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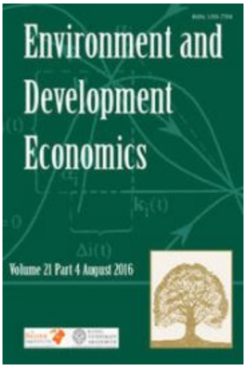

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Economic and hydrological impacts of the Grand Ethiopian Renaissance Dam on the Eastern Nile River Basin

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ABSTRACT. We propose an 'allocate-and-trade' institution to manage the eastern Nile River Basin for Ethiopia, Sudan and Egypt as the basin faces a new reality of the Grand Ethiopian Renaissance Dam (GERD). We find that a social planner could increase the region's economic welfare by assigning water rights to the riparian states. An alternative intrabasin water rights arrangement and trade could achieve more than 95 per cent of the welfare created by the social planner. GERD will change both the economic benefits and hydrological positions of the riparian countries. Economic benefits from alternative water use would be sufficient to make riparian countries better off compared with the status quo. Furthermore, riparian countries could raise more than US$680 m annually for protecting and conserving the natural resources of the region.

1. Introduction

The dialogue surrounding the Nile River has taken an unprecedented course since Ethiopia announced the construction of the Grand Ethiopian Renaissance Dam (GERD) in 2011. This dam will have a storage capacity of 60–70 billion cubic meters (bcm) of water that will be primarily intended to produce 15 billion kilowatt-hours (bkWh) of electricity from hydropower and, to a lesser extent, to irrigate agricultural land (Chen and Swain, 2014).

The views expressed are those of the authors and do not necessarily reflect the views of the Economic Research Service or the US Department of Agriculture. The authors acknowledge the constructive comments from two anonymous referees and the editor of this journal.

With the estimated cost of more than US$4 bn, for the first time in its history, Ethiopia will finance the construction of this mega dam from its own resources (GOE, 2014; Salini Impregilo, 2014). This is the first big project that has ever been attempted by the upstream Nile River riparian countries. It is widely recognized that GERD has the potential to change the hydrological position in controlling the Nile River flow and the economic benefit that riparian countries can derive from the Nile River (Gebreluel, 2014; Jeuland and Whittington, 2014).

GERD ushers in a new challenge for loosening up the existing relationships among the riparian countries in the Nile basin, and for disrupting the existing intrabasin water allocation regimes. For instance, Egypt and Sudan initially opposed the construction of GERD. Starting from 2013, Egypt alone has firmly opposed, but Sudan supports the construction of the dam (Gebreluel, 2014). With the lack of a basin-wide or sub-basin-wide water allocation agreement and management of the Nile River, the current situations could complicate the cooperative process, known as the Nile Basin Initiative (NBI), which has been in place for the past two decades (Allan, 2009; Veilleux, 2013; Gebreluel, 2014).

Our argument is that the long-sought basin-wide agreement is not a viable strategy acceptable for Nile River water allocation, as riparian countries are increasingly interested in unilaterally developing the Nile River along their national borders (Cascão, 2009; McCartney and Menker Girma, 2012). Riparian countries also differ in their economic strengths, political powers and hydrologic and climatic situations (Just and Netanyahu, 1998; Martens, 2011). Due to some typical characteristics of the region, basin-wide agreement on Nile River water allocation and management is a difficult task (Waterbury, 2002; Dinar, 2004).

Hence, we propose an alternative institution called intrabasin regional water trade, based on the principle of 'allocate-and-trade' designed to use and manage the eastern Nile River Basin (ENRB) for the riparian countries consisting of Ethiopia, Sudan and Egypt.[1] The principle of 'allocate-and-trade' will be tested on the grounds of sub-basin efficiency that can be enacted with agreement among riparian countries. The basic notion of 'allocate-and-trade' is that, first, a regional institution such as NBI will assign water rights to the three riparian countries, monitor and evaluate the performance of each riparian country, and then facilitate an intrabasin water trade among riparian countries so that water could be used for projects within the designated basin. The three riparian countries are not required to divert water out of the basin, or to transfer water to other riparian countries that are not included in the agreement, or to sell water to other countries outside the Nile basin. The design for the intended water trade is framed in an analogy to the emission market in which a similar shift in the area of water is long overdue (Olmstead and Stavins, 2008).

Similar to other economic goods, water trade has the potential to allocate water to uses where it produces the highest economic return (Saliba and Bush, 1987). Market-oriented policy instruments, if well designed and

[1] In this study, Sudan includes both South Sudan and the Republic of the Sudan.

implemented, encourage economic agents to undertake conservation and protection efforts and accommodate changing patterns in society's demand (Easter *et al.*, 1998). Studies show that the problem of burgeoning water scarcity and deteriorating water quality could be solved if water is properly treated as an economic good (Sunding, 2000). In a regional setting, water markets are also used to promote economic development and political stability (Whittington *et al.*, 1995), to increase income and crop yield (Meinzen-Dick, 1998) and to improve income distribution (Saliba and Bush, 1987).

In practice, formal and informal water markets exist in Australia, Chile, India, Mexico, Pakistan, Spain and the United States (Easter *et al.*, 1998). Analytically, water markets are designed to address a wide variety of economic and ecological issues (Dinar and Wolf, 1994; Becker, 1996; Aytemiz, 2001; Bhaduri and Barbier, 2008). For the Nile River in particular, the potential benefits of establishing regional water markets have been considered in the literature in the past (Economist, 1992; Wu, 2000). Whittington *et al.* (1995) underscored that trading water rights would be the single most notable innovation that could be introduced in a new agreement on Nile water. Abate (1994) also suggested the higher economic value of trading water among riparian countries in this region.

Previous Nile River models were designed to study the impact of: cooperation on the relationship among Nile riparian countries (Whittington *et al.*, 1995); water allocation in a game theory setting (Wu, 2000; Wu and Whittington, 2006; Dinar and Nigatu, 2013); the hydrological impacts of four dams in the Ethiopian highland (Block and Strzepek, 2010; McCartney and Menker Girma, 2012); physical water use (Kirby *et al.*, 2010); or water resources planning under climate change (Jeuland and Whittington, 2014). Recently, Kahsay *et al.* (2015) developed a static computable general equilibrium (CGE) model to analyze the impacts of GERD on the three riparian countries by distinguishing impounding and operational stages of the dam.

Introducing some water rights arrangements and water markets, internalizing the externality and evaluating the welfare values of these institutions using an economic and environmental optimization model are, however, relatively new approaches in the ENRB. In addition, this is the first attempt that quantifies the economic and hydrological impact of GERD on the region, and that assesses whether or not GERD would be part of efficient allocation.

The remainder of the paper is developed as follows. Section 2 describes the proposed empirical model. Section 3 provides the source of data and information and a review of the main parameters, while section 4 reviews allocation constraints and water rights arrangements. The research findings, and an insightful analysis of GERD, are discussed in sections 5 and 6, respectively. Finally, section 7 summarizes the main results and policy implications of the paper and reviews some of our model's limitations.

2. The Nile optimization model

The theoretical foundation for the optimization model is backed by a social welfare function that provides efficient resource allocation (Varian, 1992). In addition, the support for employing a partial equilibrium optimization model through some form of consumer-surplus function has long been recognized in welfare analysis (Harberger, 1971). For pricing-related policy interventions, partial equilibrium analysis can provide deeper insights for improved welfare, especially when policy makers face limited data and information (Schuh, 1990). With the help of such theoretical bases, we use a partial equilibrium economic optimization model originally developed by Nigatu (2012).

Irrigation and hydropower are the two economic sectors on the demand side of the model. The economic value of the volume of water used for irrigation (D_{dt}^{IR} in cubic meters (cm)/month) is defined by a non-linear inverse demand equation for each individual riparian country at each demand district, d, and month, t. It is the integral of the inverse demand function that maximizes welfare based on economic surplus, similar to the specification used in Fisher and Huber-Lee (2005). A more detailed specification of the demand equation can be found in the online Appendix, part 1, available at http://journals.cambridge.org/EDE. For hydropower, the economic surplus can be captured using the net benefit of producing hydropower calculated by the product of the amount of electricity produced (in kilowatt hour kWh_{dt}) and its unit net price (P_d^{HP}in \$/kWh). This formulation is also widely used in several basin-based hydropower research works (Wu, 2000; Aytemiz, 2001; Fisher and Huber-Lee, 2005). The objective function is specified as

$$Max\ G = \frac{\sum_d \sum_t \beta \left(D_{dt}^{IR}\right)^{(\alpha+1)}}{(\alpha+1)} + \sum_d \sum_t P_d^{HP}(kWh_{dt}), \tag{1}$$

where $\alpha < 0$; $\beta > 0$; β is a coefficient of the inverse demand function; α is an exponent of the inverse demand function standing for demand elasticity; and subject to the following four major constraints.

First is the irrigation water demand constraint that in turn depends on irrigation water used, based on crop water requirement (CWR) in each district (CWR_d in cm/ha/year), amount of land for irrigation (L_d in ha), intensity of land use (μ_d)

$$D_{dt}^{IR} = CWR_d L_d \mu_d; \tag{2}$$

on the maximum irrigated land (L_d^{MAX}) that ensures intrabasin-water allocation

$$L_d \leq L_d^{MAX}; \tag{3}$$

and on a bound on irrigation water demand contained through the maximum price, (P^{MAX} in \$/cm),

$$D_{dt}^{IR} \geq \left(\frac{P^{MAX}}{\beta}\right)^{\frac{1}{(\alpha+1)}}. \tag{4}$$

Second is the hydropower water demand constraint that can be formulated using hydropower produced (kWh_{dt}) based on a conversion factor for generating hydropower (ρ), the volume of water (D_{dt}^{HP}), the structural height of the dam (H_d, in meters), the technical efficiency of the power plant (η)

$$kWh_{dt} = \rho D_{dt}^{HP} H_d \eta; \tag{5}$$

and assuming the maximum hydropower-producing potential (kWh_{dt}^{MAX}) given as

$$kWh_{dt} \leq kWh_{dt}^{MAX}. \tag{6}$$

Third is the water mass balance constraint across the many nodes that depends on the Nile River flow along the various dams and water-use districts, as shown in figure A1 in the online appendix. This condition can be formulated based on the volume of water available for the next month at the reservoir ($R_{d,t+1}$ in cm) which in turn depends on the volume of water available for the current month at the given reservoir, (R_{dt} in cm), after accounting for the reservoir's evaporation loss (γ_{dt}^{R} in per cent), the volume of water inflow to a reservoir (WI_{dt} in cm/month) and outflow to the next reservoir (WO_{dt} in cm/month), for irrigation (D_{dt}^{IR}) and for hydropower (D_{dt}^{IR}) water demand are expressed as

$$R_{d,t+1} = \left(1 - \gamma_{dt}^{R}\right) R_{dt} + WI_{dt} - D_{dt}^{IR} - D_{dt}^{HP} - WO_{dt}; \tag{7}$$

an additional water-water balance constraint that is based on the minimum (R_{dt}^{MIN}) and maximum (R_{dt}^{MIN}) reservoir capacity

$$R_{dt}^{MIN} \leq R_{dt} \leq R_{dt}^{MAX}; \tag{8}$$

and on a water flow continuity equation along the water stream measured in each of the districts where volume of water inflow to a current reservoir (WI_{dt}) is a function of the volume of water inflow from previous reservoir ($WI_{d-1,t}$) and a fraction of return flow from previous irrigation (r^{IR}) and hydropower (r^{HP}) demand districts and expressed as

$$WI_{dt} = WO_{d-1,t} + r^{IR}\left(D_{d-1,t}^{IR}\right) + r^{HP}\left(D_{d-1,t}^{HP}\right). \tag{9}$$

We assume that 80 per cent of water used to produce hydropower returns to the basin stream ($r^{HP} = 0.8$); except in Egypt, irrigation is assumed to utilize 80 per cent of water going to the tunnel ($r^{IR} = 0.2$) (Hutson, 2004). And finally, it is subject to allocation constraints which will be discussed in section 4.

3. Data and parameters

The United Nations Food and Agricultural Organization (FAO, 1997, 2011; Allen *et al.*, 1998) and the World Bank Development Indicator Database (World Bank, 2009) are the main sources of agricultural (including crop water requirement, area coverage, potential irrigated land, intensity of land use), hydrological and economic data. The Global Runoff

Data Center (GRDC) provides the Nile River flow data at various stream gauging stations (GRDC, 2010). Kirby *et al.* (2010) furnished additional Nile River flow, its seasonal variability, evapotranspiration and current Nile River water use. The Global Energy Observatory is the main source for hydropower data (for capacity, dam characteristics, technical efficiency and reservoir volume; GEO, 2010). Block and Strzepek (2010) provided information about proposed future and current projects in Ethiopia, Sudan and Egypt.

Martinez-Espineira and Nauges (2004) reviewed some research results and found that the elasticity value ranges from −0.1 to −0.3. Schoengold *et al.* (2006) found that the direct own-price elasticity of water for irrigation in California ranges from −0.18 to −0.42. The price elasticity of irrigation water demand in Egypt was estimated at −0.2 (He *et al.*, 2006). Following Fisher and Huber-Lee (2005), who suggest using low-elasticity values for water use in the Middle East, we use −0.2 for the price elasticity of irrigation water demand in all countries.

Similar to Kahsay *et al.* (2015), who modeled GERD, riparian countries do not engage in hydropower trade, and hence transmission loss is not accounted for. It is important to note that there is an effort by NBI to construct a hydropower grid and to establish a regional power market (Kloos *et al.*, 2010; NBI, 2015). Unlike Wu (2000), we use different energy prices for the three countries in the region; US$0.06 per kWh for Ethiopia and US$0.055 per kWh for Sudan are taken from World Bank (2007). For Egypt, US$0.08 per kWh is adapted from the Egyptian Electricity Holding Company (EEHC, 2009).

The detailed specification and construction characteristic of GERD can be found in the Government of Ethiopia (GOE, 2014) and the contractor's website (Salini Impregilo, 2014). The construction started in 2011, along the Blue Nile River in Ethiopia near the Sudanese border. It is expected to have a storage capacity of 60–70 bcm of water. The primary purpose of the dam is to produce around 6,000 megawatts (MW) of electricity from hydropower starting in 2017.[2]

4. Allocation constraints and water rights arrangements

These constraints are integrated into the model by balancing the total water demanded for economic activities and supplied through various water

[2] Cost elements are very important in any economic analysis, especially for cost-benefit analysis in designing and planning a project. However, in a partial equilibrium analysis the main focus is evaluating the performance of a project. We include irrigation and hydropower dams that are constructed in different time periods; for instance, Aswan High Dam in Egypt was built in the 1970s, whereas GERD is likely to be operational in 2017. Our intention is to evaluate the economic values of projects along the Nile River at a given point in time, and assess their implication for the basin water allocation and welfare system. Hence, like many of the Nile River studies cited in this paper, investment costs for these projects are assumed to be given.

allocation arrangement scenarios. The following scenarios are identified and briefly explained below.

4.1. Allocation constraints

4.1.1. Baseline allocation

Leaving the detailed hydro-politics aside, the baseline (status quo) allocation can be used as a first reference point for calibrating the economic value for the current water use scheme. It can be specified as

$$\sum_{d}\sum_{t}\big|_{Su}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \le .25\left(\sum\nolimits_{t|AHD} S_t\right) \tag{10}$$
$$\sum_{d}\sum_{t}\big|_{Eg}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \le .75\left(\sum\nolimits_{t|AHD} S_t\right),$$

where Su and Eg stand for Sudan and Egypt, respectively, and Ev_{dt} is evaporation losses (cm/month). The fraction value on the right-hand side of the equation indicates the share for each country from the volume of water that reaches the Aswan High Dam (AHD) on the border between Sudan and Egypt, $\sum_{t|AHD} S_t$, as specified in the 1959 bilateral agreement (Whittington *et al.*, 1995).

4.1.2. Unilateral use arrangement

This arrangement literally means that a country uses the Nile River according to its natural flow without considering its immediate or distant neighbors. The situation is a prevalent strategy pursued by riparian countries because of the lack of a basin-wide water allocation treaty (Wu and Whittington, 2006; Cascão, 2009). The model is designed to address a unilateral-use arrangement based on the following specifications.

$$\sum_{d}\sum_{t}\big|_{Et}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \le \sum_{k}\sum_{t}\big|_{Et} S_{kt}$$
$$\sum_{d}\sum_{t}\big|_{Su}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \le \sum_{k}\sum_{t}\big|_{Su} S_{kt} \tag{11}$$
$$\sum_{d}\sum_{t}\big|_{Eg}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \le \sum_{k}\sum_{t}\big|_{Eg} S_{kt},$$

where Et stands for Ethiopia; k is Nile River tributaries; S_{kt} is total volume of water supplied (cm/month); $\sum_k \sum_t |_{Et} S_{kt}$ is total volume of water supplied to Ethiopia from Nile River tributaries, namely Atbara, Blue Nile and Sobat (cm/month); $\sum_k \sum_t |_{Su} S_{kt}$ is total volume of water supplied to Sudan from the White Nile, and the Atbara, Blue Nile and Sobat subbasin after water is diverted in Ethiopia (cm/month); and $\sum_k \sum_t |_{Eg} S_{kt}$ is total volume of water supplied to Egypt after water is diverted in Sudan (cm/month).

This arrangement is sometimes supported by upstream riparian countries, such as Ethiopia, that claim the adoption of 'absolute territorial sovereignty' water rights in managing transboundary rivers

(Dinar and Wolf, 1994). A similar approach was adopted by Turkey, the upstream riparian, to the Euphrates-Tigris river in its discussion with Syria and Iraq (Kibaroglu and Ünver, 2000).

In this, and all the remaining scenarios, we will analyze two independent situations: with GERD and without GERD. For the former scenario, we estimate water allocation and the resulting economic benefits for each country and the region once GERD becomes fully operational. The latter scenario excludes GERD but assumes that Ethiopia would decide to implement the irrigation project along the Sobat tributary specified by Wu and Whittington (2006) and Block and Strzepek (2010).

4.1.3. Social planner's (efficient) allocation

The social planner is intended to provide an efficient allocation of Nile River water. It means, in theory, that any other allocation could lead to a welfare value that is inferior to the social planner's outcome. Consequently, efficiency from the social planner's outcome can be used as a yardstick by which the performance of other allocation schemes can be evaluated. In this scenario, Nile water that generates the maximum economic benefit is allocated optimally for economic activities regardless of where they are located within the territories of the three riparian countries.

This scenario can be formalized using

$$\sum_{d}\sum_{t}(D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) \leq \sum_{k}\sum_{t} S_{kt}. \tag{12}$$

In the case of a common-pool resource that crosses international boundaries and sovereign nations, efficiency alone cannot stand as the primary objective for allocating resources. Moreover, protecting the natural resource base in the basin may not be the responsibility of one or another country. Therefore, an intrabasin 'allocate-and-trade', or allocation with property rights and trade, is introduced both to attain efficiency and to maintain environmental sustainability.

4.1.4. Allocation with property rights and trade

This scenario introduces an intrabasin water-trade mechanism (henceforth 'trade') that attaches a positive price to each unit of water traded among riparian countries, by applying the equimarginal principle. It helps identify the condition under which water is transferred to a riparian country with a higher marginal benefit. At the same time, a buyer riparian country is willing to compensate a seller riparian country that has a lower shadow value of water.

Under the water-trading scenario, riparian countries trade excess demand, ED_{dt}, using a price, P^{w}, that can be identified through the marginal product of the water-abundant country and the shadow value of the water-scarce country identified from the optimization equation.

Here, we used a modified version of (1) shown below:

$$MaxG = \frac{\sum_d \sum_t \beta \left(D_{dt}^{IR}\right)^{(\alpha+1)}}{(\alpha+1)} + \sum_d \sum_t P_d^{HP}(kWh_{dt}) + P^w \sum_d \sum_t ED_{dt}. \tag{13}$$

Along with the initial WRA, $\overline{W}^i$, the excess demand and the related constraint can be further specified as

$$\sum_d \sum_t |_i ED_{dt} = \sum_d \sum_t |_i (D_{dt}^{IR} + D_{dt}^{HP} + Ev_{dt}) - \sum_i \overline{W}^i, \tag{14}$$

with the following additional condition for supply constraint:

$$\sum_i \overline{W}^i \leq \sum_k \sum_t S_{kt}, \tag{15}$$

where country $i = Et$, Su and Eg.

4.1.5. Internalizing the externality

The prevailing resource degradation problem of about 525 million cm of topsoil erosion in Ethiopia hinders the region's capacity to sustain both ecological life and economic activity Arsano and Tamrat (2005). The threat of environmental damage in the basin is significantly degrading even the existing freshwater supplies (Elhance, 1999). Hence, managing eastern Nile River water without dealing with the resource degradation problem may worsen the existing water-scarcity challenges facing these nations. In addition to attaining a significant portion of water efficiency, water trade could also be used as a best alternative to address the problem of the externality. When water trade is introduced along with WRA, internalizing the externality becomes a cost-effective intervention that could save cost compared to the regulation or command-and-control policy (Hansjurgens, 2005; Olmstead and Stavins, 2008).[3]

In order to deal with this resource degradation problem, (1) is modified in the following way:

$$\begin{aligned} MaxG = {} & \frac{\sum_d \sum_t \beta \left(D_{dt}^{IR}\right)^{(\alpha+1)}}{(\alpha+1)} + \sum_d \sum_t P_d^{HP}(kWh_{dt}) + P^w \sum_d \sum_t ED_{dt} \\ & - c \sum_d \sum_t \left[D_{dt}^{IR} + D_{dt}^{HP}\right], \end{aligned} \tag{16}$$

where c is the average cost of the resource degradation in the ENRB (which is around US\$0.009/cm of Nile water) estimated in Nigatu (2012).

[3] Nigatu (2012) provides detailed theoretical formulations and proofs for achieving efficiency, equity and sustainability in a river basin setting.

Table 1. *Proposed WRA of the Nile River water among Eastern Nile Basin riparian countries*

	WRA					
	I	*II*	*III*	*I*	*II*	*III*
ENRB riparian	*% share*			*(bcm)*		
Ethiopia	12.2	38.4	50	12.0	37.8	49.2
Sudan	22	14.1	12.5	21.7	13.9	12.3
Egypt	65.8	47.5	37.5	64.8	46.8	37.0
Total	100	100	100	98.5	98.5	98.5

4.2. Water rights arrangements (WRA)

Economic theory requires that a precondition for any traded good is well-specified property right systems, and that property right systems be modified in the direction required to take account of economic effects created by trade (Demsetz, 1967). Especially in a common-pool resource such as river water, clearly defined property rights play a vital role in addressing a number of issues, including sharing benefits (equity) and internalizing the externality (Schlager and Ostrom, 1992). Here, we propose three WRA (table 1) to initiate water trade, based on suggestions from Nile River experts, historical facts, and past and present hydro-politics in the basin.

According to Whittington *et al.* (1995), a Nile basin institution will assign 12.2 per cent of Nile water to the upstream country, Ethiopia, and 87.8 per cent to downstream riparian countries, Sudan and Egypt (identified as WRA I). The United Nations Convention's Article 5, 'equitable and reasonable utilization and participation', is the basis for formulating WRA II (UN, 1997), but the formulation is based on per capita water use using the 1960 population in the basin. This is because the major dialogues behind Nile water allocation revolve around the 1959 bilateral allocation of Nile River water between Sudan and Egypt. Based on Beaumont (2000), 50 per cent of Nile water is allocated to Ethiopia because it is the source of the Nile River, and the remaining 50 per cent is assigned to downstream riparian countries based on their historic use (WRA III). Sudan and Egypt will share 25 and 75 per cent, respectively, of the combined downstream portion according to the 1959 water-sharing agreement for WRA I and WRA III.

5. Results

The setup of the optimization model is similar to the approach used in McKinney and Savitsky (2006). The mean annual runoff of 98.5 bcm, calculated using the last 50 years of Nile River flow, is used as the main input for calibration and estimation of the various allocation scenarios (GRDC, 2010). The main choice variables are irrigation water released, land irrigated, hydropower water released, electricity generated and volume of water traded. Prices and values are expressed in 2010 US$ price level.

Table 2. *Model results and data for baseline allocation*

	Sectors	*Units*	*Riparian countries* Ethiopia	Sudan	Egypt	ENRB
Nile water use	Irrigation	bcm	1.3	15.1	50.8	67.2
	Hydropower	bcm	2.5	2.4	5.1	10.0
	Evaporation	bcm	1.5	1.8	17.9	21.2
	Total	bcm	5.3	19.3	73.9	98.5
	Share	%	5.3	19.6	75.1	100
Economic benefits	Value	billion US$	0.5	2.5	6.0	8.9
	Share	%	5.2	27.6	67.2	100
	Shadow value	US$/cm	NA	0	0.097	NA
Sectoral composition from model	Land irrigated	1,000 ha	250	2,263	4,376	6,889
	Share	%	3.6	32.9	63.5	100
	Hydropower produced	bkWh	3.2	1.7	7.8	12.7
	Share	%	24.9	13.7	61.4	100
Data	Land irrigated[a]	1,000 ha	88	1,831	3,402	5,321
	Hydropower produced[b]	bkWh	4.9	6.2	13	24.1

Notes: NA: not applicable; total can be affected by rounding off.
Sources: [a]FAO (2011); [b]IEA (2014).

5.1. Baseline allocation

One of the main purposes of estimating the baseline allocation is to calibrate the situation on the ground along with the 1959 bilateral treaty between Egypt and Sudan, as specified in equation (10), and to assess its welfare level using the specified model. The data and model results are presented in table 2. The results confirm that Egypt uses the volume of water specified in the 1959 treaty, and that Sudan uses less water than the volume assigned in this treaty. Although the treaty did not explicitly allocate water to Ethiopia, it currently uses almost 5.3 bcm of water from the Nile River. The model estimates that there are more than two and four million ha of land under irrigation in Sudan and Egypt, respectively, and that the region produces around 13 bkWh of electricity from hydropower.[4]

The economic benefit for the ENRB from the baseline allocation is US$8.9 bn. The shadow values indicate that allocating additional water to Egypt would result in increased economic benefit, *ceteris paribus*. The shadow value for additional water to Sudan is negligible. Since Ethiopia did not have an allocation through the 1959 treaty, its water use does not reflect its shadow value of using additional water. Wu and Whittington (2006) estimated US$4 bn (2000 US$ price level), for the economic benefit of this allocation using a different model setting and pricing structure. Except for hydropower production in Sudan and irrigated land in Ethiopia,

[4] The baseline allocation does not include GERD since this dam is expected to be operational by 2017.

our calibrated results using the model and the actual data are relatively similar for most variables. Since the model optimizes the current situation based on the baseline allocation and capacity, it is reasonable to expect some variations between data and our model results.

5.2. Unilateral use arrangement

We assume that riparian countries will unilaterally decide to use the Nile River water for existing as well as planned projects along the Nile River. One of the most prominent projects in this regard is GERD, which will be in operation by 2017. Even though this project is intended to use the Nile River water for generating electricity from hydropower and is considered a non-consumptive water use sector, the sheer size of the reservoir, the potential loss to evaporation and the estimated capacity to generate up to 15 bkWh of electricity can affect water allocation in the ENRB.

As shown in table 3, the welfare value for the ENRB from unilateral use with and without GERD could reach US$9.6 bn and US$9.0 bn, respectively. Both with GERD and without GERD scenarios could improve the economic benefit for the region compared with the baseline allocation. Unilateral use of Nile water among the three riparian countries with GERD would reduce the economic benefit of Sudan and Egypt as compared to without GERD allocation. This indicates that the enormous size and potential of GERD will change both the economic benefits and hydrological positions of riparian countries and it will give Ethiopia more of an advantage in using Nile water. This result is consistent with the finding in Kahsay *et al.* (2015), who modeled GERD's impact on the Blue Nile economies using a static CGE model.

As expected, Ethiopia could use a significant portion of Nile water, 24.6 per cent or 24.2 bcm, with GERD, compared to 12.6 per cent or 12.4 bcm without GERD. The economic benefit from unilateral use with GERD for Ethiopia is more than five times what the country is currently receiving from the Nile River. GERD alone will enable Ethiopia to irrigate around 500,000 ha of land and to produce 15 bkWh of electricity. On the other hand, unilateral use without GERD would increase the economic benefit of the Nile water to Sudan and Egypt. Part 2 of the online appendix provides additional information about interpreting Nile water allocation.

The shadow value of water reveals that Egypt is the only riparian country with a positive value, while Ethiopia and Sudan would have a zero shadow value for this allocation. This result is due to their geo-economic position; both countries could be able to meet their water demand through unilateral use arrangement, and more water would not provide an extra economic benefit for both riparian countries, *ceteris paribus*.[5] If Ethiopia and

[5] In this study, and in most river basin cooperation agreements and consistent with the NBI principle, the focus is on intrabasin water use; diverting water out of the designated basin or natural river flow stream is not perceived. The authors use FAO data for irrigation potential that countries could cultivate within the Nile basin. If the irrigated land were not constrained in this way, Sudan and Ethiopia could irrigate several million additional hectares, and their additional benefit from using one more unit of water would be positive.

Table 3. *Model results for unilateral use arrangement*

	Sectors	*Units*	*With GERD* Ethiopia	*With GERD* Sudan	*With GERD* Egypt	*With GERD* ENRB	*Without GERD* Ethiopia	*Without GERD* Sudan	*Without GERD* Egypt	*Without GERD* ENRB
Nile water use	Irrigation	bcm	10.8	18.4	22.0	51.2	7.5	19.5	26.4	53.4
	Hydropower	bcm	11.0	7.7	5.1	23.9	3.6	13.6	5.1	22.3
	Evaporation	bcm	2.4	2.5	18.4	23.3	1.3	2.3	19.2	22.8
	Total	bcm	24.2	28.7	45.6	98.5	12.4	35.4	50.7	98.5
	Share	%	24.6	29.1	46.3	100	12.6	36.0	51.5	100
Economic benefits	Value	billion US$	2.5	2.9	4.1	9.6	1.4	3.2	4.5	9.0
	Share	%	26.2	30.5	43.3	100	15.6	34.9	49.5	100
	Shadow value	US$/cm	0.00	0.00	0.08	NA	0.00	0.00	0.07	NA
Sectoral composition from the model	Land irrigated	1,000 ha	1,987	2,765	1,900	6,652	1,487	2,952	2,276	6,714
	Share	%	29.9	41.6	28.6	100.0	22.1	44.0	33.9	100.0
	Hydropower produced	bkWh	18.2	4.9	7.8	30.9	3.2	9.1	7.8	20.1
	Share	%	59.0	15.8	25.2	100	16.1	45.2	38.7	100

Sudan were to divert the Nile water away from the ENRB, their shadow values would be positive. Since this allocation does not take into account increasing the welfare of the ENRB, there would be no shadow value associated to the region as a whole.

5.3. Social planner's allocation

Based on maximizing ENRB's welfare, the social planner could assign 21.1 bcm of Nile water to the upstream riparian country, Ethiopia, and 77.4 bcm to the downstream riparian countries, Sudan and Egypt, with GERD, as shown in table 4. But the allocation without GERD would be 11.2 and 87.3 bcm to upstream and downstream countries, respectively. From the downstream portion of Nile water, around 80 and 20 per cent would be allocated to Egypt and Sudan, respectively. The social planner with GERD could allocate amounts of water to riparian countries similar to the suggestion by the experts working in the region (Whittington *et al.*, 1995).

For Egypt, the social planner's water allocation is higher than the unilateral-use arrangement. This is because Egypt uses Nile water more efficiently than the other riparian countries even though Ethiopia and Sudan get water ahead of Egypt due to their geographic location. The economies of scale, through accumulated experience and technological advancement, are the main sources of efficiency in Egypt. There are no economic benefits from generating hydropower in Sudan. Hence, allocating water to a sector or to a riparian country that could use the Nile water more efficiently increases the economic pie of the region. The optimization result confirms the efficiency condition of using water in a place where it could generate the highest welfare benefits for the region.

This allocation could improve the welfare of the region compared with the baseline and unilateral use. In addition to the highest welfare gain of US$10.1 bn with GERD and US$9.7 bn without GERD, the social planner's allocation results in the highest shadow value of water for the ENRB compared with other scenarios. Using optimal resource allocation, the region could cultivate around 7 million ha of land and produce around 24 bkWh of electricity with GERD. Without GERD, it is estimated to irrigate around 8 million ha of land and to produce around 11 bkWh of electricity. The social planner's economic benefits represent a significant improvement compared to the current economic values of US$8.9 bn from cultivating 6.9 million ha of land and producing 12.7 bkWh of electricity. GERD represents a comparative advantage in producing hydropower by Ethiopia. Wu and Whittington (2006) estimated around US$8 bn (2000 US$ price level) economic return from optimum allocation using a game theory setup and assuming that Ethiopia would build four dams along the Blue Nile River. On top of using different pricing structures and proposed dams in Ethiopia, the reason for the difference between our model and the Wu and Whittington (2006) results is that we maximize regional welfare by including the impact of GERD on changing the Nile River water utilization.

Since the social planner's allocation does not take into account separately increasing the welfare of an individual country, there would be no shadow

Table 4. *Model results for social planner's allocation*

			With GERD				*Without GERD*			
	Sectors	*Units*	*Ethiopia*	*Sudan*	*Egypt*	*ENRB*	*Ethiopia*	*Sudan*	*Egypt*	*ENRB*
Nile water use	Irrigation	bcm	8.8	13.3	38.2	60.4	7.5	14.9	47.7	70.1
	Hydropower	bcm	9.8	0.0	5.1	15.0	2.2	0.0	5.1	7.4
	Evaporation	bcm	2.4	1.4	19.3	23.1	1.5	2.2	17.3	21.1
	Total	bcm	21.1	14.7	62.6	98.5	11.2	17.1	70.1	98.5
	Share	%	21.5	14.9	63.6	100	11.4	17.4	71.2	100
Economic benefits	Value	billion US$	2.4	2.4	5.3	10.1	1.4	2.5	5.8	9.7
	Share	%	23.5	24.1	52.4	100	14.3	25.9	59.8	100
	Shadow value	US$/cm	NA	NA	NA	0.58	NA	NA	NA	0.52
Sectoral composition from the model	Land irrigated	1,000 ha	1,696	1,999	3,299	6,994	1,487	2,225	4,109	7,820
	Share	%	24.2	28.6	47.2	100	19.0	28.4	52.5	100
	Hydropower produced	bkWh	15.8	0.0	7.8	23.6	2.8	0.0	7.8	10.6
	Share	%	66.9	0.0	33.1	100	26.5	0.0	73.5	100

Table 5. *GERD situation, trade scenario and internalizing externality results for different WRA*

			Without GERD		*With GERD*	
	Unit	*Scenario*	*Without trade*	*With trade*	*Without trade*	*With trade*
Economic benefit	billion US$	WRA I	9.5	9.6	9.7	10.0
		WRA II	9.0	9.6	9.6	9.8
		WRA III	9.0	9.5	9.6	9.8
% of social planner's economic benefit recovered	%	WRA I	94	96	97	99
		WRA II	90	95	95	97
		WRA III	90	95	95	97
Amount of water traded	bcm	WRA I	–	2	–	9
		WRA II	–	25	–	15
		WRA III	–	39	–	18
Average price of water in trade	$/cm	WRA I	–	0.055	–	0.07
		WRA II	–	0.04	–	0.06
		WRA III	–	0.025	–	0.03
Level of abatement needed	million US$	WRA I	686	691	683	678
		WRA II	676	677	672	673
		WRA III	676	689	672	670
		Social planner	696	696	685	685

value associated with additional water to each country. In addition to estimating the optimal economic value of Nile River water, the social planner's allocation can also be used as a yardstick to evaluate the performance of intrabasin water trade. As economic theory suggests, the market could bring about a desired economic value in allocating a resource among competing sectors and agents even though market failure and the externality may hamper its performance.

5.4. Allocation with property rights and trade

The basic notion of water trade is introduced based on the type of water rights established where a country with a higher shadow value of water can get more water from a riparian country with a lower shadow value. This could be facilitated through the existing regional institution such as the NBI. The results for the three different WRA with and without the situation of GERD for both without trade and with trade scenarios are shown in table 5. These results are also compared with the corresponding social planner's results. In the case of both the without GERD situation and the trade scenario, the region's economic benefit would reach US$9–9.5 bn depending on the WRA. This amount could recover up to 94 per cent of the social planner's economic benefit. But once trade is introduced, the region's welfare could reach more than US$9.5 bn, and trade could recover more than 95 per cent of the social planner's benefits.

In the case of GERD but without trade, the region's economic benefit would reach up to US$9.7 bn, and up to 97 per cent of the social planner's economic benefit could be recovered. For both the GERD and the trade scenarios, the region's economic benefit could reach up to US$10 bn and this could recover up to 99 per cent of the social planner's results. This is the biggest amount of economic value among the GERD situation and trade scenarios, and the best possible recovery for the social planner's benefit. Hence, it is viable to claim that allocation of water under water trading also leads to a Pareto efficient outcome (with limited buyers) in additional to reaching 95–99 per cent of total benefits guaranteed by the social planner.

It is shown that the economic benefit of WRA without trade could be increased through introducing a regional intrabasin water trade. This is supported by the economic theory of managing common-pool resources. The results indicate that the region's economic benefit will be increased by up to US$500 m depending on WRA. Trade could also help recover a significant portion of the social planner's economic benefit. Even though the underlying economic theory suggests that trade could attain the optimal efficiency level, our model indicates that the time needed to transfer water from one district to the other and the evaporation loss in the reservoirs prevent the model from attaining 100 per cent of the social planner's economic benefit.[6]

5.5. Internalizing the externality

On top of reducing the economic benefit for the ENRB, the formulation in equation (15) enables us to estimate the amount of abatement investment that each country could make for reducing or eliminating resource degradation. As shown in table 5, the social planner's solution could raise more than US$680 m in protecting the resource base, the highest amount compared to any of the other allocation schemes. For all WRA, trade could provide more abatement dollars than without trade scenarios. This result is consistent with the merit of trade in resource management where trade provides sufficient abatement based on incentive and marginal returns from resource use (Hanley *et al.*, 1997). This abatement could solve unsustainable agricultural practices and deforestation, which are the leading causes of soil erosion and siltation (Longin *et al.*, 2005).

Furthermore, we found that the externality cost of GERD and the level of investment needed for abatement is less than without GERD. This supports some of the claims presented by upstream countries for the benefit of regulating and managing the Nile River water at the source. Hence, on top of producing a very significant economic benefit, the model results indicate that GERD would help reduce some of the externality cost incurred by riparian countries. The region's efficiency as well as internalizing the externality would be facilitated by the construction of GERD.

[6] Some economic losses could be incurred due to evaporation loss; they are not necessarily from receiving lower volume of water (such as in the case of Egypt for WRA I with the GERD scenario). Additional trade results for the three countries can be found in the online Appendix, part 3 and table A1.

Table 6. *Some significant changes as a result of GERD*

		Allocation scenario	
	Unit	*Unilateral*	*Social planner*
Hydropower produced using GERD	bkWh	15	14.6
The proportion of potential hydropower produced in GERD	%	100	98
Land irrigated using GERD	1,000 ha	500	211
The proportion of potential irrigation land in GERD	%	100	42
Ethiopian water use with GERD	bcm	24	21
Ethiopian water use without GERD	bcm	12	11
Total Nile water needed for GERD	bcm	12	10
The proportion of Nile water used for GERD	%	12	10

From our result, it can be inferred that implementing resource conservation and protection activities by assigning WRA alone is an inefficient approach to managing a resource. Even though establishing water rights is a necessary condition for conserving and protecting resources, other mechanisms such as trade could supplement the sufficient condition of attaining economic efficiency. This result is consistent with the economic theory and management practice of common-pool resources in which property rights play a vital role (Schlager and Ostrom, 1992).

6. Discussion

The landscape of the region as well as the Nile River flow have changed since GERD. As shown in different parts of the results, the Nile River water use and the participation of individual countries will be changed once GERD is fully operational. Most importantly, GERD will significantly increase Ethiopian non-consumptive water use from the current 5.3 to over 20 bcm and its economic benefit from the baseline value of US$0.5 bn to more than US$2.3 bn. As shown in table 6, Ethiopia may claim more than 10 bcm of additional Nile River water (more than 10 per cent of the Nile River water) for GERD depending on the various allocation scenarios. This is on top of more than 60 bcm of water that is intended to be stored in the reservoir.

GERD will enhance Ethiopian hydropower production capability. This also confirms the findings of most previous works and recommendations of experts that Ethiopia has a comparative advantage from using the Nile River water for hydropower production (Abate, 1994; Wu and Whittington, 2006). For a country where power outages are rampant and more than 76 per cent of the population lacks access to electricity, this is a meaningful additional supply of electricity that could bring a significant change in Ethiopia's electricity grid (World Bank, 2014). In addition, Ethiopia has signed agreements with Kenya, South Sudan, Sudan and Djibouti to sell electricity and is currently selling electricity to Sudan and Djibouti (Davison, 2014). It considers electricity export as an important source of its foreign exchange and as a new strategy to help its economic development process. The multiplier effect of producing cheap electricity will spur growth in other sectors of the economy and speed up economic development aside from the predominant agriculture. Hence, GERD will significantly change the Nile River water allocation among riparian countries and the economic benefit that they get from using the river resources.

Another interesting result concerning GERD is that it would be a viable project in the social planner's allocation, as shown in table 6. In general, GERD would increase the region's welfare and the shadow value of using the basin's water in an economic sector that would produce a higher return. The ecological benefit of regulating the basin's water and decreasing other externalities are also added benefits of GERD. Even though Ethiopia unilaterally decided to construct GERD, downstream countries could economically (for instance, through purchasing cheap electricity) and ecologically (for instance, through decreasing siltation and evaporation) benefit from the dam.

Since the change in government in Egypt after the Arab Spring and the secession of South Sudan from Sudan, the Nile River's asymmetry in political power has taken on a new dimension. Changes in the politics of these two downstream riparian countries and the involvement of China as a financer and a contractor of big projects (like GERD) give leverage to the upstream countries (such as Ethiopia) to undertake their own initiatives in implementing projects (Hatton, 2011). In the meantime, sticking to the old political power asymmetry and relying on the status quo for Nile River allocation could not result in stability in the region. Hence, with the reality of GERD taking shape, the basic concepts of water rights and intrabasin water trade will open a new window for future Nile River dialogue.

In a further discussion, electric power grid networks would appear to be incompatible in Africa (Sebitosi and Okou, 2010). Despite some recent progress, previous efforts regarding electricity trade in the region have faced a number of setbacks, such as lack of proper ownership, unclear and conflicting reform objectives and uncertainty of integration outcomes (Pineau, 2008). There is less experience in multinational trade in electricity in the east Nile region. Hence, before modeling electricity trade, we focus on modeling water trade that takes the natural flow and could be used to develop electricity by one nation and sold to other countries. By identifying the comparative advantages, our results can help incorporate many dimensional elements and issue linkages that help facilitate regional dialogue and strengthen cooperation among riparian countries.

7. Conclusion

The results indicate that baseline and unilateral use arrangements are suboptimal compared to the social planner, and Egypt could use Nile water more efficiently than the other countries. The social planner assigns the Nile River water for an economic sector and agent that generates the highest economic benefit to the region regardless of initial WRA. Its welfare gain is the 'first-best' economic solution, which is practically challenging to implement in the real world, but the gain helps evaluate the performance of other allocations.

As an alternative to the use and management, the proposed WRA with trade may be politically sensitive; they provide a plausible alternative to utilizing the Nile River water. It is estimated that intrabasin regional water trade could make better off those downstream riparian countries that hold a firm position on maintaining the baseline allocation. Trade could lead to an important step in the Nile dialogue that is stalled by the fear that any intervention could affect the economic benefit of the downstream riparian countries. If there is a regional or basin-wide consensus in the form of a treaty or formal negotiation among riparian countries, which adopts the prevailing realities of the region or basin, a water market will provide more cost-effective tools for resource protection than WRA alone. Such trade will compensate negatively affected countries and promote sustainable resource management practices.

The results suggest that Ethiopia could produce more electricity than its potential use once GERD is fully operational. This helps diversify its agriculture-based economy to a new frontier of selling electricity to its neighboring countries, and importing food commodities, which otherwise results in inefficient use of the region's resource.

GERD demonstrates the possibility of addressing the scarcity of food, water and energy in a developing region by exchanging water and energy, based on their marginal productivity across the basin states. This food–water–energy nexus as a package of considerations at the basin level demonstrates the likelihood for cooperation and trade (including water and electricity) in the region. It is among the feasible projects that satisfies both efficiency and sustainability conditions of the social planner's problem. Unilateral hydropower projects by upstream countries do not necessarily reduce the water available to downstream countries nor hurt their economic sectors since generating hydropower is a non-consumptive water use. Future work may address regional electricity trade and integrate issue linkages with comparative advantages to provide more insight for regional dialogue in resource management.

Finally, it is important to mention some of the limitations of the model. First, annual Nile River flow variation could change the results. Secondly, the model integrates an exogenous cost estimate for the externality and excludes the transaction cost of establishing the market for water and managing it. Finally, the model is a partial equilibrium model that includes only two economic sectors and three riparian countries of ENRB among the 11 countries which share the entire Nile River basin.

Supplementary materials and methods

The supplementary material referred to in this paper can be found online at http://journals.cambridge.org/EDE.

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