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Incentive compatibility and conflict resolution in international river basins: A case study of the Nile Basin

Xun Wu[1] and Dale Whittington[2]

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[1] Nation-states rarely go to war over water, but it is equally rare that water conflicts in an international river basin are resolved through cooperation among the riparian countries that use the shared resources. Gains from cooperation will mean little to individual riparians unless the required cooperative behaviors are incentive compatible. Cooperative game theory offers useful insights for assessing cooperative solutions for water conflicts in international river basins. Applying cooperative game theory concepts such as core, nucleolus, and Shapley value to Nile water conflicts, we examine the incentive structure of both cooperative and noncooperative strategies for different riparian countries and establish some baseline conditions for incentive-compatible cooperation in the Nile basin.

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1. Introduction

[2] It may be true that nation-states rarely go to war over water [*Beaumount*, 1994; *Wolf*, 1998], but it is equally rare that water conflicts in an international river basin are resolved through cooperation among the riparian countries that utilize the shared resources. Cooperation in international river basins has often been hindered by domestic politics, uncertainty, and high transaction costs. Ruling elites may shore up political support by exaggerating or exploiting unresolved water conflicts with neighboring riparians, whereas undertaking cooperative initiatives may give the appearance of betraying national interests [*Elhance*, 2000]. Uncertainty about future supply and demand for water makes it difficult for riparian countries to enter into the long-term commitments necessary for reaching cooperative agreements. Furthermore, the transaction costs involved in reaching cooperative solutions are often substantial, especially in basins shared by more than two riparian states. Successful negotiation of cooperative solutions requires a substantial outlay of resources over a long period, a condition rarely possible in international river basins in developing countries.

[3] As demand for water resources continues to grow, however, the prospective gains from cooperation in international river basins can no longer be overlooked. In the Nile basin, for example, the Nile water is presently used virtually in entirety by two downstream countries, Egypt and Sudan. Many upstream riparian countries have become increasingly assertive in claiming a share of the water [*Waterbury and Whittington*, 1998]. Population in these countries (e.g., Ethiopia and Uganda) is projected to double or triple in the next 50 years [*Whittington*, 2004]. Unilateral actions in water resource development will set these countries on a collision course, and commentators have already warned that armed conflicts could arise [*Homer-Dixon*, 1994]. Although we believe that the risk of water wars will turn out to be a false alarm, unresolved water conflicts can severely hamper the economic development in the basin as a whole, a dire consequence for the populations along the Nile, some of which are among the poorest in the world.

[4] By contrast, the gains from cooperation could be substantial. Significant losses to evaporation can be prevented if water is stored upstream [*Waterbury*, 1990; *Guariso and Whittington*, 1987]. There is also tremendous potential for hydropower development in upstream riparian countries [*Waterbury and Whittington*, 1998; *Waterbury*, 2002; *Swain*, 2002], which could benefit all countries in the basin. A large surplus of hydropower generated upstream (e.g., in Ethiopia and Uganda) could provide much needed energy for downstream countries to expand agricultural production and foreign exchange for upstream producers. Such electricity trades could increase flows of agricultural output from downstream states to upstream states, and thus reduce upstream countries' water requirements for domestic consumption [*Whittington et al.*, 1995].

[5] However attractive the economic gains from cooperation may seem from the perspective of the basin as a whole, individual riparian countries will remain cool to such prospects unless they can benefit by acting cooperatively. It is thus of paramount importance that the Nile riparians reach an agreement for equitable sharing of any gains from cooperation. In recent years scholars have proposed various allocation schemes based on different notions of equity in anticipation of the need for guidance in negotiations that are sure to come. For example, *Beaumount* [2000] has proposed dual allocation guidelines: 50% of the water to areas where the flow is generated, and the remaining 50% to areas of historical use, according to principles of "prior appropriation." *Van der Zaag et al.* [2002] have suggested an "equitable" allocation scheme based primarily on population.

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[1] Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore.

[2] Department of Environmental Sciences and Department of Engineering, City and Regional Planning, and Public Policy, University of North Carolina, Chapel Hill, North Carolina, USA.

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[6] Although allocation schemes thus far have tended to focus on apportionment of the Nile water itself, greater benefits from cooperation could come from nonconsumptive uses of the water, such as hydropower [*Whittington et al.*, 2005]. Allocation of the economic benefits of cooperative water utilization thus deserves greater attention. However, perhaps a more fundamental shortcoming of research to date is that incentive compatibility for cooperation has largely been ignored. Cooperation is voluntary by nature, and the glue for any sustained, voluntary cooperation among riparian countries would have to be the self-interest of each participating riparian [*Waterbury*, 1997].

[7] Two conditions are necessary for any allocation scheme to be incentive compatible. The first is individual rationality, which requires that benefits of cooperation allocated to any participating country must at least equal what that country would obtain by acting unilaterally. A critical distinction should be made here between acting unilaterally and maintaining the status quo. The status quo is often used as a convenient reference point for comparative projections of the economic benefits of cooperative behavior, but such results can be misleading. The distribution pattern created by a status quo scenario heavily favors the existing primary beneficiaries from the Nile water (Egypt and Sudan), and it tends to disregard other riparian countries' increasing capability to pursue water resource development projects independently.

[8] The second necessary condition for successful international cooperation is group rationality, which requires that the aggregate benefits allocated to any subgroup of riparian countries be at least the same as what that partial coalition could achieve on its own. Taking such partial coalitions into account may complicate analyses because individual riparian countries are then acknowledged to have many other options than either acting unilaterally or joining a grand coalition. However, that admission could actually simplify and facilitate the negotiation process. Owing to the symmetrical nature of the problem, group rationality for other countries may constrain the maximum share that a particular country can demand, essentially setting an upper limit for negotiation.

[9] Our argument in this paper is that incentive compatibility should be given more prominence in the resolution of international water conflicts in general and in the Nile basin in particular, and that cooperative game theory may offer a useful framework for identifying solutions that are incentive compatible. Three considerations arise here. First, any cooperative schemes agreed upon in some special circumstance may eventually break down if incentive compatibility conditions such as individual and group rationality are not satisfied. Second, taking incentive compatibility into account may reduce the transaction costs of conflict resolution, because it may narrow the search for potential cooperative solutions. Third, although the polities and economies of the Nile riparians are interlinked by factors beyond the economics of utilizing the Nile water [*Dinar and Alemu*, 2000; *Waterbury*, 2002; *Sadoff and Grey*, 2002; *Song and Whittington*, 2004], an analysis focusing on the economic incentives for cooperation in water use can equip leaders in these countries with a better understanding of the interaction between the economic and noneconomic factors involved.

[10] Following the pioneering work by *Rogers* [1969], cooperative game theory has been applied to international river basins in a number of studies [*Dufournaud*, 1982; *Harshadeep*, 1996; *Becker and Easter*, 1997; *Kucukmehmetoglu and Guldmann*, 2004]. Cooperative game theory offers an analytical framework in which economic gains from basin-wide cooperation, individual rationality, and group rationality can be considered jointly. By determining the "core" (an important concept in cooperative game theory) one may arrive at a set of characteristic functions that specify minimum benefits under all potential coalitions (as well as noncooperation). Cooperative game theory solution concepts such as the Shapley value and the nucleolus can serve as logical focal points where considerations of incentive compatibility and equity can be simultaneously satisfied, as they are rooted in some normative notions of fairness. Discussion below examines the incentive structure of both cooperative and noncooperative strategies for different riparian countries in the cooperative game theory framework and establishes some baseline conditions for incentive-compatible cooperation regimes for the Nile basin.

[11] We first present some of the key characteristics of Nile water conflicts and the potential for cooperation. We then apply a cooperative game theory framework for the Nile basin, using the Nile Economic Optimization Model [*Wu*, 2000]. Cooperative game theory concepts and solutions for cooperation in the Nile basin are further reported, with policy implications. Our analysis concludes with suggestions for future research.

2. Water Conflicts in the Nile Basin and Potential for Cooperation

[12] Measured at 6700 km, the Nile is the longest river in the world. Its basin is shared by 10 countries: Egypt, Sudan, Ethiopia, Uganda, Kenya, Tanzania, Burundi, Rwanda, Democratic Republic of Congo, and Eritrea (Figure 1). Few other major river systems serve so great a number of vying national interests. Yet water conflicts in the Nile basin have some characteristics in common with conflicts along other international rivers. First of all, there is a big gap between the quantity of water available in the basin and the amount of water sought by individual riparian countries for water resource development projects. For example, the government of Egypt has plans to irrigate an additional 5 million acres by 2025, which would require an additional 20 billion m^3 of water annually from the Nile. In Sudan, irrigation and hydropower projects already on the drawing board would demand an additional 12 billion m^3 of water beyond its current annual allocation under its 1959 Agreement with Egypt [*Knott and Hewitt*, 1994]. Furthermore, Ethiopia, which hitherto has used almost no water from the Nile, now has ambitious irrigation plans to meet the needs of a dramatically increasing population. If all the plans on the drawing boards were enacted, the annual water deficit in the Nile basin would probably exceed 50 billion m^3 (the commonly cited average mean annual flow as measured at Aswan is 84 billion cubic meters).

[13] The Nile water conflicts are also characterized by features unique to the Nile basin, such as downstream countries' high dependency on the water, the drastic dis-

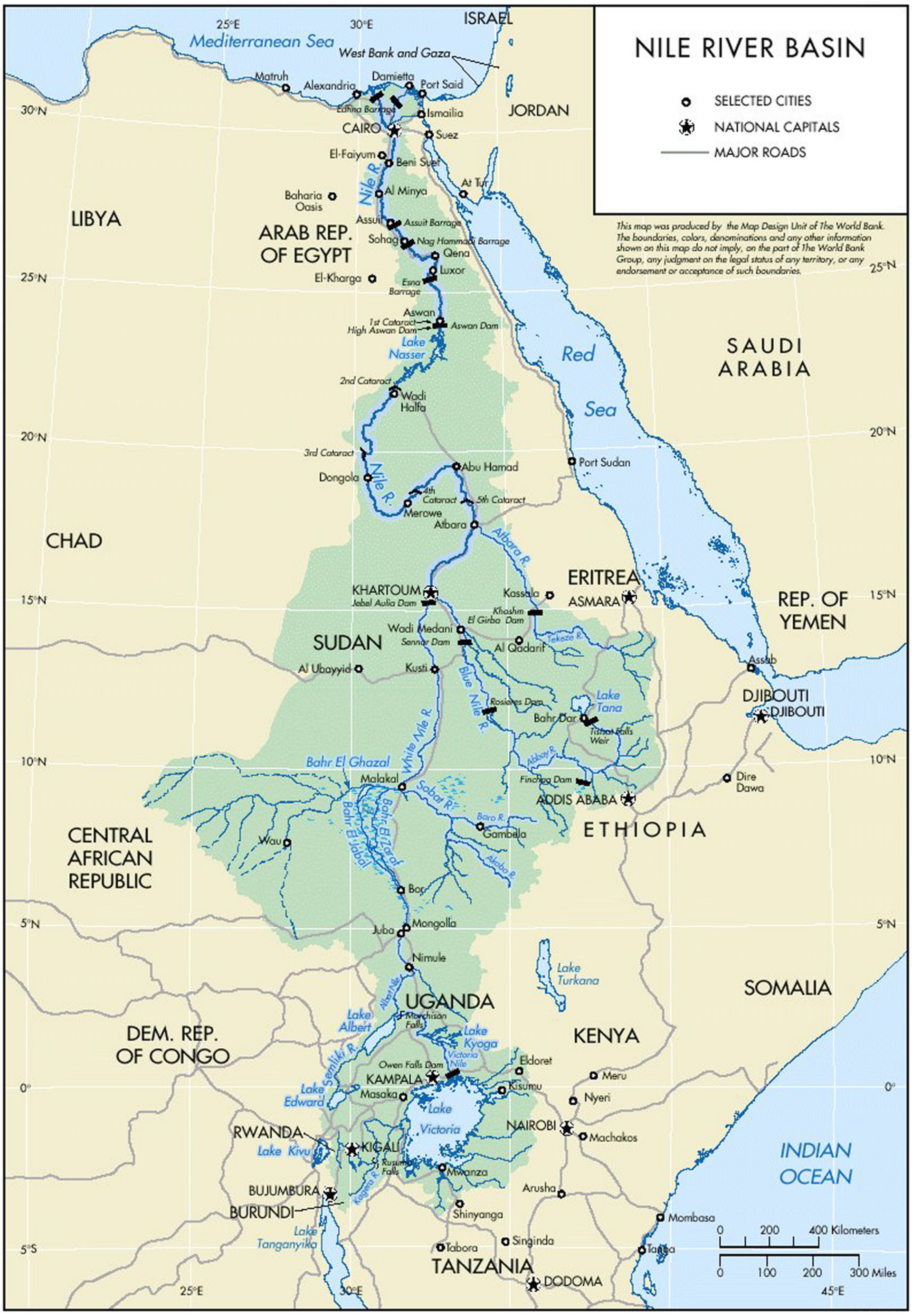

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Figure 1. Nile Basin.

juncture between contribution to and utilization of the Nile water among the chief riparian countries, and the dominance of Egypt in political and military power despite its geographical position at the end of downstream supply. Egypt contributes essentially nothing to the flow of the Nile, but it depends upon the Nile for 97% of its water supply, and currently consumes more than 80% of all Nile water. Ethiopia, in the uplands, contributes 85% of the water flow in the Nile basin yet uses almost none of that water for irrigation. Dominant in political and military power, Egypt has so far been able to guard its access to a large share of the Nile water, but upstream countries' claims to the water resources in the Nile basin can no longer be ignored, as populations in these countries are booming [*Whittington*, 2004]. *Homer-Dixon* [1994] has observed that "conflict is most probable when a downstream riparian is highly dependent on river water and is strong in comparison to upstream riparians." On the basis of such characterizations, the Nile has been considered one of the few international river systems that has the potential for breeding armed conflict among its riparian nations.

[14] Despite these sociopolitical tensions, the Nile basin offers huge prospects for water resource conservation and development. Much of the Nile water is presently lost to

Table 1. Irrigation and Hydropower Potential of Nile Basin Countries[a]

Country	Irrigation Potential, $\times 10^3$ ha	Irrigation Area, $\times 10^3$ ha	Hydropower Power Potential, MW	Hydropower Installed, MW
Burundi	185	14	1366	36
Congo	NA	11	530000	2829
Egypt	4434	3266	3210	2825
Eritrea	NA	28	NA	NA
Ethiopia	3637	190	162000	378
Kenya	352	67	30000	611
Rwanda	160	4	3000	59
Sudan	4843	1946	1900	225
Tanzania	828	190	20000	339
Uganda	202	9	10200	155

[a] Data source is African Development Bank, Policy for Integrated Water Resources Management, February 2000.

evaporation and seepage as it flows north toward the Mediterranean, but such losses can be significantly reduced. The Main Nile flows through severe desert, where net evaporation seepage losses are substantial in comparison to southern reaches of the river. If the water were stored upstream (in Ethiopia) to reduce such evaporation and seepage losses, a significant amount of additional water would become available for use. The White Nile flows through the Sudd wetlands, where half of its water is lost to evaporation. Much of that water could be conserved if a canal were built to bypass the Sudd. The Nile basin is also amply endowed with potential for hydropower generation. Table 1 suggests that hydropower development could become an avenue to economic growth for some upstream riparian countries. A study done by the U.S. Bureau of Reclamation in 1964 estimated that if implemented, hydropower projects along the Blue Nile could bring some of the best economic returns of any such facilities in the world [*Guariso and Whittington*, 1987].

[15] To realize such potentials, the Nile riparian countries must cooperate with each other. For example, Egypt has long regarded riparian development projects upstream as potential threats to its water security, on the basis of an age-old fear that upstream rivals might withhold the water in times of crisis. Such fears will not dissipate until the upstream countries can agree upon a cooperative scheme. No Nile riparian country now disputes the necessity of cooperation. Rather, the critical challenge is to identify economic incentives that will persuade all riparian countries to embrace cooperative strategies. Our goal here is to contribute to that prospect by establishing some baseline conditions for incentive-compatible cooperation.

3. Incentive Compatibility and Cooperative Game Theory

3.1. Cooperative Game Theory Framework

[16] Economic incentives for a riparian country's cooperation are first determined by its hydrostrategic position. The better that position, the less interest that country will have in reaching a cooperative agreement [*Wolf*, 1996]. Thus greater incentives will be required to guarantee its presence in negotiation or cooperation. For instance, other things being equal, Ethiopia would have to be given strong incentives to cooperate with other upstream countries, as most of the Nile water originates in Ethiopia. The second determinant for economic incentives is how well a riparian country can do if it acts unilaterally. This capability is somewhat related to hydrostrategic position, but it is also limited by the country's internal economic and financial conditions. For example, if that country does not have the financial resources to launch large-scale water resource development projects, it may occupy a weaker position in negotiations, obliged to depend on assistance from other countries or international organizations to accomplish its goals. Economic incentives are also determined by a third factor, a country's ability to form strong alliances with other countries. Greater economic incentives to cooperate must be offered to a country that can secure the bulk of its share through independent, partial coalitions with one or more neighbors. Cooperative game theory offers a framework for analyzing the relative strength of these three determinants (hydrostrategic position, noncooperative behavior, and openness to partial cooperative schemes) for the 10 riparian countries that share the Nile basin, with the aim of identifying economic incentives for cooperation that are appropriate for each.

[17] A typical cooperation game consists of three elements: (1) a set of N players, (2) a set of feasible actions associated with each possible coalition, and (3) a set of characteristic functions, one for each coalition in the game. Although there are 10 riparian countries (potential players) in the Nile basin, Including every riparian country as an independent player in the game would thus unnecessarily complicate our analysis. We instead limit our players to Egypt, Sudan, Ethiopia, and a hypothetical coalition of equatorial states. In our analysis the equatorial states' coalition is assumed to be a single, stable, decision-making entity established among its constituents.

[18] Treating the equatorial states (Uganda, Kenya, Tanzania, Burundi, Rwanda, and Democratic Republic of Congo) as a single entity is of course unrealistic. Our analysis thus represents a first step in understanding multiparty negotiations in the Nile Basin, and a more careful analysis of the likely behavior of the equatorial states is surely needed. In addition to the analytical advantages, we offer four reasons for this simplifying assumption. First, with the exception of Uganda, the saliency of Nile basin issues is much less in the equatorial states than in Egypt, Sudan, and Ethiopia. This is largely because the equatorial states receive more rainfall than other riparian countries, and have other important sources of water. Second, the equatorial states contribute less to the total flow of the Nile than Ethiopia, the other upstream state, and thus have less negotiating power. The water claims from countries such as Burundi, Rwanda, Democratic Republic of the

Table 2. List of All Coalitions

Type	Coalitions
Coalitions with one member	{Egypt}, {Sudan}, {Ethiopia}, and {equatorial states}
Coalitions with two members	{Egypt-Sudan}, {Egypt-Ethiopia}, {Egypt-equatorial states}, {Sudan-Ethiopia}, {Sudan-equatorial states}, and {Ethiopia-equatorial states}
Coalitions with three members	{Egypt-Sudan-Ethiopia}, {Egypt-Sudan-equatorial states}, {Egypt-Ethiopia-equatorial states}, and {Sudan-Ethiopia-equatorial states}
Grand coalition	{Egypt-Sudan-Ethiopia-equatorial states}

Congo, are likely to be small. Third, with the exception of hydropower and storage sites in Uganda, there are few large-scale infrastructure projects on the drawing boards of the equatorial states. Fourth, because of the high transaction costs of participating in a serious manner in international negotiations on the Nile basin, it might well make sense for the equatorial states to pool their resources and coordinate their actions.

[19] Each player in the game has three feasible actions from which to choose: to act unilaterally, to join the grand coalition that includes all players, or to make partial coalition(s) with one or more other players. A coalition is defined as any subset of players (riparian countries) that are able to make a binding agreement. The coalition of all players {Egypt-Sudan-Ethiopia-equatorial states} is termed the grand coalition. Coalitions with more than one member but fewer than the total number of players are partial coalitions: for example, {Egypt-Sudan}, {Sudan-Ethiopia}, or {Egypt-Sudan-Ethiopia}. Coalitions with only one member, such as {Egypt}, {Sudan}, {Ethiopia}, and {equatorial states}, represent a situation where a player acts unilaterally. Table 2 shows all the possible coalitions in our analysis.

[20] The characteristic function of a cooperative game specifies the extra value created by different coalitions. The characteristic function can be used to evaluate whether conditions of individual rationality and group rationality are satisfied, because unless each riparian country or partial coalition receives at least the same benefits it would have obtained on its own, it will have no incentive to participate in the grand coalition.

3.2. Partial Coalitions in the Nile Basin

[21] Riparian countries along international rivers may form partial coalitions for a variety of reasons. First, they may share the same goals. In the Nile basin, for example, neither Egypt nor Sudan contributes much to the flow of the river, but both depend heavily upon it. They have a common interest in securing their water supplies against increasing pressure to share with upstream countries. Second, riparian countries may form partial coalitions to explore mutual advantages. For example, Sudan and Ethiopia might be good partners in a coalition to develop water resources of the Blue Nile: with excellent hydropower prospects, Ethiopia could provide cheap electricity to Sudan and use the proceeds from such sales to import food for its growing population. Third, it is much easier to form partial coalitions than to achieve a grand coalition among all riparian countries. Establishing a grand coalition typically requires considerably greater political resources and expenditure of time and funds. Selected examples of partial coalitions will illustrate how these factors interplay.

3.2.1. Egypt-Sudan

[22] As noted above, an Egypt-Sudan coalition is appealing to both countries because of their similar geopolitical positions in the Nile basin: both rely heavily on the Nile water but contribute little to its sources. Forming a partial coalition would allow them to establish a unified front to deal with claims from upstream riparian countries. Such a stance is in fact clearly stated in a clause of the 1959 Agreement: "to study together [the claims of other Nile basin states] and adopt a unified view thereon." From Egypt's perspective, having Sudan on its side will definitely help to establish legitimacy for the current allocation of the Nile water because a water allocation for the partial coalition would include supplies for very poor households in Sudan, thus addressing the international community's goal of poverty alleviation. From Sudan's perspective, Egypt's strong political, economic, and military positions can help keep water supplies secure.

3.2.2. Sudan-Ethiopia

[23] Although an Egypt-Sudan coalition would increase negotiation powers for both countries in a larger coalition, that bond might not be as unshakable as Egypt would hope. Construction of more Blue Nile storage facilities (mostly in Ethiopia) would enable Sudan to expand its irrigation system more rapidly, as water stored in those locations would be delivered by gravity flow and pumping expenses would be kept to a minimum. New Blue Nile development could also better protect Sudan's existing reservoirs (Roseires, Sennar, Khashm el-Girba) from further siltation and provide flood control benefits for Sudan. In alliance with Sudan, Ethiopia might be better positioned in seeking international financing for its Blue Nile projects than if it tried to act unilaterally. Or the two countries might pool their resources to develop Blue Nile projects for joint benefits. Another important consideration for Ethiopia is that with Sudan on board, the 1959 Agreement between Egypt and Sudan, a critical barrier to any new Nile allocation scheme, might finally be sidestepped.

3.2.3. Egypt-Sudan-Ethiopia

[24] Another potential alliance is a coalition of Egypt, Sudan, and Ethiopia. Because the Blue Nile projects would not directly affect the equatorial states, all potential opposition would effectively be removed in face of this powerful three-member coalition. Blue Nile projects could be developed in full. Further benefits of such a coalition could arise from additional hydropower generation, water savings from shifting storage upstream from the Aswan High Dam to Blue Nile dams and joint management of both White and Blue Nile flows (to the extent that the White Nile can be managed by control structures in Sudan and Ethiopia). Those who believe the current alliance between Egypt and Sudan is hard to break because of

the political economy of the basin might view an Egypt-Sudan-Ethiopia coalition as a viable extension of existing powers rather than a dramatic shift. In addition, given the difficulties of achieving a grand coalition, an Egypt-Sudan-Ethiopia coalition might be an attractive alternative.

3.2.4. Egypt-Sudan-Equatorial States

[25] Although in recent years much attention has been directed toward implications of development projects along the Blue Nile, some early Nile planners believed that joint development of the White Nile and the Main Nile was the key to successful management of the basin. For example, the "century storage" scheme proposed by *Hurst et al.* [1946], called for the construction of regulatory facilities on the White Nile, the Jonglei Canal, an over-year reservoir in Lake Tana (in Ethiopia), and an additional seasonal storage reservoir on the Main Nile. The potential of an Egypt-Sudan-equatorial states coalition has certainly not escaped the notice of leaders of those countries. In 1991 four equatorial states (Tanzania, Uganda, Congo, and Rwanda), along with Egypt and Sudan, formed an intergovernmental organization called Tecconile (Technical Committee for the Promotion of the Development and Environmental Protection of the Nile Basin) to foster information exchange and joint development of the Nile basin.

[26] It is important to note that a partial coalition will have an impact on the outcome(s) of final negotiations, even if it is only potential. In many cases, the prospect or threat of alternative partial coalition(s), rather than their existence, is sufficient to influence decisions and actions by other participants. Countries able to develop multiple coalitions with different players (whether they do so or not) are often better positioned to negotiate successfully, as they can make credible threats of leaving a grand coalition or abandoning other partial coalitions.

3.3. Nile Economic Optimization Model and the Characteristic Function

[27] The Nile Economic Optimization Model (NEOM) is formulated as a nonlinear, constrained optimization problem designed to determine the annual pattern of water use that will maximize the sum of economic benefits from irrigated agriculture and hydropower generation in the Nile basin. The model includes all the existing reservoirs and irrigation schemes in the basin, as well as new reservoirs, new irrigation schemes, and other water resource development projects (see Figure 2).

[28] Specifically, we have considered five Blue Nile storage projects located in Ethiopia that were proposed by the *U.S. Bureau of Reclamation* [1964]: reservoirs (dams) in Lake Tana, Karadobi, Mabil, Mandaia, and Border (see Figure 2). These projects would not only generate large quantities of electricity for Ethiopia but also provide water savings for the whole basin, because evaporation losses at Aswan High Dam would be reduced if water were stored in upstream Blue Nile dams. Although there may be more attractive alternative multipurpose sites elsewhere in the Blue Nile basin, the potential dam projects studied by the U.S. Bureau of Reclamation, now on the drawing board for over 40 years, are all still considered viable options and have remained under active consideration by Ethiopian water resources planners.

[29] We have also considered wetland reduction ("conservation") projects in the White Nile, such as Jonglei I, Jonglei II, Machar Marshes, and Bahr el-Ghazal. Jonglei I is a canal from Jonglei to Bahr el-Zeraf to allow the White Nile flow to bypass the Sudd area, and is expected to increase downstream water supplies by 3.8 billion m^3 once completed. Jonglei II would involve excavating a parallel canal alongside Jonglei I and would increase downstream flow by an additional 3.2 billion m^3. The Machar Marshes project calls for the construction of flood embankments and a canal from Baro to the White Nile. The Bahr el-Ghazal projects involve both new embankments and channelization. These projects combined would increase downstream flows by about 4 billion m^3. We have also considered the demolition of Jebel Aulia dam, which would result in water savings of about 3 billion m^3. Also, we have further considered two storage facilities (Lake Kyoga and Lake Albert) and six power stations. Total installed capacity of these power stations has been estimated to reach 2300 MW.

[30] The mathematical formulation of NEOM can be expressed as

$$\text{Maximize} \sum_{c} \left\{ \sum_{i,c} P_w^{i,c} \sum_{t} Q_t^{i,c} + \sum_{i,c} P_e^{i,c} \sum_{t} KWH_t^{i,c} \right\}, \quad (1)$$

where $P_w^{i,c}$ represents the economic value of water for irrigation at site i for country c (in US$ per cubic meter), $Q_t^{i,c}$ represents the quantity of water withdrawal for irrigation at site i for country c in month t, $P_e^{i,c}$ is the electricity price at site i for country c (in US$ per kWh), and $KWH_t^{i,c}$ is the hydropower generated at site i for country c in month t. (Constraints to the model are explained in Appendix A.)

[31] The model uses a time increment of one month and solves for values of the decision variables S_t^i (reservoir storage), R_t^i (release for outflow), $Q_t^{i,c}$ (withdrawal for irrigation), $f(S_t^i, S_{t+1}^i)$ (average net head), and $KWH_t^{i,c}$ (electricity generated) for a single year to determine (1) the combination of monthly releases from a specified set of Nile hydropower generation facilities and (2) the monthly abstractions at specified sets of irrigation schemes that will generate the greatest annual economic benefits to the riparian countries as a whole (The NEOM does not include the costs of building new control structures, nor does it include flood control benefits). Table 3 compares the status quo with projected results for full cooperation in the Nile basin (assuming the value of water for irrigation is US$0.05 per cubic meter and value for hydropower is US$0.08 per kWh). These are not market prices for irrigation water and electricity in the Nile basin today. Rather these unit values are used for purposes of illustration; they are generally consistent with international experience in well-run irrigation schemes and power systems. These values should thus be considered illustrative of what it may be possible to achieve in irrigation and hydropower generation in the intermediate term, not an accurate characterization of status quo conditions in the Nile basin today (see *Whittington et al.* [2005] for a more detailed discussion of the sensitivity of the NEOM results to changes in assumptions about the value of water for irrigation and the value for hydropower, including differences among riparians).

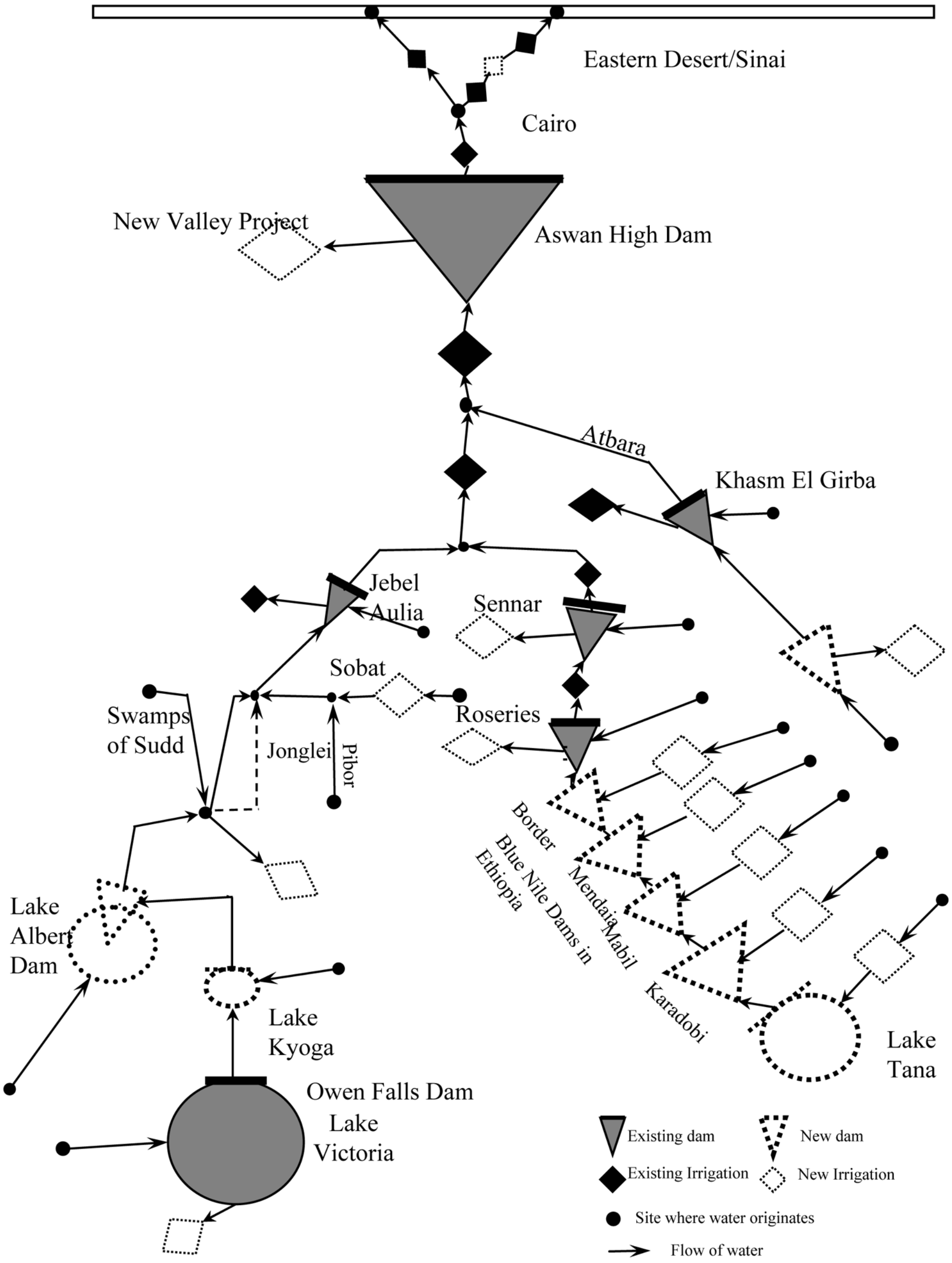

Figure 2. Nile Basin as represented in the Nile Economic Optimization Model.

[32] The NEOM formulation has numerous other limitations [*Whittington et al.*, 2005]. It does not explicitly include the economic benefits of flood control. Water quality considerations, groundwater flows, and sediment transport are not incorporated [*Falkenmark and Lannerstad*, 2005]. The NEOM is a deterministic, annual model that assumes that the managers of the system know the pattern of inflows throughout the basin over the coming year; it does not address the complexity of overyear storage issues. Most importantly, the capital costs of the infrastructure development projects are not included. Moreover, to use the NEOM to calculate the game theory results, the analyst must make assumptions about the specific infrastructure projects that (1) each country would build in the absence of cooperation, and (2) each partial coalition would build in the absence of the grand coalition.

[33] The game theory results do not incorporate the transaction costs associated with the multiparty negotiations required to achieve either partial coalitions or the grand coalition. To the extent that multilateral donors facilitate and subsidize these negotiations, ignoring such transaction costs may not affect our results greatly.

[34] Given these qualifications, the total benefits from utilizing the Nile waters cooperatively will more than double the gross benefits available under the status quo. The task of allocating these benefits is challenging because riparian countries have hitherto relied on unilateral action or partial coalitions as the dominant strategies in Nile water utilization.

[35] Taking individual rationality and group rationality into account can offer some useful insights into the allocation of benefits from cooperation. To determine how indi-

Table 3. Annual Economic Value of Nile Basin Cooperation

	Annual Economic Value, $\times 10^6$ US$	
	Status Quo	Cooperation
Egypt	3,198	3,015
Sudan	729	515
Ethiopia	50	4,311
Equatorial states	190	1,272
Total	4,180	9,112

vidual rationality and group rationality might affect the strategic choices available to the riparian countries, we modified the NEOM to derive projected economic benefits for different hypothetical coalition choices (including unilateral action). The mathematical formulation can be stated as

$$\text{Maximize} \sum_{c}^{\varphi} \left\{ \sum_{i,c} P_w^{i,c} \sum_{t} Q_t^{i,c} + \sum_{i,c} P_e^{i,c} \sum_{t} KWH_t^{i,c} \right\}, \quad (2)$$

where φ represents a particular coalition status (grand coalition, partial coalition(s), unilateral action). The objective is to maximize the sum of economic benefits for that group (or single country) instead of for the whole basin.

[36] The characteristic function of the Nile cooperation game is presented in Table 4. The first three rows correspond to the requirements of individual rationality. For example, Ethiopia will not have an incentive to participate in any cooperation unless the gross annual benefits allocated to it are at least US$600 million, the amount it would obtain by acting unilaterally. It is important to notice that although Ethiopia's annual gross benefit is only US$50 million under the status quo (Table 3), the benefits it can secure by acting unilaterally would be much larger than that. The remaining rows correspond to group rationality. The characteristic function value for each coalition indicates the minimum extra benefits to be allocated to the group of players in that coalition if they agree to participate in the grand coalition. For example, the characteristic function for an Egypt-Sudan coalition is US$274 million annually: at minimum, US$274 million would be allocated to Egypt and Sudan as a group, on top of the amounts satisfying the individual rationality for each. Otherwise Egypt and Sudan would not have the incentives to join the grand coalition.

4. Core, Incentive-Compatible Cooperation, and Negotiation

[37] The set of allocations that satisfies both individual rationality and group rationality can be represented by a cooperative game theory concept called the core. The core is a set of all benefit allocation vectors u^K, such that $\Sigma u_i \leq v(I)$ and $\Sigma(i \subseteq S)u_i \geq v(S)$, with I being the grand coalition composed of all players and S being the set of all possible coalitions except the grand coalition, while v(I) and v(S) are payoffs for the grand coalition and for other possible coalitions. In the context of international river basins, the core represents the economic incentives necessary to bring riparian countries into the cooperative scheme. The first condition, $\Sigma u_i^K \leq v(I)$, ensures that the summation of benefits for riparian countries will be less than the total benefits available for allocation (an adding-up condition). The second condition, $\Sigma(i \subseteq S)u_i^K \geq v(S)$, guarantees that each riparian country will do better by participating in the full cooperation scheme (i.e., the grand coalition) than by acting unilaterally or by forming partial coalition(s).

[38] We cannot display the sphere of the core graphically, as doing so requires four dimensions. However, we can show the boundary of the core by solving four constrained maximization problems, one for each player in our game. The objective function for the maximization problem for each player is $P(i)$,with i = Egypt, Sudan, Ethiopia, or the equatorial states. Benefits can be allocated for each specific player. Constraints are the adding-up condition and the individual rationality and group rationality conditions. The results of these maximization models are reported in Tables 5 and 6. Table 6 displays the lower and upper bounds of the benefits that can be allocated to each player and compares these values with the allocation based on full cooperation. These bounds can be viewed as delimiting the boundary of the core.

[39] The lower bounds defining the core reflect the "bottom line" for all players in negotiation: a player will have no incentive to stay with the cooperative scheme if its share from such an endeavor is less than the lower bound, and the upper bounds of the core reflect a set of maximum alloca-

Table 4. Characteristic Function of the Nile Cooperation Game

Row	Coalition	Benefits of the Coalition, $\times 10^6$ US$/yr	Characteristic Function Value of the Coalition
1	{Egypt}	1,804	V(Egypt) = 1804 (1804-0)
2	{Sudan}	1,029	V(Sudan) = 1029 (1029-0)
3	{Ethiopia}	600	V(Ethiopia) = 600 (592-0)
4	{equatorial states}	1,233	V(equatorial states) = 1233 (1233-0)
5	{Egypt-Sudan}	3,107	V(Egypt-Sudan) = 274 (3107-1804-1029)
6	{Ethiopia-Sudan}	3,131	V(Ethiopia-Sudan) = 1502 (3131-600-1029)
7	{Ethiopia-Egypt}	3,759	V(Ethiopia-Egypt) = 1355 (3759-1804-600)
8	{Egypt-equatorial states}	3,731	V(Egypt-equatorial states) = 694 (3731-1804-1233)
9	{Sudan-equatorial states}	2,990	V(Sudan-equatorial states) = 728 (2990-1029-1233)
10	{Ethiopia-equatorial states}	1,833	V(Ethiopia-equatorial states) = 0 (1833-600-1233)
11	{Egypt-Sudan-Ethiopia}	6,746	V(Egypt-Sudan-Ethiopia) = 3313 (6746-1804-1029-600)
12	{Egypt-Sudan-equatorial states}	5,509	V(Egypt-Sudan-equatorial states) = 1443 (5509-1804-1029-1233)
13	{Egypt-equatorial states-Ethiopia}	5,684	V(Egypt-equatorial states-Ethiopia) = 2047 (5684-1804-1233-600)
14	{Ethiopia-Sudan-equatorial states}	4,642	V(Ethiopia-Sudan-equatorial states) = 1780 (4642-600-1029-1233)
15	Grand coalition	9,112	V(grand coalition) = 4446 (9112-600-1804-1029-1233)

Table 5. Core of the Nile Allocation Game

	Annual Economic Value, $\times 10^6$ US$			
	Maximizing Egypt	Maximizing Sudan	Maximizing Ethiopia	Maximizing Equatorial States
Egypt	4,170	3,851	2,498	1,804
Sudan	3,109	3,428	1,778	1,339
Ethiopia	600	600	3,603	3,603
Equatorial states	1,233	1,233	1,233	2,366
Total	9,112	9,112	9,112	9,112

tions a player can possibly request while keeping all other players in the cooperative scheme. In general, the values of the lower and upper bounds represent the relative bargaining power each player has: the higher the bounds, the greater the bargaining power. For example, Sudan could command a significant premium for its participation in a cooperative scheme because it is the only player whose lower bound is higher than its benefit from acting unilaterally, highlighting its pivotal role in the search for Nile basin cooperation.

[40] Knowledge of the core can be used in several ways to assist decision makers or negotiators in dealing with water conflicts in international river basins. First, the core can be applied to describe the grounds for potential agreement among riparian countries. In the literature, such grounds are known as the negotiation set [*Luce and Raiffe*, 1957] or the contract zone [*Bacharach and Lawter*, 1981] or the bargaining arena [*Kennedy et al.*, 1980]. All too often, the parties involved may come to the table with unrealistic demands because the reasonable ranges of relevant demands are unknown to them. Establishing boundaries to negotiation through analysis of the core would expedite the search for the ultimate viable allocation scheme, thus permitting primary attention to focus on resolving key differences, rather than attempting to justify allocations that may be out of bounds (located outside the core).

[41] Second, knowledge of the core can contribute to the long-term stability of allocation schemes. For example, a particular water agreement may serve various political and/or economic purposes of the moment, but it is unlikely to be sustained if a fundamental economic rationale is absent. Boundaries identified by the core can be used as criteria for economic incentives that all proposed allocation schemes would have to meet. Until all countries' expectations regarding potential demands are located within the core, the political conditions for serious negotiation may be lacking.

[42] Third, knowledge of the core can help to gauge unilateral or group behavior and to anticipate potential moves. *Radford* [1977] has characterized negotiation as a sequence of moves in which adversaries attempt to arrive at a favorable agreement. Such moves can be communicative or structural. A communicative move informs players about the truth or falsehood of their opponents' stated preferences or intentions. A structural move is an overt action, commitment, or proposal. Because a country's bargaining power will be strengthened by its potential for forming alliance(s) with other countries, we may expect to see more communicative moves from the key players toward such goals, but such moves should not be taken at face value, Sudan may go out of its way to illustrate to Egypt and Ethiopia that it can form coalitions with the equatorial states in order to strengthen its position in negotiations on cooperative development of the Blue Nile, but such a move may benefit Sudan the least judging from its allocation when the benefits for equatorial states are maximized (Table 5).

5. Nucleolus, Shapley Value, and Fairness

[43] Whereas the core may serve to set boundaries for negotiation, other game theoretical solutions can be useful in identifying focal points for negotiation that are incentive compatible. We now describe and compute two such solutions, the nucleolus and Shapley value, and discuss their implications for exploring cooperative solutions for water allocation in the Nile basin.

5.1. Nucleolus

[44] The nucleolus in our case is the allocation that has the lexicographically smallest associated excesses. For an allocation u^K, the expression $v(S) - \sum u_i$ can be viewed as the objection raised by a coalition S against this allocation, and the calculation of the nucleolus identifies the payoff that minimizes the maximum objection for all possible coalitions, that is,

$$\mathrm{Min}\left\{\underset{S}{\mathrm{Max}}\left[v(S) - \sum_{i \in S} u_i\right]\right\}. \tag{3}$$

[45] It is of special interest to point out that the nucleolus solution is consistent with Rawls's notion of "the veil of ignorance" [*Rawls*, 1971], that is, it is the allocation that might be preferred if no player knows his or her future

Table 6. Boundary for the Core of the Nile Allocation Game

	Annual Economic Value, $\times 10^6$ US$		
Country	Lower Bound	Upper Bound	No Cooperation (All Players Act Unilaterally)
Egypt	1,804	4,107	1,804
Sudan	1,339	3,109	1,029
Ethiopia	600	3,603	600
Equatorial states	1,233	2,366	1,233

Table 7. Nucleolus of the Nile Allocation Game

	Annual Economic Value, $\times 10^6$ US$	
	Nucleolus Allocation	Per Capita Nucleolus Allocation
Egypt	3,051	2,996
Sudan	2,309	2,255
Ethiopia	1,952	2,344
Equatorial states	1,800	1,516

identity [*Loehman*, 1995]. Rawls postulates that if people are unaware of their personal interests and future identities, they might want to maximize the net benefits to be obtained from the worst possible outcome that can happen. In fact, Rawls assumes that every individual would act to ensure that, whatever course of action was taken by others, she would receive the "least worst" possible outcome. Thus the value of any possible action would depend wholly on the worst possible outcome regardless of how small its possibility. An allocation based on Rawls's theory would give absolute priority to the interests of the most disadvantaged party.

[46] Computationally, the nucleolus can be found by solving the min-max problem given above subject to the constraints of the core, which implies that the nucleolus would satisfy the conditions for both individual rationality and group rationality. Using the general algebraic modeling system (GAMS) linear programming algorithm to solve the above optimization problem, the nucleolus of this allocation game can be determined as shown in Table 7. (Because it is not easy to give a general formula to calculate the nucleolus, mathematical software with an optimization algorithm is often used for computation.)

[47] One of the critiques of the nucleolus is that it considers only the excess benefits of a coalition, not the size of the coalition (the number of players in a given coalition). The per capita nucleolus, a variant of the nucleolus, can alleviate this problem. In computing the per capita nucleolus, we replace $v(S) - \sum u_i$ with $(v(S) - \sum u_i)/r$, with r being the size of the coalition S.. Using this new formulation, we see in Table 7 that the per capita nucleolus gives more weight to Egypt and Sudan.

[48] The nucleolus can be a very useful solution when applied to international water conflicts. First, it may be an appealing option when an arbitrator is called in to decide upon the final allocation but negotiators are unsure of the arbitrator's preferences about the allocation. Second, because the nucleolus is necessarily contained in the core, it ensures the economic incentives automatically. Third, because the nucleolus (especially per capita nucleolus) tends to equalize the claims of all participants, a nucleolus solution might approximate a proposal for equalizing the excess benefits for all players.

5.2. Shapley Value

[49] Another point solution that can yield important practical implications to water conflicts is the Shapley value, which can be computed as

$$\phi_i = \sum_{S \subset N} \frac{(s-1)!(n-s)!}{n!}[v(S) - v(S-i)], \tag{4}$$

where N is any finite carrier of v. To interpret this formula, consider the players in N to be randomly ordered, with every ordering equally possible. Player i's marginal contribution to coalition S is defined as $[v(S) - v(S-i)]$, and the weight assigned to coalition S is the probability that the predecessors of player i in the random ordering, which can be computed as $(s-1)!(n-s)!/n!$. Thus the Shapley value for player i is an average of player i's marginal benefits from all coalitions, including the empty set. Note that the formula for calculating the Shapley value is not bounded by conditions such as individual rationality and group rationality.

[50] The Shapley value represents a distinctive approach to the problems of complex strategic interaction in a cooperative game framework, and it is perhaps the most useful of all cooperative game theoretical solution concepts. It provides an index of each player's strength in terms of the strength of the coalition(s) of which the player is a member, relative to those in which the player is not a member. Because it imposes equal treatment on players who make the same contribution in the game [*Tisdell and Harrison*, 1992], the Shapley value is often used as a benchmark of fairness.

[51] Although Ethiopia and the equatorial states contribute to all of the flow of the Nile basin, the significance of that contribution will be balanced by unique contributions made by downstream riparian countries. For example, we have assumed that in any coalition lacking Egypt's presence, modifications to the Jebel Aulia, as well as wetland projects in the White Nile and at least two reservoirs in the Blue Nile, will not be completed. That is, the effects of Egypt's absence from such a coalition can be used to project the magnitude of its potential contribution were it to be present in a cooperative solution. This contribution, along with the fact that Egypt is able to obtain a high level of economic benefits on its own, will entitle Egypt to a sizable share from cooperation, even though it does not contribute to the flow of the river.

[52] One of the more unrealistic aspects of the Shapley value solution in water allocation games is its assumption of symmetry. Symmetry implies that any coalition with the same number of players will have the same probability of being formed and that each player will have the same probability of joining these coalitions. However, in the context of international river basins, there are several factors that might make some coalitions easier to form than others. For example, an Egypt-Sudan coalition might be more likely to occur than coalitions such as Egypt-Ethiopia or Ethiopia-equatorial states. Specific political constraints may result in zero probability for some coalitions. In addition, the order in which players enter a particular coalition or grand coalition may matter. For example, Sudan is probably less likely to be the last player to join the grand coalition than are Ethiopia or the equatorial states. Furthermore, lack of symmetry can also arise when players have different bargaining abilities or diplomatic resources.

[53] A generalized (or weighted) Shapley value can be adopted that drops the assumption of symmetry. Thus

$$\phi_i = \sum_{S \subset N} r_i(S)[v(S) - v(S-i)], \tag{5}$$

where $r_i\,(S)$ are weights satisfying $\sum_{i \in T} \sum_{T \subset S} r_i(S) = 1$.

Table 8. Probability Weights for Shapley and Generalized Shapley Value

Egypt			Ethiopia			Sudan			Equatorial States		
(Coalition S-I)I	Shapley	Generalized Shapley	(Coalition S-I)I	Shapley	Generalized Shapley	(Coalition S-I)I	Shapley	Generalized Shapley	(Coalition S-I)I	Shapley	Generalized Shapley
(Egypt)	0.250	0.200	(Ethiopia)	0.250	0.300	(Sudan)	0.250	0.200	(equatorial states)	0.250	0.300
(Sudan)Egypt	0.083	0.100	(Egypt)Ethiopia	0.083	0.000	(Egypt)Sudan	0.083	0.200	(Egypt)equatorial states	0.083	0.000
(Ethiopia) Egypt	0.083	0.000	(Sudan) Ethiopia	0.083	0.100	(Ethiopia) Sudan	0.083	0.500	(Sudan) equatorial states	0.083	0.100
(Equatorial states) Egypt	0.083	0.000	(equatorial states) Ethiopia	0.083	0.000	(equatorial states) Sudan	0.083	0.100	(Ethiopia) equatorial states	0.083	0.000
(Sudan-Ethiopia) Egypt	0.083	0.300	(Egypt-Sudan) Ethiopia	0.083	0.100	(Egypt-Ethiopia) Sudan	0.083	0.000	(Egypt-Sudan) equatorial states	0.083	0.100
(Sudan-equatorial states) Egypt	0.083	0.300	(Sudan-equatorial states) Ethiopia	0.083	0.100	(Ethiopia-equatorial states) Sudan	0.083	0.000	(Sudan-Ethiopia) equatorial states	0.083	0.000
(Ethiopia-equatorial states) Egypt	0.083	0.000	(Egypt-equatorial states) Ethiopia	0.083	0.000	(Egypt-equatorial states) Sudan	0.083	0.000	(Egypt-Ethiopia) equatorial states	0.083	0.000
(Sudan-Ethiopia-equatorial states) Egypt	0.250	0.100	(Egypt-Sudan-equatorial states) Ethiopia	0.250	0.400	(Egypt-Ethiopia-equatorial states) Sudan	0.250	0.000	(Egypt-Sudan-Ethiopia) equatorial states	0.250	0.500

[54] An important aspect of calculating the generalized Shapley value is to determine the value of r_i for all players in various coalitions. This task can become extremely complicated, as different players (and analysts) may assign different weights to r_i on the basis of differing knowledge and belief. To illustrate such effects, we specify a scenario in which the following assumptions are implied: (1) Because Egypt and Sudan are more likely to be involved in certain kinds of coalitions, there is less chance that either will act unilaterally. (2) Either Ethiopia or the equatorial states' coalition will likely be the last to join the grand coalition. (3) There is no chance that Sudan will be the last to join the grand coalition.

[55] Table 8 gives a comparison of the probability weights between Shapley value and generalized Shapley value, for each possible coalition. In the first column the names in parentheses indicate coalition members preceding *i*. Some coalitions have been assigned zero probability. Though all potential partial coalitions may be admissible in theory, not all of them are feasible in practice, or at least not all of them have equal probability of realization. For example, coalitions such as Egypt-Ethiopia, Egypt-equatorial states, or Egypt-equatorial states-Ethiopia are likely to encounter an implementation problem, as Sudan can unilaterally disrupt these coalitions by diverting more water. The Ethiopia-equatorial states coalition may also have low probability of occurring because it does not provide much excess benefit compared with unilateral action for these two parties.

[56] Note that weights for both Egypt and Sudan decreased when Shapley value is generalized: that is, their bargaining powers decline, along with economic share (Table 9). This may seem surprising in view of the prominent treatment we have given to an Egypt-Sudan coalition. However, Ethiopia and the equatorial states, which cannot join the grand coalition until Egypt and Sudan are in (assumption 2 above), find their negotiation leverage relatively increased. This overall shift in power may arise because an Egypt-Sudan coalition will perform less well if White Nile power stations are not built, which could happen only if the equatorial states are brought into the deal. In addition, Ethiopia and the equatorial states' position as the last and marginal players may enhance their bargaining powers: a marginal player can literally hold up the grand coalition unless compensated handsomely.

5.3. An Assessment of Game Theoretical Solutions

[57] The differences we see between the Shapley value and nucleolus will have been anticipated, as the two are rooted in different normative notions of fairness. The Shapley value is more egalitarian than the nucleolus, because the nucleolus gives priority to the most dissatisfied coalition(s), whereas the Shapley value grants all coalitions equal status. The Shapley value and the nucleolus also differ in their relationship with the core. The nucleolus is derived from core-minded thinking and thus automatically belongs to the core. The Shapley value is derived from reasonable set thinking; its occurrence within the core is more by accident than by design.

[58] Some common criteria are needed to evaluate and reconcile the solutions derived from these competing notions of fairness. The first criterion we employ here is the core. As we stated earlier, the core represents the

Table 9. Shapley Value and Generalized Shapley Value

Country	Shapley Value		Generalized Shapley Value	
	Economic Value, $\times 10^6$ US$	Share, %	Economic Value, $\times 10^6$ US$	Share, %
Egypt	2,960	32	2,835	31
Sudan	2,280	25	1,900	21
Ethiopia	2,049	22	2,386	26
Equatorial states	1,823	20	1,987	22

economic incentive necessary for each riparian country to participate in cooperation. Solutions or proposals that do not fall within the core need to be revised before they can be seriously considered in negotiation or political processes. Nucleolus solutions will always fall within the bounds of the core. However, solutions based on Shapley values, which may or may not happen to fall within the core, require further scrutiny and adjustment.

[59] Our second criterion is the magnitude of the differences between these solutions and a potential focal point for the players. Given that four players are involved and that the core involves a set of complex relationships among the various players, sorting out a potential focal point becomes a formidable problem. We can simplify the task by splitting the difference for each of the four players. On the basis of maximum and minimum value for each player as shown in the core of the game (Table 6), splitting the difference would yield the allocation shown in Table 10. We may then compute the differences between this allocation and each of the solutions or proposals, to see which one(s) will be closer to this hypothetical focal point.

[60] A third useful criterion for assessing different solutions is the propensity to disrupt. Player i's propensity to disrupt is defined as the ratio of other players' loss, if i refuses to cooperate, to i's loss from refusing to cooperate. For example, in the Nile allocation game Ethiopia's propensity to disrupt can be calculated as $[P(\mathit{Egypt}) + P(\mathit{Sudan}) + v(\mathit{The\ equatorial\ states}) - v(\mathit{Egypt\text{-}Sudan\text{-}The\ equatorial\ states})]/P(\mathit{Ethiopia}) - v(\mathit{Ethiopia})$. It is clear that on this basis the higher a player's propensity to disrupt, the more negotiation power that player will have in the game.

[61] Table 11 compares nucleolus, per capita nucleolus, Shapley value, and generalized Shapley value solutions for our Nile basin cooperation game in terms of each of the three evaluative criteria we have described. All of these game theoretical solutions satisfy the requirements of the core. Thus each provides an acceptable estimation of economic incentives necessary to induce cooperative behavior. When measured against the sum of the absolute value of the differences between the four solutions analyzed and the allocations associated with the focal point, each solution differs greatly from the others, ranging from US$131 million for the Shapley value solution to US$921 million for the generalized Shapley value solution. High differences from focal point normally signal the presence of big winner(s) and big loser(s). Such solutions might face heavier resistance in implementation. In that event, the Shapley value is an appealing solution, with all values close to the focal point and relatively low prospects for disruption. If a particular country's propensity to disrupt is an issue of concern, the generalized Shapley value solution will be the least favored by Egypt and Sudan and most favored by Ethiopia and equatorial states. The per capita nucleolus solution offers Ethiopia, Sudan and Ethiopia sufficient incentives to form the grand coalition. The focal point yields equal propensity to disrupt for all riparian countries, suggesting that an equilibrium could perhaps be established in that solution.

6. Concluding Remarks

[62] A critical barrier to cooperative water utilization in international river basins is that there is no clear rule for allocating the gains from prospective cooperation among the riparian countries that participate. As a result, the economic gains from cooperation may mean very little to individual riparian countries if the economic incentives for participating in cooperative schemes are not guaranteed. In this article we have shown that game theoretical concepts and solutions can help to identify such incentive-compatible cooperative solutions for the Nile basin.

[63] Knowledge of the core of the game cannot serve to pinpoint a single solution to water conflicts, but it can establish limits that exclude allocations that should never be considered, thus narrowing the set of possible solutions. The core is based on considerations of individual rationality and group rationality. For example, an allocation scheme that grants an individual country less than it would achieve on its own cannot be counted as a viable solution. Similarly, when building a grand coalition, a partial coalition (allied subgroup) must be allocated combined benefits that exceed what its members can collectively achieve on their own. By determining and comparing such prospective benefits for the array of possible coalitions, it becomes possible to establish boundaries for determining solutions to the Nile water allocation game.

Table 10. A Hypothetical Focal Point for the Nile Water Allocation Game

	Annual Economic Value, $\times 10^6$ US$				
	Maximizing Egypt	Maximizing Sudan	Maximizing Ethiopia	Maximizing Equatorial States	Splitting the Difference
Egypt	4,170	3,851	2,498	1,804	3,081
Sudan	3,109	3,428	1,778	1,339	2,414
Ethiopia	600	600	3,603	3,603	2,102
Equatorial states	1,233	1,233	1,233	2,366	1,516

Table 11. An Assessment of Game Theoretical Solutions

Solution	Allocation	Individual Rationality and Group Rationality Conditions	Difference to the Focal Point	Propensity to Disrupt
1. Nucleolus		satisfied		
Egypt	3,051		85	0.90
Sudan	2,309		77	0.87
Ethiopia	1,952		157	1.22
Equatorial states	1,800		7	1.00
2. Per capita nucleolus		satisfied		
Egypt	2,996		30	0.98
Sudan	2,255		23	0.96
Ethiopia	2,344		235	0.72
Equatorial states	1,516		290	3.00
3. Shapley value		satisfied		
Egypt	2,960		6	1.05
Sudan	2,280		48	0.92
Ethiopia	2,049		60	1.07
Equatorial states	1,823		17	0.92
4. Generalized Shapley value		satisfied		
Egypt	2,835		131	1.29
Sudan	1,900		332	1.75
Ethiopia	2,386		277	0.68
Equatorial states	1,987		181	0.50
5. Hypothetical focal point		satisfied		
Egypt	2,966		-	1.04
Sudan	2,232		-	1.00
Ethiopia	2,109		-	0.99
Equatorial states	1,806		-	0.98

[64] Analyses of game theoretical solutions such as the Shapley value and the nucleolus can help decision makers and negotiators from riparian countries to identify the sources and magnitude of their bargaining powers and to gauge how such powers may fare in differing circumstances. For example, benefits for Ethiopia and the equatorial states increase markedly if a Shapley value solution is modified to a generalized Shapley value solution. Those countries may accordingly benefit from waiting to be the last to join in cooperation. When a hypothetical focal point is established by splitting the differences for the core, the Shapley values for these upstream riparian countries closely approximate that point. In combination these results make a Shapley value approach an attractive guiding concept for solutions to allocation problems.

[65] The cooperative game theory framework established in this article can also serve as a basis for designing gaming exercises for training purposes or for actual negotiations among riparian countries. One example might be an interactive game in which each participant in a particular gaming session would represent a riparian country and negotiate with other players over the terms of a potential agreement on water allocation. The game could be designed to simulate an actual negotiation process in which decision makers and negotiators are required to make decisions, over several sessions, on a set of strategic choices such as entering an agreement with other riparian countries, forming partial coalitions with other riparian countries, or taking unilateral actions. At the end of each session, scores could be displayed indicating the economic benefits obtained for each country by its representative player. Such gaming exercises can generate valuable insights for decision makers and negotiators as a preparatory phase before undertaking formal negotiations.

[66] For students of the Nile basin, some of the results of this specific application of game theory are of particular interest. *Waterbury* [2002] described Sudan as "the Master of the Middle," and highlighted the critical role Sudan would play in the search for basin-wide cooperative solutions. Our modeling results confirm this insight: the core of the game suggests that Sudan could command a significant premium for its participation in a cooperative scheme because it is the only player whose lower bound is higher than its benefit from acting unilaterally. Of course, the fact that Sudan has this power does not necessarily mean that she will use it to her neighbors' disadvantage.

[67] Interestingly, in many solutions Egypt's willingness to cooperate will be high as seen from relatively low propensity to disrupt. This result will perhaps surprise some observers, but it simply reflects the fact that Egypt benefits significantly from most cooperative solutions (and is most at risk from unilateral actions by upstream riparians). Similarly, Ethiopia benefits greatly from most cooperative solutions. The fact that most of the Nile waters originate in Ethiopia is not a good reason for Ethiopia to avoid cooperation on river basin development. Indeed, in terms of the benefit allocations that we examined, Ethiopia stands to gain the most (in both absolute and relative terms) from joining the grand coalition, relative to the status quo.

[68] Perhaps the main lesson from our analysis is that all Nile riparians stand to gain substantially from the grand coalition, and that there are numerous benefit sharing rules that seem both feasible and equitable.

Appendix A: Constraints of NEOM

[69] 1. Continuity constraints for reservoir nodes,

$$\begin{aligned} S_{t+1}^{i} = {} & S_{t}^{i} + I_{t}^{i} + \left(1 - EV_{t}^{j-i}\right) R_{t}^{j} - \left(e_{t}^{i} - r_{t}^{i}\right) \\ & \cdot \left[a^{i} + b^{i}\left(\frac{S_{t}^{i} + S_{t+1}^{i}}{2}\right)\right] - Q_{t}^{i,c} - R_{t}^{i}, \end{aligned} \tag{A1}$$

for t = 1, 2, 3 ... 12.

[70] 2. Continuity constraints for intermediate nodes,

$$\left(1 - EV_t^{j-i}\right)R_t^j + I_t^i = R_t^i + Q_t^{i,c}, \tag{A2}$$

for t = 1, 2, 3 … 12 (j indicates nodes immediate before i and can be more than one node).

[71] 3. Storage capacity constraints for reservoir nodes,

$$S_{\text{Min}}^i \leq S_t^i \leq S_{\text{Max}}^i. \tag{A3}$$

[72] 4. Irrigation water withdrawal pattern,

$$Q_t^{i,c} = Q^{i,c}\delta_t^i, \tag{A4}$$

for t = 1, 2, 3 .. 12.

[73] 5. Hydropower generation equations,

$$KWH_t^{i,c} = \eta R_t^i f\left(S_t^i, S_{t+1}^i\right)\varepsilon, \tag{A5}$$

for t = 1, 2, 3 .. 12.

[74] 6. Hydropower generation capacity constraints,

$$KWH_t^{i,c} \leq CAP^{i,c}, \tag{A6}$$

for t = 1, 2, 3 … 12

[75] 7. Nonnegativity constraints,

$$S_t^i, R_t^i, Q_t^i, KWH_t^{i,c} \geq 0, \tag{A7}$$

for all the decision variables and for t = 1, 2, 3 … 12.

[76] S_t^i is reservoir storage for reservoir *i* in month *t*; I_t^i is the inflow to site *i* in month *t*; R_t^i = the release (or the outflow) from site *i* in month *t*; EV_t^{j-i} is the percentage of evaporation loss for water flowing from site j (where *j* indicates immediate nodes before site *i*, and can be more than one) to site *i*; e_t^i is the evaporation rate at site *i* in month *t*; r_t^i is the addition to flow at site *i* in month *t* due to rainfall; a^i and b^i are the constant and the slope of the area storage relation of the reservoir, respectively; S_{Min}^i and S_{Max}^i are the minimum and maximum storage for any reservoir at site *i*; $Q^{i,c}$ is the irrigation withdrawal for irrigation site *i* in October; δ_t^i = the coefficients of irrigation withdrawal for site *i* in month *t* in relation to irrigation withdrawal for site *i* in October; η is unit conversion constant; $f(S_t^i, S_{t+1}^i)$ is function determining average productive head; ε is hydropower efficiency; and $CAP^{i,c}$ is the maximum hydropower that can be generated at site *i* in month *t*.

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D. Whittington, Department of Environmental Sciences, University of North Carolina, Chapel Hill, NC 27599, USA. (dale_whittington@unc.edu)

X. Wu, Lee Kuan Yew School of Public Policy, National University of Singapore, 29 Heng Mui Keng Terrace, Singapore 119620. (sppwuxun@nus.edu.sg)