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Mutually Beneficial and Sustainable Management of Ethiopian and Egyptian Dams in the Nile Basin

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Abstract

Ongoing pressures from population growth, recurrent drought, climate, urbanization and industrialization in the Nile Basin raise the importance of finding viable measures to adapt to these stresses. Four tributaries of the Eastern Nile Basin contribute to supplies: the Blue Nile (56%), White Nile-Albert (14%), Atbara (15%) and Sobat (15%). Despite much peer reviewed work addressing conflicts on the Nile, none to date has quantitatively examined opportunities for discovering benefit sharing measures that could protect negative impacts on downstream water users resulting from new upstream water storage developments. The contribution of this paper is to examine the potential for mutually beneficial and sustainable benefit sharing measures from the development and operation of the Grand Ethiopian Renaissance Dam while protecting baseline flows to the downstream countries including flows into the Egyptian High Aswan Dam. An integrated approach is formulated to bring the hydrology, economics and institutions of the region into a unified framework for policy analysis. A dynamic optimization model is developed and applied to identify the opportunities for Pareto Improving measures to operate these two dams for the four Eastern Nile Basin countries: Ethiopia, South Sudan, Sudan, and Egypt. Results indicate a possibility for one country to be better off (Ethiopia) and no country to be worse off from a managed operation of these two storage facilities. Still, despite the optimism of our results, considerable diplomatic negotiation among the four riparians will be required to turn potential gains into actual welfare improvements.

Keywords: Nile, reservoir storage, water sharing, benefit sharing, Pareto Improvement, negotiated settlement.

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2 Background

In much of the Nile Basin, rainfall patterns as well as climate limit water supply, use, and economic development opportunities. Water resources in that basin could be more efficiently, equitably, and sustainably managed if the riparian nations involved could come to a mutually acceptable agreement on allocating the Basin’s supplies. In the face of growing evidence of climate change and variability, it is unlikely that overall supplies in this basin will increase, though debates on this question continue to occur (Sherif and Singh, 1999). Hydroelectric power supplies 32 percent of Africa’s energy. Still, per capita power consumption in Africa is the lowest in the world; access to electricity is uneven; power supplies are often unreliable; conflict has damaged existing services in some areas; only 3 percent of the Nile Basin’s potential has been currently developed for hydroelectricity (United Nations Environmental Program, 2010).

Debates over water rights and access to the Nile likely predate the written record (Allen, 1997). Some of the oldest surviving written records of water use patterns of the Nile comes from the ancient Egyptians (Bell, 1970). Today (2015), the Nile continues to have major economic importance for all 11 riparians’ national security and community livelihoods.

2.1 Institutions

The Nile has supported civilization for centuries. In 1133-73, the Ethiopian king, Lalibela, presented a plan to divert the Nile but was discouraged from doing so in part because of a willingness by the Egyptians to pay an annual tribute to protect the Nile’s inflows into Egypt (Hecht, 1988). In 1902, after 20 years of Egyptian occupation by Great Britain, an Anglo-Ethiopian treaty was signed and included a passage that precluded construction of any storage facility on the Blue Nile (Kendie, 1999). In 1927, Ethiopia sent Workineh Martin to recruit American Engineers to Lake Tana to formulate a development plan (Abraham, 2002). In 1929 another agreement was signed between Egypt and Great
Britain stipulating a plan to preclude water storage developments at the headwaters of the Nile (Kendie, 1999). Cooperation between the US and Ethiopia brought a physical survey of the Nile in 1930 (Abraham, 2006), taking more than three decades to finish at a cost of $9 million.

In 1959, Egypt signed a second bilateral agreement with Sudan on use of the whole Nile, for which Ethiopia was not a signatory (Abdalla, 1971). Later, Ethiopia was hit by two recurrent, sustained, and catastrophic drought-induced famines. The first occurred in 1973-74 and the second 1984-85 with high suffering that could have been reduced with greater storage combined with collaboration from the downstream countries (Abraham, 2004). Storage supplied by the High Aswan Dam (HAD) in Egypt enabled Egypt to avert the cost of both droughts.

A HYDROMET project was established by the communities of the Equatorial Lakes to gather hydro-meteorological data on the Nile River. It became operational over the period from 1967 to 1992. In 1992, another cooperation, TECCO NILE (technical cooperation committee for the Promotion of Development and Environmental Protection of the Nile Basin), established a framework for negotiation (Abseno, 2013). In 1999, the ministers of water affairs of many of the Nile Basin countries formed NBI-Nile Basin Initiative constituted of Nile-COM (Council of Ministers), Nile-TAC (Technical Advisory Committee) and Nile-SEC (Secretariat). Though the NBI still operates in 2015, another cooperative agreement emerged known as CFA (Mekonnen, 2010). Under this arrangement a number of upstream states, including Ethiopia, Kenya, Uganda, Rwanda, Tanzania and Burundi have made concerted efforts to accelerate the formulation of the CFA. This was initiated in May 2010 to put bounds on the control that Egypt and Sudan had secured on the waters of the Nile Basin (Mekonnen, 2010).

In 2011, for the first time in history and after many decades of completed surveys, Ethiopia started building a dam on the Nile for hydropower generation, the Grand Ethiopian Renaissance Dam (GERD). The site for the dam had been initially identified by the United States Bureau of Reclamation during a Blue Nile survey conducted from 1956 - 1964. The Ethiopian Government surveyed the site in
2009 and 2010. In 2011 a US $4.7 billion contract was awarded, and the dam’s cornerstone was laid in April of that year by Ethiopia’s prime minister. It is slated to be operational in 2017 (Whittington et al., 2014).

Currently, Africa generates 4% of the world’s electricity and according to a 2010 World Bank report, 24 percent the population in Sub-Saharan Africa has access to electricity (Crousillat et al., 2010), while other low income countries have reached 40 percent coverage. In 2010, Egypt’s electricity coverage per capita achieved 3.0 times the level of Sudan as well as 4.4 times that of Ethiopia (Tesfa, 2013). Power demands by Ethiopia have been growing at an average rate of 25 percent per year since 2010, and demand forecasts by 2020 are 32 percent per annum from the Ethiopian Electric Power Corporation. The GERD as designed stands to increase the current Ethiopian power capacity by a factor of three. Under some plans, the power would be exported to other East Africa countries where the price is high enough to economically justify export.

2.2 Research Literature

Much research has been presented in peer reviewed journals, and many secondary data sources have been analyzed. In 2004, the hydro- and geo-politics of Africa were investigated, from which an integrated management of water resources as well as a basin system cooperation was seen as a measure that could bring about welfare improvements to all countries (Kitissou, 2004).

Mathematical mass balance, numerical routing, and multiple regression models were used to study the effect of new water projects in upper Egypt on hydropower generation and different scenarios of discharging, inflows, and heads (Abdel-Salam et al., 2007). Such approaches can be used to indicate flow allocations based on technical relationships that can secure mutually beneficial water allocation and power production relation between GERD and the Aswan High Dam (HAD). This approach was used
to investigate Sudan’s midstream riparian-position, power and policy using principles of hydro-hegemony after Sudan’s emergence as an oil-exporting country (Saleh, 2008).

A 2009 work recommended that Egypt reconsider its position with respect to the basin and prepare for the potential of reduced future supplies (Dinar, 2009). In the subsequent year, a study was published analyzing the dynamics of power relations and its influence on the management and allocation of shared Nile water resources (Zeitoun et al., 2010).

One investigation examined the importance of thresholds in greenhouse gas concentrations above which associated climate change impacts become economically, socially or environmentally unacceptable. The question was posed by investigating potential impacts of climate change on the water resources of the Nile River and associated impacts on the Egyptian economy through the use of a general equilibrium model. Results showed that Egypt increased its dependence on imports to meet food demand, greatly decreasing grain self-sufficiency, while increasing protein self-sufficiency (Strzepek, 2000).

Another investigation analyzed alternative water futures for the Ganges and Nile Basins using a combined green and blue water accounting framework. Results showed the importance of green and blue water accounting, showing a range of agricultural and technology policy options for increasing global crop productivity across a span of potential futures in these basins (Sulser et al., 2010). A recent work investigated a dynamic water accounting framework for the Eastern Nile Basin in which the basin was treated as a value chain with multiple services including production and storage (Tilmant et al., 2015). Another recent paper developed a hydro-economic model that links a reduced form hydrological component, with economic and environmental components. The findings were applied to an arid region in southeastern Spain to analyze the effects of droughts and to assess alternative drought and climate adaptation policies (Kahil et al., 2015).
Work on the hydro-politics of the Nile Basin investigated unconventional solutions to the water problem (Yohannes, 2009). The author concluded that sustainable Nile water governance could succeed if it treated local hydrological communities as a building blocks for regional hydrological integration. Using principles of virtual water flows of the Nile Basin for water, the authors measured water consumed by selected crop and livestock products (Zeitoun et al., 2010). Results confirmed that virtual water trade occurs where it is economically feasible. A related work (Biswas and Tortajada, 2012) indicated the difficulties of assessing impacts from dams and attributing benefits and costs to one single activity due to many factors.

A 2013 article examined the relevant international law surrounding the debates between Egypt and Ethiopia over the latter country’s construction of the GERD on the Blue Nile, and recommended a balanced diplomatic engagement to move forward (Yihdego, 2013). Another study from that year assessed the distributional aspect of various allocation schemes applied to the Blue Nile in Africa using a game theory approach (Dinar and Nigatu, 2013). They indicated that more allocation of water for irrigated agriculture by Ethiopia could produce a potential return flow benefits for downstream countries. Another 2013 study attempted to estimate the benefits of the GERD project for Sudan and Egypt based on World Bank data. Results showed a 200% improvement in the value of power supplied to Ethiopia, an 86% removal of silt and sedimentation in Sudan and Egypt, as well as a steady water flow and avoidance of flood damages and water conservation benefits in the Ethiopian highlands (Tesfa, 2013).

A recent investigation on filling options of the GERD conducted a quantitative analysis of water resources management to show a reduced risk of hydrological variability and optimum upstream regulation capacities (Mulat and Moges, 2014). To defuse the tension between Ethiopia and Egypt and suggest directions for a win-win deal, a study on the Nile Basin (Whittington et al., 2014) identified a
modest set of losses from GERD to downstream riparians, based on the recognition that hydropower is largely a non-consumptive water use.

GERD filling options were evaluated using a climate adaptation approach (King, 2013). The author recommended either percent or threshold based filling policies depending on potential futures for a changing climate. Win-win solutions were found to have some potential, but may require coordination and cooperation beyond a simple filling policy. A 2014 work estimated the quantity of water in the GERD reservoir under five scenarios of Dam elevation capacity, 88, 117, 137, 145 and 170 meters, by using a Digital Elevation Model (Ali, 2014).

The water professional community has been alerted to seek alternatives and policy proposals that incur lower costs and/or higher benefits (Merrey, 2009). Integrated models are needed for comprehensive benefit-cost measure of the economically efficient allocation of water, including demand management, supply enhancement, or combinations (Booker et al., 2012). In a Cooperative Game Analysis of Transboundary Hydropower Development in the Lower Mekong (Bhagabati et al., 2014), the authors observed that greater cooperation has the potential to raise the minimum level of net benefits for the worst off country, although it provides no guarantee of higher aggregate net benefits summed over riparians (Cascao, 2008). The widely-publicized Helsinki Rules (International Law Association Committee on the Uses of the Waters of International Rivers, 1967), United Nations Convention on International Waters (McCaffrey and Sinjela, 1998), and Berlin Rules (International Law Association, 2004) have influenced the history of cooperation over shared waters across the world, and have become part of international customary law. A contentious but primary point of discussion was the conflict between the principles of "equitable apportionment" vs "no significant harm" between the parties, typically upstream and downstream (Chokkakula, 2012; Ward, 2013).

In investigating the economic value of coordination in large-scale multi-reservoir systems of the Parana River, the authors found that gains could be secured for each riparian, offering valuable
information to support negotiations and benefit sharing arrangements received by different agents (Marques and Tilmant, 2013). There is a range of cooperative options that may inform riparians in determining workable modes of cooperation (Sadoff and Grey, 2005). The concept of hydrosolidarity can be an important principle used to balance numerous interests with asymmetrical power that exists within a river basin (van der Zaag, 2007).

Benefit-sharing arrangements can play a major role in reconciling the interests of upstream and downstream states (McIntyre, 2015). A 2013 study assessed infrastructure development, along with cost sharing arrangements, offer the possibility of allowing riparian countries to move closer to benefit-sharing positions that are mutually acceptable (Wu et al., 2013).

2.3 Gaps and Objectives

Many forums have been prepared, research conducted, institutions established, and water sharing arrangements proposed, but few or none have reduced Egypt’s concerns of unfavorable outcomes that would stem from a renegotiated multi-national agreement for sharing flows of the Nile at or downstream of Ethiopia. On the other hand Ethiopia continues to face a long history of periodic poverty and hunger, partly driven by unreliable control over water supplies for hydropower, irrigation, and commercial tourism benefits that could be secured with greater control. Despite many meetings, committee discussions and debate among ministers of the riparian countries, results have been mostly inconclusive with few effective signed documents.

Moreover, no peer reviewed literature to date has quantitatively examined opportunities for a practical benefit sharing arrangement, under which at least one country could be better off with no country being worse off with the development and management of new storage infrastructure on the Nile. Results from this research could give insight into opportunities for altered water development and
use patterns that are Pareto Improving, in which at least one country is better off and no other country is worse off economically.

This research aims to fill some gaps excluded from previous research and not yet achieved despite a long history of attempted political negotiation. It does so by examining the potential for mutually beneficial and sustainable benefit sharing management from operation of the Ethiopian Grand Renaissance and Egyptian Aswan High Dams. The approach of this paper is to construct, apply, and interpret findings from an empirical hydro-economic model developed for and applied to the Nile Basin. Results from the model are used to search for benefit sharing arrangements in which all countries in the basin could be at least as well off with as without the construction and operation of the Ethiopian dam. It seeks to identify an operation plan for the dam that could produce a Pareto Improving pattern of water use throughout that part of the Basin in or downstream of Ethiopia. The optimized pattern of discounted net economic benefits investigated by our research has a mission of providing tangible and measurable potential for practical integrated management that could inform basin level cooperation (Biswas, 2004).

3 Methods of Analysis

3.1 Study Area

The Nile rises from two origins. The first is from 1600 meters above sea level in Northern Burundi, the White Nile. The second, the Blue Nile, originates near Lake Tana, 1,800 meters above sea level in the Ethiopian Highlands (United Nations Environmental Program, 2010). From south to north, the main river sub-basins flowing from the Ethiopian highlands into Sudan are illustrated in Figure (1). The Grand Ethiopian Renaissance Dam is being constructed on the 40 km long reach of the Blue Nile, from the Ethiopian-Sudan border in the Guba districts of Ethiopia on Blue Nile River, largest tributary of the Nile.
A number of headwater locations, river gauges, water use nodes, and reservoir nodes were investigated, shown in the schematic of Figure (2). The figure is based on existing tributaries of the Nile, actual river flow measuring gauges, and irrigated regions along the river in each of the four Eastern Nile Basin countries shown above. Also shown are the two mega-dams on the Nile. A mass balance of the hydrology of the Nile was used to configure the geometry and network of the flow of the Nile River in the basin in preparation for the development of an optimization model, implemented using the GAMS (General Algebraic Modelling System) software described on the vendor’s home page at gams.com.

### 3.2 Data

Figure 2 shows the four major headwater contributors to the Nile. These include the Albert Nile, the Baro-Sobat River, the Blue Nile and the Tekeze-Atbara River. All sources, except the first are from the Ethiopian Highlands. To account for stochastic flow under normal climate variability, the headwater flows were simulated over 40 years of recent history (Blackmore and Whittington, 2008). Based on the recent trend of climate change in the past few years in the Nile basin, the headwater supplies for a dry scenario were set at 75 percent of the normal flow years (FAO, 2014) and (NBI, 2014). This, of course, is a major assumption, for which considerable ongoing and still unresolved debate continues to occur in the scientific literature and in the policy debate sphere.
3.3 Economics

3.3.1 Efficiency

Our analysis examines alternative water allocations for irrigation, recreation, and power over time and space. It investigates a set of water allocations that achieves an algebraic maximization of the discounted net present value of economic benefits summed over uses, riparians, locations, and time periods, while also respecting a number of institutional, political, and hydrologic constraints.

The three economic benefit-producing uses of water used for this study are hydroelectric power production, tourist based recreation, and farm income. The three uses are summed over time periods, locations within countries, and countries with and without the GERD in place. Important constraints include a sustainability requirement and a political/justice international water allocation constraint. In principle, if the price of water includes all real marginal costs, an efficient resource allocation can be found for which marginal net economic benefits of water are equal across different uses. If such measures could be found, the basin’s water-related economic welfare is made as high as possible with available water (Briscoe, 1996), sometimes termed most economically efficient.

3.3.2 Equity

In 2002 the United Nations adopted a declaration:

November 2002, the Committee on Economic, Social and Cultural Rights adopted General Comment No. 15 on the right to water. Article I.1 states that "The human right to water is indispensable for leading a life in human dignity. It is a prerequisite for the realization of other human rights". Comment No. 15 also defined the right to water as the right of everyone to sufficient, safe, acceptable and physically accessible and affordable water for personal and domestic uses (United Nations, 2002).

Under the declaration, the right entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses. Equity takes on an important role for our analysis, for which it is defined as operating the GERD so that all countries at or downstream of it are as well or better-off with the storage as without it. Practically, this constraint requires searching for...
a way to ensure that economic benefits from water use patterns could be as high or higher for Ethiopia and for all downstream countries of Ethiopia, including Sudan, South Sudan, and Egypt.

In principle, this notion of basin wide equity could potentially be implemented if the completed GERD stored water by reducing irrigation water use within Ethiopia. Another possibility is to fill the GERD during wet years or seasons of the year, after which releases occurred during the dry seasons or years. This second view sees the regulatory role of the GERD as a mechanism to control and manage flows of the Nile throughout any given year and across years so that the downstream countries will be no worse off while Ethiopia will be better off economically.

3.3.3 Sustainability

By one definition, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al., 1987). Our analysis implements a kind of sustainability goal by way of setting lower bounds on the sustainable use of water resources as well as sustained ecosystem stability and resilience in the process of filling and operating GERD. By imposing this constraint on the reservoir storage volume, equally sustainable water supplies and uses under both policy alternatives (without and with the dam) is protected.

3.4 Basin Scale Framework

The basin scale analysis treats the entire part of the basin in our study area as an integrated unit. The hydrology, economics and institutions of the Nile Basin at and downstream of the GERD were integrated within a single framework for policy analysis. The model begins with four major headwaters: the Blue Nile (Abbay), Atbara (Tekeze), Sobat (Baro-Akobo) and White Nile (Albert), (Figure 2). Countries upstream are not hydrologically affected by the GERD. In terms of total economic benefit, two
important priced water uses are irrigated agriculture and actual as well as potential hydropower production. Unpriced tourism-based recreation values are also included for both storage projects.

A regional integrative approach presents a benefit to managing the water, energy and food nexus from the use of the transboundary water resource, as shown in a recent study of Central Asia (Jalilov et al., 2013). This approach is applied in the present research with more quantitative measurement of the uses from each sector. Hydro economic models offer a management resource to efficiently and consistently integrate hydrologic, economic, and institutional impacts of policy proposals to support basin scale cost-benefit environmental and economic assessments (Ward, 2009). A study using portfolio analysis investigated the importance of larger benefits by considering a diversified portfolio of options for adapting to a diverse set of demands in an extensive geographic setting using integrated hydroeconomic analysis (Rosenberg et al., 2008).

A dynamic optimization framework was used to formulate the model presented here. The General Algebraic Modeling System (GAMS) permits the building of large maintainable models that can be adapted quickly to new water supply conditions, economic conditions, or policy debates that emerge. The model is used for headwater sources, crop water demands per unit land, crop yield, time, crop prices, and are assigned for a predefined sets of hydrological attributes. That configuration is used to discover the constrained economically optimum values of the hydrologic, agronomic, institutional, technical, and economic variables. These variables include crop output, land use, energy and water use as specified by empirical hydrologic and economic relations. Results from each climate scenario and each policy choice required separate models. Four models were run, one for each combination of two reservoir developments and two climate scenarios. The analysis seeks to protect the status quo or better in total benefits of water use, with development and operation of the GERD that could promote
win-win cooperation, reducing the potential for, extent of, cost from, and burdens shouldered by conflict.

3.5 Strategic Approach

Our strategy investigates a politically constrained economic optimization of water for the three major uses of water in the basin: hydropower, irrigated agriculture, and recreation. Water level variability at the two reservoirs provide a framework to guide thinking. In coordination with optimized inflow, storage, and release patterns, the GERD needs to be filled to a level where it can produce an economically beneficial level of hydropower, while protecting the water stocks in the HAD to an equal level as would occur without the GERD’s presence, as well as assuring beneficial use of flows used for irrigation in the downstream countries. This is a tall order. It requires a considerable amount of planning, ingenuity, calculation, review, and adjustment where needed.

In the search for policies that could achieve this ambitious mission, we initially considered three policy alternatives associated with storage at the GERD:

- Reducing irrigation water use from Ethiopia to allow additional water to flow into the GERD for hydropower production while not reducing downstream deliveries
- Reducing water deliveries to downstream countries to contribute to the same
- A combination of both

Either option (2) or (3) makes it difficult to achieve a Pareto Improvement without additional infrastructure development, since either option would release less water downstream for beneficial use.

Bearing that in mind, only the first alternative is considered for this article, as only it could produce a policy outcome that assures that no country is worse off overall with the GERD than without it (mathematical appendix). We hope to pursue various elements of the last two options at a future time.
4 Results

4.1 Overview

Results shown in table 1 – table 6 reveal several overarching messages. A primary message with important policy implications is that the development and operation of the GERD has the potential to reach a Pareto improving outcome, making at least one country better off and no country worse with as without its storage. These results provide a resource to guide debates over the practical opportunity for a concept introduced in 2005 as benefit sharing (Sadoff and Grey, 2005). A primary message of our findings is that this potential for a benefit sharing outcome is shown to occur under both the base and dry climate scenario.

Nevertheless, an important secondary message tempers these sanguine findings: The four riparian countries will need to undertake considerable political negotiation in the search for settlements to secure these potential benefits for all countries that are indicated only as potential outcomes by our results. Third, protecting base levels of economic welfare or better (without the GERD) for the downstream countries requires Ethiopia to fill its dam from reductions in its own agriculture water use.
Large-scale hydropower plants like GERD with storage can partly de-couple the timing of hydropower generation from variable natural river flows. Large storage reservoirs may be sufficient to buffer seasonal or multi-seasonal losses from the costs of very low or very high flows. Although not presented in our results, considerable hydropower production potential from the GERD could allow Sudan to export more of its diminished petroleum production to the international market by importing cheap and environmentally friendly hydropower from Ethiopia.

4.2 Water

4.2.1 Headwater flows

Table 1 shows synthesized flows for the four headwater sources of the Nile we used for our model: The Albert White Nile, Baro-Sobat, Blue Nile and Tekeze-Atbara. They were designed to replicate the year-to-year mean and variance of supplies at those four sources for the base climate scenario, as well as replicating 75% of mean flows for the dry climate scenario. In that table as well as the remaining ones, the abbreviation ‘wo_dam’ stands for ‘without the dam,’ while ‘wi_dam’ stands for ‘with the dam.’ The stream gauge abbreviations are described in the map schematic figure 1.

All sources of the Nile except the Albert rise in the Ethiopia Highlands, for which the three Ethiopian sources contribute about 86% of the Basin’s total. The remaining 14% is contributed by the Albert, originating from Lake Victoria. Headwater supplies are identical with and without the GERD Dam since, with the exception of micro-climate effects, building the dam will have no major effect on supplies entering the system.

Table 1 About Here
4.2.2 Streamflow Gauges

Table 2 shows predicted annual streamflow levels throughout the Nile Basin, by Gauge, Policy, and Climate Scenario. Flows at all gauges below the GERD are directly influenced by the reservoir’s operation. Flows are shown only for a 20 year average to limit use of space. Detailed year-by-year flows are available from the authors on request. Flows in Table are shown for all 26 mainstem and tributary locations and tributaries of Nile River for the four countries used for our model.

These gauges include the Nimule, a source of Albert Nile headwater in South Sudan; Baro, source of Sobat Nile headwater at Ethiopia; Bahir Dar, source of Blue Nile headwaters at Ethiopia, and Kassala, source of Atbara Nile headwater at Ethiopia. Gauges at the lower ends of the basin occur at Edfina and Zifta Gauges in Egypt, the approximate location of the outflow to the Mediterranean.

Reductions in river flow between any two gauges indicate net quantities of water depleted by water users (ungauged sources minus uses) in the river reach between the gauges. Net depletions are diversions minus return flow that make it back to the river subsequent to diversion.

Three important features can be seen from this table. First, the table shows impacts of the development and operation of the GERD on each of the downstream gauges as well as the overall flow patterns of the Basin. Second, impacts are shown from reduced overall flows in the dry scenario with and without the GERD. Finally, the table shows the water redistribution impact of the GERD among gauges. For both base and dry scenarios, entries in contiguous columns show the difference in flows without the dam compared to with the dam.

Under the ‘change’ column, a positive/negative entry indicates that greater/less gauged flow would occur under ‘with Dam’ policy at a given river gauge, compared to the ‘without Dam’ policy. In comparing the without Dam and with Dam policy, a positive change in flow can only occur with reduced agricultural use or increased reservoir releases or a combination of the two. For example, the Dinder gauge in Ethiopia shows 2.13 bcm more streamflow for the base climate scenario and 1.38 bcm more...
streamflow for the dry scenario with the dam than without. This occurs because the GERD takes water
from the upstream agricultural use within Ethiopia. The gauge immediately downstream of the GERD,
Ro Series, shows that under historical supply conditions, there is no change in water under both the
normal and dry scenario with and without the dam.
For a given level of total supply of water flowing into the HAD in Egypt, higher reservoir releases
reduce the HAD’s reservoir storage volume and at the same time increases the flow rate immediately
below the HAD. Outflows at the two last gauges in Egypt, Zifta and Edfina, match flows both with and
without Dam, ensuring that ‘with Dam’ policy protected environmental values are associated with
outflows to the Mediterranean, which we label protection guarding against seawater intrusion.
A closer look at Table 2 also shows that the ‘with Dam’ policy results in no overall change in
predicted flows at the lower end of the basin with the GERD compared to without it. This indicates no
change in outflow from the basin that would occur in the face of the regulating mechanism supplied by
the GERD. There is a reduction in flows in both the base and dry climate scenario at one of the gauges of
South Sudan (Kosti) (Haregeweyn et al., 2015) and four of the gauges in Sudan (Thmaniat, Hesnab,
Berber and Dongola). An additional regulating role of the GERD reallocates the Nile’s waters throughout
the basin so that benefits are optimized to the greatest extent possible while also protecting respect for
the Pareto (economic) Improvement requirements established by our analysis.
Table 2 also reveals the geographic distribution of the 26 gauges, showing five each for Ethiopia
and South Sudan, ten for Sudan and six for Egypt. Flows at these gauges indicate how much water flows
into, within, and out of each country by climate and policy scenario. For example, column three of Table
2 shows an average of 48.1 bcm crossing the border from Ethiopia to Sudan without the dam under base
climate conditions, while another tributary from Ethiopia carries 12.57 bcm of water to South Sudan.
The Albert White Nile adds flow to South Sudan at the Nimule gauge that receives 14.81 bcm of water
from Uganda, originally sourced at the Equatorial Lakes. Sudan receives 26.33 bcm of water from South
Sudan and 59.8 bcm from Ethiopia, which sums to 86.13 bcm and delivers 75.46 bcm to Egypt at the entrance to the Aswan Dam at the Aswan upper gauge. Among other things, this respects the institutional constraint in favor of the status quo water agreement between Egypt and Sudan meets the 1959 Nile Treaty flows.

Table 2 About Here

4.3 Agriculture

4.3.1 Water Use

Table 3 shows water use and farmland in production by crop type, riparian, policy, and water supply scenario, averaged over the 20 year time horizon. Under the constrained optimization results, Ethiopia is predicted to use an annual average of 2.9 bcm of water from the Nile system for its irrigated agriculture for the base climate scenario. Under a dry climate scenario, average water use is predicted to decrease to 2.1 bcm per annum. By contrast, downstream countries including South Sudan and Sudan use the same amount of water for each climate scenario and each reservoir development policy. These results re-affirm that the politically constrained reservoir operation presents an opportunity to supply an Actual Pareto Improvement, defined earlier in the paper. Egypt in this case will be affected by change in the climate conditions, showing reduced water consumption by 31%, because of the large differences in headwater supplies between the base and dry climate scenario. This shows that climate change stands to be an important factor leading to declines in water supply and agricultural water use in Egypt as well as in other parts of the basin.

Tabled results show that GERD could possibly be developed and operated to produce no negative impact on the water supply and irrigated agriculture of Egypt or other downstream riparians. Home to the largest irrigated agriculture in the basin, Egypt diverts and consumes much more water for irrigated agriculture than the other three riparians combined. Under the ‘no dam’ policy Egypt is shown
by our results to consume on average 56.75 bcm water during the base period and 39.54 bcm for the
dry climate scenario. Ethiopia uses the second smallest amount of Nile water for irrigated agriculture
according to our data sources.

**Table 3: About Here**

| 4.3.2 Land |

Table 3 also presents the important message that total irrigated land in production shows no
reduction with the GERD compared to without it for the downstream countries. For operation of the
GERD to achieve an Actual Pareto Improvement, Ethiopia is shown to decrease its agricultural land by
270,000 ha from the Nile Basin flows at the base climatic scenario due to the reduced water from the
agricultural use used to supply water storage to the dam. On the other hand, model results shown in the
table indicate that the GERD has the potential to allow Egypt to maintain its status quo level of irrigated
land for both the base and dry climate scenarios.

A close inspection of the table reveals that the operation of the GERD dam has the potential to
promote a higher income crop mix, especially a mix associated with higher income crop specialization.
These results point to an opportunity for crop selection and specialization after the construction and
operation of the GERD. A Pareto Improving use of water could result in more land for highly profitable
non-staple crops. Non staple crops typically require more stable water supplies.

On the other hand, benefits from the Nile River in Sudan and South Sudan have little to no effect
as a consequence of the construction and operation of the dam with respect to their irrigated crop
selection. Greater detail could be presented by a model with a quarterly or even monthly time step
compared to the annual time step we used. While excluded from the model results, it is possible that
the operation of GERD has the potential to serve as a mechanism to raise the economic profitability of
the crop mix within each riparian with dam compared to without it. These impacts of the dam on the
cropping pattern of the region are shown for staple crops, including major grains (maize, wheat, sorghum) as well as selected vegetables. Non-staple crops include major cash crops such as cotton and sugar cane, for which the GERD could increase production because of the greater reliability of flows with the dam.

4.4 Energy

4.4.1 Reservoir Storage

Table 4 shows the storage volume and the corresponding power production by reservoir, GERD development policy, and water supply scenario average over 20 years. The results from the table show that the GERD is filled only to about one-fifth of the design capacity averaged over that period. This is due to the constraint imposed that requires filling of the GERD only from reduced irrigation water use within Ethiopia to meet the stringent and demanding requirements of Actual Pareto Improvement.

A closer look at table 4 show that the trends in the GERD filling process throughout the 20 years bear little relation with equivalent trends in HAD. The average volume of HAD reservoir with the dam is the same as without the dam both at the base and the dry climate scenario. This means filling options undertaken by this study do not affect the volume of the HAD in Egypt. Egypt could potentially be at least as well off with constant levels at the HAD under the dry climate scenario from the base climate scenario. This occurs because of the sustained release from the GERD for hydropower generation throughout all periods, even during the dry climatic scenario.

Table 4: About Here
4.4.2 Energy Production

Table 4 also summarizes results of hydropower production for GERD in Ethiopia and the HAD in Egypt by climate scenario and GERD development policy. The second data row contains Ethiopian hydropower production potential with the construction and operation of the GERD averaged over the coming 20 years. A minimum of 7,580 GWH (dry climate) and a maximum of 11,309 GWH per year (base climate) is forecast by our analysis to be potentially generated from the GERD.

From the last two rows of Table 4, results show that Egypt would produce equal levels of power output at the HAD, at 12,900 GWH per year (base climate) as well as 8,582 GWH per year (dry climate) with and without the GERD. That means that the construction and operation of the GERD has the potential to avoid negative impacts on hydropower production supplied by the HAD. The reason for this is that the Ethiopian dam is shown in the model to be filled only to about one fifth of its capacity, a result that comes from reducing irrigated agriculture from Ethiopia’s use of the Nile upstream of the GERD.

A closer look at Table 4 indicates that the electricity production from GERD may decrease by one third on average for the dry climate scenario as compared to the base climate scenario. On the other hand, according to the option taken for this research, HAD hydropower production is constrained to be unaffected and this is shown by the results from the Table where the amount of electric power generated by HAD is the same with the dam as without it.

Generating this much electricity for Ethiopia, GERD has the potential to have little significant effect on the hydropower generated by HAD. Egypt is predicted to produce equal electric power from HAD, with the GERD in place than without it. This occurs because the release from the GERD causes an unchanged level of the HAD reservoir storage volume. If the reservoir volume of HAD increases, the head of the dam increase which increases its hydropower generation.
4.5  Economics

4.5.1  Economic Value of Agriculture

Table 5 shows that agricultural, energy and recreational benefits of the four riparian has different values and trends throughout the forecasted period. Ethiopian agricultural benefit shows fluctuation both 'with the dam' and 'without the dam' policy and with the base and dry climate scenario. Due to the construction and operation of GERD, Ethiopia will lose $1,218 million every year on average and a total of $15,130 million over the forecast 20 years period from reductions in irrigated agriculture. This loss in Ethiopian agricultural benefits is forecast by our optimization results to be more than offset by the large additional benefits from the hydroelectricity and modest recreational values of the new Dam. Both Sudan and South Sudan have the same agricultural benefit over the reservoir policy and climate scenario and throughout the 20 years as they show unchanged water use for irrigated agriculture. While Egypt's agricultural benefit is not affected by the GERD development, it is highly affected by the climate scenario. Thus, during drought periods, Egypt is shown to lose on average $5,467 million every year to native water supply shortages and a discounted total of $59,543 million lost from a dry climate, both with and without the GERD being built upstream.

4.5.2  Economic Value of Energy

Table 5 also shows the energy benefits from hydropower generation by country, Ethiopian reservoir development policy and climate scenario. The hydropower price for Ethiopia is (optimistically) estimated at $ US 0.15 per kwh, about seven to eight times the Egyptian electricity tariff. Multiplying the hydroelectric power production in Table 4 above with its corresponding price equals the hydropower benefit from the two dams. Averaged over 20 years, there will be a yearly average hydropower energy benefit of $1.21 billion during the base period and $855 million during the dry climate scenario.
4.6 Total Economic Benefit

Table 5 shows total discounted net economic benefits over 20 years by country, policy, water supply scenario, and water use category. Examining the case of Ethiopia, results show that the loss of agricultural benefit and the expense for the construction of the dam will be more than offset by considerable addition in economic benefits from the hydroelectric power benefits added to augmented recreational benefits from the newly built and operated storage capacity.

Ethiopia could experience a gain in total net benefit of about $2.6 billion for the base climate scenario and $1.3 billion for the dry climate scenario. Total net benefits for the midstream riparian including Sudan and South Sudan shows no change with and without the Ethiopian storage policy and the climate scenario. The first reason for this is our Actual Pareto Improvement constraint that requires all riparian countries’ total benefit to be at least as high with the GERD dam as without it. A second reason is the effect of the GERD regulating effect on the downstream river regime. A third reason sometimes forgotten is that the tradeoffs in water use between irrigation and hydropower production can be complementary. That is, a reservoir release at the dam could be used to generate hydropower as well as irrigate downstream croplands. Properly managed, a single cubic meter of water can be used many times from the headwaters to the sea.

The complementarity characteristic of water use between hydropower production and irrigated agriculture leads to expanded basin benefits. Thus, despite reduced agricultural benefit, the absolute total economic benefit of Ethiopia increased by 13.7% with the dam than without it. Moreover, the GERD protects against welfare losses for all downstream countries. For instance, Egypt’s discounted net economic benefits as well as the total basin wide total show no change for both climate scenarios.

Results presented in this analysis indicate only possibilities. Benefits shown by our results make no guarantee of those benefits being realized. Water negotiators will not necessarily take advantage of benefit sharing arrangements that improve all riparians’ welfare predicted by this study. Still our results
clearly indicate the potential of win-win outcome that could be secured through a carefully negotiated settlement among the four riparians at and downstream of Ethiopia’s new dam.

### 4.7 Shadow Prices

Table 6 shows the economic value of an additional 1000 cubic meters of water at the headwaters of the Blue Nile if it could be made available. That economic value of the additional river flow comes by putting that water to its best use somewhere in the basin while respecting all the constraints placed upon that use of the water discussed earlier in this paper. Results are shown by year, reservoir development policy, and climate scenario. Values of water are measured in $US per 1000 cubic meters at the headwaters.

These values provide important information supporting decisions made for the Nile Basin water community. Members of that community include ordinary water consumers, urban water suppliers, power buyers and suppliers, ministry personnel, and other water stakeholders who wish information on the performance of measures that would discover and/or develop alternative sources of water.

Examples of new sources of water include additional groundwater aquifers discovered through remote sensing, successful well-drilling, desalination, and the like. It could also include water importation, investments in water conservation technology that substitutes labor, land, or infrastructure for water, or measures to mitigate (proven) climate change or climate variability. Other possibilities are measures to increase groundwater recharge, weather modification, rainwater harvesting, and development of additional storage. Institutional measures for finding additional supply can include actions like reducing existing demands for water, raising or restructuring water tariffs, clarifying the legal right to use water, and introducing of economic measures for finding new water such as water trading.

Several patterns emerge from table 6:
The marginal value of water increases with the GERD in place compared to without that storage in place. This occurs because a reservoir with greater storage capacity has greater powers of regulation for handling fluctuations in headwater supplies. A larger reservoir capacity produces a higher marginal value, especially in drier years, because of its greater utility in putting fluctuating supplies to high valued economic uses, rather than having to send unused water downstream or, worse yet, facing the risk of no water in the reservoir in dry years (Hurst, 1956).

Marginal values are generally higher under the reduced flow climate scenario. This occurs because the scarcity value of additional water increases as water scarcity grows.

Marginal values are higher in drier years, such as years 2, 3, and 6, as shown by comparing Table 2 (headwater supplies) and Table 6 (marginal values). Marginal values are generally lower under scenarios for which the GERD is not built, since given headwater supplies are less able to be used at the preferred time without a reservoir to regulate those supplies.

Table 6: About Here

5 Discussion

This investigation has examined the potential for mutually beneficial and sustainable benefit sharing measures from operation of the Ethiopian Grand Renaissance and Egyptian Aswan High Dams. It has identified how and where water could be allocated and used to achieve the objective of an Actual Pareto Improvement. A constrained dynamic optimization model was developed to identify the potential for a Pareto Improving operation that guards against negative impacts associated with the development of the GERD for the four Eastern Nile countries: Ethiopia, South Sudan, Sudan, and Egypt.

Headwater flows, river flows, water use patterns, reservoir storage volume, and their associated economic values were among the variables optimized to identify the potential impacts and benefits of the GERD. Discounted total economic benefits over a 20 year period for each country can be at least as
large with both dams in place as with only the existing High Aswan Dam. This opportunity for a benefit sharing result could provide a real motivation for dialogue and cooperation among these countries.

Findings from this research have the potential to inform multilateral negotiations through information provided by results of our optimized water allocation constrained by the requirements of a politically acceptable benefit sharing arrangements. In addition, these findings also could guide unilateral decision making for each riparian country as out results also show economically optimized cropping and hydropower production patterns.

With Ethiopia planning to increase its electricity generation through schemes such as the Grand Renaissance Dam, Sudan may anticipate importing more electricity from Ethiopia. The results of this research could serve as guidance for win-win negotiations between Ethiopia and Egypt, from which the former could be relieved from its age old burden of poverty and hunger and the latter seeing protection of its water supply.

Other alternatives of water allocation and benefit analysis could profitably be explored in future work. While not examined in this analysis, significant amounts of water could possibly be conserved by storing more water at the GERD and less at the HAD for the purpose of reducing overall system evaporation from Ethiopia’s higher elevation and cooler climate (Tadesse, 2008). Another example is a reduced burden of growing stocks of silt or reduced costs of silt removal. Either benefit could prolong the effective life of the HAD, an idea developed more fully elsewhere (Tadesse, 2008).

Future work could profitably examine more impacts excluded from this study. There could be expanded basin wide benefits of industry developed as a consequence of additional affordable electric power in the basin. This is properly considered a consumer surplus associated with reduced power prices in Ethiopia compared to existing levels, or greater quantities at existing prices. A power price forecasting model would be most useful. Including these effects could provide a more comprehensive foundation to inform water policy decisions for improved management of the Nile Basin system. Still,
even with all this additional analysis discussed, considerable diplomatic negotiation among the four riparian states will be required to turn potential gains into actual on-the-ground welfare improvements.
6 References


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Merrey, D.J., 2009. Will Future Water Professionals Sink under Received Wisdom, or Swim to a New Paradigm? Irrigation and Drainage, 58: S168-S176.


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Table 1. Synthesized Headwater Supply by Source, Year, Storage Development Policy, and Climate Scenario (Billion Cubic Meters/Year)

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Table 2. Predicted Streamflow by Gauge, Policy, and Scenario, Averaged over Future Years, 20 years

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Table 3. Water Use and Farmland in Production of Staples and Non-Staples by Riparian, Policy, Water Supply Scenario, Averaged over 20 Year Time Horizon

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Table 4: Storage Volume and Power Produced by Riparian, Policy and Supply Scenario, Averaged over 20 Year Time Horizon
Table 5. Total Economic Benefits by Country, Policy, Water Supply Scenario, and Water Use (Million, Discounted, US$, Summed over 20 Year Time Horizon)

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Table 6. Economic Value of one Additional Unit of Water (Shadow Price) at Blue Nile Headwater Above the Grand Renaissance Ethiopian Dam, by Year, Policy, and Climate Scenario (US$ Per 1000 Cubic Meters)

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Figure 1: Nile Basin
Figure 2: Schematic, Nile Basin

[Map of the Nile River Basin showing key locations such as Aswan Dam, Gezira Dam, and major cities and rivers.]
Appendix: Mathematical Documentation, Nile Basin Model

1. Overview

This appendix presents the essential elements of the mathematical documentation of our integrated hydro-economic framework for policy evaluation for the Nile Basin. It is an extension of similar recent works for the Rio Grande Basin (Ward et al., 2006) and Amu Darya Basin (Jalilov et al., 2013). Constraints are imposed to account for hydrology, food security, and the requirements of a Pareto Improvement. While this model and its documentation were developed for application to the Nile Basin, it was designed to be adaptable to the hydrology, land use patterns, economics, and institutions of any basin.

2. Sets

Sets are the basic building blocks that characterize the Nile basin. Each set and element of the basin is defined:

- **Flows** – Flow nodes of all types (83 in total, including individual inflows, streamflows, diversions, use, return flows, reservoir releases, reservoir evaporation, and hydropower turbine nodes, described in more detail with the subsets below)

  - inflow(i)  Headwater gauges  /Albert_WN_h_f, Sobat_h_f, BlueNile_h_f, Atbara_h_f/

  - river (i)  River flow gauges (26)  /1-Nimule_v_f.......25-Edfina_v_f/

  - divert(i)  Diversion nodes (15)  /1-Ethiopia_d_1_f.......4-Egypt_d_3_f/
| 905 | use(i) | Consumptive use flow nodes (15) | /1-Ethiopia_u_1_f ..........4-Egypt_u_3_f/ |
| 906 | return(i) | Surface water return flow nodes (15) | /1-Ethiopia_r_1_f .......... 4-Egypt_r_3_f/ |
| 907 | rel(i) | Reservoir-to-river release flow nodes | /1-GERD_rel_f , 2-ASWAN_rel_f/ |
| 908 | evap(i) | Reservoir evaporation flow nodes | /1-GERD_evap_f , 2-ASWAN_evap_f/ |
| 909 | hydro(i) | Reservoir turbine gauges | /11-Ro_seires_v_f, 20-Aswan_dn_v_f/ |
| 910 | u | Stocks of all kinds (room for aquifers in future work) |
| 911 | res(u) | reservoir elements | /1-GERD_res_s, 2-ASWAN_res_s/ |
| 912 | j | crop | /cotton, Maize, Sugarcane, Wheat, Sorghum, Vegetables/ |
| 913 | js(j) | staple crops | /maize, wheat, sorghum, vegetables/ |
| 914 | jo(j) | non staple crops | /cotton, Sugarcane/ |
| 915 | p | policy | /wo_dam, wi_dam/ |
| 916 | s | water supply scenario | /Base, Dry/ |
| 917 | r | riparian countries | /Ethiopia, SouthSudan, Sudan, Egypt/ |
| 918 | t | year | /1 * 20/ |
3. Data

Terms ending in _p refers to parameter, data read by the model. Those parameters are:

- **Bv_p(i,river)**: Hydrologic Balance Map... Basin geometry is summarized through use of integers: 1, -1, and 0
- **Bd_p(i, divert)**: Wet river table, enforces nonnegative flows at each use node (wet river)
- **BLv_p(rel, res)**: Links reservoir stocks to downstream release flows
- **Ber(evap, res)**: Links reservoir evaporation to volume loss
- **Be_p(evap, res)**: evaporation by reservoir (meters/year)
- **user_p(use, r)**: maps water use nodes to riparian countries
- **stock_p(res, r)**: reservoir stocks and riparian countries combination
- **Bu_p(i, j)**: crop water demand, divert and use and return (1000 cubic meter per ha per year)
- **chk_use_p(use, j)**: checks that divert = use + return
- **Yield_p(use, j)**: Crop Yield, proportional to ET when technology varies (tons/ha)
- **Price_p(use, j)**: Crop Prices ($ US per ton)
Cost_p(use,j)  Crop Production Costs ($ US per ha)

sour_p(inflow)  long term average measured inflow at each headwater node (bcm per year)

aswan_inflow_p(t)  historical inflows into Aswan Dam 1987-2006 (bcm per year)

aswan_outflow_p(t)  historical outflows from Aswan Dam 1987-2006 (bcm per year)

capacity_p(res,p)  GERD and HAD Reservoir maximum capacity (bcm)

power_p(res,p)  power production dummy variable

MBe_p(res)  coefficient for recreation multiplied by square root storage volume.

elas_rec_p(res)  elasticity of recreational benefit with respect to each reservoir stocks (unitless)

hydro_price1 (res,t)  check units here ($ per kwh)

Actual_irrland_p (r)  total irrigated land from Nile surface water by countries (million hectares)

Potential_irrland_p (r)  total irrigable land by countries (million hectares)

land_crop_pct_p(r, j)  percentage observed land by crop and country agricultural node (0-100)

land_region_pct(use, r)  observed proportion of irrigated land by region and country (0-100)

intercept_p(res,p)  slope coefficient connecting head to storage unique to each reservoir
4. Variables

Unknown variables end in _V to distinguish from unknowns from known data. These are optimized by the model. The most comprehensive variable is total economic benefit from three sectors such as agriculture, hydropower and reservoir’s recreations. The most important ones are:

- $X_v(i,t,p,s)$: water flows of all kinds—diversions, streamflows, use, returns, and the like (billion cubic meters per year)
- $Ben_s_v(res, t,p,s)$: economic benefits from stocks ($US million per year)
- $Ag_Ben_j_v(use,j,t,p,s)$: agricultural benefits by crop ($US million per year)
- $tot_ben_v(p,s)$: total use benefits, summed over riparians ($US million per year)
- $Z_v(res,t,p,s)$: storage volume (billion cubic meter)
- $Za_v(res, t,p,s)$: storage area (billion square meters)
- $reservoirs_h_v(res, t,p,s)$: reservoir head (meters depth)
- $energy_prod_v(res,hydro,t,p,s)$: hydroelectric production by the reservoir stocks (GWH per year)
energy\_ben\_v (res, hydro, t, p, s) benefits from hydro energy production of the reservoir stocks

hydro\_price\_v (res, hydro, t, p, s) price of hydroelectricity ($ US per GWH)

Land\_use\_r\_j\_v (use, r, j, t, p, s) land in production (million ha)

Xw\_v (use, r, j, t, p, s) water use (bcm per year)

5. Equations

Relationships among variables and parameters are represented with equations. The most important relationships deal with hydrology, agriculture, institutions, and economics.

5.1. Hydrology

Mass balance is enforced, both for surface flow interactions and reservoir levels. Mass balance principles account for headwater flows, river flows, reservoir levels, water from surface applied to various uses, and the impact of surface flows on current and future reservoir storage levels.

Details follow.

5.1.1. Headwater Runoff
Total natural runoff inflows into the basin are defined as total annual flows at each of four headwater stream gauges. Inflow at each h-th headwater gauges in year t, GERD Dam policy p, climate scenario s, equals total source supplies:

(1) \( X_v(\text{inflow},t,p,s) = \text{source}_p(\text{inflow},t,p,s) \)

5.1.2. River Flow

River flow at each gauge, equals the sum of flows over any upstream node those activities directly influence that flow. These include: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream reservoir releases. Total flows, which cannot be negative, are defined for each of those five types of nodes, respectively, as:

(2) \( X_v(\text{river},t,p,s) = \sum(i, B_v_p(i, \text{river}) \times X_v(i, t,p,s)) \),

Each of the five vectors of \( Bv_p \) coefficients takes on values of 0 for non-contributing sources, 1 for sources that add flow, and -1 for sources that deplete flow.

5.1.3. Water Diverted
Crop irrigation water use is met by river diversions. However, in many of the world’s dry places, historical record often show periods of zero flow in periods of high demand and low runoff. The following equation, a “wet water” condition, requires that no diversion exceeds available river flow at the point of diversion. That is, each diversion must be less than the sum of all five classes of upstream sources: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream reservoir releases. A diversion, which cannot be negative, is:

\[ (3) \ X_v(\text{divert}, t, p, s) \ < \ \text{sum}(i, \ Bd_p(i, \ \text{divert}) \ * \ X_v(i, t, p, s)) \]

where the right hand side terms are the sum of all contributions to flow from upstream sources at the point of diversion. The various Bd_p terms, which indicate presence (1) or absence (0) of upstream flow sources for a given node, are used to accurately configure the basin’s geometry.

5.1.4. Water Use

Any node’s consumptive use, is an empirically-determined proportion of total water diverted. For irrigation, consumptive is the quantity of water lost through plant evapotranspiration (ET), Bu_p, to any future use in the system.
For hydropower generation, use is the quantity of water flowing through turbines. However, that water can be reused for other downstream uses if the timing is right or if storage is available. That water use generates energy, which cannot be negative. It is measured as:

\[
\text{energy}_{\text{prod}}(\text{res}, \text{hydro}, t,p,s) = \text{energy}_{\text{prod}}^\text{v}(\text{res}, \text{hydro}, t,p,s) = K g E \times \text{power}_{\text{p}}(\text{res}, p) \times \text{reservoirs}_{\text{h}}(\text{res}, t,p,s) \times X_v(\text{hydro},t,p,s).
\]

This equation states that energy production increases with the power coefficient, reservoir head, and flow through the reservoir turbines.

Coefficients are: \( g \), gravitational constant; \( E \) is Turbine Efficiency, which can vary from 0 to 1.

For agricultural nodes, water use is measured as:

\[
\text{Xw}_{\text{v}}(\text{use}, r,j,t,p,s) = \text{land}_{\text{j}}(\text{use}, j,t,p,s) \times \text{Bu}_{\text{p}}(\text{use}, j) \times \text{user}_{\text{p}}(\text{use}, r)
\]

Consumptive use by irrigation (ET) at any given node, is proportional to total land area in production for any given irrigation technology, assuming that irrigators do not practice deficit irrigation, which means they will idle land before reducing application per unit land. That use is measured as the sum over crops (j) and riparians (r) of empirically estimated ET amounts per hectare by node, crop and riparian, multiplied by a matrix, \( \text{user}_{\text{p}}(\text{use}, r) \), that maps nodes to riparian countries.
5.1.5. Reservoir Storage

Each reservoir’s water stock is tracked for the year $t$, policy $p$ and scenario $s$. That reservoir’s water stock, equals its stock in the previous year, minus the net release (outflow minus inflow) from the reservoir, added to net evaporation from the reservoir. Reservoir storage volume is:

$$Z_v(res, t, p, s) = Z_v(res, t-1, p, s) - \sum_{rel} BLv_p(rel, res) * X_v(rel, t, p, s) - \sum_{evap} Ber_{evap}(evap, res) * X_v(evap, t, p, s)$$

Economically attractive electric power comes from building a reservoir on a river that has an economically viable elevation drop. There are few economically viable hydroelectric plants in flat places. The dam stores water behind it in the reservoir, and a higher storage volume of water in the reservoir means that the water falls a greater distance and reaches a greater velocity when passing through the turbines. The turbine converts the energy of flowing water into mechanical energy. The hydroelectric generator converts mechanical energy into electricity. The hydraulic head for each reservoir’s dam in was empirically estimated to fit conditions for our two Nile Basin reservoirs, GERD and HAD:

$$reservoirs_h_v(res, t, p, s) = \text{[intercept}_p(res, p) * [Z_v(res, t, p, s)] ** \text{exp}_p(res, p)]$$
The idea of the equation is this: Based on data from the engineering design and previous research (King, 2013) on the two reservoirs’ water volume, a function of dam height, shows a find nonlinear relation between storage volume and head of the dams, so we can predict dam height (head) as a function of storage volume.

5.2. Land Use

Land use patterns affect the demand for water. For irrigated agriculture, total land in production is expressed as:

\[
(8) \text{ Sum}((j, \text{use}), \text{Land}_j(v, j, r, t, p, s)) < \text{RHS}_p(r, t, p, s)
\]

This states that irrigated land in production by node, crop, riparian, and time, summed over crops and use nodes cannot exceed existing available land \(\text{RHS}_p(r, t, p, s)\), by riparian, time period for any given policy and scenario. In many of the dry rural regions of the world, like the downstream Nile Basin, water is often more limiting than land. While we used the maximum current capacity in irrigated land for countries of the Basin as the upper limit on available land, more area will likely become available if greater long term water supplies can be secured and if institutions adjust to permit the extra water to be used by agriculture.
The baseline policy analysis is constrained to replicate historical irrigated land by country and crop. For the two alternative policies, those constraints are removed by allowing water tradeoffs to occur, either within a single country or among irrigated areas across countries. Either policy permits existing water to be reallocated to higher economic valued water uses where the economic gain motivates such a reallocation.

5.3. Economics

Economic benefits are produced by water depletions at use nodes for irrigated agriculture, by water flowing through turbines to generate energy at reservoir nodes, and by recreation benefits from the artificial lakes created by the two reservoirs. For agricultural uses, the net revenue generated by the contribution of water equals crop price multiplied by yield minus cost of production. For energy benefits, total revenue is measured as the price of electricity multiplied by the quantity produced. In the current implementation of the model, that electricity price is set at recent observed levels in the basin. Recreation benefits vary nonlinearly with increased storage volume.

Agricultural benefits are measured as:

\[
\text{Ag\_Ben\_j\_v(\text{use,j,t,p,s}) = [Price\_p(\text{use,j}) * Yield\_p(\text{use,j}) - Cost\_p(\text{use,j})] * land\_j\_v(\text{use,j,t,p,s})}
\]
Where \( Ag_{\text{Ben}} \) is cost of production in that node \( u \) per crop \( j \) in riparian \( r \). The cost per unit land of any particular crop is taken as 80 percent of the product of the price and yield for this research because of our inaccessibility to reliable data from any of the Nile Basin countries on costs of production.

The function describing the economic benefits from hydropower produced is expressed as:

\[
\text{energy}_{\text{ben}_v}(\text{res,hydro},t,p,s) = \text{energy}_{\text{prod}_v}(\text{res,hydro},t,p,s) \times \text{hydro}_{\text{price}_v}(\text{res,hydro},t,p,s)
\]

where \( \text{energy}_{\text{ben}_v} \) is energy benefits produced in the \( \text{res} \)-th reservoir, in year \( t \), in policy \( p \) and scenario \( s \); \( \text{energy}_{\text{prod}_v} \) is energy production in a given reservoir in year \( t \), policy \( p \) and scenario \( s \); \( \text{hydro}_{\text{price}_v} \) is electricity price, set to equal to \$US 0.03 per kwh for Egypt and \$0.15 per kwh (optimistically) for Ethiopia.

The recreation benefit from boating, fishing, hiking, photography, and related tourism, from reservoir storage is:

\[
M_{\text{Be}_p}(\text{res}) \times (Z_v(\text{res},t,p,s))^{**} \text{elas}_{\text{rec}_p}(\text{res})
\]
Where $MBe_p$ is the marginal benefit from recreational value of the lakes, and $elas_{rec\_p}$ is the elasticity or responsiveness of recreational benefit with each reservoir’s volume.

5.4. Bounds

Several bounds are established to assure that the model replicates real world data, technology, and water user behavior, while also producing realistic responses to future climate or policy adaptations to climate. A lower bound $(.lo)$ on each water flows and land used assures no water flows have negative values.

Reservoir contents in the starting (first) period are:

$$Z_{v\_fx}(res, t\_{first}, p, s) = Z_0\_p(res)$$

The upper bound on the reservoir’s contents is defined as:

$$Z_{v\_up}(res, t, p, s) = capacity\_p(res, p);$$

This equation guarantees that the no storage volume ever exceeds its capacity.
To assure the historical starting volume of Aswan dam is replicated, data of inflows and outflows into and from Aswan of 1987-2006 in billion cubic meters by year are used as follows:

\[ Z_v.fx('2-aswan_res_s', t,p,'base') = aswan_storage_p(t); \]

The actual land under crop production in each country is a minimum bound for the optimization of water and land use for agriculture as used by the constraint below:

\[ \text{Land}_use_r_j_v.lo (use,r,j,t,p,s) = \text{Act}_farmland_p (use,r,j); \]

5.5. Objective Function: Discounted Net Present Value

Finally, the basin scale integrated model maximizes discounted net present value across all water uses, water environments, and time periods while respecting hydrologic and institutional constraints described above:

\[ \text{TBt}_v (r,t,p,s) = \sum (\text{use}, \text{ag}_ben_v(use,t,p,s) * \text{user}_p(use, r)) \]
Summing \(TBt_v\) over all periods produces discounted net present value of benefits. The net present value of total water-based benefits for all nodes in Nile Basin, DNPV, sums income over countries and time periods, which discounts future incomes more heavily when faced by a higher discount rate. The current model implementation uses a 5% discount rate. The model allocates water among the basin's water uses, locations, and time periods to maximize DNPV, subject to the above stated constraints.