Long-term economy-wide impacts of the Grand Ethiopian Renaissance Dam on Sudan

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Abstract

The Grand Ethiopian Renaissance Dam (GERD) – a multi-year hydropower storage dam under construction on the Blue Nile River in Ethiopia – is expected to double the Ethiopian electricity generation. The GERD is expected to impact downstream water users in Egypt and Sudan. Several studies assessed the effects of the GERD on water supply and hydropower generation in Sudan and Egypt. However, less attention was given to the economic benefits and costs of GERD operation to the downstream countries. This study analyzes the potential impacts of the steady-state operation of the GERD on Sudan and provides recommendations for short- and medium-term policymaking. We feed a calibrated economy-wide Computable General Equilibrium (CGE) model of Sudan with the expected biophysical impacts of the steady-state operation of the GERD on irrigated agriculture and hydropower generation in the country. The biophysical impacts are obtained from daily hydrological, water allocation, and crop models. We assess three cooperation states between Ethiopia and Sudan on the operation of the GERD: unilateral action, coordination, and collaboration. These cooperation states are examined considering irrigation expansion in the Blue Nile Basin in Sudan based on three possible cropping patterns. The analysis also considers the expected changes to hydropower generation in Sudan. Results suggest that Sudan's accumulated GDP gains from the steady-state operation of the GERD (2020—2060) would range between US$ 27 billion and US$ 29 billion compared to a baseline without the GERD. Results on household welfare for 2020 to 2060 show disparities between the gains of different household groups. High levels of cooperation between Ethiopia and Sudan on the steady-state operation of the GERD can lead to less economic gains if combined with certain cropping patterns in new irrigation schemes compared to lower levels of cooperation.

Keywords: GERD; Sudan; economic impact analysis; Eastern Nile Basin; irrigation; water balance

1 Introduction

Ethiopia is constructing the largest hydropower dam in Africa, the Grand Ethiopian Renaissance Dam (GERD), on the Blue Nile River about 20 km upstream of the Ethiopian-Sudanese border. With a storage capacity of 74,000 km^3 and a hydropower capacity of 5,150 MW, the GERD is expected to make double Ethiopia's electricity generation. However, the dam will have impacts on water supply and hydropower generation in Egypt and Sudan, which are located downstream.

Several studies analyzed the impacts of the initial reservoir filling and steady-state operation of the GERD on Sudan and Egypt using a variety of modeling approaches. We classify these approaches into (1) partial equilibrium modeling and (2) general equilibrium modeling. Partial equilibrium river basin models have been used to analyze the impacts of GERD filling and long-term operation on water supply and hydropower generation in Sudan and Egypt (King and Block, 2014; Liersch et al., 2017; Wheeler et al., 2016, 2018; Zhang et al., 2016, 2015). Some studies used partial equilibrium hydro-economic models to analyze the impacts of GERD (Basheer et al. 2018; Digna et al. 2018; Jeuland et al. 2017; Nigatu and Dinar 2016). Kahsay et al. (2015) and Kahsay et al. (2019) used static economy-wide Computable General Equilibrium (CGE) models of Ethiopia, Sudan, and Egypt to analyze the long-term impacts of the GERD on the three countries. They used the GTAP-W framework – a global CGE model based on the GTAP (Global Trade Analysis Project) model and its database. Their results show that GERD will positively affect the three countries. Kahsay et al. (2015) and Kahsay et al. (2019) did not consider the possibility of irrigation expansion in Sudan as a result of the flow regulation effect of the GERD.

We acknowledge the efforts put by previous studies on the economic and biophysical implications of GERD operation. However, most of the previous studies used a partial equilibrium approach and thus did not consider the indirect and induced impacts of the GERD. Moreover, previous general equilibrium modeling studies on GERD used static CGE models and consequently omitted the temporal dynamics of GERD impacts. Although the flow regulation effect of the steady-state operation of GERD has been acknowledged by most of the previous studies, only Basheer et al. (2018) analyzed the potential benefits that Sudan could gain from a regular flow in terms of irrigation expansion on the Blue Nile River. Basheer et al. (2018) used a partial equilibrium hydro-economic model of the Blue Nile Basin and found that the basin-wide economic gain from the GERD increases as the level of cooperation between Ethiopia and Sudan increases. However, the economic gain of each riparian country does not necessarily follow the same pattern. Their analysis does not consider the impact on the economy at large, as they use a partial equilibrium modeling approach. Consequently, they did not account for the forward and backward linkages between sectors and the inter-sectoral competition on production factors such as land and water.

Based on the above backdrop, there is a lack of dynamic economy-wide analyses on the impacts of the steady-state operation of the GERD on the Sudanese economy, considering different sectors, institutions, commodity and factors markets, and irrigation expansion potentiality. This study uses the most up-to-date dynamic CGE model of Sudan to analyze the potential impacts of the steady-state operation of the GERD on the Sudanese economy. We feed the CGE model with the biophysical impacts that the GERD would pose on irrigated agriculture in Sudan based on the analysis of Basheer et al. (2018). We also consider the impacts of the steady-state operation of the GERD on hydropower generation in Sudan based on Wheeler et al. (2016). We analyze nine scenarios that comprise combinations of three cooperation states between Sudan and Ethiopia on the steady-state operation of the GERD and three cropping patterns for irrigation expansion on the Blue Nile. These scenarios are based on the analysis of Basheer et al. (2018).

The rest of the paper is organized as follows. First, the modeling methods, data, and simulation scenarios are described. Then, the results on GDP, total absorption, and household welfare are presented. Lastly, conclusions and policy implications are provided.

2 Methods

2.1 Computable general equilibrium model

In this study, a recursive-dynamic computable general equilibrium (DCGE) model was developed for Sudan to analyze the economy-wide impacts of the steady-state operation of the GERD on the country. The structure and mathematical formulation of the standard model are provided in Diao and Thurlow (2012). The model includes four agent types: households, enterprises, the government, and the rest of the world. Households and enterprises receive payments from producers in exchange for factors of production, pay direct taxes, and save based on saving propensities. Enterprises pay their income to households in the form of dividends. Households use their income to purchase commodities according to a Linear Expenditure System (LES) utility function. The government receives revenue from production taxes, sales taxes, direct taxes, and import tariffs. The government spends its income on transfers to households, enterprises, and the rest of the world. The government purchases commodities and saves the remaining income (with budget deficits representing negative savings). All savings of households, enterprises, the government, and the rest of the world (foreign savings) are collected in a savings pool from which investment is financed.

The Sudanese economy is simulated as a competitive economy with flexible prices such that consumers maximize their utility, and producers maximize their profits. The economy is connected with the rest of the world via trade, remittances, and other transfers. Producers are assumed to be price takers in output and input markets and maximize their profits using constant returns to scale technologies. Demands for production factors are determined using constant elasticity of substitution, whereas intermediate input demands are calculated using a Leontief function. Production for domestic and foreign markets is governed by constant elasticity of transformation functions that distinguish between exported and domestically consumed commodities. This approach captures quality differences between exported and domestically consumed commodities. Based on the small-country assumption, Sudan was assumed to have perfectly elastic import demand and export supply curves at fixed world prices. Imported and domestically produced commodities are treated as imperfect substitutes in both final and intermediate demands under constant elasticity of substitution Armington specification. Households use part of their income to consume commodities according to fixed budget shares.

The DCGE model includes three macroeconomic accounts: a government balance, a current account balance, and a savings-investment account. Macro-closure rules are specified to balance the three macro accounts taking into consideration how the Sudanese economy functions. On the government account, fiscal balance, and therefore public savings, are endogenous. Government demand is fixed, and all tax rates are held constant so that government savings or deficits depend on the level of economic activity. An investment-driven closure rule is assumed, such that the share of investment in total absorption is fixed, while household saving rates adjust to generate the necessary funds. External capital inflows are fixed, while flexibility is provided to the exchange rate.

The model was calibrated to the most recent social accounting matrix (SAM) of Sudan (Siddig et al. 2018). Given the importance of agriculture for income generation and satisfaction of consumer needs, the SAM disaggregates the agriculture sector by crop type; linkages between crop production and other sectors such as food processing, manufacturing, and services are specified in the SAM. The SAM includes 71 production activities, 58 commodities, 14 factors of production, and ten household types. The SAM includes 35 agricultural production activities that are split into livestock, forestry, rubber, and crop production activities. Agriculture contributes about one third to Sudan's gross domestic product (GDP) and more than two-thirds of employment (Central Bank of the Sudan 2018; Ministry of Human Resources Development and Labor 2013). The agriculture sector provides production inputs to agro-industry, uses various services in the economy (e.g., transportation), and competes with other sectors on electricity, capital, and water. The SAM of Sudan classifies households into rural and urban, and income quintiles differentiate each. The model includes 12 labor categories, disaggregated by regional affiliation (rural and urban), gender status (male and female), and skill level (unskilled, semi-skilled, skilled).

All labor types are assumed to be fully employed and mobile across sectors. The assumption of full employment is consistent with widespread evidence in Sudan that, while relatively few people have formal sector jobs, most working-age people engage in activities that contribute to GDP. Capital accumulation is modeled assuming a "putty-clay" formulation whereby new investments are allocated across sectors according to the rate of return differentials, but once installed, capital remains immobile within periods (Diao and Thurlow 2012). In agriculture, cultivable land, is assumed to be fully employed, but activity-specific. The assumption of limited mobility of agricultural land allows a strict implementation of the additional area to be irrigated as a result of the flow regulation effect of the GERD.[1]

2.2 Simulation scenarios

Herein, the economy-wide impacts of the steady-state operation of the GERD are based on the analysis and scenarios of Basheer et al. (2018). Basheer et al. (2018) used daily hydrological, water allocation, and crop models to examine the impacts of the steady-state operation of GERD in three states of cooperation between Sudan and Ethiopia: unilateral action, coordination, and collaboration. In the unilateral action state, they assume that Ethiopia independently operates the GERD to maximize firm annual energy generation regardless of downstream implications. In the coordination state, it was assumed that Ethiopia maximizes the firm annual energy generated by the GERD and shares information with Sudan in advance on the GERD outflow. Sharing information would provide flexibility to Sudan on the operation of the Roseires Dam, which is located in the vicinity of the GERD (Figure 1). In the collaboration state, Ethiopia shares information with Sudan on the GERD outflow and prioritizes releasing, at least, the water demands of Sudan.

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[1] As a sensitivity analysis, we ran the simulation with the assumption of full land mobility. Results at the sectors and aggregate levels are not significantly different.

For each cooperation state between Ethiopia and Sudan, Basheer et al. (2018) determined possible expansion in irrigated agriculture based on three cropping patterns. Table 1 shows the three cropping patterns considered. Cropping pattern 1 distributes the cultivable area equally between crops (14.3 % each). Cropping pattern 2 distributes the cultivable area between crops according to their relative annual gross margin. Cash crops are prioritized in cropping pattern 3 (i.e., cotton, sesame, and sugarcane), giving each 20 % of the cultivated area and 10 % to each of the remaining crops. As Figure 1 illustrates, potential irrigation on the Blue Nile includes four schemes on the left bank of the Blue Nile, namely, Kenana 1, Kenana 2, Kenana 3, Kenana 4 and four others on the right bank, namely, Roseires, Dinder South, Dinder North, Rahad 2 South, and Rahad 2 North (Basheer et al. 2018).

The steady-state operation of the GERD is expected to increase hydropower generation in Sudan (Wheeler et al. 2016). In the present study, we combine the analysis of Basheer et al. (2018) and Wheeler et al. (2016) to determine hydropower generation in Sudan under different cooperation states and cropping patterns. From Wheeler et al. (2016), we derived an average long-term increase in hydropower generation in Sudan of around 20%. We adjusted this increase in hydropower generation based on the analysis of Basheer et al. (2018), which provides hydropower generation in the Blue Nile under different cooperation states and cropping patterns. We acknowledge that this approach is simple and overlooks the impact of different cooperation states and cropping patterns on hydropower generation for the Merowe Dam (located in Sudan on the Main Nile; see Figure 1). However, we deem our analysis a first step towards understanding the long-term economic impacts of the GERD.

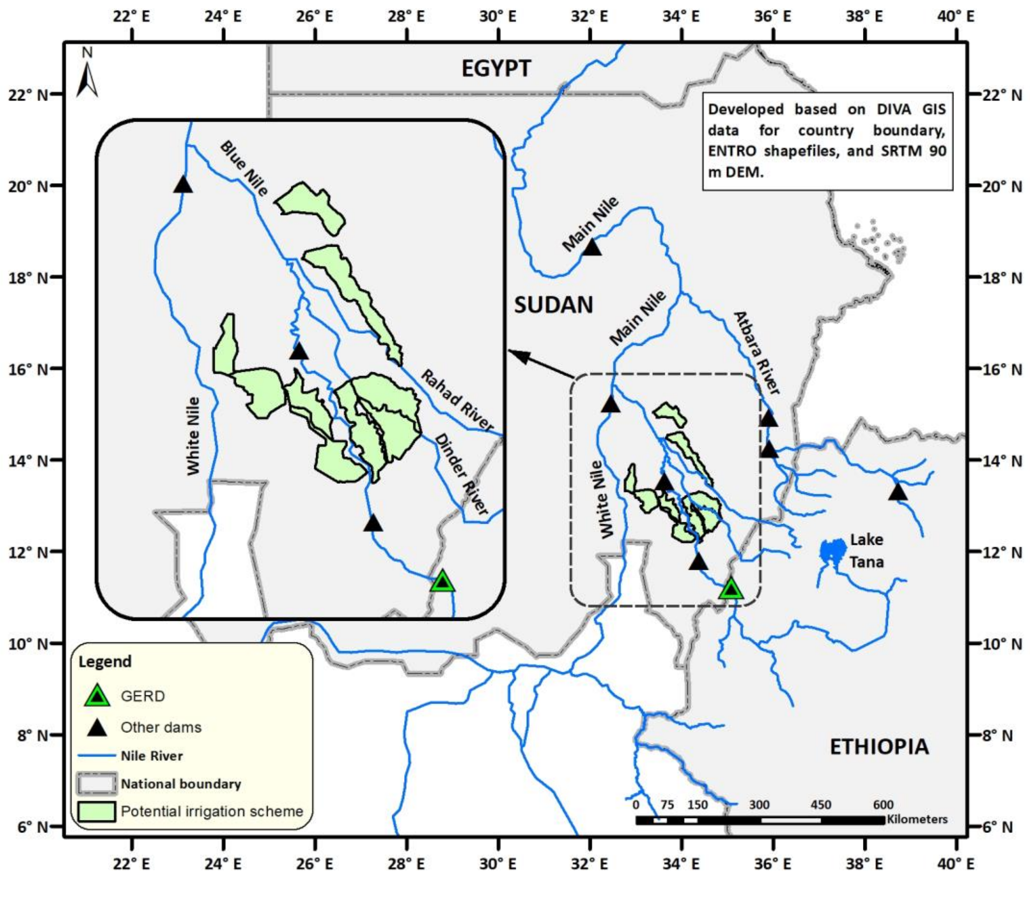

Figure 1. General features and potential irrigation schemes in Sudan downstream the Grand Ethiopian Renaissance Dam.

Herein, we assume that the steady-state operation of the GERD will begin in 2027, and Sudan would start implementing the nine new irrigation schemes immediately with the start of the steady-state operation. We also assumed that Sudan would implement one irrigation scheme at a time with three years between implementing every two schemes[2]. Appendix-Table 3 reports the temporal evolution of the total area in Sudan for some crops under the three assumed cropping patterns and irrigation expansion plan. These changes in crop areas have been introduced to the DCGE model as shocks to determine the economy-wide impacts.

Appendix-Table 4 shows the additional hydropower generation in Sudan over time under different scenarios. The increase in hydropower generation as result of the flow regulation effect of the GERD is assumed to be immediately absorbed by the Sudanese economy. This is because of the current large gap between electricity supply and demand in Sudan. The percentage changes in hydropower generation reported in Appendix-Table 4 has been introduced to the DCGE model.

In summary, a total of nine scenarios have been examined which comprise combinations of the three cropping patterns and three cooperation states. We feed the DCGE model of Sudan with the impacts of the GERD on crop areas and hydropower generation in Sudan. We apply these changes to the DCGE model by increasing the land demands of the respective crop sectors, the availability of water for irrigation, and total hydropower generation.

Table 1. Distribution of cultivated area in new irrigation schemes in under the three cropping patterns

Crop	Cropping pattern 1 (%)	Cropping pattern 2 (%)	Cropping pattern 3 (%)
Cotton	14.3	28.1	20.0
Sesame	14.3	22.4	20.0
Wheat	14.3	4.7	10.0
Sunflower	14.3	1.7	10.0
Sorghum	14.3	0.2	10.0
Sugarcane	14.3	39.4	20.0
Groundnuts	14.3	3.5	10.0
Total	100.0	100.0	100.0

Source: Basheer et al. (2018), pp. 1315.

3 Results and Discussion

3.1 Impacts on agriculture

We present results for the nine scenarios relative to a baseline without the GERD for the period from 2020, when the filling of the GERD starts, through 2027, the year in which GERD is assumed to get into steady-state operation, until 2060. The results are discounted annually using a 5 % discount rate. Figure 2 depicts time series of the discounted change in the contribution of crops to GDP compared to the baseline scenario. The figure shows that crops' GDP increases in all cooperation states and cropping patterns. The increase in crops' GDP declines beyond 2050 because by then all the irrigated agriculture extensions are implemented, hence, no more increases in irrigated land and water are introduced in

[2] Note that for the implementation of the new area extensions, the length of project implementation will not essentially affect results of the model, especially if accumulated costs and benefits of the dam are taken into account.

the non-baseline simulations. Figure 2 reveals that the highest increase in crops' GDP occurs in the collaboration state with cropping pattern 2 followed by the scenarios of cropping pattern 2 in the unilateral action and coordination states. The average annual growth rates of GDP contributions of the crops planned for cultivation in potential irrigation schemes are depicted in Appendix-Table 1. Results show that all crops have positive average growth rates in all the scenarios. In all scenarios, average growth rates are higher than the baseline with sorghum scoring the highest growth rate among crops followed by sesame and groundnuts. Cotton recorded the lowest average growth rate. The production of these seven crops grows due to an increase in land availability implemented under each simulation. Irrigated land increases due to the flow regulation effect of the GERD.

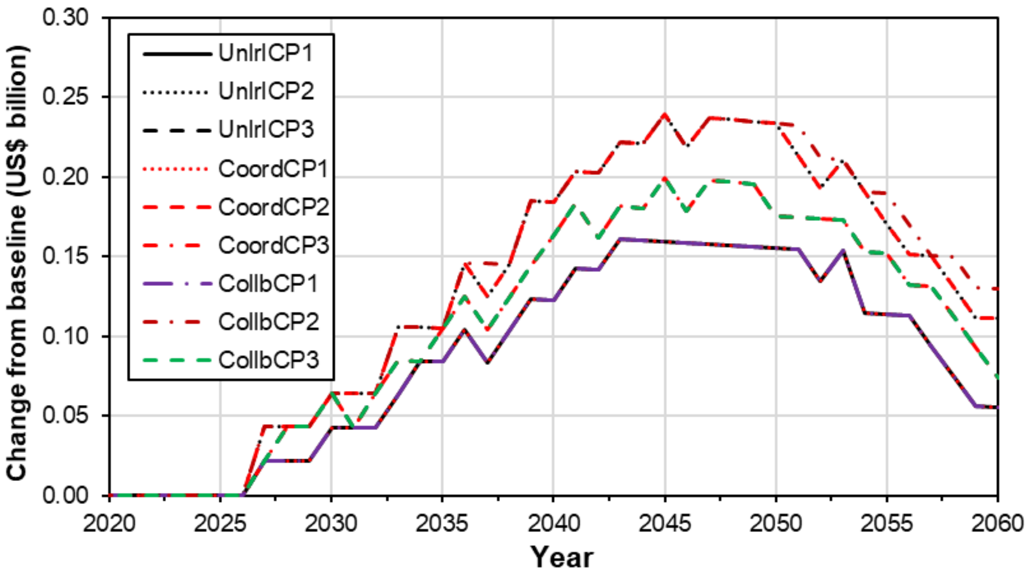

Figure 2. Temporal evolution of crops' contribution to GDP at factor cost under different cooperation states and crop scenarios.

Table 2 reports the accumulated direct contributions of corps to GDP. The forward and backward linkages of the increase in irrigated agriculture contribute to GDP growth. Results show minor variations across scenarios. Cropping pattern 2, which distributes land between different crops according to their gross margin, scores the highest percentage deviation from the baseline, i.e., 1.63% with the unilateral actions (UnlrlCP2) and coordination (CoordCP2) scenarios and 1.68% with the collaboration scenario (CollbCP2). Cropping pattern 3 comes second with a 1.37% increase compared to the baseline with each of the three states of coordination. Cropping pattern 1, which distributes land equally between crops, results in the lowest percentage deviation from the baseline (1.10%) regardless of the level of cooperation.

Table 2. Accumulated discounted crops' GDP between 2020 and 2060 in Sudanese pounds and 2012 US dollars.

Scenario	Accumulated values (2020 to 2060)		Deviation from Baseline	
	SDG[3] billions	US$ billions	US$ billions	%
Baseline	1,428.70	324.70	0.00	0.00
UnlrlCP1	1,444.45	328.28	3.58	1.10
UnlrlCP2	1,452.05	330.01	5.31	1.63
UnlrlCP3	1,448.21	329.14	4.43	1.37
CoordCP1	1,444.45	328.28	3.58	1.10
CoordCP2	1,452.05	330.01	5.31	1.63
CoordCP3	1,448.21	329.14	4.43	1.37
CollbCP1	1,444.45	328.28	3.58	1.10
CollbCP2	1,452.72	330.16	5.46	1.68
CollbCP3	1,448.21	329.14	4.43	1.37

Table 3 presents the impact of the different scenarios on the contribution of the agriculture sector to GDP. The agriculture sector includes irrigated and rainfed crops, livestock, fishery, and forestry. Details of the sectors represented in the model are provided in Appendix-Table 2. Results show that the choice of cropping pattern has a stronger economic impact compared to the level of cooperation between Ethiopia and Sudan. This is because even with a low level of cooperation between Ethiopia and Sudan on the operation of the GERD, the Blue Nile flow would be regular enough to enable significant expansion in irrigation. The total benefit to Sudan's agriculture sector from the implementation of planned irrigation schemes during the period (2020-2060) would be US$ 2.84 billion based on cropping pattern 1. Under cropping pattern 2, the gains increase to US$ 4.52 billion, US$ 4.50 billion, and US$ 4.67 billion, with the unilateral action, cooperation, and collaboration states, respectively. With cropping pattern 3, the gains are US$ 3.65 billion, US$ 3.63 billion, and US$ 3.63 billion, under the unilateral actions, cooperation, and coordination states, respectively. A striking result is that the economic gains of the agricultural sector under cropping pattern 3 decreases with increasing the level of cooperation between Ethiopia and Sudan. Further investigations reveal that the level of cooperation is not the source of this decrease. Instead, expansion in irrigation using cropping pattern 3 negatively impacts other agriculture-related activities (i.e., rainfed crops, livestock, fishery, and forestry), resulting in a net decline in the contribution of the agriculture sector to GDP with higher levels of cooperation.

Overall, the benefits to the agriculture sector are close to but slightly less than those of the crops sectors (Table 2). This occurred due to forward and backward linkages within the agriculture sector, where some subsectors lose compared to the baseline. The contribution of the livestock sector to GDP declines by up to US$ 0.85 billion compared to the baseline. However, the contribution of the fruit and vegetable sector to GDP increases by up to US$ 0.02 billion compared to the baseline, while the rest of the subsectors within agriculture generate gains of about US$ 0.12 billion compared to the baseline. The decline in the GDP contribution of livestock is driven by a slight decrease in capital use in the sector.

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[3] SDG = Sudanese pound (in 2012, 1 US$ = 4.4 SDGs).

Table 3. Accumulated discounted contribution of the agriculture sector to GDP between 2020 and 2060 in Sudanese pounds and 2012 US dollars.

Scenario	Accumulated values (2020 to 2060)		Deviation from Baseline	
	SDG[4] billions	US$ billions	US$ billions	%
Baseline	3,738.36	849.63	0.00	0.00
UnlrlCP1	3,750.84	852.46	2.84	0.33
UnlrlCP2	3,758.23	854.14	4.52	0.53
UnlrlCP3	3,754.40	853.27	3.65	0.43
CoordCP1	3,750.84	852.46	2.84	0.33
CoordCP2	3,758.14	854.12	4.50	0.53
CoordCP3	3,754.31	853.25	3.63	0.43
CollbCP1	3,750.84	852.46	2.84	0.33
CollbCP2	3,758.90	854.30	4.67	0.55
CollbCP3	3,754.31	853.25	3.63	0.43

3.2 Impacts on industry and services

Agriculture contributes 28 % to the national GDP of Sudan. The remaining 72 % comes from the industry and services sectors, which contribute 27% and 45%, respectively. Table 4 shows the contributions of the industry and services sectors to GDP with different cooperation states and cropping patterns compared to the baseline. The contribution of the industry sector increases in all scenarios compared to the baseline owing to the closer linkages and complementarities with agriculture. The increase in industry contribution to GDP can go up to US$ 2.15 billion with cropping pattern 1. The contribution of the services sector to GDP showed a decline of up to US$ 0.92 billion compared to the baseline. For services, the highest decline occurs under cropping patterns 1 and 3 regardless of the cooperation state, and the lowest loss occurs under cropping pattern 2. The contribution of the services sector to GDP declines in all scenarios relative to the baseline due to lower capital allocation to services with irrigation expansion. Except for water-transport, all the services sub-sectors receive less capital, on average, under the nine scenarios compared to the baseline.

Table 4. Accumulated discounted contribution of the industry and services sectors to GDP between 2020 and 2060 in 2012 US dollars.

Scenario	Industry			Services		
	Value (US$ billions)	Change (US$ billions)	Change (%)	Value (US$ billions)	Change (US$ billions)	Change (%)
Baseline	1,373.93	0.00	0.00	2,586.68	0.00	0.00
UnlrlCP1	1,403.49	29.56	2.15	2,585.76	-0.92	-0.04
UnlrlCP2	1,400.69	26.76	1.95	2,585.88	-0.81	-0.03
UnlrlCP3	1,402.50	28.57	2.08	2,585.76	-0.92	-0.04
CoordCP1	1,403.49	29.56	2.15	2,585.76	-0.92	-0.04
CoordCP2	1,400.92	26.99	1.96	2,585.88	-0.81	-0.03
CoordCP3	1,402.71	28.78	2.09	2,585.76	-0.92	-0.04
CollbCP1	1,403.49	29.56	2.15	2,585.76	-0.92	-0.04

[4] SDG = Sudanese pound (in 2012, 1 US$ = 4.4 SDGs).

Scenario	Industry			Services		
	Value (US$ billions)	Change (US$ billions)	Change (%)	Value (US$ billions)	Change (US$ billions)	Change (%)
CollbCP2	1,399.12	25.19	1.83	2,585.84	-0.85	-0.03
CollbCP3	1,402.71	28.78	2.09	2,585.76	-0.92	-0.04

3.3 Macro impacts

The impacts of the nine scenarios on overall real GDP as compared to the baseline are reported in

Table 5. The GDP increases compared to the baseline by between US$ 27.04 billion in the CollbCP2 scenario and US$ 29.32 billion in the CoordCP3 and CollbCP3 scenarios. On average, GDP increases by US$ 28.89 billion, US$ 28.99 billion, and US$ 28.52 billion in the unilateral action, coordination, and collaboration scenarios, respectively. Raising the level of cooperation enables the use of cropping patterns that are water-intensive but not necessarily beneficial to the macro-economy. This choice of cropping pattern is key to maximizing economic gains even with a high level of cooperation. The average benefits with each cropping pattern (average over the three cooperation states) are US$ 29.21 billion, US$ 27.92 billion, and US$ 29.27 billion for cropping patterns 1 to 3, respectively.

Table 5. Accumulated discounted national GDP between 2020 and 2060 in Sudanese pounds and 2012 US dollars.

Simulations	Accumulated values (2020 to 2060)		Deviation from Baseline	
	SDG billions	US$ billions	US$ billions	%
Baseline	21,609.21	4,911.18	0.00	0.00
UnlrlCP1	21,737.74	4,940.40	29.21	0.59
UnlrlCP2	21,733.70	4,939.48	28.29	0.58
UnlrlCP3	21,737.56	4,940.35	29.17	0.59
CoordCP1	21,737.74	4,940.40	29.21	0.59
CoordCP2	21,734.29	4,939.61	28.43	0.58
CoordCP3	21,738.24	4,940.51	29.32	0.60
CollbCP1	21,737.74	4,940.40	29.21	0.59
CollbCP2	21,728.17	4,938.22	27.04	0.55
CollbCP3	21,738.24	4,940.51	29.32	0.60

Note: SDG = Sudanese pound.

Total absorption, which comprises private and public consumption and investment demand, can be used as an economy-wide measure of welfare. Table 6 reports the impacts of the nine scenarios on total absorption compared to the baseline. The steady-state operation of the GERD could increase Sudan's total absorption by up to US$ 29.32 billion in scenarios CoordCP3 and CollbCP3. The lowest increase in absorption occurs in scenario CollbCP2 (US$ 29.03 billion) due to the choice of cropping pattern, as explained earlier. These results are driven by changes in household consumption, which increases by US$ 27.06 billion in scenarios CoordCP3 and CollbCP3, while increasing only by US$ 24.97 billion in the CollbCP2 scenario relative to the baseline. The increases in the other scenarios relative to the baseline fall between these two values. On average, total absorption increases by US$ 28.87 billion, US$ 29.00 billion and US$ 28.52 billion with the unilateral action, cooperation, and collaboration scenarios, respectively. The average benefits within each cropping pattern (average over the three cooperation states) are US$ 29.19 billion, US$ 27.93 billion, and US$ 29.27 billion with cropping patterns 1 to 3, respectively (simple average calculations from Table 6). This shows that relatively equal allocation of land between the seven crops (i.e., cropping patterns 1 and 3) generates higher benefits to the Sudanese people as measured by total absorption because the benefits would spread over a broader spectrum of the population.

Table 6. Accumulated discounted national absorption between 2020 and 2060 in Sudanese pounds and 2012 US dollars.

Simulations	Accumulated values (2020 to 2060)		Deviation from Baseline	
	SDG billions	US$ billions	US$ billions	%
Baseline	25,353.83	5,762.24	0.00	0.00
UnlrlCP1	25,482.28	5,791.43	29.19	0.51
UnlrlCP2	25,478.22	5,790.50	28.27	0.49
UnlrlCP3	25,482.09	5,791.38	29.15	0.51
CoordCP1	25,482.28	5,791.43	29.19	0.51
CoordCP2	25,479.15	5,790.72	28.48	0.49
CoordCP3	25,482.86	5,791.56	29.32	0.51
CollbCP1	25,482.28	5,791.43	29.19	0.51

Simulations	Accumulated values (2020 to 2060)		Deviation from Baseline	
	SDG billions	US$ billions	US$ billions	%
CollbCP2	25,472.78	5,789.27	27.03	0.47
CollbCP3	25,482.86	5,791.56	29.32	0.51

Note: SDG = Sudanese pound.

3.4 Distributional impacts

Indirect compensation of all households, rural households, and urban households are presented in Table 7. Generally, the results show that rural households would benefit more from the steady-state operation of the GERD than urban households would. The steady-state operation of the GERD affects each household group differently based on sources of income and consumption patterns. While scenarios applying cropping pattern 3 are favorable to "all households" and to rural households, scenarios with cropping pattern 1 generates the highest welfare gain for urban households (US$ 6.28 billion). A welfare gain to "all households" of US$ 24.89 billion occurs in the CoordCP3 and CollbCP3 scenarios, while scenario UnlrlCP3 generates welfare gains of US$ 24.77 billion.

For all households and rural households, the highest level of cooperation (collaboration) is not a favorable option unless combined with cropping pattern 3. However, on average, households gain a total of US$ 24.27 billion compared to the baseline in the collaboration scenario. These gains increase in the unilateral action and coordination states to US$ 24.43 billion and US$ 24.53 billion, respectively, compared to the baseline due to the choice of cultivated crops. On average, cropping patterns 1 and 3 generate more gains to all households and urban households than those generated by cropping pattern 2. For all households, the average gains are US$ 24.50 billion, US$ 23.88 billion, and US$ 24.85 billion with cropping patterns 1, 2, and 3, respectively, compared to the baseline. Results for rural households are different in that cropping pattern 3 is more favorable, generating on average gains of US$ 15.12 billion compared to US$ 14.64 billion and US$ 14.91 billion with cropping patterns 1 and 2, respectively.

Table 7. Accumulated discounted indirect compensation between 2020 and 2060 in Sudanese pounds, US (2012) dollars, and percentage for all, rural and urban households

Simulations	Accumulated values (2020 to 2060) in US$ billions			Deviation from Baseline (US$ billions)			Deviation from baseline (%)		
	All	Rural	Urban	All	Rural	Urban	All	Rural	Urban
Baseline	4,996.20	2,307.92	2,056.58	0.00	0.00	0.00	0.00	0.00	0.00
UnlrlCP1	5,020.70	2,322.56	2,062.86	24.50	14.64	6.28	0.49	0.63	0.31
UnlrlCP2	5,020.23	2,322.95	2,062.31	24.02	15.03	5.73	0.48	0.65	0.28
UnlrlCP3	5,020.98	2,323.00	2,062.79	24.77	15.08	6.21	0.50	0.65	0.30
CoordCP1	5,020.70	2,322.56	2,062.86	24.50	14.64	6.28	0.49	0.63	0.31
CoordCP2	5,020.41	2,323.01	2,062.33	24.20	15.09	5.75	0.48	0.65	0.28
CoordCP3	5,021.09	2,323.06	2,062.83	24.89	15.14	6.24	0.50	0.66	0.30
CollbCP1	5,020.70	2,322.56	2,062.86	24.50	14.64	6.28	0.49	0.63	0.31
CollbCP2	5,019.61	2,322.52	2,061.93	23.41	14.61	5.35	0.47	0.63	0.26
CollbCP3	5,021.09	2,323.06	2,062.83	24.89	15.14	6.24	0.50	0.66	0.30

Note: SDG = Sudanese pound.

4 Conclusions and Policy Implications

This study performs an economic analysis of the impacts of the steady-state operation of the GERD on Sudan, considering expansion in irrigation because of the flow regulation effect that the GERD would pose. We feed an up-to-date calibrated DCGE model of Sudan with the biophysical impacts of the GERD on the country. The analyzed scenarios comprise combinations of three cooperation states between Ethiopia and Sudan on the operation of the dam and three cropping patterns for irrigation expansion.

Results suggest that Sudan's GDP accumulated over 2020-2060 and annually discounted by 5%, increases by between US$ 27.04 billion and US$ 29.32 billion compared to a baseline without the GERD online. These gains result from the additional crop output due to agricultural expansion and the value-added across the economy. The GDP gains generated from crop expansion would range between US$ 3.58 billion and US$ 5.46 billion under different scenarios relative to the baseline. The increase in the contribution of the agricultural sector to the GDP would be between US$ 2.84 billion and US$ 4.67 billion relative to the baseline, with some agricultural sub-sectors losing due to competition on production factors. The contribution of the industry sector to GDP increases compared to the baseline by between US$ 25.19 billion and US$ 29.56 billion. The contribution of the services sector to GDP declines by between US$ 0.81 billion and US$ 0.92 billion compared to the baseline.

Results on household welfare show disparities between different household groups. This occurred because irrigation expansion benefits the land and capital owners (mostly rural rich) as well as agricultural workers (mostly rural non-rich), while additional energy generation mostly benefits urban consumers. The benefits to all households range between US$ 23.41 billion and US$ 24.89 billion compared to the baseline. The benefits to rural households range between US$ 14.61 billion and US$ 15.14 billion and while the benefits to urban households range between US$ 5.35 billion and US$ 6.28 billion compared to the baseline.

We found that raising the level of cooperation between Ethiopia and Sudan on the steady-state operation of the GERD could be beneficial but only if combined with specific cropping patterns. The choice of which crops to be grown in new irrigation schemes plays a significant role in determining the overall gain to Sudan from the steady-state operation of the GERD.

This study has several limitations that could be addressed in future research. Several positive and negative biophysical impacts of the GERD have not been accounted for in the present analysis. The negative impacts of the GERD on recession agriculture and ecosystem services have not been included. Moreover, the positive impacts of the GERD in terms of reduced fluvial floods and reservoir sedimentation are not modeled. Future studies could use biophysical models that can quantify these impacts. Lastly, our analysis did not account for the economic impacts of the initial investment and operation cost of new irrigated areas (e.g., construction and maintenance of irrigation canals and pumping stations).

5 References

Abulnaga, B. E., 2019. Dredging the Clays of the Nile: Potential Challenges and Opportunities on the Shores of the Aswan High Dam Reservoir and the Nile Valley in Egypt. In Handbook of Environmental Chemistry 79, pp. 331–355. DOI: 10.1007/698_2017_133.

Ali, Y.S.A.; Crosato, A.; Mohamed, Y. A.; Abdalla, S. H.; Wright, N. G., 2014. Sediment balances in the Blue Nile River Basin. In International Journal of Sediment Research 29 (3), pp. 316–328. DOI: 10.1016/S1001-6279(14)60047-0.

Alrajoula, M. T.; Al Zayed, I. S.; Elagib, N. A.; Hamdi, M. R., 2016. Hydrological, socio-economic and reservoir alterations of Er Roseires Dam in Sudan. In Science of the Total Environment 566-567, pp. 938–948. DOI: 10.1016/j.scitotenv.2016.05.029.

Arjoon, D.; Mohamed, Y.; Goor, Q.; Tilmant, A., 2014. Hydro-economic risk assessment in the eastern Nile River basin. In Water Resources and Economics 8, pp. 16–31. DOI: 10.1016/j.wre.2014.10.004.

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. In Science of the Total Environment 630, pp. 1309–1323. DOI: 10.1016/j.scitotenv.2018.02.249.

Calzadilla, Alvaro; Rehdanz, Katrin; Tol, Richard S.J., 2011. The GTAP-W model. Accounting for water use in agriculture. Kiel Institute for the World Economy (IfW) (Kiel Working Papers, 1745). Available online at https://ideas.repec.org/p/zbw/ifwkwp/1745.html.

Central Bank of the Sudan, 2018. The 58th Annual Report of the Central Bank of the Sudan. Central Bank of the Sudan (CBoS). Khartoum: CBoS.

Diao, X., Thurlow, J., 2012. A recursive dynamic computable general equilibrium model, pp. 17–50. Available online at http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/127080.

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. In Water (Switzerland) 10 (7). DOI: 10.3390/w10070921.

Digna, Reem F.; Mohamed, Y. A.; van der Zaag, P.; Uhlenbrook, S.; Corzo, G. A., 2017. Nile River Basin modelling for water resources management – a literature review. In International Journal of River Basin Management 15 (1), pp. 39–52. DOI: 10.1080/15715124.2016.1228656.

Dinar, Ariel; Nigatu, Getachew S., 2013. Distributional considerations of international water resources under externality: The case of Ethiopia, Sudan and Egypt on the Blue Nile. In Water Resources and Economics 2-3, pp. 1–16. DOI: 10.1016/j.wre.2013.07.001.

Donia, N.; Negm, A., 2019. Impacts of Filling Scenarios of GERD's Reservoir on Egypt's Water Resources and Their Impacts on Agriculture Sector. In Handbook of Environmental Chemistry 74, pp. 391–414. DOI: 10.1007/698_2018_330.

Elganainy, M. A.; Eldwer, A. E., 2018. Stochastic Forecasting Models of the Monthly Streamflow for the Blue Nile at Eldiem Station. In Water Resources 45 (3), pp. 326–337. DOI: 10.1134/S0097807818030041.

Habteyes, B. G.; Hasseen El-bardisy, H.A.E.; Amer, S. A.; Schneider, V. R.; Ward, F. A., 2015. Mutually beneficial and sustainable management of Ethiopian and Egyptian dams in the Nile Basin. In Journal of Hydrology 529, pp. 1235–1246. DOI: 10.1016/j.jhydrol.2015.09.017.

International Rivers, 2017. 5 Myths Surround the Grand Ethiopian Renaissance Dam (GERD). International Rivers, 1330 Broadway, 3rd Floor, Oakland CA 94612, USA. Available online at https://www.internationalrivers.org/blogs/not-yet-assigned/5-myths-surround-the-grand-ethiopian-renaissance-dam-gerd, checked on 13-Jan-19.

Jeuland, M.; Wu, X.; Whittington, D., 2017. Infrastructure development and the economics of cooperation in the Eastern Nile. In Water International 42 (2), pp. 121–141. DOI: 10.1080/02508060.2017.1278577.

Kahsay, T. N.; Kuik, O.; Brouwer, R.; van der Zaag, P., 2015. Estimation of the transboundary economic impacts of the Grand Ethiopia Renaissance Dam: A computable general equilibrium analysis. In Water Resources and Economics 10, pp. 14–30. DOI: 10.1016/j.wre.2015.02.003.

Kahsay, T. N.; Kuik, O.; Brouwer, R.; van der Zaag, P., 2017. Economic impact assessment of the grand ethiopian renaissance: Dam under different climate and hydrological conditions. In The Grand Ethiopian Renaissance Dam and the Nile Basin: Implications for Transboundary Water Cooperation. DOI: 10.4324/9781315160122.

King, A.; Block, P., 2014. An assessment of reservoir filling policies for the Grand Ethiopian Renaissance Dam. In Journal of Water and Climate Change 5 (2), pp. 233–243. DOI: 10.2166/wcc.2014.043.

Ministry of Human Resources Development and Labor, 2013. Sudan Labor Force Survey 2011 (SLFS 2011). Khartoum: MHRDL.

Nigatu, G.; Dinar, A., 2016. Economic and hydrological impacts of the Grand Ethiopian Renaissance Dam on the Eastern Nile River Basin. In Environment and Development Economics 21 (4), pp. 532–555. DOI: 10.1017/S1355770X15000352.

Siddig, K., Elagra, S., Grethe, H., Mubarak, A., 2018. A post-separation Social Accounting Matrix for the Sudan (MENA RP Working Paper 8. Washington, D.C. and Cairo, Egypt: International Food Policy Research Institute (IFPRI), 8). Available online at http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/132312.

Wheeler, K.G., Basheer, M., Mekonnen, Z., Eltoum, S., Mersha, A., Abdo, G., Zagona, E., Hall, J., Dadson, S., 2016. Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. Water International 8060, 1–24. https://doi.org/10.1080/02508060.2016.1177698

Wheeler, K., Hall, J., Abdo, G., Dadson, S., Kasprzyk, J., Smith, R., Zagona, E., 2018. Exploring cooperative transboundary river management strategies for the Eastern Nile Basin. Water Resources Research 9224–9254. https://doi.org/10.1029/2017WR022149

6 Appendix

Appendix-Table 1. Average annual growth in crop's GDP at factor cost for 2020 to 2060.

	Cotton	Sesame	Wheat	Sunflower	Sorghum	Sugarcane	Groundnuts
Baseline	1.05	2.98	1.85	1.63	3.81	1.70	3.01
UnlrlCP1	1.37	3.06	1.97	2.19	4.53	1.85	3.07
UnlrlCP2	1.52	3.05	1.93	2.32	4.26	1.86	3.07
UnlrlCP3	1.45	3.06	1.95	2.25	4.47	1.86	3.07
CoordCP1	1.37	3.06	1.97	2.19	4.53	1.85	3.07
CoordCP2	1.52	3.05	1.93	2.32	4.26	1.86	3.07
CoordCP3	1.45	3.06	1.95	2.25	4.47	1.86	3.07
CollbCP1	1.37	3.06	1.97	2.19	4.53	1.85	3.07
CollbCP2	1.56	3.05	1.94	2.35	4.27	1.87	3.07
CollbCP3	1.45	3.06	1.95	2.25	4.47	1.86	3.07

Appendix-Table 2. List of sectors in the SAM and model of Sudan classifies by type of activity

Activity Code	Description	Activity Code	Description
Agriculture: Crops		Agriculture: Fruits and vegetables	
aCot_irg	Cotton – irrigated	aFruts_irg	Fruit – irrigated
aCot_mr	Cotton – mechanized rainfed	aFruts_trf	Fruit – traditional rainfed
aSrg_irg	Sorghum – irrigated	aVegt_irg	Vegetables – irrigated
aSrg_mr	Sorghum – mechanized rainfed	aVegt_trf	Vegetables – traditional rainfed
aSrg_trf	Sorghum – traditional rainfed	Agriculture: Other agriculture	
aWht_irg	Wheat – irrigated	aGmarbc	Gum Arabic
aWht_trf	Wheat – traditional rainfed	aOthfrst	Other forest products
aMze_irg	Maize – irrigated	aFish	Fish products
aMze_trf	Maize – traditional rainfed	Agriculture: Livestock	
aGdnt_irg	Groundnut – irrigated	aCattle	Cattle
aGdnt_trf	Groundnut – traditional rainfed	aSheep	Sheep
aMlet_irg	Millet – irrigated	aGoats	Goats
aMlet_mr	Millet – mechanized rainfed	aPltrymt	Poultry meat
aMlet_trf	Millet – traditional rainfed	aOthlvk	Other livestock products
aSme_irg	Sesame – irrigated	aMilkrw	Raw milk
aSme_mr	Sesame – mechanized rainfed	aEggs	Eggs
aSme_trf	Sesame – traditional rainfed		
aSugr_irg	Sugar – irrigated		
aEgbn_irg	Egyptian bean – irrigated		
aSnflr_irg	Sunflower – irrigated		
aSnflr_mr	Sunflower – mechanized rainfed		
aOthcrp	Other crops		

Appendix-Table 3. Temporal evolution of the total area in Sudan for some crops under the three assumed cropping patterns and irrigation expansion plan.

Crop	Initial area (Hectare)	CP's	2027		2030		2033		2036		2039		2042		2045		2049		2052		All years	
			Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)	Area (Hectare)	Change (%)
Cotton	147840	CP1	15714	10.6	16857	10.3	21429	11.9	11143	5.5	17571	8.3	3429	1.5	15143	6.5	18857	7.6	19429	7.2	139571	94.4
		CP2	30855	20.9	33099	18.5	42075	19.9	21879	8.6	34502	12.5	6732	2.2	29733	9.4	37026	10.7	38148	9.9	274049	185.4
		CP3	22000	14.9	23600	13.9	30000	15.5	15600	7.0	24600	10.3	4800	1.8	21200	7.9	26400	9.1	27200	8.6	195400	132.2
Sesame	26460	CP1	15714	59.4	16857	40.0	21429	36.3	11143	13.8	17571	19.2	3429	3.1	15143	13.4	18857	14.8	19429	13.3	139571	527.5
		CP2	24684	93.3	26479	51.8	33660	43.4	17503	15.7	27601	21.4	5386	3.4	23786	14.7	29621	16.0	30518	14.2	219239	828.6
		CP3	22000	83.1	23600	48.7	30000	41.6	15600	15.3	24600	20.9	4800	3.4	21200	14.4	26400	15.7	27200	14.0	195400	738.5
Wheat	171780	CP1	15714	9.1	16857	9.0	21429	10.5	11143	4.9	17571	7.4	3429	1.3	15143	5.9	18857	6.9	19429	6.7	139571	81.3
		CP2	5192	3.0	5570	3.1	7080	3.9	3682	1.9	5806	3.0	1133	0.6	5003	2.5	6230	3.0	6419	3.0	46114	26.8
		CP3	11000	6.4	11800	6.5	15000	7.7	7800	3.7	12300	5.7	2400	1.0	10600	4.6	13200	5.4	13600	5.3	97700	56.9
Sunflower	26460	CP1	15714	59.4	16857	40.0	21429	36.3	11143	13.8	17571	19.2	3429	3.1	15143	13.4	18857	14.8	19429	13.3	139571	527.5
		CP2	1815	6.9	1947	6.9	2475	8.2	1287	3.9	2030	6.0	396	1.1	1749	4.8	2178	5.7	2244	5.6	16121	60.9
		CP3	11000	41.6	11800	31.5	15000	30.5	7800	12.1	12300	17.1	2400	2.8	10600	12.2	13200	13.6	13600	12.3	97700	369.2
Sorghum	407400	CP1	15714	3.9	16857	4.0	21429	4.9	11143	2.4	17571	3.7	3429	0.7	15143	3.1	18857	3.7	19429	3.7	139571	34.3
		CP2	231	0.1	248	0.1	315	0.1	164	0.0	258	0.1	50	0.0	223	0.1	277	0.1	286	0.1	2052	0.5
		CP3	11000	2.7	11800	2.8	15000	3.5	7800	1.8	12300	2.7	2400	0.5	10600	2.3	13200	2.8	13600	2.8	97700	24.0
Sugarcane	65094	CP1	15714	24.1	16857	20.9	21429	21.9	11143	9.4	17571	13.5	3429	2.3	15143	10.0	18857	11.3	19429	10.5	139571	214.4
		CP2	43362	66.6	46516	42.9	59130	38.2	30748	14.4	48487	19.8	9461	3.2	41785	13.8	52034	15.1	53611	13.5	385133	591.7
		CP3	22000	33.8	23600	27.1	30000	27.1	15600	11.1	24600	15.7	4800	2.7	21200	11.4	26400	12.8	27200	11.7	195400	300.2
Groundnuts	150780	CP1	15714	10.4	16857	10.1	21429	11.7	11143	5.4	17571	8.1	3429	1.5	15143	6.4	18857	7.5	19429	7.2	139571	92.6
		CP2	3861	2.6	4142	2.7	5265	3.3	2738	1.7	4317	2.6	842	0.5	3721	2.2	4633	2.6	4774	2.6	34293	22.7
		CP3	11000	7.3	11800	7.3	15000	8.6	7800	4.1	12300	6.3	2400	1.2	10600	5.0	13200	6.0	13600	5.8	97700	64.8
Total	995814		110000	11.0	118000	10.7	150000	12.3	78000	5.7	123000	8.5	24000	1.5	106000	6.6	132000	7.7	136000	7.4	977000	98.1

Source: CBoS (2013) and Authors calculations.

Notes: CP1, CP2 and CP3 are cropping patterns. The years indicate the sequence of implementing area extensions in the model and they correspond to the 9 new are area extensions as follows respectively, Kenana 1, Kenana 2, Kenana 3, Kenana 4, Roseires, Dinder South, Dinder North, Rahad 2 South, and Rahad 2 North. Note also that the last project (Rahad 2 North), cannot be implemented under cropping pattern 2 if combined with unilateral actions or collaboration states of cooperation.

Appendix-Table 4. Implementing additional hydropower generation under the nine scenarios

Scenario	Increase in hydropower generation (%)		
	2027	2028	2029
UnlrlCP1	6.667	6.667	6.667
UnlrlCP2	6.174	6.174	6.174
UnlrlCP3	6.511	6.511	6.511
CoordCP1	6.667	6.667	6.667
CoordCP2	6.226	6.226	6.226
CoordCP3	6.563	6.563	6.563
CollbCP1	6.667	6.667	6.667
CollbCP2	5.837	5.837	5.837
CollbCP3	6.563	6.563	6.563

Source: Basheer et al. (2018) and Wheeler et al. (2016).

Note: to calculate the annual increase in hydropower generation, we applied a discount factor to avoid applying the growth rates on the top of each other.