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Distributional considerations of international water resources under externality: The case of Ethiopia, Sudan and Egypt on the Blue Nile [☆],[☆☆]

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ABSTRACT

Common pool resources, such as international river basins with multiple riparian states, are hard to manage efficiently and equitably. In this paper, we suggest a methodology to assess the distributional aspects of various water allocation schemes applied to the Blue Nile in Africa. Based on previous analysis, a social planner allocation is found superior to the existing status quo in that it is inclusive, and expands the net benefit frontier of the basin. Water trade is introduced to demonstrate that such institution can alleviate the performance of existing institutions associated with the status quo and enable cooperation. Cooperative game theory concepts that address relative power of the riparian states in capturing incremental benefits from cooperation, such as the Core, the Shapley Value, and the Nash–Harsanyi (N–H) solution are compared under several scenarios, namely with and without water trade, and with and without existence of unidirectional externalities in the form of soil erosion and siltation impact. We find that the stability of Shapley and N–H benefits allocations are sensitive to the initial water rights allocation, which may explain the present caution of the basin states to be engaged in

cooperation arrangements. We also find that when a Core exists it is very small, which indicates also a fragile basis for cooperation.

1. Introduction

For many years, scholars have debated the issues of cooperative vs. non-cooperative solutions to common pool resource allocation [36]. The literature provides good examples, demonstrating that under certain conditions, cooperative solutions to common pool resource allocation problems produce a bigger payoff pie than in non-cooperation, which allows the parties (players), if they agree on the allocations, to increase their benefits from cooperation. The remaining question is whether or not the players find such allocations acceptable. Cooperative game theory literature distinguishes between games (arrangements) with non-transferrable utility (NTU), and games with transferable utility (TU) [19], which is often called by scholars in other fields "benefit sharing" [60].

One important aspect that has been neglected by many of those advocating for cooperation in common pool resource allocation problems is that even if the benefits from cooperation are significant compared with the non-cooperation state, there are reasons for the players to prefer non-cooperation. That is, players would prefer not to establish the grand coalition and rather find sub-coalitional arrangements, or even remain in the singleton (status quo) coalition stage. As suggested by Just and Netanyahu [28] for the general case, high coordination cost associated with cooperation of large number of participants, and by Gilman et al. [24], and Kempkey et al. [29] for the case of the La Plata, transaction costs embedded in the grand coalition arrangements and absence of proper institutions to secure country interests may impede cooperation.

Sharing international water has been a subject in the literature that demonstrates the dominance of cooperative behavior over non-cooperative behavior of the riparian states. On the other hand, many real-world efforts to support cooperation in international water shared basins do not yield results on the ground, which demonstrate the need for modifying cooperative arrangements. Examples include the Nile Basin Initiative (NBI) which, for more than a decade, has not moved the riparian states beyond the status quo despite of actual attempts to demonstrate to the riparian states the potential for cooperation and the significant potential of "benefit transfer" embedded in the cooperative arrangements [15,50,59].

In an early attempt to explain the reason for the rejection of a cooperative solution to an international water game, Dinar and Wolf [17,18] evaluated a possible water trade in the Nile Basin and the Jordan Basin between Egypt, Israel, and the Palestinian Authority. While the "cooperative dividend" was high and complied with stability, and individual and group rationality conditions, Egypt would reject the proposed solution because the incremental gains from cooperation do not reflect the role Egypt plays in that game [17] and based on the relative distributional gain among the other entities involved [48].

As with any other economic good, countries have the potential of allocating water to areas in which it produces the highest economic return [45]. Market-related policy instruments, if well designed and implemented, encourage economic agents to undertake conservation and protection efforts to accommodate changing patterns in society's demand [20]. 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 [49]. In a regional setting, water markets are also used to promote economic development and political stability [55], increase income and crop yield [38], and improve income distribution [45].

Water markets are designed to address a wide variety of economic and ecological issues [17,9,7,11]. For the Nile River, in particular, the potential benefits of establishing regional water markets have been considered for long time [51,58]. Whittington et al. [55] underscored that trading water rights would be the single most notable innovation that could be introduced in a new agreement on Nile water. In addition, Abate [2] proposed a high economic value of trading water among the eastern and

northern regions of the Nile. Introducing a water market and evaluating its cooperation value are, however, relatively new approaches in the Nile River Basin.

The existing literature advocating for water trade in an international basin context has focused mainly on physical feasibility [35]. In addition, environmental externalities have been given less emphasis. For example, resource degradation (e.g., soil erosion), which originates in the upstream country – Ethiopia, could affect all riparian countries through siltation of reservoirs, clogging the irrigation canals, and reducing agricultural productivity ([33], [6]).

Another complication that has not fully been addressed in the literature includes considerations of unidirectional negative externalities, such as upstream to downstream damages. Theoretically, if addressed correctly, externalities could increase the likelihood of cooperation by finding arrangements for compensation or reduction of the negative impact alongside with increasing the basin welfare value compared with no cooperation [43,14]. In a recent paper, Swain [50] introduces a new angle and challenges the cooperation prospective for the entire Nile Basin in light of the appearance and influence of China – a new political player in the region – which offers financial support for basin-unilateral water projects, hence reduces the attractiveness of a basin-wide grand coalition.

Recent studies that introduce water trade and allocation among riparians in a game setting include Ambec and Ehlers [4], Ansink and Weikard [5], Brink et al. [13], Laan and Moes [32], Houba et al. [27], and Wang [53]. Except for Houba et al [27], who applied their model to the Mekong River Basin, all other works that introduce water trade and allocation are theoretical, using stylized models of a basin. Brink et al. [13] and Laan and Moes [32] address pollution externality in a basin setting, using a stylized basin model as well.

In this paper, we refer to the Eastern Blue Nile (Blue Nile from hereafter), which faces a long-term stagnation in terms of basin-wide agreement. We introduce water trade as a mean to alleviate the performance of existing institutions associated with the status quo and to enable cooperation among Blue Nile countries sharing the resource, under conditions of soil erosion externality. The purpose of this paper is to move beyond the stage of the concept of basin-wide cooperative gains into the realm of the distributional considerations of these gains. As suggested by Dinar et al. [19], there is a major difference between NTU and TU games. This is especially correct in the field of international water in which present agreements mainly deal with allocation of the resource rather than allocation of the benefits from using the resource. The paper presents a Blue Nile Basin model that includes water trade and soil erosion aspects. The Blue Nile includes three riparian players: Ethiopia, Sudan, and Egypt. The model is used to calculate the value of the characteristic functions of various coalitional settings and to generate the values that allow the use of cooperative allocation schemes. We are aware that the Nile Basin is comprised of 11 states (as of 2011) and two main rivers, the White and the Blue Niles. The May 2010 Ethiopian-led river Nile agreement signed without Egypt and Sudan [1] suggests that the institutions to manage the Blue and the White Nile are far from being available for the states involved. Moreover, Water allocation in Sudan and Egypt is not influenced by what happens on the White Nile, but rather by what happens on the Blue Nile [61,62]. This is because the Blue Nile accounts for about 85 percent of water that reaches Sudan and Egypt [34]. Therefore, at this point in time we focus on the Blue Nile allocation issues, with a plan to extend our modeling efforts in the future to the White and Blue Nile, when data and hydrological information would be more readily available.

The basin model for the Blue Nile that is used for calculations of scenario-based values of characteristic functions of various coalitions is presented in Section 2. Then in Section 3, we develop the game theory framework applied to the Blue Nile. A detailed discussion of the various water rights allocations is provided in Section 4. In Section 5 we present the empirical calculations of the various benefit allocations to the riparians, and in Section 6 we discuss aspects of stability of the possible allocation agreements. Section 7 concludes with policy implications.

2. The Blue Nile model

We use a model developed in Nigatu and Dinar [41]. It is a non-linear optimization model, solved using the GAMS-NLP solver. In this section, we present the features of the model, including the objective function and the constraints.

The model is characterized by an objective function that includes various irrigation and hydropower district nodes in the various regions of the riparian countries. In addition, the model includes constraints of water mass balance across these nodes, reservoir capacity, irrigation requirements by crops and nodes that are affected by local climate, hydropower production requirements, and initial water right allocation constraints among the basin riparians.

The model maximizes net annual returns to all Blue Nile riparians[1]

$$Max \ G = \frac{\sum_d \sum_t \beta (D_{dt}^{IR})^{(\alpha+1)}}{\alpha+1} + \sum_d \sum_t P_d^{HP}(kWh_{dt}) - c\sum_d \sum_t \left[D_{dt}^{IR} + D_{dt}^{HP} \right] + \sum_d \sum_t P_{dt}^{ED}(ED_{dt}). \tag{1}$$

Subject to:

$$D_{dt}^{IR} \geq \left(\frac{P^{MAX}}{\beta} \right)^{1/\alpha} \tag{2}$$

$$ST_{d,t+1} = (1-\gamma_{dt}^{ST})ST_{dt} + WI_{dt} - D_{dt}^{IR} - D_{dt}^{HP} - WO_{dt} \tag{3}$$

$$ST_{dt}^{MIN} \leq ST_{dt} \leq ST_{dt}^{MAX} \tag{4}$$

$$WI_{dt} = WO_{d-1,t} + r^{IR}(D_{d-1,t}^{IR}) + r^{HP}(D_{d-1,t}^{HP}) \tag{5}$$

$$kWh_{dt} = \rho D_{dt}^{HP} H_d \eta \tag{6}$$

$$kWh_{dt} \leq kWh_{dt}^{MAX} \tag{7}$$

$$D_{dt}^{IR} = CWR_d L_d \mu_d \tag{8}$$

$$L_d \leq L_d^{MAX} \tag{9}$$

And a set of constraints that reflect the relevant Water Right Allocation (WRA) considered in the analysis:

$$\sum_d \sum_t (D_{dt}^{IR} + D_{dt}^{HP})|j \leq WRA_{kj} \ \forall k = 1, \ 2, \ 3; \ j = Et, \ Su, \ Eg \tag{10}$$

$$\sum_j WRA_{kj} \leq \overline{W}_k \ \forall k \tag{11}$$

where: d is the demand district d; t the month ($t = 1,\dots, 12$); k the water rights allocation (WRA) ($k = 1$, 2, 3); Et the Ethiopia, $Su =$ Sudan, $Eg =$ Egypt; β the coefficient of inverse demand function; α the exponent of inverse demand function for demand elasticity; η the technical efficiency of the power plant; ρ the a conversion factor for water in generating hydropower; μ_d the intensity of land use in district d; D_{dt}^{IR} the irrigation water demand (m^3 per month); L_d the amount of land for irrigation (hectare); L_d^{Max} the maximum irrigation potential land (hectare); CWR_d the crop water requirement (m^3/hectare/year); D_{dt}^{HP} the hydropower water demand (m^3 per month); kWh_{dt} the amount of electricity produced (kilowatt-hour, kWh); kWh_{dt}^{MAX} the maximum potential electricity produced (kilowatt-hour, kWh); P_d^{HP} the unit price of electricity (US\$ per kWh); H_d the structural height associated with the dam in district d (meter); ED_{dt} the excess water demand (m^3 per month); P_{dt}^{ED} the shadow price of excess demand (US\$ per m^3); P^{MAX} the maximum unit price for irrigation water (US\$ per m^3); c the average unit cost of resource degradation (US\$ per m^3); $ST_{d,t+1}$ the volume of water stored in a reservoir at the beginning of the following month (m^3); ST_{dt} the volume of water stored in a reservoir at the beginning month (m^3); ST_{dt}^{MIN} the minimum volume of water stored in a reservoir (m^3); ST_{dt}^{MAX} the maximum capacity of water stored in a reservoir (m^3); WI_{dt} the volume of water inflow to a reservoir (m^3 per month); WO_{dt} the volume of water outflow to the next reservoir (m^3 per month); $WO_{d-1,t}$ the volume of water outflow from the previous reservoir (m^3 per month); γ_{dt}^{ST} the

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[1] For the empirical analysis, some of the parameters are constant along time and across districts.

share of stored water lost due to evaporation; r^{IR} the share of return flow after water is used for irrigation; r^{HP} the share of return flow after water is used for hydropower; WRA_{kj} the Water Right Allocation scheme k to riparian j, $k=1,2,3$; $j=Et, Su, Eg$; and $\overline{W}_k$ the total Nile water considered for allocation in the kth WRA.

The first component of the right hand side (RHS) of Eq. (1) is the economic value of irrigation water, which is defined by a non-linear inverse demand equation for individual riparian countries in each demand district, d, for each month, t. It is the integral of the inverse demand function, similar to the specification used by Fisher et al. [23]. The second component of the RHS of Eq. (1) is the net benefit of producing hydropower. The price is a net benefit of selling each kWh of electricity after accounting for all costs. Unlike Wu [58], we use different selling energy prices for the three countries in the basin.[2] It is also assumed that 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 establish a regional power market [39,31]. The third component of Eq. 1 is designed to take into account the cost of resource degradation, which reduces the total economic value of the Nile basin. It can be used as a first step to inform riparian countries on the need to abate soil erosion based on the economic value of Nile water. Given the complexity of the physical relationship between water use and erosion in the Ethiopian uplands, we simplify the calculation of the overall resource degradation cost by multiplying the average unit cost of resource degradation, c, by irrigation water, D_{dt}^{IR}, and hydropower, D_{dt}^{HP}, water demands. We assume[3] that the price (marginal benefit) equals the average cost of supplying additional higher-quality water in the long-term. A detailed explanation is provided in Section 4. The last component of Eq. (1) introduces the value of water trade through identifying excess demand, ED_{dt}, and the shadow value of water at each of the water rights allocation, P_{dt}^{ED}. Depending on the type of coalition established, a country with a higher shadow value of water can get more water from a member of the coalition with a lower shadow value.

Constraint (2) addresses the irrigation water demand, which is used to estimate the consumer surplus (unless it becomes infinite); Constraint (3) is the mass balance constraint, with its bounds expressed in (4); it determines the volume of water available in the reservoir that can be used for economic activities, depending on various hydrological, climatic and institutional conditions. It must be equal to the net (of evaporation) storage in month t, ST_{dt}, plus any additional water inflow during the present month due to rainfall, runoff and previous reservoir capacity, WI_{dt}, minus diversion for irrigation, D_{dt}^{IR}, and hydropower, D_{dt}^{HP}, and outflow to the next reservoir, WO_{dt}. The reservoir bound, constraint (4), insures that water stored in the reservoir remains between the maximum storage capacity, ST_{dt}^{MAX}, and its minimum capacity, ST_{dt}^{MIN}, usually called "dead storage." Constraint (5) guarantees continuity of river flow in the basin, where the volume of water inflow to a reservoir, WI_{dt}, is the sum of outflow from the previous reservoir, $WO_{d-1,t}$, return flow, $r^{IR}(D_{d-1,t}^{IR})$ and $r^{HP}(D_{d-1,t}^{HP})$, from previous irrigation and hydropower districts, respectively. We build on McKinney and Savitsky [37] and on the assumption that agricultural-water use is consumptive whereas hydropower use is non-consumptive. In our model, we assume that 80% of hydropower and 20% of the agricultural-water use will return to the basin's system.

Hydropower production is defined by the flow of water through the turbines of the power plant, the structural height associated with the dam, H_d, and the technical efficiency of the power plant, η. In constraint (6) ρ is a conversion factor for water flow in generating hydropower.[4] Constraint (7) determines the upper bounds for capacity constraints where at any time and district, the total amount of power produced does not exceed its maximum installed capacity, kWh_{dt}^{MAX}.

The irrigation constraints help determine irrigation water demand (Constraint (8)) and irrigated land (Constraint (9)). Irrigation water demand, D_{dt}^{IR}, depends on crop water requirement, CWR_d, the amount of land available for irrigation, L_d, and intensity of land use, μ_d. The amount of irrigated land is

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[2] We use $0.06 and $0.055 per kWh of electricity for Ethiopia and Sudan, Respectively [57], and $0.08 per kWh of electricity for Egypt [21].

[3] In a case of perfect competition, equating price and marginal cost provides the first necessary condition for equilibrium allocation. Since we do not have a functional form, we estimate the average cost to reflect the marginal cost (which is feasible in the long-run).

[4] See Edwards (2003) for the standard detailed specification. We assume that all the reservoirs attain the desired height, a different approach of filling reservoir sequentially was applied by Block and Strzepek [12].

bounded by the maximum irrigation potential, L_d^{MAX}. CWR_d and μ_d, are based on FAO [22] and Allen et al. [3]. CWR_d depends on climate, crop, and soil characteristic. Intensity of land use is the frequency of land used for rainfed agriculture, which depends on the seasonal nature of rain, restricting the land use to time when the field can be planted. Hence, the total amount of irrigated land is the product of available land and intensity of land use.

Constraints (10) and (11) balance the total water demanded for the economic activities and supplied through the various water right allocations (WRA) scenarios that will be discussed and analyzed in Section 4. Further information on parameters and data used for this paper are available in Nigatu and Dinar [41].

3. The game theory framework applied to the Blue Nile

We depart from the model presented in the previous section. To further simplify, we refer to the three states – Ethiopia, Sudan, and Egypt – as rational players whose objective is to maximize their total payoff from using water either individually or jointly. We also assume that each player obeys the decisions made by the rest of the players regarding any of the coalitional arrangements made with the rest of the three basin states. The status quo that exists in the basin in the past 50 years indicates that this assumption is not too strong. We make use of possible water trade arrangements, which allow the riparian states to apply side payments.

History and scholarly research suggest that negotiations over international water can be characterized by two types of arrangements. First, states can depart from a given status quo of basin water use and allocate the shared water flow among them. Then each state remains with its allocated water property rights and tries to maximize its net benefits. A second arrangement introduces features that pertain to the Coase theorem, in which the states are allowed to trade in the water right allocations they were awarded.[5] As theory suggests, the initial allocation will always lead to trade as long as there are differences in the marginal productivity of water utilization among the riparian states. The trade institution is associated with some transaction costs that are not included in our analysis. The total basin benefits are compared to the first best – a social planner allocation – that maximizes the entire basin's benefits. Under certain conditions the basin's aggregated benefits under trade arrangement are very close to the socially efficient water allocation. [56] argue that when a fraction of the water released by one country to another is lost in transit, the efficiency condition needs to be modified to account for such losses before the released water reaches the receiving country. Therefore, it is interpreted as transit loss during trading.

3.1. Properties of the Basin Game

By assuming rationality of the players, we suggest that they are interested only in the monetary benefits from utilizing water for economic activities (in our model these activities include irrigated agriculture and hydropower production, which together account for the majority of the Nile water use in the three countries, as well as losses to evaporation). If the basin water trade game creates excess benefits compared with the status quo, there is a potential for coalitional arrangements among riparians. In the case of the Blue Nile, the three riparian states – Ethiopia (*Et*), Sudan (*Su*), and Egypt (*Eg*) – create coalitions that trade their water rights with transfer of water and proceeds from water sales, assuming similar utility levels of similar monetary values across countries. Water will be sold from one state to the other at the marginal value of product of water. The net benefits accrued to each country would then be used in the calculation of various net benefit allocation schemes, allowing for income transfers (Shapley Value,

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[5] This can be done either through negotiations or through an external agency or a basin agency. While our approach is static, we can easily suggest that the allocation is marginally time dependent, taking into account ad-hoc water situations in the basin at the beginning of the year [30].

Nash–Harsanyi solution)[6] for each of the two scenarios: (1) Trade in water rights institution only; and (2) Internalization of soil erosion externality and water trade institution. The model in Section 2 is used to calculate net benefits to coalitions of countries according to the various scenarios. The Shapley Value and the Nash–Harsanyi solution allow all coalitional permutations among the players and their results are easily interpreted in the context of the existing situation in the basin.

4. The various scenarios and their use in the analysis

We introduce two sets of scenarios as follows: first, we consider three water rights allocations (WRAs). Second we introduce, in addition to trade in water, an environmental externality in the form of soil erosion and a proposed approach for its internalization. We apply the trade and internalization of the soil erosion externality to each WRA.

4.1. Nile water allocations

We start with the initial allocations of the Nile water according to a set of water rights allocations, which are the basis for the quantitative analysis. A long-term flow of 98.5 billion cubic meters (bcm) of Nile water, taken from the Global Runoff Data Centre [25], is used for all WRAs. Nigatu and Dinar [41] identified five WRAs, of which we apply only three (keeping their enumeration) for demonstration purposes, as is discussed below.

WRA-I [55] allocates 12.2, 22.0, and 65.8 percent, respectively, to Ethiopia, Sudan, and Egypt.[7] WRA-II [52] uses an equitable water allocation based on the United Nations Convention Article 5.[8] That article suggests several factors and circumstances for equitable allocation: (a) Physical factors, (b) Social and economic needs of the watercourse states, (c) The population dependent on the watercourse in each riparian state; (d) The effects of the use or uses of the watercourses in one watercourse state on other watercourse states; (e) Existing and potential uses of the watercourse; (f) Conservation, protection, development and economy of use of the water resources of the watercourse and the costs of measures taken to that effect; and (g) The availability of alternatives, of comparable value, to a particular planned or existing use. We apply one of the factors, the population principle, to allocate the Nile water. Using the 1960 population in the 3 riparian countries an equitable allocation would be 38.4, 14.1, and 47.5 percent (37.8, 13.9 and 46.8 bcm) to Ethiopia, Sudan, and Egypt, respectively. WRA-IV [8] allocates 50.0, 12.5, and 37.5 percent, respectively, to Ethiopia, Sudan, and Egypt. Annex 1 includes a summary of the values and assumptions used for each WRA.

Each of the WRAs is justified on the basis of various legal, political, or economic theories. WRA-I is based on the notion of Egypt's long-term use patterns and on the fact that Ethiopia's share should be at least equal to Sudan's, given the irrigable potential in both countries. WRA-II is based on the notion of equitable access to a common pool resource as reflected in the 1997 Convention. And WRA-IV recognizes Ethiopia as being the source of the Blue Nile, which endows it with half of the long-term flow. The remaining flow is divided between Egypt and Sudan, taking into account their historic use [55,52,8]. A summary of the WRAs can be found in Annex 1.

4.2. Trade in water rights allocations

Once water rights are allocated to each riparian, they can trade and collect the proceeds from the water traded. The model allows both transfer of water from low marginal productivity uses/users and payment transfer back to the sellers. It is assumed that the institution to handle such trade is in place

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[6] Comparing more allocation schemes could add substance to the game theory section of the paper but not to the overall discussion of benefit distribution in the basin and the stability of possible allocation agreements. The Shapley Value and the Nash–Harsanyi solution have been commonly used in previous works where allocation issues have been the source of conflict [42].

[7] The suggested allocation includes 6.0 BCM for seepage and evaporation [55].

[8] http://untreaty.un.org/ilc/texts/instruments/english/conventions/8_3_1997.pdf.

in the form of the Nile Basin Initiative (NBI).[9] Results of benefits to individual countries in the no-trade arrangement, the coalitional net benefits from trade, and benefits to individual excluded (from trade) countries are presented in Table 1.

4.3. Soil erosion and its internalization within a water trade institution[10]

The Nile River is known to have more than 13 bcm of water per year lost annually to evaporation at the High Aswan Dam in Egypt and 525 million cubic meters of topsoil erosion in Ethiopia, respectively [6]. The soil eroded in Ethiopia ends up in Sudan and Egypt, and is considered a unidirectional externality. The damage from soil erosion is not confined only to Ethiopia, where it is considered as a lost fertility, but can be also seen in Sudan in the form of siltation of irrigation canals and reservoirs, and in Egypt in the form of siltation of the High Aswan Dam. By equating the externality cost with the amount of abatement needed to address the resource degradation, Nigatu and Dinar [41] estimated the costs of resource degradation, and the amount that riparian countries allocate to abate (internalize) the externality and to protect the resource base, which depends on their own use.

An estimation of the total cost of resource degradation (soil erosion in Ethiopia and siltation in Sudan and Egypt) in relation to agriculture is based on some previous studies, available data and informed assumptions [41]. In Ethiopia alone, the cost of soil degradation was estimated at 2–3 percent of the agricultural GDP [10]. Dividing the basin's annual economic loss due to resource degradation (0.745 billion US$) by annual eastern Nile River flow (around 80 bcm) results in the average unit cost of resource degradation, which is around $0.009 per cubic meter of Nile water ([41]: Table 1). This cost is represented by the parameter, c, in Eq. (1).

Eighty five percent of the Blue Nile water originates in the Ethiopian highlands. Soil erosion is the major cause of siltation downstream. It is blamed on existing agricultural practices, poor soil and water management policies and deforestation [34]. Hence, the estimated average unit cost of resource degradation takes into account only agricultural sector GDP loss.[11]

We calculated the net benefits from internalizing the erosion externality and allowing the water trade institution to operate in the basin. The results can be found in Table 2. Internalizing the resource degradation externality is expected to change the optimal allocation of benefits among the basin riparians, compared with allocation solutions that do not take into account that externality. A discussion of these results will be presented in Section 6.

5. The game theory allocations

We demonstrate the use of cooperative game theory solutions mainly to tell the story of possible cooperation in the Nile Basin, and under which situations it might be possible, using the Shapley Value [47] to a cooperative game in the characteristic form and the Nash–Harsanyi solution [26]. Cooperation in the Blue Nile is evaluated via water trade, in which the riparian states buy and sell water in volume and exchange payments.

The Shapley Value (Eq. 12) [47] is a unique solution concept in cooperative game theory that allocates the total surplus that is generated by the members of a coalition to each member based on each player's average contribution to all coalitions in that game. It satisfies Core conditions, namely that the cooperative allocation satisfies individual rationality – each state will be better off in the grand (basin-level) coalition compared with the status quo; group rationality – the sum of benefits to any sub-group in the grand coalition will exceed the sum these states could obtain if they were

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[9] We should emphasize that this is a very strong assumption. Transaction costs associated with managing such market could also lead to its non-functioning.

[10] The true cost of abatement may be higher than what we have estimated. One needs a damage function to estimate the exact cost of resource degradation, which we did not have. This is a limitation of our estimation.

[11] Prior to the construction of various dams along the Nile River, Sudanese and Egyptian farmers were benefiting from fertile soil brought by erosion. Currently, reservoirs, constructed in the Nile basin, block the eroded fertile soil and suffer from sediment deposition [33].

Table 1
Net benefits accrued by various coalitions in the basin under coalitional arrangements, water trade/no trade, and allocation scenarios (Billion US$ in 2010 prices).

Allocation Scenario	No trade			W. Trade: Ethiopia+Sudan $v(\{Et, Su\})$	W. Trade: Ethiopia+Egypt $v(\{Et, Eg\})$	W. Trade: Sudan+Egypt $v(\{Su, Eg\})$	W. Trade: Ethiopia+Sudan+ Egypt $v(\{Et, Su, Eg\})$
	Ethiopia $v(\{Et\})$	Sudan $v(\{Su\})$	Egypt $v(\{Eg\})$				
Social planner[a]							9.63
Trade following WRA-I	1.34	2.76	5.36	4.13 (1.45; 2.68)[b]	6.79 (1.32; 5.47)	8.15 (5.39; 2.76)	9.48 (1.34; 2.78; 5.36)
Trade following WRA-II	2.49	2.35	4.06	5.10 (2.90; 2.20)	7.09 (2.63; 4.46)	7.08 (4.29; 2.79)	9.56 (2.76; 2.44; 4.38)
Trade following WRA-IV	2.70	2.87	3.32	5.27 (2.76; 2.51)	7.30 (2.88; 4.42)	6.69 (3.67; 2.92)	9.10 (2.61; 2.31; 4.18)

[a] Social planner results assume central allocation that maximizes basin's benefits.
[b] In parenthesis are the respective payoff to each riparian in the coalition before allocation.

Table 2
Net benefits accrued by various coalitions in the basin under coalitional arrangements, water trade/no trade, abatement of erosion, and allocation scenarios (Billion US$ in 2010 prices).

Allocation Scenario	No trade			W. Trade and internaliz: Ethiopia+Sudan $v(\{Et, Su\})$	W. Trade and internaliz: Ethiopia+Egypt $v(\{Et, Eg\})$	W. Trade and internaliz: Sudan+Egypt $v(\{Su, Eg\})$	W. Trade and internaliz: Ethiopia+Sudan +Egypt $v(\{Et, Su, Eg\})$
	Ethiopia $v(\{Et\})$	Sudan $v(\{Su\})$	Egypt $v(\{Eg\})$				
Social planner[a]							9.28
Trade/abatement following WRA-I	1.29	2.62	4.83	3.94 (1.33; 2.61)[b]	5.71 (1.31; 4.40)	7.55 (5.00; 2.55)	8.77 (1.76; 2.29; 4.72)
Trade/abatement following WRA-II	2.21	2.56	3.91	4.62 (2.29; 2.33)	6.60 (2.56; 4.04)	6.80 (4.12; 2.68)	9.21 (3.10; 2.37; 3.74)
Trade/abatement following WRA-IV	1.90	2.30	4.85	3.95 (1.98; 1.97)	6.22 (2.21; 4.01)	6.76 (4.46; 2.30)	8.60 (2.53; 2.38; 3.69)

[a] Social planner results assume central allocation that maximizes basin's benefits.
[b] In parenthesis are the respective payoff to each riparian in the coalition before allocation.

cooperating in a sub-coalition; and, finally, efficiency – the additional benefits from cooperation are totally allocated to the players.

$$\theta_j = \sum_{\substack{s \subseteq S \\ j \in s}} \frac{(n-|s|)!(|s|-1)!}{n!} \cdot [v(s) - v(s - \{j\})] \ \forall j = Et, \ Su, \ Eg \tag{12}$$

where, θ_j is the Shapley allocation to state j, s is any coalition, S is the set of all possible coalitions, n is the number of players in the coalition, and $v(s)$ is the characteristic function of coalition s. The Shapley allocations for all three WRA scenarios with and without internalization of externalities are presented in Table 3.

The Nash–Harsanyi (N–H) allocation (Eq. 13) [26] maximizes the difference between the allocation to a state in the grand coalition and the value that state gets as a singleton (in the non-trade scenario). The N–H allocation satisfies two conditions only, namely individual rationality and efficiency. The N–H allocations for all three WRA scenarios with and without internalization of externalities are presented in Table 3.

$$Max \prod_{j \in s} [h_j - v(\{j\})] \quad \forall j = Et, \ Su, \ Eg \tag{13}$$

Table 3
Shapley and N–H allocations of trade benefits among the Blue Nile riparian states for the various water trade and externality situations (Billion USD in 2010 prices).

Basin institution	Shapley				N–H		
	Et	Su	Eg	In the Core?	Et	Su	Eg
WRA-I followed by trade	1.36	2.75	5.35	No	1.35	2.77	5.36
WRA-II followed by trade	2.62	2.55	4.40	No	2.71	2.57	4.28
WRA-IV followed by trade	2.77	2.55	3.79	No	2.77	2.94	3.39
WRA-I followed by trade and externality internalization	1.20	2.79	4.78	No	1.30	2.63	4.84
WRA-II followed by trade and externality internalization	2.33	2.61	4.27	Yes	2.39	2.74	4.08
WRA-IV followed by trade and externality internalization	1.75	2.22	4.63	No	No Nash Solution*		

Note: total allocation sums may not match the basin benefit due to rounding error.
   * No positive zone of incremental benefits exceeding the non-cooperation benefits.

where h_j is the N–H benefit allocation and $v(\{j\})$ is the non-cooperative (no trade) benefits to country j.

To demonstrate the set of Core equations, we use the WRA-II allocation results with trade and internalization of soil erosion. We use this WRA and the associated scenarios because it is the only set of WRA that is in the core. Results for the other sets of WRA and trade and externality scenarios can be found in Tables 1 and 2.

$v(\{Et\})=2.21$
$v(\{Su\})=2.56$
$v(\{Eg\})=3.91$
$v(\{Et, Su\})=4.62$
$v(\{Et, Eg\})=6.60$
$v(\{Su, Eg\})=6.80$
$v(\{Et, Su, Eg\})=9.21$

The first set of three equations represents the lower boundaries of the individual rationality condition. The second set of three equations represents the lower boundaries of the group rationality condition. And the last equation represents the efficiency condition, namely that all benefits are allocated.

The resulting Shapley allocation is as follows:

$\theta_{Et}=2.33$
$\theta_{Su}=2.61$
$\theta_{Eg}=4.27$
Which fulfills the Core conditions:

$\theta_{Et}=2.33 \geq v(\{Et\})=2.21$
$\theta_{Su}=2.61 \geq v(\{Su\})=2.56$
$\theta_{Eg}=4.27 \geq v(\{Eg\})=3.91$
$\theta_{Et} + \theta_{Su}=4.94 \geq v(\{Et, Su\})=4.62$
$\theta_{Su} + \theta_{Eg}=6.88 \geq v(\{Su, Eg\})=6.80$
$\theta_{Et} + \theta_{Eg}=6.60 \geq v(\{Et, Eg\})=6.60$
$\theta_{Et} + \theta_{Su} + \theta_{Eg}=v(\{Et, Su, Eg\})=9.21$

As can be seen $\theta_j \geq v(\{j\})$, $j = Et, Su, Eg$, which suggest that individual rationality was met, $\theta_{Et} + \theta_{Su} \geq v(\{Et, Su\})$; $\theta_{Et} + \theta_{Eg} \geq v(\{Et, Su\})$; and $\theta_{Su} + \theta_{Eg} \geq v(\{Su, Eg\})$, which suggests that group rationality was met for the partial coalitions between Ethiopia and Sudan, the partial coalition

between Sudan and Egypt, and the partial coalition Ethiopia and Egypt, and $\theta_{Et} + \theta_{Su} + \theta_{Eg} = 9.21$, which suggest that the efficiency allocation condition was met. Therefore, the Shapley allocation meets the Core conditions in the case of WRA-II with trade and internalization of soil erosion damages. Similar analysis can be conducted for the remaining results of the Shapley allocation in Table 3.[12] Plotting the results for WRA-II with internalization of externalities (Fig. 1) suggests that the N–H allocation is not in the Core. The results also suggest that the Core is very small. In real-world terms this means a likely unstable set of possible allocations. In other words, the potential zone of agreement is not attractive. We will discuss this finding in light of present attempts to promote basin-wide cooperation by moving from a focus only on water or benefits from water to linkage of issues other than water [43]. This aspect will be addressed in the next section, and in the conclusion and policy implications section.

The results in Tables 1 and 2 for all WRAs indicate that introducing trade-only, and trade and externality internalization produces an economically efficient solution that reaches 94–99 percent and 93–99 percent of the social planner basin-wide solution, respectively.[13] This means that institutions, such as water trade and abatement of the soil erosion are important features of a possible basin-wide agreement. The results indicate also that there is a wide range of benefit allocation among the basin states that should be acknowledged and explained. For example (Table 3), for the Shapley benefit allocation under trade-only, Ethiopia faces a range of benefits between $1.20 and $2.77 billion. Although a major variation in benefit allocation for Egypt and Sudan, it is less significant than in the case of Ethiopia. For the N–H benefit allocation Ethiopia, again, faces major variation, ranging between $1.36 and $2.77 billion. Sudan faces more or less similar benefit allocations under all three WRAs, but Egypt faces major variation, ranging from $3.39 to $5.36 billion. Clearly, the initial WRA allocation has an impact on the performance of the water market with and without internalizing the erosion externality. This is very much expected as one need to remember that due to the sequential locations of the states in the basin in our model (Ethiopia, Sudan, and Egypt), there will be positive externalities in the form of return flows to any country placed downstream to another country. Therefore, any allocation to Ethiopia, for example, will benefit Sudan and Egypt, via increased return flows from Ethiopia, with more water available for their economic activities than their initial allocation (see also Ward and Pulido-Velazquez [54] for additional discussion about the role of return flows in a basin wide context). WRAs that prefer downstream countries (e.g., WRA-I) will prevent Ethiopia from benefits related to return flows.

Scrutiny of the results in Table 3 suggests that only the WRA-II (with trade and internalization of the soil erosion externality) allocation leads to a Shapley benefit allocation that resides in the Core. A Core allocation solution is considered to be more stable than an allocation solution that is not in the Core. The Nash–Harsanyi solution follows only individual rationality and efficiency requirements. In the case of the N–H solution, the WRA-I resulted in a zone of agreement that is impossible to comply with individual rationality, because cooperation is less preferred than non-cooperation. The corresponding Shapley Value solution is of course not in the Core for WRA-I.

In the next section, we discuss the stability implications of the Shapley allocation solution that is in the Core, which can be connected to policy implications.

6. Stability considerations of the game theory allocations

We find that none of the N–H allocation solutions are in the core, and that only one scenario – WRA-II with trade and internalization of soil erosion externality – for the Shapley solution – is in the Core [46]. Our analysis of stability of the various solutions refers to only the Shapley solution that is in the Core, since by not being in the Core a solution implies to be inferior and unstable in the sense that some players will not be satisfied with it and may desert the coalition. However, being in the Core

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[12] As indicated in Table 3, all other scenarios do not yield solutions that lay in the core. We will discuss these results in Section 6.

[13] To remind the reader, a social planner allocation solution is the allocation based on treating the basin as one unit and maximizes the entire basin's benefits.
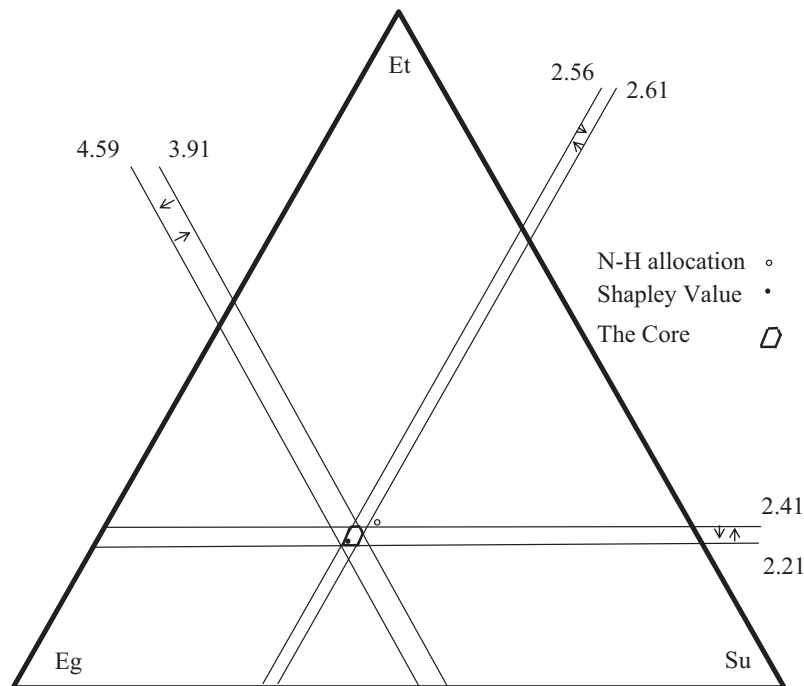
Fig. 1. Illustration of the Core and Shapley and N–H solutions in the case of WRA-II followed by trade and externality internalization.

does not guarantee that a solution is stable in the sense that players have considerations other than individual and group rationality.

As was seen in Table 3, only WRA-II with internalization of soil erosion externality yielded a Shapley benefit allocation solution that is in the Core. We apply three criteria to initiate a discussion about the stability of this allocation. The first measure is the share of the country in the grand coalition benefits; the more equal the shares are among the players, the more stable the coalition is. The second measure is the incremental gain to a country from being in the grand coalition compared with the non-cooperation benefits; the more uneven the gains across the countries, the less stable is the coalition. The third stability measure is the Loehman Power index. This measure compares the gains to a player with the gains to the coalition. If the power is distributed more or less equally among the players, then the coalition is more likely to be stable under various scenarios. The stability measure is simply the coefficient of variation calculated over all players in a given allocation solution and scenario [16]; the higher the value of the coefficient of variation, the lower the stability of the coalition. Results are presented in Table 4.

Scrutiny of Table 4 suggests that the Shapley Value and the N–H solution (of the WRA-II with internalization of the soil erosion externality) are very close in terms of the first stability measure – shares of total basin benefits that are captured by each of the riparian states. The second stability measure, the percentage gain in benefits above non-cooperation introduces a new aspect to the stability discussion. States are not only interested in their share of the basin benefits from cooperation but also in their relative gain compared with the non-cooperation stage [48]. We observe a more diverse set of results under this stability measure across the Shapley Values and the N–H solutions. We interpret the results to mean that the higher the diversity in the states' gains, the less likely this solution will be stable. States envy states [48]. It is also clear that the N–H solution is more equitable than the Shapley Value, and that the N–H solution "prefers" Ethiopia, while the Shapley Value "prefers" Egypt. The Loehman power index produces results suggesting that both N–H solution and the Shapley Value are stable at almost the same level (Standard Deviation in the range of 0.30).

The stability of the allocation agreements (for WRA-II with trade and internalization of the soil erosion externality) can also be evaluated by drawing the Core, the Shapley, and the N–H solutions. The extreme points of the Core [46] for the WRA-II with trade and internalization of soil erosion are calculated by drawing (Fig. 1) the following constraints that have to be met for any allocation, Ω, in

Table 4
Shapley and N–H benefit allocation results and stability of the coalitional solutions for the core solution (billions USD in 2010 prices).

Benefit allocation scheme	Shapley			N–H		
WRA-II followed by trade and externality internalization, benefit allocation (Billions USD)	2.33	2.61	4.27	2.39	2.74	4.08
Share in total basin benefits (%)	25	28	46	25	30	45
Gains above no cooperation (%)	5.4	1.9	9.2	8.1	7.0	4.3
Loehman Power Index	0.34			0.29		

order to be in the Core. Values for the various coalitions are taken from Table 3 (first row) for $v(\{\cdot\})$ and from Table 4 (5th row of values) for Ω_i.

$\Omega_{Et} \geq v(\{Et\})$
$\Omega_{Et} \leq v(\{Et, Su, Eg\}) - v(\{Su, Eg\})$
$\Omega_{Su} \geq v(\{Su\})$
$\Omega_{Su} \leq v(\{Et, Su, Eg\}) - v(\{Et, Eg\})$
$\Omega_{Eg} \geq v(\{Eg\})$
$\Omega_{Eg} \leq v(\{Et, Su, Eg\}) - v(\{Et, Su\})$

As can be seen from Fig. 1, the Core of the WRA-II with trade and internalization of soil erosion externality game is very small, containing the Shapley Value but not the N–H solution. The small size of the Core suggests that most of the allocation solutions would not be included in it, which indicates instability of such solutions.

7. Conclusion and policy implications

In the field of international water, present agreements deal mainly with allocation of the resource (water) rather than allocation of the benefits from using the resource. The main purpose of this paper was to address the distributional considerations of gains from cooperation, and their impact on the stability of the proposed allocation arrangements. The approach is demonstrated using the case of the Blue Nile Basin. While the negotiated issues in the Blue Nile (and the Nile as a whole) far exceed questions of water allocation only, the focus on water allocation and allocation of benefits from water use help demonstrate the point in our paper.

The introduction of a water trade institution to deal with international water conflicts is not new. However, it has not been rigorously applied in the past. Implementation of a water trade institution in an international basin, while economically and politically promising, can fail just because of the complexity of the transaction costs associated with its establishment and operation. We assumed that such complications have been taken care of through an existing basin authority. Another point that we would like to address is the assumption of states in the basin respecting the sub-coalitional arrangements; for example, a water trade arrangement between Ethiopia and Egypt will be respected by Sudan, or a water trade arrangement between Egypt and Sudan will be respected by Ethiopia. While this may look unbelievable, we rely on the example of Ethiopia "respecting" at present the water allocation of the 1959 Nile agreement between Egypt and Sudan, despite the fact that Ethiopia is the source of nearly 85 percent of the Nile water.

The results from our analysis clearly suggest that the proposed initial water rights allocations have a significant effect on the total benefits in the basin. This may look controversial as the Coase Theorem suggests that no matter what the initial allocation may be, the final optimal solution will always be the same. However, the Coase Theorem does assume that all externalities and/or transaction costs are accounted for. In the case of the Blue Nile, the sequence of the states'

Table A1
Summary of the sources, values and assumptions used in the calculation of the WRAs.

WRA	Source	Assumptions	% Allocation		
			Et	*Su*	*Eg*
WRA-I	[55]	6.0 BCM for evaporation. Based on Egypt's long-term use patterns and on the fact that Ethiopia's share should be close to Sudan's.	12.2	22.0	65.8
WRA-II	[52]: Article 5	Assuming equitable access to a common pool resource on a per capita basis, Using 1960 population figures.	38.4	14.1	47.5
WRA-IV	[8]	Recognizes Ethiopia as being the source of the Blue Nile, which endows it with half of the long-term flow. The remaining flow is divided between Egypt and Sudan, taking into account their historic use.	50.0	12.5	37.5

Annual Nile water available for allocation and evaporation is 98.5 BCM.

geographical positioning would affect the return flow use in a water trade institution. One possible explanation for the differences in total basin benefits follows: If the WRA is such that more water is allocated to Ethiopia, then Sudan and Egypt will benefit from return flows. However, if more water is allocated to Egypt, Ethiopia will not benefit from return flows in Egypt. Our basin model includes equations that address the return flows between districts in each of the riparian states and between states.

Of all WRAs, the equitable allocation (WRA-II) is the only one that is in the Core, and only in the case of trade and internalization of the soil erosion externality. The other WRAs preferred one country over the rest, in terms of the initial allocations. The integration of the erosion externality with the water trade leads to more stable basin benefit arrangements compared with the trade-only scenario. This is a reasonable outcome, which suggests that the internalization of the externality benefits the basin as a whole, including the 'victims' and the 'polluter'. It is expected that future basin agreements will include not only water allocation for hydropower and food production, but also externality considerations, including the soil erosion from Ethiopia's highlands.

Finally, drawing the Core concept helps us realize that the benefits obtained from institutionalizing a water trade arrangement, or a water trade arrangement coupled with internalization of the soil erosion externality, does not produce sufficient incremental gains and thus results in a very small and non-stable Core. It is no surprise that of the three WRAs, only one produces an allocation solution that is in the Core, which explains the difficulty of arriving at a negotiated solution that will be stable. We conclude that if a basin-wide solution is sought (such as in the case of the Nile Basin Initiative[14] that is backed up by many donor countries) there is a need to find an issue linkage that will extend the negotiated scope beyond just water. Since our model included all water-related benefits (irrigation, hydropower, abatement of siltation), "beyond water" means literally introducing issues that are of reciprocal interest to the parties, which can create the linkage effect. The most known issue with linkage effects is a regional trade zone that is suggested in the case of the Mekong [43], and is already practiced (the Mercosur) in the case of the La Plata [44]. Additional potentially linked issues could include climate-related projects that would consist of taking advantage of one country's capacity and natural endowments to benefit other countries in exchange for water-related activities. Since the prolonged status quo in the Nile Basin does not advance the region in terms of water welfare, local policy makers could get out of the gridlock by trying such other options. The analysis in this paper suggests that indeed focusing only on the traditional ineffective set of water issues has to be abandoned.

Appendix A

See Appendix Table A1.

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[14] To learn more about the NBI basin-wide approach see NBI [40].

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