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

(Supplementary Material)

Contents:

Section S1

S1.1 Modeling components of the WEFNAF framework

S1.1.1 The hydrological model

The soil water assessment tool (SWAT; Arnold, 1994) is the hydrological model used to simulate the daily streamflow of thirteen river sub-basins of the Eastern Nile Basin (ENB) countries (Sub-basin outlets are listed in Table S2.3 and indicated in Figure 1). The model is spatially semi-distributed, in which a river basin is divided into smaller units, based on land slope, soil type, and land cover, to create homogenous hydrological response units (HRUs). For each HRU, the surface runoff is estimated using the SCS curve number method. Infiltration, percolation to different soil layers, evapotranspiration, and soil moisture content are also simulated. Water is allowed to flow on the surface and within the subsurface layers of the HRUs until it reaches the river network to form the streamflow that is routed to the watershed outlet using Muskingum-Cunge method (Cunge, 1969). In this study, the model was set to run for the period between 1981 and 2016 with the first two years as a spin-up period. Observed daily and monthly streamflow were used to calibrate and validate the model using the dynamically dimensioned search calibration algorithm (Tolson and Shoemaker, 2007). Calibration and validation results are shown in section S2.2. The main purpose of this model is to generate streamflow to drive the second model (i.e., the WEF model).

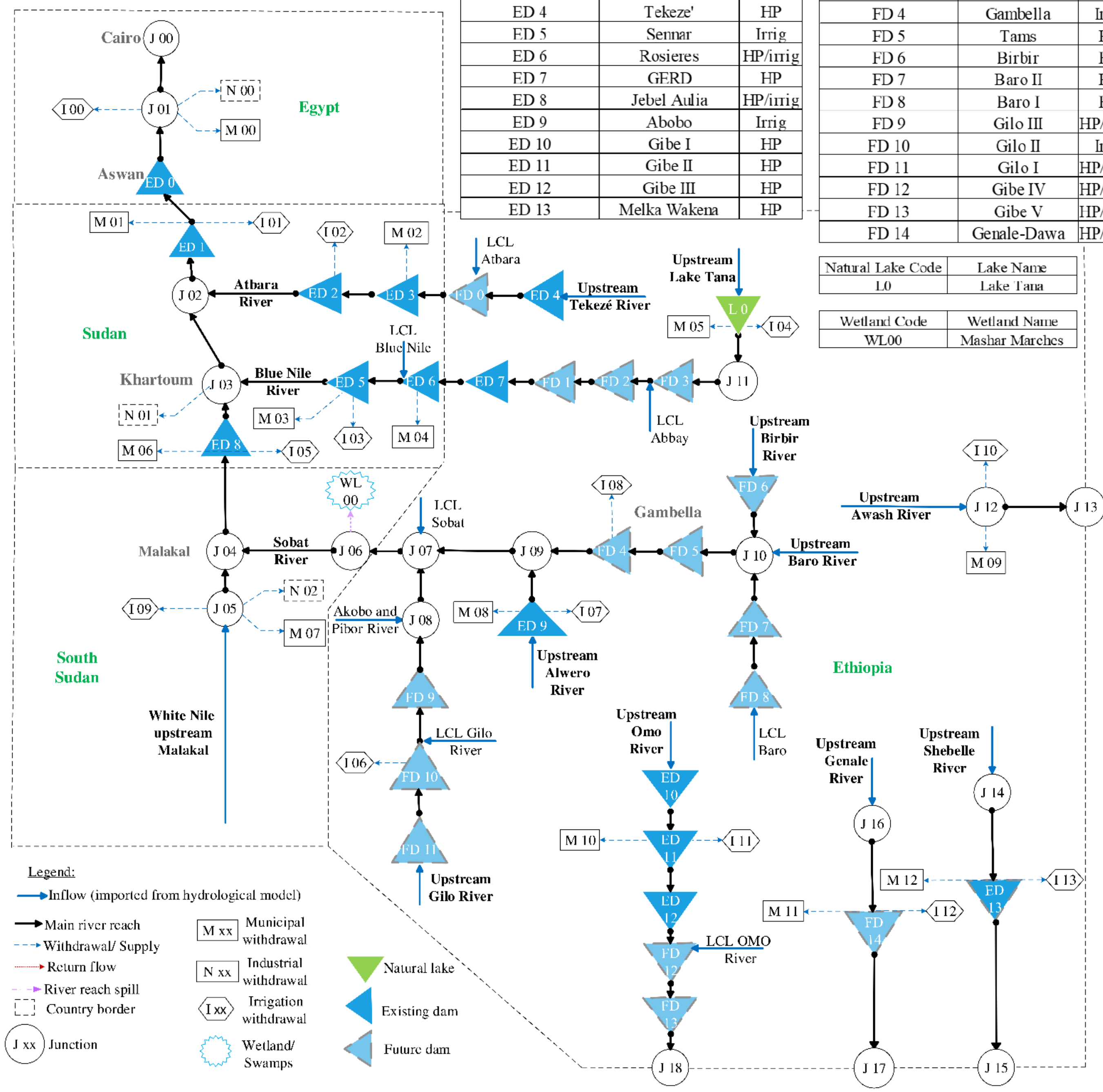
S1.1.2 The Water, Energy, Food (WEF) nexus model

The water-energy-food (WEF) model was built for this study using a system dynamics simulation environment (i.e., Stella Architect; https://www.iseesystems.com) to simulate the water and food (agricultural and animal products) demand and supply and the hydropower production for each of the ENB countries. The surface water resources system of the study area was incorporated in the WEF model, whereby the daily flow generated by SWAT was used as a boundary condition for the river and reservoir networks as in Figure S1.1. The daily municipal water demand at a specific location of the river system was estimated by multiplying the per-capita water demand (MWRI, 2010; and NBI, 2017) and the portion of the country's population living at this particular location (WorldPOP, 2020). The daily irrigation demand at each irrigation scheme was estimated by summing the daily irrigation water requirements over all the cultivated crop areas divided by irrigation efficiency. The daily irrigation water requirement was evaluated based on the soil moisture shortage estimated from a daily soil moisture balance, as illustrated in (Allen et al., 1998). This soil moisture balance considers the antecedent soil moisture, precipitation data, and potential evapotranspiration that was calculated based on the Hargreaves method (Hargraves and Samani, 1982). The industrial water demand was defined in the model as input data at the relevant locations (MWRI, 2010; and NBI, 2017). Water supply occurs based on logical priority rules; municipal demand takes the highest priority, followed by industrial demand, then the irrigation water demand. Accordingly, in case of insufficient water to meet all demands, irrigation water supply would be less than the irrigation demand, resulting in an irrigation water shortage. Daily hydropower generation was calculated within the WEF model at each relevant dam location as the multiplication of the dam water release, the head of water stored in that dam, the specific weight of water, and power generation efficiency at each dam (Munoz-Hernandez and Jones, 2012).

In Ethiopia, Sudan, and South Sudan there is insufficient and uncertain information about groundwater use and potential, thus, we only considered river flows as the major source of blue water supply (Berhanu et al., 2014; Omer, 2008). However, for Egypt the increased scarcity of surface water flows through the Nile means that the hyper-arid country utilizes other water sources. These include deep and shallow groundwater, wastewater and agricultural drainage water reuse, and desalination, which are all included in the WEF model as water supply sources for Egypt as described in detail in Abdelkader et al. (2018).

The agricultural production of 21 crops and crop groups cultivated in the study area was simulated within the WEF model. Crop yield was assumed to vary spatially, where due to the technology gap, the maximum yield achievable for each crop (Y_m) varies between the four countries. Further, to estimate the actual crop yields (Ya), Y_m is adjusted for spatial soil moisture availability, which varies based on the specific location inside each country (Doorenbos and Kassam, 1979). For this purpose, each country in the study area was divided into smaller units named agriculture calculation units (ACU; Figure S1.2), where a daily soil water balance was calculated for each crop based on antecedent soil moisture, precipitation, and potential evapotranspiration estimates for each ACU (Allen et al., 1998). To account for the effect of irrigation water application on soil moisture, the soil water balance was performed for the rainfed sub-sector and the irrigation sub-sector separately. Accordingly, the crop production of each crop, for the crops indicated in Figure S1.4, was calculated for each ACU and each sub-sector by multiplying the adjusted crop yield (tonnes/ ha) and its cultivated area (ha). The national crop production was calculated by summing the crop production over the sub-sectors and ACUs of each country. To estimate food production, the crops used by humans as food were accounted for separately. Additionally, animal production was estimated for each country in the study area, where the per head animal productivity (kg/head; FAO, 2021) of each animal product was multiplied by the number of producing animals (heads, FAO, 2021). This was done for four major animal products of red meat, milk, poultry, and eggs, following the approach used in Abdelkader et al. (2018) for Egypt.

Food demand was also calculated in the WEF model, whereby the per capita nutritional energy demand (NED; Kcal/cap) from all food products was partitioned over each food product by multiplying the NED by the ratios of each food product in the daily NED. Then using conversion factors (kg/Kcal), the per capita food demand was calculated in weight units (kg/cap) for each product. The national demand for the different food products can be calculated by multiplying the per capita food demand (kg/cap) by the national population. Net food exports were calculated for the different food products as the surplus in production over the demand, after accounting for food production losses. Animal feed demand and supply were estimated within the WEF model, where the per head annual feed demand was compiled from Mekonnen and Hoekstra (2012) and multiplied by the annual population of livestock available in each country to calculate the national feed demand. For Egypt, the feed supply was assumed to occur from irrigated fodders (i.e., Egyptian clover), and in case of shortage, feed imports occur. As for Ethiopia, Sudan, and South Sudan, the source of feed was assumed to be rainfed pasture as those countries rely heavily on grazing (NBI, 2017).



Existing Dam Code	Dam Name	Purpose
ED 0	High Aswan Dam	HP/irrig
ED 1	Merowe	HP
ED 2	Khashm Elgerba	Irrig
ED 3	Rumaylah Complex	HP/irrig
ED 4	Tekeze'	HP
ED 5	Sennar	Irrig
ED 6	Rosieres	HP/irrig
ED 7	GERD	HP
ED 8	Jebel Aulia	HP/irrig
ED 9	Abobo	Irrig
ED 10	Gibe I	HP
ED 11	Gibe II	HP
ED 12	Gibe III	HP
ED 13	Melka Wakena	HP

Future Dam Code	Dam Name	Purpose
FD 0	Humera	HP/irrig
FD 1	Mendaia	HP/irrig
FD 2	Beko-Abo	HP
FD 3	Karadobi	HP
FD 4	Gambella	Irrig
FD 5	Tams	HP
FD 6	Birbir	HP
FD 7	Baro II	HP
FD 8	Baro I	HP
FD 9	Gilo III	HP/ irrig
FD 10	Gilo II	Irrig
FD 11	Gilo I	HP/ irrig
FD 12	Gibe IV	HP/ irrig
FD 13	Gibe V	HP/ irrig
FD 14	Genale-Dawa	HP/ irrig

Natural Lake Code	Lake Name
L0	Lake Tana

Wetland Code	Wetland Name
WL00	Mashar Marches

Figure S1.1: A schematic diagram for the surface water resources system as represented in the WEF model.

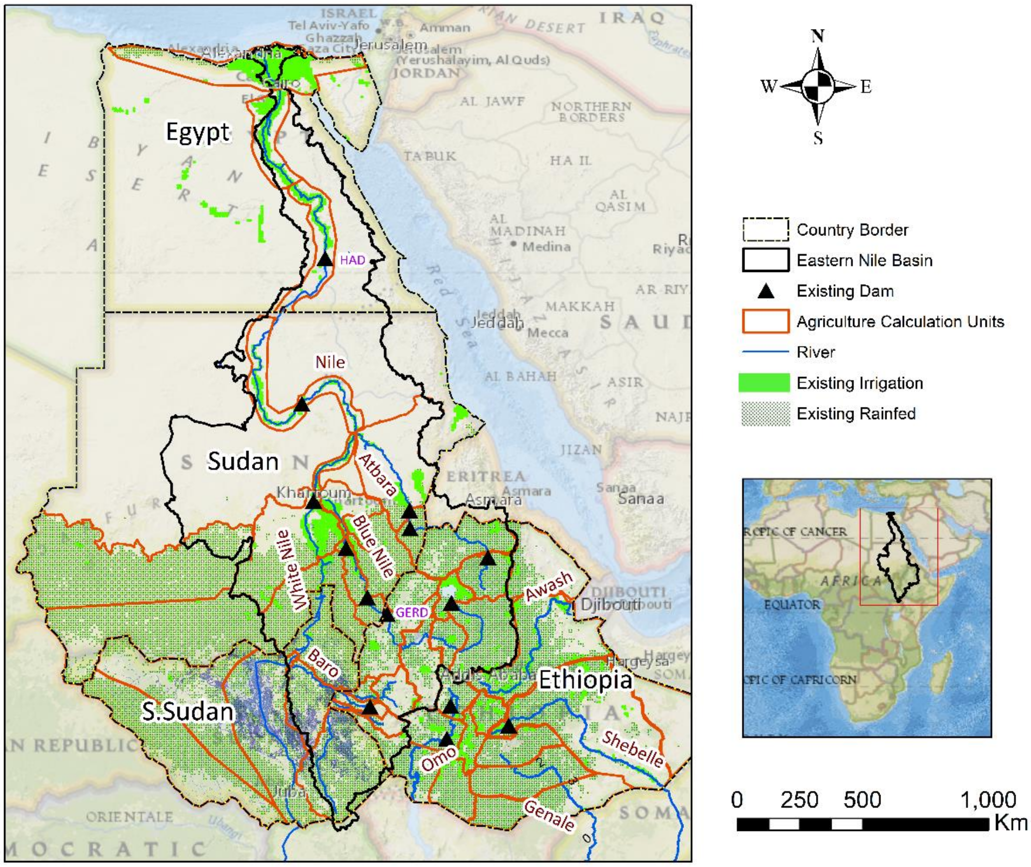


Figure S1.2: The agriculture calculation units (ACU) of the ENB countries as represented in the WEF model.

S1.2 Selected level of reliability for the RHP, GM equation, and weather generator

There is a tradeoff between a required level of reliability and the hydropower that can be generated at this level. Decision-makers must decide the level of reliability they want, which will differ from one decision-maker to another and could vary over time for the same decision-maker. In this study, a reasonable selection for the level of reliability is made using a value of 80%; it is understood that there is no right or wrong about this value, it is a matter of preference. It logically will not be 100%, and likely not less than 50%. Different decision-makers will pick different values according to their objectives and needs. Importantly, the selected value of 80% was fixed for all countries under all driver change scenarios and development plans, which sets a valid basis for comparing RHP.

The combined gross margin of agriculture and hydropower was calculated by adding the agriculture gross margin (AGM) and hydropower gross margin (HGM) that are calculated as in the following equations:

$$AGM_c(\mathrm{t}) = \sum_{i=1}^{L}(PL_{ci}(t) - VC_{ci}(t)) * PROD_{ci}(t) + \left(PG_{ci}(t) - PL_{ci}(t)\right) * EXP_{ci}(t)$$

$$HGM_c(\mathrm{t}) = \left(PE_c(t) - VE_c(t)\right) * NHP_c(t)$$

where $PL_{ci}(t)$ is the local market price of crop i in a country c and year t, $VC_{ci}(t)$ is the variable costs of producing the same crop. $PROD_{ci}(t)$ is the national production of crop i after accounting for any production losses. $PG_{ci}(t)$ is the global market price of crop i in a year t. $EXP_{ci}(t)$ is the exported quantity of crop i. L is the total number of crops produced. $PE_c(t)$ is the price of electricity in country c for year t. $VE_c(t)$ is the variable costs of hydropower production, a country average value was used for all power stations inside the same country. $NHP_c(t)$ is the national hydropower production from all hydropower dams of a country c and year t. All monetary values are in USD.

In this study, we used a daily weather generator based on the inverse approach (Culley et al., 2019), which was introduced as a technique to generate hydrometeorological timeseries that meet "target" changes in specific climate attributes, such as a specific mean annual precipitation. The approach begins by setting target values for the attributes that need to be changed. The target changes may be represented as absolute values (e.g., 3 °C increase in annual mean temperature) or percentage changes in attributes relative to historical climate (e.g., a 10% decrease in mean annual precipitation). Once the attribute targets are identified, the next step is to apply a formal optimization method that involves modifying the parameters of the daily weather generator, such that to optimize a measure between the relevant attributes of the simulated weather time series and the target attributes. In this study, we used Gamma distribution and Normal distribution to randomly sample the daily precipitation and temperature, respectively. The parameters of those distributions were optimized such that to generate daily timeseries that meet the target changes listed in Table S2.1 More details about the used approach are provided in Culley et al. (2019).

S1.3 Decision variables considered in WEF development plans

Table S1.1: Decision variables names, limits, and allowed values of change in each country.

Country	WEF sector	Decision variable name	Current value/ State as in year 2016	Limits of increase/ change	Data / info. source	Set of allowed values for each decision variable as a percentage of the limits of increase/ change
Egypt	Food	Rainfed agriculture land area	0.04 million ha	-	(MWRI, 2010)	-
		Irrigated agriculture land area	3.8 million ha	Add 0.9 million ha		0% - 25% - 50% -100%
		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	(Ayyad and Khalifa, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	8000 GWh/ year	-	(MWRI, 2010; McCarl, et al., 2015)	-
	Water	Irrigation efficiency	63%	Increase to 90%		65% - 75% - 90%
		Water withdrawal from Non-River sources	25.0 $\times 10^9$ m^3/year	Add 5.0 $\times 10^9$ m^3/year		0% - 25% - 50% -100%
		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 38 million ha	(Berry, 2015)	0% - 25% - 50% -100%
		Irrigated agriculture land area	1.8 million ha	Add 0.5 million ha	(Berry, 2015)	0% - 25% - 50% -100%
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase to match Egypt's crop yields (see Figure S1.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	10,000 GWh/ year	-	-	-
	Water	Irrigation efficiency	50%	Increase to 90%	(Al Zayed et al., 2015)	65% - 75% - 90%
		Water from Non-river Sources	-	-	-	0% - 25% - 50% -100%
		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 54 million ha	(Diao et al., 2012)	0% - 25% - 50% -100%
		Irrigated agriculture land area	0.12 million ha	-	(FAO, 2021)	-
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase to match Egypt's crop yields (see Figure S1.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	-	-	-	-
	Water	Irrigation efficiency	50%	Increase to 90%	(NBI, 2012)	65% - 75% - 90%
		Water from Non-river Sources	-	-	-	-
		Irrigation dam(s)	-	-	-	-
		Hydropower dam(s)	-	-	-	-
Ethiopia	Food	Rainfed agriculture land area	15.0 million ha	Add more 35 million ha	(Alemayehu et al.,2020)	0% - 25% - 50% -100%
		Irrigated agriculture land area	0.89 million ha	Add more 1.0 million ha	(Seleshi et al., 2014)	0% - 25% - 50% -100%
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure S1.3)	Increase to match Egypt's crop yields (see Figure S1.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure S1.4	Shift between cereals, and cash crops within 10% of the national cultivated area (see Figure S1.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	10,000 GWh/ year	Add 42,000 GWh/year	(Seleshi et al., 2014)	0% - 25% - 50% -100%
	Water	Irrigation efficiency	50%	Increase to 90%	(Asres, 2016)	65% - 75% - 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)	(Seleshi et al., 2014)	Dams are selected based on the irrigated land expansion value and its spatial location
		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)	(Seleshi et al., 2014)	Dams are selected based on the irrigated land expansion value and its spatial location

S1.4 Crop yield of major crops in the ENB countries

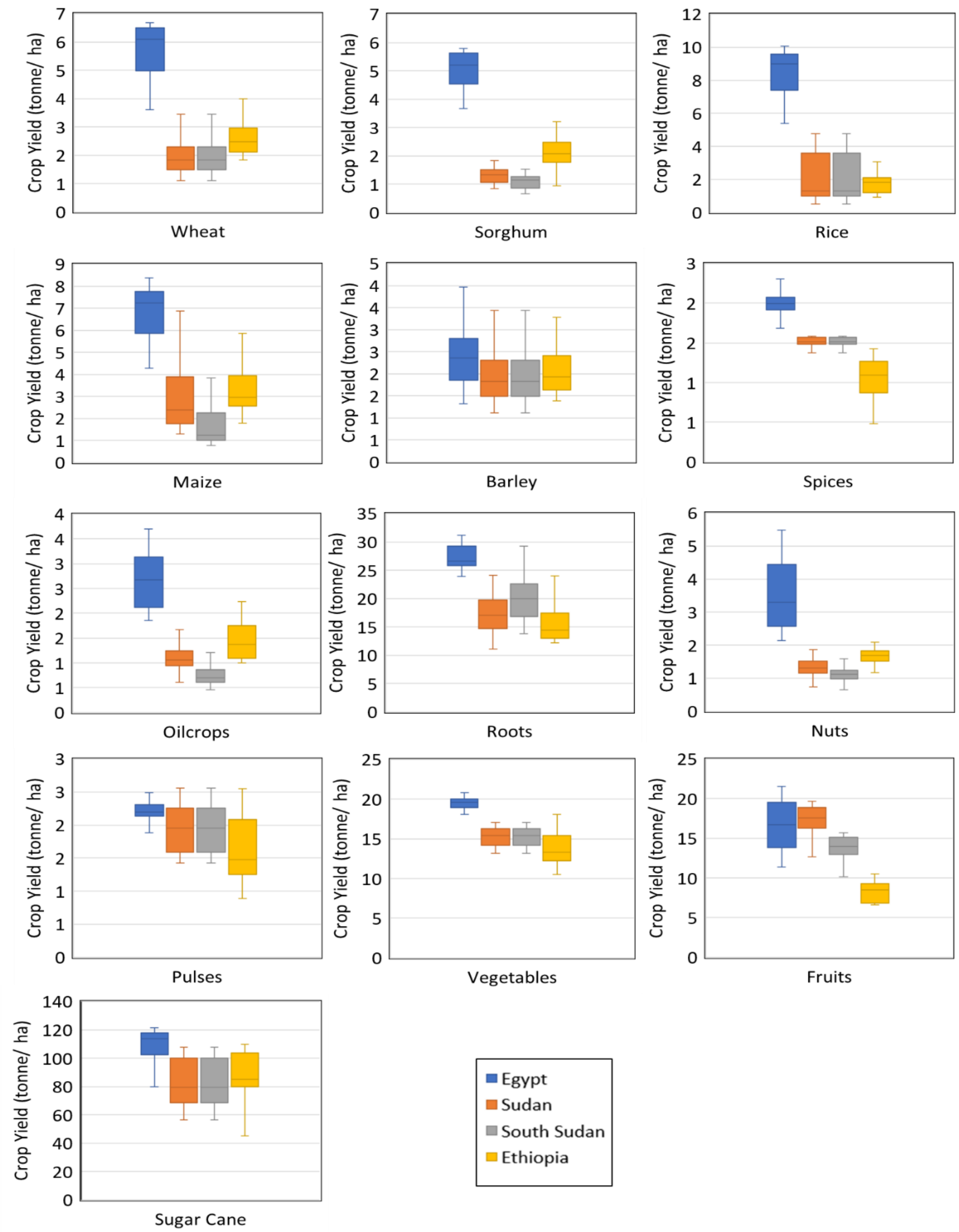


Figure S1.3: The maximum yield achievable (Y_m) for major crops cultivated in each country in the ENB countries. The boxplot shows the range of historical values between 1983 and 2016. The figure shows the yield technology gap between Egypt and the three countries of Sudan, South Sudan, and Ethiopia. This figure was developed based on an analysis of FAO data (FAO, 2021).

S1.5 Cropping patterns of the ENB countries

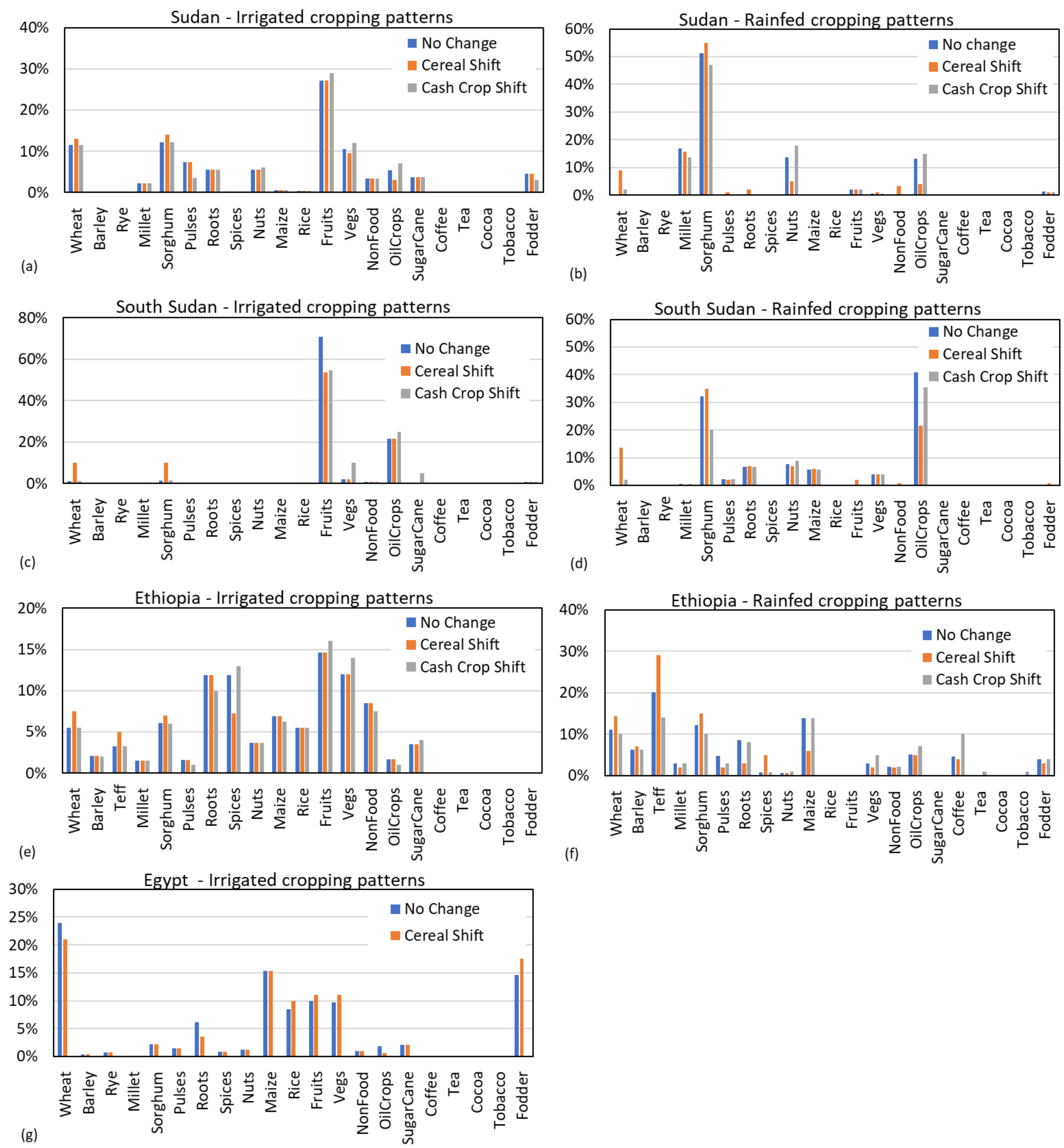


Figure S1.4: Cropping Pattern of the ENB countries for (a) Sudan – Irrigation sub-sector, (b) Sudan – Rainfed sub-sector, (c) South Sudan – Irrigation sub-sector, (d) South Sudan – Rainfed sub-sector, (e) Ethiopia – Irrigation sub-sector, (f) Ethiopia – Rainfed sub-sector, (g) Egypt – Irrigation sub-sector. The vertical axis indicates the percentage of the area of each crop from the total national cultivated area of each agriculture sub-sector. Figures are based on analysis of FAO data (FAO, 2021).

S1.6 Planned and under construction dams in the ENB countries

Table S1.2: the key characteristics of the planned and under-construction dams considered in this study. Notably, all these dams are planned to be in Ethiopia as indicated in Figure S1.1.

Dam Name	Purpose	River Sub-Basin	Status	Storage ($\times 10^9$ m^3)	Hydropower Generation (GWh/ Year)	Irrigation Potential (ha)
Humera Dam	HP/irrig	Atbara/ Nile	planned	6.5	650.0	83,000
GERD	HP	Blue Nile	under construction	74.0	15000.0	-
Mendaia	HP/ irrig		planned	48.0	6350.0	300,000
Beko-Abo	HP			31.0	6000.0	
Karadobi	HP			37.5	3000.0	-
Gambella	Irrig	Baro/ Nile		2.5	-	91,000
Tams	HP			10.0	3000.0	-
Baro II	HP			0.1	1100.0	-
Baro I	HP			1.5	420.0	-
Birbir	HP			2.8	1000.0	-
Gilo III	HP/ irrig			1.5	50.0	33,000
Gilo II	Irrig			2.8	-	159,000
Gilo I	HP/ irrig			3.6	420.0	150,000
Gibe IV	HP/ irrig	Omo River		9.0	1500.0	75,000
GibeV	HP/ irrig			5.0	3500.0	75,000
Genale-Dawa	HP/ irrig	Genale		3.0	10.0	34,000
			Total	**239**	**42,000**	**1,000,000**

S1.7 Sample Development Plans

Table S1.3 shows a sample of four out of the 6,912 development plans developed for this study. As the Table shows, each plan is composed of 9 decision variables, and each decision variable is changed simultaneously in the same way in each of the four ENB countries.

The first development plan (DP 1) features very limited change from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, cropping pattern, hydropower generation, water withdrawals from non-river sources, number of irrigation dams, and number of hydropower dams, are the same as the reference scenario for all four ENB countries. Only the Irrigation efficiency is assumed to increase from 63% in Egypt, and 50% in Sudan, South-Sudan, and Ethiopia, to 65% in each of the four countries, as indicated in Table S1.3. Development plan DP 2 features limited changes from the reference scenario. The rainfed agriculture area is assumed to increase by 25% of the limit for expansion for each country. For Ethiopia, Sudan, South-Sudan, and Egypt this means additional rainfed land areas of 8.75, 13.5, 9.5, and 0 million ha, from the limits for expansion of 35, 54, 38, 0 million ha (Table 1), in the four countries, respectively. Likewise, the irrigated agriculture land area is assumed to increase by 25%, and the crop yields to increase by 25% of their limits of increase. Irrigation efficiency is assumed to increase to 65% in each of the four countries. Cropping pattern is the same as the reference scenario, while water withdrawals from non-river sources are assumed to increase by 25% from the limits of increase. The hydropower generation is also assumed to increase by 25% of the limits of increase, stated in Table 1. To meet these changes in the irrigated land areas, and hydropower generation, two Ethiopian dams of Mendaia (i.e., irrigation and hydropower dam) and Baro I (i.e., hydropower dam) were added to the ENB river system, as indicated by the values given to Irrigation dams and hydropower dams in Table S1.3.

Development plan DP 3 features moderate changes from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, hydropower generation, water withdrawals from non-river sources, all increase by 50% of the limits of increase. Irrigation efficiency is assumed to increase to 75% in each of the four ENB countries. Cropping pattern is assumed to change to a cropping pattern with increased cereal crops (cereal shift). To meet these changes in the irrigated land areas, and hydropower generation, five Ethiopian dams are added to the river system of the ENB: Mendaia, Gilo I (i.e., irrigation and hydropower dams); Beko-Abo, Baro II (i.e., Hydropower dams); and Gambella (i.e., Irrigation dam), as indicated by the values given to Irrigation dams and hydropower dams in Table S1.3. Development plan DP 4 features the highest changes from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, hydropower generation, water withdrawals from non-river sources, all increased by 100% from the limits of increase. Irrigation efficiency is assumed to increase to 90% in each of the four ENB countries. Cropping pattern is assumed to change to a cropping pattern with increased cash crops (cash shift). To meet these changes in the irrigated land areas, and hydropower generation, all the proposed Ethiopian dams listed in Table S1.2 are added to the river system of the ENB.

Table S1.3: Four sample development plans from the 6,912 development plans generated in this study.

Development Plan Number	Rainfed agriculture land area (million ha)				Irrigated agriculture land area (million ha)				Crop yield technology			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	0.04	15.5	1.62	15	3.8	1.8	0.12	0.89	Ref.	Ref.	Ref.	Ref.
DP 2	0.04	25	15.12	23.75	4.03	1.93	0.12	1.14	Ref. + 25%	Ref. + 25%	Ref. + 25%	Ref. + 25%
DP 3	0.04	34.5	28.62	32.5	4.25	2.05	0.12	1.39	Ref. + 50%	Ref. + 50%	Ref. + 50%	Ref. + 50%
DP 4	0.04	53.5	55.62	50	4.70	2.30	0.12	1.89	Ref. + 100%	Ref. + 100%	Ref. + 100%	Ref. + 100%

Decision Variable Name / Country

Development Plan Number	Irrigation efficiency (%)				Cropping patterns				Hydropower generation (GWh/ year)			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	65%	65%	65%	65%	No change				8,000	10,000	0	25,000
DP 2	65%	65%	65%	65%	No change				8,000	10,000	0	31,750
DP 3	75%	75%	75%	75%	Cereal Shift				8,000	10,000	0	38,500
DP 4	90%	90%	90%	90%	Cash crop shift				8,000	10,000	0	52,000

Decision Variable Name / Country

Development Plan Number	Water withdrawal from non-River sources ($\times 10^9$ m^3/year)				Irrigation dams (number of dams)				Hydropower dams (number of dams)			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	25	0	0	0	1	6	0	5	1	4	0	8
DP 2	26.25	0	0	0	1	6	0	6	1	4	0	10
DP 3	27.50	0	0	0	1	6	0	8	1	4	0	11
DP 4	30.00	0	0	0	1	6	0	14	1	4	0	21

Section S2

S2.1 WEF System Drivers

Table S2.1: WEF system drivers, their historical values and possible future scenarios.

Driver Type	Country	Driver Name	Value as in 2016	Considered Socio-economic Scenarios		
				High	Moderate	Low
Social Drivers	Egypt	Population Growth Rate	2.00%	3.00%	2.00%	1.00%
	Sudan		2.50%			
	South Sudan		2.30%			
	Ethiopia		2.80%			
	Egypt	Per capita Food Demand (Kcal/ day)	3500	3800	3500	3000
	Sudan		2300	3500	3000	2300
	South Sudan		2300			
	Ethiopia		2300			
	Egypt	Per capita Municipal Water Demand (m^3/ year)	115	130	115	70
	Sudan		25	115	90	
	South Sudan		19			
	Ethiopia		11			

Driver Type	Country	Driver Name	Value as in 2016	Possible Future Changes (Increase by this value at the year 2050)				
Climate Drivers	-	Annual mean Temperature (°C)	Spatially Varied	+0.5	+1.5	+3	+3.5	+4

Driver Type	Country	Driver Name	Value as in 2016	Possible Future Changes (percent change in the long-term mean of the period between 2017 and 2050 Compared with the long-term mean of the period between 1983 and 2016)								
Climate Drivers	-	Mean Annual Precipitation	Spatially Varied	-10%	-5%	0%	5%	10%	15%	20%	25%	30%

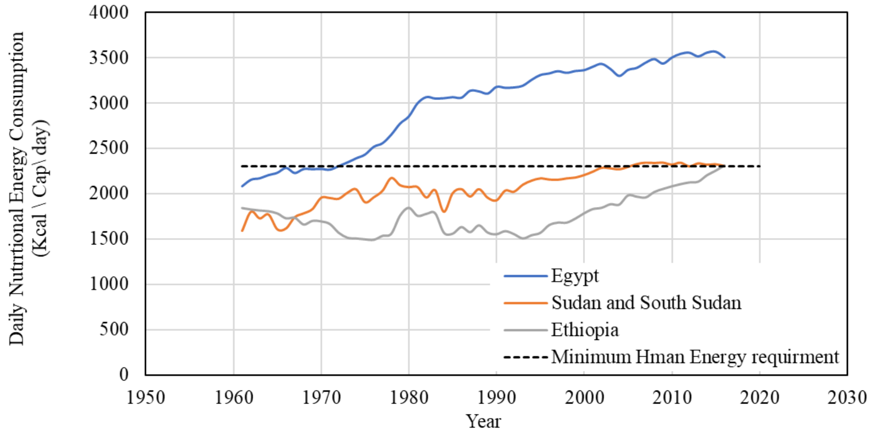


Figure S2.1: The temporal variation of the per capita daily nutritional energy consumption for the Eastern Nile Basin courtiers, 1960 to 2016.

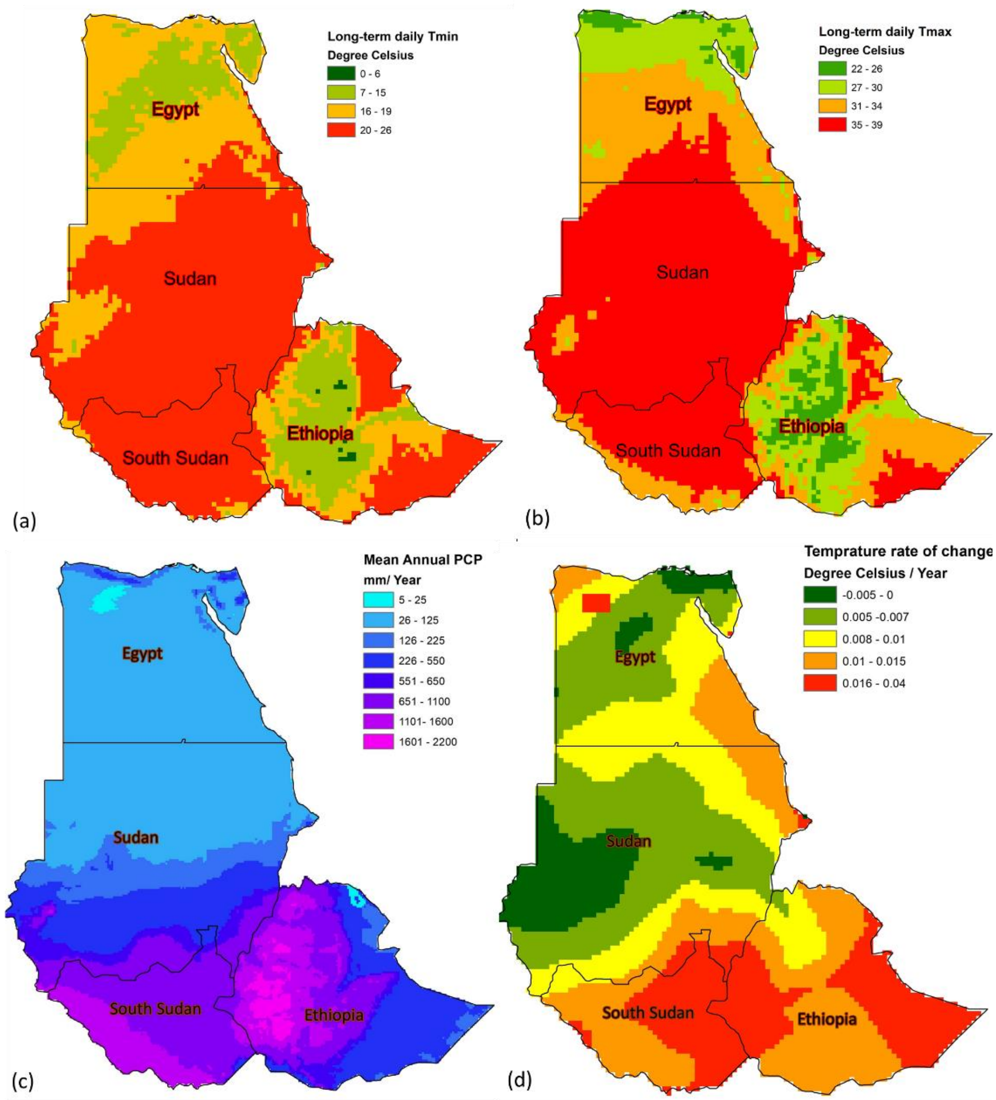


Figure S2.2: The Spatial distribution of selected characteristics of climate variables in the ENB countries, (a) long-term mean of the daily minimum temperature, (b) long-term mean of the daily maximum temperature, (c) Mean annual precipitation, for the period between 1981 and 2016, and (d) annual rate of change of the mean annual temperature averaged for the period between 1981 and 2016. Data used to plot this figure are compiled from the climate hazards group infrared precipitation with station data (CHIRPS; Funk et al., 2015), and the observational reanalysis hybrid temperature dataset (ORH; Sheffield et al., 2006).

S2.2 Results of the hydrological model calibration and validation

Table S2.2: SWAT fitted calibration parameter values for selected major sub-basins. The cells representing the Nile River sub-basins are shaded in blue color, and green color indicates rivers in Ethiopia that are not connected to the Nile.

				Fitted value/ Sub-Basin						
Model parameter name	Description	Changing method *	Calibration range	Atbara	Blue Nile	Baro	Awash	Shebelle	Genale	OMO
RCHRG_DP	Deep aquifer percolation fraction	Replace	0 - 1	0.04	0.00	0.24	0.18	0.10	0.23	0.20
GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur (mm)		0 - 5000	3190.83	205.00	1407.56	1433.12	5000.00	1090.32	951.96
GW_REVAP	Parameter to control movement from shallow aquifer to root zone		0.02 - 0.2	0.08	0.16	0.12	0.03	0.02	0.18	0.09
GW_DELAY	Groundwater delay time (days)		15 - 450	15.00	39.80	15.00	50.48	15.00	51.10	15.00
REVAPMN	Threshold depth of water in the shallow aquifer to move to root zone (mm)		0 - 500	495.05	204.50	109.73	292.22	500.00	92.80	427.19
ALPHA_BF	Index of base flow response to recharge (1/day)		0 - 1	0.87	0.67	0.87	0.10	0.87	0.48	0.62
CH_N2	Manning's (n) for the main channel		0 - 0.3	0.16	0.17	0.21	0.03	0.01	0.26	0.28
CH_K2	Hydraulic conductivity of main channel (mm/ hr)		0 - 150	49.12	82.35	0.00	18.46	28.95	45.10	44.83
SURLAG	surface runoff lag coefficient		0 - 24	6.99	1.27	24.00	19.48	23.68	0.40	0.00
CANMX	Maximum canopy storage as a water depth (mm)		0 - 10	6.31	5.07	4.96	1.81	6.38	10.00	5.74
SLSUBBSN	Average slope length (m)	Relative	-0.5 - +0.5	-0.14	0.21	-0.25	0.32	-0.01	0.11	0.20
SOL_Z()	Soil layer depth (mm)			0.11	0.02	-0.25	-0.50	0.32	-0.28	0.40
SOL_AWC	Available soil water capacity (mm)			-0.38	-0.02	0.44	-0.50	-0.47	-0.41	-0.24
SOL_K()	Saturated hydraulic conductivity (mm/hr)			-0.50	0.22	0.50	0.50	0.43	0.40	-0.33
CN2	SCS Curve Number			0.25	0.24	0.11	-0.17	-0.14	-0.21	0.18

* Changing method is the method used to perturb model parameters during the calibration process, *replace* method is used for parameters that do not change spatially within the sub-basin, where the fitted value replaces the parameter value in the model for all the HRUs., while *relative* change method is used with parameters that are spatially variant, where the parameter value in each HRU is multiplied by (1+ fitted value).

Table S2.3: Results of calibration and validation of simulated river flows of the study area. SWAT model does not incorporate the capability of including detailed reservoir operation rules, thus, the simulated flows from SWAT were calibrated-validated first, then transferred to the WEF model, which has more accurate reservoir operation rules, thus, flows are refined and become more accurate in the WEF model. The values in the table reflect the results of both the calibration-validation within SWAT model, and the flow refinement in the WEF model. The model was calibrated at nine flow gauges on the Nile River and its tributaries (blue color), and four other gauges for rivers in Ethiopia that are not connected to the Nile (green color). See Figure 1 for the flow gauge locations, and Figure S2.3 for flow timeseries plots. Calibration and validation periods differ between gauge station, as indicated in Figure S2.3.

Flow gauge station	Sub-Basin/ River	Calibration		Validation	
		NSE	PBIAS	NSE	PBIAS
Atbara K3	Atbara/ Nile	85%	-13%	78%	6%
Eldeim	Blue Nile	91%	-1%	90%	-7%
Upstream Roseries Dam		88%	-3%	86%	-4%
Downstream Sennar Dam		85%	-13%	82%	-10%
Khartoum		88%	1%	85%	8%
Gambella	Baro/ Nile	90%	-16%	82%	-15%
Hillet Dolieb		85%	8%	80%	8%
Upstream Jebel Aulia Dam (White Nile at Malakal, Upstream of Baro confluence)	White Nile	68%	-2%	67%	3%
Dongola	Main Nile	89%	4%	70%	1%
Downstream Awash	Awash River	78%	-11%	80%	-15%
Downstream Shebelle	Shebelle River	60%	-5%	60%	4%
Doolow	Genale River	61%	-3%	60%	-1%
Downstream OMO	OMO River	82%	9%	88%	3%

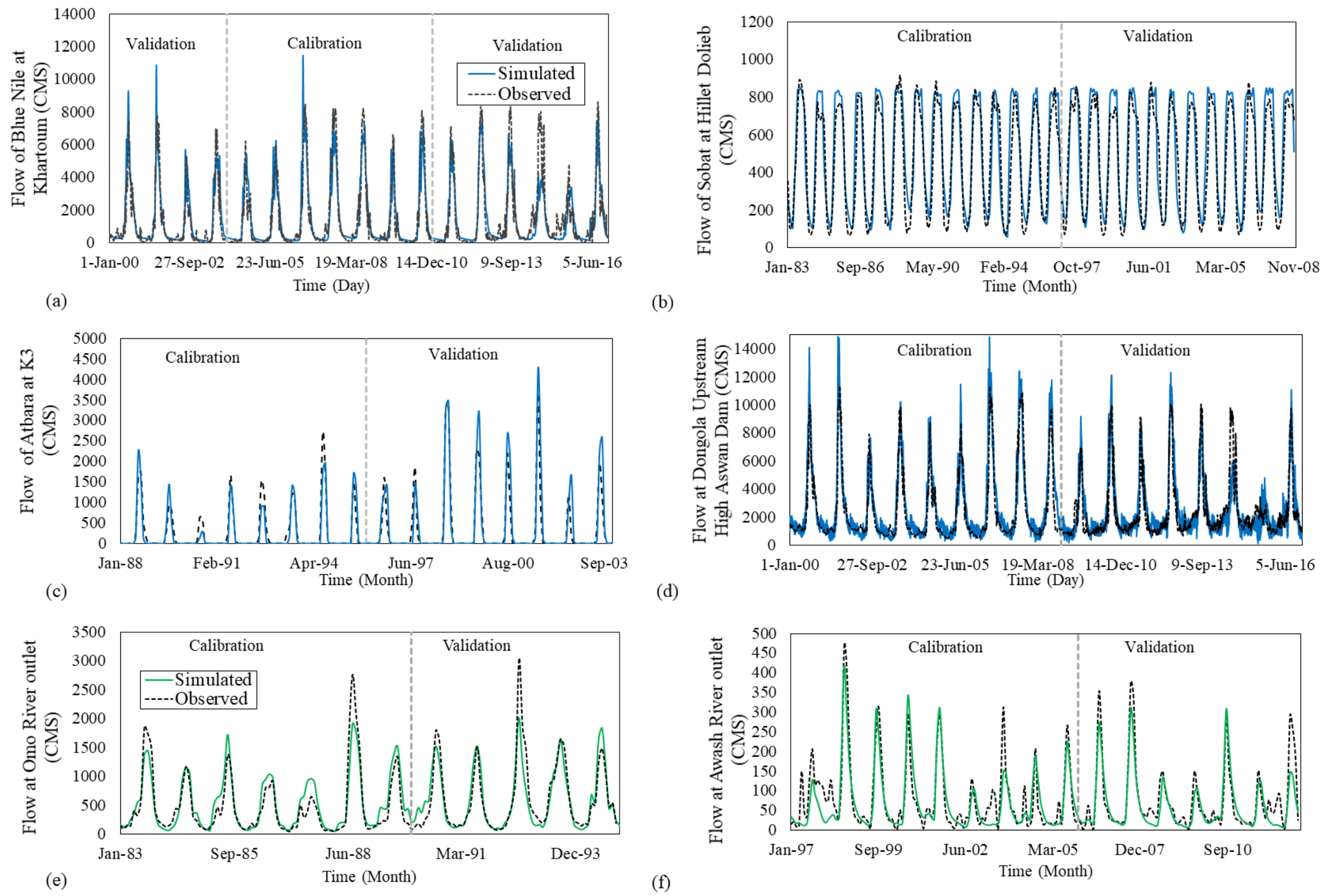
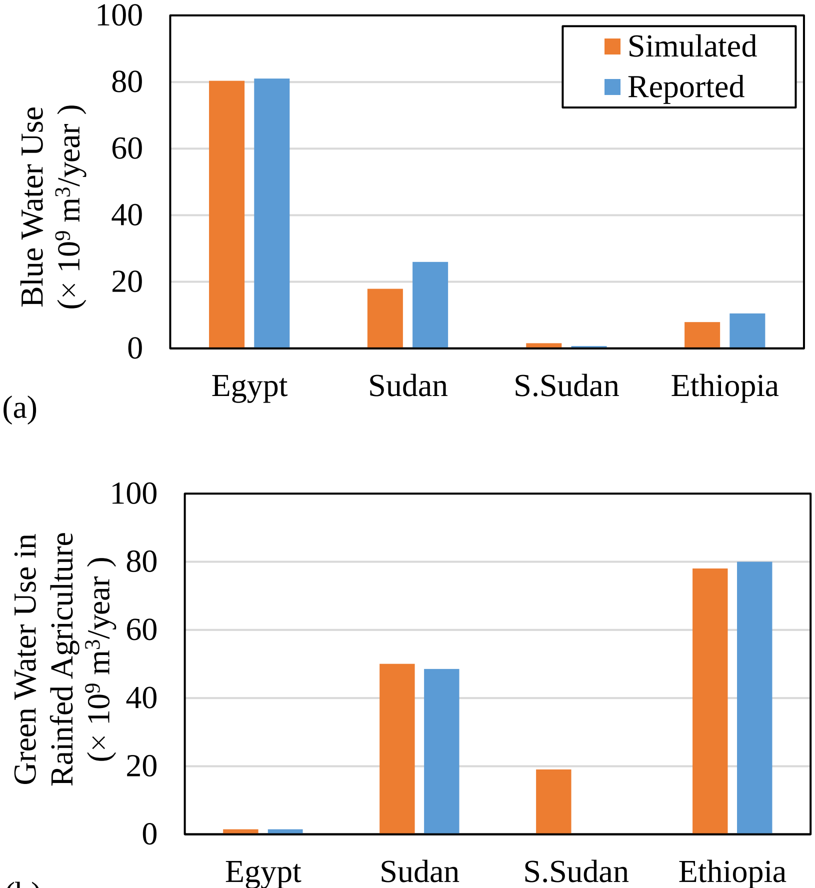


Figure S2.3: Simulated and observed flow time-series for the calibration-validation period at selected gauge stations of (a) Khartoum, (b) Hillet Dolieb, (c) downstream Atbara (i.e., at k3), (d) Dongola, and (e) downstream OMO, and (f) downstream Awash. The first four sub-plots are for gauge stations on the Nile, while the last two stations are for rivers in Ethiopia that do not contribute to the Nile. Daily flows were used for calibration and validation as indicated for Khartoum and at Dongola, otherwise monthly flow was used. Notably, to prevent initialization issues, during model calibration run at Khartoum station, the regular spin-up period of 2 years was increased to 22 years, then was set back to 2 years during model validation run.

S2.3 Simulated and reported water supply of the ENB countries



(a)

(b)

Figure S2.4: Simulated and reported (a) blue water use, and (b) green water use for the four countries of the ENB. Reported blue water supply of South Sudan, Sudan, and Ethiopia are from FAO (2015a; 2015b; 2016), while reported green water use in these three countries is retrieved from (Mekonnen and Hoekstra, 2011). Egypt's reported blue water supply and green water use is from MWRI (2010).

2.4 Nile River Flow Upstream of HAD for the SDP Under Drivers Change

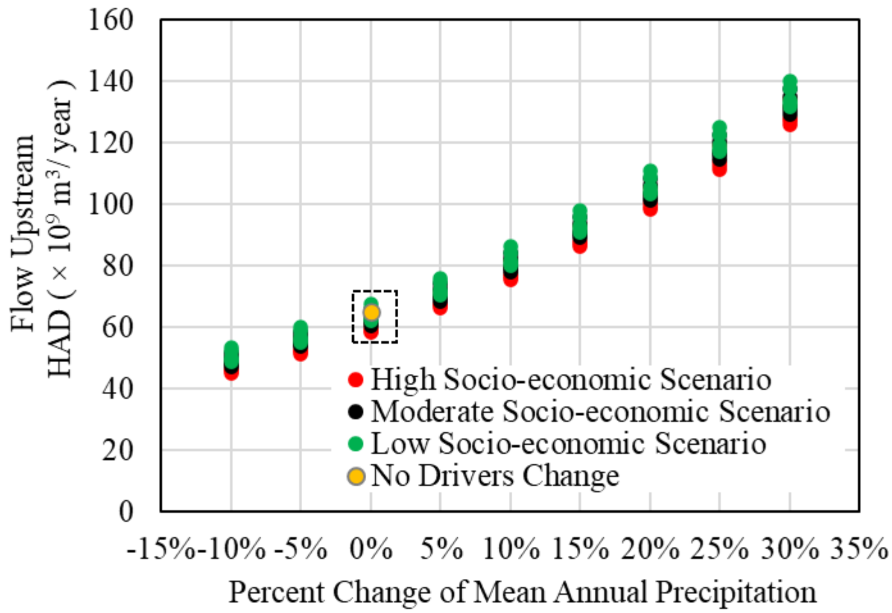


Figure S2.5: Nile River flow reported upstream of the High Aswan Dam. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the annual flow averaged for the period between 2016 and 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 flow values under social drivers change, but no mean annual precipitation change.

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