Quantifying the Economic Impact of the Grand Ethiopian Renaissance Dam on the Nile River Basin

A Technical Report submitted to the Department of Engineering Systems and Environment

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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Spring, 2022

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract— **Tensions between Egypt, Sudan, and Ethiopia have grown as a result of concerns regarding water security. These tensions have been magnified by the construction of the Grand Ethiopian Renaissance Dam along the Nile River. The dam has potential to increase power production of the region while also creating risk for downstream countries. Therefore, this research will focus on quantifying the economic impact of the Grand Ethiopian Renaissance Dam to understand its implications for the Nile River basin. This will be accomplished by utilizing historical data and case studies to identify factors which may significantly change as a result of the dam construction for the countries of Egypt, Sudan, and Ethiopia. Cases of interest include the High Aswan Dam in Egypt as well as the Merowe Dam located in Sudan. Ultimately, the results of this research take the form of analysis conducted on water security, land use, agriculture, hydropower and the broader economic considerations for the Nile River basin. Additionally, despite the uncertainty of future management strategies, revenue generation was projected using two filling timelines. By quantifying the economic impact of the dam, the results of this research will provide an understanding of how the Grand Ethiopian Renaissance Dam will influence the future of the Nile River region.**

I. Introduction

The Nile River Basin contains numerous reservoirs that serve the purpose of irrigation, hydroelectricity, domestic and industrial use as well as to buffer flooding and droughts. Currently, the Nile River contains 30 large dams that encompass over 200 billion cubic meters of water, accounting for over 25% of Africa's storage capacity [1]. Many of these reservoirs operate independently, often focused towards benefiting their respective regions rather than pursuing a larger basin-scale approach [2].

In 2011, Ethiopia announced the construction of the Grand Ethiopian Renaissance Dam (GERD), located on the Blue Nile River in western Ethiopia. When completed, the GERD is expected to generate 6,000 megawatts of power for both domestic use and export, becoming the largest dam in Africa [3]. The dam is expected to create access to hydropower for over 65 million rural Ethiopian citizens [4]. Both Egypt and Sudan are heavily dependent on the Nile for agriculture and domestic water use, accounting for 80% and 17% of the Nile's water withdrawals [5]. In general, the region has also experienced an increase in urbanization and creating greater stress on agricultural and water resources [6]. Additionally, with 85% of the main Nile's water originating in Ethiopia and almost all water consumption from the Nile occurring in Sudan and Egypt, major concerns have arisen over the construction of the GERD [2].

Figure 1. Nile River Basin. [15].

II. Data

Agricultural, water use, and land use information was collected from World Bank datasets AQUASTAT [7] and FAOSTAT [8]. Data used to model the filling process of the dam and subsequent hydropower production was collected from Zaroug et al. [9], Samra, et al. [10], and Kansara et al. [11]. Economic data including energy consumption, gross domestic product, and net imports was collected from the World Bank datasets [14].

III. Methods

Analysis of the Nile River region was conducted in five main sections: water security, land use changes, agriculture, hydropower, and broader economic implications for the region.

*Research supported by the World Bank.

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A. Water Security

Egyptian water use, economic, and population data were analyzed to better understand the potential for volatilization of the Nile system that filling GERD poses. Water stress defined by SDG 6.4.2 [12] is calculated as total water withdrawals divided by total freshwater resources less environmental flow requirements. Correlation was calculated through linear regression between water stress and population for 1977-2018. GDP and water stress were then compared for similarities in trends.

B. Land Use

Land use consists typically of three categories: agriculture, forest, and urban land areas. For this study, focus was given to agriculture and urban land use as these land areas are dependent on water. Agricultural land use and urbanization data was imported into Microsoft Excel to examine trends for each respective country. Both crop index and hydroelectricity data were used to analyze agricultural production and hydroelectricity generation trends relative to agricultural land use.

C. Agriculture

Agricultural data for Egypt, Sudan, and Ethiopia was analyzed in order to determine potential effects from implementation of the GERD. Variables used to accomplish this included fertilizer consumption per hectare of arable land, at-risk crops (sugar cane and rice), and international trade for agricultural products across the three countries. Summary statistics were calculated in Microsoft Excel.

D. Hydropower

GERD filling and hydropower projections required data collection from available sources. Data regarding the dam filling regime is scarce, therefore data was aggregated from multiple sources to make a sufficiently robust model. Literature was consulted regarding GERD design specifications in order to determine constants for the model.

TABLE I. HYDROPOWER MODEL PARAMETERS

Parameter	Symbol	Value	Source
Hydropower Potential	P	Variable	[16]
Turbine Efficiency	n	87.50%	[17]
Density of Water	ρ	1,000 kg / m^3	-
Volumetric Flow Rate	Q	Variable	[9]
Hydraulic Head	h	Derived from Fig.	[10],[11]
Capacity Factor	Cf	0.3	[18]
Electricity Price	π	\$0.50 / kWh	[19]
Gravity Constant	g	9.81 m / s^2	-

Two distinct time periods are referenced in this analysis: filling and maintenance. Filling coincides with peak Blue Nile flow, when reservoir volume increases rapidly from June to August [9]. Maintenance occurs during months of decreased Blue Nile flow (August to June), during which water levels in the dam are constant or decreasing [10].

Linear regression was performed on datasets acquired from remote sensing publications in order to acquire parameters for a projection model of reservoir levels. The output from reservoir projection will be the input for the hydropower model, resulting in a projection of hydropower production for both 6 and 12-year filling regimes. This will be forecasted until the reservoir maximum capacity of 74 billion cubic meters (BCM) has been reached. The model used for forecasting was adapted from Mays [16] and can be seen in (1) where the parameters are described in Table 1.

$$P = (n \cdot \rho \cdot g)(Q)(h)(Cf) \tag{1}$$

$$\text{Value Created} = P \times t \times \pi \tag{2}$$

To convert from hydropower potential to value of hydropower produced, hydropower potential in watts was multiplied by the number of hours in each month (Jan-Dec). The monetary conversion follows with the listed electricity value, shown in Table 1. This calculation can be seen in (2) where the output of (1) is multiplied by the number of hours and the price per kilowatt hour.

E. Economics

In the broader economic environment, the GERD has influenced flow of the Nile and the resiliency of economies in times of drought. Additionally, although Ethiopia will benefit from hydropower directly, the additional supply of energy in the region will change how energy is traded in the region. However, due to the uncertainty regarding the management practices which will be employed at the dam, the implications of the GERD on the resilience of the economies in the region and the change in trade are also uncertain.

Therefore, to understand how the GERD could potentially influence the broader regional economy, historical data is used to assess how resilient the economies for Egypt, Sudan, and Ethiopia have been to drought in the past as well as assess how previous hydropower infrastructure has influence the dynamics of energy trade. To accomplish this, rainfall amounts are binned according to percentile and the mean agricultural productions are compared according to country. Additionally, the impact of additional energy supply in the region is assessed by using historical data on energy imports, particularly in the context of changes following the construction of both the High Aswan Dam of Egypt and the Merowe Dam of Sudan.

IV. RESULTS

A. Water Security

The GERD is interfering with an already water scarce system in the Nile River Basin; Egypt is independently suffering from water stress. The only variable currently changing is total water withdrawals, as total resources are reported as a steady 55.5 billion cubic meters per year (BCM/yr) [7], which may be explained by population growth. Water stress in Egypt correlates strongly with population growth, as highlighted by the correlation coefficient which was calculated to be 0.98. As GDP rises, according to Fig. 2, so does water stress. These factors suggest that Egypt's growing population and subsequent need for food and water are the principal strain on their Nile resources. 11.3% of Egypt's GDP comes from agricultural production, and nearly 30% of jobs are agricultural [13]. Accordingly, a significant portion of GDP increases are related to agriculture. The water-intensive nature of agriculture thus supports why GDP increases as water stress increases. The High Aswan Dam's reservoir, Lake Nasser, provides a buffer from normal hydrologic variability such that Egypt's water security is not currently tied to upstream hydrology under normal flow conditions, but rather is primarily tied to downstream intensity of water stress. The total freshwater available from the Nile to Egypt has not changed, yet water stress has consistently increased.

B. Land Use

Over the past 40 years, the percentage of agricultural land has remained relatively constant for Egypt, Ethiopia, and Sudan, with marginal increases for Ethiopia. Additionally, there has been increases in the percentage of urban populations for Ethiopia and Sudan with a plateau in Egypt. Crop Index, a measure of agricultural production relative to the baseline average set from 2014-2016 has increased for both Egypt and Ethiopia since the 1990's. However, as shown in Fig. 3 there has been no significant increase in agricultural land.

In addition to producing hydroelectricity, dams can store water which can be used for irrigation practices. Therefore, hydroelectricity produced by dams can be used as a proxy for water available for irrigation. Shown in Fig. 4 is variation in hydroelectricity generation and agricultural land percentage for each respective country. As seen, there is relatively no increase in agricultural land for an increase in hydroelectricity for Ethiopia and Sudan. Meanwhile, hydroelectricity and agricultural land remain relatively constant for Egypt.

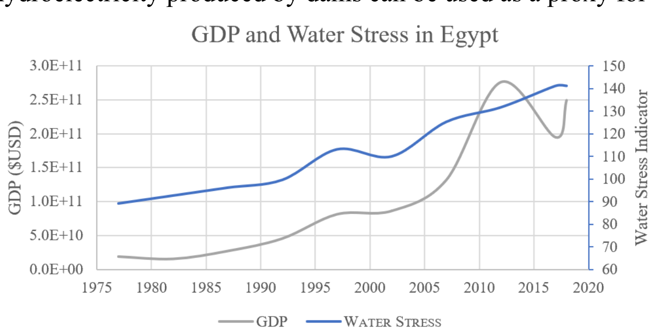

Figure 2. GDP and Water Stress in Egypt over Time.

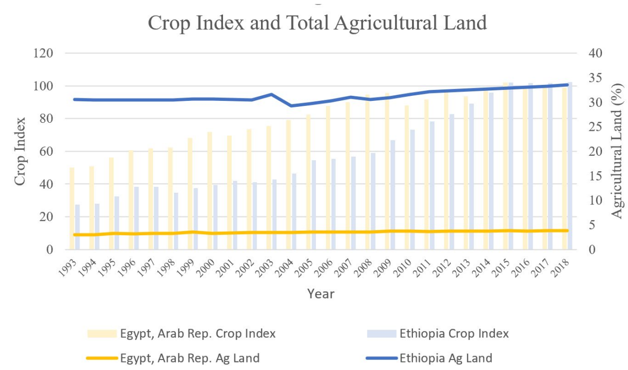

Figure 3. Crop Index and Agricultural Land in Egypt and Ethiopia over Time.

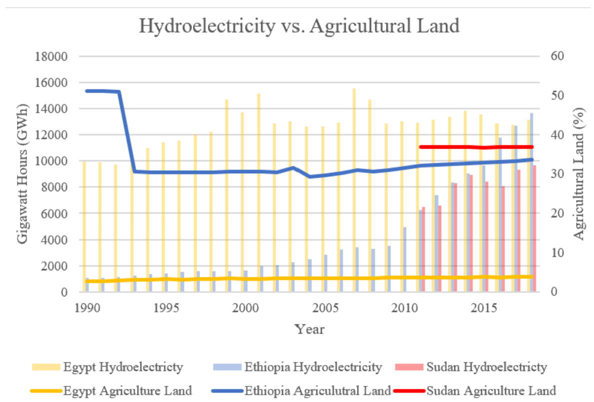

Figure 4. Hydroelectricity Generation versus Agricultural Land in Nile Basin over Time.

C. Agriculture

With the prevalence of moderate or severe food insecurity in the total population of Egypt at 27.8%, there is a need to address agriculture production at a basin-wide scale [8]. Furthermore, assessing the GERD's potential influence over certain agricultural variables will be essential to increase the resilience and economic gains associated with agricultural development in Egypt, Sudan, and Ethiopia.

Fertilizer use in Sudan and Ethiopia is minimal and has not changed a significant amount over time, thus Egypt will be the primary country of study for this variable. From 1990-2018 there was a 5.33% increase in the amount of fertilizer used and with fertilizer consumption amounting to 569.12 kilograms per hectare of arable land in 2018 [14]. However, there is a

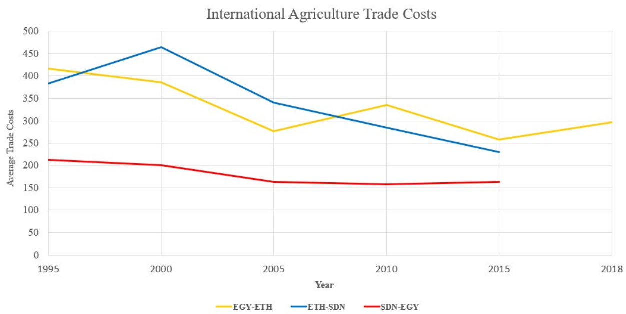

Figure 5. Bilateral Trade Costs for Basin Countries

plateauing effect for fertilizer consumption in Egypt, confirming that the amount of arable land in the country is stable.

Two major Egyptian crops that are most at-risk from changes in water availability are sugar cane and rice. Sugar cane and rice use the most amount of water per hectare, indicating that these crops are of the most risk as the GERD is implemented upstream. Furthermore, sugar cane is the highest produced crop by volume in Egypt, where in 2019 16.32 million tons of the crop were generated [8].

International trade between Egypt, Sudan, and Ethiopia from 1995-2018 can be seen in Fig. 5 [14]. The reported values are an index value that shows the rate at which trade costs have evolved over time. This figure shows the bilateral trade costs across the three countries under analysis, where the costs involved in trading goods internationally with another country relative to trading goods domestically has decreased for all three scenarios. With Egypt and Ethiopia having the highest bilateral trade costs for agriculture, it can be determined that trading the same goods with other countries may prove more beneficial as water flows change in the Nile.

D. Hydropower

Using the model adapted from Mays [16], the results from the linear regression are seen in Tables 2 and 3. If the GERD water management regime continues as it has for the past two years, it can be expected that the dam will reach its maximum capacity of 74 BCM by 2032, approximately 12 years. Seeing as how Ethiopia desires to have the reservoir filled in 4-6 years so that they can receive the full benefits of Africa's largest hydroelectric dam, it is possible that the dam operators may begin taking a more aggressive approach in filling the reservoir of the GERD, thus limiting the amount of water released downstream. The reservoir volume and area projections are seen in Fig. 6.

By doubling the amount of water that is stored in the dam each year, a 6-year filling period is derived and set to conclude by 2026.

TABLE II. LINEAR REGRESSION OUTPUT

Time	Variable	Period	Value	Unit
12 Years	Volume	Filling	0.1038	BCM/day
12 Years	Volume	Maintenance	-0.0012	BCM/day
12 Years	Area	Filling	2.8917	km^2/day
12 Years	Area	Maintenance	-0.1242	km^2/day
6 Years	Volume	Filling	0.2076	BCM/day
6 Years	Volume	Maintenance	-0.0012	BCM/day
6 Years	Area	Filling	5.7834	km^2/day
6 Years	Area	Maintenance	-0.1242	km^2/day

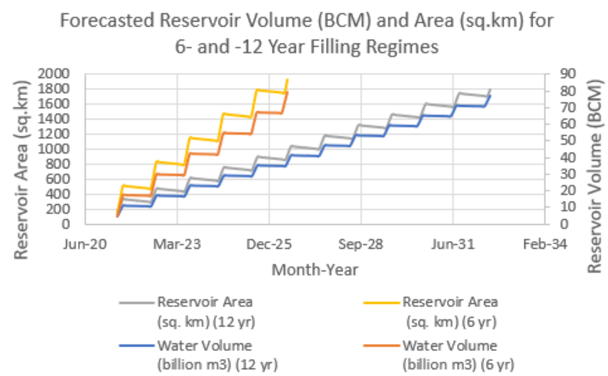

Figure 6. 6- and 12-Year Reservoir Filling Scenarios.

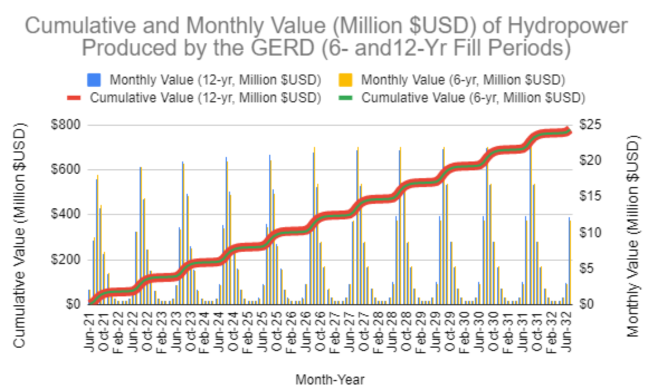

Figure 7. Revenue Generation via Hydropower Production in 6- and 12-Year Filling Scenarios.

After the models for 6- and 12-year filling regimes were created, the average reservoir head data was calculated by dividing the reservoir volume by the area, then entered into the hydropower model. The model displays the monthly and cumulative values of hydropower produced by the GERD in millions of $USD. Output from the model is plotted in Fig. 7. Under both 6- and 12-year filling regimes, the dam will be producing approximately $22 million USD worth of hydropower during the peak flow month of August each year, and down to a low of around $1 million USD worth of hydropower per month during low flow (Jan-May).

Under a 6-year filling regime, the cumulative value of hydropower produced after 12 years will be approximately the same as the projected value for the 12-year filling regime. This indicates that the dominating factor in this hydropower model is the volumetric flow rate, because peak power production and value generation both correspond with the maximum Blue Nile Flow period from June to August, as indicated by Zaroug et al. [9].

E. *Economics*

Droughts influence water availability which directly affects agriculture in the region. The presence of the GERD creates a risk which may magnify the impact of droughts within the region. Plotting agricultural growth over precipitation in the year, as shown in Fig. 8, demonstrates the significant variability found in the production of each country. However, when means for growth were compared in drought versus non-drought years, there was not statistically significant evidence at the 5% level to suggest that drought years had lower agricultural growth. This is explained by the fact that improvements to agricultural technology and other factors such as temperature and the presence of natural disasters also play a crucial role in determining agricultural production. Additionally, as economies rely less on agriculture, the change in agriculture value added will decrease as fewer resources are dedicated to the sector so the variability will be less than that of countries whose increased reliance on the sector magnified variability from year to year.

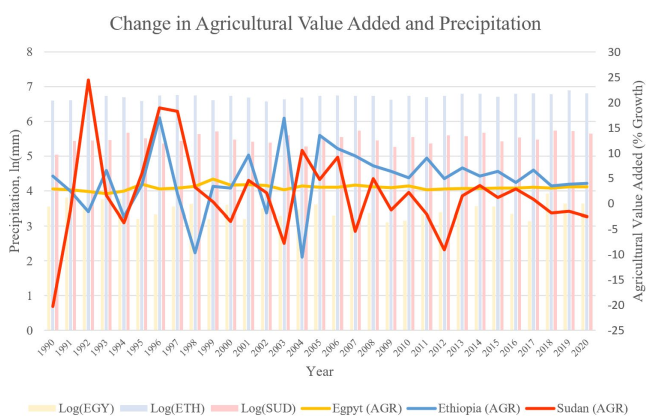

Figure 8. Change in Agriculture's Value Added versus Precipitation over Time.

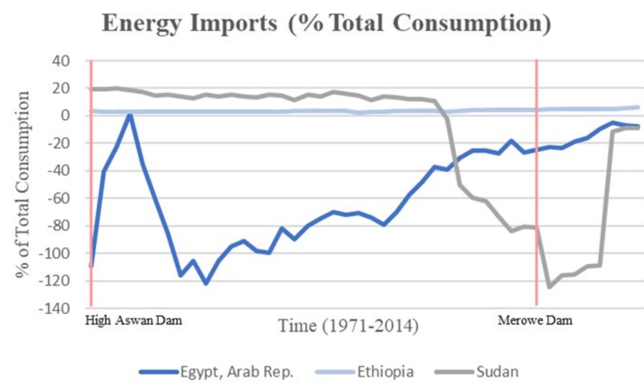

Figure 9. Energy Imports over Time for Nile Basin Countries.

When analyzing the trends of energy imports within the region, Ethiopia is the only country of the three which is a net importer. Fig. 9 shows that in the most recent decade, both Egypt and Sudan are net exporters of energy. While data from the EIA suggest both of these countries rely on fossil fuels to contribute to this, it is important to note that following the construction of large hydropower facilities within the country, the country remained an exporter even as demand for energy increased.

V. Conclusion

In regards to the water security of downstream nations such as Egypt, it can be seen that if the availability of freshwater does decrease upstream due to the filling of the GERD, then Egypt will have abnormally low flow conditions into Lake Nasser, meaning Egypt will have increased water stress from the numerator (total withdrawals) and denominator (total inflow) of the water stress equation.

From a land-use viewpoint, it was hard to correlate agricultural land percentage to both crop index and hydroelectric generation. However, after analyzing the data, it can be noted that Egypt and Ethiopia are contributing more to the agricultural markets without increasing agricultural land. Additionally, hydroelectricity generation was seen to have little to no impact on agricultural land for Ethiopia and Sudan, although data for Sudan was sparse. Egypt remained relatively constant with respect to agricultural land and hydroelectricity. Therefore, similar results may be seen upon completion and filling of the GERD.

The dominating factor in the hydropower model for this study was the monthly discharge in the Blue Nile River, as opposed to the filling regime of the dam. In spite of a six-year difference in filling periods, by the end of the first twelve years, both of the filling regimes were projected to produce roughly the same value of electricity for Ethiopia. This finding may be useful for international dam management conversations, as it is possible that the dam could be filled slower, resulting in less water strain on Sudan and Egypt and minimal loss in hydroelectric generation capacity for Ethiopia.

With regards to the broader economic implications of the GERD, the conclusions which can be drawn are limited. While findings were not statistically significant, the GERD is a part of a much larger system whose relationships and dependencies which were not completely discussed in this research. On main example of this is translating energy availability to future economic growth. While energy itself is a source of revenue for the country of Ethiopia, the question remains whether this will spark greater economic innovation and investment into the countries of the Nile River Basin.

Acknowledgment

The team consisting of C. Bass, M. Fitzsimmons, S. Keith, T. Lam, and A. O'Neill would like to thank Venkataraman Lakshmi for his continual assistance over the course of this technical research.

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