the revenue and the variable production costs of this activity (Brink and McCarl, 1978; Abdelkader and Elshorbagy, 2021). AGM was calculated as the summation of the national production of crops (tonnes) multiplied by the net revenue of crop production (USD/ tonne), where the global market price was used for the portion of crops that is exported. HGM was calculated as the national generated hydropower (NHP; GWh/ yr) multiplied by the net revenue of hydropower generation, as represented in the equations provided in the supplementary material, Section S1.2. To estimate future GM, prices were assumed to continue growing at the rates observed in the historical period, also future cost to price ratios were assumed to be the same as historical values. This was applied for all future scenarios considered in this study, including the reference scenario.

$$GM_c(\mathrm{t}) = AGM_c\ (t) + HGM_c\ (t) \tag{4}$$

3.3 WEF Nexus Reference Scenario

After validating the two models of the WEFNAF framework using historical model forcing variables from 1983 to 2016, the reference scenario was created by extending the values to the year 2050. However, it was assumed for this scenario that no WEF development plan is implemented, i.e., only dams that are currently under construction were assumed to be implemented and operational (i.e., GERD, Figure 1; Wheeler et al., 2016), and there was no expansion in the currently cultivated agricultural land, and no changes in current cropping patterns, crop yields, or irrigation efficiencies. Moreover, in this scenario it was assumed that WEF drivers continued as observed in their historical period. Socioeconomic WEF drivers of population growth rate, per-capita municipal water demand, and per-capita food demand were assumed to have their historical values (Table S2.1). Likewise, climate WEF drivers of precipitation and temperature were assumed to follow their historical trends. This was achieved by applying a weather generator (Section S1.2; Culley et al., 2019) to generate daily future precipitation time series until 2050, assuming no change in mean annual precipitation, and to generate temperature that follows the spatially varied historical rate of increase in annual mean temperature observed in the study area (Figure S2.2d). The scenario thus represents a future reference state of the WEF nexus, which is important for comparing the changes due to development plans and/or WEF drivers.

3.4 WEF Development Plans

A WEF development plan is a set of changes to decision variables that might be adopted to increase the national supply of water, food, and hydropower energy. In this study, each WEF development plan constitutes nine decision variables that control the future WEF supply. Table 1 lists those variables and their values, while Table S1.1 provides additional details and includes the sources of those values. As Table 1 shows, each decision variable is capped with country-specific limits. The rainfed agricultural land area expansion is limited by land suitability and rainfall availability. The region's potential expansion is estimated to be 127 million ha (Berry, 2015; Diao et al., 2012; Alemoyehu et al., 2020), which can be added to the 32 million ha of currently cultivated rainfed land areas in South Sudan, Sudan, and Ethiopia. The irrigated agriculture land area expansion is very limited, mainly due to the scarce river water resources available. Egypt, Sudan, and Ethiopia could add 0.9, 0.5, and 1.0 million ha, respectively, to their current irrigated land area of 6.6 million ha. Food supply could also increase significantly if crop yield technology is improved; in the ENB countries there is a significant crop yield gap, whereby Egypt's crop yields are twice those of the other three countries (Figure S1.3). In this study, the crop yields of Sudan, South Sudan, and Ethiopia were assumed to have the potential to match Egypt's current values, whereas Egypt's crop yields were assumed to increase with values that vary by crop, up to 30% for wheat and maize (Ayyad and Khalifa, 2021). The cropping pattern is also an important decision variable that can increase food production with no change in agricultural area or crop yield. We considered three possible cropping patterns: The historical cropping pattern (i.e., as in the reference scenario), an increased area allocated to cereals (i.e., cereal-shift) but a reduced area for cash crops, and an increased area of cash crops (i.e., cash crops-shift) but smaller area for cereals, as in Figure S1.4.

The hydropower production of the ENB countries has a high potential for increase, especially for Ethiopia, which has several planned hydropower projects (Seleshi et al., 2014). The national hydropower generation target of Ethiopia was considered to increase by up to 42,000 GWh/yr, adding to the existing 10,000 GWh/yr (Table 1). Egypt, Sudan, and South Sudan have limited potential for increasing hydropower generation; thus, future hydropower generation increase in the three countries was ignored.

Increasing water resources availability is an important determinant to meet the future WEF supply. In this regard, Egypt has limited potential, thus, only 5.0×10^9 m^3/yr was added to its existing supply, mainly from wastewater and agricultural drainage water reuse, desalination, and deep groundwater withdrawals (MWRI, 2010). Ethiopia plans to face the temporal variability of river flows by enhancing river water availability for irrigation and hydropower by adding up to 16 dams to the river system with a storage potential of 239×10^9 m^3 (Seleshi et al., 2014; Table S1.2). The four countries of the ENB countries could also enhance water availability by saving water usage within the irrigation sector as it is the major water user; irrigation efficiency could potentially increase from 63% in Egypt and 50% in Ethiopia, Sudan, and South Sudan to an idealized value of 90%.

To form a WEF development plan, each of the nine decision variables was changed from its existing value by increments of 0%, 25%, 50, or 100% of the limits explained above, except for the irrigation efficiency, which could increase to 65%, 75%, or 90%. The cropping pattern could be historical, cereal-shift, or cash crop-shift. The priority for spatial implementation of rainfed and irrigation expansion was given to spatial locations with the highest annual rainfall and annual river flow volumes. Likewise, the implementation of hydropower dams was spatially prioritized for rivers with higher annual flow volumes. Adding irrigation dams to the system was dependent on the irrigation expansion (i.e., magnitude of expansion and its spatial locations), while adding hydropower dams was dependent on the amount of hydropower generation increase and its spatial locations. Both types of dams were selected from the list in Table S1.2. Based on these assumptions, all possible combinations of the decision variables of the four countries were considered. As stated in Table S1.1, each of the four decision variables of the rainfed agriculture land area, irrigated agriculture land area, crop yield technology, water withdrawals from non- river sources, has four possible changes; while each of the three decision variables of cropping patterns, hydropower generation, and irrigation efficiency has three possible changes; whereas the remaining two decision variables of building irrigation dams and hydropower dams are dependent on other decision variables of irrigated agriculture land area and hydropower generation. This makes the total number of development plans generated in this study to be 4 raised to the power of 4, multiplied by 3 raised to the power of 3, resulting in 6,912 development plans that were simulated. A sample of the generated development plans is presented in Table S1.3. Importantly, all changes in the decision variables were assumed to occur simultaneously in all the ENB countries to limit the computational burden of the modeling exercise. Moreover, decision-variable changes were assumed to occur at the beginning of the simulation (i.e., 2017), no transient or gradual change was assumed for development plans.

432 Table1: Decision variables names, current values, and limits of change in each country.

Country	WEF sector	Decision variable name	Current value/ State as in year 2016	Limits of increase/ change
Egypt	Food	Rainfed agriculture land area	0.04 million ha	-
		Irrigated agriculture land area	3.8 million ha	Add up to 0.9 million ha
		Crop yield technology	Highest crop yield in the ENB (see Figure S1.3)	Variant by crop but up to 30% increase for wheat and maize yield
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)
	Energy	Hydropower generation	8000 GWh/ year	-
	Water	Irrigation efficiency	63%	Increase up to 90%
		Water withdrawal from Non-River sources	25.0 $\times 10^9$ m^3/year	Add up to 5.0 $\times 10^9$ m^3/year
		Irrigation dam(s)	Only High Aswan Dam (HAD) Exists	-
		Hydropower dam(s)	Only High Aswan Dam (HAD) Exists	-
Sudan	Food	Rainfed agriculture land area	15.5 million ha	Add up to 38 million ha
		Irrigated agriculture land area	1.8 million ha	Add up to 0.5 million ha
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase up to match Egypt's crop yields (see Figure S1.3)
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)
	Energy	Hydropower generation	10,000 GWh/ year	-
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non-river Sources	-	-
		Irrigation dam(s)	6 Dams exist on the Nile River and its tributaries (as in Figure S1.1)	-
		Hydropower dam(s)	4 Dams exist on the Nile River and its tributaries (as in Figure S1.1)	-
South-Sudan	Food	Rainfed agriculture land area	1.62 million ha	Add up to 54 million ha
		Irrigated agriculture land area	0.12 million ha	-
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase up to match Egypt's crop yields (see Figure S1.3)
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)
	Energy	Hydropower generation	-	-
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non-river Sources	-	-
		Irrigation dam(s)	-	-
		Hydropower dam(s)	-	-
Ethiopia	Food	Rainfed agriculture land area	15.0 million ha	Add up to more 35 million ha
		Irrigated agriculture land area	0.89 million ha	Add up to more 1.0 million ha
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase up to match Egypt's crop yields (see Figure S1.3)
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)
	Energy	Hydropower generation	10,000 GWh/ year	Add up to 42,000 GWh/year
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non-river Sources	-	-
		Irrigation dam(s)	5 dams exist on different rivers (see Figure S1.1)	Add up to 9 dams on different rivers (See Figure S1.1 and Table S1.2)
		Hydropower dam(s)	7 dams exist on different rivers (See Figure S1.1)	Add up to 14 dams on different rivers (See Figure S1.1 and Table S1.2)

3.5 Changes in WEF Drivers

WEF nexus drivers are variables with limited or no control by decision-makers but can cause significant changes to future WEF demand and supply. These include three socio-economic drivers, population growth rate, per capita nutritional energy demand, and per capita municipal water demand, which are the major demand drivers considered in this study. These, implicitly reflect changes in economic status (e.g., GDP increase), and when added to climate variables (precipitation and temperature) form a set of five nexus drivers that influence both demand and supply sides of the WEF nexus. The current population growth rates in the ENB are among the highest in the world with 2.0%, 2.5%, 2.3%, and 2.8% for Egypt, Sudan, South Sudan, and Ethiopia, respectively. The future rate of each country was assumed to change to one of three values of 3%, 2%, or 1%, which cover the full range of the historical population growth rates in the region and those projected by the United Nations (2022) and World Bank (2023). The per capita nutritional energy demand (NED; Kcal /cap/day) varies greatly among the ENB countries (Figure S2.1). Egypt's demand has increased significantly from 2000 Kcal/cap/day in 1960 to the current value of 3500 Kcal/cap/day. Comparing Egypt's NED with global values implies that it has very limited potential to increase (FAO, 2021), therefore, it was assumed that future values at the year 2050 can be one of 3800, 3500, or 3000 Kcal/cap/day. However, due to poverty and lack of food availability, Ethiopia, Sudan, and South Sudan have low NED, below the minimum human energy requirement of 2300 Kcal/cap/day (Tontisirin and de Haen, 2001) until recently. The future values for those three countries were assumed to approach Egypt's current value, thus, future values could be 3500, 3000, or remain at 2300 Kcal/cap/day. Egypt has relatively better socioeconomic conditions and water accessibility, with per capita municipal water demand of 115 m^3/yr (MWRI, 2010). Conversely, Sudan, South Sudan, and Ethiopia have much lower values of 25, 19, and 11 m^3/yr (NBI, 2017), respectively, and their future values were assumed to increase to approach that of Egypt, whereas Egypt's value was assumed to slightly increase to 130 m^3/yr; remain at its current value; or through policies and water pricing, decrease to 70 m^3/yr.

The three social drivers explained above were used to build three social driver change scenarios that were based on the level of stress they would cause to the water and food systems of the region. These are: high socio-economic growth scenario, with the highest demand for municipal water and food, hence the highest stress to the water and food system; moderate; and low socio-economic scenario, as explained in Table S2.1.

The climate of the ENB countries is characterized by high spatiotemporal variability. The highest precipitation falls on the highlands of Ethiopia and the western part of South Sudan with long-term mean annual values that reach 2200 mm/yr. This value drops gradually moving north and reaches nearly zero in Egypt (Figure S2.2c). The hottest temperatures are observed across southern Egypt, Sudan, and South Sudan; milder temperatures exist along the Egyptian northern region and Ethiopian highlands (Figure S2.2a and S2.2b). Based on our analysis of the ORH ENB temperature dataset, the basin countries' mean annual temperature has been increasing at a rate that spatially varies between 0.005 to 0.04 °C/yr (Figure S2.2d), with minor areas showing a declining or zero trend. In this study, the future daily climate time series was generated using a daily weather generator (Section S1.2; Culley et al., 2019), covering the range of the projected values generated by the 21 general circulation models that ran under the full range of representative concentration pathways, as included in the Coupled Model Intercomparison Project phase 6 (Eyring et al., 2016). The annual mean temperature was assumed to increase by between +0.5 and +4 °C by 2050, and long-term mean annual precipitation was assumed to change from between -10% and +30%. Within these ranges, the temperature was assumed to have five possible perturbations, while precipitation was assumed to have nine possible perturbations, as stated in Table S2.1. All possible combinations of those five temperature changes, nine precipitation changes, and the three social drivers' future scenarios were generated, which resulted in a total of 135 drivers change combinations.

Importantly, all changes in the climate WEF drivers were assumed to occur in a spatially consistent way (e.g., if mean annual precipitation assumed to increase by 5%, this value was applied simultaneously at all locations within the ENB). Moreover, driver changes were assumed to occur at the beginning of the simulation (i.e., 2017), no transient or gradual change was assumed, except for the annual mean temperature changes that were assumed to occur gradually according to a linear trend until the year 2050.

4 Results

4.1 WEFNAF Models Validation

The performance of the hydrological model in simulating historical daily river flows at 13 different flow gauge stations was assessed for the period 1983 to 2016. The model was calibrated and validated using Nash-Sutcliffe Efficiency (NSE) and Percent bias (PBIAS) and resulted in values between 60% and 91%, and -16% and +9%, for NSE and PBIAS, respectively over the whole period (details are provided in section S2.2). These are considered acceptable for daily flow prediction, in light of previous studies in the region (Betrie et al., 2011; Mengistu et al., 2021).

The WEF model results were also evaluated against the best available information. There is a limited availability of reported annual water supply to different sectors in each country, the simulated water supply data are presented for the year 2016 in Figure 3a. Egypt's modeled water supply totaled 82 × 10^9 m^3/yr, of which 82% is supplied to irrigated agriculture, including animal feed production, 13% to municipal uses, and 2.5% to industrial uses. Egypt's water supply is mainly sourced from blue water sources (i.e., freshwater flows or surface and subsurface storage). This includes 55.5 × 10^9 m^3/yr from the Nile, 6.3 × 10^9 m^3/yr from shallow groundwater, 2.2 × 10^9 m^3/yr from deep groundwater, 16.0 × 10^9 m^3/yr from agricultural drainage reuse, and 0.3 × 10^9 m^3/yr from seawater desalination. Egypt's hyper-aridity does not allow for rainfed agriculture except in very limited areas on the north coast and Sinai (i.e., less than 1% of Egypt's cultivated land); in the WEF model 1.7 × 10^9 m^3/yr of green water was simulated for Egypt's agriculture. These simulated values for the Egyptian annual water supply were consistent with the values reported by governmental reports and other studies (MWRI, 2010; Allam and Allam, 2007).

In contrast, most of the water use in Sudan, South Sudan, and Ethiopia is sourced from green water that contributes to rainfed crop agriculture, pasture, and other natural vegetation and forests. However, within the WEF model, the green water use was only quantified for rainfed crop agriculture. For Sudan, the modeled water use in 2016 was 85.6 × 10^9 m^3/yr, where 67.7 × 10^9 m^3/yr was green water used for rainfed agriculture. Blue water sources supplied 17.3 × 10^9 m^3/yr for irrigated agriculture, and 0.6 × 10^9 m^3/yr for municipal supply. In South Sudan, the modeled water use was 26.2 × 10^9 m^3/yr in 2016, with 24.6 × 10^9 m^3/yr of green water used for rainfed agriculture. Blue water supplied for irrigated agriculture and municipal sectors was 1.6 × 10^9 m^3/yr. Ethiopia's water use is the highest among the ENB countries with a modeled water use of 116.1×

10^9 m^3/yr, of which 108.0 × 10^9 m^3/yr are green water used for rainfed agriculture. Blue water supplied to municipal and irrigated agriculture sectors was 7.9 × 10^9 m^3/yr. For Sudan, South Sudan, and Ethiopia, the blue water supplied within the WEF model was assumed to occur entirely from river flows, where for Sudan and South Sudan the supply occurs from the Nile, while for Ethiopia the modeled blue water supplied from the Nile tributaries was 1.4 × 10^9 m^3/yr, and 6.5× 10^9 m^3/yr from the other rivers (Figure 1). The blue water supply simulated for Sudan, South Sudan, and Ethiopia (Figure S2.4) was comparable to values reported by FAO (2015a, 2015b, and 2016). The same was true for the green water use of the three countries, which was evaluated for the period 1996 to 2005 and found to be close to the values reported in Mekonnen and Hoekstra (2011).

In addition to water supply, the WEF model performance in simulating existing dams' operation was assessed. Figure 3b shows the comparison of observed and simulated monthly elevation of High Aswan Dam (HAD), which is considered satisfactory with NSE of 65% and PBIAS of 1%. The simulated flow at calibration stations were validated within the WEF model, daily inflow to HAD compared with observed data at Dongola station resulted in an NSE of 70% and PBIAS of 1%. Likewise, the inflow to Rosieres and outflow of Sennar Dams in Sudan were compared with observations and showed NSE of 86% and 82% and PBIAS of -4% and -10%, respectively, as discussed in section S2.2 and Table S2.3. Because of limited data availability, the operation of the other dams in the study area (Figure S1.1) was simulated using the long-term monthly mean reservoir elevation data extracted from other existing models and studies (ENTRO, 2020).

The annual hydropower generated from all dams in each country was also evaluated. As Figure 3c shows, the simulated hydropower matches well the reported average annual hydropower of each country. Ethiopia and Sudan built hydropower dams over the historical period, which explains the stepped increase in their hydropower generation. By the year 2009, the Merowe dam in Sudan and Tekeze dam in Ethiopia were operational, and since then, the three countries of Egypt, Sudan, and Ethiopia have generated comparable annual hydropower that ranges between 8,000 and 10,000 GWh/ yr.

The performance of the WEF model in simulating the national crop and animal agriculture production in the four countries of the study area was also assessed. Figure 4 shows the ranges of production for the period between 1983 and 2016. The crop production of the ENB countries is diverse with 21 crops and crop groups. Cereals are considered important strategic crops in the region, as they represent an affordable source of high nutritional energy. In 2016, Egypt produced 10 million tonnes of wheat, Sudan and South Sudan produced 7.6 million tonnes of sorghum, while Ethiopia produced 8 million tonnes of maize, 6 million tonnes of teff, and considerable production of wheat and sorghum. The WEF model simulated crop and animal production ranges that match well the data reported by FAO (Figure 4). Overall, the model shows good performance in simulating the historical water, food, and hydropower conditions of the study area and can be reliably used to project future WEF conditions.

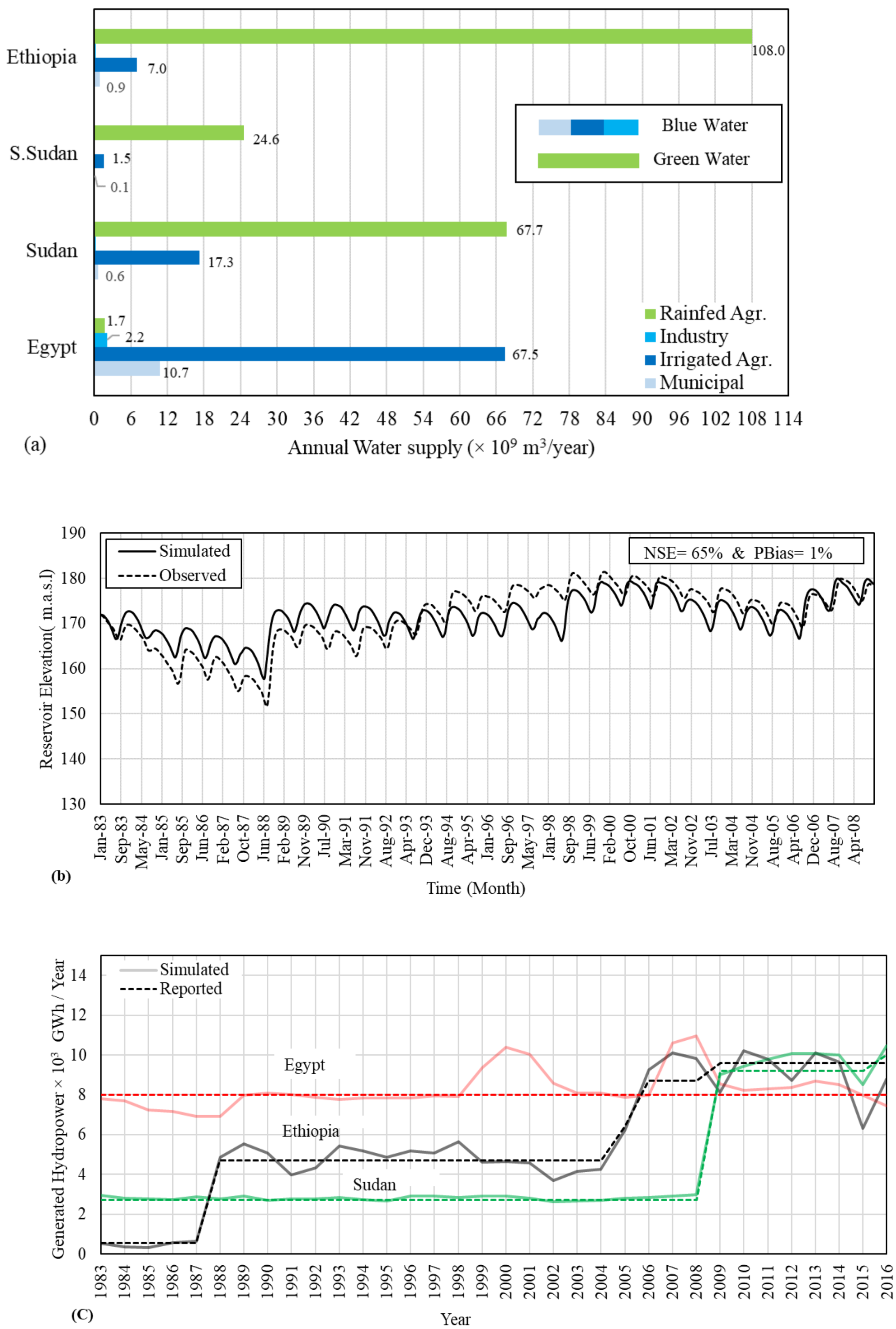

Figure 3: Evaluation of the ENB WEF model for (a) simulated blue and green water resources use for different sectors as in 2016, (b) High Aswan Dam Reservoir elevation, and (c) annual national hydropower generated in each country.

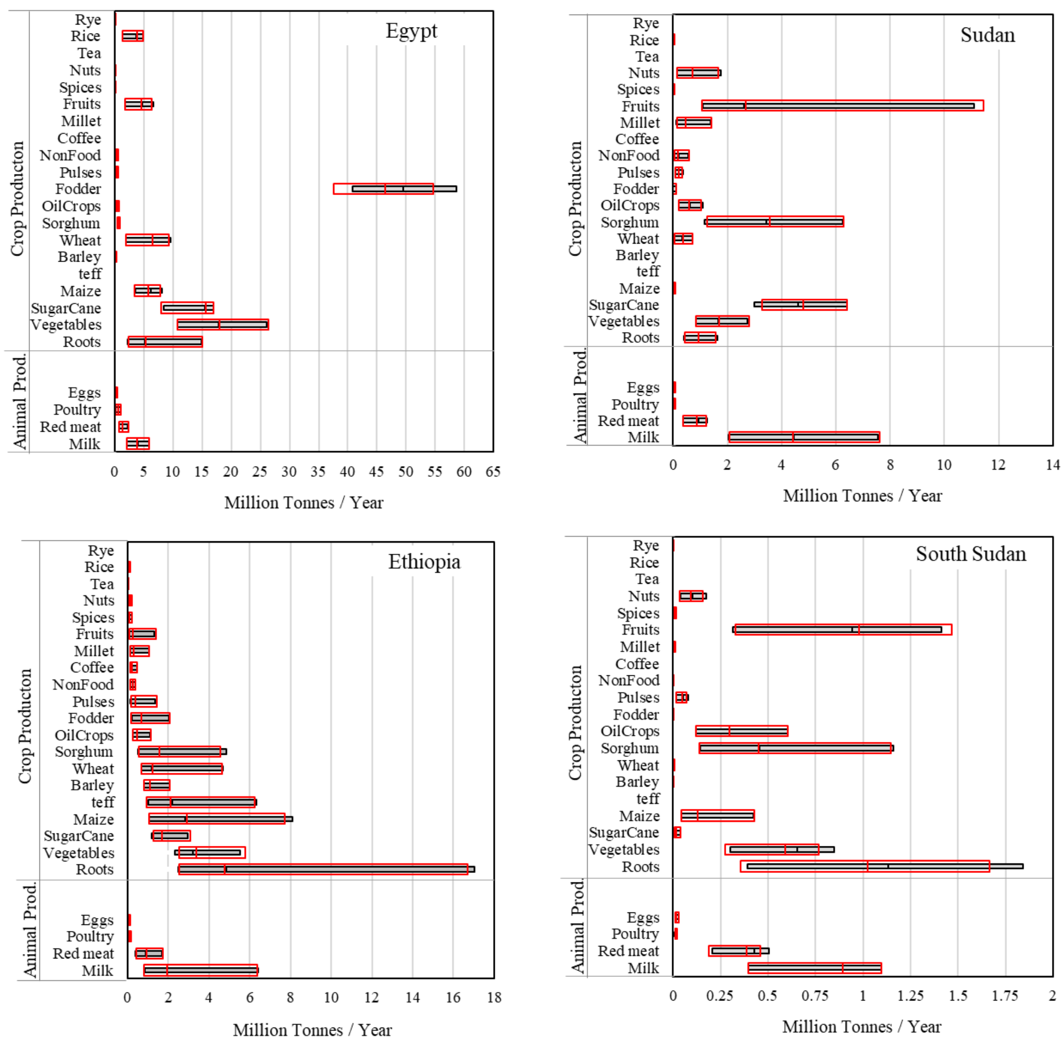

Figure 4: Evaluation of the ENB WEF model for agricultural production, the gray bars represent the range of annual national agricultural crop and animal production as simulated for the period between 1983 and 2016, and the red bars are for the FAO reported production (FAO, 2021).

4.2 Reference Scenario Results

In this scenario, used as a reference for comparison, no WEF development occurs, except for projects under construction (i.e., GERD), and future WEF system drivers follow the observed patterns/trends of the historical period, as explained in section 3.3. The simulated renewable water use reflects the worsening water conditions in the region due to high population growth (Figure 5a), whereby 2016 values were reduced by a factor of 2 due to the doubled population by 2050.

Egypt is the largest sufferer as its 2016 RWU of 650 m^3/cap/day is projected to drop to 332 m^3/cap/day in 2050. In contrast, South Sudan does not seem to be under any physical water stress; RWU drops from 30,000 m^3/cap/day in 2016 to 15,400 m^3/cap/day in 2050, while Sudan and Ethiopia are in between these two extremes with RWU reaching 2,010 and 1,392 m^3/cap/day in 2050, respectively. In the reference scenario it was assumed that temperature continued to increase according to the historical trend, however, this did not significantly impact crop water requirements and water stress impacts on crop yields; accordingly, food production under the reference scenario is insignificantly different from current production. However, the high population growth increases food demand, which results in a larger food gap, projected to grow significantly by 2050 (Figure 5b). Egypt and South Sudan could reach values of 60% in 2050, increasing from 40% in 2016, while Sudan and Ethiopia reach values of 40% and 50%, respectively. The availability of water and suitable arable land in Sudan, South Sudan, and Ethiopia reflects the fact that the food gap in the region could be reduced compared to those values reported for the reference scenario because it was assumed in this scenario that no action was taken by decision-makers.

Although the hydropower systems of Egypt and Sudan can produce comparable maximum annual hydropower production between 10,000 and 11,000 GWh/yr (Figure 5c), Sudan can achieve higher reliable hydropower generation (RHP) of 9,500 GWh/yr, compared to 7,700 GWh/yr for Egypt. This is due to the limited annual variation in hydropower production of Sudan under the reference scenario, as the country produces its hydropower energy from several small-scale dams that will benefit from the regulated flow releases of the GERD. Ethiopia's hydropower production would be the largest in the region, after GERD is added to the system, with RHP of 22,800 GWh/yr.

The combined gross margin of agriculture and hydropower is projected to increase in the future; however, this is mainly due to the continued growth of prices at the rates observed in the historical period. Egypt, Sudan, and Ethiopia have comparable economic benefits from water use in agriculture and hydropower production, while the economic benefit for South Sudan is significantly less. Stemming from the current conditions and worsening future projections, decision-makers of the region are most likely to intervene to implement WEF development plans that aim to decrease the food gap, increase energy production and its reliability, increase the gross margin, and eradicate or diminish the worsening water stress conditions.

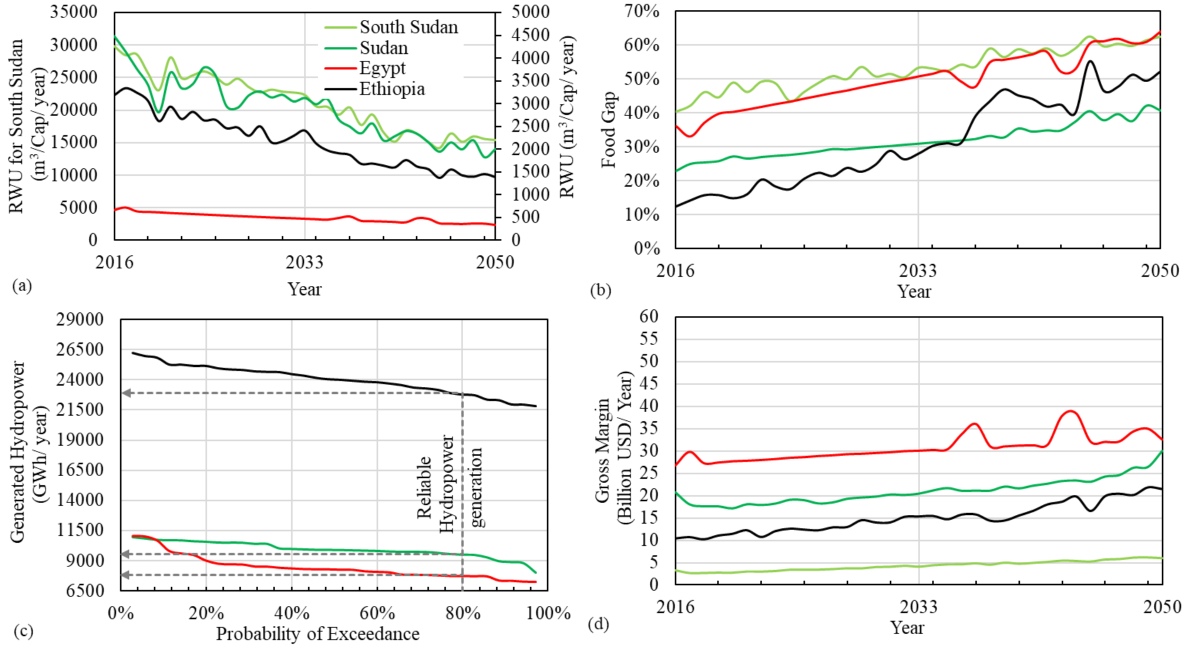

Figure 5: WEF nexus performance measures of (a) renewable water use (RWU; the left axis is for South Sudan and right axis for three other countries), (b) food gap (FG), (c) reliable hydropower generation (RHP), and (d) combined gross margin of agriculture and hydropower (GM), evaluated for the reference scenario

4.3 WEF Nexus Performance Under Development Plans

Results of the four WEF performance measures used to evaluate the 6,912 generated development plans for the period between 2016 and 2050 are shown in Figures 6, 7, 8, and 9. To enhance the readability of the figures, only the decision variables that significantly impact each of the performance measures were included.

4.3.1 Renewable Water Use

Under the studied ENB development plans, renewable water use is found to vary mainly due to irrigation. In particular, the two most sensitive decision variables are increasing irrigated area, which increases river withdrawals and RWU; and increasing irrigation efficiency, which reduces river water withdrawals and RWU. Notably, most withdrawal for irrigation occurs from the shared, scarce, and fully utilized water resources of the Nile. Accordingly, the changes to withdrawals and

RWU upstream in the Nile have a trade-off with water availability, withdrawals, and RWU downstream. Figure 6 shows RWU changes in the four countries under the considered plans. The first two axes show the two major decision variables impacting RWU; the first axis has increments of 0%, 25%, 50%, and 100% for irrigated land expansion (i.e., Irrig. Expansion), in which 100% expansion corresponds to an additional irrigation area stated in Tables 1 and S1.1. The second axis represents irrigation efficiency, set to increase to three possible values as explained in Tables 1 and S1.1. Axes from three to five indicate RWU values for South Sudan, Sudan, and Ethiopia, respectively. The sixth axis indicates the Nile River flow upstream of the High Aswan dam (HAD) corresponding to each plan, which indicates the shared Nile water resources that arrive at the Egyptian border and indirectly reflects the water withdrawals that occurred upstream. Egypt's RWU is represented on the last axis. Importantly, the changes in the decision variables for each development plan are assumed to occur simultaneously in all the ENB countries (e.g., a plan with 100% irrigation expansion, means that 100% of the potential area in each country was expanded).

Development plans were divided into clusters based on their resulting RWU for the four countries and Nile flow upstream of the HAD, clusters of interest are colored in blue, green, and red in Figure 6, while the results for the rest of the 6,912 development plans are indicated in grey color. A major cluster with the highest improvement in irrigation efficiency (90%) but no change in the irrigated areas from their current values (0%; blue lines in Figure 6) leads to reduced river water withdrawals in South Sudan, Sudan, and Ethiopia, hence, reducing RWU relative to the reference scenario (the solid black line in Figure 6). However, this enhances the Nile flows that arrive in Egypt and leads to the maximum enhancement for water availability and the RWU of Egypt. In contrast, the red cluster, which represents the highest expansion of irrigated areas (100%) but the least improvement in irrigation efficiency, 65%, results in the highest RWU for Sudan and Ethiopia relative to the reference scenario, but the least Nile flow to Egypt, reducing its RWU, and resulting in the most severe water stress conditions for the country. Interestingly, the green cluster indicates that maximized irrigation efficiency could balance these negative impacts of upstream irrigation expansion on the water stress of the downstream countries. As Figure 6 shows, Egypt's RWU retains the level of the reference scenario when the irrigation potential of the upstream countries is fully exploited simultaneously with an improved irrigation efficiency reaching 90%.

Importantly, the relatively high RWU values for the three countries of South Sudan, Sudan, and Ethiopia indicate that they will not suffer significant water stress when compared to Egypt. RWU values for those three countries remain high under the full range of the considered irrigation expansion and irrigation efficiency changes, as the lowest values reported for 2050 were 15364, 1933, and 1378 m^3/cap/yr for South Sudan, Sudan, and Ethiopia, respectively. In contrast, Egypt's RWU is projected to be low (i.e., 334 m^3/cap/yr) in 2050, mainly due to high population growth, and some of the development plans that withdraw Nile water in the upstream countries will further exacerbate this water stress with RWU values as low as 322 m^3/cap/yr (Figure 6).

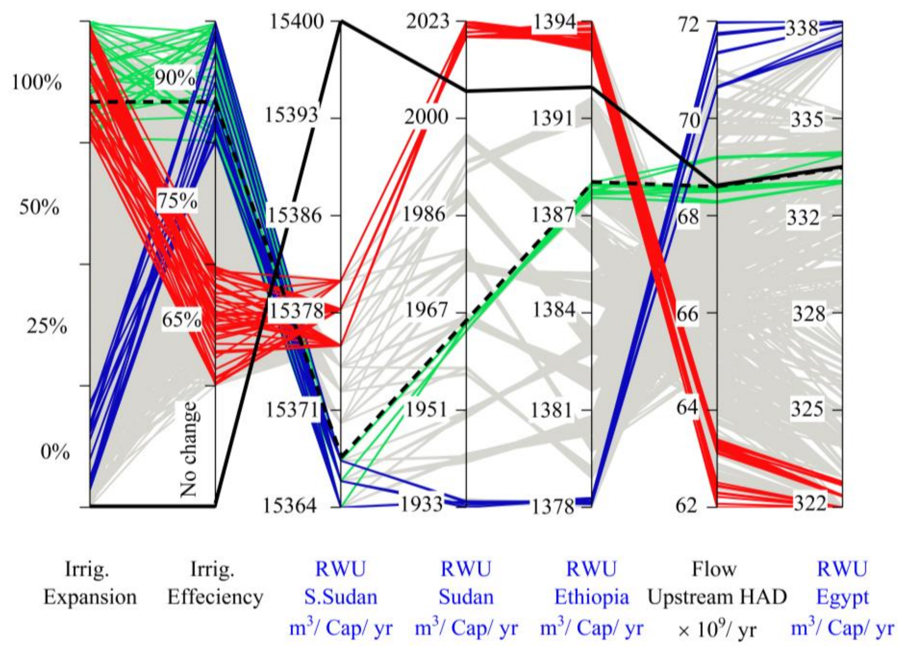

Figure 6: Parallel coordinate plot for the WEF system performance measure of renewable water use (RWU), reported for the year 2050, for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting RWU are included in the figure. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.3.2 Reliable Hydropower Generation

In the studied development plans, it was assumed that hydropower generation increase by building new dams would only occur in Ethiopia; no hydropower dams would be built in South Sudan, Sudan, or Egypt due to the flatter topography and consequent negligible potential in those three countries. The first axis in Figure 7 refers to the increase in hydropower generation in Ethiopia, while the second reflects the Nile flow upstream HAD. The third to the sixth axes indicate the reliable hydropower generation (RHP) of Sudan, Ethiopia, and Egypt, respectively. South Sudan does not have significant hydropower generation and was excluded from this figure for simplicity.

Figure 7 shows that the RHP of each country is dependent on the combination of the decision to increase hydropower generation in Ethiopia, and other development decisions that rely on Nile water withdrawals, e.g., expansion of irrigated area. Interestingly, Sudan's RHP is better than that of the reference scenario (i.e., 9,500 GWh/yr, the black solid line) under all development plans; up to an additional 800 GWh/ yr could be achieved. This is attributed to the more regulated flows that occur under all development plans, due to adding more dams upstream in Ethiopia. However, the magnitude of this increase would be lower when the hydropower development in Ethiopia is combined with more water withdrawals from the Nile in Ethiopia and Sudan (red cluster). The RHP of Ethiopia changes mainly due to the increased hydropower generation from additional hydropower dams. Under the highest increase in hydropower generation (i.e., all considered hydropower dams are built), RHP can reach 50,300 GWh/yr, 220% higher than the reference scenario. However, other internal development decisions in Ethiopia that result in withdrawing more water from the Nile would marginally decrease the RHP, which can be observed by comparing the red and green lines in Figure 7, maximized withdrawals from the Nile (lowest flow at HAD; red lines) result in slightly lower RHP. Egypt's RHP would be changed mainly based on the upstream withdrawals from the Nile, higher upstream withdrawals (i.e., lower flow upstream HAD) would result in reduction of the RHP, with the lowest value of 6,000 GWh/yr occurring under the highest upstream withdrawals, compared to 7,700 GWh/yr under the reference scenario.

A trade-off exists between irrigation development and the benefits of existing and expanded hydropower generation in the ENB countries. This can be seen by comparing the green and red clusters in Figure 7. In both clusters, it is assumed that all considered Ethiopian hydropower dams are built. When this is combined with no irrigation area expansion and maximum improvement of irrigation efficiency (i.e., the green cluster), the generated RHP is maximized for each of the ENB countries and totals 68,300 GWh/yr. However, when combined with maximized irrigation area expansion and minimal irrigation efficiency improvement, the generated RHP of the ENB would be lowered by 11% to be only 60,500 GWh/yr.

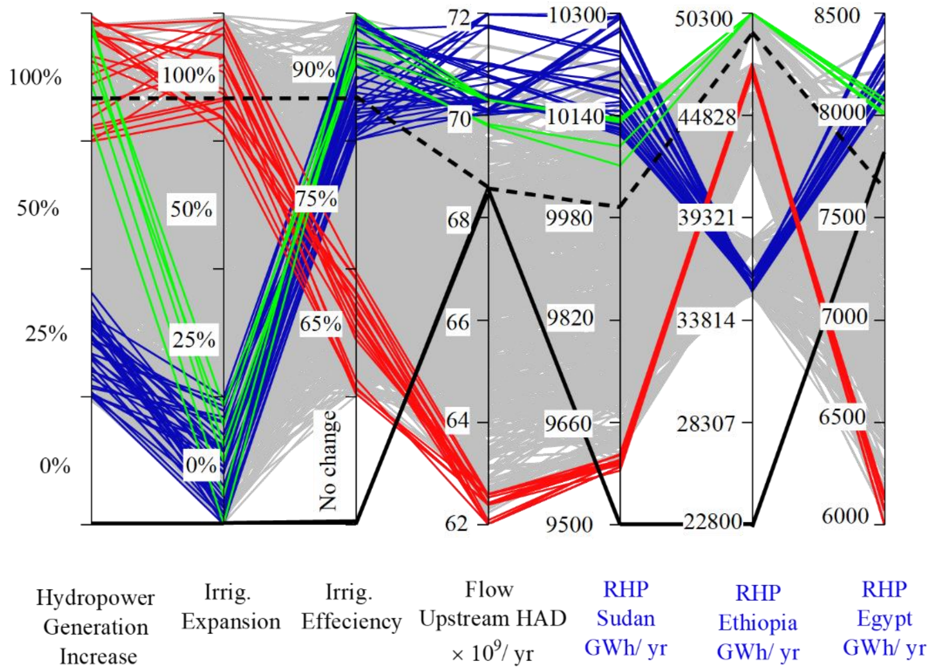

Figure 7: Parallel coordinate plots for the WEF systems performance measures of Reliable hydropower generation (RHP), for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting RHP are included in the figures. RHP is a summary hydropower production measure (i.e., 80% exceedance probability) for the whole period from 2017 to 2050. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.3.3 Food Gap

The food gap (FG) of the ENB countries is sensitive to the combination of changes in decision variables that control food production (Figure 8). Due to the limited potential for expanding irrigated area, utilizing the full potential of irrigation expansion (i.e., red lines in Figure 8) will not result in a significant change in the FG of South Sudan, Sudan, and Ethiopia compared to the reference scenario. Nonetheless, this irrigation expansion in the upstream countries, which occur with limited improvement to irrigation efficiency, as indicated by the red lines, will result in a significant reduction in the Nile flow upstream of HAD, diminishing Egypt's ability to reduce its FG. In such a case, even if Egypt expanded its irrigated area to the maximum potential, the FG would worsen compared to the reference scenario and increase from 60% in 2050 to up to 66%. Under this condition, if Egypt increased its maximum potential for water withdrawals from sources other than the Nile (i.e., as in Figure 8; non-river water withdrawal increases to 100%; equivalent to withdrawing an additional 5×10^9 m^3/yr), this would slightly lower the FG to be closer to the reference scenario with a value of 61% (i.e., the lower group of red lines on the last axes on Figure 8).

In contrast, the expansion of rainfed agriculture areas will significantly improve the FG of the ENB countries, especially if accompanied by enhancements in crop yields, switching cropping patterns toward cereal crops, and improving irrigation efficiency of existing irrigated lands to the maximum of 90% (i.e., blue lines in Figure 8). This can considerably lower the food gap of the three upstream countries while saving more of the Nile water flows to Egypt to be utilized to reduce its FG; under these conditions, FG values as low as 47% could be reached. Therefore, it is important to pay attention to the role of technology (irrigation efficiency and yield gap closure) in addressing water shortage and potential conflict in the ENB.

Under the full expansion of the rainfed and irrigated areas, the highest improvement of crop yield technology, shifting cropping patterns to allocate more areas to cereal crops, the FG improves significantly in comparison to the reference scenario for South Sudan, Sudan, and Ethiopia to achieve values of 4%, 12%, and 17%, by the year 2050, respectively (green lines in Figure 8). However, under this condition the Nile water that arrives in Egypt will be less than that for rainfed expansion only (the blue lines in Figure 8); Egypt's best FG value would be only 50%, as indicated by the green lines in Figure 8.

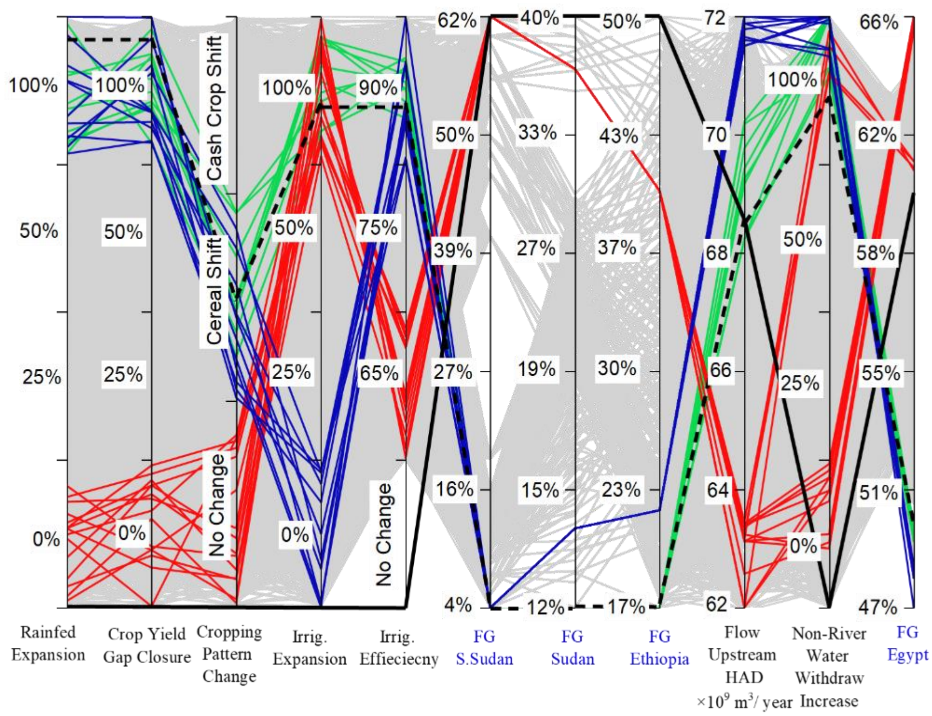

Figure 8: Parallel coordinate plot for the WEF systems performance measures of food gap (FG) reported for the year 2050 for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans (grey). Only major decision variables affecting FG are included in the figure. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers of change.

4.3.4 Gross Margin of Agriculture and Hydropower

Increasing hydropower production will contribute to improving the socio-economic conditions in Ethiopia, however, the direct economic benefit from this increase will be small compared with the direct benefits of increasing agricultural production, mainly through rainfed expansion. The highest contribution hydropower can make to the Ethiopian GM is 2 billion USD/yr, whereas the agricultural production increase could add up to 106 billion USD/yr. The same observation applies to the other ENB countries, in which the major contribution to GM comes from agriculture. Notably, there are also some other indirect economic benefits that need to be quantified and included in such comparisons, electricity for example can drive industry and other economic sectors. The combined direct and indirect economic benefits could lead to different conclusions; however, this is out of the scope of this study.

Similar to FG, the most significant decision variables to increase GM in the ENB countries are rainfed area expansion and crop yield technology improvement, while Egypt's GM is based on irrigated agriculture, thus, the flow that arrives upstream HAD is an important indicator for the country. As Figure 9 shows, under the highest expansion of the rainfed agricultural areas, and with the full closure of the yield gap, these two decision variables, combined with cropping pattern shift to increase the area allocated to cash crops, the GM of South Sudan, Sudan, and Ethiopia can reach 166, 89, and 107 billion USD/yr (blue lines in Figure 9), which is 27, 3, and 5 times the GM with no agricultural development case (i.e. the reference scenario; solid black line in Figure 9). Under these conditions, the Nile flow upstream of the HAD allows Egypt to achieve GM values of 44 billion USD/yr or higher. Increasing the irrigated area only without expanding rainfed, with no significant change in irrigation efficiency, nor change to the cropping patterns, and without improving the crop yield technology will result in the least improvement to the GM of the ENB countries. This will also reduce the Nile flow that arrives in Egypt, and result in GM lower than the reference scenario (as indicated by the red lines versus the solid black line in Figure 9).

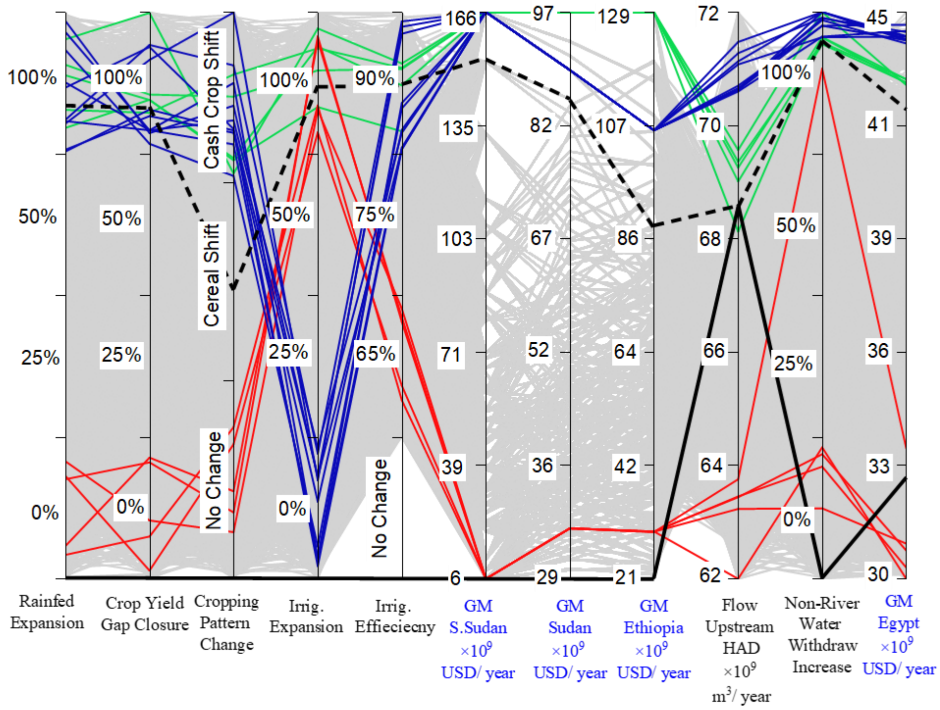

Figure 9: Parallel coordinate plots for the Gross Margin of Agriculture and Hydropower (GM) reported for the year 2050, for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting GM are included in the figures. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.4 The Selected WEF Development Plan

Development decisions in the water, food, and energy sectors in each of the ENB countries could result in trade-offs, but also synergies. These occur among the sectors of the same country but are more pronounced across sectors of different countries. A major synergy occurs in the energy sectors of Ethiopia and Sudan, in which the increase of Ethiopian hydropower generation by adding new hydropower dams to the Nile River system results in more regulated Nile flows, and consequently higher hydropower generation from existing Sudanese dams (as indicated in Figure 7). The major trade-off across the ENB countries is associated with development plans that rely on increasing water withdrawals from the shared water resources of the Nile. More specifically, plans in South Sudan, Sudan, and Ethiopia that lead to increased withdrawals from the Nile (e.g., irrigation) reduce Nile water availability for Egypt and affect the performance of its WEF sectors. As Figures 6, 7, 8, and 9 show, under the studied development plans, the Nile mean annual flow upstream of the HAD can drop by 10%, compared to the reference scenario, and consequently, Egypt's RWU, FG, RHP, and GM will significantly deteriorate (red lines on the figures), whereas internal Egyptian planning decisions will be much less effective in improving the WEF sectors' performance.

It is clearly prudent to adopt development plans that reduce this major trade-off between upstream development and the negative consequences on Egypt. A thematic pathway would be to acknowledge Egypt's water scarcity problem when pursuing WEF development in the upstream countries. The goal would be to minimize additional Nile water withdrawals, while achieving enhanced WEF conditions. To this end, the potential of rainfed agriculture should be prioritized over irrigation for food production and enhancing the economy. The use of technology could play an important role in enhancing crop yields and closing the food gap. Irrigation efficiency improvement in existing and future projects is very important to guarantee that upstream irrigation expansion does not significantly reduce Nile water availability for Egypt, although it might not fully counterbalance the increase in demand as shown by Multsch et al. (2017). Hydropower growth through building new dams upstream might be doable, as long as downstream operational concerns are addressed (Wheeler et al., 2020), especially under prolonged drought and flood conditions. Following this, one of the studied development plans was selected for further analysis under a wide range of change in WEF exogenous drivers.

Although the selected development plan (thereafter SDP) may not necessarily represent optimal development for the ENB, it has some superior features as indicated by black dotted lines on Figures 6, 7, 8, and 9. The SDP significantly reduces the food gap for all ENB countries; FG values drop to 4%, 12%, 17%, and 50% compared with 62%, 40%, 50%, and 60% under the reference scenario for South Sudan, Sudan, Ethiopia, and Egypt, respectively. Gross margins for the four countries are significantly improved, with South Sudan, Sudan, Ethiopia, and Egypt having values of 154, 86, 88, and 41 billion USD/yr, which are 26, 3, 4, and 1.3 times the reference scenario values. The SDP shows high hydropower generation for Ethiopia and Sudan with RHP of 50,000 GWh/yr and 9,985 GWh/yr, respectively. Importantly, this SDP does not exacerbate water problems for Egypt, as the same levels of Nile flows and water stress conditions are maintained as in the reference scenario. To achieve this good performance, the SDP assumes that the rainfed agricultural area is expanded to the maximum potential in South Sudan, Sudan, and Ethiopia, by adding 54 million ha, 38 million ha, and 35 million ha, respectively. Concurrently, crop yield should be improved to close the yield gap in the ENB countries. Additionally, cropping patterns need a shift to allocate more area to cereal crops. Irrigation was assumed to expand to the maximum potential with additional 0.5, 0.9, and 1 million ha added to the irrigated lands of Sudan, Egypt, and Ethiopia, respectively. The total number of 14 hydropower dams stated in Table S1.2 were assumed to be implemented, and importantly, the maximum improvement of irrigation efficiency to reach an idealized value of 90% was assumed to occur in all countries, such that the mean annual Nile flows that arrives at Egypt remains at the same value as in the reference scenario. In addition, Egypt was assumed to utilize its maximum potential of withdrawing 5×10^9 m^3/yr from sources other than the Nile.

4.5 The Selected WEF Development Plan under Changing Conditions

As discussed in the previous section, the selected development plan (SDP) has good values for all performance measures, when evaluated under the assumption that socio-economic and climate drivers continued/trended as observed in their historical period (i.e., no driver change). However, under the full range of plausible projections for those socio-economic and climate drivers, the performance measures of the ENB would significantly vary.

In each country, performance measures of the SDP are worsened under the high socio-economic scenario compared with the case of no driver change, as indicated within the dotted boxes on Figures 10 and 11. This is expected, as the higher population growth rate of 3% would increase the level of competition over river water resources and stress the WEF systems. More per capita municipal water demand, as assumed under this scenario, will increase water withdrawals, however, due to the high population growth, the overall impact will be worsened RWU. The higher population growth combined with higher per capita food demand will increase national food demand, thus, worsen the FG. This scenario leads to higher river withdrawals for municipal supply and less river water is left for hydropower and irrigation, which result in reduced RHP and GM. Contrarily, as indicated by comparing the green and orange points within the dotted boxes on Figures 10 and 11, in each country, the low socio-economic scenario that features mild population growth rate of 1% resulted in less stress on river water resources, and thus, WEF performance measures are improved compared to the case of no driver change.

In addition to these changes caused by socio-economic scenarios, the studied climate driver changes resulted in significant impacts on the WEF performance measures of the SDP (Figures 10 and 11). Higher mean annual precipitation enhances both blue and green water availability and allows for more withdrawals for different uses, which improves the RWU and boosts food production leading to better FG values. This also increases the flow arriving to the river system, keeping the reservoir elevations at high levels and increasing the turbine water releases, thus, having a compound increasing effect on RHP. This enhanced hydropower and agriculture production leads to significant improvements in the GM of each of the ENB countries. However, the assumed increases in the annual mean temperature by an additional +0.5 °C to +4 °C by the year 2050 will marginally worsen the WEF performance measures. Higher temperatures increase evapotranspiration and reduce blue and green water availability but also increase water demand, which reduces the RWU, FG, RHP, and GM, as shown by Figures 10 and 11. Importantly, temperature increases could lead to heat stress, which may impact vegetation biophysical processes. This was not considered in our model and may cause additional reductions to crop production and GM and increases FG.

In the three countries of Ethiopia, Sudan, and South Sudan, FG seems to be more sensitive to precipitation reductions than precipitation increases. This is attributed to the fact that a major part of food production comes from rainfed agriculture, which is dependent on soil water availability (i.e., green water). There is a threshold of the mean annual precipitation increase after which the soil water availability is enhanced to the level that minimizes water stress for crop production (i.e., soil water availability approaches crop potential evapotranspiration), leading to maximized food production, any higher precipitation will not considerably impact crop production. Notably, the increased precipitation might also reflect increased flooding risks, which may cause damage to vegetations and reduce crop production, however, this was not considered in the model.

Remarkably, under all drivers of change combinations, the RWU of Ethiopia, Sudan, and South Sudan is still relatively good and does not reflect water stress conditions as severe as for Egypt. Under the most extreme combination of driver change, i.e. the highest population growth of 3%, the largest reduction to mean annual precipitation of -10%, and the highest increase in annual mean temperature of +4 °C, the RWU would be 1,180, 1,614, and 10,886 m^3/cap/yr, for Ethiopia, Sudan, and South Sudan, respectively, which is 7 to 72 times Egypt's value of 150 m^3/cap/yr, as Figures 10 a, b, c, and d show.

Population growth rate is a major driver for improving the region's food conditions. Under the lowest growth rate of 1%, the food gap would significantly improve, values as low as 20%, 9%, 5%, and 2% could be reached in Egypt, Ethiopia, Sudan, and South Sudan, respectively. Importantly, due to the large agricultural area cultivated under the SDP, these low values remained nearly unchanged under the full range of considered climate changes (i.e., green points on Figures 10 e, f, g, and h).

Importantly, the impacts of socio-economic and climate driver changes on the WEF performance measures are not constrained by country boundaries. Driver changes in the upstream countries of the ENB that impact the shared water resources of the Nile will cause extended impacts to the downstream countries. This is most obvious for Egypt, being the most downstream country with hyper-arid climate and high dependency on the Nile as the major source of all water uses. Figure S2.5 shows the combined impacts of driver changes in the upstream on the Nile flow that arrive at Egypt. These impacted Nile flow values combined with the internal driver changes of Egypt dictated the WEF performance measures indicated in Figure 10 d and h, and Figure 11 d and h.

As Figures 10 and 11 imply, among the four countries of the ENB, Egypt's water, food, and economic conditions are the most sensitive to the considered internal and external driver changes. Even if the WEF development plans of the upstream countries are optimized, decision-makers should anticipate the fact that the outcomes of Egyptian WEF planning decisions would be surrounded by high uncertainty stemming from climate and socio-economic changes in the upstream countries and within Egypt.

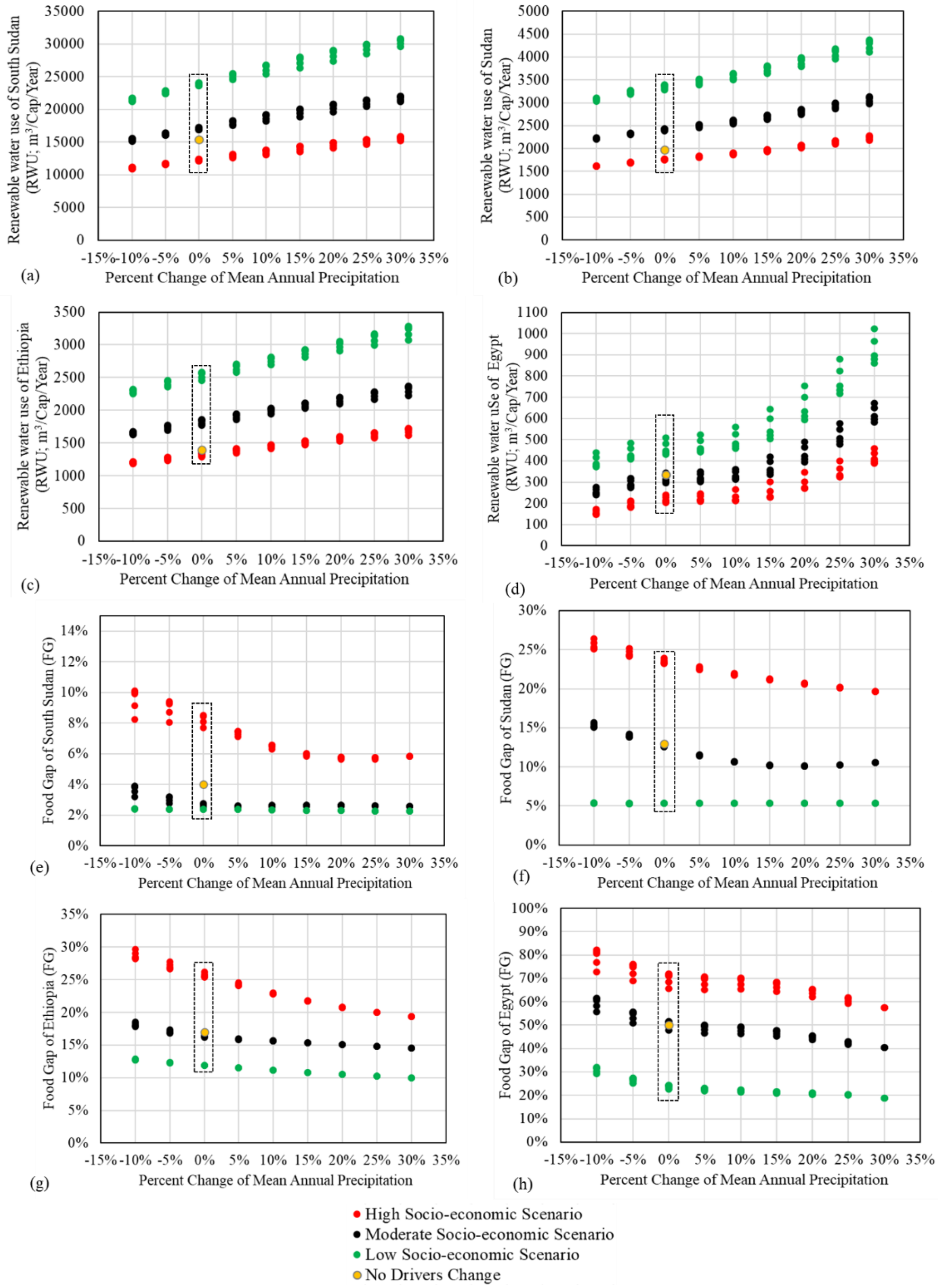

Figure 10: scatter plot for WEF nexus performance measures of renewable water use (RWU) for (a) South Sudan, (b) Sudan, (c) Ethiopia, and (d) Egypt; and food gap (FG) for (e) South Sudan, (f) Sudan, (g)Ethiopia, and (h) Egypt. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the performance measure values. RWU and FG are reported for the year 2050. The orange point on the figures refers to evaluations under no social nor climate drivers

*change, whereas point colors of green, black, and red, refer to one of the three socio-economic scenarios, as listed in table S2.1. At a given value for the percent change of mean annual precipitation, the vertical variations of the points with the same color are due to the different annual mean temperature changes***.** *Points surrounded by a dotted box represent the performance measure values under social drivers change, but no mean annual precipitation change.*

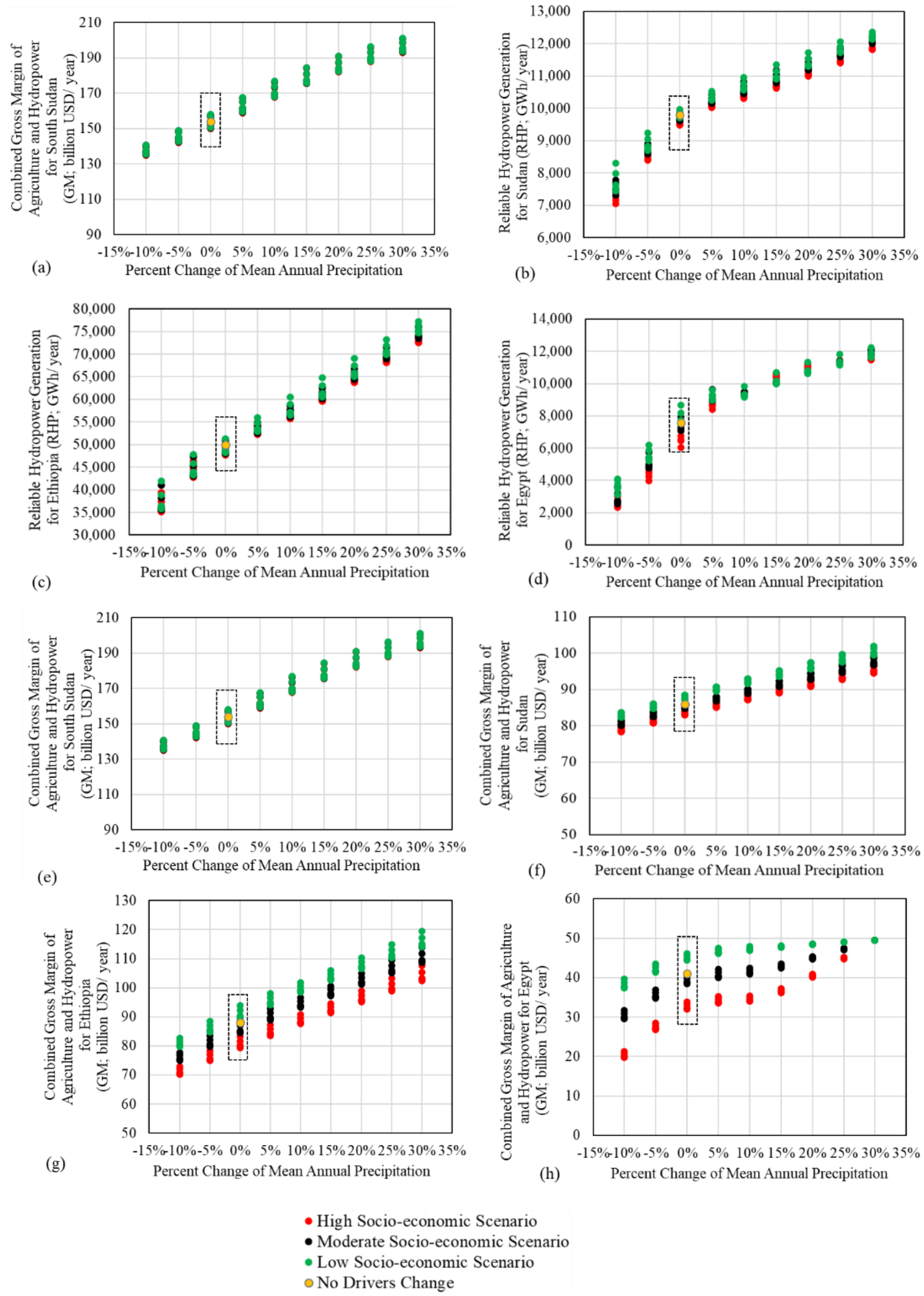

Figure 11: scatter plot for the WEF nexus performance measures of reliable hydropower generation (RHP) for (a) South Sudan, (b) Sudan, (c) Ethiopia, and (d) Egypt; and combined gross margin of agriculture and hydropower (GM) for (e) South Sudan, (f) Sudan, (g) Ethiopia, and (h) Egypt. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the performance measure values. RHP estimation considers a summary measure (i.e., 80% exceedance probability) for the whole period between 2016 and 2050, while GM is reported for the year 2050. The orange point on the figures

refers to evaluations under no social nor climate drivers change, whereas point colors of green, black, and red, refer to one of the three socio-economic scenarios, as listed in table S2.1. At a given value for the percent change of mean annual precipitation, the vertical variations of the points with the same color are due to the different annual mean temperature changes. *Points surrounded by a dotted box represent the performance measure values under social drivers change, but no mean annual precipitation change.*

5 Discussion of Limitations and Uncertainties

In this study, we explored the WEF nexus of the ENB countries under a wide range of plausible changes of socio-economic and climate drivers. The mean annual precipitation of the region was the driver that impacted the WEF nexus performance the most. However, there are specific climatic conditions that could critically stress the WEF nexus and were not explicitly considered in this study. Importantly, drought has severely impacted water and food systems of the ENB countries in the past and will likely reoccur in the future (Siam and Eltahir, 2017). Notably, under the SDP, discussed in this study, droughts are expected to cause less severe impacts on WEF performance measures compared to the case of no development (i.e., reference scenario). This is mainly due to the additional storage capacity of the planned reservoirs that would be added to the river system of the ENB and expected to act as a buffer that reduces the negative consequences of droughts (Wheeler et al., 2020; and Siam and Eltahir, 2017), subject to a basin agreement for reservoir filling and operation to ensure equitable benefit sharing. However, while this might benefit irrigated agriculture, rainfed agriculture, which is the major food production sector of the ENB, might not benefit from this increased storage and might be left susceptible to risks from climate variability. In such case, the huge benefits from expanding rainfed agriculture, as explored in this study, might be. significantly reduced due to droughts. Accordingly, there is a need for explicit consideration of drought scenarios to quantify how drought characteristic changes might impact the WEF conditions, and specifically impact the rainfed agriculture, which we recommend for future research. A further impact of climate change that was not considered in this study is climate change-induced sea level rise, which will possibly submerge portions of the delta region in Egypt (Hereher, 2010), leading to risks of losing fertile land and expanding the food gap values estimated for Egypt.

For all considered development plans, it was assumed that the reservoirs added to the river system were filled to the full supply level at the beginning of future simulation period. This allowed for the exploration of the long-term impacts of development plans after reservoirs are added to the system and become operational but does not investigate the WEF nexus conditions during the filling period of the studied reservoirs. However, this has been extensively discussed for the case of GERD, where relatively longer periods of filling (i.e., 7 years or more) were found to cause significantly less impacts on the downstream countries, compared to shorter filling periods (i.e., 2-6 years; Heggy et al., 2021; Elsayed et al., 2020; and Wheeler et al., 2020). Other than the GERD, there are 12 other dams, with a total storage capacity of 148×10^9 m^3 that have been considered in this study, to be built on the Nile, which is a huge storage compared to the annual flow of the Nile. When more of those reservoirs are filled concurrently and in shorter filling periods, sharp reductions of shared river flows are likely to occur, and hence, severe impacts on the WEF conditions would happen. Those reservoirs will thus require to be filled in a staged form and will likely require long time. It is important to study and assess the impacts of different scenarios of reservoir filling on the WEF performance measures of the ENB countries. Moreover, it is important to put the findings of such assessment in the context of the feasibility of adding such huge storage to the river system, which we recommend for future work.

Additionally, reservoir operation rules were assumed fixed for all the studied development plans and under all social and climate driver changes, which is a reasonable assumption in accordance with the objective of this study, and for the evaluation of the long-term values of the WEF nexus performance. However, reservoir operation rules are important decision variables that have been widely discussed for the case of the GERD (Basheer et al., 2018, Wheeler et al., 2016; and Wheeler et al., 2018). Ethiopian operational decisions of the GERD, which has a huge storage capacity, would affect the seasonality, magnitude, and timing of the Blue Nile flow that arrives to Sudan, which has a few reservoirs with small storage capacities. Sudanese operational concerns about the GERD release rates, which might be either too high and exceed the capacities of the small Sudanese dams with risks of dam overtopping and failures or be too low at critical times of water withdrawal with risks of water shortages need to be considered. Egypt's operational concerns are related to how the dam is operated under severe and prolonged droughts, as it can either amplify or dampen the drought impacts on Egypt. The GERD's, and possibly other planned Ethiopian dams', operational needs for Egypt and Sudan conflict with the operational needs of Ethiopia (i.e., maximize hydropower), thus, operational trade-offs exist. Ethiopia has plans to build up to 15 dams, of which 12 are on the Nile tributaries, with a total storage capacity of 148×10^9 m^3, which provides more control on the natural flow pattern, and in certain cases could result in conflicts with Egypt's and Sudan's operational needs. The operation of these reservoirs becomes a more critical variable and needs to be explored in future studies.

Due to limited data availability, the water resource system of the ENB countries was not fully represented in this study, as we considered only seven (Figure 1) out of the 12 rivers that originate in Ethiopia. However, the considered rivers' flows represent 95% of the flow of the 12 rivers. Moreover, for the same reasons, freshwater lakes and groundwater availability and usages were not considered. The inclusion of these ignored water resources in the analysis might marginally improve the Ethiopian WEF performance measures.

The energy production sector of the ENB countries was not fully represented in the model used in this study, only hydropower was considered. However, there are other sources of energy that currently exist and/or could be developed to produce more energy in the future. Relying on those other sources could result in additional trade-offs or synergies between the WEF sectors in one or more countries. For instance, expanding thermal energy generation as a major energy production source could result in additional water withdrawal from the river system for cooling purposes, which might limit water availability and result in additional trade-offs within the WEF nexus. Another example is expanding biofuel energy production, which will compete with the food production sector over water and land utilization. A possible improvement to the work presented in this study would be to consider the full energy production system (e.g., fossil fuel, thermal electricity stations, biofuels, solar system, wind turbines, etc.) and how this complete energy sector interacts with the water and food sectors of the ENB region.

Under the studied development plans, the full potential of rainfed agriculture area in the ENB countries was assumed to be utilized before 2050, although this may be unrealistic as it would require large investments, which may reduce the short-term economic gains of those expansions. A detailed cost benefit analysis might be required to incorporate the capital costs required for such expansions and to evaluate net economic returns by 2050. The same requirement applies for the studied improvements of the irrigation and the hydropower sectors (Cervigni et al., 2015).

Despite all the limitations stated above, this study was able to determine and quantify the trade-offs and the possible future pathways of the WEF development planning process for the ENB countries. Although there are some conflicting pathways, we introduced a thematic pathway of development, which showed good WEF nexus performance for all ENB countries. Moreover, the study of development plans under a wide range of driver changes revealed the high sensitivity of the WEF system to these changes. Accordingly, future WEF planning approaches may need to not only consider such thematic pathways of development, but also consider development plans that could be robust and perform well under wide driver changes (Abdelkader and Elshorbagy, 2021). The WEFNAF framework introduced in this study allowed us to generate and assess WEF plans, but more importantly, this framework includes a rich database of thousands of plans that can be assessed by policymakers and used for any future WEF negotiations among the ENB countries.

Although each of the ENB countries has a food gap, some countries still have considerable production surplus in one or more crops that could be exported. In the formulation of the ENB WEF model, it was assumed that any crop with production surplus was traded with the global market, with no priority given to food trade among the four countries of the ENB. However, if such intra-regional trade is prioritized, the food gaps reported in this study could reach much lower values. In the studied development plans, Sudan and South Sudan had the largest crop surpluses that could be utilized to reduce Egypt's and Ethiopia's food gaps. For instance, in the year 2050, under the selected development plan and the reference WEF drivers' values, the food gap was projected to be 50% and 17% for Egypt and Ethiopia, respectively (Figure 8). Egypt's and Ethiopia's major crop deficits were in cereal crops. Egypt also had a considerable deficit in sugar crops. These deficits can be filled by the surplus of the same crops that are produced in Sudan and South Sudan, resulting in much lower food gap values of 10% and 5% for Egypt and Ethiopia, respectively. Moreover, if this intra-region trade prioritization was combined with a regional cropping pattern planning that target diminishing the food gap of the region as a whole, lower food gap values could have been reached for Egypt and Ethiopia, while Sudan and South Sudan would completely close their food gaps.

6 Conclusions

A modeling framework that simulates the water resources demand and supply, food production, and hydropower generation of the Eastern Nile Basin (ENB) countries was introduced. The framework was validated for a historical period, then used to generate a wide range of plausible future water, energy, and food (WEF) development plans up to 2050. Results indicated that increased water withdrawals upstream (i.e., Ethiopia, Sudan, and South Sudan) would reduce Nile water arriving at Egypt, and due to Egypt's high dependency on the Nile River, this will result in exacerbating Egypt's water scarcity problem, widening its food gap, and reducing its economic benefit from agriculture. Accordingly, a thematic WEF development pathway that aims to reduce this major trade-off among the region's countries was identified.

In this pathway, the neglected potential of rainfed agriculture sector was considered as a critical component for future development and should be prioritized over irrigation to enhance food production and improve the economy without stressing the shared water resources of the Nile. Accordingly, more land areas were proposed to be utilized for rainfed agriculture, but more importantly, the reliance on technology would be instrumental as significant improvements in crop yields will be necessary to boost food production and enhance the economy. Moreover, as the upstream countries do not have the physical water scarcity problem of Egypt, it is proposed that they can limit their Nile water resource withdrawals to help Egypt minimize its water scarcity. To this end, upstream irrigation land expansion could be minimized or pursued with a commensurate irrigation efficiency enhancement, such that the total upstream withdrawals from the Nile do not significantly change from the existing conditions. Building new hydropower dams in the upstream countries would significantly increase the energy production, but importantly, coordination would be needed to address the downstream operational concerns.

However, the analysis of such pathway under social and climate drivers' changes revealed the high sensitivity of the WEF development outcomes of the ENB countries to future changes in the upstream mean annual precipitation, especially for Egypt, which would be the largest sufferer with increased water scarcity. The compound changes of some major socio-economic drivers, like population growth rates, per capita municipal water demands, and per capita nutritional energy demands were found to significantly impact WEF nexus conditions. Such impacts are not limited to the country where those socio-economic changes originate but often extends beyond the country's boundaries to impact other countries in the basin. Therefore, these drivers could be considered as key tools to face climate change impacts on WEF nexus. Under low population growth rates, moderate per capita municipal water demands, and moderate per capita nutritional energy demands, the climate change impacts were found to be much less severe.

The current WEF development path in the Eastern Nile Basin is characterized by unilateralism and claims of sovereignty in utilizing the shared water resources, and political tension is on the rise among the region's countries (Helal and Bekhit, 2023). In this study, we introduced an alternate development pathway (i.e., thematic pathway) that demonstrates that all ENB countries can achieve significantly improved WEF conditions with minimal trade-offs and conflicts. This represents a great opportunity for cooperation and coordinated development that could create long-lasting political stability in the region. Cooperation might include knowledge sharing and directing investments to achieve technological advancements to improve crop yields and irrigation efficiencies. Another important aspect is to reach agreements that guarantee consensual dam building, high coordination and cooperation on dam operation, and information sharing among the ENB countries to allow for managing the consequences of social and climatic driver changes in the region.

7 Data Availability Statement

The software used in the WEFNAF framework are SWAT [ArcSWAT Version 2012.10.4.21] for the hydrological model and Stella Architect [Version 2.0.3] to build the WEF nexus model, which are available from https://swat.tamu.edu/ and https://www.iseesystems.com , respectively. CHIRPS precipitation data set are available in Funk et al. (2015). ORH Temperature data can be downloaded freely from the Terrestrial Hydrology Research Group, Princeton University (http://hydrology.princeton.edu/). The SRTM data can be downloaded from https://www.usgs.gov/ . Soil data can be downloaded from International Soil Reference and Information Centre (ISRIC, 2012). Land Cover data are available from the European Space Agency (ESA, 2010). Spatial data for soil available water capacity downloaded from https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=545 . Spatial distribution of crop areas is estimated based on Portmann et al., (2010). Crop yields, food demand, production losses, food prices, and production cost data were compiled from FAO (2021).

References

Abdelkader, A., & Elshorbagy, A. (2021). ACPAR: A framework for linking national water and food security management with global conditions. *Advances in Water Resources*, *147*.

Abdelkader, A., Elshorbagy, A., Tuninetti, M., Laio, F., Ridolfi, L., Fahmy, H., & Hoekstra, A. Y. (2018). National water, food, and trade modeling framework: The case of Egypt. *Science of the Total Environment*, *639*, 485–496.

Alemayehu, S., Ayana, E. K., Dile, Y. T., Demissie, T., Yimam, Y., Girvetz, E., Aynekulu, E., Solomon, D., & Worqlul, A. W. (2020). Evaluating land suitability and potential climate change impacts on alfalfa (Medicago sativa) production in ethiopia. Atmosphere, 11(10), 1–21.

Alaminie, A. A., Tilahun, S. A., Legesse, S. A., Zimale, F. A., Tarkegn, G. B., & Jury, M. R. (2021). Evaluation of Past and Future Climate Trends under CMIP6 Scenarios for the UBNB (Abay), Ethiopia. Water, 13(15), 2110.

Allam, M. M., & Eltahir, E. A. B. (2019). Water-energy-food nexus sustainability in the upper Blue Nile (UBN) basin. *Frontiers in Environmental Science*, *7*(JAN), 1–12.

Allam, M. N., & Allam, G. I. (2007). Water resources in Egypt: Future challeges and opportunities. *Water International*, *32*(2), 205–218.

Arnold, J. (1994). SWAT-soil and water assessment tool.

Al-Saidi, M., & Hefny, A. (2018). Institutional arrangements for beneficial regional cooperation on water, energy and food priority issues in the Eastern Nile Basin. *Journal of Hydrology*, *562*(May), 821–831.

Ayyad, S., & Khalifa, M. (2021). Will the Eastern Nile countries be able to sustain their crop production by 2050? An outlook from water and land perspectives. *Science of the Total Environment*, *775*, 145769.

Basheer, M., Wheeler, K. G., Ribbe, L., Majdalawi, M., Abdo, G., & 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. *Science of the Total Environment*, *630*, 1309–1323.

Basheer, M., & Elagib, N. A. (2019). Temporal analysis of water-energy nexus indicators for hydropower generation and water pumping in the Lower Blue Nile Basin. *Journal of Hydrology*, *578*, 124085.

Beck, M. B., & Walker, R. V. (2013). On water security , sustainability , and the water-food-energy-climate nexus. *Frontiers of Environmental Science & Engineering*, *7*(5), 626–639.

Benson, D., Gain, A. K., & Rouillard, J. J. (2015). Water governance in a comparative perspective: From IWRM to a "nexus" approach? *Water Alternatives*, *8*(1), 756–773.

Berry, L. V. (2015). Sudan, a country study.

Berhanu, B., Seleshi, Y., & Melesse, A. M. (2014). Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development. Nile River Basin, 97-117.

Bernauer, T. (2002). Explaining success and failure in international river management. In *Aquat. Sci* (Vol. 64).

Betrie, G. D., Mohamed, Y. A., Griensven, A. V., & Srinivasan, R. (2011). Sediment management modelling in the Blue Nile Basin using SWAT model. Hydrology and Earth System Sciences, 15(3), 807-818.

Brink, L., & Mccarl, B. (1978). The Tradeoff Between Expected Return and Risk Among Cornbelt Farmers. *American Journal of Agricultural Economics*, *60*(2), 259–263.

Cai, X., Wallington, K., Sha, M., & Marston, L. (2018). Understanding and managing the food-energy-water nexus – opportunities for water resources research. *Advances in Water Resources*, *111*, 259–273.

Cervigni, R., Liden, R., Neumann, J. E., & Strzepek, K. M. (Eds.). (2015). Enhancing the climate resilience of Africa's infrastructure: the power and water sectors. World Bank Publications.

Culley, S., Bennett, B., Westra, S., & Maier, H. R. (2019). Generating realistic perturbed hydrometeorological time series to inform scenario-neutral climate impact assessments. *Journal of Hydrology*, *576*(April), 111–122.

Damkjaer, S., & Taylor, R. (2017). The measurement of water scarcity: Defining a meaningful indicator. Ambio, 46(5), 513-531.

Diao, X., You, L., Alpuerto, V., & Folledo, R. (2012). Assessing Agricultural Potential in South Sudan – A Spatial Analysis Method. Application of Geographic Information Systems, 1–23.

Digna, R. F., Castro-Gama, M. E., van der Zaag, P., Mohamed, Y. A., Corzo, G., & Uhlenbrook, S. (2018). Optimal operation of the Eastern Nile System using Genetic Algorithm, and benefits distribution of water resources development. *Water (Switzerland)*, *10*(7).

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., and Rulli, M. C. (2018). The global food-energy-water nexus. Reviews of geophysics, 56(3), 456-531.

Doorenbos, J., & Kassam, A. (1979). Yield Response to Water. FAO Irrigation and Drainage Paper No. 33.

Dunne, K. A., & Willmott, C. J. (1996). Global distribution of plant-extractable water capacity of soil. [Dataset]. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *16*(8), 841–859.

Elsayed, H., Djordjević, S., Savić, D. A., Tsoukalas, I., & Makropoulos, C. (2020). The Nile Water-Food-Energy Nexus under Uncertainty: Impacts of the Grand Ethiopian Renaissance Dam. *Journal of Water Resources Planning and Management*, *146*(11), 04020085.

Elshamy, M. E., Seierstad, I. a., & Sorteberg, A. (2009). Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrology and Earth System Sciences*, *13*, 551–565.

ENTRO. (2017). Eastern Nile Multi-Sector Investment Opportunity Analysis, Eastern Nile Technical Regional Office, Addis Ababa, Ethiopia.

ENTRO. (2020) governmental data collected for several reservoir simulation modeling studies, Eastern Nile Technical Regional Office, Addis Ababa, Ethiopia.

ESA. (2010). *European Space Agency GlobCover Land Cover Maps*. [Dataset] http://due.esrin.esa.int/page_globcover.php

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958.

FAO. (2015a). Aquastat Reports- Country Profile - South Sudan.

FAO. (2015b). Aquastat Reports- Country Profile-Sudan.

FAO. (2016). Aquastat Reports - Country profile - Ethiopia.

FAO. (2021). *FAOSTAT, Food and Agriculture Organization*. [Dataset]. http://www.fao.org/faostat/en/#data

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. [Dataset]. *Scientific Data*, *2*, 1–21.

Falkenmark, M. (1989). The massive water scarcity now threatening Africa: why isn't it being addressed?. Ambio, 112-118.

Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2018). Evaluation of multiple climate data sources for managing environmental resources in East Africa. Hydrology and Earth System Sciences, 22(8), 4547-4564.

Gumbel, E.J. (1958) Statistics of Extremes, Columbia University Press, New York.

Hanjra, M. A., & Qureshi, M. E. (2010). Global water crisis and future food security in an era of climate change. *Food Policy*, *35*(5), 365–377.

Hargraves, G.H. , Samani, Z. A. (1982). Estimating Potential Evapotranspiration, Technical Note. *Journal of Irrigation and Drainage Engineering*, *108*(3), 225–230.

Helal, M., and Bekhit, H.M., (2023). So near, yet so far: an Egyptian perspective on the US-facilitated negotiations on the Grand Ethiopian Renaissance Dam, Water International.

Hereher, M. E. (2010). Vulnerability of the Nile Delta to sea level rise: an assessment using remote sensing. Geomatics, Natural Hazards and Risk, 1(4), 315-321.

Heggy, E., Sharkawy, Z., & Abotalib, A. Z. (2021). Egypt's water budget deficit and suggested mitigation policies for the Grand Ethiopian Renaissance Dam filling scenarios. Environmental Research Letters, 16(7), 074022.

ISRIC. (2012). *International Soil Reference and Information Centre, Harmonized World Soil Database*.[Dataset] https://data.isric.org/geonetwork/srv/eng/catalog.search#/home

Liersch, S., Tecklenburg, J., Rust, H., Dobler, A., Fischer, M., Kruschke, T., ... & Hattermann, F. F. (2018). Are we using the right fuel to drive hydrological models? A climate impact study in the Upper Blue Nile. Hydrology and Earth System Sciences, 22(4), 2163-2185.

Mengistu, D., Bewket, W., Dosio, A., & Panitz, H. J. (2021). Climate change impacts on water resources in the Upper Blue Nile (Abay) River Basin, Ethiopia. Journal of Hydrology, 592, 125614.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). National water footprint accounts: the green, blue and grey water footprint of production and consumption. Volume 2: appendices.

Mekonnen, M., & Hoekstra, A. (2012). A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems*, *15*(3), 401–415.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Sustainability: Four billion people facing severe water scarcity. *Science Advances*, *2*(2), 1–7.

Mera, G. A. (2018). Drought and its impacts in Ethiopia. Weather and climate extremes, 22, 24-35.

MOEE. (2021). Annual Report of 2020/2021. Egyptian Electricity Holding Company. Ministry of Electricity and Renewable Energy.

Mohamed, M., and El-Mahdy, M. (2021). Evaluation of climate change impact on extreme temperature variability in the Blue Nile Basin, Ethiopia. *Geoscientific Instrumentation, Methods and Data Systems*, *10*(1), 45–54.

Multsch, S., Elshamy, M. E., Batarseh, S., Seid, A. H., Frede, H. G., & Breuer, L. (2017). Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin. Journal of hydrology: regional studies, 12, 315-330.

MWRI. (2010). The Water Resources Devlopment and Management Strategy in Egypt till 2050. Ministry of water resources and irrigation.

Namara, R., Makombe, G., Hagos, F., & Awulachew, S. B. (2008). Rural poverty and inequality in Ethiopia: Does access to small-scale irrigation make a difference? Proceedings of the Symposium and Exhibition on Impact of Irrigation on Poverty and Environment in Ethiopia, p. 97-116, November 27-29, 2007.

NBI. (2017). Nile Basin Water Resources Atlas, Nile Basin Initiative, Entebbe, Uganda

NBI. (2018). Nile encyclopedia [Data set], Nile Basin Initiative, Entebbe, Uganda.

Omer, A. M. (2008). Water resources and freshwater ecosystems in Sudan. Renewable and Sustainable Energy Reviews, 12(8), 2066-2091.

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. [Dataset]. *Global Biogeochemical Cycles*, *24*.

Rabus, B., Eineder, M., Roth, A., & Bamler, R. (2003). The shuttle radar topography mission - A new class of digital elevation models acquired by spaceborne radar. [Dataset]. *ISPRS Journal of Photogrammetry and Remote Sensing*, *57*(4), 241–262.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., & Qiang, Z. (2010). Managing water in rainfed agriculture-The need for a paradigm shift. *Agricultural Water Management*, *97*(4), 543–550.

Seleshi, Y., Demaree, G. R., Melesse, A., Garriguet, D., Colley, R., Bushnik, T., Ababa, A., AGRA, Toxboe, A., Abdo, K. S., Fiseha, B. M., Rientjes, T. H. M., Gieske, A. S. M., Haile, A. T., Dinku, T., Block, P., Sharoff, J., Hailemariam, K., Osgood, D., Bewket, W. (2014). Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development. In Nile River Basin. In *Environmental Development* (Vol. 119, Issue 4). Springer, Cham.

Siam, M. S., & Eltahir, E. A. (2017). Climate change enhances interannual variability of the Nile River flow. Nature Climate Change, 7(5), 350-354.

Sheffield, J., Goteti, G., & Wood, E. F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *Journal of Climate*, *19*(13), 3088–3111.

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

Tontisirin, K., de Haen, H. (2001). Human Energy Requirements. Report of a Joint FAO/WHO/UNU Expert Consultation.

United Nations (2022). World Population Prospects 2022. Department of Economic and Social Affairs Population Division. Retrieved from: https://population.un.org/wpp/

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W., & Dadson, S. J. (2016). Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. *Water International*, *41*(4), 611–634.

Wheeler, K. G., Hall, J. W., Abdo, G. M., Dadson, S. J., Kasprzyk, J. R., Smith, R., & Zagona, E. A. (2018). Exploring cooperative transboundary river management strategies for the Eastern Nile Basin. Water Resources Research, 54(11).

Wheeler, K. G., Jeuland, M., Hall, J. W., Zagona, E., & Whittington, D. (2020). Understanding and managing new risks on the Nile with the Grand Ethiopian Renaissance Dam. Nature communications, 11(1), 1-9.

World Bank. (2019). *Access to electricity as a percentage of population*. Retrieved from: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

World Bank (2023). Population estimates and projections. Retrieved from: https://databank.worldbank.org/source/population-estimates-and-projections

Wu, L., Elshorbagy, A., Pande, S., & Zhuo, L. (2021). Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. Resources, Conservation and Recycling, 164, 105192.

Wu, L., Elshorbagy, A., & Alam, M. S. (2022). Dynamics of water-energy-food nexus interactions with climate change and policy options. Environmental Research Communications, 4(1), 015009.